

**DEVELOPING PREDICTION MODELS FOR BIOMASS
COMPONENTS OF *Tectona grandis* L.**

Thesis

**Submitted to the Punjab Agricultural University
in partial fulfilment of the requirements
for the degree of**

**MASTER OF SCIENCE
in
FORESTRY
(Minor Subject: Fruit Science)**

By

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CERTIFICATE - I

This is to certify that the thesis entitled “**Developing prediction models for biomass components of *Tectona grandis L.***” submitted for the degree of **Master of Science** in the subject of **Forestry and Natural Resources** (Minor subject: **Fruit Science**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Anmoldeep Singh** (L-2013-A-49-M) under my supervision and that no part of this thesis has been submitted for any other degree.

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

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ABSTRACT

The present investigation entitled 'DEVELOPING PREDICTION MODELS FOR BIOMASS COMPONENTS OF *Tectona grandis* L' was carried out at the University Seed Farm, Ladhawal, Punjab Agricultural University (PAU), Ludhiana during the year 2015-16. *Tectona grandis* belonging to family Verbenaceae is widely distributed and economically important species for timber and furniture. Species is being planted at many places in Punjab and many farmers are showing interest in the species. Keeping in view of its encouraging response under Punjab conditions, so far no biomass prediction models/equations are available to ascertain the growing stock, which will be a usually handy tool to know the biomass. The proposed study was a step formed in this direction. Among many models developed by using different tree growth parameters [Height (H), girth at breast height (GBH) and $GBH^2 \times H$], the best fit equations were found with Linear and exponential regression functions using GBH and $GBH^2 \times H$ parameters as independent factor with various dependent factors [total green and dry biomass (TGB & TDB), total above and below ground green (AGB & BGB) and dry biomass (ADB & BDB)]. Among developed models, the logarithm function i.e. $TGB = 240.794 \ln GBH - 668.336$ and quadratic equation $TGB = 0.029GBH^2 + 7.853GBH - 53.814$ with approximately the same Adj. R^2 0.94 and 0.92, respectively were found best fit lines to predict total green and dry biomass of tree. Similarly, for above ground green and dry biomass, logarithm function $AGB = 204.418 \ln GBH - 591.945$ with Adj. R^2 value of 0.94 and quadratic function $AGB = -0.001GBH^2 + 5.195GBH - 26.301$ with Adj. R^2 value of 0.93 both were found best fit to predict above ground biomass and for below ground green and biomass prediction. The power function $BFB = 3.257GBH^{(0.714)}$ with maximum Adj. R^2 value of 0.71 followed by exponential function $BFB = 29.668e^{(0.011GBH)}$ with Adj. R^2 value of 0.67 and logarithm function $BFB = 43.243 \ln GBH - 112.919$ with minimum Adj. R^2 value of 0.66 were significantly found best fit. Even the regression coefficient of the logarithm and quadratic function were very high but in validation these models shows less reliability in prediction for higher and lower GBH class components so we give preference to linear and exponential functions due to their more compatibility with all components in all GBH classes. Biomass expansion factor (BEF) showed decreasing trend as the range of the girth classes increased. For different GBH classes, the values of BEF ranged from 1.61 to 1.24 and with increase in girth class.

Keywords: *Tectona grandis*, biomass, equation, linear, exponential.

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ਮੌਜੂਦਾ ਜਾਂਚ “ਟੈਕਟੋਨਾ ਗਰੈਡਿਸ ਦੇ ਨੈਵਿਕ ਘਟਕਾਂ ਲਈ ਪੇਸ਼ੀਨਗੋਈ ਮਾਡਲ ਵਿਕਸਤ ਕਰਨਾ” ਸਿਰਲੇਖ ਹੇਠ ਪੰਜਾਬ ਐਗਰੀਕਲਚਰਲ ਯੂਨੀਵਰਸਿਟੀ ਲੁਧਿਆਣਾ ਦੇ ਲਾਡੋਵਾਲ ਸੀਡ ਫਾਰਮ ਉੱਪਰ ਕੀਤਾ ਗਿਆ। ਟੈਕਟੋਨਾ ਗਰੈਡਿਸ ਵਰਬੀਨੋਸੀ ਪਰਿਵਾਰ ਨਾਲ ਸਬੰਧਿਤ ਰੁੱਖ ਕਾਫੀ ਇਲਾਕਿਆਂ ਵਿੱਚ ਪਾਇਆ ਜਾਣ ਵਾਲਾ ਫਰਨੀਚਰ ਅਤੇ ਸ਼ਤੀਰੀ ਲਈ ਆਰਥਿਕ ਤੌਰ ਤੇ ਮਹੱਤਵਪੂਰਨ ਰੁੱਖ ਹੈ। ਇਹ ਪ੍ਰਜਾਤੀ ਪੰਜਾਬ ਵਿੱਚ ਕਾਫੀ ਲਗਾਈ ਜਾ ਰਹੀ ਹੈ ਪੰਜਾਬ ਦੇ ਕਈ ਕਿਸਾਨ ਇਸ ਵਿੱਚ ਦਿਲਚਸਪੀ ਲੈ ਰਹੇ ਹਨ। ਪੰਜਾਬ ਦੀਆਂ ਹਾਲਾਤਾਂ ਵਿੱਚ ਮਿਲ ਰਹੇ ਇਸ ਹੁੰਗਾਰੇ ਅਤੇ ਨੈਵਿਕ ਭਾਰ ਲਈ ਆਸਾਨ ਔਜਾਰ ਬਾਇਓਮਾਸ ਪੇਸ਼ੀਨਗੋਈ ਮਾਡਲ / ਸਮੀਕਰਣ ਦੀ ਅਣਹੋਂਦ ਨੂੰ ਮੱਦੇਨਜ਼ਰ ਰੱਖਦੇ ਹੋਏ ਇਹ ਅਧਿਐਨ ਕੀਤਾ ਗਿਆ। ਵੱਖ-ਵੱਖ ਵਿਕਾਸ ਮਾਪਦੰਡਾਂ ਨੂੰ ਵਰਤ ਕੇ ਬਣਾਏ ਅਨੇਕਾ ਮਾਡਲਾਂ ਵਿੱਚੋਂ ਸਭ ਤੋਂ ਫਿਟ ਸਮੀਕਰਣ GBH ਅਤੇ $GBH^2 \times H$ ਮਾਪਦੰਡਾਂ ਨੂੰ ਆਜ਼ਾਦ ਅਤੇ ਕਈ ਨਿਰਭਰ ਕਾਰਕ (ਕੁੱਲ ਹਰਾ ਅਤੇ ਸੁੱਕਾ ਤਾਰਾ TGB ਅਤੇ TDB) ਜ਼ਮੀਨ ਤੋਂ ਉਪਰਲਾ ਅਤੇ ਹੇਠਲਾ ਕੁੱਲ ਹਰਾ ਅਤੇ ਸੁੱਕਾ (AGB ਅਤੇ BGB, ADB ਅਤੇ BDB) ਨੂੰ ਵਰਤ ਕੇ ਬਣੀ ਲੀਨੀਅਰ ਅਤੇ ਐਕਸਪੋਨੇਂਸ਼ੀਅਲ ਰਿਗਰੇਸ਼ਨ ਫੰਕਸ਼ਨ ਸੀ। ਬਣਾਏ ਮਾਡਲਾਂ ਵਿੱਚ ਲਾਗਰਿਥਮ ਫੰਕਸ਼ਨ ਜੋ ਕਿ $TGB=240.794 \ln GBH-668.336$ ਅਤੇ ਕੁਆਡਰੇਟਿਕ ਸਮੀਕਰਣ $TGB=0.029GBH^2 + 7.853GBH-53.814$ ਜਿੰਨ੍ਹਾਂ ਦਾ ਕ੍ਰਮਵਾਰ $Adj R^2$ 0.94 ਅਤੇ 0.92 ਸੀ, ਰੁੱਖ ਦਾ ਕੁੱਲ ਹਰਾ ਅਤੇ ਸੁੱਕਾ ਭਾਰ ਦਾ ਅੰਦਾਜ਼ਾ ਲਾਉਣ ਲਈ ਸਭ ਤੋਂ ਸਹੀ ਲਾਇਨ ਸੀ। ਇਸੇ ਤਰ੍ਹਾਂ ਜ਼ਮੀਨ ਉੱਪਰਲੇ ਹਰੇ ਅਤੇ ਸੁੱਕੇ ਭਾਰ ਲਈ ਲਾਗਰਿਥਮ ਫੰਕਸ਼ਨ $AGB=204.418 \ln GBH=591.945$ ਜਿਸਦੇ $Adj R^2$ ਦਾ ਮਾਨ 0.93 ਸੀ ਅਤੇ ਕੁਆਡਰੇਟਿਕ ਫੰਕਸ਼ਨ $AGB=0.001GBH^2H + 5.195GBH-26.31$ ਜਿਸਦੇ $Adj R^2$ ਦਾ ਮਾਨ 6.93 ਦੋਨੋਂ ਜ਼ਮੀਨਦੋਜ਼ ਅਤੇ ਜ਼ਮੀਨ ਉਪਰਲੇ ਹਰੇ ਅਤੇ ਸੁੱਕੇ ਭਾਰ ਦਾ ਅੰਦਾਜ਼ਾ ਲਾਉਣ ਲਈ ਉਚਿਤ ਸਨ। ਪਾਵਰ ਫੰਕਸ਼ਨ $BFB=29.668e^{0.011 GBH}$ ਜਿਸਦਾ $Adj R^2$ 0.67 ਅਤੇ ਲਾਗਰਿਥਮ ਫੰਕਸ਼ਨ $BFB=43.243 \ln GBH-112.919$ $Adj R^2$ ਮਾਨ 0.66 ਅਰਥਪੂਰਨ ਤੌਰ ਤੇ ਫਿੱਟ ਪਾਏ ਗਏ। ਹਾਲਾਂਕਿ ਲਾਗਰਿਥਮ ਅਤੇ ਕੁਆਡਰੇਟਿਕ ਫੰਕਸ਼ਨ ਦਾ ਰਿਗਰੇਸ਼ਨ ਕੋਫੀਸ਼ੈਂਟ ਜ਼ਿਆਦਾ ਸੀ ਪਰ ਪੁਸ਼ਟੀਕਰਣ ਤੇ ਉੱਪਰਲੀਆਂ ਤੇ ਹੇਠਲੀਆਂ GBH ਕਲਾਸ ਘਟਕਾ ਦੀ ਪੇਸ਼ੀਨਗੋਈ ਲਈ ਘੱਟ ਭਰੋਸੇਯੋਗ ਪਾਇਆ ਗਿਆ। ਇਸ ਕਰਕੇ ਅਸੀਂ ਲੀਨੀਅਰ ਅਤੇ ਐਕਸਪੋਨੇਂਸ਼ੀਅਲ ਫੰਕਸ਼ਨ ਨੂੰ ਉਨ੍ਹਾਂ ਦੇ ਜ਼ਿਆਦਾ ਅਨੁਕੂਲ ਹੋਣ ਕਰਕੇ ਤਰਜੀਹ ਦਿੱਤੀ ਗਈ। ਵੱਖ-ਵੱਖ GBH ਕਲਾਸ ਲਈ BEF ਦਾ ਮਾਨ 1.61 ਤੋਂ 1.24 ਦੇ ਵਿਚਕਾਰ ਸੀ ਅਤੇ ਮੋਟਾਈ ਦੇ ਵੱਧਣ ਨਾਲ BEF ਦਾ ਘਟਣਾ ਇਹ ਦਰਸਾਉਂਦਾ ਹੈ ਕਿ ਰੁੱਖ ਦੇ ਕੁੱਲ ਬਾਇਓਮਾਸ ਵਿੱਚ ਤਣੇ ਦਾ ਹਿੱਸਾ ਵੱਧ ਗਿਆ ।

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CHAPTER I

INTRODUCTION

Trees are indispensable component of agriculture for protection of land, nutrient cycling, micronutrient modification and oldest associate of man to meet needs for timber, fuel, fodder, etc. Trees on agricultural landscape owes capabilities only to provide multiple outputs of trees/crop based products to meet needs of local people and industries and also facilitate the amelioration of environment. However day by day rising demands and more developed modes for exploitation, the country's natural resources are declining at a shocking rate. The rising pressures of industrialization and urbanization are leading to deprivation of land, water, air and shortages for food, fodder and fuel. It has resulted in a serious resource shortage that is affecting the peoples in all walks of life and the overall economy of the country.

Biomass measurement is essential not only for planning for future development programmes but also for researchers to assess the productivity of ecosystem, meeting industrial demands, reducing pressure on traditional forests, carbon budgets, environmental amelioration etc (Zheng *et al* 2004, Zianis and Pandey *et al* 2010 and Sen 2014). Measurement of biomass is an important pre-requisite for carbon sequestration studies. Recently, the biomass estimation studies are increasingly being used to know the pools and fluxes of greenhouse gases relationship with land use and land cover changes in terrestrial biosphere (Cairns *et al* 2003). Short rotation trees play a significant role not only for material demands but for protection of traditional forests.

The accurate calculation of forest productivity in forests or man made plantation is critical with respect to its practical applications such as for commercial exploitation of wood as timber, forest preservation and elucidating the role and importance of forests in the global carbon cycle. The measurement of forest biomass is significant in relation to the global carbon cycle using forests to reduce climate change through recently emerged and most advocated mechanisms such as REDD (Reducing Emissions from Deforestation and Forest Degradation) under developing countries of the United Nations Framework Convention on Climate Change (UNFCCC 2008). Recently, there is increasing interest for knowing the biomass calculation aspects and carbon sequestration potential (Walker *et al* 2008, Bombelli *et al* 2009 and Epron *et al* 2009) under the framework of Kyoto Protocol Convention which focused on land-use change and forestry and Clean Development Mechanism (CDM) projects (Saint-André *et al* 2007).

Many studies were conducted on estimation of biomass and carbon stocks in traditional Indian forests and plantations. Hingane (1991) carried out studies in Indian forests and measured the total phytomass carbon pool stocks as 2,587 Tg C ha⁻¹ and carbon density as 49.2 Mg C ha⁻¹, respectively. Ravindranath *et al* (1997) studied the above and below ground

biomass of Indian forests in 1986 as 8,375 Mt and out of which the proportion of carbon storage was 4,178 Mt. The total carbon storage pooling forests of India including soil was found to be as 9,578 Mt. Dadhwa *et al* (1998) measured the carbon pool at 3117 Tg C and carbon density at 60.2 Mg C ha⁻¹ by using FAO inventory data of different ecological zones. However, these estimates reveal a lot of variations (both temporal and spatial) in biomass and C stocks. Hence, developing suitable biomass prediction methods for correct and constant reporting of forest carbon inventories is important. Short rotation tree material is graded on biomass basis rather than in volume.

Forest stock assessment modelling involves an extensive understanding of the system and an approach for knowing the association in different predicting framework. In addition, tree growth and biomass model development is often a combined effort between forest scientists, statistician and end users. A model must be representative of reality to some degree, otherwise inadequate prediction requires re-calibration and its validation for its practical application.

Regression models are the tools designed for making estimation. The purpose of growth models are to update forest inventories; estimate alternative forest tending operation; predict the effect of agents like insects or diseases; assess sustainable yield of forest products; and simplify local/regional/ national/international trends in forestry. The information of Growth and yield is required to make all major management decision including import export balance, market demands, sustainable harvesting/utilization of resources or carbon sequestration potential, etc. These estimates would also support the forest management plan .

On farm trees are regarded a valuable contributor for sequestering carbon, improve ecosystem productivity, nutrient cycling, protection of agricultural areas besides a source of economics. Rapid research interest has been generated in last three decades. Agroforestry systems can play an important role in carbon mitigation through long term carbon sequestration and reduce the pressure on existing natural forests for direct (fuel, fodder, timber and other wood products) and indirect benefits (soil/water/biodiversity conservation, soil nutrients enrichment, microclimate modification, etc). Tree incorporation on crop and pasture lands results in greater net above-ground as well as below-ground carbon sequestration (Palm *et al* 2004 and Haile *et al* 2008). Carbon sequestering through tree-based systems is now also being considered as an attractive economic opportunity for carbon trading in developing nations, which provides environmental benefits and developmental opportunities as more than fifty percent of total CDM projects are biomass based projects. In India, where a maximum of the population is dependent on agriculture, agroforestry systems provide a long-term options to increase the amount of carbon while still allowing growing food crops. Finding cost effective ways to mitigate GHGs including carbon is now emerging as a major issue in the reference of global climate change. Tree-based systems produce large

amounts of biomass and sequester carbon from the atmosphere. Even though the importance of trees for carbon sequestration and climate change mitigation have been recognized well but still the assessment of the carbon sequestration potential of tree-based systems is still underdeveloped for varied technical and policy reasons. Practice of plantation forestry as on and off farm have lot of scope for sequestering C as they have the potential to sequester 0.8-2.2 Pg of C/annum globally across a long period of fifty years (Dixon *et al* 1994). However, the accounting inaccuracies could not benefit the farmers as it had been projected.

