MODELLING LEAF AREA AND BRANCH BIOMASS ESTIMATION FOR ARABICA COFFEE *(Coffea arabica* L.*)* GROWN AT DIFFERENT ALTITUDES OF MANA DISTRICT, JIMMA ZONE

M.Sc. THESIS

By

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Modelling Leaf Area and Branch Biomass Estimation for Arabica Coffee *(Coffea arabica* L.) Grown at Different Altitudes of Mana District, Jimma Zone

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A Thesis

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MSc THESIS APPROVAL SHEET

We, the undersigned, member of the Board of Examiners of the final open defense by **Zerihun Misgana** have read and evaluated his/her thesis entitled **"Modeling Leaf Area and Branch Biomass Estimation for Arabica Coffee (*Coffea Arabica* L.) Grown at Different Altitudes of Mana District, Jimma Zone"** and examined the candidate. This is therefore to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree Master of Science in **Agronomy.**

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DEDICATION

This thesis manuscript is dedicated to my beloved children Miracle Zerihun and Simera Zerihun.

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STATEMENT OF AUTHOR

I declare that this thesis is the result of my own work and that all sources or materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for the degree of Master of Science in agriculture (Agronomy) at Jimma University, College of Agriculture and Veterinary Medicine and is reserved at the University Library to be made available to users. I confidently declare that this thesis has not been submitted to any other institutions anywhere for the award of any academic degree, diploma, or certificate.

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BIOGRAPHICAL SKETCH

Zerihun Misgana Bora was born in February 1983 at Hababo Guduru Woreda, Horo Guduru Wollega Zone of Oromia Regional State. He attended his elementary and junior secondary school at Imbabo Elementary and Junior Secondary School and attended high School at Ambo Comprehensive Senior Secondary School. Following the completion of his secondary education; he joined Asella ATVET, and graduated with Diploma in Plant Science on August 01, 2006.After graduation, he was employed at Hababo Guduru Woreda, Agriculture and Rural Development Office and served there for four years. Then after he joined the undergraduate study program at Jimma University College of Agriculture and Veterinary Medicine in 2010 to pursue his study leading to a BSc degree in Plant Science and graduated on June 28, 2012.

After graduation he joined Techno Serve Ethiopia where he served as Supervisor and Business Advisor for one and two year respectively. Then after; he joined the graduate study program at Jimma University College of Agriculture and Veterinary Medicine in 2014 to pursue his study leading to a Master of Science degree in Agronomy.

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ACRONYMS AND ABBREVIATIONS

ANCOVA	Analysis of covariance
CSA	Cross-sectional area
FAO	Food and Agriculture Organization
FSA	Agro forestry System
GNP	Growth National Product
R^2	Coefficient of determination
RMSE	Root Mean Square Error
SE	Standard Error
SEE	Standard Error of Estimate
SSE	Sum of Square Error
T	Tolerance
WFP	World Food Product
VIF	Variance Inflation Factor

Modeling Leaf Area and Branch Biomass Estimation for Arabica Coffee (*Coffeaarabica*L.)Grown at Different Altitudes of Mana District, Jimma Zone

ABSTRACT

This study was aimed at establishing allometric models for estimating LA (Leaf Area) and branch biomass of eight Coffea arabica genotypes in Mana district of Jimma Zone Oromia Regional State, South Western Ethiopia. Many Methodologies and instruments have been devised to facilitate measurement of leaf area and branch biomass. However, these methods are destructive, laborious and expensive. For modeling leaf area; leaf width, leaf length and leaf area of 1,200 leaves (50 leaves for each genotype) was measured for model construction and the respective measurements on 960 leaves were used for model validation. For modeling branch biomass branch diameter of 960 branches (40 branches for each genotype) were measured for model construction and the respective measurements on 360 branches were used for model validation. Linear measurement was taken from leaves and branch diameter of eight genotypes of C. arabica, cultivated in field following a randomized complete blocks design at three altitudes (high, medium and low) were evaluated to identify best option for input in the models, and to validate the method to estimate the leaf area and branch biomass. Linear and non-linear models were tested for their accuracy to predict both leaf area and branch biomass of the eight C. arabica genotypes. The use of linear model resulted in high accuracy for all of the eight C. arabica genotypes. No significant effect of growing altitude and genotype was obtained among the slopes of the models for leaf area estimation but there was a significant effect of genotype on the models for branch biomass estimation. For leaf area estimation one single model was fitted to the combined data of all genotypes at all altitudes (LA = 0.6434LW). Comparison between observed and predicted leaf area were made using this model in another independent dataset, conducted for model validation, exhibited a high degree of correlation (r= 0.98–0.99 $P < 0.01$*).)The over or under estimation of the leaf area using this model ranges between 0.02 to 1.7% and this model is adequate to estimate the leaf area for the eight C. arabica genotypes. In the contrary genotype specific models were developed for each genotype for branch biomass estimation and one general model (BM=62.059x-2.0532) was developed for all genotypes. Comparison between observed and predicted branch biomass were made using genotype specific and general models in another dataset, conducted for model validation, exhibited a high degree of correlation (r= 0.83–0.96,* $P < 0.01$*).General models over or under estimates branch biomass with more than 13 % and less than 38% in three of the coffee genotypes but the over or under estimation of the genotype specific model is between 0.3 to 7.8%. Hence genotype specific models can satisfactorily estimate the Branch biomass of the eight C. arabica genotypes at different altitudes.*

Key words: *Coffea arabica* L., Modeling, Leaf Area Estimation, Branch Mass Estimation

1. INTRODUCTION

Arabica coffee plays a significant role in Ethiopian economy, contributing over 35 % of the total export value; 4 to 5% to National Gross Domestic Product and generating 20% of government revenue (Petit 2007). It also plays a central role as source of income for over one million coffee growing households, and over 15 million people derive their livelihood directly or indirectly from this crop along the value chain (Petit, 2007; Labouisse *et al*., 2008).

In Ethiopia the variability of coffee character is very wide for making use of the planting materials for different purposes. The presence of genetic diversity enables the country to select the planting materials for disease resistance, high yielding and of top quality coffee production in the country. This genetic diversity requires special care and proper utilization for sustainability of coffee production in the country in particular and to the world in general (http://www.ecea.org.et/altitude-and-climate).

It has been reported that leaves play an important role for plants to undertake gas exchange and carbon assimilation. Leaf area influences the growth and physiologies of the plants in many ways (Kurt *et al*., 2005; Singh, 2011; Zhang and Pan, 2011;Wang and Zhang, 2012). It strongly affects light interception, physiology as well as productivity of the plant. It also affects photosynthesis, evapotranspiration, and response to fertilizer and irrigation (Antunes *et al*., 2008; Ghezehei *et al.*, 2009; Singh, 2011; Zhang and Pan, 2011). Therefore, the knowledge of leaf area is vital and employed as key trait for Eco physiological and agronomic studies (Singh, 2011; Normand and Lauri, 2012;Fascella *et al*., 2013). For this reason, quantifying Leaf Area is fundamental for assessing plant primary productivity (Pandey & Singh, 2011) and as a functional component of crop modeling (Lizaso *et al*., 2003).

Many Methodologies and instruments have been devised to facilitate measurement of leaf area (copying on graph paper, photographing, use of a portable scanning planimeter, analysis of images using software (Fallovo *et al*., 2008) and these methods may or may not be destructive (Ilkaee *et al*., 2011). Biomass can be estimated by either destructive or non-destructive methods. The former method is laborious and expensive because it involves cutting down trees and measuring the dry weight of their components (Araujo *et al.* 1999).With this method only a sub-

sample of tree biomass are taken for further investigation and tree variability may be rather high, which underlines the need of an appropriate scaling methodology.

An essential aspect of studies on plant growth and reproduction is the accurate and nondestructive estimation of key variables of interest such as leaf area, foliage or stem biomass, and total (stem + leaves) biomass, using the least amount of measurements. Such estimation implies the need for accurate and reliable predictive models (Normand and Lauri,2012).These models are based on statistical relationships between a key variable of interest and one or several variables that are easy to measure (Parresol, 1999). The theoretical basis of these models is allometry which is defined as the measure and the study of growth or size of a part in relation to entire organism(Beets *et al*., 2012).

Allometric models have mainly been developed for their application for coffee Arabica. But as new processes of breeding and selections are performed, some morphological traits of the plants may be influenced, making it necessary to develop new methods. Leaf area have been developed by many authors and for different coffee genotypes such (Antunes *et al.,* 2008) coffee (*Coffea arabica* and *Coffea canephora*), (Brinate *et al.,* 2015) for genotypes of conilon coffee and (Muñoz *et al.,* 2015) (*Coffea Arabica* L.) of the Castillo variety.

However, this research did not consider the altitude differences of coffee genotypes to be incorporated in to the model for leaf area estimation and so far there has not been any research conducted for non-destructive leaf area estimation for *Coffea arabica* genotypes in Ethiopia at different altitude. In Ethiopia 37 improved (34 varieties and-3 hybrids) coffee varieties were released for different agro ecological areas of Ethiopia (Abrar and Negussie, 2013). But there has not been any research conducted to develop allometric nondestructive branch growth and leaf area estimation for these genotypes.

Therefore, developing models that allow prediction of leaf area and branch biomass of the released genotypes of *Coffea arabica* in accurate and simple ways are very important, as they are less economically costly and enable measurements on the same leaf over time, making it possible to describe accurate patterns of growth. To this effect, the current research was initiated with the following objectives as indicated below

Objective

- To develop simple and reliable model for nondestructive leaf area and branch biomass estimation of eight *Coffea arabica* L. genotypes grown at three different altitudes of Mana District, Jimma Zone

2. LITERATURE REVIEW

2.1 Botanical Classification of Coffee

Coffee (*Coffea arabica* L.) belongs to the genus *Coffea* in the Rubiaceae family. Among 124 species in the genus *Coffea* (Davis *et al*., 2011), only two *Coffea arabica.* L. *(*Arabica coffee) and *Coffea canephorapiere* (Robusta coffee) economically dominate the world trade, being responsible for about 99% of world bean production (DaMatta and Ramalho, 2006). Arabica coffee accounts for about 70 % of coffee consumed and Robusta coffee for the remaining per cent (DaMatta and Ramalho, 2006).

Arabica coffee (*Coffea arabica* Linnaeus) is the only tetraploid species ($2n = 4x = 44$), and Robusta coffee (*Coffea canephora* Pierre) is the diploid species ($2n = 2x = 22$) are the two most important commercial species (Gichuru *et al*., 2008). In addition, Arabica coffee is an amphidiploid species formed by hybridization between *Coffea eugeniodes* and *Coffea canephora*, or ecotypes related to these diploid species (Lashermes *et al*., 1999). Arabica coffee is believed to have originated in southwestern Ethiopia, while Robusta coffee originated from central and western equatorial Africa (Ferwerda, 1976).

