BIOMASS CARBON ESTIMATION OF IMPORTANT NORTH–WESTERN HIMALAYAN TREE SPECIES

Thesis

by

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CERTIFICATE – I

This is to certify that the thesis titled **“Biomass carbon estimation of important North-Western Himalayan tree species ”** submitted in partial fulfillment of the requirements for the award of degree of **Master of Science** (Forestry) in the discipline of **Silviculture** to **Dr. Yashwant Singh Parmar University of Horticulture & Forestry, Nauni, Solan (HP) – 173 230** is a bonafide research work carried out by **Ms. Aditi Sharma (F-2014-37-M)** daughter of Mr. Pawan Dev Sharma under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE – II

This is to certify that the thesis titled **“Biomass carbon estimation of important North-Western Himalayan tree species”** submitted by **Ms. Aditi Sharma (F-2014-37-M)** daughter of **Mr. Pawan Dev Sharma** to **Dr. Yashwant Singh Parmar University of Horticulture & Forestry, Nauni, Solan (HP) – 173 230**, **India** in partial fulfillment of the requirements for the award of degree of **MASTER OF SCIENCE** (Forestry) in the discipline of **Silviculture** has been approved by the Advisory Committee after an oral examination of the student in collaboration with an External Examiner.

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ABBREVIATIONS USED

a m sl	above mean sea level
AGB	Above Ground Biomass
BGB	Below Ground Biomass
C	Carbon
CCF	Crown Competition Factor
CO_2	Carbon dioxide
D^2H	Diameter squared Height
DBH	Diameter at Breast Height
E	East
et al	Co-workers
FRI	Forest Research Institute
FSI	Forest Survey of India
GBH	Girth at Breast Height
H P	Himachal Pradesh
IPCC	Intergovernmental Panel on Climate Change
M	Meter
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
mm	mili meter
N	North
NE	North East
NW	North West
^{o}C	Degree Celsius
R/S	Root: shoot ratio
R^2	Coefficient of Determination
$\bar{R}^2$	Adjusted R squared
S	Sigmoidal
SOC	Soil Organic Carbon
Sp	Species
TCD	Total Carbon Density
Tg C	Tera gram Carbon
V	Volume
Viz	*Videlicet*
$Mg\ ha^{-1}$	Mega gram per hectare
$Pg\ C\ yr^{-1}$	Petagrams of carbon per year
$t\ ha^{-1}yr^{-1}$	tonne per hectare per year
$t\ C\ ha^{-1}$	tonne Carbon per hectare
$t\ ha^{-1}$	tonne per hectare

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Chapter-1

INTRODUCTION

Forests play an important role in regional and global carbon (C) cycles because they store large quantities of C in vegetation and soil, exchange C with the atmosphere through photosynthesis and respiration and are sources of atmospheric C when they are disturbed by human or natural causes, become atmospheric C sinks during re-growth after disturbance, and can be managed to sequester or conserve significant quantities of C on the land (Brown *et al.*, 1996; Sharma *et al.*, 2011). This global importance of forest ecosystem emphasizes the need to accurately determine the amount of carbon stored in different forest ecosystem (Nizami, 2010).

Quantification of forest biomass and volume may be important for several reasons. Quantification of amount of biomass, and subsequent C, is presently an important component in the REDD+ initiatives. REDD+ is a system of financing mechanisms and incentives aiming at mitigating climate change by reducing deforestation and forest degradation. Participating countries in REDD+ projects are required to produce accurate estimates for their forest C stocks and changes through robust Measurements, Reporting and Verification (MRV) schemes. The assessment of REDD+ has been done by comparing current rate of deforestation and forest degradation against established historical rate known as Reference Emission level/Reference Levels and its estimation utilizes biomass models. Quantification of biomass is also essential for issues related to energy production (fuelwood and charcoal production) in conventional forest management planning.

Various models may be employed to quantify forest C stocks. The most common and accurate approach involves the use of models for prediction of tree dry weight, from which C stock may be derived (e.g. Brown, 1997; Chave *et al.*, 2005; 2014). Development of models requires destructive sampling of trees to determine aboveground biomass (AGB) and belowground biomass (BGB).

There are two main approaches to estimation of tree biomass. One is to obtain biomass as a product of tree volume and wood density. However, since most of the volume equations consider only the merchantable part of the tree, a biomass expansion factor that expands merchantable volume directly to total aboveground biomass is usually applied. The second approach is the direct use of biomass models. Now a day, allometric models are being used for quantifying biomass and carbon storage in terrestrial ecosystems. The allometric relationship considering tree parameters i.e. Diameter at Breast Height (DBH) and height is the important, most common, and easily measurable parameter that can be used to predict the biomass carbon than any other characteristics. Regression models used to estimate the biomass of the standing trees depend on several variables including diameter at breast height (DBH), total tree height (ht), crown diameter and wood density (ρ) (Cannell, 1984; Chave *et al*., 2005; Goodman *et al*., 2014). Allometric equations, relating to the biomass with one or more tree dimensions are frequently used to compute average tree biomass (Whittakar and Woodwell, 1968). The volume equations earlier developed by FRI (1996) and FSI (1996) for softwood and hardwood using multiple regression methods in which basal area, girth or DBH along with height or form factor were used to predict volume and biomass. These volume equations have further been used by Singh *et al.* (2011) and Salunkhe *et al.* (2016) for biomass estimation.

The forests of Himachal Pradesh have its utmost ecological importance in this region with a forest cover of 25.8 percent of the geographic area as per Forest Survey of India Report (2015). According to National Forest Policy, 1988, atleast two third i.e., 66 percent of geographical area should be under forest in the hill states like Himachal Pradesh. However keeping in view about 20 percent of the area inaccessible and beyond the tree limit, the state Government aims to bring 50 percent of the geographical area under forest cover. The forest of state has been classified on an ecological basis as laid down by Champion and Seth; it can be broadly classified into Coniferous Forest and Broad-leaved Forests. Distribution of various species follows regular altitudinal stratification. The vegetation varies from Dry Scrub Forests at lower altitudes to Alpine Pastures at higher altitudes. Larger area of the state is inhibited by chil, oaks, deodar, kail, fir and spruce and so far no local biomass tables or allometric equations have been developed for biomass carbon estimation.

Global models have the advantage of being in principle, applicable anywhere. However, due to great variation in climatic and edaphic factors, such models can yield large error locally. Thus a model developed on data from the similar region will within that region give more accurate estimates. Similarly, a model developed generally for a large number of species is more versatile in application phase, but will yield estimates with large errors for those species that are a typical relative to mean relationships between response and the input variables. A species-specific model has a more narrow range of application, but will give better estimate for that particular species. Therefore, the study was conducted on important tree species of Himachal Pradesh with the objectives as:

Objectives:

i) To develop allometric relationship of DBH and height with biomass carbon.

ii) To formulate model for biomass carbon estimation.

Chapter-2

REVIEW OF LITEATURE

The pertinent literature from the sources available has been reviewed under the following heads:

2.1 Allometric relationship

2.2 Volume tables derived from allometric relationships

2.3 Testing and validation of allometric model

Field method for estimation of volume and biomass carbon is quite labour intensive, time consuming and difficult due to methodological inadequacies. Therefore, reliable models have been developed through statistical techniques with more specified procedure for biomass and carbon stock studies. Now a day, allometric models are being used for quantifying biomass and carbon storage in terrestrial ecosystem. The allometric relationship considering tree parameters i.e., DBH (diameter at breast height) and tree height is the important, most common, and easily measurable parameter that can be used to predict the biomass carbon than any other characteristics. Allometric equations, relating to the biomass with one or more tree dimensions are frequently used to compute average tree biomass (Whittakar and Woodwell, 1968).

In India, various allometric equations have been developed for important softwood and hardwood Himalayan species namely; *Pinus roxburghii*, *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow*, *Picea smithiana* and *Quercus leucotrichophora* using multiple regression methods in which basal area, girth or DBH along with height or form factor were used to predict volume and biomass. FSI (1996). Singh *et al*. (2011) has applied equations developed by FRI (1996) for estimating the biomass and carbon stock in small diameter trees in Terai region of central Himalayas. On the same line, relationships have been developed for *Cedrus deodara* (Chaturvedi, 1973), *Pinus roxburghii* (Chauhan and Sahoo, 1997; Sharma and Nanda, 2008), *Acacia catechu* (Lal, 2004), *Azadirachta indica* (Jain *et al*., 1998), *Acacia auriculiformis* (Jain *et al*., 1996; Mittal *et al*., 1991) and *Acacia catechu* (Mishra and Singh,1985).

Similarly several generalized biomass prediction equations have been developed for tropical species (Brown *et al*., 1989; Chambers *et al*., 2001; Chave *et al*., 2005; Djomo *et al*., 2010; Henry *et al*., 2010; Ebuy *et al*., 2011; Fayolle *et al*., 2013), temperate species (Overman *et al*., 1994) and mangrove trees in northeast Brazil (Zarnovican, 1991). However, Ter-Mikaelian and Korzukhin (1997) has reported a list of biomass equations for sixty-five North American tree species collected from various sources of literature.

2.1 ALLOMETRIC RELATIONSHIPS

Kittredge (1944) was one of the earliest to use allometric method to estimate amount of foliage on trees. He observed a significant relationship between foliage biomass and log DBH and advocated that this relationship was applicable to trees of different sizes, densities, crown classes and ages.

Ker (1980) used logarithmic equations for total aboveground biomass based on DBH, height, crown diameter and crown length for 10 tree species in Nova Scotia, Canada and reported R^2 values for aboveground biomass as high as 0.99 for *Populus termuloides, Betula* sp., *Larix laricina, Acer ruberum, Pseudotsuga menziesii, Pinus resinosa, Picea mariana, Picea glauca,* 0.97 for *Abies balsamea* and 0.98 for *Pinus banksiana.*

Payandeh (1983) developed one logarithmic regression model and two simple non-linear power function based on DBH and height for *Betula alleghaniensis* and *Acer saccharum* and revealed that simple power function was the best fit for observed biomass and that the addition of height as a variable did not improve the goodness of fit significantly.

Rawat and singh (1988) while studying structure and function of 3 area of Himalayan oak forest developed significant allometric equations relating biomass of different tree components to GBH (girth at breast height) in *Quercus leucotricophora, Quercus floribunda* and *Rododendron arborium.* Total forest floor biomass ranged between 4.6 and 6.2 t ha^{-1} .

DBH is the best predictive variable for stem volume estimation as reported by Negi *et al*. (1998) in *Prosopis juliflora*. Similarly Wan *et al.* (1989), Dogra and Sharma (2003) and Ashwani kumar (2004) reported logarithmic function as best fit in *Acacia mangium, Toona ciliata, Eucalyptus* hybrid, respectively. On the other hand parabolic function in teak as reported by Chakarbarti and Gaharwar (1995) and polynomial in *Pinus caribaea* by Allen (1991) were found to be best fit.

Tandon *et al.* (1991) regressed individual total biomass and biomass of various components against independent variables for *Populus deltoides.* They developed logrithmic equation and a simple linear regression equation using DBH, DBH^2*H as a predictor variables. Therefore found that DBH was the most reliable parameter for prediction of biomass through allometric relationship.

Chakrabarti and Gaharwar (1995) utilized the volume equations developed for teak based on data from various inventory surveys carried out by Forest Survey of India (FSI) from time to time over various parts of India for establishing a statistical relationship between average volume and mid diameter for country as a whole. They concluded that for lower diameter classes (up to 30 cm), linear relationship ($V=-0.1163+2.8013D$) and for higher diameter class parabolic equation ($V=0.1657-1.1235D+8.0855D^2$) could be used satisfactorily for calculating volume.

Ter-Mikaelian and Korzukhin, (1997) gave comprehensive review of the biomass equations for sixty- five North American tree species. All equations are of the form $M = aD^b$ where M was the oven-dry weight of the biomass component of a tree (kg), D was diameter at breast height (DBH) (cm), and a and b are parameters. Equations for the following tree components were included in the review: total aboveground biomass, stem wood, stem bark, total stem (wood and bark), foliage, and branches (wood and bark). A total of 803 equations were presented with the range of DBH values of the sample, sample size, coefficient of determination R^2, standard error of the estimate, fitting method used to estimate the parameters a and b, correction factor for a bias introduced by logarithmic transformation of the data, site index and geographic location of the sampled stand(s), and a reference to the paper in which the equation (or the data) was published. The review is a unique source of equations that can be used to estimate tree biomass and/or to study the variation of biomass components for a tree species.

Pereira *et al*. (1997) destructively sampled the trees of *Acacia mearnsii* and derived regression equations for the aboveground biomass and estimated biomass from DBH. Using these equations, the biomass was estimated 158.51 t ha^{-1}, 12.3 percent belonging to the canopy (leaves 4.23, live branches 11.28 and dead branches 4.02 t ha^{-1}) and 87.7 percent belonging to the stems (wood 125 and bark 13.98 t h^{-1}).

Cairns *et al.* (1997) reviewed and summarized the literature containing root biomass measurements and tested the relationships between both root biomass density (Mg ha^{-1}) and root: shoot ratios (R/S) as dependent variables and various edaphic and climatic independent variables, singly and in combination. None of the tested independent variables of aboveground biomass density, latitude, temperature, precipitation, temperature, precipitation ratios, tree type, soil texture, and age had important explanatory value for R/S. However, linear regression analysis showed that aboveground biomass density, age and latitudinal category were the most important predictors of root biomass density and together explained 84 percent of the variation. A comparison of root biomass density estimates based on their equations with those based on use of generalized R/S ratios for forests in the U. S. indicated that their method tended to produce estimates that were about 20 percent higher.

Monserud and Marshall (1999) developed allometric equation predicting individual branch and total crown leaf area, leaf biomass and branch wood mass for Douglas fir, Ponderosa pine and western white pine. Non-linear regression with general allometric equation was used to estimate all parameters. For the branches, branch diameter and length, foliated length and position in the crown explain 82-97 percent of the variation. Specific leaf area (leaf area/mass) differed significantly among species and increased with distance from the tree top. For whole trees, sapwood area at breast height, crown ratio and length and crown competition factor (CCF) explained 94-99 percent of the variation.

Pant (2001) studied various growing stock parameters (inventory) of *Pinus caribaea* in Madhya Pradesh and found that the most suitable regression model was logarithmic regression model and DBH was the best predictive variable for the single tree volume. This was compared with other regression equations and was found most suitable and widely applicable. The results obtained were highly significant. Number of stems ha^{-1}, basal area and volume ha^{-1} were also calculated with confidence at 95 percent probability ($P=0.05$).

Haripriya (2002) studied the allometric relationship for forest types in her study on softwood and hardwood species. The results showed high value of R^2 for the evergreen and semi-evergreen forest with R^2 values between 0.56 and 0.99 for the relationship between number of stem [Ln(N)] and diameter (D) as linear for all forest types, i.e., Fir and spruce ($R^2=0.56$), Deodar ($R^2=0.84$), Chir pine ($R^2=0.69$), Mixed conifers ($R^2=0.85$) and Hardwood mixed with conifers ($R^2=0.64$).

Goodale *et al.* (2002) estimated forest sector C budgets for Canada, the United States, Europe, Russia and China that were derived from forest inventory information, allometric relationships and supplementary data sets and models. Together they suggested that northern forests and woodlands provided a total sink for 0.6–0.7 Pg C year^{-1} during the early 1990s', consisting of 0.21 Pg C yr^{-1} in living biomass, 0.08 Pg C yr^{-1} in forest products, 0.15 Pg C yr^{-1} in dead wood and 0.13 Pg C yr^{-1} in the forest floor and soil organic matter.

Cairns *et al.* (2003) developed species-specific biomass regression models for the six most common species of large (>10 cm DBH) trees and for the nine most common species of small (<10 cm DBH) trees from the destructive harvest of 698 trees. Mass of large trees were used to derive the regression model, where Y was the total dry weight (kg), D the DBH (cm), and TH the total height (m). Total aboveground tree biomass was estimated to be 225 Mg ha^{-1}, and was dominated (85%) by the biomass of the large trees. The actual biomass of each of the 195 large trees was compared to individual tree biomass calculated with a published regression model $Y = \exp\{-2.173 + 0.868 \ln(D^2TH)+0.0939/2\}$ of FAO (1997) that is based on measurements of 29 trees. It was found that the published model underestimated biomass of these trees by 31 percent (37.6 versus 54.4 Mg). Calculated biomass was less than measured biomass for 29 of 33 species. The current study points to the value of site-specific assessment of aboveground biomass and may contribute to more accurate estimates of dry tropical forest biomass densities currently used to estimate greenhouse gas flux from land management activity.

Haripriya (2003) used the model developed by Kurz *et al*. (1992) taking into account the growing stock, leaf, flower, fruits, dead biomass, litter, SOC, harvesting losses, effect of pests, fire, extraction of timber for estimation of carbon and reported that Indian forest ecosystems were net source of 12.8 Tg C for 1993-1994. The net change of carbon in all forest types was 0.2 t ha^{-1} year^{-1} in all forest types. Maximum loss of 0.58 t ha^{-1}year^{-1} was noticed in temperate broadleaved forests while subtropical and alpine forests acted as net sinks of carbon at the rate of 0.09 and 0.19 t ha^{-1} year^{-1}.

Kraenzel *et al.* (2003) estimated the carbon storage potential of 20 years old Panamanian teak (*Tectona grandis*) plantations. A regression related to diameter at breast height (DBH) to total tree carbon storage was constructed and was used to estimate plantation-level carbon. Litter, undergrowth and soil compartments were estimated to contain

3.4, 2.6 and 225 t C ha^{-1}, respectively. The carbon storage in Panamanian harvest-age teak plantations was estimated to be 351 t C ha^{-1}.