The role of forests/plantations in carbon sequestration of carbon has been realized in the academia throughout the world but a very little work has been done to evaluate the production of biomass and its involvement in carbon sequestration. *Tectona grandis* which belongs to family Verbenaceae, is widely distributed species in tropical and humid climate and rated as one of the important timber species of India. Teak owes its importance and value to the wood desirable physical and mechanical properties, such as durability and stability, natural resistance to attack from fungi insects pests and borers. Apart from these the colour, density and grain are very important qualitative aspects that make it one of the most valued hardwoods in the world. *Tectona grandis* wood has straight and light sapwood, very different from the heartwood which is bright brown in colour, mean apparent density of 0.65g/cm³, which offers good resistance to weight, traction and flexion. The wood contracts very little when dried. Approximately, one million hectare of *Tectona grandis* plantation has been established in small woodlots and agroforestry setting in the tropics and subtropics (Anon 2002). In India, it is found in eastern sub-Himalayan tract, Indo-Gangetic plains, Aravali Hills, central India, western Peninsula and western Himalayas. It grows well in temperature ranging from 1°C to 48°C with annual rainfall ranging from 1800 to 2,300 mm and prefers fertile alluvial soils.

Sagwan, is native to south and southeast Asia mainly India, Sri Lanka, Indonesia and Myanmar, and now it is being planted in other parts of the world mainly in Africa and the Caribbean. Nearly, half of the world's naturally occurring teak population distribution is in the Myanmar's teak forests. The studies at molecular level demonstrate that teak has 2 centers of origin i.e. one in India and the other in Myanmar. The density of teak is 720 kg/meter cube, whereas, its wood is hard and ring porous. Farmers of Punjab have resorted for the species and the species is found spread in whole state but no biomass estimation are available to facilitate the farmers. The proposed study would be a step formed in this direction in *Tectona grandis*. Species specific biomass models are essential to check the differences in allometry, architecture, wood, etc. Above ground biomass have been developed in the department on different species like hybrid eucalyptus (Singh and Dhanda 1990), *Acacia nilotica* (Dhanda and Singh 1989), *Dalbergia sissoo* (Singh and Dhanda 1989), but not on *Tectona grandis*. Bohre *et al* (2013) have predict biomass model for *Tectona grandis* but the models solely

based on data outside Punjab, which may or may not be applicable in local conditions. The development of new biomass models that cover the actual conditions for Punjab is essential for the farmers to know the content of their trees therefore, this study has been planned with following two objectives.

- i. To develop allometric biomass models for different tree components of *Tectona grandis* L. (Roxb.)
- ii. To develop relationship among different biomass components for estimating biomass exponential factor (BEF).

CHAPTER II

REVIEW OF LITERATURE

Biomass measurement of individual tree or whole stand have long been in practise but complete tree utilization concept is of recent origin. General volume tables or local volume tables based on graphical methods were the non-destructive means of determining volume of standing tree and/or crops. Accumulation of biomass both above/below ground has generalised a great deal of interest among the foresters/researchers for evaluation and management of forest stands on sustainable basis. Radial prediction of timber or products is vital for financial assessment of afforestation programme for regional or national production planning, implementation of periodic decisions, intensity of interventions or modification at all levels. In spite of large number of commercial species in the forests, very few allometric biomass equations/models exist for commercial short rotation trees. The available prediction equation/models are developed from small samples (narrow ranges) and applicable to limited area, Biomass partitioning on component basis is lacking. Tree allometric equations are critical tools to improve our understanding in tree productivity and carbon sequestration in woody vegetation (Jara *et al* 2014).

2.1 Predictive models (biomass/volume) in *Tectona grandis* L. (Roxb.)

Mbaekwe and Mackenzie (2008) measured biomass growth and its division in an age gradations of 5, 8, 11 and 14 year old plantations of Sagwan at Gambari Forest Reserve, Oyo State, Nigeria. In the selected plots having size of 50 m x 50 m, total ten representative trees were selected and were harvested for the fresh and dry weights of different tree components. Only oven dry weights of the tree components were regressed with their bole diameters at breast height. The log allometric model was used to calculate the total biomass. They clearly observed that biomass estimates of the leaves, branches, dead wood branches having size < 5 cm and total tree biomass increased to a maximum by the 8th year and dropped to its lower level by the 11th year before increasing again in the 14th year. They also noticed that the increase in different biomass components was much larger between the 5th year to the 8th year. In majority of cases the increase in biomass was almost double, whereas, the increase from the 11th to the 14th year was comparatively less. This implies that teak growth rate and biomass accumulation could be taking place more rapidly around the 8th year under similar environmental conditions.

Bohre *et al* (2013) conducted an experiment on two tree species of family Verbenaceae i.e. white teak (gamar) and teak (sagwan) to measure biomass and carbon sequestration potential on coal mine overburden of Singrauli, M.P., India by adopting non destructive method. The data for growth were collected for 72 trees of gamar (*Gmelina arborea*) and 49 trees of Sagwan (*Tectona grandis*) having diameter at breast height above 5

cm. The best fit equations were applied to determine the accumulation of total biomass i.e. above and below ground and carbon by content by adopting IPCC guidelines. The trees from the plantations were selected in all available ages representing different diameters and heights of plantations. The linear correlation between basal area vs volume, DBH vs volume and basal area vs total biomass was found to be significant in both tree species. The values of R^2 were closer to +1, which indicated the better line fits of the data.

Jha (2015) carried out an experiment to know the carbon stocks and their sequestration rate, to develop allometric models for estimation of biomass in an age-series of young *Tectona grandis* plantations of 1, 5, 11, 18, 24 and 30 years by using both biomass estimation and regression, respectively. The plantations were raised in tropical moist deciduous forests of Kumaun Himalayan tarai, Uttarakhand. Total carbon stocks estimate for these plantations were at the tune of 1.6, 15.8, 35.4, 39.0, 61.5 and 73.2 Mg ha⁻¹, respectively. Above and below ground carbon storage increased with the increasing plantation age. However, the range of their per cent contribution showed little variation i.e. 87.8–88.2 and 11.7–12.7 %, respectively. The rate of carbon sequestration potential for these respective plantations was 1.06, 6.95, 5.46, 5.42, 3.39 and 5.37 Mg ha⁻¹. Forty per cent of the above-ground annual storage was retained in the tree while 60 per cent was released in the form litter including foliage, twigs, and fruit. In case of total (tree) annual production, 43 per cent was retained while 57 per cent was released as litter including root. Carbon stock, carbon sequestration rate, accumulation ratio (1.4–18.1), root:shoot carbon ratio (0.61–0.13) and production efficiency (0.01–0.18) were comparable to some earlier results reported for other tree species. The findings could be beneficial in deciding the early harvesting age for teak with respect to carbon storage and sequestration rate. Four allometric models were developed between biomass (twice the carbon stock) and diameter, girth, and height of the tree at different ages by using linear regression equations. Among all models, only diameter based model was found more suitable for carbon stock prediction under similar conditions.

2.2 Predictive models (biomass/volume) in timber species

Chaturvedi (1974) was first to develop volume tables for *Eucalyptus* hybrid using the combined variable equation ($Y = b_0 - b_1 D^2 H$) with data of 579 trees. Punjab state was not represented in the data. The prediction equations gave a high value of coefficient of multiple determination ($R^2 > 0.98$). Moreover, he did not indicate about the testing of the basic assumptions of the least square theory. (Draper and Smith 1981). The same regression model was used by Shonau and Boden (1982) for *Eucalyptus globulus* for above ground biomass and volume.

Few studies on similar aspects (Sharma 1979, Singh and Upadhyay 2001 and Ajit *et al* 2011) have reported linear equations as best fit for weight in *Populus deltoids* by using $D^2 H$ and D as an independent variable, Tree growth follows non-linear pattern, so these

equations may not have universal application for a wide range of environmental conditions. Dhanda and Verma (2001) and Puri (2002) developed allometric/polynomial equations for bole weight but their statistical validation was not attempted.

Singh and Dhanda (1990) estimated the volume and biomass for the *Eucalyptus* hybrid in kandi area of Punjab from the 45 felled trees along the Bist Doab Canal near Balachaur. Data of trees were recorded for tree height (m), diameter at breast height (DBH) over bark of standing trees, total biomass (quintals) comprising fresh weight of timber (o.b.) and under bark (u.b.) of boles up to 20 cm girth. Two regression equations were used for the estimation of timber volume/biomass. The regression results showed the variance ratios (F) and the determination co-efficients (R^2) are significant in both cases at 0.1 per cent level of probability. R^2 ranged from 0.979 to 0.980 in case of volume estimation (both u.b. and o. b.) and from 0.929 to 0.978 for firewood, timber and biomass estimation by using DBH alone. While R^2 ranged from 0.964 to 0.967 in case of volume estimation and from 0.894 to 0.964 for firewood, timber and biomass estimation by using both DBH and height. This indicated that DBH alone is a better independent variable to be relied upon for estimation of both timber volume and above-ground biomass than DBH and height together in case of *Eucalyptus* hybrid. Kaul *et al* (1983) and Sharma (1979) have also developed volume tables for poplar.

Pal and Raturi (1991) evaluated the growth parameters and frequency distribution of trees of different categories in an energy plantation of *Eucalyptus hybrid* at the age of three years and observed that the growth of individual trees was very heterogeneous. Variable height was 550-990 cm and girth at breast height (GBH) 5-35 cm. The larger trees (average height 990 cm and GBH 29.0 cm) were much fewer in number (11% of the total) than the medium sized and smaller trees.

Tandon *et al* (1993) fitted many biomass equations for Maryann state in 4, 6, 8 and 10 year old plantation of *Eucalyptus hybrid*. Biomass estimates were made by using the stratified tree technique: a total of 17 sample trees were harvested and measurements were made on above-ground biomass viz, stem, bark, leaves, twigs, branches. Various equations were used for the biomass estimates. The reported equation was Biomass = $0.13533578(\text{DBH})^{2.416484}$. Density of the plantations were 1805, 1116, 844 and 955 stems/ha at 4, 6, 8 and 10 years of age, respectively. The total aboveground standing biomass was 20.1, 34.6, 88.7 and 137.7 t/ha, respectively. DBH range was 3.3-20.29 cm. Validation of model has not been performed. Biomass components increased with age but while stem biomass increased with increasing diameter and age from 54 to 78%, that of the other biomass components decreased accordingly.

Agus *et al* (2001) investigated aboveground biomass and carbon stock in *Gmelina arborea* (Roxb.) plantation by allometric model. They concluded that the biomass and

hardwood production at the end of the rotation (6 yr old) was 120 Mg ha⁻¹ and 120 m⁻³ ha⁻¹ respectively for good site, 80 Mg ha⁻¹ and 80 m⁻³ ha⁻¹ respectively for moderate site and 40 Mg ha⁻¹ and 40 m⁻³ ha⁻¹, respectively for poor site.

Fuwape *et al* (2001) measured the biomass of even aged stand of white teak (*Gmelina arborea*) and *Nauclea diderrichii* in Akure forest reserve, Nigeria through linear and allometric regression equations. The above ground biomass production of both tree species were estimated and compared. Different equations developed were analysed based on high coefficient of determination (R²), significant F-ratio, and small Furnival Index (FI) to select appropriate equation for prediction. The total volume and total dry weight of both species varies significantly by using the t-test. They concluded from their studies that white teak showed a higher value of significance than *Nauclea diderrichii*. The total above ground biomass estimate for *Gmelina arborea* and *Nauclea diderrichi* was 264,762 kg/ha and 88,293 kg/ha, respectively.

Rana *et al* (2001) conducted a study on biomass and net productivity of thirty seven year old plantation of *Casuarina equisetifolia* raised in sodic wastelands. To estimate tree biomass, two regression models i.e. dbh and d²h based were used. Biomass production varied between 137 to 199 t ha⁻¹ for dbh based model and 135 to 205 t ha⁻¹ for d²h. Non-significant differences were observed in average stand biomass (170.5-172 t ha⁻¹) by using two different models. Coefficient of variation indicated that biomass was more reliable (CV=8.5-23 per cent) in case of d²h based models in comparison to dbh based models (CV=5-21 per cent). Though, it appears that the use of dbh as an independent variable instead of d²h is an easier and precise approach for biomass estimation.

Ritson and Sochacki (2003) predicted the biomass of *Pinus pinaster* tree in Australia. To develop biomass and carbon mass prediction equations. They took destructive samples of the trees. Sampling of trees involved a wide range of trees of ages (1-47-years-old), diameter at breast height (0-47 cm) and planting distance i.e. close and open spaced. Equations were developed to predict biomass and carbon mass of whole trees and different tree components as function of stem diameter (DBH), tree height (h) and height to crown base (h_c) or basal stem diameter (d₁₀) of small trees. One equation is considered to be sufficient to predict biomass (or carbon mass) of both close and open spaced trees as a function of DBH and h_c. The weighted non-linear (WNL) model was found to be best fit if DBH was included in the predictor variables. Both log-transformed allometric (LTA) and the WNL model were best for predictions as a function of d₁₀, but a weighted combined variable (WCV) model was not found to be suitable.

Onyekwelu (2004) estimated photosynthetic biomass production for white teak plantations of ages between 5 to 21 years in Oluwa Forest Reserve, Nigeria. The findings exhibited that white teak has higher biomass yield which ranged from 83:2 t ha⁻¹ at 5 years of

age to 394:9 t ha⁻¹ at 21 years of age. Mean annual increment (m.a.i.) for biomass ranged from 16.2 to 20:9 t ha⁻¹ yr⁻¹. Average biomass allocations to different tree components were as stem 84%; branch 13% and foliage 3%. The higher biomass values were ascribed to fact of fast growth, high plant density i.e. 837–1275 trees ha⁻¹ and better site conditions of the study area. Biomass values of the different tree components (stem, branch and foliage) as well as total above ground biomass were regressed with diameter at breast height (DBH) on the one hand and with DBH and total height (in the form of D²H) on the other with the aim of choosing the most suitable equation form. All equations generated had very high adjusted R² and very low standard error of estimate. Residuals for both equation forms were distributed normally. Trees of larger DBH had slightly higher branch and foliage biomass than those of smaller DBH. The equation form involving only DBH data as independent variable was recommended for use in estimating biomass for *Gmelina arborea* (Roxb.) in Oluwa forest reserve.

Rawat and Negi (2004) studied the biomass production of the *Eucalyptus tereticornis* in different agro ecological regions of India. They found that production of biomass ranged from 11.9 t ha⁻¹ to 146 t ha⁻¹ in 3 years and 9 years old plantation, respectively under moist regions whereas, under dry tropical region, it varied from 5.65 t ha⁻¹ to 135.5 t ha⁻¹ in 5 years and 9 year old plantations, respectively. It was also noticed that biomass accumulation was comparatively more in cooler areas than to warmer areas under dry tropical regions. They concluded that higher mean annual temperature of around 25°C was found more suitable to produce higher biomass. Leaf proportion was found more on drier sites. whereas, shoot/root ratio was better in dry tropical areas.

Dhanda *et al* (2005) conducted the study on a strip plantation of *Eucalyptus tereticornis* Sm. with age more than 30 years at Punjab Agricultural University, Ludhiana, Punjab. Trees with girth at breast height (GBH) falling in the range of 80 cm to 200 cm were selected. Data were recorded on the destructive sampling of 65 Eucalyptus trees in strip plantation. For developing the timber volume and weight of firewood, and lop and tops for each tree, regression equations have been developed for their applications to the specified range.

Regression models were used by Chave *et al* (2005) to transform inventoried data to have an estimation of above ground biomass (AGB). They provided a critical re-examination system for the quality and the strength of these models in tropical forests by using the data from a large number of trees i.e. 2,410 trees having dbh ≥ 5 cm, destructively harvested in twenty seven sites selected throughout the tropics. Proportional relationships between aboveground biomass and product of wood density, cross-sectional area of trunk and total height were built. A regression model was also developed by involving wood density and stem diameter only. The models thus developed were tested for secondary and old growth for

dry, moist and wet forests under low land and montane forests and for mangrove forests. They also concluded that the best interpreters of above ground biomass of a tree were in decreasing order of importance i.e. its stem diameter, wood specific gravity, total tree height and forest type i.e. dry, moist and wet. After analysis, the over estimates prevailed, giving a bias range of 0.5–6.5 per cent when errors were averaged across all the stands. They also found that the regression models which were developed can be used unfailingly to forecast aboveground tree biomass across a broad range of tropical forests.

Murali and Bhat (2005) estimated biomass of tropical forests along with approximations of goodness of fit. They developed linear & non-linear regression equations. The data from published reports on important parameters like basal area, height of trees and tree density were used to develop equations to assess the biomass of evergreen and deciduous forests. For deciduous forests, the basal area and height of trees were found to give high goodness of fit and minimum percentage of errors among all the parameters used. Whereas, for evergreen forests, the coefficient of determination (r^2) was low. This may be due to the presence of trees of variable height under diverse canopies which could have dissimilar growth rates. For deciduous forests, the coefficient of determination was high and estimate of error was low. Hence, for deciduous forests, the biomass estimation equations were almost accurate and can be beneficial for field applications under similar conditions.