Ethiopia is the single known center of origin and genetic diversity for Arabica coffee (*Coffea arabica* L.) (Wintegens, 2004; cited in Abrar *et al*., 2014). The endowment of Ethiopia with diverse coffee types and agro-ecology allowed production of high quality coffee to world market (Abrar *et al*., 2014). Ethiopia is the largest producer of coffee in Sub-Saharan Africa and is the fifth largest coffee producer in the world next to Brazil, Vietnam, Colombia and Indonesia, contributing about 7 to 10% of total world coffee production (Gray *et al*., 2013). If we consider Arabica coffee alone, Ethiopia is the third largest producer after Brazil and Colombia (ICO, 2016). Thus, an Ethiopian coffee type is known internationally by the names Limmu, Gimbi, Yirgacheffe, Harar and *etc*.; (Taye, 2010).Among these, Limmu coffee type is one of well-known for its peculiar winy flavor and fetching very high price on the world market. In general, the total area coverage of coffee in Ethiopia is estimated to be around 800,000 ha of land with an annual production capacity of 500,000 tons which about 95% is produced by 4 million small scale farmers (Berhanu *et al.,* 2015).

Coffee is one of the most important commodities in the international agricultural trade, representing a significant source of income to several Latin America, African and Asian countries (Beer *et al*. 1998; Lin 2007; DaMatta 2004; cited in Coltri *et al*., 2015). According to the International Coffee Organization, South America is the most important coffee producing region, accounting for around 45 % of world coffee production. Brazil is by far the world's most important producer, accounting for 35 % of global production. Asia and Oceania produce around 30 % of the world's coffee, Central America (including Mexico) about 15 % and Africa10 %. Around 75 % of all coffee Brazilian production is arabica type, and Minas Gerastate is the largest *Coffea arabica* L. producer in Brazil (Coltri *et al*., 2015). The ability to measure coffee canopy structure quickly and accurately is important to understand the response of the crop to environmental factors on several scales (Ramirez and Zullo Junior 2010; Bernardes *et al*. 2012; cited in Coltri *et al*., 2015)

2.2. Production Status and Coffee Production System in Ethiopia

Ethiopia is well-known for being the home of Arabica coffee (*C. arabica*) which is highly-regarded for its very fine quality, unique aroma and flavor. The coffee types that are acclaimed for having such unique characteristics include Sidamo, Yirgachefe, Hararge, Ghimbi and Limu (Berhanu *et al.*, 2015).

In Ethiopia coffee contributes largely to the national foreign currency income and accounts for more than 35% of the total major export commodities earnings (FAO/WFP, 2008).The estimated area of land covered by coffee is about 600,000 hectares whereas the estimated annual national production of clean coffee is about 1.7 tons ha^{-1} (Alemayehu *et al*., 2008).

Jimma Zone is one of the coffee growing zones in the Oromia Regional State, which has a total area of 1,093,268 hectares of land. Currently, the total area of land covered by coffee in the zone is about 105,140 hectares, which includes small-scale farmers' holdings as well as both state and private owned plantations. Out of the 40 to 55 thousand tons of coffee annually produced in the Zone (Jzardo, 2008, cited in Techale *et al.*, 2014).

Ethiopia is the birthplace of coffee (*Coffea arabica* L.) and there exists extremely diverse genetic reserves in the mountain rainforests of southwest and south east of the country. There are four main coffee production systems in Ethiopia, namely forest, semi-forest, garden and plantation. The forest and semi-forest coffee production systems account 33% of the land covered by coffee and 25% of the annual coffee production in the country. On the other hand, the remaining two systems represent 67 and 75% of area and production of coffee of the country, respectively (Woldemariam *et al*., 2002). The contribution of forest coffee production system is dwindling as a result of deforestation (Yemane, 1998). However, the forest coffee production system is still serving as a reservoir for *Coffea arabica* genetic resource.

2.3. Climatic Factors and Environmental Requirements of Coffee

The natural habitats of all *Coffea* species are the under story of African tropical forests. Many forms of *C. canephora* can be found in the equatorial lowland forests from Guinea to Uganda, whereas natural populations of *Coffea arabica* are restricted to the highland forests of southwestern Ethiopia (Berthaud and Charrier, 1988) at altitudes of 1600-2800 m. The optimum annual rainfall range is 1200-1800 mm for Arabica coffee (Alègre, 1959). The optimum mean annual temperature range for Arabica coffee is 18-21 ºC (Alègre, 1959) Air humidity has a significant impact on the vegetative growth of the coffee tree. Robusta successfully grows under high air humidity approaching saturation, or in less humid sites, provided that the dry season is short. By contrast, Arabica coffee requires a less humid atmosphere, comparable to that of the Ethiopian highlands (Coste, 1992).

In coffee plantations subjected to large wind shears and advection, crop yield is usually depressed. Wind stress may lead to a reduction of leaf area and inter node length of the orthotropic and plagiotropic branches

2.4. Model

A model is a schematic representation of the conception of a system or an act of mimicry or a set of equations, which represents the behavior of a system. Also, a model is “A representation of an object, system or idea in some form other than that of the entity itself”. Its purpose is usually to

aid in explaining, understanding or improving performance of a system. A model is, by definition “A simplified version of a part of reality, not a one to one copy”. This simplification makes models useful because it offers a comprehensive description of a problem situation (Murthy, 2002). However, the simplification is, at the same time, the greatest drawback of the process. It is a difficult task to produce a comprehensible, operational representation of a part of reality, which grasps the essential elements and mechanisms of that real world system and even more demanding, when the complex systems encountered in environmental management (Murthy, 2002)

2.4.1. Types of Models

There are different types of models that have been developed over the years, and they can be classified into various groups or types, ranging from empirical models to explanatory models. Empirical models are based on the direct descriptions of observed data and are generally expressed as regression equations (with one or a few factors) and are used to estimate the final yield. This approach primarily examines the data, decides on an equation or set of equations and fits them to data. These models give no information on the mechanisms that give rise to the response. Examples of such models include those in agricultural experiment such as the response of crop yield to fertilizer application, the relationship between leaf area and leaf size in a given plant species and the relationship between stalk height alone or coupled with stalk number, diameter and final yield (Murthy, 2002)

Mechanistic models, explain not only the relationship between weather parameters and yield, but also the mechanism of these models (explains the relationship of influencing dependent variables). These models are based on physical selection. Static and dynamic models do not contain time as a variable even if the end products of cropping systems are accumulated over time. In contrast dynamic models explicitly incorporate time as a variable and most dynamic models are first expressed as differential equations. Deterministic models estimate the exact value of the yield or dependent variable with defined coefficients (Murthy,2002)

In Stochastic models, a probability element is attached to each output. For each set of inputs different outputs are given along with probabilities. These models define yield or state of dependent variable at a given rate. Simulation models involve Computer models with a mathematical representation of a real world system. One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management. These models use one or more sets of differential equations, and calculate both rate and state variables over time, normally from planting until harvest maturity or final harvest (Murthy, 2002).

Optimizing models have the specific objective of devising the best option in terms of management inputs for practical operation of the system. For deriving solutions, they use decision rules that are consistent with some optimizing algorithms. This forces some rigidity into their structure resulting in restrictions in representing stochastic and dynamic aspects of agricultural systems. Descriptive model defines the behavior of a system in a simple manner. The model reflects little or none of the mechanisms that are the causes of phenomena. It consists of one or more mathematical equations. An example of such an equation is the one derived from successively measured weights of a crop. The equation is helpful to determine quickly the weight of the crop where no observation is made (Kazeem and Rasaq, 2015).

Finally, explanatory models consist of quantitative description of the mechanisms and processes that cause the behavior of the system. To create this model, a system is analyzed and its processes and mechanisms are quantified separately. The model is built by integrating these descriptions for the entire system. It contains descriptions of distinct processes such as leaf area expansion (Kazeem and Rasaq, 2015).

2.4.2. What is crop Modeling

Modeling is the use of equations or sets of equations to represent the behavior of a system. In effect crop models are computer programmes that mimic the growth and development of crops (USDA, 2007 cited in Oteng-Darko *et al.,* 2013). Model simulates or imitates the behavior of a real crop by predicting the growth of its components, such as leaves, roots, stems and grains. Thus, a crop growth simulation model not only predicts the final state of crop production or

harvestable yield, but also contains quantitative information about major processes involved in the growth and development of the crop. Reactions and interactions at the level of tissues and organs are combined to form a picture of the crop's growth processes (Oteng-Darko *et al.*, 2013)

2.4.3. Crop Modeling and Simulation

To simulate means to imitate, to reproduce, and to appear similar. (Pereira, 1987 cited by Dourado-Neto *et al.*, 1998). The art of simulating is as old as man. From the origin of the civilization, man had to struggle to survive, using, even if unconsciously, simulations of real future processes to be ready for life. Simulation is, therefore, an analogy with the reality, being common in many areas. An athlete simulates during training the conditions that will prevail in the real competition; students make exercises and exams simulating their future work; pilots simulate on earth several flight conditions through the use of prototypes. In agriculture, the simulation is important to forecast the results of a certain system management or of a certain environmental condition (Wu *et al*., 1996cited by Dourado-Neto *et al.*, 1998).

2.4.4. Model Parameterization (calibration, evaluation and validation)

Model calibration involves the modification of some model parameters such that data simulated by the error free model fit the measured data. In many instances, even if a model is based on measured data, simulated values do not exactly comply with the measured data and minor adjustments have to be made for some parameters. Noncompliance may arise from sampling errors as well as from incomplete knowledge of the system. Alternatively, it may arise when the model is used in a situation that is markedly different from the one under which it was developed (Oteng-Darko*et al.*, 2013).

The model validation stage involves the confirmation that the calibrated model closely represents the real situation. The procedure consists of a comparison of simulated output and observed data that have not been previously used in the calibration stage. However, validation of all the components is not possible due to lack of detailed datasets and the option of validating only the determinant ones are adopted. For example, in a soil water crop model, it is important to validate the extractable water and leaf area components since biomass accumulated is heavily dependent on these. Evapotranspiration also becomes a determinant to validate. (Oteng-Darko *et al.*, 2013)

2.5 Growth Estimation in Crops

Allometric relationship development between growth parameters of plants are significant in ecological research and commercial purpose (Niklas, 1995; Beets *et al*., 2012). This relationship is vital to relate tree diameter at breast height to other attributes such as standing carbon stock, leaf area and other plant growth parameters. The knowledge of allometric relationship in crops is essential in growth assessment and resource optimization. The use of simple allometric model for estimating any plant growth parameters from morphological traits can enable rapid growth assessment in the field (Nyombi *et al*., 2009). Developing mathematical relations ship between growth parameters of plants and to use easily measured variables of plant growth parameters are crucial to resource management (Smith III and Whelan, 2006). A substantial number of allometric equations have been developed for trees in various climatic zones, forest types and tree species, using a variety of algebraic forms and parameter values (Ketterings *et al*. 2001).