Specht and West (2003) estimated biomass and carbon sequestration on farm forest plantations in northern New South Wales, Australia. Tree stem diameters were measured in a stratified random sample of 1–10 years old, growing eucalyptus, sub-tropical rainforest species or an exotic conifer, both in single-species and mixed-species plantations. A sample of trees was measured for biomass and estate and region specific allometric relationships were developed to predict tree biomass from tree diameter. With the stratified random sample data, the allometric relationships were used to predict total amount of carbon sequestered in tree biomass and its 95 percent confidence limit, across each estate.

Xiao and Ceulemans (2004) developed and compared trees allometric relationships for 10-year-old Scots pine (*Pinus sylvestris* L.) describing branch and needle biomass at the branch level, as well as biomass of stems, branches, needles, coarse roots, small roots and total biomass at the tree level. At the branch level, the relationships of branch diameter, branch length and whorl position were the best to predict branch and needle biomass. They were able to explain 96 percent of the observed variation for branches and needles. Simple allometric relationships of whorl height accurately predicted vertical distribution of branch and needle biomass as well as of their total, and explained more than 96 percent of the observed variation. The vertical distributions of biomass of branches, of needles and of their total, were very similar and were skewed vertically downward. At the tree level, stem diameter at breast height (DBH) and tree height were significant determinants of biomass of stems, coarse roots and small roots. Similarly DBH, tree height and crown length were the predominant variables of biomass of branches and needles, and of the entire tree biomass. All together, allometric relationships with DBH were the best to estimate biomass of all above and belowground compartments. These relationships were able to explain more than 98 percent of the observed variation. For 4.5–5.6 m tall trees with an average DBH of 7.16 cm, the entire tree biomass was 13.38 kg. On average 33.9 percent of the biomass was allocated to the stem, 25 percent to the branches, 22 percent to the needles, 17.8 percent to the coarse roots and 1.3 percent to small roots. The ratio of belowground biomass to aboveground biomass amounted to 0.26.

Chave *et al*. (2005) provided a critical reassessment of the quality and the robustness of regression models to convert inventory data into an estimate of aboveground biomass

(AGB) across tropical forest types, using a large dataset of 2,410 trees >or= 5 cm diameter, directly harvested in 27 study sites across the tropics. Proportional relationships between aboveground biomass and the product of wood density, trunk cross-sectional area, and total height were constructed. The models were tested for secondary and old-growth forests, for dry, moist and wet forests, for lowland and montane forests and for mangrove forests. The most important predictors of AGB of a tree were, in decreasing order of importance, its trunk diameter, wood specific gravity, total height, and forest type (dry, moist, or wet). Overestimates prevailed, giving a bias of 0.5-6.5 percent when errors were averaged across all stands. Their regression models can be used reliably to predict aboveground tree biomass across a broad range of tropical forests. Because they are based on an unprecedented dataset, these models should improve the quality of tropical biomass estimates, and bring consensus about the contribution of the tropical forest biome and tropical deforestation to the global carbon cycle.

Gupta and Bhardwaj (2005) studied aboveground biomass production of black wattle in mid hills of Himachal Pradesh. Some easily measurable attributes such as plant height and DBH were used to develop allometric relationship which showed that DBH was the best predictor variable for total aboveground biomass (controlling more than 80% variability) and the inclusion of height as variable in the model slightly improved the adequacy of the model.

Mural and Bhat (2005) studied biomass estimation equations for tropical deciduous and evergreen forests. In the study, linear and non linear equations were developed to estimate biomass of tropical forests along with estimates of goodness of fit and percentage of errors. Basal area and height of trees were found to give high goodness of fit and low percentage of errors for deciduous forests. Generally, the coefficient of determination (R^2) was low for evergreen forests, probably due to presence of trees of different height in different canopies that may have different growth rates. The coefficient of determination was high and estimate of error was low for deciduous forests.

Xing *et al*. (2005) sampled balsam fir (*Abies balsamea*) to investigate the effects of forest management practices, site location, within-crown composition, tree component (i.e., stem, foliage branches and roots) and tree classes on biomass and carbon partitioning in individual tree level and ecological regions. Three allometric equations of biomass and carbon that account for partitioning among different parts of the tree were developed. DBH was used as the only explanatory variable to describe the fresh biomass, dry biomass and Carbon content. All regressions showed high correlation with DBH with R^2 value > 0.95.

Zianis *et al.* (2005) formulated the stem volume and biomass equations for tree species growing in Europe. The mathematical forms of the empirical models, the associated statistical parameters and information about the size of the trees and the country of origin were collected from scientific articles and from technical reports. Total number of the compiled equations for biomass estimation was 607 and for stem volume prediction it was 230. They analysed that most of the biomass equations were developed for aboveground tree components. Most of the biomass equations were based on a few sampled sites with a very limited number of sampled trees. The volume equations were in general based on more representative data covering larger geographical regions. The collected information provided a basic tool for estimation of carbon stocks and nutrient balance of forest ecosystems across Europe as well as for validation of theoretical models of biomass allocation.

Cole and Ewel (2006) studied four tree species *Cedrela odorata*, *Cordia alliodora*, *Hyeronima alchorneoides* and *Euterpe oleracea* in humid lowlands of Costa Rica. Harvested trees were dissected into their component parts: leaves, branches, boles, and coarse roots (i.e., >0.5 cm diameter). Size class samples ranged from seedlings to small trees of 30 cm DBH. Two separate allometric equations (one for trees having only a basal diameter and another for trees having a DBH) with diameter squared times height as the metrics, were developed for each component of each species. Separate allometric equations were developed by component, for trees of different sizes. The resulting 40 equations (with one exception, involving very small trees) fit the data well and enabled the user to predict biomass for each of the four species.

Mokany (2006) analysed root-shoot biomass relations for forest and woodlands and further examined root-shoot biomass relations separately for shrublands and grasslands (including savannas) as the latter possessed a much greater range in root: shoot ratios (0.34–26.03). The mean shoot biomass of retained data (116Mg/ha) was significantly lower (P=0.001) than for either inadequate (177Mg/ha) or unverifiable (206Mg/ha) data for forest and woodland. Power function ($y=0.489x^{0.890}$) was applied to shoot data for forest and woodlands with $R^2 = 0.93$.

A study was conducted by Alamgir (2008) in the forest area of Chittagong (South) Forest Division, Bangladesh for developing allometric models to estimate biomass organic carbon stock in the forest vegetation. Allometric models were tested separately for trees (divided into two DBH classes), shrubs, herbs and grasses. Model using basal area alone was found to be the best predictor of biomass organic carbon stock in trees because of high coefficient of determination (R^2=0.74 and 0.88 for > 5 cm to ≤ 15 cm and > 15 cm DBH range, respectively) and significance of regression (P =0.000 for each DBH range) coefficients for both DBH range. The other models using height alone; DBH alone; height and DBH together; height; DBH and wood density; with linear and logarithmic relations produced relatively poor coefficient of determination. The allometric models for dominant 20 tree species were also developed separately and equation using basal area produced higher value of coefficient of determination. The allometric models developed can be utilized for future estimation of organic carbon stock in forest vegetation in Bangladesh as well as other tropical countries of the world.

A study was conducted by Sharma and Nanda (2008) on chirpine stand *(Pinus roxburghii Sargent)* in Barog forest range (R-31) under Solan Forest Division (Himachal Pradesh) to develop volume prediction model based on stem and crown characteristics. Various linear and non-linear functions based on stem volume and crown parameter relationships were developed and compared for their performances. Based on adjusted R^2, the log-linear and power function performed better among all the functions and both of them explained 99 percent variation in stand volume due to crown volume followed by crown area (90 percent), crown diameter (90 percent), crown width (88 per cent) and crown length (85 percent). However, the power function outperformed the log-linear function, when data were subjected to chi-square test of goodness of fit and thereafter using Theil-U test. The predicted volume based on crown volume was cross validated and tested for its accuracy by correlating it with observed volume and volume estimated through volume table. The accuracy was found to be 90 percent.

Basuki *et al.* (2009) developed separate equations for *Dipterocarp*, *Hopea, Palaquium*, *Shorea* and Commercial Sp. and an equation of mix of these genera taking DBH, commercial bole height (CBH), and wood density as predictors and were used for dry weight of total aboveground biomass (TAGB). Model comparison and selection were based on Akaike Information Criterion (AIC), slope coefficient of the regression, average deviation, confidence interval (CI) of the mean, paired t-test. Based on these statistical indicators, the most suitable model was ln(TAGB) = c + aln(DBH). This model used only a single predictor of DBH and produced a range of prediction values closer to the upper and lower limits of the observed mean. Additional explanatory variables such as CBH did not really increase the indicators' goodness of fit for the equation. An alternative model to incorporate wood density was considered for estimating the aboveground biomass for mixed species. Comparing the presented equations to previously published data showed that these local species-specific and generic equations differed substantially from previously published equations and that site specific equations was considered to get a better estimation of biomass. Based on the average deviation and the range of CI, the generalized equations were not sufficient to estimate the biomass for a certain type of forests, such as lowland Dipterocarp forests. The research findings were new for Dipterocarp forests, so they complemented the previous research as well as the methodology of the Good Practice Guidance for Land Use and Land Use Change and Forestry (GPG-LULUCF).

Navar (2009) developed and applied allometric equations to forest inventory data to estimate biomass and carbon stocks for temperate species and forests of Durango and Chihuahua and for tropical dry forests of Sinaloa, Mexico. Allometric equations having only DBH as an independent variable were developed for each component of each species. Since *Pinus herrerae, Pinus engelmannii, Pinus oocarpa* and *Pseudotsuga menziensii* had a small number of trees, an individual allometric equation was developed for these species. Non-linear regression was used to fit parameters of the typical allometric power equation. The resulting 31 equations (10 species or groups of species, three biomass components; bole, branch and leaves, and total aerial; and the generalized equation for coarse roots) fit the data well and enables the user to predict biomass by component for each of the 10 different groups of species or each of six temperate species. A single allometric equation that incorporated the basic specific gravity for aboveground biomass of all temperate tree species also fit the data well, and this equation provided both the detail and the accuracy supplied by species-specific, plant-part-specific equations. Biomass equations coupled with forest inventory data for temperate (637 circular, 1/10 ha plots) and tropical dry forests (166) 20 m x 20 m-quadrates) of northwestern Mexico predict a mean (confidence intervals) of 130 Mg ha^{-1} (4.2 Mg ha^{-1}) and 73 Mg ha^{-1} (7.1 Mg ha^{-1}) for total tree and total aboveground biomass, respectively. Large sample sizes and the economic and ecological importance of the species studied make this data set uniquely useful for biomass estimations and for understanding the inherent heterogeneity of tree structure in dynamic tropical and temperate environments of northwestern Mexico.

Singh *et al.* (2011) estimated biomass and carbon sequestration rate of a young (four year old) mixed plantation of *Dalbergia sissoo* Roxb., *Acacia catechu* Willd. and *Albizia lebbeck* Benth. growing in Terai region (a level area of superabundant water) of central Himalaya. Allometric equations for both above and belowground components were developed for three tree species. Five diameter classes were defined for *D. sissoo* and *A. catechu* and three for *A. lebbeck*. Five trees were harvested in each diameter class. Individual tree allometry was exercised for developing the allometric equations relating tree component (low and aboveground) biomass to DBH. Highly significant ($P < 0.001$) allometric equations were obtained for all the components of the three species. The general biomass equations of total biomass provided better fits than the species component specific allometric equations.

To estimate forest carbon pools from forest inventories it is necessary to have biomass models or biomass expansion factors. Peinado (2012) developed tree biomass models for the main hardwood forest species in Spain: *Alnus glutinosa*, *Castanea sativa*, *Ceratonia siliqua*, *Eucalyptus globulus*, *Fagus sylvatica*, *Fraxinus angustifolia*, *Olea europaea* var. *sylvestris*, *Populus x euramericana*, *Quercus canariensis*, *Quercus faginea*, *Quercus silex*, *Quercus pyrenaica* and *Quercus suber*. Different tree biomass components were considered: stem with bark, branches of different sizes, above and belowground biomass. For each species, a system of equations was fitted using seemingly unrelated regression, fulfilling the additive property between biomass components. Diameter and total height were explored as independent variables. All models included tree diameter whereas for the majority of species, total height was only considered in the stem biomass models and in some of the branch models. The comparison of the new biomass models with previous models fitted separately for each tree component indicated an improvement in the accuracy of the models. A mean reduction of 20 percent in the root mean square error and a mean increase in the model efficiency of 7 percent in comparison with recently published models.

Vieilledent *et al.* (2012) analysed destructive sample of 481 trees in Madagascar spiny dry and moist forests characterized by a high rate of endemism (95%). Among the available generic allometric models like Chave's model including diameter, height and wood specific gravity as explicative variables for a particular forest type (dry, moist, or wet tropical forest) was the only one that gave accurate tree biomass estimates for Madagascar (R^2 83%, bias

6%), with estimates comparable to those obtained with regional allometric models. When biomass allometric models are not available for a given forest site, this result showed that a simple height–diameter allometry is needed to accurately estimate biomass and carbon stock from plot inventories.

Devine *et al.* (2013) studied 11-year-old Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) plantation on a highly productive site in south-western Washington to create diameter-based allometric equations for estimating individual-tree bole, branch, foliar, and total above-ground biomass. They used these equations to estimate per hectare aboveground biomass, nitrogen and carbon content and compared these results to estimates based on biomass equations published in other studies, and estimates made using the mean-tree method rather than allometric equations. Component and total-tree biomass equations were not influenced by the presence of vegetation control, although per hectare biomass C, and nitrogen estimates were greater where vegetation control was applied. The observed biomass estimates differ from estimates using previously published biomass equations by as much as 23 percent. When using the mean-tree biomass estimation approach, they found that incorporating a previously published biomass equation improved accuracy of the mean-tree diameter calculation.

Ilyas (2013) determined the tree biomass accumulations and age-related changes of *Acacia mangium* plantations by using a destructive sampling technique. Tree biomass samples were collected in 3, 5, and 7 year old plantations in mined area and in 7 year old plantations in not mined area. Allometric equations were developed for each site to estimate root, stem, branch, and leaf, aboveground and total biomass and stem volume. Using these equations, the stem volume and biomass of each component for each stand age were estimated. A single allometric relationship for all sites was found for estimation of biomass and stem volume. Allometric expressions of diameter breast height and stem volume for *A. mangium* stand is $Y = 0.000004\ X^{2.7126}$ ($R^2=0.98$); and the relationship between diameter breast height with tree biomass for *Acacia mangium*, where allometric equation for stem is $Y = 0.4668X^{1.8287}$ with correlation coefficient ($R^2=0.98$). For the branches is $Y=0.078\ X^{2.0038}$, with correlation coefficient ($R^2= 0.95$) and for the leaf is $Y = 0.0648\ X^{1.9348}$ with correlation coefficient ($R^2 = 0.95$). The contribution of stem, branch and leaf biomass of *Acacia mangium* were 67 percent, 19 percent and 14 percent respectively.

Ahmad *et al.* (2014) estimated the biomass expansion factor (BEF) and allometeric relationship of the native tree species *Picea Smithiana* in Kumrat valley. For the assessment of BEF, destructive method of sampling was used. Five trees of exploitable diameter were selected. The trees were separated in their respective components such as branches, twigs, foliages, and stem/bole and stump portion. Stem volume of each sample tree was calculated and converted into stem biomass. The biomass of branches, twigs, foliages and roots was calculated. The results of the study revealed that the mean biomass of stem was 1919.64 ± 244.44, while the mean biomass of branches, twigs, foliages and root was 299.26 ±32.32, 55.46± 5.57, 65.90 ± 2.87 and 435.81± 77.15 kg, respectively. In total biomass, the contribution of stem biomass was 66.28 percent, while the contribution of branches, twigs, foliages, and roots was 11.28, 2.193, 2.62 and 17.05 percent. The mean above ground biomass was 2104.055±264.814 kg while the mean total biomass was 2539.87 ± 341.80 kg. The root to shoot ratio was 0.206±0.011. The mean BEF was 0.686 ±0.0027 t m^3. Relationship of Diameter with stems and branches biomass (kg**)** showed higher values through $Y = -3739+16940x +12700x^2$ ($R^2 =0.99$), $Y = -380.5 + 2075x + (-1507)x^2$ ($R^2 = 0.95$)**.** Relationship of diameter (m) with twigs and leaves biomass (kg) showed through $Y = -75.76 + 407.8 x + (-303.5)x^2$ ($R^2 = 0.99$), $Y = 49.15 + 24.37 x + 10.43 x^2$ ($R^2 = 0.98$).Relationship of diameter (m) with aboveground biomass ,and roots biomass (kg) showed through $Y = -4416 +19440 x + (-14500)x^2$ ($R^2 = 0.98$), $Y = -1103+4631x +(-3291)x^2$ ($R^2 = 0.98$).

Chave *et al.* (2014) used 4004 trees above 5 cm DBH at 58 sites spanning a wide range of environmental and vegetation types and the continents of Africa, South America, South Asia and Australia. This study concluded that when trunk diameter, total tree height and wood specific gravity were included in the aboveground biomass model as covariates, a single model was found to hold across tropical vegetation types, with no detectable effect of region or environmental factors.