For prediction of above ground biomass, the allometric models were developed by Buvaneshwaran *et al* (2006) which were based on easily measurable tree parameters like diameter at breast height and total tree height. Different steps involved were; 1) to calculate leaf, branch, and stem biomass of selected trees in each diameter class in the sample plots, 2) to assess biomass on hectare basis using diameter distribution in all sample plots. Total 5 different models i.e. linear ($y = a + bx$), polynomial ($y = a + bx^2 + cx$), logarithmic ($y = a + b \log x$), power ($y = ax^b$) and exponential ($y = aeb^x$) were tested by using diameter at breast height, height and dbh 2h as an independent variables (x). But at the end, the dbh models were selected only. In each case, the best fitting model was selected by using r^2 , standard error and residual autocorrelation as a criteria.

Gautam and Thapa (2007) developed regression equations for measurement of timber volume of poplar (*Populus deltoides*) plantations with direct measurement of 60 trees. Tree height and diameter at breast height were measured before cutting the tree. Total 6 models were tested with simple linear regression analysis technique and the results revealed that the best fit equation for tree volume was quadratic ($0.1500 - 0.0205 \text{ DBH} + 0.00105 * \text{DBH}^2$) with diameter at breast height as an independent variable. This model gave highest degree of determination ($R^2 = 0.88$) and lowest standard error among all the tested models.

Allometric biomass equations were developed by Peichl and Arain (2007) for every tree components within each stand for the entire age gradations. Mean above ground biomass

of tree was 0.3, 54, 105, and 529 kg tree⁻¹ and belowground tree biomass was 0.1, 13, 17, and 99 kg tree⁻¹ in the 2, 15, 30, and 65 year old stands, respectively. The contribution of stem biomass to the total tree biomass increased from 25 per cent for the 2 year old stand to 69 per cent for the 65 year old stand. On other hand, the relative proportion of canopy biomass components i.e. foliage and branches decreased with the increase in age of stand. The ratio of biomass of root to shoot decreased from 0.32 in the 2 year old stand to 0.24, 0.16, and 0.22 in the 15, 30, and 65 year old stands, respectively. Allometric relationships between biomass of individual aboveground tree components and tree diameter changed with the increase in age of stand. In contrast, a single allometric equation could forecast total tree biomass i.e. aboveground and belowground biomass from tree diameter only across the entire age gradation. The relationship between tree biomass component and stem volume for all above and belowground tree components and total tree biomass expressed as biomass expansion factor (BEF) which found to decrease with the increasing age of stand. In order to improve forest biomass and carbon sequestration accounting on regional and national scale, changes in tree biomass allocation and allometry throughout different stages of forest stand development need to be considered.

Alamgir and AL-Amin(2008) carried out an experiment to develop allometric models to estimate biomass and organic carbon stock in the forest vegetation in Chittagong, Bangladesh. Separate allometric models were tested for trees which were divided into two diameter classes, shrubs, herbs and grasses. The model based on basal area alone was found to be the best predictor of biomass and organic carbon stock in trees because of high coefficient of determination [r^2 is 0.73697 and 0.87703 for > 5 cm to ≤ 15 cm and > 15 cm DBH (diameter at breast height) range, respectively] and significance of regression (P is 0.000 for each DBH range) coefficients for both DBH range. The other models tested by using different parameters such as height alone; diameter at breast height alone; height and diameter at breast height together; height, diameter at breast height alone and wood density; with linear and logarithmic relations produced relatively poor coefficient of determination. Separate allometric models were also developed for 20 dominant tree species and the equation based on basal area produced better value of determination of coefficient.

Dugarjav and Pandey (2009) recorded height and diameter on randomly selected eucalyptus trees. Smalian's formula was used for volume estimation (Chaturvedi and Khanna, 2000). Normality was checked by the W test given by Shapiro and Wilk (1965). Empirical relationships were estimated through regression analysis. The coefficients of model were tested by t-test and adjusted (Adj) R^2 . The adequacy of model was tested by chi-square (Draper and Smith, 1960). They ranked the model based on different criterion, namely Adj. R^2 , bias variance, root mean square error and coefficient of dispersion. The equations $V = -0.0006 + 0.00003 D^2H$ and $V = -0.05457 + 0.00076 DH$ equations were recommended for

application.

Sharma (2009) conducted the study to establishing robust height-diameter models for chir pine (*Pinus roxburghii*) trees by using regression techniques. All those models were parsimonious (possessing few parameters) mathematically robust, and therefore have been commonly used for modelling various tree and stand attributes. It was concluded that among the twelve non-linear models fitted to height-diameter from twenty three chir pine stands, Hossfeld's model accounted for the largest portion of height variation ($R^2_{\text{adj}} = 86\%$), and appeared to be biologically most realistic.

Zewdie *et al* (2009) carried out evaluation of data collected from ten different *Eucalyptus globulus* plantations with age ranging from 11 to 60 years and coppice shoot age stands with age ranging from 1 to 9 years. Above ground tree biomass was measured through destructive method based on 7–10 sampled trees per stand. Dry weights of all tree components i.e. leaves, twigs, branches, bark and stem and total above ground biomass were measured as a function of (D)diameter tree(H)height and combination. The fit was obtained by using combinations of diameter (D) and tree height (H). Diameter (D) performed better than height (H) when only one explanatory variable was used. Total above ground biomass was linearly correlated with coppice shoot age. Contrary, a negative relationship was witnessed between the above ground biomass production and total plantation age i.e. number of cutting cycles. There was an increase of total above ground biomass from 11 t ha⁻¹ at a stand age of 1 year to 153 t ha⁻¹ at 9 years. The maximum dry weight was found in bole (stemwood) which decreased in order as: bole(stemwood) > leaves > stembark > twigs > branches. They concluded that the developed equation can be replicated to other *Eucalyptus* plantations raised under similar conditions.

Sawadago *et al* (2010) recorded the biomass of 11 native tree species through stepwise multiple regression analysis with backward elimination procedure to develop model, separately for predicting total biomass of the trees, stem biomass, and biomass of branches and twigs. All species-specific regression model were highly significant ($p < 0.001$). The best-fit equations for total above-ground biomass and stem biomass had $R^2 > 0.070$, except for the *Acacia* species; for branches including twig biomass, R^2 -values varied from 0.749 for *Anogeissus leioicarpa* to 0.183 for *Acacia macrostachya*. The use of these equations in estimating available biomass will avoid destructive sampling.

Das *et al* (2011) carried out an experiment on 27 trees representing three trees in each age i.e. one to nine years. The trees were harvested, separated, sorted, sub-sampled, dried to constant dry weight and weighted for different biomass components i.e. leaf, twig, branch, bole, stump root, lateral root, fine root. Harvesting of three trees were continued annually up to nine years of tree age and thus as mentioned above, a total of 27 selected trees were made available for analysis and fitting of models. Since, diameter at breast height alone was

considered to be a very good forecaster of dry biomass. Therefore, height parameter was not included in the present model. Various functions viz. (linear, allometric, logistic, gompertz and chapman richards) were tried for dry biomass estimation. Though, the linear model was easy to use and fit but it suffered from the 'negative estimation problem', specifically for the lower range of explanatory variate. The allometric model out performed the other models on the basis of validation criterion of the remaining non-linear models and the value of R^2 varied from 0.95 - 0.99 for the allometric models fitted on various biomass components. Therefore, the suggested models can be used for prediction of biomass (component wise) of poplar (*Populus deltoides*) under a wide range of diameter. It can also be useful to the farming communities involved in poplar cultivation for the selection of economical rotation rather than the existed traditional physical rotation. The proposed models can be used for carbon sequestration estimation which require a complete biomass estimation studies.

To predict total biomass (above and belowground) and the re-growth potential of pollarded trees of *Leucaena leucocephala* × *pallida* var. KX2, Youkhana and Idol (2011) carried out an experiment under agroforestry system to developed site-specific allometric models for trees in a shaded coffee agro-ecosystem in Hawaii. Different models were tried to compare tree growth rate potential under variant pollarding frequencies as well as additions of tree pruning residues as mulch. Among all allometric equations used, a simple power model ($Y = aX^b$) provided the best prediction of total biomass after different pollarding sequences. The simple power model based on diameter at breast height alone can provide an accurate assessment of total tree biomass as well as re-growth potential under specific site and management practices which usually varied from place to place and interest of the owner. Therefore, for optimal prediction there is need of site-specific allometric relationships.

To develop allometric models for general and site-specific conditions for total biomass (above and belowground) of trees, Mugasha *et al* (2013) taken up a study in miombo woodland area of Tanzania. The collected data were by them were based on a wide range of site conditions and tree diameters at breast height representing diameter range of 1.1 cm to 110 cm. The data were collected from four sites in the study area i.e. miombo woodland area of Tanzania. Different models were developed based on 167 and 80 selected sample trees, respectively for the estimation of above and belowground biomass. The model fitting process displayed a large variation i.e. 95-97 per cent for aboveground biomass. The came out with general recommendation that models are to apply with dbh only as an independent variable. It was also concluded that the general model can be applied over a wide range of Tanzania.

Luna *et al* (2014) developed model for biomass, volume and carbon stock for *Eucalyptus* hybrid plantations in Punjab, India. On the basis of the data of 53 trees with girth at breast ranging from 25 cm to 110 cm (17 diameter classes, 5 cm class interval), they concluded that out of ten linear and curvilinear models tested to find out the best fit prediction

equation, curvilinear models were found to be the best fit with coefficient of determination (R) ranging from 0.97 to 0.99. The high value of R showed that these models can be used efficiently to predict biomass (whole tree and different components), total tree volume and carbon sequestered.

Vidyasagaran and Paramathma (2014) measured dry biomass of *Casuarina equisetifolia* by destructive sampling method. A total of ninety trees were sampled and related by regression analysis to easily measurable tree dimensions such as diameter at breast height (dbh) or in combination of both diameter at breast height (dbh) and height (H). It was concluded from their study that out of the 10 models tried, only logarithmically transformed models (exponential forms) with diameter at breast height (dbh) alone ($\ln W = b_0 + b_1 \ln D$) and diameter at breast height (dbh) and height ($\ln W = b_0 + b_1 \ln D + b_2 \ln H$ and $\ln W = b_0 + b_1 \ln D^2 H$) demonstrated comparatively higher coefficient of determination and smaller Furnival index values. They also suggested that among various models tested, the equations using diameter at breast height (dbh) was found to be more practical rather than using diameter at breast height (dbh) and height (H). for estimation of biomass. Based on their study, the workers suggested the model “ $\ln W = b_0 + b_1 \ln D$ ” to be the best fit for forecasting total biomass and various components of above ground biomass under specific site conditions i.e. regional basis. Among different dependant variables, above ground biomass and total biomass (above ground biomass + below ground biomass) showed highest degree of correlation with diameter at breast height (dbh). As a different tree components are concerned, bole component showed maximum correlation with diameter at breast height (dbh) ($R^2 = 0.97$ at $P > 0.01$) which was followed by root ($R^2 = 0.96$), bark ($R^2 = 0.94$) and branch ($R^2 = 0.92$) components. To test the reliability of prediction models, the observed and predicted values for all the dependant variables were plotted and it was seen that the observed values were very close to the predicted values for tree parameters like bole, bark, branch, above ground biomass, root and total biomass.

Verma *et al* (2014) found from their study that the different models viz., monomolecular, logistic, gompertz, allometric, recharls, chapman and linear which were fitted to the relationship between total biomass and diameter at breast height (dbh) as independent variable, The adjusted R^2 values were more than 0.924 for all the seven models so for tried inferring that all models are seemingly equally effective. Among all six non-linear models, the allometric model ($Y = a^9 DBH^b$) satisfied the validation criterion to the best possible extent and was considered to be the best fit performer. The biomass of different tree components was best fitted to allometric models based on DBH as explanatory variable, the adjusted R^2 for fitted functions ranged from 0.872 to 0.965 for different biomass components. The t values for all the components were found non-significant (0.05P), thereby indicating that model was valid.

CHAPTER III

MATERIALS AND METHODS

The present investigation titled "DEVELOPING PREDICTION MODELS FOR BIOMASS COMPONENTS OF *Tectona grandis* L." was carried out at the University Seed Farm, Ladhawal, Punjab Agricultural University (PAU), Ludhiana, during the year 2015-16. The details about the experiment site, materials used and the methodologies adopted during the course of investigation are given in this chapter.

3.1 Experimental Site

3.1.1 Location

The experimental site is located 15 km from PAU main campus at the University Seed Farm, Ladhawal, Ludhiana, Punjab at an elevation of 223 meter above mean sea level and lies at 30° 58' latitude and 75° 45' longitude, which represents the central agro-climatic zones of Punjab.

3.1.2 Climate

The geographical location of Punjab is in the north-west of Indian sub-continent, with the western Himalaya in the north and the Thar Desert in the south determines the climatic conditions. The periodic circulation of moist air-masses from the south-west and north-west decide the occurrence of two wet periods each followed by a dry period. The south-western current of summer monsoons coming over Bay of Bengal brings the rains bearing depressions from July to September.

In general, the climate is sub-tropical with a long dry season from late October to early June and wet season from July to early September. May and June are the hottest months with intensive evapo-transpiration losses, whereas the December and January are the coldest months. The area receives an average rainfall of 732 mm per annum and 80% of total rainfall is received during July to September with an average of 37 rainy days. It is characterised by hot and dry early summers, which are followed by hot and humid monsoon period and cold winters. Mean maximum and minimum temperature shows considerable fluctuation during summer and winter. Maximum temperature of 45⁰ C is common during summer and the minimum temperature of 1⁰ to 2⁰ C. Frost is also quite common during December to January. The mean monthly temperature ranges from 12.9⁰ C (January) to 32.2⁰ C (June). The topography of study area is plain and characterized inceptisol soils (USDA classification), the soils are deep, well drained, sandy loam in texture with low humus content and soil pH of 7.0-8.0. The irrigation source is mainly the tube wells.

3.2 Methodology

Twenty five *Tectona grandis* L. trees of different girth were harvested at PAU Seed Farm, Ladhawal during june-july 2015. Trees from different girth ranges were subjected to

destructive sampling and estimation for tree component biomass. Different responsive models were used to find the best fit to predict biomass w.r.t. different growth parameters most suitable and easily applicable one (girth at collar region and girth at breast height) from the total assessed trees. All the trees were used for developing models and available secondary data were used for the validation of predicted models. Volume of the standard sized logs were ascertained for drawing the relationship with intended biomass.

3.3 Tree Selection

Trees were selected from ten girth class ranges from 20-30 (cm) to 110-120 (cm). Minimum tree girth found 26 cm in lowest girth class such as 20-30 (cm) and maximum girth was 118 (cm) found in highest girth class 110-120 (cm). A total twenty five trees have been selected according to different girth classes. So the numbers of trees having different girth size felled in different girth classes are as follow:

| Girth class (cm) | No. of trees |
|------------------|--------------|
| 20-30 | 1 |
| 30-40 | 1 |
| 40-50 | 1 |
| 50-60 | 3 |
| 60-70 | 5 |
| 70-80 | 4 |
| 80-90 | 3 |
| 90-100 | 3 |
| 100-110 | 2 |
| 110-120 | 2 |

3.4 Observations recorded

3.4.1 Girth at breast height (cm)

Girth of trees at breast height (above bark) was measured with the help of measuring tape at 1.37 m above the ground level.

3.4.2 Girth at collar region (cm)

Girth above bark at collar region of trees was measured in centimetres with the help of measuring tape.

3.4.3 Tree height (m)

Height of felled trees were measured with the help of measuring tape. Total height (H) and height upto half of dbh (H_1) were measured with tape for estimation of form factor.

3.4.4 Bole height (m)

Bole height is the distance from the ground level to the crown point. Crown point is the point at the tree where first crown forming living or dead branch occur. It was also measured with measuring tape.