2.6. Measurement of Leaf Area and the Aboveground Biomass of Coffee

Due to the importance of its cultivation to the world economy, studies related to coffee production have great relevance, especially for many developing countries that cultivate it (Peixoto, 1998; cited in Brinate *et al.,* 2015)

The estimation of leaf area is important in evaluating the plant growth, being a parameter widely used in agronomic and physiological studies, because of its high correlation with the light interception and photosynthetic capacity of the plants (Severino *et al.,* 2004).

There are different methods to determinate leaf area in coffee plants; however, the indirect method of measuring linear dimensions and the direct method of using leaf area integrators are most widely used in scientific researches (Antunes *et al*., 2008). Accurate, non-destructive measurements permit repeated sampling of the same plants over time and have the advantage that biological variation can be avoided. Especially when using unique plants, for example in genetically segregating populations, non-destructive measurements are of great value. A common approach for non-destructive leaf area estimation is to develop ratios and regression estimators by using easily measured leaf parameters such as length and width (Schwarz and Kläring, 2001).

The use of non-destructive methods to estimate the leaf area based on the linear dimensions of the leaves have been successfully used in *Coffea* spp. (Schmildt *et al.,* 2014; Tavares-*Júnior et al.*, 2002; Barros *et al.*, 1973; Partelli *et al.,* 2006). These methodologies have the great advantage of being able to be used in leaves still attached to the plant, allowing continuous evaluation of the plant growth (Fideles Filho *et al.,* 2010).

For Methods such as copying on graph paper, photographing, or using a planimeter, cutting the leaf is necessary, to measure the leaf area and it is destructive (Fallovo *et al.,* 2008). However, the greatest limitation of such methodology is the impossibility of taking successive measurements through time on the same leaf. Additionally, the resulting defoliation may alter other experimental measurements (Castelan-Estrada *et al*., 2002; Fallovo *et al*., 2008 Wang and Zhang, 2012; Fascella *et al*., 2013). In certain cases, when the number of leaves to be assessed is high, quantification of LA is costly in time and resources (Antunes *et al*., 2008). Non-destructive methods, such as the use of a portable scanning planimeter, can be fast and precise (Daughtry, 1990) but are only feasible on small plants with few leaves (Nyakwende *et al*., 1997). Alternatively, analysis of images using software is also fast and precise (Bignami and Rossini, 1996) but may be limited by not being user-friendly.

Biomass is the total weight or volume of organisms in a given area or volume, and also defined as the total amount of living matter on the surface of a tree and stated tones dry weight per unit area (Brown, 1997). The ability to measure coffee canopy structure quickly and accurately is important to understand the response of the crop to environmental factors on several scales (Ramirez and Zullo Junior 2010; Bernardes *et al*. 2012; cited in Coltri *et al*., 2015).

Biomass estimation is important in plants for evaluating energy usage, productivity, and ecosystem services (Cai *et al*., 2013). Plants that dominate a site, in terms of biomass, are a reflection of the plants that are controlling the nutrient, water, and solar resources on the plant. Therefore, biomass is often measured to assess the ecological status of a site. Measures of standing crop also reflect the amount of energy stored in the vegetation, which can indicate the potential productivity of the crop (Araujo *et al.,* 1999).

Tree biomass can be estimated by either destructive or non-destructive methods to reduce the need for destructive sampling, biomass can be estimated from an easily measured property such as stem diameter, by using ‘allometric’ scaling equations (Brown *et al*., 1995). A substantial number of allometric equations have been developed for trees in various climatic zones, forest types and tree species, using a variety of algebraic forms and parameter values (Ketterings *et al*., 2001).

3. MATERIALS AND METHODS

3.1. Description of Experimental Sites

The experiment was conducted at three different locations Buture, Gembe and Degalu all in Mana district of Jimma zone, Oromia Regional state, South Western Ethiopia (7°46'N, 36°0'E). This area receives adequate amount of rainfall with annual average rainfall of 1595 mm per annum. In this area, the driest season lasts between December and January. The maximum and minimum air temperature is 25.9^{o}c and 11.2^{o}c, respectively with the coldest month being December (Kufa, 2012). The experimental areas have the potential for coffee production and each location has different altitudes. The description of the locations in terms of altitude, latitude and longitude are as shown in (Table.1)

Table 1: Description of the three locations that were used in the study

No.	Location name	Altitude (m.a.l)	Longitude	Latitude	Distance from Jimma town in (km)
1	Degelu	1450	37°02'43" E	08°67'96" N	35
2	Gembe	1610	37°07'44" E	08°67'10" N	32
3	Buture	2063	37°02'50'' E	08°56'96" N	19

3.2. Experimental Materials

Eight coffee Arabica genotypes have already been established since June 01, 2012 at three different locations and during this experiment, these eight genotypes (74-1, 75-227, 74-54, 74-112, 74-140, 74-148, 74-158 and 74-165) were used in May 2016. Twenty five plants (in five rows having five plants in each row) of each genotype were planted in each plot with plot size measuring 10 m x 10 m in 2m x 2m spacing giving a density of 2500 plants per hectare and planting depth of 0.6m x 0.6m. Crop management practices were similar for all locations.

3.3. Experimental Design and Layout of the Experiment

The treatments were arranged in a randomized complete block design (RCBD) with three replications as indicated in the layout below. The treatments consist of eight *Coffea arabica* genotypes with three altitudes.

BLOCK-I	**74-112**	**74-165**	**75-227**	**74-1**	**74-140**	**74-158**	**74-148**	**74-54**
Block-II	**74-148**	**74-1**	**74-158**	**74-112**	**74-54**	**75-227**	**74-140**	**74-165**
Block-III	**74-158**	**74-140**	**74-54**	**74-148**	**74-165**	**74-112**	**75-227**	**74-1**

3.4. Sampling Method and Data Collection for Leaf Area Estimation

For model development, five individual plants were randomly taken for each coffee genotype at each location. For each individual plant, five twigs were sampled using cutting scissors. Then after, ten leaves per plants for each genotypes at each location were collected using method of Zhang and Pan, (2011). Fifty leaves were collected for each genotype per location for model development (five plants x ten leaves).

For model validation, four individual plants were randomly taken for each coffee genotype at each location. For each individual plant five twigs were sampled using cutting scissors; then after 10 leaves were cut per plant for each genotype. Forty leaves were collected for each genotype per location for model construction (four plants x ten leaves).

Totally, 1200 leaves (Fifty Leafs x eight Genotypes x three Locations) were used for model development and 960 leaves (Forty Leafs x eight Genotypes x three Locations) were used for model validation during leaf area measurements.

3.5. Measuring of Leaf Dimensions for Leaf Area Estimation

During measurement for model development and model validation, maximum leaf length from lamina tip to the point of petiole insertion along the midrib was measured using ruler with care. Leaf widths in centimeter at the widest point perpendicular to the midrib were measured for all leaves of the *Coffea arabica* genotypes using ruler (Ikbal *et al.,* 2016). We had to use leaf area

meter for measuring leaf area but the leaf area meter currently available in JUCAM is not functional and even we did not find it elsewhere in the country for measuring leaf area. For this reason we used square meter to measure leaf area. Area of each leaf were measured by drawing each leaf on square paper and the squares in each leaf was counted and the number was multiplied with the area of the square to get the leaf area(cm^2).

3.6. Model development and Validation for Leaf Area Estimation

Four linear regression models, one power model and one logarithmic model were employed for model building for leaf area estimation. Leaf length (L) and leaf width (W) dimensions and LA were those variables consider in building models. The following models (Y= aL+b, Y= aW+b, Y= aLW+b, Y= aL+bW+c, $Y = ax^b$, Y = aLnx + b) linear, power and logarithmic models were used, respectively. Where: Y=Leaf area (cm^2), L= Length (cm), W =Width (cm), a = Slope and b= intercept (cm^2).All models were run for each genotype at three locations and the best model was selected based on Statistical criteria for model selection. Coefficient of determination (R^2), standard error of estimates (SE) RMSE and CV were the Statistical criteria used for model selection method used by Walther & Moore, (2005). This criterion helps in evaluating the occurrence of bias and model precision and accuracy. The final model to estimate leaf area was selected based on the Statistical criteria for model selection. They are the combination of the highest $R^2$and the lowest root mean square error (RMSE) and root mean square error (RMSE), lowest bias of linear regressed line between observed versus predicted values from the 1:1 line and lowest coefficient of variance (CV)were determined using the following formulas.

$$\textbf{RMSE} = \sqrt{\sum_{i=1}^{n}(EstY_i - MeasYi)^2/n} \quad \textbf{(1)}$$

$$\textbf{Bias} = \sum \frac{(Yi - Yi)}{n} \quad \textbf{(2)}$$

Where ‘n’ is the number of observations, *‘Est Yi’ and ‘Meas Yi’* are the estimated and measured leaf area values of i^{th} observation. The RMSE tests the accuracy of the model which is defined as the extent to which predicted values approach a corresponding set of measured values. Beside this, coefficient of variation (CV) was also used to validate the models. CV was calculated from the following equation:

CV (%) = RMSE × 100 / x **(3)**

MSE= RMSE$^{1/2}$ **(4)**

Where ‘x’ is the mean observed values.

Equality of a set of regression models between each location for each genotype, were tested using *ANCOVA (*Analysis of Covariance*)*. When no significant differences were found, data were pooled to construct a single regression. Since applying two dimensional measurements would introduce potential problems of collinearity, which would lead to poor precision in the estimates of corresponding regression coefficients, the variance inflation factor (VIF, Marquardt 1970) and the tolerance value (T, Gill 1986) cited in (Souza, and Amaral, 2013) were calculated to detect collinearity in two-dimensional models as follows:

VIF = 1/ (1 – r^2) **(5)**

T = 1/VIF **(6),**

Where: *r* is the correlation coefficient.

If the VIF value is higher than 10 or T value (tolerance value) smaller than 0.10, consequently one of them will be excluded from the model because the impact of collinearity on the estimates of the parameters cannot be neglected (Cristofori *et al*., 2007; Fallovo *et al*., 2008).