Raqeeb *et al.* (2014) estimated tree density, diameter, height and volume of the dominant tree species in four blocks (Thore, Chilas, Thak Niat and Gunar) of Chilas forest sub division. The tree density of deodar was maximum with average 26 tree·ha^{-1} and minimum was of Chalgoza 4 trees·ha^{-1}. Moreover, the average maximum volume attained by the Kail, Fir, Deodar and Chalgoza trees was 1.92, 1.57, 0.46 and 0.291 m^3 $tree^{-1}$ respectively. Regression analysis was carried out to determine the relationship between diameter (cm), height(m), tree density(trees ha^{-1}) and volume(m^3 ha^1). Regression models for Average volume (m^3 $tree^{-1}$) of the dominant species with respect to diameter in the study area and type of relationship were as: Kail: $V = 0.072 - 0.015(x) + 0.007(x)^2$; Fir: $V = 0.2628 - 0.035\,x + 0.001\,x$; Deodar: $V = 0.1040 - 0.018\,x - 0.0081\,x$; and Chalgoza: $V = 0.1640 - 0.026\,x + 0.01\,x$.

Ali *et al.* (2016) developed local allomteric equation and biomass expansion factor for *Cedrus deodara*. Data was collected from 32 sample trees felled and measured for the study in natural dry temperate forests of Gilgit-Baltistan, Pakistan. Diameter at breast height (DBH) and total height of the sample tree were measured before felling. The allometric equation was developed through logarithmic transformation of dependent and independent variables. Results showed good relationship between biomass (M) as dependent variable and DBH and height as independent variables. The relationship was found highly significant with R^2 of 0.98 for equation $M= 0.1779(D^2H)^{0.8103}$. Standard Error and sum of square (SS) of the residuals also indicated good fit of the model. The BEF for *Cedrus deodara* varied between 1.17 and 2.07 with a mean of 1.37±0.039 for trees with DBH>20 cm.

Bohre and Chaubey (2016) studied the biomass production and carbon sequestration for *Azadirachta indica* and concluded that the volume of trees varied positively and linearly in response to variation in basal area ($R=0.944$, $R^2=0.893$). The variation in basal area explained nearly 89 percent of the variation in volume. Therefore, basal area was found to be a good predictor of volume in trees. The total biomass of trees varied positively and linearly with basal area ($R = 0.944$, $R^2 = 0.893$). Basal area explained a higher proportion (i.e. 89%) of variation in total biomass. Although DBH was used to estimate basal area, it explained a lower amount of variation in volume ($R = 0.96$, $R^2 = 0.92$). DBH explained 92 percent of variation recoded in volume of trees. Therefore, the minimum and maximum volume of trees ranged from 0.005 to 0.522 m^3 $tree^{-1}$. Similarly minimum and maximum total biomass of trees ranged from 0.007 to 0.675 tons $tree^{-1}$.

Salunkhe *et al.* (2016) estimated tree biomass by non-destructive method for tropical dry deciduous forest (DDF) and tropical mixed deciduous forest (MDF) in 0.1 ha permanent plots established at seven sites each in seven districts of Madhya Pradesh in central India. Tree volume was calculated using site-specific volume equation. The biomass of each species was estimated taking tree volume and species specific gravity. The relationship between basal area and above ground biomass showed positive correlation for all sites and forest types. In general DDF had higher density, basal area and biomass than MDF irrespective of sites. Significantly higher basal area (m2 ha-0.1) was recorded in DDF (6.45 ± 4.22) MDF (4.53 ± 3.56). Average above ground biomass of both DDF and MDF of all sites were 31.8 t ha^{-1} and 20.7 t ha^{-1} respectively. Estimation of aboveground tree biomass in the study provided data for tropical deciduous forests covering a large part (24.66 %) of state for further use. Regression analysis between biomass and basal area was performed for both MDF and DDF. Both types of forest showed more or less similar values of R^2 i.e., 0.96 for MDF and 0.975 for DDF showing positive relationship between biomass and basal area.

2.2 VOLUME TABLE BASED ON ALLOMETRIC RELATIONSHIPS

Mittal *et al.* (1991) tried stepwise regression methods for obtaining the best fit based on dbh, height and their different combinations for estimating and predicting the volume of *Acacia auriculiformis.* The comparison was made based on R^2 and the best fit was used to prepare general and local volume tables. Whereas, Jain *et al.* (1993) used regression equation ($V=a+bD^2H$) for estimation of total wood over and under bark of *Eucalyptus globulus* in Nilgiri Hills and prepared the volume table. However, Jain *et al.* (1996) compiled over bark and under bark volume tables for *Acacia tortilis* using best fit regression equations $VOB = -0.02174 + 0.00003451\ D^2H + 0.0001990\ DH$ (R^2=98.91%) and $VUB = -01808+0.00002876\ D^2H$ to $0.00001385\ DH$ (R^2=98.5%), respectively. Similarly, Jain *et al.* (1998) prepared volume tables for *Azadirachta indica* for Gujrat region based on the data collected by felling 25 sample trees. Different models involving DBH and height were tried and the regression equation, $VOB = 0.11512+0.00001948D^2H+0.0003026\ DH$ and $VUB= -0.12078+ 0.00001193\ D^2H + 0.000434\ DH$ having minimum FI and/or standard error of estimate and maximum R^2 were selected. The range of volume over bark and under bark was reported to be 0.023-0.491m^3 and 0.014-0.398m^3 from 20 cm x 10m tree to 37 cm x 7.6m tree, respectively.

2.3 MODEL EVALUATION

Once a model has been developed, it is important that a fair evaluation of the model be carried out. Ideally, this is done by using data not used in either model formation or calibration. The term validation as used here refers to the process of assessing in some sense the degree of agreement between the model and real system being modeled. In order to use model inferences, about the real world with confidence, the model must be subjected to a process of testing and validation. The objective of the validation process is not to establish the absolute truth or falsity of the model but rather to determine whether the model will be useful for its intended use.

Anderson *et al.* (1982) made examination and comparison of tree volume functions by cross-validation. He particularly used regression models for cross validation i.e. population of one plot at a time are excluded and predicted and measured values for that plot then compared. Chen (1982) used Jacknife technique for estimating the index of diversity with tree data from Liang Shui Forest Farm, China. Yang and Kung (1983) reported that Jacknife reduces bias in the regression estimates for volume determination when volume and diameter were normally distributed. They observed that these were especially useful where the cost ratio and the correlation between volume determination and diameter measurements were high.

Chauhan and sahoo (1997) tested and validated the volume prediction models making use of cross validation technique for chirpine and similar results were found by Pandey *et al.* (1998) in *Populus deltoides.*

West *et al.* (1999) and Enquist and Niklas (2001) studied the validity of the generalized equations and they first compared the model coefficients (β_1) with global allocation rules. These authors concluded that the extending allometric theory predicts that y is proportional to the 8/3 (2.667) power of the stem diameter of any size class. They also suggested that this allometric theory was almost universally applied in biology and that it originated in the common geometric and hydrometric principles that governed the transport of essential materials to support cellular metabolism.

Phillips *et al.* (2000) using an analytical statistical approach, estimated the measurement error, sampling error, regression error, and total error for growing stock volume, and average annual net volume growth, removals, and change in growing stock volume for forests of the five states of the southeastern FIA unit of the United States for a 6–8 year inventory period. Their analysis indicated that for the region-wide quantities given above, the total error, expressed as the 95 percent confidence interval of the mean, was 1 percent for growing stock volume, 2 to 3 percent for net volume growth and removal and almost 40 percent for change in growing stock volume. The sampling error was the largest component of the total error in these examples accounting for 90 to 99 percent.

Chave *et al.* (2005) assessed the validity of the regression model: $\ln(AGB)=a+b_1 \ln(D)+b_2 \ln(H)+b_3 \ln(q)$ across a number of different forests and asked whether a single model could be used across all sites. Based on criteria of goodness of fit, they selected a regression model using the compound variable q (D^2 H) as a single predictor. The goodness of fit of model was measured by the residual standard error of the fit (RSE). Among type II models, the simplest relationship was ln(AGB)=a+ln(q)+b ln(D), with a and b as constant across forest types. However, not only was the model a poor fit of the data (RSE = 0.38) the performance of these models was discussed using the Akaike Information Criteria (AIC) as a selection criterion. During the validation procedure, the predicted total aboveground stand biomass differed by over 20 percent from the measured value in several sites.

Sharma and Nanda (2008) studied various linear and non-linear functions for *Pinus roxburghii* based on stem volume and crown parameter relationships and compared for their performances. The best-fitted function (power function) outperformed the log-linear function. Therefore, the data were subjected to Chi-square test of goodness of fit and thereafter using Theil-U test. The predicted volume based on crown volume was cross validated and tested for its accuracy by correlating it with observed volume and volume estimated through volume table. The accuracy was found to be 90 percent.

Recent studies (Djomo *et al*., 2010; Henry *et al*., 2010; Ebuy *et al*., 2011; Vieilledent *et al*., 2012; Kuyah *et al*., 2012; Fayolle *et al*., 2013; Mwakalukwa *et al*., 2014) were local, or country-specific. The study of Djomo *et al*. (2010) added to locally collected data, other data from South America and tropical Asia to develop pan-tropical allometric equations. Since most of the data came from other locations outside Africa, the accuracy of these equations to measure tropical forest biomass in Africa was still questionable. The recent study of Chave *et al*. (2014) used data collected in Africa, Asia and South America to develop a unique allometric equation valid in all ecosystems. Although they recognized that there was a site effect, the study assumed that the site effect and forest types could be negligible if diameter, height and wood density are included and the biomass can be approximated by a single equation. Vieilledent *et al*. (2012) used a destructive sample of 481 trees in Madagascar spiny dry, wet and moist forests characterized by a high rate of endemism (95%) to develop local allometric equations and compared them to pan tropical allometric relations (Brown, 1997; Chave *et al*., 2005). Their study shows that from pan tropical equations evaluated, only the model of Chave *et al*. (2005) including diameter, height and wood specific density gave accurate tree biomass estimates for Madagascar; this was consistent with other studies in Africa (Djomo *et al*., 2010; Henry *et al*., 2010).

Chapter-3

MATERIALS AND METHODS

The present investigation entitled **“Biomass carbon estimation of important North-Western Himalayan tree species”** was carried out in Chhichar forest area of Kotgarh Forest Division Distt. Shimla (H.P.) during year 2015-2016. The details about experimental site, materials used and methodology adopted in undertaking these studies are given in this chapter.

3.1 STUDY AREA

3.1.1 Location

The experimental area is located between latitude $31^{o}8^{\prime}40^{\prime\prime}$ to $31^{o}42^{\prime}50^{\prime\prime}$ N latitude and the longitude $72^{o}18^{\prime}50^{\prime\prime}$ to $77^{o}58^{\prime}$E in the mid-hill zone of Kotgarh Forest Division of Himachal Pradesh with an elevation from 1050-3215 m above mean sea level (a.m.sl). The natural stands of *Pinus roxburghii* mixed with *Quercus leucotrichophora* were selected in Melandi UF- 255 compartment distributed at elevation from 1100 to 2000m (a.m.sl.) over an area of 10.93 ha near Kingal and Galani of Kumarsain Range. For *Pinus wallichiana, Cedrus deodara, Abies pindrow and Picea smithiana* stands were selected in compartment no. 41-a and 41-b in Chhichar forest (Narkanda) distributed at elevation from 1500m to 3000m over an area of 41.31ha and 46.57 ha, respectively of Kumarsain Range.

3.1.2 Climate

The area is a transitional zone between sub-tropical to temperate and semi arctic due to altitudinal variations. There is a considerable variation in the seasonal and diurnal temperature of experimental site. In general, May and June are the hottest months and November to February, are the coldest months and the area experiences severe heavy snowfall during the winter. On an average the annual rainfall varies from 1000-1400 mm, bulk of which is received during monsoons i.e. July-September with few pre-monsoon showers. Snowfall during winter is common phenomenon starting from November until March/April in high altitude. The mean minimum and mean maximum temperature varies from -5^{o}C during winter (January) to 25^{o}C during summer (June), whereas mean annual temperature (MAT) is 18^{o}C (Table 1).

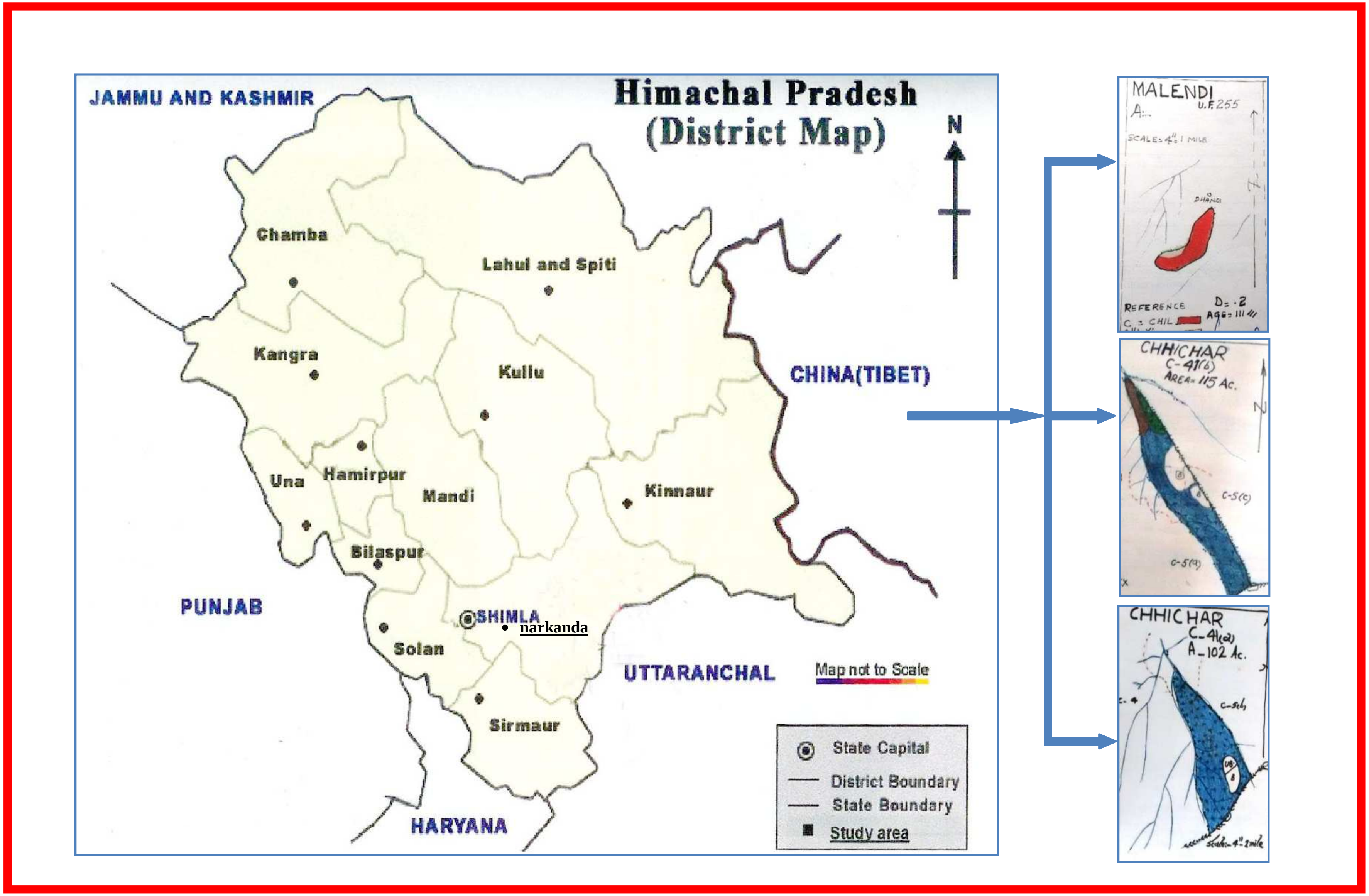

Fig. 1 Map showing study area

Table 1 Locality factors of the study area

Latitude	$31^{o}8^{'}40''$ to $31^{o}42^{'}50''$ N
Longitude	$72^{o}18^{'}50''$ to $77^{o}58^{'}$E
Altitude	1050-3215 m a.sl
Climate Type	sub-tropical to temperate
Mean annual temperature	18^{o}C

3.1.3 Topography and Soil

The study area is mountainous in nature with moderate to steep slopes and precipitous. Forest soil is of two types i.e., acidic and neutral soil. Forest soil, which has alluvium base is rich in humus found in deodar and fir Forest (Working Plan Kotgarh Forest Division, 2012-2013).

3.1.4 Geology and Rock

The study area lies between inner Himalayas and consists of metamorphic rocks mostly micaceous schists and chloritic schists with genesis, granite phyllites, slates, shales and quartzite. (Working Plan Kotgarh Forest Division, 2012-2013).

3.2 DEMARCATION AND ENUMERATION FOR MEASUREMENTS

3.2.1 Estimation of growth and standing volume

Sampling procedure

After through survey of the area, about 500 trees were enumerated and tabulated into standerd diameter classes. Out of sixty trees enumerated for each diameter class thirty trees representing different height ranges, 10 each of large, medium and small range were selected randomly(Table 2). Thus in total 240 trees each for *Pinus roxburghii, Quercus leucotrichophora, Pinus wallichiana, Cedrus deodara, Abies pindrow* and *Picea smithiana* were measured for diameter at breast height (DBH) and tree height.

Table 2 Distribution of sample trees in different diameter classes

Standard diameter class	**Diameter range (cm)**	**Number of trees enumerated**	**Number of sample trees**
V	D_1:10-20	60	30
IV	D_2:20-30	60	30
III	D_3:30-40	60	30
IIA	D_4:40-50	60	30
IIB	D_5:50-60	60	30
IA	D_6:60-70	60	30
IB	D_7 :70-80	60	30
IC	D_8:80-90	60	30

3.3 OBSERVATION RECORDED

3.3.1 Diameter at breast height

The stem diameter over bark was measured (mean of two right angle measurements) at DBH above ground level with the help of tree caliper according to the method given by Chaturvedi and Khanna (1982).