3.4.5 Canopy spread (m^2)

Canopy spread of standing trees was measured with the help of measuring tape in N-S and E-W directions of twenty five selected trees existing in different girth classes by using

equation:

$$\text{Canopy Spread (m}^2\text{)} = \text{N-S} * \text{E-W}$$

Where:

N-S = Crown length in north-south directions

E-W = Crown length in east-west directions

3.4.6 Form factor

Form factor was calculated as per procedure followed by Pressler (1865) and Bitterlich (1984):

$$F = 2h_1/3h$$

Where:

F = form factor

h_1 = height at which girth is half of gbh

h = total height (m)

3.4.7 Stem biomass (kg)

Selected trees were uprooted carefully by digging the soil around the trees with minimum possible damage to roots. The stem was separated from the roots, cut into logs for convenience in estimation of biomass and weighed immediately in the field on electronic balance to get the fresh weight (Plate 1). The representative samples from stem of each tree were collected (Fig. 1 & Plate 1) at three different heights at collar region ($disc_1$), mid height of tree ($disc_2$) and from top 1/3rd portion of tree ($disc_3$) were dried in the oven ($100\pm 2^\circ\text{C}$) till the constant dry weight was achieved. Dry matter content was calculated, using the formula:

$$\text{Dry matter content (\%)} = \frac{DW_1 + DW_2 + DW_3}{FW_1 + FW_2 + FW_3} \times 100$$

Where:

DW_1, DW_2, DW_3 = Dry weight of disc one, two and three, respectively

FW_1, FW_2, FW_3 = Fresh weight of disc one, two and three, respectively

3.4.8 Total stem dry weight (kg)

Total dry weight was calculated by multiplying the total fresh weight of the stem portion with dry matter content by using following equation:

Total stem dry weight (TSDW) = Total stem fresh weight (TFW) * Stem dry matter content (%)

3.4.9 Branch biomass (kg)

Branch biomass without leaves was calculated from twenty five randomly selected trees. Branches of selected trees were separated from the shoots and weighed immediately on electronic balance in the field to get the fresh weight. Four randomly selected branch samples from different portion of branches were taken and dried in oven ($100\pm 2^\circ\text{C}$) till the constant weight was achieved to get the oven dry weighed of the biomass. Dry matter content by was

calculated using the formula:

$$\text{Branch dry matter content (\%)} = \frac{DB_1 + DB_2 + DB_3 + DB_4}{FW_1 + FW_2 + FW_3 + FB_4} \times 100$$

Where:

DB₁, DB₂, DB₃, DB₄ = Dry weight of branch sample one, two, three and four, respectively

FB₁, FB₂, FB₃, FB₄ = Fresh weight of branch sample one, two, third and fourth, respectively

3.4.10 Total branch dry weight (kg)

Total branch dry weight was calculated by multiplying fresh weight of each tree branch with dry matter content calculated from representative samples by using equation:

$$\text{TBDW} = \text{TBFW} * \text{BDMC (\%)}$$

Where:

TBDW = Total branch dry weight

TBFW = Total branch fresh weight

BDMC = Branch Dry matter content

3.4.11 Leaf biomass (kg)

Leaves of selected trees were separated from the branches in the field and weighed immediately on electronic balance in the field itself to get the fresh weight. Five representative samples of leaves were taken and dried in oven (70±2⁰C) till the constant weight achieved to get the oven dry weight of the leaf biomass. Leaf dry matter content of leaves was calculated by using the following formula:

$$\text{Dry matter content (\%)} = \frac{DL_1 + DL_2 + DL_3 + DL_4 + DL_5}{FL_1 + FL_2 + FL_3 + FL_4 + FL_5} \times 100$$

Where:

DL₁, DL₂, DL₃, DL₄, DL₅ = Dry weight of leaf sample one, two, three, four and five, respectively

FL₁, FL₂, FL₃, FL₄, FL₅ = Fresh weight of leaf sample one, two, three, four and five, respectively

3.4.12 Total leaf dry weight (kg)

Total leaf dry weight was calculated by multiplying the fresh weight of each trees leaves with the leaf dry matter content by using the equation:

$$\text{TLDW} = \text{TLFW} * \text{LDMC (\%)}$$

Where:

TLDW = Total leaf dry weight

TLFW = Total leaf fresh weight

LDMC = Leaf dry matter content

3.4.13 Root biomass (kg)

The root portion separated from the stem was weighed with the help of electronic balance to get fresh root weight in the field. Five representative samples of the root portion were taken for oven drying at $100\pm 2^{\circ}\text{C}$ till the constant weight. Dry matter content was calculated by using the formula:

$$\text{Dry matter content (\%)} = \frac{\text{DR}_1 + \text{DR}_2 + \text{DR}_3 + \text{DR}_4 + \text{DR}_5}{\text{FR}_1 + \text{FR}_2 + \text{FR}_3 + \text{FR}_4 + \text{FR}_5} \times 100$$

Where:

$\text{DR}_1, \text{DR}_2, \text{DR}_3, \text{DR}_4, \text{DR}_5$ = Dry weight of root sample one, two, three, four and five, respectively

$\text{FR}_1, \text{FR}_2, \text{FR}_3, \text{FR}_4, \text{FR}_5$ = Fresh weight of root sample one, two, three, four and five, respectively

3.4.14 Total root dry weight (kg)

Total root dry weight was calculated by multiplying the fresh weight of each tree root portion with the root dry matter content by using the equation given below:

$$\text{TRDW} = \text{TRFW} * \text{RDMC (\%)}$$

Where:

TRDW = Total root dry weight

TRFW = Total root fresh weight

RDMC = Root dry matter content

3.4.15 Bark fresh weight (kg)

The bark portion, which was separated from sampled stem discs at three different heights (Plate 3) was weighed on electronic balance to get fresh bark weight. The bark was then dried in the oven ($100\pm 2^{\circ}\text{C}$) till the constant weight was achieved to get the constant dry bark weight to calculate the total bark portion. Only bark of the main stem was included. Total bark fresh weight was calculated by using following formula:

$$\text{Total bark fresh weight (kg)} = \frac{\text{BD}_1 + \text{BD}_2 + \text{BD}_3}{\text{FD}_1 + \text{FD}_2 + \text{FD}_3} \times \text{TSW}$$

Where:

$\text{BD}_1, \text{BD}_2, \text{BD}_3$ = Bark weight of disc one, two and three, respectively

$\text{FD}_1, \text{FD}_2, \text{FD}_3$ = Fresh weight of disc one, two and three, respectively

TSW = Total stem weight

3.4.16 Total bark dry weight (kg)

After recording the fresh weight of bark of each disc, each sample was taken and dried in an oven ($100\pm 2^{\circ}\text{C}$) to calculate the dry matter content of bark. Bark dry matter content and total dry bark weight was calculated by using following equations:

$$\text{Dry matter content (\%)} = \frac{\text{DBD}_1 + \text{DBD}_2 + \text{DBD}_3}{\text{FBD}_1 + \text{FBD}_2 + \text{FBD}_3} \times 100$$

Where:

DBD₁, DBD₂, DBD₃ = Dry bark weight of disc one, two and three, respectively

FBD₁, FBD₂, FBD₃ = Fresh weight of bark of disc one, two and three, respectively

Total bark dry weight was calculated as:

$$\text{TBDW} = \text{TBFW} * \text{BDMC (\%)}$$

Where:

TBDW = Total bark dry weight

TBFW = Total bark fresh weight

BDMC = Bark dry matter content

3.4.17 Biomass expansion factor (BEF)

Biomass expansion factor was calculated by using the formula given by FAO (1997) i.e. the ratio of above-ground (dry weight of stem + leaf + shoots) oven-dry biomass of trees to oven-dry biomass of stem. BEF was calculated by using the following equation:

$$\text{BEF} = \frac{\text{ADB}}{\text{DSW}}$$

Where:

BEF = Biomass expansion factor

ADB = Above-ground dry biomass

DSW = Dry stem weight

3.4.18 Root-to-shoot ratio (R)

Root-to-shoot ratio was calculated by using the formula which defines R as the ratio of belowground (root) to aboveground biomass (dry weight of stem + leaf + shoot), the equation used to calculate R value as follows:

$$R = \frac{W_{\text{root}}}{W_{\text{aboveground}}}$$

Where:

R = root-to-shoot ratio (dimensionless)

W_{root} = tree-root dry weight (kg)

W_{aboveground} = aboveground total dry weight (kg)

3.5 Quality Parameters

3.5.1 Specific gravity

The representative samples from stem of each tree were collected at three different heights [at collar region (disc₁), mid height of tree (disc₂) and from top portion of tree (disc₃)]

and immersed in water for 48 hours and maximum moisture weight was recorded and then dried in the oven ($100\pm 2^{\circ}\text{C}$) to get the oven dried weight till the constant weight was achieved. Specific gravity was calculated by using formula:

$$\text{Specific gravity} = \frac{1}{\frac{M_m - M_o}{M_o} + \frac{1}{GS}}$$

Where:

M_m = Weight of sample having maximum moisture

M_o = Weight of oven dried sample

GS = Constant = 1.53

3.5.2 Moisture content (%)

Moisture content in wood samples was calculated on the basis of total fresh weight and oven dry weight of wood by using formula:

$$\text{Moisture Content (\%)} = \frac{W_{\mu} - W_o}{W_{\mu}} \times 100$$

Where:

μ = Moisture content (%)

W_{μ} = Weight of the wood with moisture content μ or original fresh weight

W_o = Weight of the oven dried wood

3.5.3 Shrinkage (%)

All the wood samples that have been taken from twenty five selected trees were used for determination of shrinkage. Percentage shrinkages along the two planes were measured after specimens had been oven-dried by using Okon (2014) formula:

$$S (\%) = \frac{D_s - D_o}{D_s} \times 100$$

Where:

S = Shrinkage (%)

D_s = Dimensions of fresh sample

D_o = Dimensions of oven dried sample

3.5.3.1 Radial shrinkage (%)

Radial shrinkage was recorded from each disc (without bark) with measuring scale by using four points at the margins of the disc at equal distance. Measurements were done in the field on fresh wood samples and then after drying in oven to record radial shrinkage in the wood sample. Percentage shrinkages were measured by using Okon (2014) formula:

$$\text{RDS (\%)} = \frac{D_r - d_r}{D_r} \times 100$$

Where:

RDS = Radial shrinkage (%)

D_r = Initial dimensions along the radial axis on fresh wood

d_r = final dimensions along the radial axis on oven dry wood

3.5.3.2 Tangential shrinkage (%)

Tangential shrinkage was measured at tangential axis on same four points on the disc (without bark) from where radial shrinkage was taken both on the fresh wood samples and on oven dried wood samples. Percentage shrinkage was measured by using Okon (2014) formula:

$$\text{TGS (\%)} = \frac{D_t - d_t}{D_t} \times 100$$

Where:

TGS = Tangential shrinkage (%)

D_t = Initial dimensions along the tangential axis on fresh wood

d_r = Final dimensions along the tangential axis on oven dried wood

Average shrinkage (radial and tangential) was calculated by adding percentage shrinkage of all the three discs [at collar region (disc_1), mid height of tree (disc_2) and from top portion of tree (disc_3)] and then divide with denominator three for average. Both average radial shrinkage and average tangential shrinkage was added to get total shrinkage in the wood.

3.6 Statistical Analysis

Statistical analysis was done by using locally available software (SPSS) for the presentation and interpretation of results of the study. Different responsive models were used to find the best fit model to predict fresh and dry biomass w.r.t. different growth parameters. Correlation coefficients among different parameters had also been worked out to check the degree of relationship between different parameters.

CHAPTER IV

RESULTS AND DISCUSSION

The results of the present investigations are presented under the following six main headings:

- 4.1 Linear and non-linear functions for total green and dry biomass with different growth parameters
- 4.2 Linear and non-linear functions for above-ground green biomass (AGB) and above-ground dry biomass (ADB) with different growth parameters
- 4.3 Linear and non-linear functions for below-ground fresh biomass (BFB) and below-ground dry biomass (BDB) with different growth parameters
- 4.4 Growth characteristics of tree in different girth classes
- 4.5 Quality parameters of tree in different girth classes
- 4.6 Proportion of tree components in different girth classes

4.1 Linear and non-linear functions for total green and dry biomass with different growth parameters

The data were pooled to estimate total green and dry biomass by using various linear and non-linear functions (logarithmic, exponential curve, power function and polynomial function) where height (H), girth at breast height (GBH) and square of girth at breast height multiplied with height ($GBH^2 \cdot H$) were taken as independent factors. Adjusted R^2 and standard error of estimate are also presented along with the respective fitted functions in the text.

4.1.1 Height (H) as an independent factor

Linear and non-linear functions were developed by using total green biomass as dependent and height (H) as an independent factor. Adjusted R^2 and standard error of estimate are also presented along with the respective fitted functions. In (Table 1.0) the logarithm equation as $TGB = 564.694 \ln H - 1154.887$ gave maximum adj. R^2 value of 0.81 and minimum Adj. R^2 0.68 was found in exponential function $TGB = 40.912 e^{0.144 (H)}$. When height (H) was used as an independent factor with total dry biomass as dependent factor, the logarithm equation $TDB = 338.817 \ln H - 692.932$ was found best fit with maximum Adj. R^2 value of 0.83 followed by quadratic equation $TDB = -1.700H^2 + 72.612H - 478.352$ with Adj. R^2 value of 0.80 and minimum Adj. R^2 0.71 was found in exponential function $TDB = 25.574 e^{(0.144 H)}$. Logarithm function $TGB = 564.694 \ln H - 1154.887$ and quadratic function $TGB = -2.834H^2 + 121.020H - 797.254$ had almost approximately same Adjusted R^2 and both found best fit. Power model $TGB = 1.270H^{(2.087)}$ with adj. R^2 of 0.73 was found more accurate in prediction of teak green biomass in Punjab condition. Kachamaba *et al* (2016) highlighted the

importance of easy usage of polynomial models. But we prefer to use power function $TGB = 1.270H^{(2.087)}$ with adj. R^2 of 0.73 to predict the fresh biomass of tree because the Adj. $R^2 = 0.73$ in power model is very low but the results are more reliable because predicted values are closer to the estimated values. Linear model $TDB = 23.840H-136.44$ with Adj. $R^2 = 0.76$ was found to be best fit because it gives predicted values more closer to actual values. These results are contradicting with Kumari *et al* (2016) where they recommended exponential function for predicting green and dry biomass in *Ulmus villosa*.

Table 1: Linear and non-linear functions for total green and dry biomass with height (H)

| Total green biomass (TGB) | SE of estimate | Adj. R^2 |
|---|-----------------------|------------------------------|
| $TGB = 39.734H - 227.408$ | 44.63 | 0.79 |
| $TGB = 564.694 \ln(H) - 1154.887$ | 41.62 | 0.81 |
| $TGB = -2.834 H^2 + 121.020H - 797.254$ | 41.92 | 0.81 |
| $TGB = 1.270H^{(2.087)}$ | 0.19 | 0.73 |
| $TGB = 40.912e^{(0.144H)}$ | 0.21 | 0.68 |
| Total dry biomass (TDB) | | |
| $TDB = 23.840H - 136.44$ | 26.77 | 0.76 |
| $TDB = 338.817 \ln H - 692.932$ | 24.97 | 0.83 |
| $TDB = -1.700H^2 + 72.612H - 478.352$ | 25.15 | 0.80 |
| $TDB = 0.762H^{(2.087)}$ | 0.92 | 0.76 |
| $TDB = 25.574e^{(0.144H)}$ | 0.21 | 0.71 |

4.1.2 GBH (Girth at breast height) as an independent factor

Linear and non-linear equations were developed by using TGB as dependent and GBH as independent factor (Table 2). The best fit equations was found to be logarithm $TGB = 240.794 \ln GBH - 668.336$ and quadratic equation $TGB = 0.029GBH^2 + 7.853GBH - 53.814$ with approximately the same Adj. R^2 0.94 and 0.92, respectively. The minimum Adj. R^2 value 0.74 was found in exponential equation $TGB = 125.427e^{(0.013GBH)}$

Using TDB as dependent and GBH as independent factor, logarithm equation $TDB = 144.447 \ln GBH - 401.001$ with Adj. R^2 0.90 and quadratic function $TDB = -0.017GBH^2 + 4.712GBH - 32.88$ with Adj. R^2 value of 0.88 were reported to be best fit whereas exponential function fits the least Adj. R^2 0.74 to predict the tree biomass. Logarithm and quadratic function showed Adj. R^2 value of 0.94 and 0.92 respectively to express the best

result. The linear model $TGB = 3.706GBH+78.139$ with adjusted R^2 0.88 and $TDB = 2.224GBH+46.884$ with adjusted R^2 0.86 were almost nearby as the data which was taken in the fields. Results presented here are similar with Onyekwelu (2004) who recommended DBH alone in linear and non-linear functions as an independent factor to predict green and dry biomass of the tree but contradict to the Verma *et al* (2014), where power function alone was reported to be best fit with single variable GBH as independent factor in *Grewia optiva*. Gautam and Thapa (2007) also recorded the goodness of fit of diameter based model in *Populus deltooides*.

Table 2: Linear and non-linear functions for total green and dry biomass with Girth at breast height (GBH)

| Total green biomass (TGB) | SE of estimate | Adj. R ² |
|-------------------------------------|----------------|---------------------|
| $TGB = 3.706GBH+78.139$ | 35.59 | 0.88 |
| $TGB = 240.794\ln GBH-668.336$ | 23.54 | 0.94 |
| $TGB = -0.029GBH^2+7.853GBH-53.814$ | 27.18 | 0.92 |
| $TGB = 7.222GBH^{(0.904)}$ | 0.12 | 0.88 |
| $TGB = 125.427e^{(0.013DBH)}$ | 0.19 | 0.74 |
| Total dry biomass (TDB) | | |
| $TDB = 2.224GBH+46.884$ | 20.15 | 0.86 |
| $TDB = 144.477\ln GBH-401.001$ | 14.13 | 0.90 |
| $TDB = -0.017GBH^2+4.712GBH-32.888$ | 16.31 | 0.88 |
| $TDB = 4.333GBH^{(0.904)}$ | 0.12 | 0.82 |
| $TDB = 75.256e^{(0.013GBH)}$ | 0.19 | 0.70 |

4.1.3 GBH^2*H as an independent factor

Linear and non-linear equations by using TGB as dependent and GBH^2*H as independent factor are presented in (Table 3). The examination of data reveals that by using logarithm function $TGB = 103.34\ln GBH^2H-796.172$ fits the most appropriate with highly significant Adj. R^2 0.95 followed by power function $TGB = 4.516 GBH^2H^{(0.386)}$ with Adj. R^2 0.89. The exponential function $TGB = 222.437e^{(4.305 \times 10^{-6} GBH^2H)}$ with minimum Adj. R^2 value of 0.53 was found less expressive in the prediction of TGB with GBH^2*H as an independent factor. Similarly TDB as dependent factor, the logarithm function $TDB = 61.820\ln GBH^2H-477.703$ with maximum Adj. R^2 value of 0.91 was found to be best fit to estimate dry biomass followed by Power function $TDB = 2.710GBH^2H^{(0.386)}$ with Adj. R^2 value of 0.83.