In order to validate the selected model, estimated LA was predicted using the developed model and the slopes of the regressions between observed LA and estimated LA were tested for their significant difference from the respective of the 1:1correspondence line methods used by Dent and Blackie, (1979) cited in (Kumar and Sharma,2013).

3.7. Sampling Method and Data Collection for Branch Biomass

For model development, four individual plants were randomly for each coffee genotype at each location. Ten branches at random were taken from each randomly taken plant for each *Coffea arabica* L. genotypes and basal diameters for each branches was measured using Normand and Lauri, (2012) method. For model validation, three individual plants were randomly taken for

each genotype at each location. Five branches were random taken from randomly taken plants for each genotype and basal diameters were measured for each branch.

Totally 960 branches (40 branches x 8 genotypes x 3 locations) were used for model development and 360 branches (15 branches x 8 genotypes x three locations) were used for model validation during the experiment.

3.8. Measuring of Branch Cross-Sectional Area and Branch Biomass

Branch Basal Diameter (mm): Before cutting, two plagiotropic diameters were measured with a digital caliper at the base of the branch and the average branch basal diameter was taken. Branch basal cross-sectional area (csa) was calculated from this branch basal diameter, assuming that the area is circular methods used by Normand and Lauri, (2012).

Branch cross-sectional area = $\boldsymbol{\pi\, d^2/4}$ **(7)**

Where: *d* is the mean diameter

After cutting, branches were kept in plastic bags and rapidly brought to the laboratory. The leaves and stem of each branch separated and weighed separately. Leaves and stems were then oven-dried at 80 ° C for 72 hrs. and weighed to record their dry mass. Branch dry mass was calculated as total dry mass (stem and leaves). Hereafter, mass refers to dry mass method used by Normand and Lauri, (2012).

3.9. Model Development and Validation for Branch Biomass Estimation

Regression analysis between dependent variable (branch biomass) and independent variable (branch cross-sectional area) was carried out. One linear regression ($y = ax + b$) and two non-linear regression (power ($y = ax^b$) and logarithmic ($y = aLnx + b$)) modes were employed to build model for branch biomass estimation for *Coffea arabica* genotypes indicated above. The models were developed using branch cross-sectional area (csa) and branch biomass (BM).The three models were run for each *Coffea arabica* genotype at each location and the best model was selected based on Statistical criteria for model selection (coefficient of determination (R^2),

standard error of estimates (SE) Root Mean Square Error (RMSE) Mean Square Error (MSE) and Coefficients of Variation (CV) methods used by Walther & Moore, (2005). Equality of a set of regression models among the three locations for each genotype and among all genotypes were tested using *ANCOVA (Analysis of covariance)*. When no significant differences were found, data were pooled to construct a single regression model.

In order to validate the selected model, estimated branch weight (BW) was predicted using the developed model and the slopes of the regressions between measured BW and estimated BW were tested for their significant difference from the respective of the 1:1correspondence line.(Dent and Blackie, 1979) cited in (Kumar and Sharma, 2013).

3.10. Method of Data Analysis

All the collected data were first tested for homogeneity using Tukey's before being subjected to regression analysis and were analyzed with regression using SAS 9.3 Software. The differences in slopes and intercepts between models were tested using *ANCOVA* for testing whether two slopes and intercepts computed from two groups are significantly different.

4. RESULTS AND DISCUSSION

4.1. Models Developed for Leaf Area Estimation

Different prediction equations were obtained for estimating the LA of coffee Arabica involving two independent variables leaf length *(L)*, and leaf width (*W)*, and their product *(L×W)* were tested for estimating leaf area by using different equations (Table2 ,3 &4). Among all tested linear regression models (Y=aL+b, Y=aW+b, Y=aLW+b, Y=aL+bW+c) equations using leaf length (L), and maximum leaf width (W),Y=aLW+b had strong relationships with LA and resulted in high coefficients of determination (R^2)lowest standard error for all genotypes at all locations (Table 2,3&4). For few of the genotypes,(74-140, 74-148 and 74-54 at Buture, 74-158 and 74-54 at Degalu and 74-148 at Gembe) Y=aL+bW+c had strong relationships with Leaf Area (Table 2, 3 and 4). However, this model was neglected because there was a problem of co-linearity between L and W (VIF value was higher than 10 or/and tolerance value (T value) smaller than 0.10). Therefore, for all locations and genotypes Y=aLW+b had the most predictive power than the rest models tested to estimate leaf area of C*offea arabica* L. genotypes (Table 2, 3& 4).

Table 2. Form of model tested and their coefficient of determination (R^2), standard error of estimates (SE) root mean square error and (RMSE) and mean square error(MSE) to estimate the leaf area (LA) of eight coffee Arabica genotypes at different altitude using leaf length (L), and maximum leaf width (W) at **Buture**, where 'y' is the measured leaf area (cm^2), 'a' is the intercept, 'b' is the slope, and 'c' is the constant

Genotype	Model	SE	MSE	RMSE	R^2
	Y=aL+b	0.56910	13.95240	3.73529	0.8312
	Y=aW+b	0.74862	5.28730	2.29941	0.9360
74-112	Y=aL+bW+c	0.51896	3.15906	1.77737	0.9634
		1.10896			
	Y=aLW+b	0.01604	2.02465	1.42290	**0.9983**
	Y=aL+b	0.42239	7.38637	2.71779	0.8857
	Y=aW+b	0.91148	9.80333	3.13103	0.8484
74-165	Y=aL+bW+c	0.40908	2.47503	1.57322	0.9634
		0.76624			
	Y=aLW+b	0.02083	1.71701	1.31035	**0.9734**
	Y=aL+b	0.55133	6.67599	2.58379	0.6969
	Y=aW+b	1.55585	6.88850	2.62460	0.6873
75-225	Y=aL+bW+c	0.21823	0.84663	0.92012	0.9636
		0.60627			
	Y=aLW+b	0.02561	0.62080	0.78791	**0.9718**
	Y=aL+b	0.41041	3.94909	1.98723	0.8702
	Y=aW+b	0.82755	2.78694	1.66941	0.9084
74-1	Y=aL+bW+c	0.35445	0.90575	0.95171	0.9719
		0.85077			
	Y=aLW+b	0.01971	0.53310	0.73013	**0.9825**
	Y=aL+b	0.34057	2.53207	1.59125	0.9063
	Y=aW+b	1.45372	6.76252	2.60049	0.7497
74-140	Y=aL+bW+c	0.17348	0.34171	0.58456	**0.9881**
		0.45311			
	Y=aLW+b	0.02616	0.68556	0.82799	**0.9746**
	Y=aL+b	0.26053	2.29218	1.51399	0.9637
	Y=aW+b	1.13360	8.15289	2.85533	0.8709
74-158	Y=aL+bW+c	0.26440	0.58984	0.76801	0.*9912*
		0.61000			
	Y=aLW+b	0.01602	0.66721	0.81683	**0.9894**
	Y=aL+b	0.50099	3.81009	1.95195	0.8064
	Y=aW+b	1.72519	3.39110	1.84149	0.8277
74-148	Y=aL+bW+c	0.42795	1.26513	1.12478	**0.9403**
		1.56204			
	Y=aLW+b	0.04464	1.39954	1.18302	0.9289
	Y=aL+b	0.68468	7.21430	2.68594	0.6268
	Y=aW+b	0.76718	2.43785	1.56136	0.8739
74-54	Y=aL+bW+c	0.20182	0.43059	0.65620	**0.9790**
		0.38901			
	Y=aLW+b	0.02283	0.45444	0.67412	0.9765

Table 3. Form of model tested and their coefficient of determination (R^2), standard error of estimates (SE) root mean square error and (RMSE) and mean square error(MSE) to estimate the leaf area (LA) of eight coffee Arabica genotypes at different altitude using leaf length (L), and maximum leaf width (W) at **Degalu**, where 'y' is the measured leaf area (cm^2), 'a' is the intercept, 'b' is the slope, and 'c' is the constant.

Genotype	Model	SE	MSE	RMSE	CV	R^2
	Y=aL+b	0.67433	25.68610	5.06815	12.74186	0.8247
	Y=aW+b	0.77634	8.62340	2.93656	7.38283	0.9411
74-112	Y=aL+bW+c	0.39224 0.77937	2.88917	1.69976	4.27337	0.9813
	Y=aLW+b	0.02006	2.66309	1.63190	4.10277	**0.9818**
	Y=aL+b	0.50349	5.99308	2.44808	9.76216	0.8071
	Y=aW+b	0.97639	3.62271	1.90334	7.58993	0.8834
74-165	Y=aL+bW+c	0.23064 0.57529	0.59499	0.77136	3.07592	0.9821
	Y=aLW+b	0.01815	0.46091	0.67891	2.70726	0.9852
	Y=aL+b	0.52332	21.02033	4.58479	14.41359	0.9201
	Y=aW+b	0.43826	4.24475	2.06028	6.47707	0.9839
75-225	Y=aL+bW+c	0.75220 1.40182	3.96690	1.99171	6.26149	0.9859
	Y=aLW+b	0.00778	0.52963	0.72776	2.28791	**0.9980**
	Y=aL+b	0.49590	10.88176	3.29875	14.45553	0.8435
	Y=aW+b	0.88626	10.65887	3.26479	14.30672	0.8467
74-1	Y=aL+bW+c	0.45380 0.81946	3.59419	1.89583	8.30777	0.9506
	Y=aLW+b	0.02556	2.23524	1.49507	6.55159	0.9679
	Y=aL+b	0.29010	8.80228	2.96686	11.38840	0.9491
	Y=aW+b	0.71104	13.32293	3.65006	14.01086	0.9229
74-140	Y=aL+bW+c	0.27764 0.55312	1.66458	1.29018	4.95241	0.9908
	Y=aLW+b	0.01222	1.40914	1.18707	4.55662	**0.9918**
	Y=aL+b	0.35570	7.04992	2.65517	9.66218	0.8903
	Y=aW+b	0.68941	5.14260	2.26773	8.25229	0.9200
74-158	Y=aL+bW+c	0.30118 0.68347	1.40087	1.18358	4.30708	**0.9791**
	Y=aLW+b	0.01994	1.45664	1.20691	4.39198	0.9773
	Y=aL+b	0.45339	10.54705	3.24762	13.84528	0.7988
	Y=aW+b	1.32654	12.51075	3.53705	15.07919	0.7614
74-148	Y=aL+bW+c	0.18123 0.48686	1.09355	1.04573	4.45815	0.9801
	Y=aLW+b	0.01684	0.75342	0.86800	3.70046	**0.9856**
	Y=aL+b	0.49618	18.28722	4.27636	14.14943	0.8502
	Y=aW+b	0.43674	3.44036	1.85482	6.13715	0.9718
74-54	Y=aL+bW+c	0.34893 0.70811	2.01062	1.41796	4.69169	**0.9843**
	Y=aLW+b	0.02443	3.75733	1.93838	6.41364	0.9692