3.3.2 Tree height

The height was measured with the help of Spiegel Relaskop and expressed in meters according to the method given by Chaturvedi and Khanna (1982)

3.4 PARAMETERS ESTIMATED:

3.4.1 Volume of standing trees

Volume of standing trees was calculated by Pressler's formula (1865) and expressed in cubic meters.

$$V = ff \times h \times g$$

Where,

V = Volume
ff = Form factor
h = Total height
g = Basal area

3.4.2 Form factor

The form factor was calculated using the formula given by Pressler (1865) and Bitterlich (1984).

$$ff = \frac{2h_1}{3h}$$

Where,

ff = form factor
h_1 = Height at which diameter is half of DBH
h = Total height of the tree measured by Speigel Relaskop

3.4.4. Aboveground biomass

Woody biomass

Woody biomass was calculated by multiplying total volume of the biomass with Specific gravity

Specific gravity

Specific gravity values for the corresponding species were taken from the available literature (Table 3). The weight of wood (biomass) was estimated using the formula i.e. mass per unit volume.

Biomass = Specific gravity of stem wood x volume

Branch and foliage biomass

Branch and foliage biomass was estimated by multiplying the volume of trres of each species with their corresponding biomass expansion factors. Biomass expansion factors values for the species under study were taken from the available literature (Table 3).

Biomass expansion factor

Biomass expansion factor is ratio of total tree biomass to volume of the stem. In present study the biomass expansion factor was developed by using the following equation (Lehtonen *et al.,* 2004).

$$\text{BEF} = \frac{W}{V}$$

Where,

BEF = Biomass expansion factor (kg/m^3)
W = Total tree biomass (kg)
V = Volume of the stem (m^3)

The total aboveground biomass of the tree was comprised of the sum of stem biomass, branch biomass and the leaf biomass.

Total aboveground biomass carbon = Stem carbon + Branch carbon + Leaf carbon

3.4.5 Belowground biomass

Root biomass

Root biomass of trees was calculated by using the guidelines of IPCC (2003). Below ground biomass was calculated by multiplying aboveground biomass of trees with a factor of root: shoot ratio of particular tree species (Table 3).

Root biomass = Aboveground biomass x Root: shoot ratio.

Table 3. Biomass Expansion Factor (BEF), Specific gravity (SG) and Root-Shoo ratio (R:S) of different forest tree species

SAMPLE TREES	BEF	REFRENCES	SG	REFRENCES	R:S Ratio	REFRENCES
Pinus roxburghii	1.91	Rawat and Tandon (1993)	0.491	Rajput *et al*. (1985)	0.21	IPCC (2003)
Pinus wallichiana	1.91	Rana and Singh (1990)	0.427	Kumar (1998)	0.27	IPCC (2003)
Cedrus deodara	1.40	IPCC (2003)	0.468	Rajput *et al*. (1985)	0.27	IPCC (2003)
Abies pindrow	1.51	Haripriya (2000)	0.340	IPCC (2003)	0.21	IPCC (2003)
Picea smithiana	1.51	Haripriya (2000)	0.380	IPCC (2003)	0.21	IPCC (2003)
Quercus leucotrichophora	1.91	Rana and Singh (1990)	0.826	Raturi *et al*. (2002)	0.39	IPCC (2003)

3.4.6 Carbon estimation

Biomass was converted into carbon by multiplying it with carbon fraction (0.5) of dry matter. The calculation of carbon from biomass uses the following formula:

Carbon stock = Total Biomass x 0.5 (IPCC default value 2006)

3.5 ANALYTICAL FRAMEWORK

3.5.1 Criteria for the selection of appropriate function

1. A function is supposed to be an appropriate one if the sign and magnitude of the estimated parameters are consistent with the theory.
2. Adjusted R^2 (Gujrati, 1998) calculated as under

$$\bar{R}^2 = 1 - \left(\frac{(1-R^2)\,(n-1)}{n-k-1}\right)$$

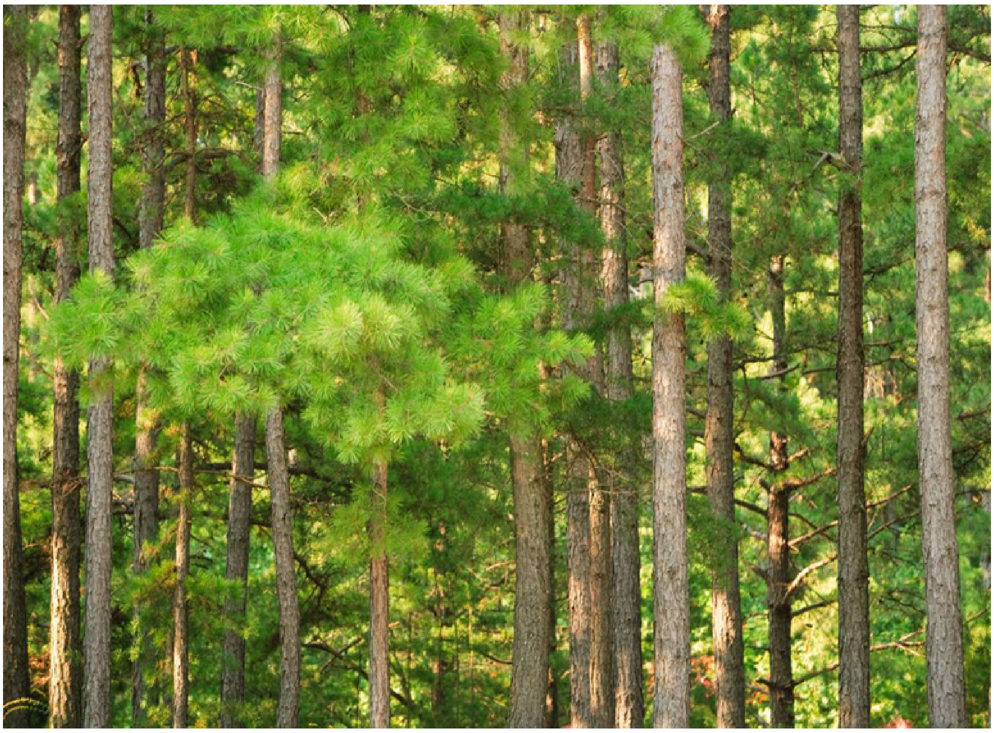

Plate 1. *Pinus roxburghii*

Plate 2. *Quercus leucotrichophora*

Plate 3. *Pinus wallichiana*

Plate 4. *Cedrus deodara*

Plate 5. *Abies pindrow*

Plate 6. *Picea smithiana*

Where,

R = Sample R-square

n = Number of observations

k = Number of parameter

Adjusted R^2 is an appropriate tool to decide the selection of fundamental form. Usually, the function with higher adjusted R^2 is selected for the purpose.

3. A function with more significant explanatory variables is considered a better function compared to other functions.

3.5.2 Regression analysis

Based on the adjusted R^2 values different regression equations *viz*. linear, logarithmic, exponential, sigmoidal and power were further developed for stem volume and biomass carbon (dependent variable) with DBH and tree height (independent variable).

3.5.3 Chi-square test of goodness of fit

A powerful tool for testing the goodness of fit, which enables us to find if the deviation of the experiment from the theory is just by chance, or due to the inadequacy of the theory to fit the observed data:

If O_i (i= 1, 2……………n) of a set of observed values and E_i (i= 1, 2 ….n) is the corresponding set of expected values, then Chi-square is given by:

$$\chi^2 = \Sigma \, [O_i - E_i)^2 / E_i]$$

Which follows Chi-square distribution with (n-1) degree of freedom (Gupta and kapoor, 1996). If the tabulated value of chi-square is less than or equal to calculated value of chi-square at specific level of significance the null hypothesis is rejected and hence it is concluded that the model is not adequate or in other words we can say that we have no evidence in favour of null hypothesis i.e., model under study is not adequate.

3.5.4 Theil's method

Theil (1965) proposed following U–statistic, to test the agreement between predicted and the actual value

$$U = \sqrt{\frac{1}{n}} \sum_{i=1}^{n} (\, (Pi - Ai)2 / \sqrt{\frac{1}{n} \sum_{i=1}^{n} Pi^2 + \sum_{n}^{1} Ai^2}$$

Where P_i and A_i are respectively the predicted and the actual values of the variable of the ith observation. When U→ ZERO, the fitting predicts perfectly. This is because in such events predicted value approximately equals the actual value in all observations.

3.5.5 Validation technique

The term validation refers to the process of accessing in some sense the degree of agreement between model and real system being modeled. Once a model that gives an adequate fit to the data is found, the next step in the process is to use the model for prediction. However, before a model is to be used, its validity should be checked.

A valid comparison of the real data and model output in the validation stage requires an understanding of the problem as well as the availability of statistical procedures that are designed to fit the conditions of the problem confidence in conclusion reached about the model would be greatest when real data used in the validation process is independent of the data used in the construction and calibration of the model (Reynolds *et al*., 1981).

Let $(y_1 , x_1),\ldots\ldots,(y_n,x_n)$ the set of data distributed independently according to some unknown function f, x is univariate and is used to predicty.

Let the model be:

$$Y = f(x, \underline{\hat{\theta}}) + \text{error}$$

Where

$\underline{\hat{\theta}}$ is the parameter vector to be estimated, f is non linear in $\underline{\hat{\theta}}$ and distribution of error is unknown.

The goodness of fit model will be evaluated by $Q\ [y, f(x, \underline{\hat{\theta}})]$.

In particular, Q is taken as absolute deviation y, using $f\ (x, \underline{\hat{\theta}})$, realistically it is probable that knowing Q on the average is the best, one can expect from the resampling procedures (Gong, 1986). This definition is useful in the discussion of prediction errors. True error is defined as:

$$E_f\ Q\ [y_0, f(x_0, \underline{\hat{\theta}}\ )]$$

If f were unknown, true error could be computed exactly, this is the case where a large number of additional samples can be drawn and true error computed by analysis it is logical that the error is best estimated in application on drawing a sufficiently large sample independent of the one used as fitting the model.

In contrast, apparent error is computed by simple applying the fitted equation to the same data which was used in calibration (fitting).

$n^{-1}\ Q[x_{i,}\ \underline{\hat{\theta}]}$

Apparent error is thus expected value of Q with respect to the empirical distribution function f. Apparent error will normally give an optimistic view of the goodness of distribution. The difference between true error and apparent error is excess error. In term of evaluating a distribution, interest lies in excess or equilently in true error.

Various validation techniques are widely used in forestry research such as cross validation, jackknifing and bootstrap method.

Chapter-4

RESULTS AND DISCUSSION

The results emerging out of the present investigation entitled **“Biomass carbon estimation of important North-Western Himalayan tree species.”** is presented in this chapter under the following heads:

4.1 Allometric relationships of tree volume with DBH and tree Height
4.2 Allometric relationships of tree biomass carbon with DBH and tree Height
4.3 Evaluation and validation of allometric models

4.1 ALLOMETRIC RELATIONSHIP OF TREE VOLUME WITH DBH AND TREE HEIGHT

The results on various linear and non-linear functions for tree volume as the dependent variable and DBH (diameter at breast height) and tree Height separately as independent variable for *Pinus roxburghii*, *Quercus leucotricophora*, *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow* and *Picea smithiana* and are presented in Tables 4 to 15.

Pinus roxburghii **(Chirpine)**

The linear and non-linear relationships of tree volume with DBH and tree Height, each taken independently, resulted in highly significant $\bar{R}^2$ (adjusted R^2) results (Table 4), where power function showed highest $\bar{R}^2$ (0.98) for tree volume with DBH. Similarly, Sigmoidal (S) function showed significant $\bar{R}^2$ (0.97) followed by linear (0.93), exponential (0.88) and log linear (0.77) function. In case of tree Height taken as predictor variable**,** power function showed highest $\bar{R}^2$ (0.95) followed by exponential (0.92), S (0.73), linear (0.72) and log linear (0.52) function. The present findings are in conformity with the findings of Ahmad *et al.* (2014) who reported DBH a best indicator of stem volume estimation as a result of quadratic linear relationship ($\bar{R}^2$=0.96) between stem volume and DBH and Nizami *et al.* (2009) on the other side have reported strong linear ($\bar{R}^2$=0.98) relationships for *Pinus roxburghii* when basal area was taken as independent variable. However, Sharma and Nanda (2008) reported the logarithmic and power functions as the best fit for the estimation of stem volume of *Pinus roxburghii* stand while taking crown parameters as predictor variables and found crown volume to explain 99 percent variation in stem volume followed by crown area, crown diameter, crown width and crown length. FSI (1996) has already developed volume equations for softwood species using multiple regression methods in which basal area, girth or DBH along with height or form factor to predict volume and biomass of *Pinus roxburghii* where, DBH individually, explained 97 per cent variation in biomass.

Table 4 Allometric linear and non-linear equations for estimation of stem volume of *Pinus roxburghii* trees based on DBH and tree Height variable

Volume	**b_0**	**b_1**	**Adj R^2**	**Model**
DBH				
$V = -2.038 +0.084D$	-2.038	0.084	0.93	Linear
$V= -10.106+3.244 \ln D$	-10.106	3.244	0.77	Log linear
$V = 0.38e^{0.065D}$	0.038	0.065	0.88	Exponential
$V= 0.000016D^{2.912}$	0.000016	2.912	0.98	Power
$V=\exp(2.514-94.427/D)$	2.514	-94.427	0.97	Sigmoidal
Height				
$V = -2.619+0.218H$	-2.619	0.218	0.72	Linear
$V= -6.496+2.902 \ln H$	-6.496	2.902	0.52	Log linear
$V = 0.12e^{0.200H}$	0.012	0.200	0.92	Exponential
$V= 0.000088H^{3.115}$	0.000088	3.115	0.95	Power
$V= \exp(1.765-29.641/H)$	1.765	-29.641	0.73	Sigmoidal

V = Volume D = diameter(cm) H = tree Height (m)

* Significant at 5% level of significance

Quercus leucotrichophora (Ban Oak)

Results pertaining to various linear and non-linear relationships (Table 5) presented for DBH as well as tree Height for stem volume estimation of *Quercus leucotrichophora* trees were significant. The power function showed highest $\bar{R}^2$ (0.96) for volume with DBH. Similarly, S function showed significant $\bar{R}^2$ (0.91) followed by exponential (0.90), linear (0.81), and log linear (0.63) function. However, power function showed highest $\bar{R}^2$ (0.75) that followed exponential (0.74), linear (0.73), S (0.59) and log linear (0.52) function when tree Height was used as predictor variable. The results have relevance with the studies conducted by Canadell and Roda (1991) who have reported logarithmic equation with DBH as independent variable as the best fit for volume estimation of *Quercus ilex* with 87 percent variation. However, FSI (1996) and FRI (1996) have developed significant relationships for volume estimation of *Quercus leucotrichophora* based on D^2H.

Table 5 Allometric linear and non-linear equations for estimation of stem volume of *Quercus leucotrichophora* trees based on DBH and tree Height variable

Volume	b_0	b_1	Adj R^2	Model
DBH				
$V = -1.514+0.058D$	-1.514	0.058	0.81	Linear
$V= -6.883+2.193\ln D$	-6.883	2.193	0.63	Log linear
$V = 0.35e^{0.059D}$	0.035	0.059	0.90	Exponential
$V= 0.000036D^{2.602}$	0.000036	2.602	0.96	Power
$V= \exp(1.816-82.349D)$	1.816	-82.349	0.91	Sigmoidal
HEIGHT				
$V = -2.247 +0.248H$	-2.247	0.248	0.73	Linear
$V= -5.406+2.608\ln H$	-5.406	2.608	0.52	Log linear
$V = 0.19e^{0.241H}$	0.019	0.241	0.74	Exponential
$V= 0.000257H^{3.011}$	0.000257	3.011	0.75	Power
$V= \exp(1.559-23.784/H)$	1.559	-23.784	0.59	Sigmoidal

V = Volume D = diameter at breast height (cm) H = tree Height (m)
* Significant at 5% level of significance

***Pinus wallichiana* (Kail)**

Various linear and non-linear relationships of tree volume with DBH as well as tree Height separately for *Pinus wallichiana* are presented in Table 6. All the relationships were significant, where power function reported highest $\bar{R}^2$ (0.99) followed by S (0.93) and exponential (0.92), linear (0.88) and log linear function that explained only 71 percent variation in volume when DBH was taken as independent variable. For tree Height variable, the significant relationships were stronger with maximum value of $\bar{R}^2$ (0.93) for power function followed by exponential (0.92), S (0.80) and linear (0.79), however, log linear (0.61) function was able to explain only 61 percent variation in volume. The results are in line with findings of Raqeeb *et al.* (2014) who explained 99 and 98 percent variation in volume of *Pinus wallichiana* when DBH and tree Height were taken separately as predictor variable, respectively. The volume and biomass equations developed by FSI (1996) for *Pinus wallichiana* using multiple regression methods in which basal area, girth or DBH along with height or form factor was used also support the results of the present study as DBH (R^2=0.96) was the best variable for the estimation of volume and biomass.