Table 3: Linear and non-linear functions for total green and dry biomass with GBH²*H

| Total green biomass (TGB) | SE of estimate | Adj. R² |
|--|-----------------------|---------------------------|
| TGB = 0 .001GBH ² H+230.495 | 49.40 | 0.74 |
| TGB = 103.34lnGBH ² H-796.172 | 20.40 | 0.95 |
| TGB = -6.286×10 ⁻⁹ (GBH ² H) ² + 0.003GBH ² H +168.323 | 37.29 | 0.85 |
| TGB = 4.516GBH ² H ^(0.386) | 0.12 | 0.89 |
| TGB = 222.437 e ^(4.305×10⁻⁶ GBH²H) | 0.25 | 0.53 |
| Total dry biomass (TDB) | | |
| TDB = 0 .001GBH ² H+138.297 | 29.64 | 0.70 |
| TDB = 61.820lnGBH ² H-477.703 | 12.24 | 0.91 |
| TDB = -3.772×10 ⁻⁹ (GBH ² H) ² + 0.002GBH ² H + 00.994 | 22.37 | 0.80 |
| TDB = 2.710GBH ² H ^(0.386) | 0.12 | 0.83 |
| TDB = 133.462 e ^(4.305×10⁻⁶ GBH²H) | 0.25 | 0.66 |

Exponential function TDB=133.462 e^(4.305×10⁻⁶ GBH²H) with minimum Adj. R² value of 0.66 was found least effective in prediction of dry biomass but as we validate the data the exponential functions (TGB = 222.437 e^(4.305×10⁻⁶ GBH²H) with adj. R² of 0.53) and TDB = 133.462 e^(4.305×10⁻⁶ GBH²H) with adj. R² of 0.66 both for green and dry biomass found more credible even the Adj R² of these models was low but values that predicted through these models found more closer to actual values. These results are in agreement with the findings of Kumari *et al* (2016) in *Ulmus villosa*. Singh and Upadhyay (2001), Durgajav and Pandey (2009), Singh and Dhanda (1990) and Dhanda *et al* (2005).

4.1.4 Multi-linear regression equation

Multi-linear equation was developed where TGB and TDB as dependent factors by taking into consideration all the growth parameters such as H, GBH and GBH²*H. Table 4 reveals that both the equation such as for total green biomass TGB = -166.139+18.692H+4.342GBH-0.001GBH²H with Adj. R² value of 0.93 and for total dry biomass TDB=-99.683+11.215H+2.605GBH+0.000 with Adj. R² value of 0.93 were found highly significant. The results presented here are in agreement with the findings of Kumari *et al* (2016) with the same growth parameters as independent factor in the multi-linear regression equations. Gonzalez-Benecke *et al* (2014) and Swadago *et al* (2010) also used multiple parameters for prediction of stem volume and biomass. They recorded R² value more than 0.70 for different species; however, in present study the adjusted R² value is much higher.

Table 4: Multi-linear regression equations for total green biomass (TGB) and total dry biomass (TDB).

| Multi-linear regression equations | SE of estimate | Adj. R ² |
|---|----------------|---------------------|
| TGB=-166.139+18.692H+4.342GBH-0.001GBH ² H | 24.07 | 0.93 |
| TDB=-99.683+11.215H+2.605GBH+0.000GBH ² H | 14.43 | 0.93 |

4.2 Linear and non-linear functions for above-ground green biomass (AGB) and above-ground dry biomass (ADB) with different growth parameters

Linear and non-linear equations developed by using AGB and ADB (fresh and dry weight of stem + leaves + branches) as dependent factors and different growth parameters such as height (H), girth at breast height (GBH) and square of girth at breast height multiplied with height (GBH²*H) as independent factor. Adjusted R² and standard error of estimate are also presented along with the respective fitted functions. Above-ground biomass followed the trend of total biomass prediction with slight variations in constant and multiple factors (coefficients) in developed models.

4.2.1 Height (H) as an independent factor

An examination of the data presented in table 5 clearly illustrates that linear function $AGB = 479.407\ln H - 1005.050$ with maximum Adj. R² value of 0.81 followed by quadratic function $AGB = -1.623H^2 + 80.514H - 547.317$ with Adj. R² value of 0.80 were best equations to predict above ground green biomass with H as independent factor. When above ground dry biomass (ADB) was used as dependent factor with H (independent factor), logarithm equation $ADB = 278.283\ln H - 606.576$ and linear equation $ADB = 19.829H - 153.128$

Table 5: Linear and non-linear functions for above-ground green and dry biomass with Height (H)

| Above ground green biomass (AGB) | SE of estimate | Adj. R ² |
|--|----------------|---------------------|
| $AGB = 33.958H - 220.942$ | 36.98 | 0.79 |
| $AGB = 479.407\ln H - 1005.050$ | 35.45 | 0.81 |
| $AGB = -1.623H^2 + 80.514H - 547.317$ | 36.38 | 0.80 |
| $AGB = 0.642H^{(2.247)}$ | 0.19 | 0.76 |
| $AGB = 26.699e^{(0.156H)}$ | 0.21 | 0.71 |
| Above ground dry biomass (ADB) | | |
| $ADB = 19.829H - 153.128$ | 22.53 | 0.78 |
| $ADB = 278.283 \ln H - 606.576$ | 22.20 | 0.79 |
| $ADB = 0.537 H^2 + 25.229 H - 261.089$ | 0.24 | 0.73 |
| $ADB = 0.096 H^{(2.688)}$ | 22.78 | 0.77 |
| $ADB = 8.214 e^{(0.187) H}$ | 0.22 | 0.77 |

resulted almost similar Adj.R² value 0.79 and 0.78 respectively. Even according to R² values the above given models were found best fit. But when we validate our models linear model with equation $AGB = 33.958H - 220.942$ with Adj. R² of 0.79 give more accurate values close to the field values. However when we validate our dry biomass models than the quadratic function $ADB = 0.537H^2 + 25.229H - 261.089$ with Adj. R² of 0.73 gave best fit results as compared to first equations.

4.2.2 GBH as independent factor

As shown in table 6, logarithm function $AGB = 204.418 \ln GBH - 591.945$ with Adj. R² value of 0.94 and quadratic function $AGB = -0.001 GBH^2 H + 5.195 GBH - 26.301$ with Adj. R² value of 0.93 were found best fit to predict above-ground biomass for *Tectona grandis* with GBH as independent factor. Linear function $AGB = 3.215 GBH + 36.707$ with Adj. R² value of 0.91 gave significant results for best approximation while compared with logarithm and quadratic function.

Table 6: Linear and non-linear functions for above-ground green and dry biomass with GBH

| Above ground green biomass (AGB) | SE of estimate | Adj. R ² |
|---|----------------|---------------------|
| $AGB = 3.215 GBH + 36.707$ | 23.14 | 0.91 |
| $AGB = 204.418 \ln GBH - 591.945$ | 20.20 | 0.94 |
| $AGB = -0.014 GBH^2 + 5.195 GBH - 26.301$ | 21.75 | 0.93 |
| $AGB = 4.178 GBH^{(0.973)}$ | 29.60 | 0.91 |
| $AGB = 88.598 e^{(0.014 GBH)}$ | 0.18 | 0.79 |
| Above ground dry biomass (ADB) | | |
| $ADB = 1.904 GBH - 4.683$ | 12.81 | 0.93 |
| $ADB = 118.781 \ln GBH - 367.295$ | 14.22 | 0.91 |
| $ADB = -0.002 GBH^2 + 2.260 GBH - 16.022$ | 12.97 | 0.92 |
| $ADB = 0.893 GBH^{(1.166)}$ | 0.12 | 0.93 |
| $ADB = 34.278 e^{(0.017 GBH)}$ | 0.19 | 0.82 |

Mugasha *et al* (2013) also recommend DBH alone as independent factor for estimation of above ground biomass in Tanzania. Using ADB as an dependent factor, the results were found similar as both linear function $ADB = 1.904 GBH - 4.683$ and power function $ADB = 0.893 GBH^{(1.166)}$ with Adj. R² value of 0.93 were found best fit to predict above ground dry biomass of *Tectona grandis*. But after validation linear model as $AGB = 3.215 GBH + 36.707$ with Adj. R² value of 0.91 and $ADB = 1.904 GBH - 4.683$ with Adj. R² value of 0.93 gives more accurate results when we compare it with the recorded values in the field. Results presented are in agreement with Onyekwelu (2004) who recommended linear function best to predict tree biomass.

4.2.3 GBH²*H as independent factor

Linear and non-linear equations were developed by using AGB as dependent and GBH²*H as independent factor given in (Table 7). The logarithm function $AGB = 87.469\ln GBH^2H - 700.476$ with maximum Adj. R² of 0.95 and power function $AGB = 2.520GBH^2H^{(0.415)}$ with Adj. R² of 0.92 were found best fit for predicting above ground green biomass gave minimum Adj. R² 0.59 among all the developed equations. Exponential function $AGB = 164.197 e^{(4.798 \times 10^{-6} GBH^2H)}$. The power function $ADB = 0.488GBH^2H^{(0.497)}$ and logarithm function $ADB = 50.817\ln GBH^2H - 430.267$ with Adj. R² of 0.94 and 0.92 respectively were found best to predict above ground dry biomass with GBH²*H as independent factor. But, after validation it was found that results obtained in exponential model $AGB = 164.197 e^{(4.798 \times 10^{-6} GBH^2H)}$ with Adj. R² of 0.59 was more near to the estimated field value. Upon validation the quadratic function such as $ADB = -2.054 \times 10^{-6} (GBH^2H)^2 + 0.001GBH^2H + 50.240$ with Adj. R² of 0.91 gave more closer values to the actual values. The results presented here are in agreement with the findings of Gautam and Thapa (2007) where they recommended the quadratic function a best fit equation to predict green and dry biomass of poplar with GBH²H as an independent factor. Singh and Upadhyay (2001), Durgajav and Pandey (2009), Singh and Dhanda (1990), Dhanda *et al* (2005) also recommended the usage of GBH²*H for appropriate reliability of models for biomass and volume prediction.

Table 7: Linear and non-linear functions for above-ground green and dry biomass with GBH²*H

| Above ground green biomass (AGB) | SE of estimate | Adj. R ² |
|--|----------------|---------------------|
| $AGB = 0.001GBH^2H + 166.052$ | 35.23 | 0.81 |
| $AGB = 87.469\ln GBH^2H - 700.476$ | 17.57 | 0.95 |
| $AGB = -4.397 \times 10^{-9} (GBH^2H)^2 + 0.002GBH^2H + 122.560$ | 27.01 | 0.89 |
| $AGB = 2.520GBH^2H^{(0.415)}$ | 0.11 | 0.92 |
| $AGB = 164.197 e^{(4.798 \times 10^{-6} GBH^2H)}$ | 0.25 | 0.59 |
| Above ground dry biomass (ADB) | | |
| $ADB = 0.001GBH^2H + 70.559$ | 17.88 | 0.86 |
| $ADB = 50.817\ln GBH^2H - 430.267$ | 13.02 | 0.92 |
| $ADB = -2.054 \times 10^{-6} (GBH^2H)^2 + 0.001GBH^2H + 50.240$ | 14.50 | 0.91 |
| $ADB = 0.488GBH^2H^{(0.497)}$ | 0.11 | 0.94 |
| $ADB = 71.929 e^{(5.859 \times 10^{-6} GBH^2H)}$ | 0.28 | 0.63 |

4.2.4 Multi-linear regression equation

Multi-linear equation was developed for AGB and ADB by taking into consideration all the growth parameters such as H, GBH and $GBH^2 \cdot H$ as independent factor in one equation (Table 8). Adj. R^2 for both the equations as $AGB = -112.035 + 13.105H + 3.044GBH + 0.000GBH^2H$ with Adj. R^2 of 0.951 and $ADB = -60.464 + 6.107H + 1.455GBH - 1.215 \times 10^{-6}GBH^2H$ with Adj. R^2 value of 0.94 were found highly significant.

Table 8: Multi-linear regression equations for above-ground green biomass (AGB) and above-ground dry biomass (ADB)

| Multi-linear regression equations | SE of estimate | Adj. R^2 |
|--|----------------|------------|
| $AGB = -112.035 + 13.105H + 3.044GBH + 0.000GBH^2H$ | 18.18 | 0.95 |
| $ADB = -60.464 + 6.107H + 1.455GBH - 1.215 \times 10^{-6}GBH^2H$ | 10.92 | 0.94 |

4.3 Linear and non-linear functions for below-ground fresh biomass (BFB) and below ground dry biomass (BDB) with different growth parameters

Linear and non-linear equations developed by using BFB and BDB (fresh and dry weight of roots,) as an dependent factor and different growth parameters such as height (H), girth at breast height (GBH), square of girth at breast height multiply with height ($GBH^2 \cdot H$) as independent factors in (Table 9 to 12). Adjusted R^2 and standard errors of estimate are worked out along with the respective fitted functions. Usually below ground biomass is estimated by using root to shoot ratio but species specific regression models would be more reliable in predicting the below ground biomass than making use to root to shoot ratio.

4.3.1 Height (H) as independent factor

A review of the data presented in table 9 clearly indicated that power function $BFB = 0.328H^{(1.994)}$ with Adj. $R^2 = 0.89$ should be highly significant followed by logarithm function $BFB = 123.669 \ln H - 259.73$, quadratic function $BFB = -0.292H^2 + 17.221H - 117.208$ and exponential function $BFB = 8.575e^{(0.141H)}$ had same Adj. R^2 value of 0.87 was found best fit to evaluate BFB among the developed models.

Linear function, The equation $BFB = 8.836H - 58.579$ with minimum Adj. R^2 value of 0.87 did not differ significantly while compared with power, logarithm and exponential function. Linear function $BDB = 4.860H - 32.218$, quadratic function $BDB = -0.161H^2 + 9.471H - 64.547$ and exponential function $BDB = 0.4716e^{(0.141GBH)}$ with Adj. R^2 of the same value 0.83 were found significantly best fit in prediction of dry root weight with H as independent factor. But after validation we found that if we take H as an independent factor then both for green and dry biomass the logarithmic $BFB = 123.669 \ln H - 259.736$ and quadratic function $BFB = -0.292H^2 + 17.221H - 117.208$ with same Adj. R^2 of 0.87 were more reliable and for dry biomass $BDB = 68.018 \ln H - 142.855$ and $BDB = -0.161H^2 + 9.471H - 64.547$ with

Adj. R² of 0.80 and 0.83 respectively gives predicted values more closer to the actual values which were recorded in the fields.

Table 9: Linear and non-linear functions for below-ground fresh and dry biomass with H

| Below ground green biomass (BFB) | SE of estimate | Adj. R² |
|---|-----------------------|---------------------------|
| BFB = 8.836H-58.579 | 7.28 | 0.87 |
| BFB= 123.669lnH-259.736 | 7.22 | 0.87 |
| BFB = -0.292H ² +17.221H-117.208 | 7.20 | 0.87 |
| BFB = 0.328H ^(1.994) | 0.10 | 0.89 |
| BFB = 8.575e ^(0.141H) | 0.11 | 0.87 |
| Below ground dry biomass (BDB) | | |
| BDB = 4.860H-32.218 | 4.00 | 0.83 |
| BDB = 68.018lnH-142.855 | 3.97 | 0.80 |
| BDB = -0.161H ² +9.471H-64.547 | 3.96 | 0.83 |
| BDB = 0.180H ^(1.994) | 0.10 | 0.81 |
| BDB = 0.4716e ^(0.141H) | 0.11 | 0.83 |

4.3.2 GBH as an independent factor

Data presented in table 10 clearly depict that power function BFB = 3.257GBH^(0.714) gave maximum Adj. R² value of 0.71 followed by exponential function BFB = 29.668e^(0.011GBH) with Adj. R² value of 0.67 and logarithm function BFB = 43.243lnGBH-112.919 with Adj. R² value of 0.66 respectively in prediction of BFB with GBH as independent factor. Using BDB as dependent factor, the results were same as

Table 10: Linear and non-linear functions for below-ground fresh and dry biomass with GBH

| Below-ground green biomass (BFB) | SE of estimate | Adj. R² |
|--|-----------------------|---------------------------|
| BFB = 0.684GBH+19.778 | 11.98 | 0.65 |
| BFB = 43.243lnGBH-112.919 | 11.86 | 0.66 |
| BFB = -0.004GBH ² +1.233GBH+2.630 | 11.94 | 0.66 |
| BFB = 3.257GBH ^(0.714) | 0.17 | 0.71 |
| BFB = 29.668e ^(0.011GBH) | 0.18 | 0.67 |
| Below-ground dry biomass (BDB) | | |
| BDB = 0.376GBH+10.878 | 6.59 | 0.61 |
| BDB = 23.484lnGBH-62.105 | 6.52 | 0.60 |
| BDB = -0.002GBH ² +6.73GBH+1.446 | 6.57 | 0.58 |
| BDB = 1.791GBH ^(0.714) | 0.17 | 0.68 |
| BDB = 16.318e ^(0.011GBH) | 0.18 | 0.62 |

BFB. The power function $BDB = 1.791GBH^{(0.714)}$ gave maximum Adj. R^2 value of 0.68 which showed its high significance then other functions. Logarithm function $BDB = 23.484\ln GBH - 62.105$ gave minimum Adj. R^2 value of 0.60. After the validation both for green and dry below ground biomass linear functions $BFB = 0.684GBH + 19.778$ and $BDB = 0.376GBH + 10.878$ with same Adj. R^2 values of 0.65 found to be more reliable in biomass prediction values. The results presented are in line with Mugasha *et al* (2013) that GBH alone as independent factor was effective for estimation of below-ground biomass modelling in Tanzania.