Table 4. Form of model tested and their coefficient of determination (R^2), standard error of estimates (SE) root mean square error and (RMSE) and mean square error(MSE) to estimate the leaf area (LA) of eight coffee Arabica genotypes at different altitude using leaf length (L), and maximum leaf width (W) at **Gembe**, where 'y' is the measured leaf area (cm^2), 'a' is the intercept, 'b' is the slope, and 'c' is the constant

Genotype	Model	SE	MSE	RMSE	CV	R^2
	Y=aL+b	0.58419	14.29919	3.78143	9.03186	0.8519
	Y=aW+b	1.81789	17.00191	4.12334	9.84850	0.8239
74-112	Y=aL+bW+c	0.49698	4.48719	2.11830	5.05951	0.9566
		1.41827				
	Y=aLW+b	0.02572	2.28571	1.51186	3.61104	**0.9763**
	Y=aL+b	0.85493	20.39905	4.51653	17.33377	0.5740
	Y=aW+b	0.80571	6.41729	2.53324	9.72219	0.8660
74-165	Y=aL+bW+c	0.18326	0.71254	0.84412	3.23961	0.9859
		0.30792				
	Y=aLW+b	0.01649	0.57570	0.75875	2.91197	**0.9880**
	Y=aL+b	0.60591	22.83943	4.77906	12.81357	0.8538
	Y=aW+b	0.94980	11.79019	3.43368	9.20636	0.9245
75-225	Y=aL+bW+c	0.50163	4.67332	2.16179	5.79616	0.9718
		1.09443				
	Y=aLW+b	0.02578	3.98859	1.99715	5.35473	**0.9745**
	Y=aL+b	0.63930	17.68543	4.20540	13.69142	0.7131
	Y=aW+b	1.54402	19.22816	4.38499	14.27610	0.6881
74-1	Y=aL+bW+c	0.21514	1.62029	1.27291	4.14417	0.9752
		0.49831				
	Y=aLW+b	0.02782	1.86606	1.36604	4.44737	**0.9697**
	Y=aL+b	0.94886	10.07410	3.17397	9.66692	0.7107
	Y=aW+b	1.16942	6.25428	2.50086	7.61682	0.8204
74-140	Y=aL+bW+c	0.24103	0.45018	0.67096	2.04352	0.9881
		0.37702				
	Y=aLW+b	0.01276	0.17546	0.41888	1.27579	**0.9950**
	Y=aL+b	0.31085	4.30139	2.07398	7.53698	0.9328
	Y=aW+b	0.89049	4.46002	2.11188	7.67470	0.9303
74-158	Y=aL+bW+c	0.31001	0.90416	0.95087	3.45554	0.9867
		0.87216				
	Y=aLW+b	0.01522	0.54979	0.74148	2.69458	**0.9914**
	Y=aL+b	0.72791	19.56533	4.42327	12.73487	0.8344
	Y=aW+b	0.98644	14.74855	3.84038	11.05670	0.8751
74-148	Y=aL+bW+c	0.56282	4.63761	2.15351	6.20009	**0.9631**
		0.87849				
	Y=aLW+b	0.03191	4.79200	2.18906	6.30245	0.9594
	Y=aL+b	0.84654	18.54633	4.30654	13.03656	0.7037
	Y=aW+b	1.16308	11.28951	3.35999	10.17118	0.8196
74-54	Y=aL+bW+c	0.40366	2.72202	1.64985	4.99435	0.9589
		0.71083				
	Y=aLW+b	0.03016	2.06936	1.43853	4.35464	**0.9669**

The models, power ($Y = ax^b$), logarithmic ($Y = aLnx + b$) and linear ($Y = ax + b$) models were tested. Among the three tested models (linear $Y = ax + b$) had the highest coefficients of determination R^2 and therefore, model was selected for all genotypes at all locations (Table 5,6&7). However, a better fit was achieved using L*W without intercept *(Y= a LW)* than using L*W with intercept*(Y= a LW+b)* for all of the eight *Coffea arabica* genotypes tested (Table5, 6and 7).

Table 5. Form of model tested and their coefficient of determination (R^2), to estimate Leaf Area of eight coffee Arabica genotypes at different altitude using the product of Length and Width at Buture, where 'y' is the measured leaf area (cm^2), 'a' is the slope, 'b' is the intercept, and 'x' is the independent variable.

Genotype	Model	a	B	R^2	Equation
74-112	y = ax + b	0.6742	-1.2666	**0.9813**	Y = 0.6742(x)-1.2666
	y = ax	0.6506	-	**0.9980**	Y=0.6506(x)
	y = aLnx + b	32.349	-92.732	0.9318	Y = 32.349ln(x)-92.732
	$y = ax^b$	0.619	1.0112	0.9791	$Y = 0.619(x)^{1.0112}$
74-165	y = ax + b	0.6276	71.0097	**0.9848**	Y = 0.6276(x)+71.0097
	y = ax	0.6477	-	**0.9987**	Y= 0.6477(x)
	y = aLnx + b	29.894	-83.318	0.9481	Y = 29.894ln(x)-83.318
	$y = ax^b$	0.7883	0.9479	0.9819	$Y = 0.7883(x)^{0.9479}$
75-225	y = ax + b	0.6577	-0.4412	**0.9730**	Y = 0.6577(x)-0.4412
	y = ax	0.6471		**0.9992**	Y= 0.6471(x)
	y = aLnx + b	27.018	-73.436	0.9543	Y = 27.018ln(x)-73.436
	$y = ax^b$	0.6333	1.0055	0.969	$Y = 0.6333(x)^{1.0055}$
74-1	y = ax + b	0.6117	0.9588	**0.9775**	Y = 0.6117(x)+0.9588
	y = ax	0.6347	-	**0.9991**	Y = 0.6347(x)
	y = aLnx + b	23.77	-61.769	0.9602	Y = 23.77ln(x) -61.769
	$y = ax^b$	0.7535	0.954	0.9765	$Y = 0.7535(x)^{0.954}$
74-140	y = ax + b	0.6309	0.6095	**0.9854**	Y = 0.6309(x)+0.6095
	y = ax	0.6450	-	**0.9989**	Y= 0.6450(x)
	y = aLnx + b	25.309	-66.765	0.972	Y = 25.309ln(x)-66.765
	$y = ax^b$	0.6682	0.9908	0.9804	$Y = 0.6682(x)^{0.9908}$
74-158	y = ax + b	0.6464	0.5068	**0.9682**	Y = 0.6464(x)+0.5068
	y = ax	0.6563	-	**0.9986**	Y=0.6563(x)
	y = aLnx + b	30.633	-86351	0.9465	Y = 30.633ln(x)-86351
	$y = ax^b$	0.7322	0.972	0.9664	$Y = 0.7322(x)^{0.972}$
74-148	y = ax + b	0.6065	71.293	**0.9239**	Y = 0.6065(x)+71.293
	y = ax	0.6351	-	**0.9978**	Y= 0.6351(x)
	y = aLnx + b	26.651	-72.52	0.9116	Y = 26.651ln(x)-72.52
	$y = ax^b$	0.7995	0.9564	0.9216	$Y = 0.7995(x)^{0.9564}$
74-54	y = ax + b	0.6156	0.7748	**0.9768**	Y = 0.6156(x)+0.7748
	y = ax	0.6357	-	**0.9990**	Y= 0.6357(x)
	y = aLnx + b	22.17	-56.026	0.9532	Y = 22.17ln(x) -56.026
	$y = ax^b$	0.7456	0.9563	0.9758	$Y = 0.7456(x)^{0.9563}$

Table 6. Form of model tested and their coefficient of determination (R^2), to estimate Leaf Area of eight coffee Arabica genotypes at different altitude using the product of Length and Width at **Degalu**, where 'y' is the measured leaf area (cm^2), 'a' is the slope, 'b' is the intercept, and 'x' is the independent variable.

Genotype	Model	a	b	R^2	Equation
	$y = ax + b$	0.6503	-0.8269	**0.9785**	$Y = 0.6503(x)-0.8269$
	$y = ax$	0.6380	-	**0.9987**	$Y = 0.6380(x)$
74-112	$y = aLnx + b$	39.576	-122.6	0.9544	$Y = 39.576\ln(x)-122.6$
	$y = ax^b$	0.5962	1.0157	0.9779	$Y = 0.5962(x)^{1.0157}$
	$y = ax + b$	0.5942	1.3995	**0.9806**	$Y = 0.5942(x)+1.3995$
	$y = ax$	0.6266	-	**0.9991**	$Y = 0.6266(x)$
74-165	$y = aLnx + b$	43.398	-64.257	0.9665	$Y = 43.398\ln(x)-64.257$
	$y = ax^b$	0.7621	0.9482	0.9773	$Y = 0.7621(x)^{0.9482}$
	$y = ax + b$	0.6607	-0.4945	**0.9903**	$Y = 0.6607((x)-0.4945$
	$y = ax$	0.6514	-	**0.9987**	$Y = 0.6514(x)$
75-225	$y = aLnx + b$	31.615	-89.182	0.9165	$Y = 31.615\ln(x)-89.182$
	$y = ax^b$	0.6391	1.004	0.9857	$Y = 0.6391(x)^{1.004}$
	$y = ax + b$	0.666	-0.5462	**0.9753**	$Y = 0.666(x)-0.5462$
	$y = ax$	0.6528	-	**0.9975**	$Y=0.6528(x)$
74-1	$y = aLnx + b$	24.901	-64.635	0.9235	$Y = 24.901\ln(x)-64.635$
	$y = ax^b$	0.6652	0.9933	0.9508	$Y = 0.6652(x)^{0.9933}$
	$y = ax + b$	0.6280	1.0732	**0.9891**	$Y = 0.628(x)+1.0732$
	$y = ax$	0.6503	-	**0.9982**	$Y = 0.6503(x)$
74-140	$y = aLnx + b$	26.879	-70.756	0.9574	$Y = 26.879\ln(x)-70.756$
	$y = ax^b$	0.7568	0.9613	0.9837	$Y = 0.7568(x)^{0.9613}$
	$y = ax + b$	0.6272	0.7945	**0.9898**	$Y = 0.62729x)+0.7945$
	$y = ax$	0.6442	-	**0.9988**	$Y= 0.6442(x)$
74-158	$y = aLnx + b$	25.22	-66.153	0.9628	$Y = 25.22\ln(x)-66.153$
	$y = ax^b$	0.6886	0.9829	0.9827	$Y = 0.6886(x)^{0.9829}$
	$y = ax + b$	0.6323	0.1912	**0.9865**	$Y = 0.6323(x)+0.1912$
	$y = ax$	0.6365	-	**0.9988**	$Y = 0.6365(x)$
74-148	$y = aLnx + b$	28.342	-77.998	0.9712	$Y = 28.342\ln(x)-77.998$
	$y = ax^b$	0.6181	1.0079	0.9810	$Y = 0.6181(x)^{1.0079}$
	$y = ax + b$	0.6312	0.7028	**0.9841**	$Y = 0.6312(x)+0.7028$
	$y = ax$	0.6439	-	**0.9978**	$Y= 0.6439(x)$
74-54	$y = aLnx + b$	29.692	-82.343	0.9448	$Y = 29.692\ln(x)-82.343$
	$y = ax^b$	0.67	0.9903	0.9805	$Y = 0.67(x)^{0.9903}$

Table 7. Form of model tested and their coefficient of determination (R^2), to estimate Leaf Area of eight coffee Arabica genotypes at different altitude using the product of Length and Width at **Gembe,** where 'y' is the measured leaf area (cm^2), 'a' is the slope, 'b' is the intercept, and 'x' is the independent variable.