Table 6 Allometric linear and non-linear equations for estimation of stem volume of *Pinus wallichiana* trees based on DBH and tree Height variable

Volume	**b_0**	**b_1**	**Adj R^2**	**Model**
DBH				
$V = -2.244 + 0.090D$	-2.244	0.090	0.88	Linear
$V= -10.487+3.384\ln D$	-10.487	3.384	0.71	Log linear
$V = 0.42e^{0.064D}$	0.042	0.064	0.92	Exponential
$V= 0.000030D^{2.767}$	0.000030	2.767	0.99	Power
$V= \exp(2.329-84.281/D)$	2.329	-84.281	0.93	Sigmoidal
HEIGHT				
$V = -3.317+0.242H$	-3.317	0.242	0.79	Linear
$V= -10.066+4.039\ln H$	-10.066	4.039	0.61	Log linear
$V = 0.016e^{0.180D}$	0.016	0.180	0.92	Exponential
$V= 0.000027D^{3.445}$	0.000027	3.445	0.93	Power
$V= \exp(2.525-47.468/H)$	2.525	-47.468	0.80	Sigmoidal

V = Volume D = diameter H = tree Height (m)

* Significant at 5% level of significance

Cedrus deodara (Deodar)

The data presented in Table 7 for *Cedrus deodara* showed significant relationships for various linear and non-linear function used for stem volume estimation with DBH as well as height when used independently. The results revealed that power function was strong with $\bar{R}^2$ =0.97 followed by S (0.96), linear (0.88), exponential values (0.85) and log linear (0.71) function when DBH alone was used as independent variable. Similarly stronger relationships were found for tree Height variable with maximum value of $\bar{R}^2$ by power function (0.88) followed by exponential value (0.87), S (0.73), linear (0.60) and log linear (0.41). Ahmad *et al*. (2014) have also found significant relationships when quadratic relationships were used that explained with 93 percent variation in volume of *Cedrus deodara* due to DBH, respectively. Similarly, Raqeeb *et al*. (2014) have found significant quadratic relationship that explained with 98 and 99 percent variation in volume of *Cedrus deodara* due to DBH and tree Height variable, respectively when taken separately. However, Chaturvedi (1973) got 99 percent variation in volume of *Cedrus deodara*, both due to diameter and height (D^2H). Similarly, FRI (1996) and FSI (1996) have developed volume equations for *Cedrus deodara* using multiple regression methods in which basal area, girth or DBH along with height or form factor were used to predict volume and biomass with significant relations and found Quadratic Linear functions the best fit that explained 98 percent of variation in volume of *Cedrus deodara* due to DBH only.

Table 7 Allometric linear and non-linear equations for estimation of stem volume of *Cedrus deodara* trees based on DBH and tree Height variable

Volume	b_0	b_1	Adj R^2	Model
DBH				
$V = -2.063 + 0.087D$	-2.063	0.087	0.88	Linear
$V = -9.968 + 3.247 \ln D$	-9.968	3.247	0.71	Log linear
$V = 0.40e^{0.065D}$	0.040	0.065	0.85	Exponential
$V = 0.000019D^{2.886}$	0.000019	2.886	0.97	Power
$V = \exp(2.439 - 87.770/D)$	2.439	-87.770	0.96	Sigmoidal
HEIGHT				
$V = -2.238 + 0.188H$	-2.238	0.188	0.60	Linear
$V = -5.303 + 2.482 \ln H$	-5.303	2.482	0.41	Log linear
$V = 0.016e^{0.173H}$	0.016	0.173	0.87	Exponential
$V = 0.00021H^{2.778}$	0.00021	2.778	0.88	Power
$V = \exp(1.588 - 26.551/H)$	1.588	-26.551	0.73	Sigmoidal

V = Volume D = diameter at breast height H = tree Height (m)

* Significant at 5% level of significance

Abies pindrow (Silver fir)

The perusal of data in Table 8 revealed that various linear and non-linear equations to find out stem volume of *Abies pindrow* trees with DBH as well as height independently were significant. The power function showed highest $\bar{R}^2$ (0.97) value that followed S (0.93), exponential (0.88), linear (0.85) and log linear (0.65) relationships whereas, highest $\bar{R}^2$ (0.87) value was noted in power function followed by exponential (0.83), S (0.75), linear (0.71) and log linear (0.52) function. On the same line, Raqeeb *et al.* (2014) found significant linear relationships between tree volume and DBH for *Abies pindrow* with $R^2 = 0.98$. In contrary, Ahmad *et al*. (2014) reported quadratic linear (polynomial inverse 3rd order) regression equation developed taking Deodar, Kail, Fir and spruce jointly as the best fit for estimation of volume that explained 96 percent of variation in volume of forests based on basal area alone. Similarly, volume equations developed by FSI (1996) explained 95 percent variation in volume of *Abies pindrow* due to diameter and height taken separately as well as jointly as predictor variables.

Table 8 Allometric linear and non-linear equations for estimation of stem volume of *Abies pindrow* trees based on DBH and tree Height variable

Volume	**b_0**	**b_1**	**Adj R^2**	**Model**
DBH				
$V = -2.337 + 0.095D$	-2.337	0.095	0.85	Linear
$V = -10.987 + 3.553 \ln D$	-10.987	3.553	0.65	Log linear
$V = 0.058e^{0.060D}$	0.058	0.060	0.88	Exponential
$V = 0.000054D^{2.642}$	0.000054	2.642	0.97	Power
$V = \exp(2.333 - 79.861/D)$	2.333	-79.861	0.93	Sigmoidal
HEIGHT				
$V = -3.821 + 0.240H$	-3.821	0.240	0.71	Linear
$V = -11.666 + 4.418 \ln H$	-11.666	4.418	0.52	Log linear
$V = 0.018e^{0.161H}$	0.018	0.161	0.83	Exponential
$V = 0.000015H^{3.530}$	0.000015	3.530	0.87	Power
$V = \exp(2.566 - 53.123/H)$	2.566	-53.123	0.75	Sigmoidal

V = Volume D = diameter at breast height H = tree Height(m)

* Significant at 5% level of significance

Picea smithiana (Spruce)

Data in the Table 9 evinced various linear and non-linear equations of stem volume independently for DBH and tree Height of *Picea smithiana* trees. The relationships between stem volume and DBH were significant, where power function showed highest $\bar{R}^2$ (0.98) followed by exponential (0.93), S (0.87), linear (0.84) and log linear (0.65) function. Whereas, for tree Height, the relationships were significantly strong with highest $\bar{R}^2$ (0.87) given by power function that followed exponential (0.83), S (0.75), linear (0.71) and log linear (0.52) function. The results are in conformity to the findings of Ahmad *et al*. (2014) who have reported 98 and 99 percent variation in volume of *Picea smithiana* trees due to tree DBH and tree height when used separately and basal area explained 96 variations when used alone in quadratic regression analysis.

Table 9 Allometric linear and non-linear equations for estimation of stem volume of *Picea smithiana* trees based on DBH and tree Height variable

Volume	b_0	b_1	Adj R^2	Model
DBH				
$V = -2.435 + 0.094D$	-2.435	0.094	0.84	Linear
$V = -10.625 + 3.418\ln D$	-10.625	3.418	0.65	Log linear
$V = 0.33e^{0.067D}$	0.033	0.067	0.93	Exponential
$V = 0.000022D^{2.833}$	0.000022	2.833	0.98	Power
$V = \mathrm{Exp}(2.194 - 81.694/D)$	2.194	-81.694	0.87	Sigmoidal
HEIGHT				
$V = -2.609 + 0.218H$	-2.609	0.218	0.71	Linear
$V = --8.541 + 3.624\ln H$	-8.541	3.624	0.52	Log linear
$V = 0.34e^{0.149H}$	0.034	0.149	0.83	Exponential
$V = 0.00019H^{2.854}$	0.00019	2.854	0.87	Power
$V = \exp(1.984 - 34.237/H)$	1.984	-34.237	0.75	Sigmoidal

V = Volume D = diameter at breast height (cm) H = tree Height (m)

* Significant at 5% level of significance

4.2 ALLOMETERIC RELATIONSHIPS OF BIOMASS CARBON WITH DBH AND TREE HEIGHT

The results pertaining to various functions used to estimate biomass carbon of *Pinus roxburghii*, *Quercus leucotricophora, Pinus wallichiana*, *Cedrus deodara, Abies pindrow* and *Picea smithiana* based on DBH (diameter at breast height) and tree Height as independent variable are presented in Tables 10 to 15 and graphically shown in Fig. 2 to 13.

Pinus roxburghii **(Chirpine)**

The linear and non-linear relationships of biomass carbon with DBH and tree Height, each taken independently, resulted in highly significant $\bar{R}^2$ results (Table 10) for *Pinus roxburghii*, where power function showed highest $\bar{R}^2$ (0.98) for biomass carbon with DBH. Similarly, Sigmoidal (S) function showed significant $\bar{R}^2$ (0.97) followed by linear (0.93), exponential (0.88) and log linear (0.77) function. In case of tree Height taken as predictor variable**,** power function showed highest $\bar{R}^2$ (0.95) followed by exponential (0.92), S (0.75), linear (0.73) and log linear (0.52) function. The results are at par with the study conducted by

Nizami *et al*. (2009) who have reported strong linear (R^2=0.98) relationships for *Pinus roxburghii* when basal area was taken as independent variable for the estimation of biomass carbon. However, Chaturvedi and Singh (1982) have developed significant linear relationship between biomass of different tree components to girth at breast height (GBH) and D^2H for *Pinus roxburghii*.

Table 10 Allometric linear and non-linear equations for estimation of tree biomass carbon of *Pinus roxburghii* trees based on DBH and tree Height variable

Biomass carbon	b_0	b_1	**Adj.** R^2	**Model**
DBH				
$C = -1.611 + 0.066D$	-1.611	0.066	0.93	Linear
$C = -7.992 + 2.566 \mathrm{Ln} D$	-7.992	2.566	0.77	Log linear
$C = 0.030e^{1.067D}$	0.030	1.067	0.88	Exponential
$C = 0.000012D^{2.923}$	0.000012	2.923	0.98	Power
$C = \exp(2.292 - 94.989/D)$	2.292	-94.989	0.97	Sigmoidal
HEIGHT				
$C = -2.071 + 0.172H$	-2.071	0.172	0.73	Linear
$C = -5.137 + 2.295 \mathrm{Ln} H$	-5.137	2.295	0.52	Log linear
$C = 0.009e^{0.201H}$	0.009	0.201	0.97	Exponential
$C = 0.000066H^{3.134}$	0.000066	3.134	0.95	Power
$C = \exp(1.549 - 29.996/H)$	1.549	-29.996	0.75	Sigmoidal

C = Carbon D = diameter at breast height (cm) H = tree Height (m)
* Significant at 5% level of significance

Quercus leucotrichophora **(Ban oak)**

Results pertaining to various linear and non-linear relationships presented in Table 11 for DBH as well as tree Height for biomass carbon estimation of *Quercus leucotrichophora* trees were significant. The power function showed highest $\bar{R}^2$ (0.96) for biomass carbon with DBH. Similarly, S function showed significant $\bar{R}^2$ (0.91) followed by exponential (0.90), linear (0.81) and log linear (0.64) function. However, power function showed highest $\bar{R}^2$ (0.75) that followed exponential (0.74), linear (0.73), S (0.59), and log linear (0.52) function when tree Height was used as predictor variable. The results are in line with the findings of Navar (2009) who have reported DBH as the best indicator for aboveground biomass estimation of *Quercus* spp based on DBH that explained variation of 95 percent with power function. The results are also supported by the studies conducted by Rawat and Singh (1988) who reported 94 percent variation in biomass where GBH was taken a independent variable for *Quercus leucotrichophora* and *Quercus floribunda*.

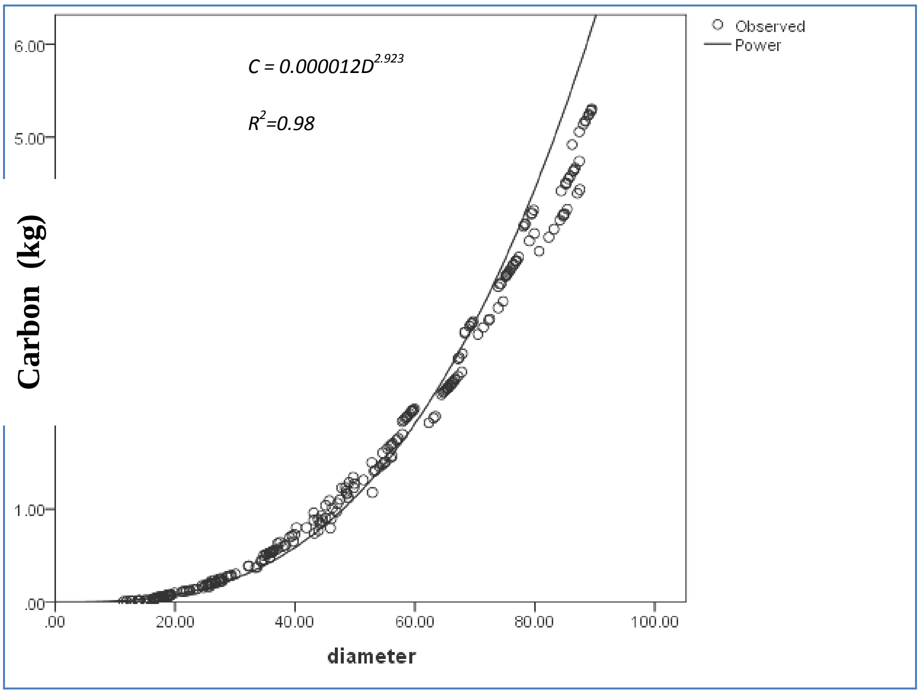

Fig. 2. Relationship between biomass carbon and DBH

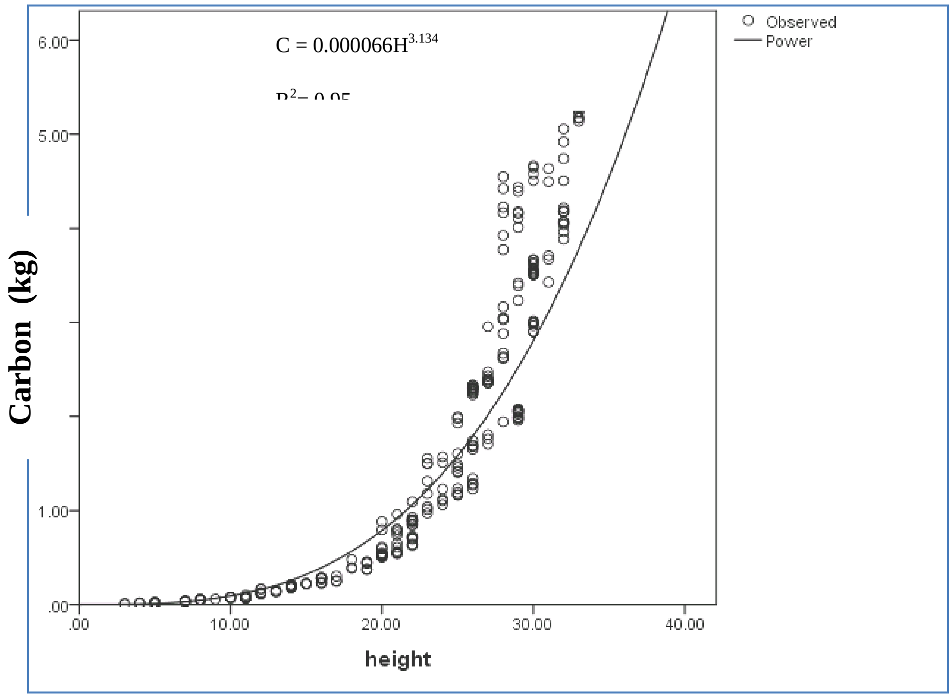

Fig. 3. Relationship between biomass carbon and tree height

Pinus roxburghii

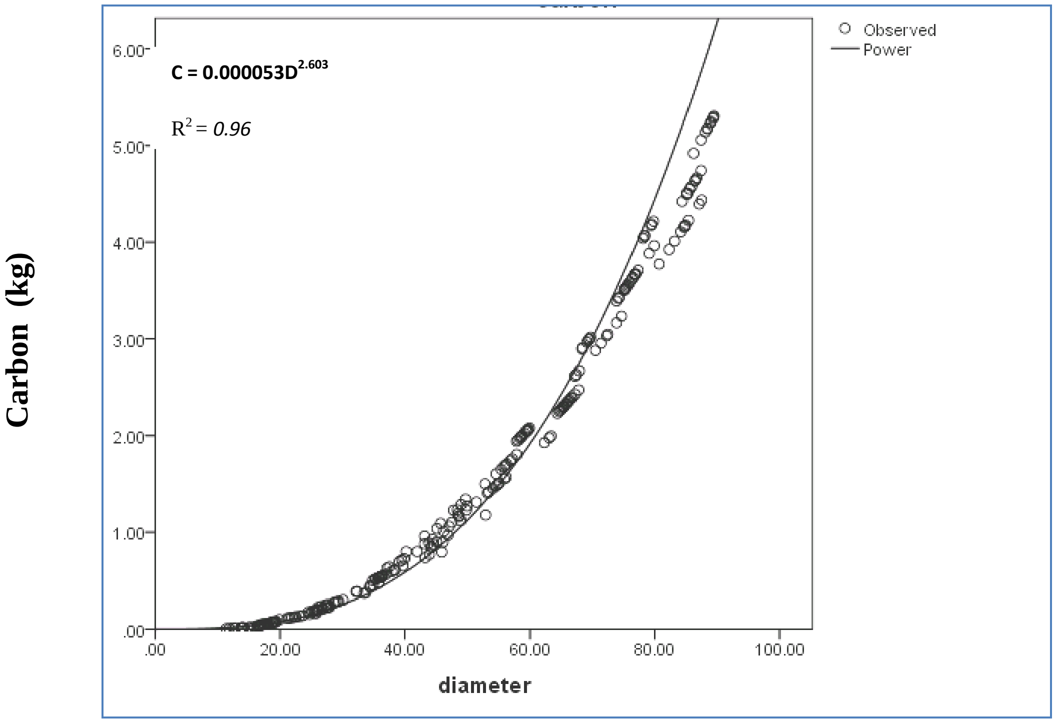

Fig. 4. Relationship between biomass carbon and DBH

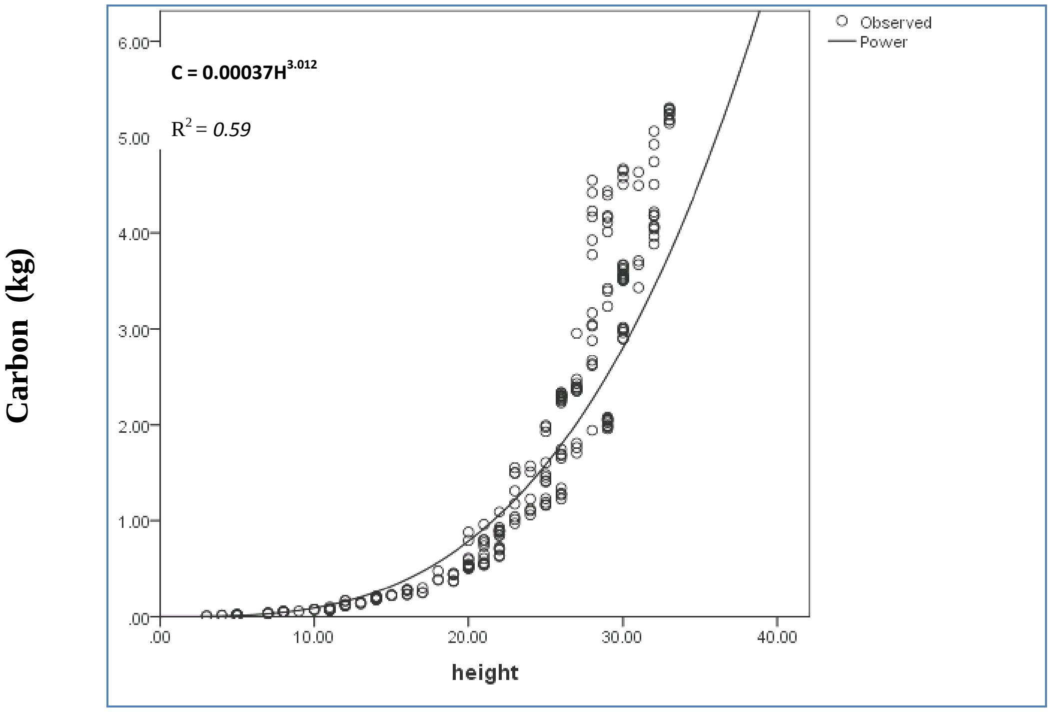

Fig. 5. Relationship between biomass carbon and tree height

Quercus leucotrichophora

Table 11 Allometric linear and non-linear equations for estimation of tree biomass carbon of *Quercus leucotrichophora* trees based on DBH and tree Height variable