4.3.3 $GBH^2 \times H$ as independent factor

Data presented in table 11 clearly reveal that power function $BFB = 0.315GBH^2H^{(2.013)}$ gave maximum Adj. R^2 value of 0.77 and followed by quadratic function $BFB = -1.433 \times 10^{-9}(GBH^2H)^2 + 0.010GBH^2H + 32.490$ with Adj. R^2 value of 0.77. The exponential function $BFB = 46.425 e^{(3.908 \times 10^{-6} GBH^2H)}$ had least Adj. R^2 value of 0.58. By using BDB as dependent factor. The results obtained were same as that of BFB as dependent factor i.e. power function $BDB = 1.107GBH^2H^{(0.315)}$ with maximum Adj. R^2 value of 0.77 followed by quadratic function $BDB = -7.879 \times 10^{-10}(GBH^2H)^2 + 0.00GBH^2H + 17.870$ with Adj. R^2 value of 0.70 and logarithm function $BDB = 10.527\ln GBH^2H - 78.640$ with Adj. R^2 value of 0.67. Linear models found to be more reliable for

Table 11: Linear and non-linear functions for below-ground fresh and dry biomass with $GBH^2 \times H$

| Below-ground fresh biomass (BFB) | SE of estimate | Adj. R^2 |
|--|----------------|------------|
| $BGB = 0.000GBH^2H + 46.659$ | 12.66 | 0.61 |
| $BFB = 19.140\ln GBH^2H - 142.651$ | 10.73 | 0.72 |
| $BFB = -1.433 \times 10^{-9}(GBH^2H)^2 + 0.010GBH^2H + 32.490$ | 10.36 | 0.74 |
| $BFB = 2.013GBH^2H^{(0.315)}$ | 0.15 | 0.77 |
| $BFB = 46.425 e^{(3.908 \times 10^{-6} GBH^2H)}$ | 0.21 | 0.58 |
| Below-ground dry biomass (BDB) | | |
| $BDB = 0.000GBH^2H + 25.663$ | 6.96 | 0.58 |
| $BDB = 10.527\ln GBH^2H - 78.640$ | 5.90 | 0.67 |
| $BDB = -7.879 \times 10^{-10}(GBH^2H)^2 + 0.00GBH^2H + 17.870$ | 5.69 | 0.70 |
| $BDB = 1.107GBH^2H^{(0.315)}$ | 0.15 | 0.72 |
| $BDB = 25.534 e^{(3.908 \times 10^{-6} GBH^2H)}$ | 0.21 | 0.55 |

prediction of biomass among all the tested models $BGB = 0.000GBH^2H + 46.659$ and $BDB = 0.000GBH^2H + 25.663$ with Adj. R^2 values of 0.61 and 0.57 respectively give more closer results to the actual values. Sharma and Jain (1977) developed regression model based on

D²H in *Gmelina arborea* but their value of regression determination coefficient was less for volume prediction.

4.3.4 Multi-linear regression equation

Multi-linear equation was developed for estimation of BFB and BDB, H, GBH and GBH²*H as independent factor in one equation. The data presented in Table 12 clearly depict that both the equations were effective. BFB as dependent factor, the equation $BFB = -61.008 + 8.165H + 0.253GBH - 6089 \times 10^{-5}GBH^2H$ with Adj. R² value of 0.87 and the equation $BDB = -33.554 + 4.491H + 0.139GBH - 3.789 \times 10^{-6}GBH^2H$ with Adj. R² value of 0.94 were found best fit to predict below-ground fresh and dry biomass in *Tectona grandis*. Very limited predictive models have been developed to estimate below ground biomass due to laborious exercise than above ground biomass. Ajit *et al* (2011) have attempted to develop below ground prediction models in the *Populus Deltoides*.

Table 12: Multi-linear regression equations for below-ground fresh biomass (BFB) and below-ground dry biomass (BDB)

| Multi-linear regression equations | SE of estimate | Adj. R ² |
|---|----------------|---------------------|
| $BGB = -61.008 + 8.165H + 0.253GBH - 6089 \times 10^{-5}GBH^2H$ | 7.35 | 0.87 |
| $BGDB = -33.554 + 4.491H + 0.139GBH - 3.789 \times 10^{-6}GBH^2H$ | 10.92 | 0.94 |

4.4 Growth characteristics of trees in different girth classes

Trees are divided into three main parts known as crown, bole and roots. A well-developed trunk supports the crown and both are sustained by root system. Growth and biomass of tree are influenced by the genetic constitution of the tree species, as well as the environmental factors viz. rainfall, relative humidity, temperature, light, soil nutrients and moisture, etc. Ideal biotic and abiotic conditions allow a species to flourish. Both biotic and abiotic factors determine the growth behaviour of the tree. The growth and biomass production of different tree species is based on quality of planting stock, spacing of trees, site quality, climate management practices, etc. (Tiwari 1995). Swamy *et al* (2003) also reported that growth parameters (diameter at breast height, total height and number of branches) varied significantly due to the difference in age and site quality.

4.4.1 Tree height (m)

The mean height of trees in girth class of 110-120 cm was maximum (19.00 m) and it was found minimum (10.00 m) in lowest girth class 20-30 cm, Fig. 1 clearly indicate an increasing trend in the height parameter with different girth classes. The difference in the tree heights are due to the age difference of different girth classes. Increment in height becomes static after 70-80 cm girth.

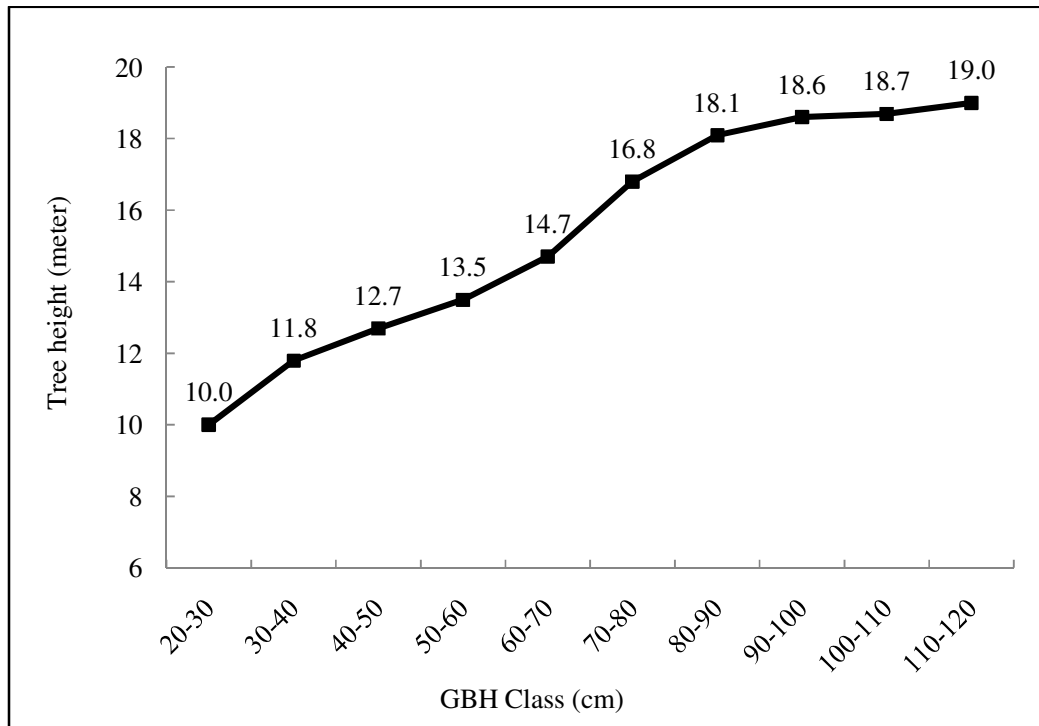


Fig. 1: Mean height in different girth classes

4.4.2 Canopy spread (m²)

The mean size of the canopy spread also showed increasing trend with the increasing range in girth classes (Fig. 2) The maximum size (112.5 m²) of canopy spread was recorded in highest girth class 110-120 cm followed by (111.3 m²) in 100-110 cm girth class and found minimum (34 m²) in lowest girth class i.e. 20.30 cm.

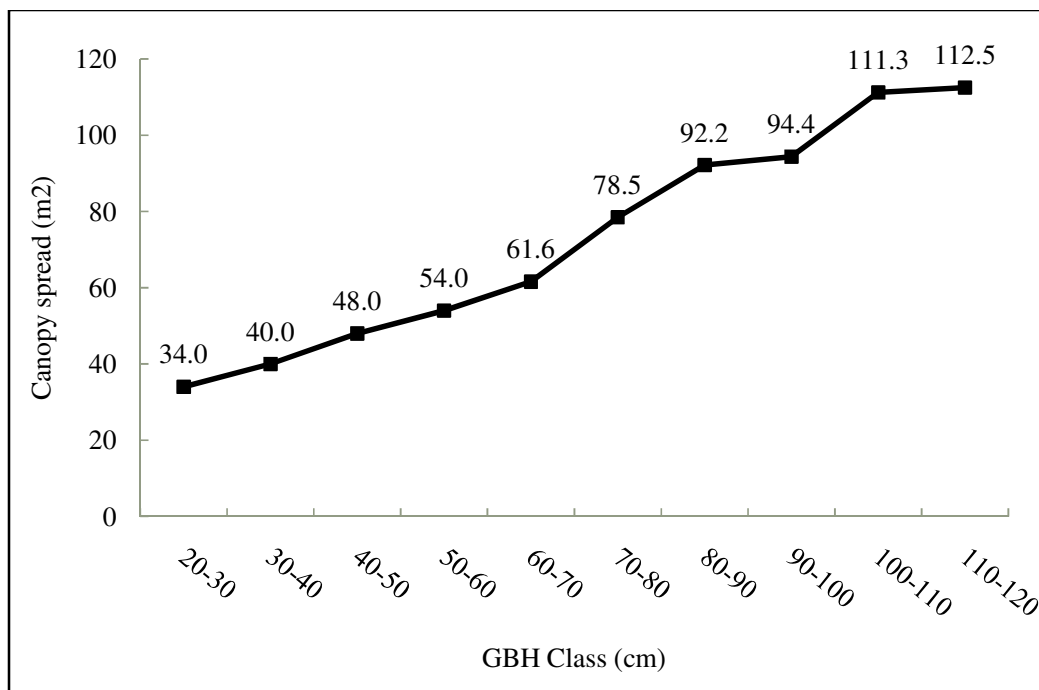


Fig. 2: Mean canopy spread increment in w.r.t girth classes

4.4.3 Collar girth (cm)

The mean values of collar girth shows consistent increasing trend from lowest (20-30) to highest (110-120) GBH class (Fig 3). The minimum value of collar girth 51cm was found in the lowest girth class (20-30 cm) and the maximum value of collar girth 138.5cm was found in highest girth class 110-120 cm.

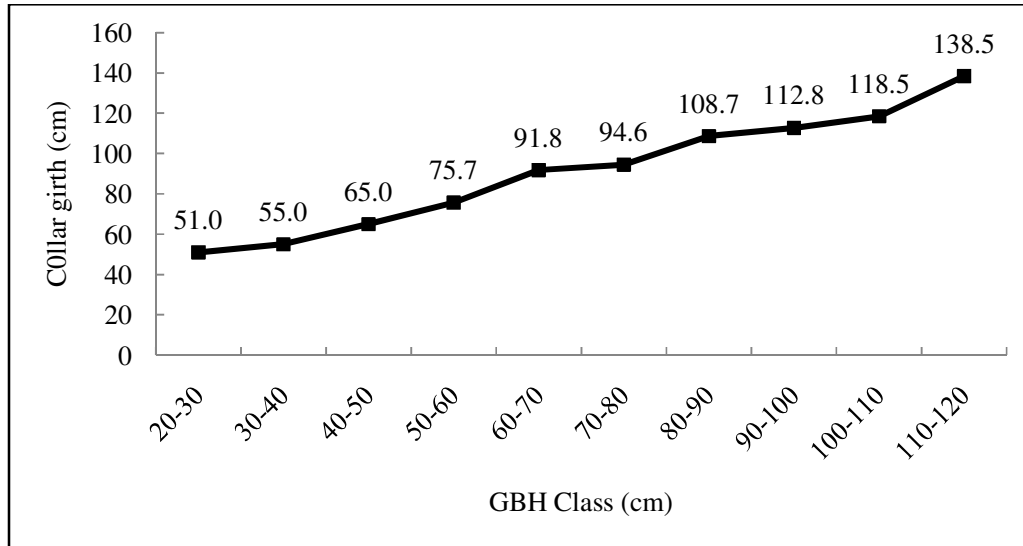


Fig. 3. Mean increment of trend of collar girth (cm) w.r.t. girth classes

4.4.4 Stem fresh and dry weight (kg)

Mean data of stem weight of each class presented in (Fig 4) clearly depict that as the girth class increased, the stem weight also increased. The minimum value of stem fresh weight (68 kg) and stem dry weight (28 kg) was found in lowest girth class i.e.(20-30) cm

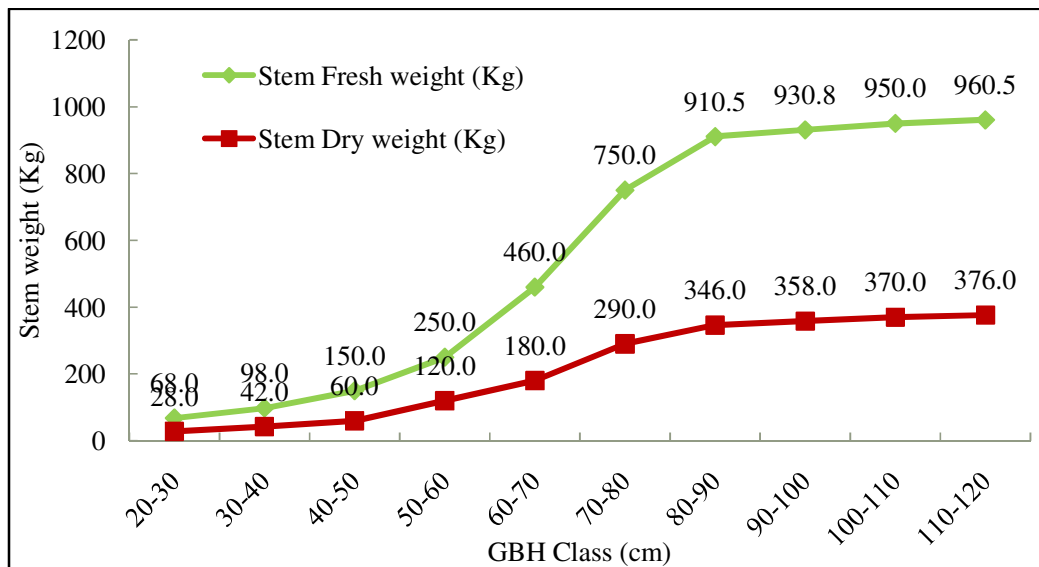


Fig. 4: Mean increment trend in stem fresh weight (kg) and stem dry weight (kg) w.r.t. to girth classes

followed by (98kg) of stem fresh weight and (42 kg) of stem dry weight in second higher GBH class i.e. 30-40. The maximum value of mean stem fresh weight (960 kg) and stem dry weight (376 kg) was recorded in the highest GBH class (110-120cm).

4.4.5 Branch fresh and dry weight (kg)

Mean data of branch weight of each class presented in (Fig 5) clearly depict that as the girth classes increased the branch weight also increased. Minimum value of branch fresh weight (15 kg) and branch dry weight (5 kg) was found in lowest girth class (20-30) cm and maximum mean branch fresh weight (99Kg) and branch dry weight (49.3 kg) was found in the highest GBH class (110-120) cm.