Genotype	Model	a	b	R^2	Equation
	y = ax + b	0.6372	-0.3045	**0.9766**	Y = 0.6372(x)-0.3045
	y = ax	0.6339	-	**0.9985**	Y = 0.6339(x)
74-112	y = aLnx + b	41.096	-129.31	0.9321	Y = 41.096ln(x)-129.31
	$y = ax^b$	0.6876	0.9803	0.9704	$Y = 0.6876(x)^{0.9803}$
	y = ax + b	0.636	-0.0565	**0.9886**	Y = 0.636(x)-0.0565
	y = ax	0.6348	-	**0.9993**	Y = 0.6348(x)
74-165	y = aLnx + b	26.641	-72.013	0.9668	Y = 26.641ln(x)-72.013
	$y = ax^b$	0.6351	0.9997	0.9881	$Y = 0.6351(x)^{0.9997}$
	y = ax + b	0.6577	-0.5511	**0.9848**	Y = 0.6577(x)-0.5511
	y = ax	0.6499	-	**0.9981**	Y = 0.6499(x)
75-225	y = aLnx + b	42.081	-130.36	0.9540	Y = 42.081ln(x)-130.36
	$y = ax^b$	0.5961	0.02	0.9840	$Y = 0.5961(x)^{0.02}$
	y = ax + b	0.6516	-0.0844	**0.9784**	Y = 0.6516(x)-0.0844
	y = ax	0.6499	-	**0.9982**	Y = 0.6499(x)
74-1	y = aLnx + b	30.745	-86.382	0.9522	Y = 30.745ln(x)-86.382
	$y = ax^b$	0.6365	1.005	0.9774	$Y = 0.6365(x)^{1.005}$
	y = ax + b	0.6193	1.7383	**0.9844**	Y = 0.6193(x)+1.7383
	y = ax	0.6539	-	**0.9982**	Y = 0.6539(x)
74-140	y = aLnx + b	28.413	-76.989	0.9535	Y = 28.413ln(x)-76.989
	$y = ax^b$	0.7518	0.9654	0.9838	$Y = 0.7518(x)^{0.9654}$
	y = ax + b	0.6104	1.3566	**0.9821**	Y = 0.6104(x)+1.3566
	y = ax	0.6388	-	**0.9979**	Y = 0.6388(x)
74-158	y = aLnx + b	24.776	-64.464	0.9429	Y = 24.776ln(x)-64.464
	$y = ax^b$	0.791	0.9448	0.9754	$Y = 0.791(x)^{0.9448}$
	y = ax + b	0.6127	2.1606	**0.9722**	Y = 35.269(x)-103.89
	y = ax	0.6447	-	**0.9980**	Y= 0.6447(x)
74-148	y = aLnx + b	35.269	-103.89	0.9531	Y = 35.269ln(x)-103.89
	$y = ax^b$	0.7916	0.9515	0.960	$Y = 0.7916(x)^{0.9515}$
	y = ax + b	0.6361	0.4031	**0.9881**	Y = 0.6361(x)+0.4031
	y = ax	0.6433	-	**0.9985**	Y = 0.6433(x)
74-54	y = aLnx + b	31.839	-91.613	0.9517	Y = 31.839Ln(x)-91.613
	$y = ax^b$	0.6255	1.0069	0.9609	$Y = 0.6255(x)^{1.0069}$

Slopes of the models developed for each genotype at each location showed no significant difference (*P> 0.05*) among the genotypes (Table 8). Then the data were pooled and a single regression model was developed for each genotype at all locations (Table 8). Slopes of the models developed for each genotype at all location also showed no significant difference *P> 0.05*) among the three locations (Table8and appendix1).

Table 8.Slopes of the model (*Y=a LW)* estimating leaf area using leaf length (L) and width (W) of eight Arabica coffee genotypes at three locations, (L) and (W) in cm and Y in cm^2. Differences in slopes of the models between location and genotypes were tested using *ANCOVA*

Genotypes	**Location**	**Selected Model For Each location**		**Common Model for each genotype at all location**				
		Model Y=aLW		**Regression coefficients**				
		Slope	**R^2**	**Slope**	**RMSE**	**MSE**	**CV**	**R^2**
74-112	**Buture**	0.6506[a]	**0.9980**	0.6395[a]	1.64	2.70	4.32	**0.9983**
	Degalu	0.6380[a]	**0.9987**					
	Gembe	0.63308[a]	**0.9985**					
74-165	**Buture**	0.6471[a]	**0.9987**	0.6380[a]	1.01	1.038	3.65	**0.9995**
	Degalu	0.6266[a]	**0.9991**					
	Gembe	0.6409[a]	**0.9993**					
75-225	**Buture**	0.6471[a]	**0.9992**	0.6453[a]	1.347	1.815	4.15	**0.9995**
	Degalu	0.65136[a]	**0.9987**					
	Gembe	0.6409[a]	**0.9982**					
74-1	**Buture**	0.6347[a]	**0.9991**	0.6456[a]	1.221	1.492	4.60	**0.9993**
	Degalu	0.6528[a]	**0.9975**					
	Gembe	0.6499[a]	**0.9981**					
74-140	**Buture**	0.6429[a]	**0.9989**	0.6527[a]	1.182	1.397	4.30	**0.9992**
	Degalu	0.6536[a]	**0.9982**					
	Gembe	0.6592[a]	**0.9982**					
74-158	**Buture**	0.6563[a]	**0.9986**	0.6468[a]	1.246	1.554	4.22	**0.9993**
	Degalu	0.6442[a]	**0.9988**					
	Gembe	0.6388[a]	**0.9979**					
74-148	**Buture**	0.6351[a]	**0.9978**	0.6389[a]	1.458	2.128	4.60	**0.9993**
	Degalu	0.6365[a]	**0.9988**					
	Gembe	0.6447[a]	**0.9980**					
74-54	**Buture**	0.6357[a]	**0.9990**	0.6410[a]	1.342	1.803	4.38	**0.9994**
	Degalu	0.6474[a]	**0.9978**					
	Gembe	0.6433[a]	**0.9985**					

Values followed by different letters within a column show significant differences at (p<0.05).

All the leaf data from the eight genotypes at the three locations were pooled and a single regression model was developed for all genotypes (Table 9).Single regression model which was fitted to the combined data of all genotypes (LA = 0.6434LW) had the highest coefficient of determination (R^2) and high precision (small SE) and Root mean square Error (RMSE) (Table 9). We found that the linear regression model (LA = 0.6434LW) best predicted the leaf area in respective of locations and genotypes of the eight *Coffea arabica* genotypes (Table 9). This finding was in agreement with other finds that developed a linear model for leaf area estimation in perennial crops (Tsialtas *et al*., 2008).

Table9. Common Model for all genotypes at all location Y- Leaf area, Coefficient of determination (R^2), Standard Error (SE) and Root mean square Error(RMSE)

Model	**Regression coefficient**			**R^2**	**Equation**
Y=aLW	Slope	SE	RMSE		
	0.6434	0.0008	1.2385	**0.9993**	**Y=0.6434LW**

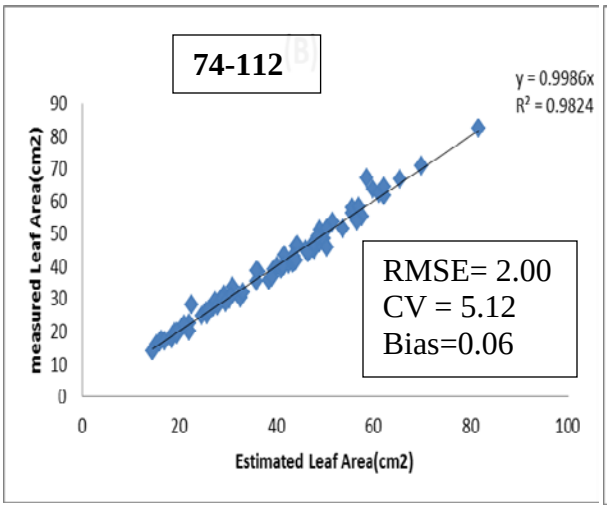
4.2. Model validation for leaf area estimation