Biomass carbon	b_0	b_1	**Adj.** R^2	**Model**
DBH				
$C = -2.230+0.086D$	-2.230	0.086	0.81	Linear
$C = -10.134+3.229LnD$	-10.134	3.229	0.64	Log linear
$C = 0.51e^{0.0.59D}$	0.51	0.059	0.90	Exponential
$C = 0.000053D^{2.603}$	0.000053	2.603	0.96	Power
$C = \exp(2.204-82.365/D)$	2.204	-82.365	0.91	Sigmoidal
HEIGHT				
$C = -3.303+0.364H$	-3.303	0.364	0.73	Linear
$C = -7.960+3.839LnH$	-7.960	3.839	0.52	Log linear
$C = 0.29e^{0.241H}$	0.29	0.241	0.74	Exponential
$C = 0.00037H^{3.012}$	0.0003	3.012	0.75	Power
$C= Exp(1.946-23.796/H)$	1.946	-23.796	0.59	Sigmoidal

C =Carbon D= diameter at breast height (cm) H= tree Height (m)

* Significant at 5% level of significance

Pinus wallichiana (Kail)

Various relationships of biomass carbon with DBH as well as height taken separately as independent variable for *Pinus wallichiana* are presented in Table 12. All the relationships were significant, where power function reported highest $\bar{R}^2$ (0.99) followed by S (0.93), exponential (0.92), linear (0.88) and, log linear function (0.71) that explained 71 percent variation in biomass carbon when DBH was taken as independent variable. For height variable, the significant relationships were stronger with maximum value of $\bar{R}^2$ (0.93) for power function followed by exponential (0.92), S(0.80) and linear (0.79), however, log linear (0.61) function was able to explain only 61 percent variation in biomass. The present findings are in line with the findings of Ahmad *et al*. (2014) who reported that quadratic linear regression equation developed on Deodar, Kail, Fir and spruce jointly, as the best fit for estimation of biomass and basal area explained 96 percent of variation in biomass of the forests.

Table 12 Allometric linear and non-linear equations for estimation of tree biomass carbon of *Pinus wallichiana* trees based on DBH and tree Height variable

Biomass carbon	b_0	b_1	Adj R^2	Model
DBH				
$C = -1.587+0.064D$	- 1.587	0.064	0.88	Linear
$C = -7.404+2.852LnD$	-7.404	2.852	0.71	Log linear
$C = 0.30e^{0.1066D}$	0.30	0.1066	0.92	Exponential
$C = 0.000021D^{2.767}$	0.000021	2.767	0.99	Power
$C = \exp(1.988-84.397/D)$	1.988	- 84.397	0.93	Sigmoidal
HEIGHT				
$C = -2.344+0.171H$	-2.344	0.171	0.79	Linear
$C = -7.104+2.852LnH$	-7.104	2.852	0.61	Log linear
$C = 0.011e^{0.181H}$	0.011	0.181	0.92	Exponential
$C = 0.000019H^{3.454}$	0.000019	3.454	0.93	Power
$C = \exp(2.188-47.573/H)$	2.188	-47.573	0.80	Sigmoidal

C = Carbon D = diameter at breast height (cm) H = tree Height (m)
* Significant at 5% level of significance

***Cedrus deodara* (Deodar)**

The data presented in Table 13 for *Cedrus deodara* showed significant relationships for various linear and non-linear function used for biomass carbon estimation with DBH as well as tree Height when used independently. The results revealed that power function was strong with $\bar{R}^2$=0.97 followed by S (0.96), linear (0.88), exponential values (0.85) and log linear (0.72) function when DBH alone was used as independent variable. Similarly, stronger relationships were found for tree Height variable with maximum $\bar{R}^2$ values by power function (0.88) followed by exponential value (0.87), S (0.74), linear (0.60) and log linear (0.41). The present value of R^2 are more or less similar to values as reported by Ali *et al.* (2016) who have reported power and log linear function as the best fit for estimation of aboveground biomass for *Cedrus deodara.* It explained 98 percent of variation in aboveground biomass based on DBH and height (D^2H) as independent variable. Similarly, Chave *et al*. (2005) have developed nonlinear models (power function) using DBH, tree height and wood density separately for the estimation of aboveground biomass of dry tropical forests that explained more than 91 percent variation.

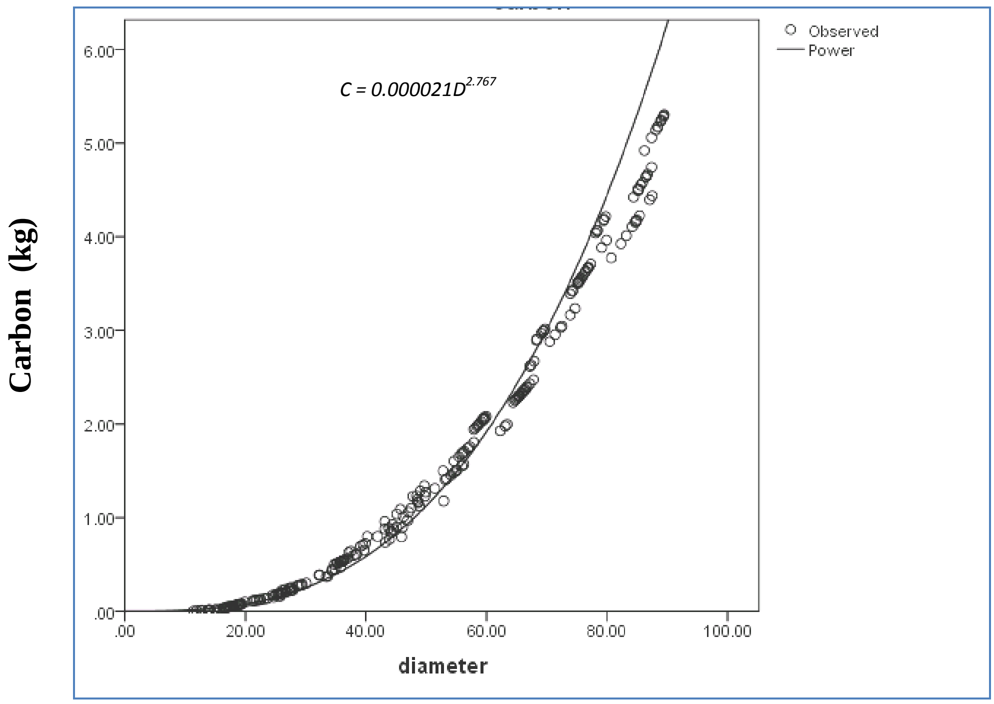

Fig. 6. Relationship between biomass carbon and DBH

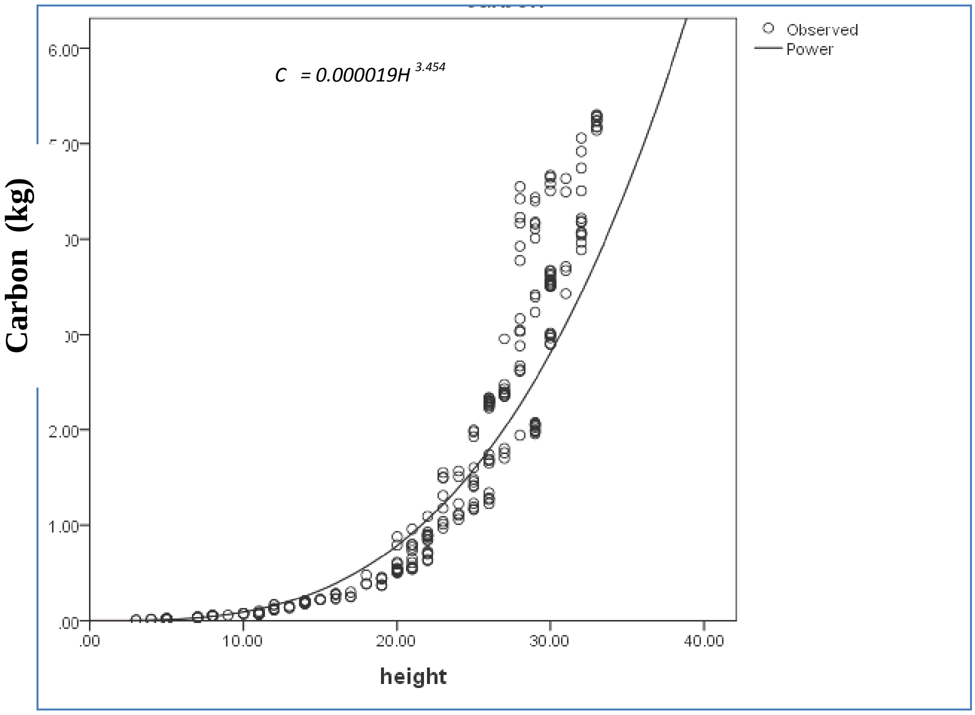

Fig. 7. Relationship between biomass carbon and tree height

Pinus wallichiana

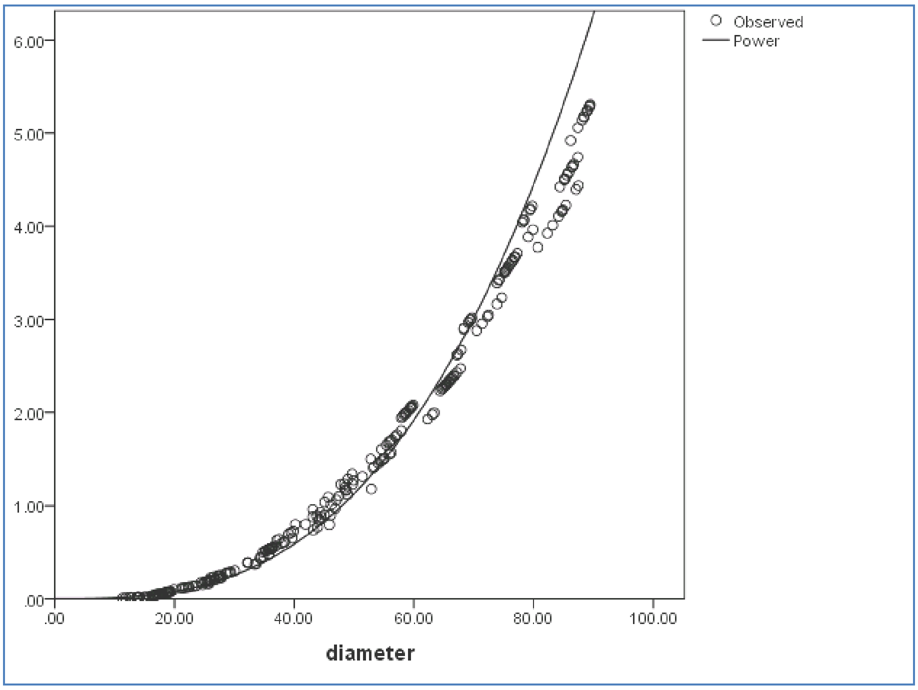

Fig. 8. Relationship between biomass carbon and DBH

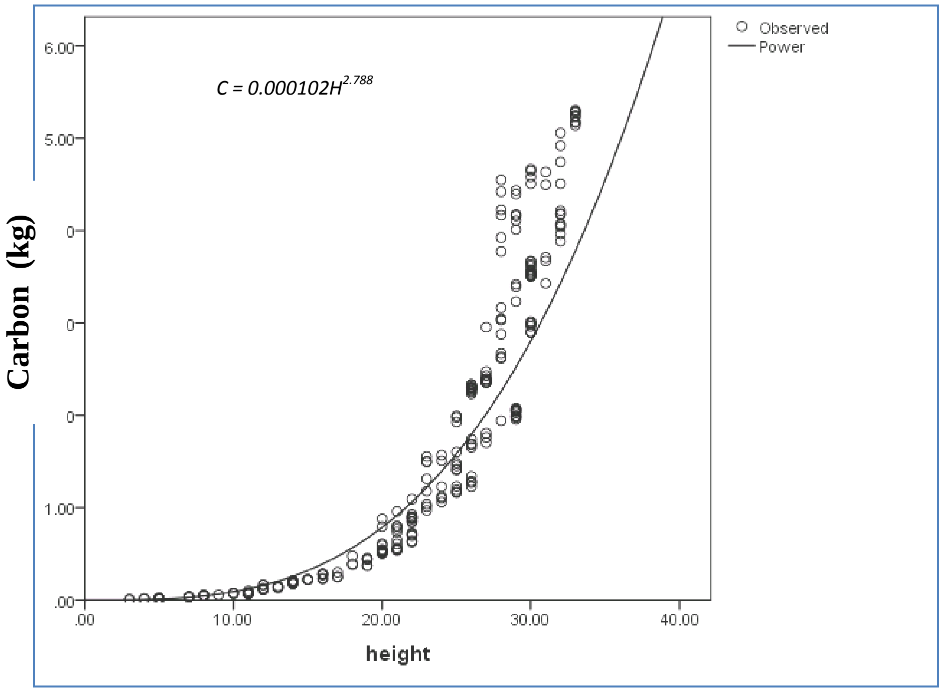

Fig. 9. Relationship between biomass carbon and tree height

Cedrus deodara

Table 13 Allometric linear and non-linear equations for estimation of tree biomass carbon of *Cedrus deodara* trees based on DBH and tree Height variable

Biomass	**b_0**	**b_1**	**Adj $\bar{R}^2$**	**Model**
DBH				
$C = -1.051+0.044D$	-1.051	0.044	0.88	Linear
$C = -5.080+1.655 \mathrm{Ln} D$	-5.080	1.655	0.72	Log linear
$C = 0.020e^{0.065D}$	0.020	0.065	0.85	Exponential
$C = 0.000010D^{2.889}$	0.000010	2.889	0.97	Power
$C = \exp(1.770-87.986/D)$	1.770	-87.986	0.96	Sigmoidal
HEIGHT				
$C = -1.142+0.096H$	-1.142	0.096	0.60	Linear
$C = -2.706+1.266 \mathrm{Ln} H$	-2.706	1.266	0.41	Log linear
$C = 0.008e^{0.175 H}$	0.008	0.175	0.87	Exponential
$C = 0.000102H^{2.788}$	0.000102	2.788	0.88	Power
$C = \mathrm{Exp}(0.920-26.672/H)$	0.920	-26.672	0.74	Sigmoidal

C = Carbon D = diameter at breast height (cm) H= tree Height (m)
* Significant at 5% level of significance

***Abies pindrow* (Silver fir)**

The perusal of data in Table 14 revealed that various linear and non-linear equations to estimate biomass carbon of *Abies pindrow* trees with DBH as well as tree Height independently were significant. The power function showed highest $\bar{R}^2$ (0.97) value that followed S (0.93), exponential (0.88), linear (0.85) and log linear (0.68) relationships whereas, highest $\bar{R}^2$ (0.87) value was noted in power function followed by exponential (0.83), S (0.75), linear (0.71) and log linear (0.52) function which showed only 52 percent variation due to tree Height. On the contrary, Brown and Schroeder (1999) reported exponential and sigmoidal models to be highly significant with stronger relationship between aboveground biomass and DBH with R^2 value as high as 0.98 for southern and eastern softwood species (fir & spruce) in the United States. However, Ahmad *et al*. (2014) have noted 96 percent variation in biomass of forests when basal area was taken as a variable in quadratic linear regression equation for *Abies pindrow*. Chave *et al*. (2005) on the other hand found more than 91 percent variation in the aboveground biomass of dry tropical forests due to DBH, tree height and wood density when taken individually in nonlinear models (power function).