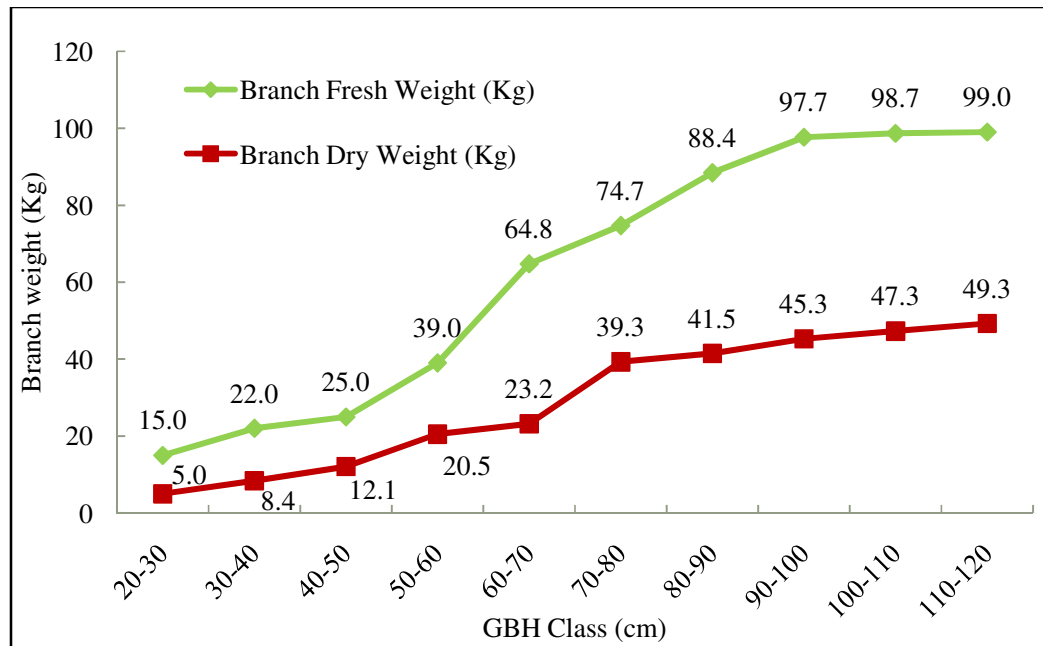


Fig. 5: Mean increment trend in branch fresh and dry weight (kg) w.r.t. to girth classes

4.4.6 Leaf fresh and dry weight (kg)

Mean leaf weight of each class presented in (Fig 6) clearly depict that as the girth class increased the leaf weight also increased. The minimum value of leaf fresh (13.4 kg) and leaf dry weight (9.4 kg) was observed in the lowest girth class (20-30) cm and maximum mean leaf fresh (59.5 kg) and leaf dry weight (26.7 kg) was found in the highest GBH class (110-120cm).

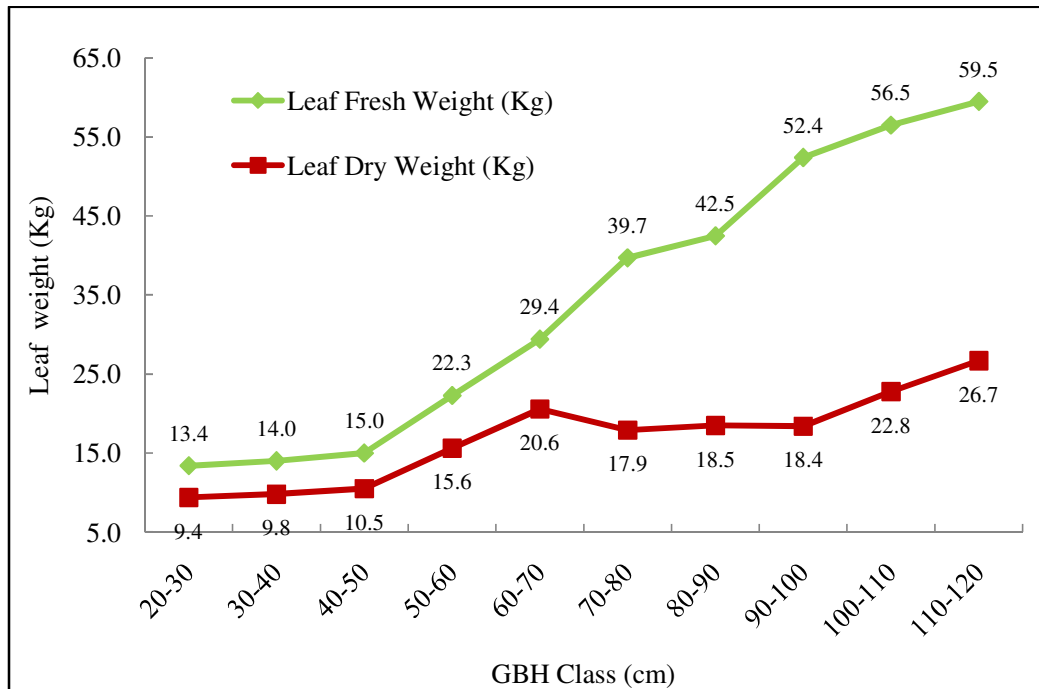


Fig 6: Increasing trend of leaf fresh weight (kg) and dry weight (kg) w.r.t. girth classes

4.4.7 Bark fresh and dry weight (kg)

Mean data of bark weight of each class presented in (Fig 7) clearly depict that as the girth class increased, the bark weight also increased trend. The minimum value of bark fresh (12 kg) and dry weight (7.2 kg) were found in lowest girth class (20-30 cm) and maximum mean bark fresh (72 kg) and bark dry weight (32.1 kg) was found in the highest GBH value class i.e. 110-120 cm.

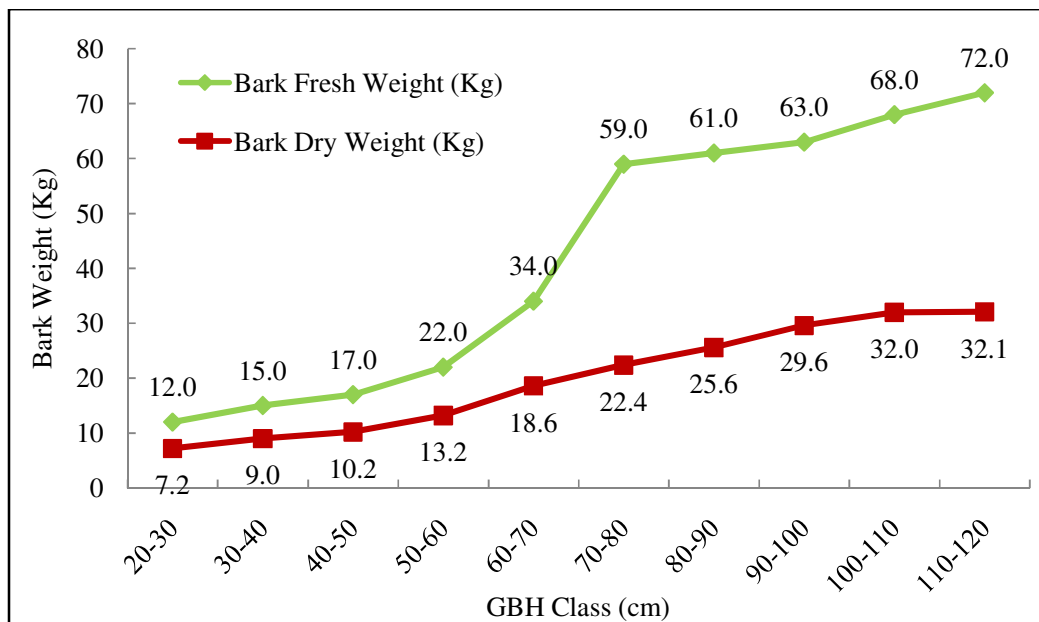


Fig. 7: Increasing trend in bark fresh weight (kg) and bark dry weight (kg) w.r.t. girth classes

4.4.8 Root fresh and dry weight (kg)

Mean root weight of each class presented in (Fig 8) depict that increase in girth class resulted in enhancement of the root weight. The minimum value of root fresh (19.8 kg) and root dry weight (9.9 kg) were found in lowest girth class (20-30 cm) and maximum mean root fresh (210.3 kg) and root dry weight (95.4 kg) was found in the highest GBH class (110-120 cm).

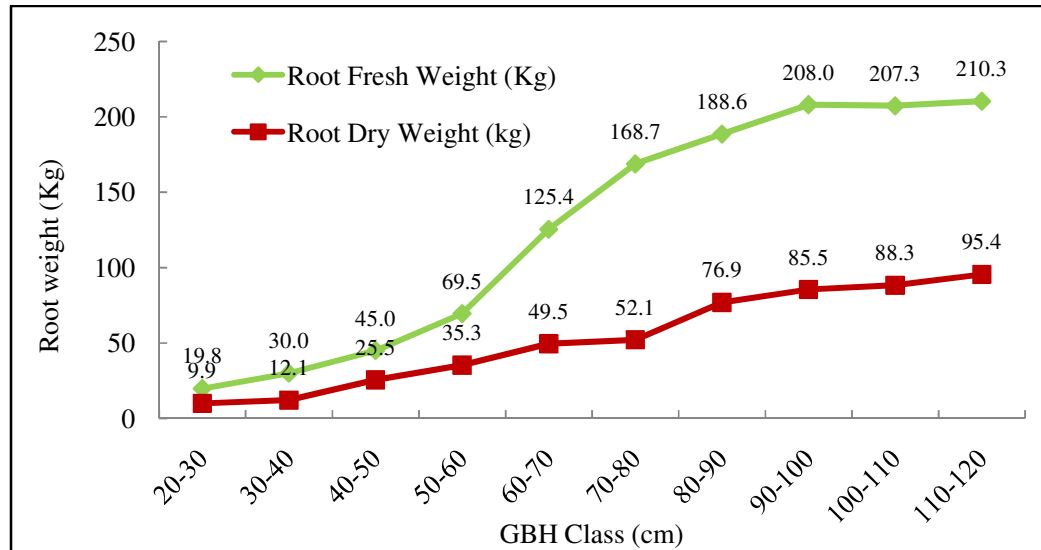


Fig. 8: Mean increment trend in root fresh weight (kg) and root dry weight (kg) w.r.t. girth classes

4.4.9 Total tree fresh and dry weight (kg)

The data present in graphical form fig 9 show an increasing trend in the total tree fresh and dry weight with the increase in GBH class from (20-120 cm). The minimum value of total fresh (128.2 kg) and

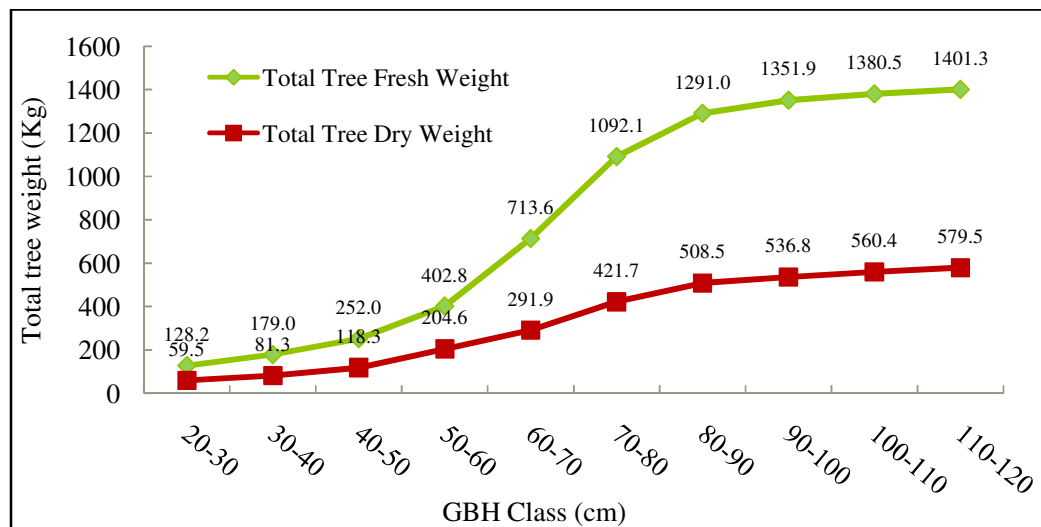


Fig 9: Mean increment total tree fresh weight (kg) and dry weight (kg) w.r.t. girth classes

dry weight (59.5kg) were found in lowest girth class (20-30 cm) and maximum value of mean total tree fresh weight (1401.3 kg) and total tree dry (579.5 kg) was found in the highest GBH class (110-120 cm). Bohre *et al* (2013) also prescribed the similar trend from seedling to sapling and tree stage for biomass trend in *Gmelina arborea*.

4.5 Quality parameters of tree in different girth classes

4.5.1 Radial shrinkage (%)

Mean data of radial shrinkage presented in figure10 clearly depict that the highest radial shrinkage(5.035%) in *Tectona grandis* was found in top region wood samples in the lowest girth class 20-30cm and the minimum value 1.52 % in the highest girth class (110-120 cm). The radial shrinkage of middle region was maximum 4.18% in the lowest girth class (20-30 cm) and the minimum (0.55 %) in highest girth class (110-120 cm). Similar trend was observed in the collar region where maximum (3.76 %) of radial shrinkage in the lowest girth class(20-30 cm) and the minimum (0.33 %) shrinkage was found in the highest girth class (110-120 cm). The increase in the shrinkage towards the top region of the tree from the collar region was due to the decreasing in the maturity of the wood from collar to top region. The age of the tree increased mature wood on all the three regions (top, middle and collar) also increased so the shrinkage percentage with the advancing in age in the girth classes.

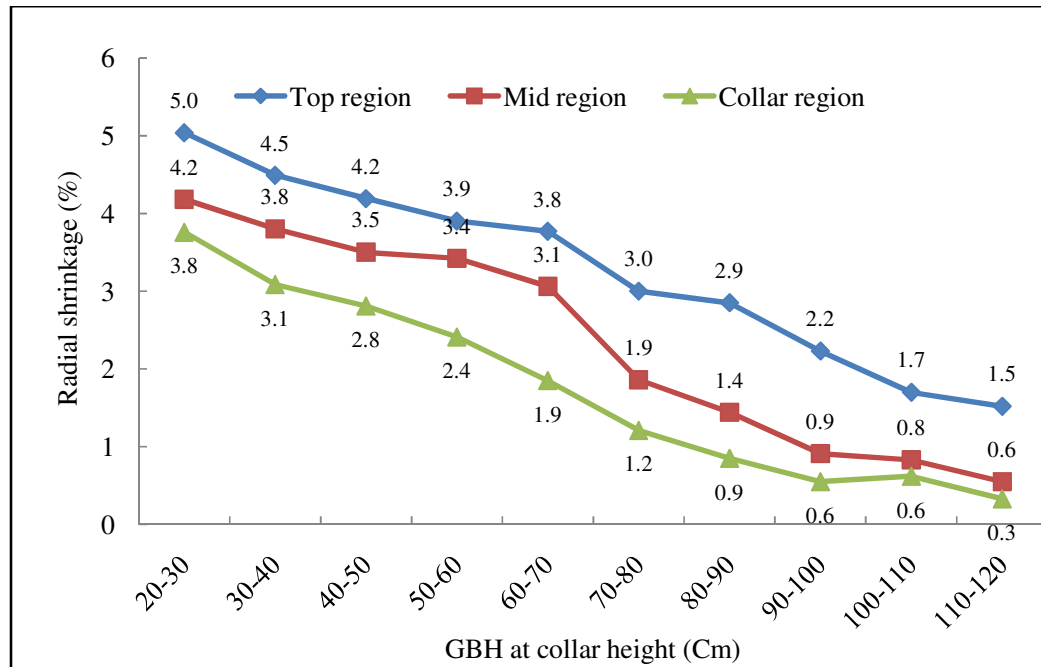


Fig 10: Mean data of radial shrinkage (%) on top, middle and collar region of tree w.r.t. to girth classes

4.5.2 Tangential Shrinkage (%)

Mean data of tangential shrinkage presented in figure11 clearly depict that the highest(4.87%) tangential shrinkage was found in top region in the lowest girth class (20-30 cm) and the minimum (2.64 %) in the highest girth class 110-120 cm irrespective of region.

The maximum shrinkage value (3.6 %) was found in the lowest girth class (20-30 cm) and the minimum value 1.45 % was found in highest girth class (110-120 cm) in the middle region. Similar trend was observed in the collar region tangential shrinkage. The increase in the shrinkage towards the top region of the tree from the collar region was due to the decrease in the maturity of the wood from collar to top region and when the age of the tree increased the mature wood on all the three regions (top, middle and collar) also increased so the shrinkage also decreased in all the regions (top, middle and collar) towards increase in the girth class. It is also observed that percentage in the study reported that the tangential shrinkage decreased with the increase in the range of girth class. Higher tangential shrinkage is also in agreement with the findings of Okon (2014), where almost double tangential shrinkage was observed than radial shrinkage due to physiological activities, cell structure and cellulose molecules with in cell wall, etc.