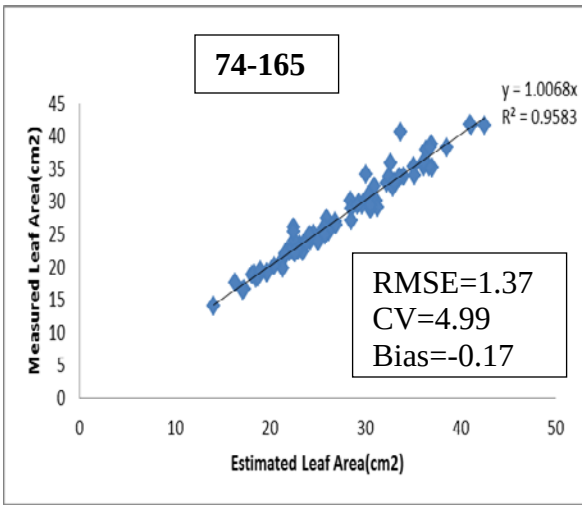
The relationship between measured LA and predicted LA using the general equation (LA = 0.6434LW) validated and had a good fit (Figure. 1) for all the eight *Coffea arabica* genotypes. No significant difference (*P>0.01*) was obtained between the slopes of the regressions between Measured Leaf Area (MLA) and Estimated Leaf Area (ELA) from the 1:1 relationship (figure 1). The leaf area estimated by the model was strongly correlated ($r = 0.99$, $P < 0.01$, $r = 0.98$, $P < 0.01$, $r = 0.99$, $P < 0.01$, $r = 0.98$, $P < 0.01$, $r = 0.99$, $P < 0.01$, $r = 0.99$, $P < 0.01$, $r = 0.98$, $P < 0.01$, $r = 0.98$, $P < 0.01$) with the measured value of leaf area for 74-112, 74-165, 75-225, 74-54, 74-1, 74-140, 74-158 and 74-148 *Coffea arabica* genotypes respectively. The model overestimated the areas of 74-112 and 74-1 with 0.17% and 0.035%, respectively and underestimated the areas of 74-165, 75-225, 74-140, 74-158, 74-148and74-54 with 0.65%,1.66%,1.47%,0.76%, 0.54% and 0.091%, respectively. The bias of estimated area from the measured area is also very small which ranges between (-0.44 to 0.06) (Figure 1) for all genotypes, showing the potential of estimating the leaf area. The findings of the present study were in agreement with many of the previous studies by Barros *et al*. (1973); cited in Antunes *et al*., 2008) for *Coffea arabica* (LA= 0.667LW); Brinate *et al*. (2015) for *Coffea canephora* Pierre ex Froehner var. Conilon LA=0.6587(LW) and LA=0.6533(LW); Muñoz *et al*. (2015), for

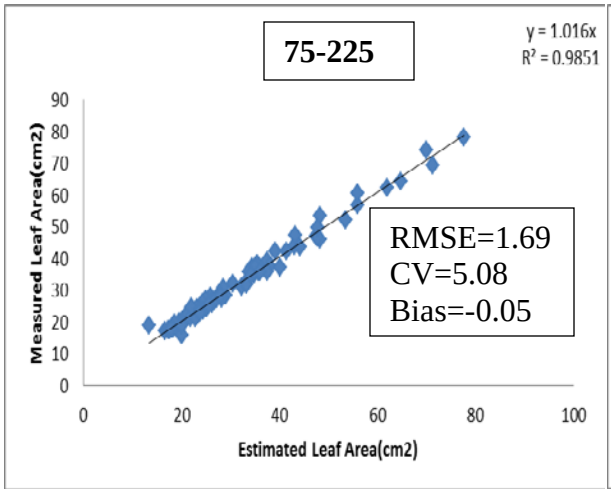
(*Coffea arabica* L.) of the Castillo LA = LW * 0.6612). Many researchers also found similar results for other crops such as Cittadini and Peri (2007) for sweet cherry LA = 0.690LW; De Swart, *et al* (2004), for *Capsicum annuum* L. LA = 0.587 (L×W); Tsialtas *et al* (2008) for grapevine LA = 0.587 (L×W).

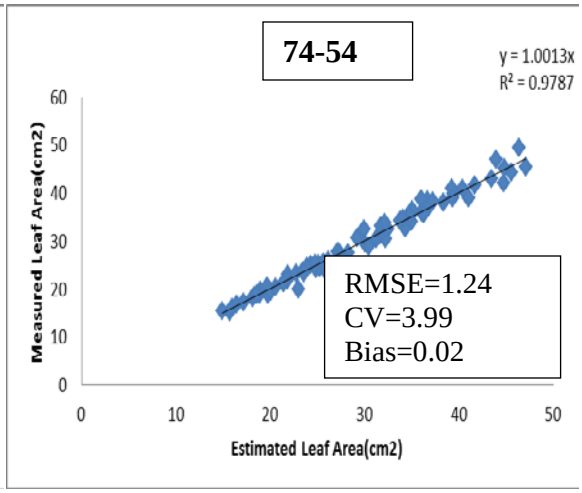
The same product of linear dimensions were also successfully used to estimate leaf area, with good accuracy and excellent precision, in different agronomic species, such as Kumar and Sharma (2010 and 2013) (LA=−3.44+0.729 LW) for saffron (*Salvia sclarea* L.) and (Y = 0.333 + 0.603LWfor Picrorhizakurroa, respectively, which depending on length multiplied by width (LW) as independent variable gave more accurate estimation of leaf area compared to other models. Many other researchers also reported that leaf area can be estimated by linear measurement such as leaf width and leaf length in plants, such as Souza and Amaral (2013) LA=0.463+0.676WL *Vernonia ferruginea*; Follavo *et al* (2008) (LA = 0.03 + 0.71 LW for raspberry, LA = 1.72 + 0.69 LW for redcurrant, LA = 0.90 + 0.70 LW for blackberry, LA = 0.58 + 0.72 LW for gooseberry, and LA = 0.54 + 0.68 LW for high bush blueberry), Cristofori, *et al*. (2007) hazelnut; Peksen (2007) for faba bean (*Vicia faba* L.) and Rivera, *et al*. (2007) for eggplant for developing simple and non-destructive models for estimating plant leaf area by using simple linear regression measurement. Also Lakshmanan and Pugazhendi, (2013) found that the best fitting equations for estimating leaf area of oleander was (LA = −22.562 + 21.209W) and (LA = −22.226 + 2.978L) with R^2=0.847 and 0.893 respectively.

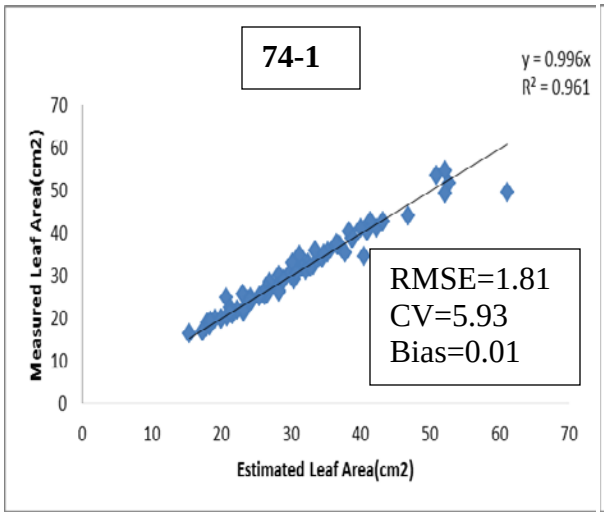
On the contrary power models was found by Antunes *et al*., 2008) LA = 0.6626 $(LW)^{1.0116}$ and Pompelli *et al*,2011), LA = 0.803 $(LW)^{0.985}$ for *Coffea arabica* L and *Jatropha curcas L* respectively, which is not in agreement with this findings.

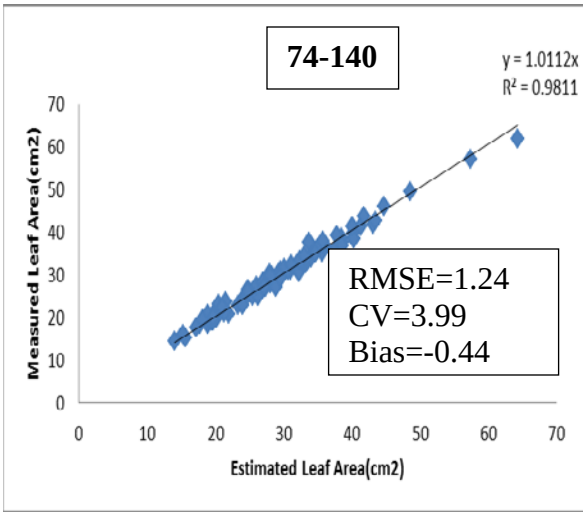

74-112
y = 0.9986x
R² = 0.9824
RMSE= 2.00
CV = 5.12
Bias=0.06
measured Leaf Area(cm2)
Estimated Leaf Area(cm2)


74-165
y = 1.0068x
R² = 0.9583
RMSE=1.37
CV=4.99
Bias=-0.17
Measured Leaf Area(cm2)
Estimated Leaf Area(cm2)


75-225
y = 1.016x
R² = 0.9851
RMSE=1.69
CV=5.08
Bias=-0.05
Measured Leaf Area(cm2)
Estimated Leaf Area(cm2)


74-54
y = 1.0013x
R² = 0.9787
RMSE=1.24
CV=3.99
Bias=0.02
Measured Leaf Area(cm2)
Estimated Leaf Area(cm2)


74-1
y = 0.996x
R² = 0.961
RMSE=1.81
CV=5.93
Bias=0.01
Measured Leaf Area(cm2)
Estimated Leaf Area(cm2)


74-140
y = 1.0112x
R² = 0.9811
RMSE=1.24
CV=3.99
Bias=-0.44
Measured Leaf Area(cm2)
Estimated Leaf Area(cm2)

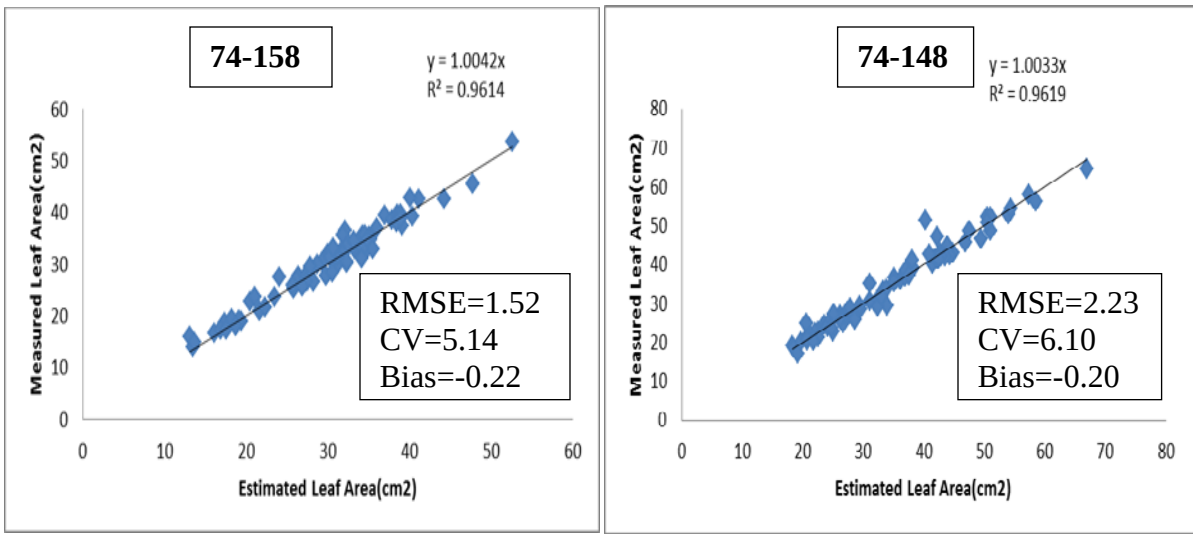


Figure 1. Plot of Estimated leaf area (ELA) using best fitted model versus Measured values of Leaf Areas (MLA) for eight *Coffea arabica* L. genotypes (See table 5, 6 and 7). Dotted lines represent the 1:1 relationship between the predicted and measured values.