Table 14 Allometric linear and non-linear equations for estimation of tree biomass carbon of *Abies pindrow* trees based on DBH and tree Height variable

Biomass carbon	b_0	b_1	**Adj** R^2	**Model**
DBH				
$C = -0.919+0.037D$	-0.919	0.037	0.85	Linear
$C = -4.324+1.398LnD$	-4.324	1.398	0.68	Log linear
$C = 0.023e^{0.060D}$	0.023	0.060	0.88	Exponential
$C = 0.000021D^{2.641}$	0.000021	2.641	0.97	Power
$C = \exp(1.400-79.84/D)$	1.400	-79.84	0.93	Sigmoidal
HEIGHT				
$C = -1.504+0.094H$	-1.504	0.094	0.71	Linear
$C = -4.591+1.739LnH$	-4.591	1.739	0.52	Log linear
$C = 0.007e^{0.161H}$	0.007	0.161	0.83	Exponential
$C = 0.000006H^{3.529}$	0.000006	3.529	0.87	Power
$C= Exp(1.634-53.121/H)$	1.634	-53.121	0.75	Sigmoidal

C = Carbon D = diameter at breast height (cm) H= Height (m)

* Significant at 5% level of significance

***Picea smithiana* (Spruce)**

Data in the Table 15 evinced various linear and non-linear equations of stem volume independently for DBH and tree Height of *Picea smithiana* trees. The relationships between biomass carbon and DBH were significant, where power function showed highest $\bar{R}^2$ (0.98) followed by exponential (0.93), S (0.88), linear (0.84), and log linear (0.65) function. Whereas, for tree Height, the relationships were significantly strong with highest $\bar{R}^2$ (0.87) given by power function that followed exponential (0.85), linear (0.83), S (0.68) and log linear (0.63) function. The results are in conformity to the findings of Ahmad *et al*. (2014) who have reported 98 percent variation in aboveground biomass of *Picea smithiana* trees due to DBH, however, basal area explained 96 percent of variation in biomass while using quadratic analysis. The results of the study are further supported by the results of Chave *et al*. (2005) who have reported power function as the best fit for dry tropical forests with strong relationship (R^2 >= 90%) between aboveground biomass and DBH, tree height and wood density when analyzed separately.

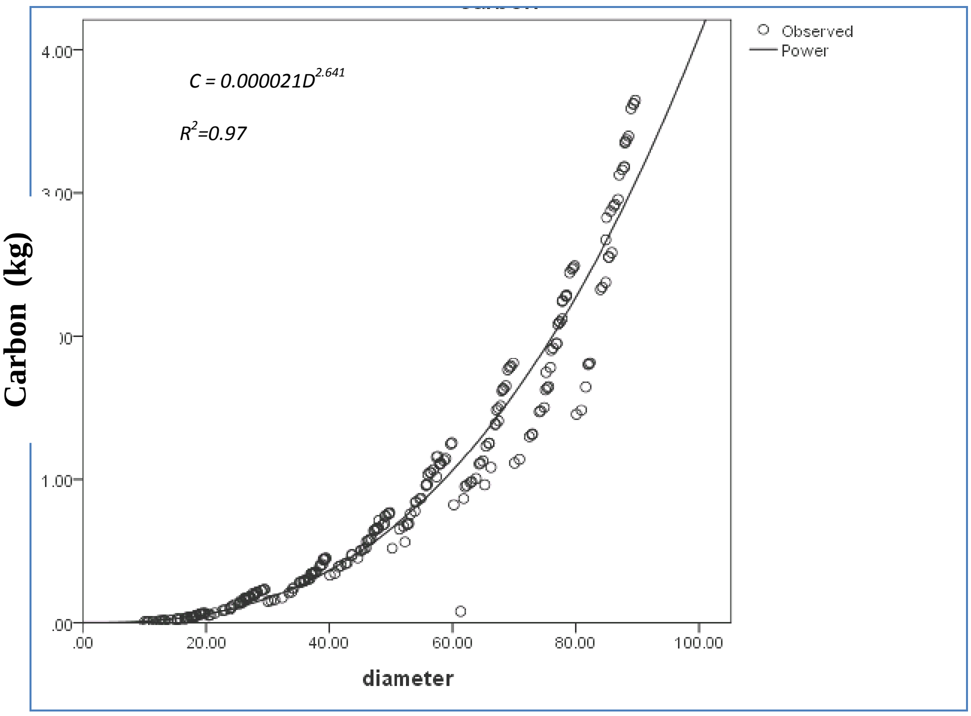

Fig. 10. Relationship between biomass carbon and DBH

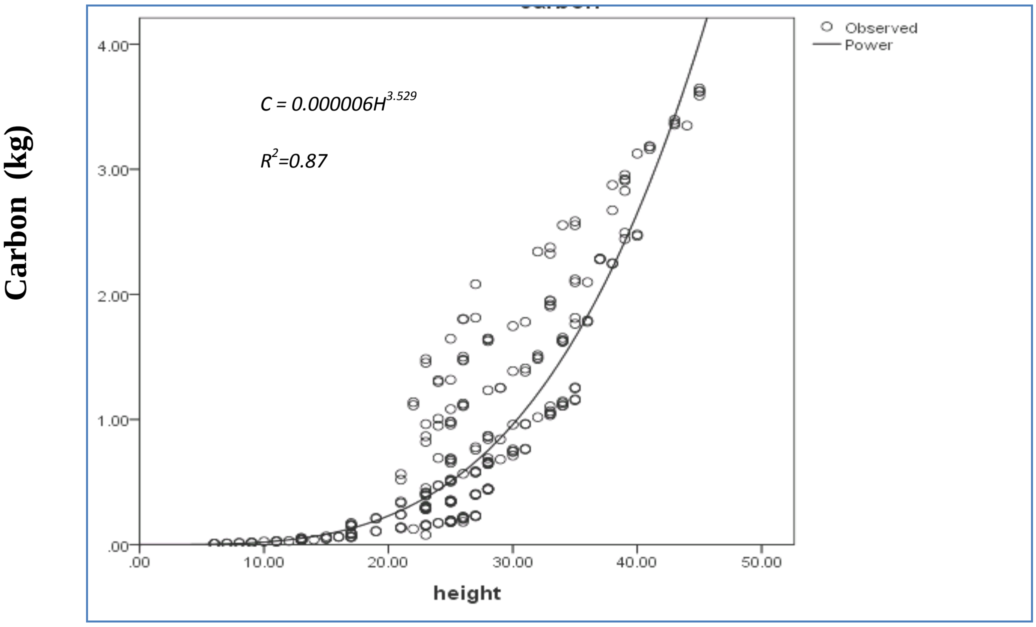

Fig. 11. Relationship between biomass carbon and tree height

Abies pindrow

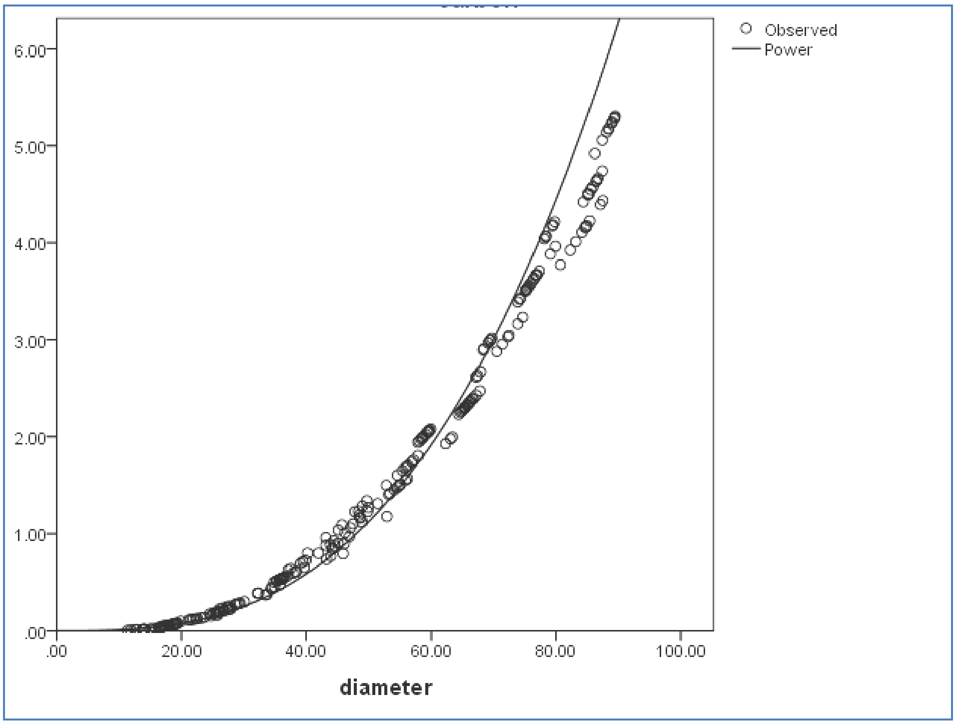

Fig. 12. Relationship between biomass carbon and DBH

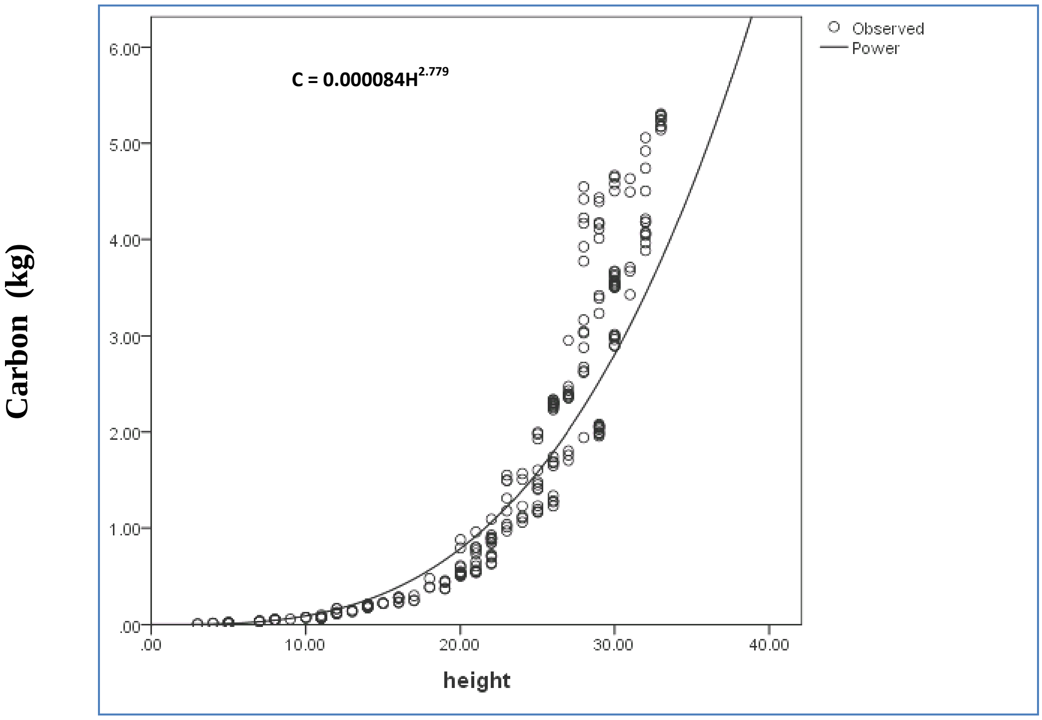

Fig. 13. Relationship between biomass carbon and tree height

Picea smithiana

Table 15 Allometric linear and non-linear equations for estimation of tree biomass carbon of *Picea smithiana* trees based on DBH and tree Height variable

Biomass carbon	b_0	b_1	Adj R^2	Model
DBH				
$C = -1.067+0.041D$	-1.067	0.041	0.84	Linear
$C = -4.658+1.498 \mathrm{Ln} D$	-4.658	1.498	0.65	Log linear
$C = 0.015e^{0.067D}$	0.015	0.067	0.93	Exponential
$C = 0.000010D^{2.824}$	0.000010	2.824	0.98	Power
$C = \exp(1.372-81.495/D)$	1.372	-81.495	0.88	Sigmoidal
HEIGHT				
$C = -1.146+0.096H$	-1.146	0.096	0.83	Linear
$C = -3.743+1.590 \mathrm{Ln} H$	-3.743	1.590	0.64	Log linear
$C = 0.015e^{0.149H}$	0.015	0.149	0.85	Exponential
$C = 0.000084H^{2.779}$	0.00008	2.779	0.87	Power
$C = \mathrm{Exp}(1.166-34.165/H)$	1.166	-34.165	0.68	Sigmoidal

C = Carbon D = diameter at breast height (cm) H = Height (m)
* Significant at 5% level of significance

4.3 MODEL EVALUATION

The power function for tree Height as predictor variable resulted in lower values of adjusted R^2 as compared to adjusted R^2 values for DBH. Tree height is more tedious to measure and may not explain more of the variance at the site where the data originated, but its incorporation has the advantage of increasing potential applicability of the equation to different sites (Ketterings *et al.*, 2001). Hence, equations based on DBH variable were considered for further testing. Adjusted R^2 value cannot only be used as the criterion for choosing the best-fitted function. We followed more criteria to choose the best one i.e., the adjusted R^2, goodness of fit and Theil’s-U Statistics.

On comparison the adjusted R^2 values of DBH of different functions (Table 4-15) it was revealed that power function ($C= a \times D^b$) performed well when DBH was taken as predictor variable for estimation of biomass of chirpine, ban oak, kail, fir and spruce, with reasonable accuracy. To test the goodness of fit, the Chi-square test was applied. The Chi-square values were found significant at 5 percent level of significance, hence for the final selection, Theil’s-U statistics was applied to power function. The application of Chi-square test of goodness of fit and Theil’s-U statistics revealed that power function using DBH as independent variable was best fit (Table 16). The Theil’s-U values were approaching to zero, thus models based on power function for tree species under study were finally selected for their validation. Such results have also been reported by Pandey *et al.* (1998).

Table 16 Comparison of power function for biomass carbon estimation based on DBH

Sample trees	Adjusted R ^{2}	χ^2	Theil-U statistics
Pinus roxburghii	0.98	7.35	0.07
Pinus wallichiana	0.99	4.22	0.04
Cedrus deodara	0.97	12.62	0.11
Abies pindrow	0.97	7.10	0.08
Picea smithiana	0.98	5.55	0.07
Quercus leucotrichophora	0.96	22.40	0.09

Significant at 5% level of significance

Before a model is recommended, it needs the validation. For checking the adequacy, power biomass carbon function having highest values of $\overline{R}^2$ and lowest chi-square were subjected to cross-validation.

All 240 observations on DBH were selected and the model selected was cross-validated and fitted. The fitted model was used to predict the stem volume and biomass of actual 120 observations which were used in the calibration and then the apparent error, true error, excess error and Chi-square values of original and independent entire data was computed. Model selected for cross validation were as under:

- $V = a(D)^b$
- $C = a(D)^b$

Table 17 Cross validation result of stem volume model

Sample trees	Model	Adjusted R^2	AE	TE	EE	X^2 orignal	X^2 (independent)	X^2 (Overall)
Pinus roxburghii	$V= 0.000016D^{2.912}$	0.98	0.1	-0.1	-0.2	43.4	44.9	1.5
Pinus wallichiana	$V= 0.000030D^{2.767}$	0.97	0.0	-0.1	-0.1	19.9	21.5	1.6
Cedrus deodara	$V= 0.000019D^{2.886}$	0.97	0.1	-0.1	-0.1	90.9	94.8	3.9
Abies pindrow	$V= 0.000022D^{2.833}$	0.97	0.0	0.0	0.0	71.2	72.9	1.7
Picea smithiana	$V= 0.000036D^{2.602}$	0.88	2.4	0.0	-2.4	49.6	51.1	2.1
Quercus leucotrichophora	$V= 0.000036D^{2.602}$	0.97	7.0	0.0	-6.9	34.1	35.5	1.4

D = diameter at breast height C = Carbon TE = Total Error
EE = Excess Error AE = Apparent error

The results of cross-validation for stem volume and biomass carbon is given in Table 17 and Table 18, respectively. In all the sets, apparent error as well as true error were found to be negligible, which reflects that the model prediction is nearly correct and selected variable for the model is correct.

Table 18 Cross validation result of biomass carbon model

Sample trees	Model	Adjusted R^2	AE	TE	EE	X^2 orignal	X^2 (independent)	X^2 (Overall)
Pinus roxburghii	$C= 0.000012D^{2.923}$	0.98	7.8	-0.1	-7.9	25.9	26.9	1.0
Pinus wallichiana	$C = 0.000021D^{2.767}$	0.99	4.8	0.0	-4.8	10.7	11.6	0.9
Cedrus deodara	$C = 0.000010D^{2.889}$	0.97	6.0	-0.1	-6.1	32.5	33.5	0.8
Abies pindrow	$C = 0.000021D^{2.641}$	0.97	4.0	0.0	-4.0	12.2	12.6	0.3
Picea smithiana	$C = 0.000010D^{2.824}$	0.98	1.3	0.0	-1.3	25.8	26.2	0.4
Quercus leucotrichophora	$C = 0.000053D^{2.603}$	0.96	10.0	0.1	-10.0	74.2	77.1	3.0

D = diameter at breast height C = Carbon TE = Total Error
EE = Excess Error AE = Apparent error

Among various linear and non-linear functions tried for volume prediction, power functions (0.98) were having highest value of adjusted R^2. The application of Chi-square test of goodness of fit and Theil's-U statistics revealed that power function using DBH as independent variable was best fit (Table 17-18). Following the same procedure, Sharma and Nanda (2008) reported negligible apparent error as well as true error after cross validating the best fitted power function for estimation of stem volume based on crown volume for *Pinus roxburghii*. The linear models satisfying all statistical assumptions suffered from problems of outliners whereas non-linear performed well then the linear models for precision and validation therefore such findings are in proximity with those of Ajit *et al.* (2000) and Shrivastva *et al.* (2000).