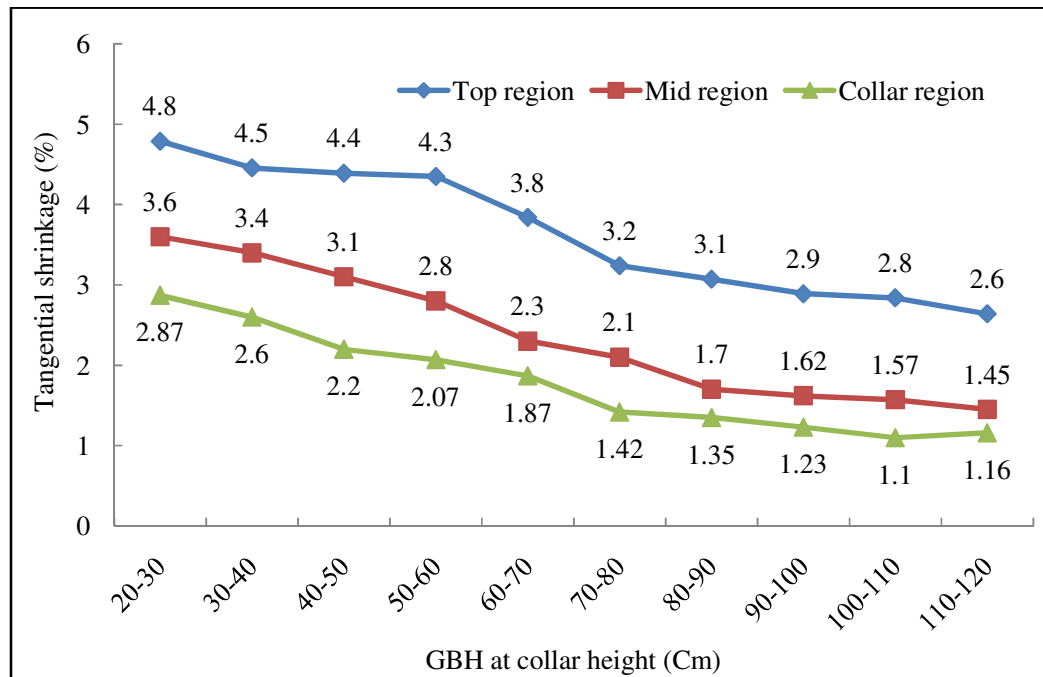


Fig 11: Mean data of tangential shrinkage (%) on top, middle and collar region of tree w.r.t. to girth classes

also recorded increase in both the shrinkage from butt log to Crown Point. The shrinkage values are comparable to the values reported by Shanavas and Kumar (2006) for four tree species (*Acacia auriculiformis*, *Acacia mangium*, *Grevillea robusta* and *Tectona grandis*).

4.5.3 Specific gravity

Mean data of specific gravity pertaining to variable heights of plants presented in figure 12 depict that minimum (0.35) specific gravity was found in top region of wood samples from the lowest girth class (20-30 cm). The values increased with increase in girth class. The maximum (0.62) reported specific gravity was the 0.62 in the highest girth class in

110-120 cm. The specific gravity of middle and collar region of the tree was found to be minimum in lowest girth class (20-30cm) and vice versa maximum value 0.76 of middle region specific gravity was found in highest girth class 110-120 (cm) and same trend was found in the collar region specific gravity i.e. the minimum value 0.66 of the specific gravity was found in the lowest girth class 20-30 (cm) and the maximum value 0.95 of specific gravity was found in the highest girth class i.e. 110-120 (cm). The decrease in the specific gravity towards the top region of the tree from the collar region was due to the decreasing the maturity of the wood from collar to top region and when the age of the tree increased the mature wood on all the three regions (top, middle and collar) also increased so the specific gravity was also increased in all the regions (top, middle and collar) towards increasing girth class which can be related to increasing tree age. This change is due to the cell wall thickness and cell size, which varies with age and maturity of the cambium.

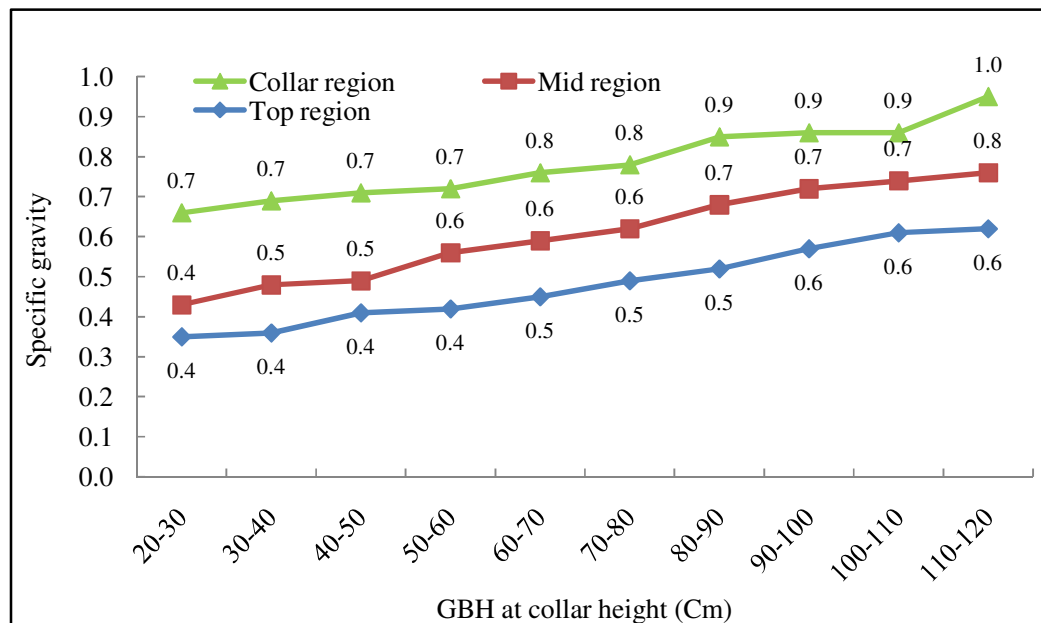


Fig 12: Mean data of specific gravity on top, middle and collar region of tree w.r.t. to girth classes

The trend showed in figure 12 clearly depict that the pooled average of specific gravity increased with increase in the range of girth class. Chauhan *et al* (2001) recorded impact of height on specific gravity due to differential sapwood and heart wood ratio at different tree heights.

4.5.4 Biomass expansion factor (BEF) and root-to-shoot ratio (R)

BEF showed decreasing trend with increase in the range of the girth classes. It is depicted in (table13) clearly that the maximum value of BEF 1.61 was found in GBH class 20-30 cm followed by very closer value of BEF 1.58 in GBH class 30-40 cm and the

minimum value of BEF 1.24 was found in highest girth class 120-130 cm. The root-to-shoot ratio of *Tectona grandis* reveals that irrespective of girth class the root: shoot ratio remained almost static from (80-130 cm) girth classes. The highest value 0.42 was found in lowest girth class (20-30 cm) and the minimum value 0.23 was found in 90-100 cm girth classes.

Table 13: Mean data of biomass expansion factor (BEF) and root-to-shoot ratio (R) w.r.t. girth classes

| Girth class (cm) | Biomass expansion factor (BEF) | Root-to-Shoot ratio (R) |
|------------------|--------------------------------|-------------------------|
| 20-30 | 1.61 | 0.42 |
| 30-40 | 1.58 | 0.38 |
| 40-50 | 1.53 | 0.36 |
| 50-60 | 1.49 | 0.36 |
| 60-70 | 1.45 | 0.32 |
| 70-80 | 1.41 | 0.30 |
| 80-90 | 1.38 | 0.24 |
| 90-100 | 1.34 | 0.23 |
| 100-110 | 1.31 | 0.24 |
| 110-120 | 1.28 | 0.25 |
| 120-130 | 1.24 | 0.25 |

4.6 Proportion of tree components in different girth classes

A perusal of data presented in figure 13 clearly shows that in the lowest girth class the proportion of stem (51.72 %) and root (21.6 %) in total biomass was more than the branch (21.6 %) and leaf (4.95 %) comparing the mean proportion of stem and root towards the higher girth classes increased whereas proportion of branch and leaves in the total biomass decreased with increase in girth class. The maximum value (67.37 %) of stem proportion and (10.73 %) of root proportion, which showed a decreasing trend as compared to lower girth classes. Study conducted by Singh (1998) on partitioning of biomass in which stem wood alone constituted almost 55 % of the tree biomass, 22% branch and twigs, 17 % root and 16-8 % leaf. The results presented here about partitioning of biomass agreed with the study of Singh (1998). As shown in the figure 13 that the proportion of stem and root increased and proportion of branch and leaf decreased with the increase in girth classes of the *Tectona grandis*.

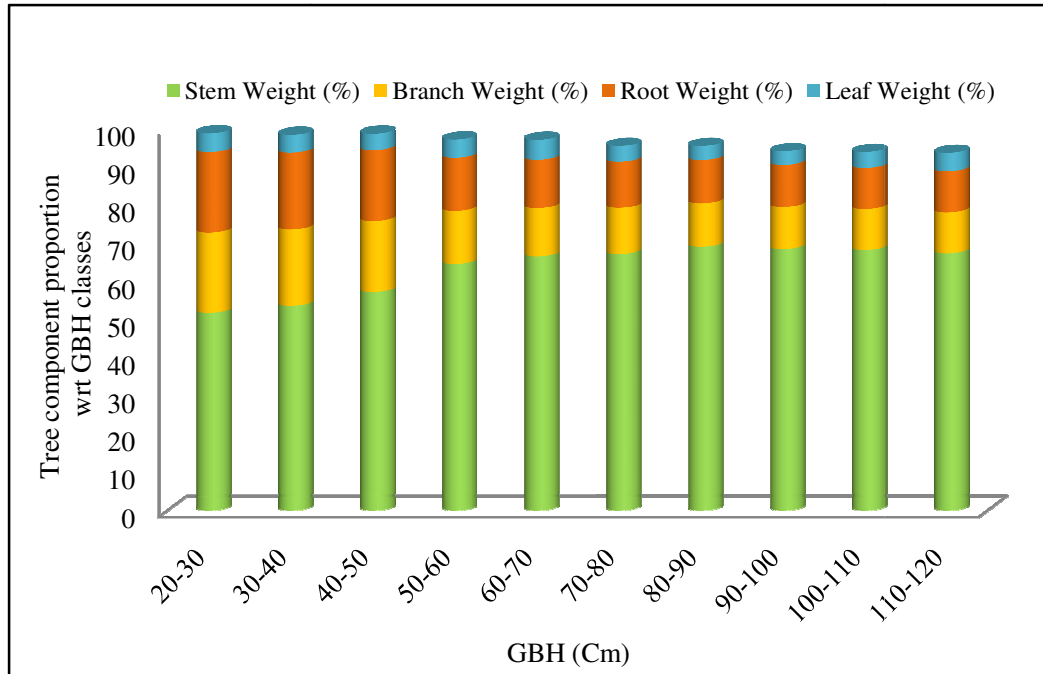


Fig 13: Tree component proportion w.r.t. girth at breast height (GBH) classes

CHAPTER V

SUMMARY

Biomass assessment is important for national development planning as well as for scientific studies of ecosystem productivity, meeting industrial demands, reducing pressure on traditional forests, carbon budgets and import-export balance, etc. Recently, biomass is being increasingly used to quantify the pools and fluxes of greenhouse gases (GHG) from terrestrial biosphere associated with land use and land cover changes. Reliable biomass/volume forecasts are required for planning plantation projects. *Tectona grandis* L. (Roxb.) It is a moderately fast growing tree species is most widely distributed. This species is economically important for timber, fuel and pulp production. This has been introduced recently in Punjab and showing encouraging results of establishment and growth. But there is lack of biomass prediction models to ascertain the growing stock. Prediction models are usually considered as handy tool to know the standing tree biomass.

The present investigation entitled **“Developing Prediction Models for Biomass Components of *Tectona grandis* L. (Roxb.)”** was designed to develop prediction biomass for different tree components including relationship among different biomass components for estimating biomass exponential factor (BEF). The twenty five trees of *Tectona grandis* L. (Roxb.) were selected for recording various parameters i.e. diameter at collar region, girth at breast height (GBH), tree height and crown spread. Trees were harvested to record the above ground fresh and dry biomass of different components (stem, bark, branch and leaf).

Linear and non-linear functions were used to draw biometric function in teak. The best fit function with height was the logarithm equation of $TGB = 564.694\ln(H) - 1154.887$ with maximum adj. R^2 value of 0.81. For total dry biomass (TDB) the logarithm equation $TDB = 338.817\ln H - 692.932$ was found best fit with maximum Adj. R^2 value of 0.83. By using TGB and TDB as dependent and girth at breast height (GBH) as independent factor. The best fit equation with GBH observed to be $TGB = 240.794\ln GBH - 668.336$ with maximum Adj. R^2 value of 0.94 and $TDB = 144.447 GBH - 401.001$ with Adj. R^2 value of 0.90. The logarithm function with GBH^2H was $TGB = 103.34\ln GBH^2H - 796.172$ found to fit with highly significant Adj. R^2 0.95 followed by power function $TGB = 4.516 GBH^2H^{(0.386)}$ with Adj. R^2 Value 0.89. The logarithm function of $TDB = 61.820\ln GBH^2H - 477.703$ with maximum Adj. R^2 0.91 was found best fit to predict dry biomass in case of GBH^2*H as independent factor. Multi-linear equations were also developed for TGB and TDB by taking into consideration all the growth parameters namely as H, GBH and GBH^2*H as independent factor in one equation. Both the equations like total green biomass $TGB = -166.139 + 18.692H + 4.342GBH - 0.001GBH^2H$ with Adj. R^2 value of 0.93 and total dry biomass $TDB = -99.683 + 11.215H + 2.605GBH + 0.000$ with Adj. R^2 value of 0.93 were found to

be highly significant with prediction accuracy of biomass.

The total green and dry biomass of the tree were partitioned into above-ground green and above-ground dry biomass, below-ground fresh and below-ground dry biomass and subjected to linear and non-linear functions for developing allometric equation. The linear function of $AGB = 479.407\ln H - 1005.050$ with maximum Adj. R^2 value of 0.81 and quadratic function $AGB = -1.623H^2 + 80.514H - 547.317$ with Adj. R^2 value of 0.80 were observed to be best equations to assess above ground green biomass while H was taken as independent factor. Similarly taking above ground dry biomass (ADB) as dependent factor with H (independent factor). The logarithm, equation $ADB = 278.283\ln H - 606.576$ and linear equation $ADB = 19.829H - 153.128$ resulted similar significant Adj. R^2 value 0.79 and 0.78 respectively. By using AGB as dependent and GBH as independent factor, logarithm function $AGB = 204.418\ln GBH - 591.945$ with Adj. R^2 value of 0.94 and quadratic function $AGB = -0.001GBH^2H + 5.195GBH - 26.301$ with Adj. R^2 value of 0.93 both were found best fit to predict above-ground biomass for *Tectona grandis* with GBH as independent factor and by Using ADB as dependent factor, the results were found similar as both linear function $ADB = 1.904GBH - 4.683$ and power function $ADB = 0.893GBH^{(1.166)}$ with Adj. R^2 value of 0.93 were found fit to predict above ground dry biomass for *Tectona grandis* with DBH as independent factor. By using AGB and ADB as dependent and $GBH^2 * H$ as independent factor. The equation of logarithm function $AGB = 87.469\ln GBH^2H - 700.476$ with maximum Adj. R^2 value of 0.95 and the power function $ADB = 0.488GBH^2H^{(0.497)}$ with maximum Adj. R^2 of 0.94 were found best fit to predict above-ground biomass of the tree. Multi-linear equation was developed for AGB and ADB by taking into consideration growth parameters namely H, GBH and $GBH^2 * H$ as independent factor in one equation and contribution of all the factors were found significant.

Linear and non-linear equations were developed for below-ground fresh biomass (BFB) as dependent and H as independent factor. The power function of $BFB = 0.328H^{(1.994)}$ had Adj. $R^2 = 0.89$ followed by logarithm function $BFB = 123.669\ln H - 259.736$, quadratic function $BFB = -0.292H^2 + 17.221H - 117.208$ and exponential function $BFB = 8.575e^{(0.141H)}$ had same Adj. R^2 value of 0.87 was found best fit for prediction of fresh root weight. Equation developed through linear function for $BDB = 4.860H - 32.218$, quadratic function $BDB = -0.161H^2 + 9.471H - 64.547$ and exponential function $BDB = 0.4716e^{(0.141GBH)}$ gave Adj. R^2 value of (0.83) and were found significantly best fit in prediction of dry root weight. By using BFB as dependent and GBH as independent factor. The power function equation of $BFB = 3.257GBH^{(0.714)}$ with maximum Adj. R^2 value of 0.71 were found best fit in case of GBH as independent factor. Whereas in BDB when we take as dependent factor, the results were similar to BFB. The power function $BDB = 1.791GBH^{(0.714)}$ with maximum Adj. R^2 value of 0.68 was observed to be best fit to predict dry below-ground biomass. The power function

equation of $BFB = 0.315GBH^2H^{(2.013)}$ with maximum Adj. R^2 value of 0.77 and quadratic function $BFB = -1.433 \times 10^{-9} (GBH^2H)^2 + 0.010GBH^2H + 32.490$ gave same value Adj. R^2 (0.77) and were found considerably best fit in prediction of below-ground fresh biomass (BFB) in case of GBH^2H factor. The developed Multi-linear equations were $BFB = -61.008 + 8.165 + 0.253GBH - 609 \times 10^{-5}GBH^2H$ with Adj. R^2 value of 0.87 and $BDB = -33.554 + 4.491H + 0.139GBH - 3.789 \times 10^{-6}GBH^2H$ with Adj. R^2 value of 0.94 and found to be best fit to predict below-ground fresh and dry biomass, respectively in *Tectona grandis*. Even the regression coefficient of the logarithm and quadratic function was high but after validation these models showed less reliability in prediction under higher and lower GBH classes. Biomass expansion factor (BEF) showed decreasing trend with the increase in the range of girth classes from 20-120 cm. For different GBH classes, the values of BEF found to range from 1.61 to 1.24.

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