Computed value of the Chi-square for original set, independent set and both the sets when taken together were found to be non-significant thereby proving the validity of selected models. The results of the present findings are in collaboration with the observations made by Anderson *et al.* (1982) as they examinated and compared the tree volume functions by cross-validation. However, on the similar lines, Chen (1982) used Jacknife technique for estimating the index of diversity with tree data from Liang Shui Forest Farm, China. As per the studies by Yang and Kung (1983) who reported that Jacknife reduces bias in the regression estimates for volume determination when volume and diameter were normally distributed. They observed that these were especially useful where the cost-ratio and the correlation between volume determination and diameter measurements were high.

Chapter-5

SUMMARY AND CONCLUSION

The present investigations entitled **“Biomass carbon estimation of important North-Western Himalayan tree species”** was carried out during year 2015-2016 to develop allometric models to estimate tree volume and total biomass carbon in Kumarsain Range of Kotgarh Forest Division, Himachal Pradesh. The natural stands of *Pinus roxburghii* mixed with *Quercus leucotrichophora* were selected in Melandi UF- 255 compartment at elevation from 1100 to 2000m (a.m.sl.) distributed over an area of 10.93 ha near Kingal and Galani of Kumarsain Range. For *Pinus wallichiana, Cedrus deodara, Abies pindrow and Picea smithiana* stands were selected in compartment no. 41-a and 41-b in Chhichar forest (Narkanda) distributed at elevation from 1500m to 3000m over an area of 41.31ha and 46.57 ha, respectively of Kumarsain Range.

After through survey of the area, thirty trees each of eight DBH class (10-20cm to 80-90cm) and in each DBH class, ten trees each representing trees of height range i.e. large, medium and small height were selected and in total 240 trees each for *Pinus roxburghii, Quercus leucotrichophora, Pinus wallichiana, Cedrus deodara, Abies pindrow* and *Picea smithiana* were measured for diameter at breast height (DBH) and tree Height. Volume of trees was calculated and transformed into biomass using specific gravity. Branch and foliage biomass of each species was estimated using BEF and root biomass of trees was calculated by using root-shoot ratio (IPCC, 2003).

The actual data on DBH and total Height with stem volume and total biomass carbon were used in the calibration of various linear and non-linear models. The functions having high value of adjusted R^2, lowest calculated chi-square values and lowest Theil’s-U statistic values were preferred for further investigation and selected functions were finally subjected to cross-validation to ensure its adequacy. The salient findings of the investigation are summarized as under:

- The values of adjusted R^2 reveals that power function performed well when DBH and tree Height regressed on stem volume and biomass carbon. Among DBH and tree

Height; DBH is the best predictive variable for estimation of stem volume and tree biomass carbon.

- Power function were best fitted for all the species to estimate stem volume based on DBH with adjusted R^2 values as *Pinus roxburghii* (0.98), *Pinus wallichiana* (0.99), Cedrus deodara (0.97), *Abies pindrow* (0.97), *Picea smithiana* (0.98) & *Quercus leucotrichophora* (0.96). Similarly, for tree Height, the power function was best fitted with adjusted R^2 values each for *Pinus roxburghii* (0.95), *Pinus wallichiana* (0.88), *Cedrus deodara* (0.88), *Abies pindrow* (0.88), *Picea smithiana* (0.88), *Quercus leucotrichophora* (0.86). For DBH predictor variable, on the basis of adjusted R^2 value, the power function was best fitted for estimation of stem volume with adjusted R^{2} values ranging between 0.96 to 0.99 for ≤ 10 cm and ≥ 90 cm (DBH respectively and were highly significant (*P* is 0.05 for each dbh range).

- Adjusted R^2 values for tree biomass carbon with DBH as independent variable are as: *Pinus wallichiana* (0.99), *Picea smithiana & Pinus roxburghii* (0.98), *Abies pindrow & Cedrus deodara* (0.97), *Quercus leucotrichophora* (0.96). Similarly adjusted R^2 values for biomass carbon with tree Height as independent variable were as: *Pinus roxburghii* (0.95*), Pinus wallichiana* (0.93), *Cedrus deodara* (0.88), *Abies pindrow & Picea smithiana* (0.87), *Quercus leucotrichophora* (0.75). For model using tree Height alone, on the basis of adjusted R^2 value, the power function was best fitted for total biomass carbon with linear and non-linear relationships produced relatively poor adjusted R^{2} values ranging from 0.75 to 0.95 (for different height ranges) and were highly significant (*P* is 0.05 for each tree height).

- Regression analysis of various linear and non-linear functions reveals that all functions showed significant values of adjusted R^2 but chi-square test of goodness of fit and Theil's-U statistic proves that power function outperform all other functions. DBH is the best predictive variable for estimation of stem volume and biomass carbon.

- Regression analysis also indicates that value of adjusted R^2 cannot be taken the sole criteria in judging the performance of a prediction model because even the models with high value of adjusted R^2 could not pass the test of cross-validation. The model $\{Y=a(X)^b\}$ is the best fit for the data to predict stem volume and biomass carbon.

CONCLUSIONS

- Both DBH and tree Height independently were significant variables for the estimation of tree volume and tree biomass carbon.
- The power function was the best fitted functions among all functions, based on adjusted R^2 values.
- The model prediction was nearly correct and selected variables for the model are correct.
- The biomass carbon prediction model are as: *Pinus roxburghii* ($C=0.000012D^{2.923}$), *Quercus leucotrichophora* ($C=0.000053D^{2.603}$), *Pinus wallichiana*($C= 0.000021D^{2.767}$), *Cedrus deodara* ($C=0.000010D^{2.889}$), *Abies pindrow* ($C=0.000021D^{2.641}$) and *Picea smithiana* ($C=0.000010D^{2.824}$).

Finally, to the scope of future work, the proposed model formulated and validated may be tested for large number of sample trees with different diameter classes using advanced validation techniques. The information generated would be of great help to the foresters and forest biometricians in particular for the estimation of volume and biomass carbon of species under study.

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APPENDIX – I

Biomass Expansion Factor, Specific Gravity and R:S ratio of different forest tree species

SAMPLE TREES	BEF	REFRENCES	SG	REFRENCES	RSR	REFRENCES
Pinus roxburghii	1.91	Rawat and Tandon (1993)	0.491	Rajput *et al*. (1985)	0.21	IPCC (2003)
Pinus wallichiana	1.91	Rana and Singh (1990)	0.427	Kumar (1998)	0.27	IPCC (2003)
Cedrus deodara	1.40	IPCC (2003)	0.468	Rajput *et al*. (1985)	0.27	IPCC (2003)
Abies pindrow	1.51	Haripriya (2000)	0.340	IPCC (2003)	0.21	IPCC (2003)
Picea smithiana	1.51	Haripriya (2000)	0.380	IPCC (2003)	0.21	IPCC (2003)
Quercus leucotrichophora	1.91	Rana and Singh (1990)	0.826	Raturi *et al*. (2002)	0.39	IPCC (2003)

APPENDIX-II

ANOVA TABLES

ANOVA 1 Allometric linear and non-linear equations for estimation of stem volume of *Pinus roxburghii* trees based on DBH and tree Height variable (Table 4)

DBH

Equation	R Square	F	df	Sum of squares
Linear	0.93	3197.049	1	897.60
Logarithmic	0.77	814.538	1	746.35
Power	0.98	16544.086	1	610.07
S	0.97	7962.974	1	592.36
Exponential	0.88	1843.821	1	540.32

Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.72	632.942	1	700.88
Logarithmic	0.52	259.339	1	502.90
Power	0.95	4496.660	1	579.40
S	0.73	670.562	1	450.26
Exponential	0.92	9094.435	1	594.51

ANOVA 2 Allometric linear and non-linear equations for estimation of stem volume of *Quercus leucotricophora* trees based on DBH and tree Height variable (Table 5)

DBH

Equation	R Square	F	df	Sum of squares
Linear	0.81	1031.912	1	429.26
Logarithmic	0.63	416.588	1	336.10
Power	0.96	5670.643	1	473.31
S	0.91	2341.374	1	447.67
Exponential	0.90	2161.556	1	444.26

Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.73	655.548	1	387.55
Logarithmic	0.52	261.460	1	276.53
Power	0.75	705.518	1	366.77
S	0.59	344.768	1	291.76
Exponential	0.74	690.566	1	366.77

Pinus wallichiana

ANOVA 3 Allometric linear and non-linear equations for estimation of stem volume of *Pinus wallichiana* trees based on DBH and tree Height variable (Table 6)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.880	1748.356	1	1069
Logarithmic	.706	570.361	1	857.10
Power	.990	23675.427	1	573.25
S	.927	3037.847	1	536.94
Exponential	.918	2656.454	1	531.40

Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.79	902.558	1	448.55
Logarithmic	0.61	372.050	1	372.59
Power	0.93	3205.474	1	550.80
S	0.80	944.402	1	486.11
Exponential	0.92	2814.782	1	529.87

ANOVA 4 Allometric linear and non-linear equations for estimation of stem volume of *Cedrus deodara* trees based on DBH and tree Height variable (Table 7)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.882	1786.537	1	974.76
Logarithmic	.716	599.549	1	790.73
Power	.973	8484.086	1	641.97
S	.959	5621.927	1	615.89
Exponential	.853	1384.071	1	547.77

Tree height

Equation	R Square	F	df	Sum of squares
Linear	.600	356.994	1	662.76
Logarithmic	.409	164.573	1	451.57
Power	.882	1774.508	1	566.05
S	.731	647.805	1	469.48
Exponential	.871	1607.055	1	559.16

ANOVA 5 Allometric linear and non-linear equations for estimation of stem volume of *Abies pindrow* trees based on DBH and tree Height variable (Table 8)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.848	1324.200	1	1155.01
Logarithmic	.665	495.050	1	920.76
Power	.970	7724.743	1	509.08
S	.926	2991.914	1	486.10
Exponential	.881	1760.571	1	462.28

Tree height

Equation	R Square	F	df	Sum of squares
Linear	.709	580.678	1	967.06
Logarithmic	.522	260.224	1	712.12
Power	.866	1542.544	1	454.63
S	.749	712.064	1	393.31
Exponential	.826	1130.249	1	433.49

ANOVA 6 Allometric linear and non-linear equations for estimation of stem volume of *Picea smithiana* trees based on DBH and tree Height variable (Table 9)

DBH

Equation	**R Square**	**F**	**df**	**Sum of squares**
Linear	0.84	1206.567	1	1143.83
Logarithmic	0.65	438.841	1	887.91
Power	0.98	10558.306	1	610.04
S	0.88	1704.465	1	547.34
Exponential	0.93	3147.961	1	579.94

Tree Height

Equation	**R Square**	**F**	**df**	**Sum of squares**
Linear	0.71	1176.174	1	967.06
Logarithmic	0.52	417.609	1	712.12
Power	0.87	1554.032	1	454.67
S	0.75	502.601	1	393.31
Exponential	0.83	1309.821	1	433.49

Biomass carbon

ANOVA 7 Allometric linear and non-linear equations for estimation of biomass carbon of *Pinus roxburghii* trees based on DBH and tree Height variable (Table 10)

DBH

Equation	**R Square**	**F**	**df**	**Sum of squares**
Linear	.931	3197.029	1	561.38
Logarithmic	.774	814.566	1	466.79
Power	.984	15056.520	1	605.93
S	.974	8875.352	1	599.44
Exponential	.882	1783.649	1	543.05

Tree height

Equation	**R Square**	**F**	**df**	**Sum of squares**
Linear	.727	632.906	1	438.34
Logarithmic	.521	259.352	1	314.53
Power	.953	4844.647	1	586.69
S	.749	710.912	1	461.13
Exponential	.973	8505.500	1	538.75

ANOVA 8 Allometric linear and non-linear equations for estimation of stem volume of *Quercus leucotricophora* trees based on DBH and tree Height variable (Table 11)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.813	1031.854	1	230.47
Logarithmic	.636	416.579	1	728.75
Power	.960	5654.782	1	473.36
S	.908	2341.685	1	447.85
Exponential	.901	2157.137	1	444.34

Tree height

Equation	R Square	F	df	Sum of squares
Linear	.734	655.554	1	840.09
Logarithmic	.523	261.463	1	599.44
Power	.748	705.980	1	368.98
S	.592	345.301	1	292.06
Exponential	.744	690.356	1	366.88

ANOVA 9 Allometric linear and non-linear equations for estimation of biomass carbon of *Pinus wallichiana* trees based on DBH and tree Height variable (Table 12)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.884	1819.651	1	533.86
Logarithmic	.708	576.483	1	427.29
Power	.991	26642.151	1	573.62
S	.931	3208.405	1	538.43
Exponential	.917	2644.829	1	530.62

Tree height

Equation	R Square	F	df	Sum of squares
Linear	.789	891.566	1	476.49
Logarithmic	.608	369.477	1	367.17
Power	.931	3199.328	1	538.28
S	.801	958.782	1	463.35
Exponential	.920	2753.481	1	532.26

ANOVA 10 Allometric linear and non-linear equations for estimation of biomass carbon of *Cedrus deodara* trees based on DBH and tree Height variable (Table 13)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.882	1785.654	1	253.15
Logarithmic	.716	599.292	1	250.34
Power	.971	7974.624	1	625.97
S	.960	5727.653	1	618.98
Exponential	.851	1355.763	1	548.38

Tree height

Equation	R Square	F	df	Sum of squares
Linear	.600	357.002	1	172.13
Logarithmic	.409	164.528	1	117.26
Power	.883	1789.930	1	568.19
S	.736	663.063	1	474.38
Exponential	.869	1578.489	1	560.18

ANOVA 11 Allometric linear and non-linear equations for estimation of biomass carbon of *Abies pindrow* trees based on DBH and tree Height variable (Table 14)

DBH

Equation	R Square	F	df	Sum of squares
Linear	.848	1324.098	1	178.98
Logarithmic	.675	495.027	1	142.59
Power	.970	7712.054	1	508.84
S	.926	2993.643	1	145.92
Exponential	.881	1759.745	1	462.65

Tree Height

Equation	R Square	F	df	Sum of squares
Linear	.709	580.681	1	149.77
Logarithmic	.522	260.228	1	110.29
Power	.866	1543.951	1	454.84
S	.750	712.987	1	393.27
Exponential	.826	1130.406	1	433.49

ANOVA 12 Allometric linear and non-linear equations for estimation of biomass carbon of *Picea smithiana* trees based on DBH and tree Height variable (Table 15)

DBH

Equation	**R Square**	**F**	**df**	**Sum of squares**
Linear	.840	1251.941	1	220.03
Logarithmic	.651	444.904	1	170.59
Power	.979	10903.750	1	606.37
S	.879	1731.098	1	544.72
Exponential	.930	3145.473	1	576.02

Tree height

Equation	**R Square**	**F**	**df**	**Sum of squares**
Linear	.829	1154.042	1	217.08
Logarithmic	.635	414.844	1	166.39
Power	.866	1537.914	1	536.57
S	.678	501.534	1	420.20
Exponential	.845	1300.222	1	523.74

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Title of the thesis : **“Biomass carbon estimation of important North-Western Himalayan tree species”**
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ABSTRACT

The present investigation entitled “Biomass carbon estimation of important North-Western Himalayan tree species” was carried out in Kumarsain Range of Kotgarh Forest Division of Himachal Pradesh located, at latitude $31^{o}8^{'}40''$ to $31^{o}42^{'}50''$ N and longitude $72^{o}18^{'}50''$ to $77^{o}58^{'}$E at elevation from 1050-3215 m above mean sea level (a.m.sl.) during year 2015-2016 to develop allometric models for estimation of tree volume and tree biomass carbon of important north-western Himalayan tree species viz., *Pinus roxburghii, Pinus wallichiana, Cedrus deodara, Abies pindrow* , *Picea smithiana* and *Quercus leucotrichophora* . Thirty trees each of eight DBH class (10-20cm to 80-90cm) representing trees of all height range i.e., large, medium and small height were measured for diameter at breast height (DBH) and tree Height. Volume of trees was calculated and transformed into biomass using specific gravity. Branch and foliage biomass of each species was estimated using biomass expansion factor and root biomass of trees was calculated by using the guidelines of IPCC (2003). All biomass values were transferred to tree biomass carbon by a factor of 0.5. Various linear and non-linear relationships were developed taking DBH and tree Height as predictor variables individually. Out of linear and nonlinear function derived for the estimation of volume and biomass carbon based on DBH and tree Height, the power functions were best fitted for all the species under study with significant adjusted R^2 values. Adjusted R^2 values for biomass carbon with diameter at breast height as independent variable was as: *Pinus wallichiana* (0.99), *Picea smithiana & Pinus roxburghii* (0.98), *Abies pindrow & Cedrus deodara* (0.97), *Quercus leucotrichophora* (0.96). Similarly, adjusted R^2 values for tree biomass carbon with tree Height as independent variable were as: *Pinus roxburghii* (0.95), *Pinus wallichiana* (0.93), *Cedrus deodara* (0.88), *Abies pindrow & Picea smithiana* (0.87), *Quercus leucotrichophora* (0.75). However, in this research, Model comparison and selection was based on adjusted R^2, goodness of fit and Theil’s-U statistics that were finally cross-validated to ensure further adequacy. The allometric models developed in the present study can be utilized for future estimation of tree volume and tree biomass carbon of species under study.

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