4.3 Model to predict branch biomass of Coffee Arabica genotypes

Allometric equations and relationships developed using branch cross-sectional area for estimating branch biomass for eight coffee Arabica genotypes is presented (Table13).Among all tested models (linear $y = ax + b$, power $y = ax^b$, and logrithmatic $y = aLnx + b$) the linear model $y = ax + b$ had relatively good coefficients of determination R^2 (Table 10, 11, and 12).

Table 10. Form of model tested and their coefficient of determination (R^2), to estimate the branch biomass of eight coffee Arabica genotypes at different altitude using Branch cross sectional area at **Buture,** where 'y' is the measured leaf area (cm^2), 'a' is the slope, 'b' is the intercept, and 'x' is the independent variable.

Genotype	Model	A	B	R^2	Equation
74-112	$y = ax + b$	81.119	-5.7174	**0.9444**	$Y=81.199(x)-5.7174$
	$y = ax^b$	466.46	2.3184	0.9075	$Y=466.46x^{2.3184}$
	$y = aLnx + b$	10.55	26.894	0.897	$Y=10.55\ln(x)+26.894$
74-165	$y = ax + b$	86.594	-5.1028	**0.8185**	$Y=86.594(x)-5.1028$
	$y = ax^b$	381.07	2.063	0.7797	$Y=381.07x^{2.063}$
	$y = aLnx + b$	9.78	26.33	0.7815	$Y=9.78\ln x+26.33$
75-225	$y = ax + b$	99.845	-8.6704	**0.8665**	$Y=99.845(x)-8.6704$
	$y = ax^b$	493.73	2.3896	0.8619	$Y=493.73x^{2.3896}$
	$y = aLnx + b$	14.488	34.395	0.7941	$Y=14.488\ln(x)+34.395$
74-1	$y = ax + b$	69.286	-2.8499	**0.9436**	$Y=69.286(x)-2.8499$
	$y = ax^b$	83.395	1.2788	0.9430	$Y=83.395x^{1.2788}$
	$y = aLnx + b$	10.978	29.038	0.7145	$Y=10.978\ln x+29.038$
74-140	$y = ax + b$	62.146	0.5654	**0.7145**	$Y=62.146x+0.5654$
	$y = ax^b$	65.909	1.0725	0.652	$Y=65.909(x)^{1.0725}$
	$y = aLnx + b$	13.338	33.568	0.707	$Y=13.338\ln(x)+33.568$
74-158	$y = ax + b$	57.026	-0.8014	**0.9202**	$Y=57.026(x)-0.8014$
	$y = ax^b$	71.335	1.1935	0.8999	$Y=71.335(x)^{1.1935}$
	$y = aLnx + b$	11.698	29.873	0.9113	$Y=11.698\ln(x)+29.873$
74-148	$y = ax + b$	88.918	-7.0085	**0.7429**	$Y=88.918(x)-7.0085$
	$y = ax^b$	149.61	1.6853	0.7204	$Y=149.61(x)^{1.6853}$
	$y = aLnx + b$	14.389	34.049	0.6794	$Y=14.389\ln(x)+34.049$
74-54	$y = ax + b$	64.211	-5.5485	**0.875**	$Y=64.211(x)-5.5485$
	$y = ax^b$	248.5	2.1323	0.8338	$Y=248.5(x)^{2.1323}$
	$y = aLnx + b$	11.803	26.942	0.8736	$Y=11.803\ln(x)+26.942$

Table 11. Form of model tested and their coefficient of determination (R^2),) to estimate the branch biomass of eight coffee Arabica genotypes at different altitude using Branch cross sectional area at **Gembe,** where 'y' is the measured leaf area (cm^2), 'a' is the slope, 'b' is the intercept, and 'x' is the independent variable.

Genotype	Model	A	B	R^2	Equation
74-112	$y = ax + b$	75.208	-5.2013	**0.8878**	Y=75.208(x)-5.2013
	$y = ax^b$	169.19	1.7926	0.8656	$Y=169.19(x)^{1.7926}$
	y = aLnx + b	11.783	28.897	0.8513	Y==11.783ln(x)+28.897
74-165	$y = ax + b$	90.209	-51093	**0.9542**	Y=90.209(x)-51093
	$y = ax^b$	196.36	1.6844	0.933	$Y=196.36(x)^{1.6844}$
	y = aLnx + b	13.194	33.955	0.9309	Y=13.194ln(x)+33.955
75-225	$y = ax + b$	103.05	-8.4737	**0.9278**	Y=103.05(x)-8.4737
	$y = ax^b$	868.02	26.6054	0.8023	$Y=868.02(x)^{26.6054}$
	y = aLnx + b	15.224	36.366	0.8978	Y=15.224ln(x)+36.366
74-1	$y = ax + b$	69.563	-3.0572	**0.7805**	Y=69.563(x)-3.0572
	$y = ax^b$	74.917	1.262	0.7002	$Y=74.917(x)^{1.262}$
	y = aLnx + b	9.182	25.068	0.6859	Y=9.182ln(x)+25.068
74-140	$y = ax + b$	48.758	0.9697	**0.9028**	Y=48.758(x)+0.9697
	$y = ax^b$	44.198	0.8828	0.8683	$Y=44.198(x)^{0.8828}$
	y = aLnx + b	8.0828	23.983	0.8733	Y=8.0828ln(x)+23.983
74-158	$y = ax + b$	51.874	-1.3163	**0.699**	Y=51.874(x)-1.3163
	$y = ax^b$	107.45	1.4511	0.5757	$Y=107.45(x)^{1.4511}$
	y = aLnx + b	5.1634	15.85	0.6877	Y=5.1634ln(x)+15.85
74-148	$y = ax + b$	80.877	-4.2211	**0.9068**	Y=80.877(x)-4.2211
	$y = ax^b$	220.97	1.7798	0.8765	$Y=220.97(x)^{1.7798}$
	y = aLnx + b	10.668	28.577	0.8769	Y=10.668ln(x)+28.577
74-54	$y = ax + b$	67.324	-5.2564	**0.9293**	Y=67.324(x)-5.2564
	$y = ax^b$	121.08	1.7187	0.8944	$Y=121.08(x)^{1.7187}$
	y = aLnx + b	11.573	27.142	0.8613	Y=11.573ln(x)+27.142

Table 12. Form of model tested and their coefficient of determination (R^2),) to estimate the branch biomass of eight coffee Arabica genotypes at different altitude using Branch cross sectional area at **Degalu,** where 'y' is the measured leaf area (cm^2), 'a' is the slope, 'b' is the intercept, and 'x' is the independent variable.

Genotype	Model	A	B	R^2	Equation
74-112	y = ax + b	43.842	-1.0842	**0.7652**	Y=43.842(x)-1.0842
	$y = ax^b$	78.914	1.7075	0.7075	$Y=78.914(x)^{1.7075}$
	y = aLnx + b	5.4896	15.941	0.6949	Y=5.4896ln(x)+15.941
74-165	y = ax + b	47.835	-0.4633	**0.6149**	Y=47.835(x)-0.4633
	$y = ax^b$	42.253	0.9972	0.4961	$Y=42.253(x)^{0.9972}$
	y = aLnx + b	5.3191	16.708	0.53	Y=5.3191ln(x)+16.708
75-225	y = ax + b	81.35	-5.6839	**0.7662**	Y=81.35(x)-5.6839
	$y = ax^b$	187.11	1.8069	0.7309	$Y=187.11(x)^{1.8069}$
	y = aLnx + b	15.083	35.216	0.7698	Y=15.083ln(x)+35.216
74-1	y = ax + b	41.922	1.3375	**0.6707**	Y=41.922(x)+1.3375
	$y = ax^b$	30.891	0.7513	0.6364	$Y=30.891(x)^{0.7513}$
	y = aLnx + b	4.2918	15.774	0.6356	Y=4.2918ln(x)+15.774
74-140	y = ax + b	61.111	0.6904	**0.7652**	Y=61.111(x)+0.6904
	$y = ax^b$	35.802	0.7513	0.6505	$Y=35.802(x)^{0.7513}$
	y = aLnx + b	3.4274	14.125	0.6736	Y=3.4274ln(x)+14.125
74-158	y = ax + b	64.094	-0.4475	**0.7728**	Y=64.094(x)-0.4475
	$y = ax^b$	71.999	1.1032	0.7428	$Y=71.999\ (x)^{1.1032}$
	y = aLnx + b	3.6026	13.87	0.6534	Y=3.6026ln(x)+13.87
74-148	y = ax + b	109.45	-8.3483	**0.8865**	Y=109.45(x)-8.3483
	$y = ax^b$	505.18	2.2305	0.831	$Y=505.18(x)^{2.2305}$
	y = aLnx + b	16.492	39.828	0.8706	Y=16.492ln(x)+39.828
74-54	y = ax + b	62.491	-2.7002	**0.7708**	Y=62.491(x)-2.7002
	$y = ax^b$	136.94	1.6047	0.7058	$Y=136.94(x)^{1.6047}$
	y = aLnx + b	5.85	17.186	0.7102	Y=5.85ln(x)+17.186

Slopes of the models developed for each, genotypes at each location showed no significant difference among the altitudes ($p>0.05$). (See appendix4). But the intercept for 74-1, 74-140, 74-158, 74-148 and 74-54 showed significant difference ($p<0.05$) among the altitudes (Table 13 and Appendix 5). This shows the relationship of branch biomass and branch cross-sectional area for these five *Coffea arabica* genotypes differ with altitude.

To develop a single regression model for each genotype the data from all locations were pooled and a single regression model was developed (Table 14). The Slopes of the models developed for 74-112, 74-165, 74-1, 75-225, 74-140, showed no significant difference ($p>0.05$)among the genotypes, but their intercept showed significant difference ($p<0.05$) among the genotypes (Appendixes6 and 7). This result is similar with the findings of Normand and Lauri (2012) in predict vegetative growth of mango that for the three branch characteristics the cultivar had a significant effect on the y -intercept of the allometric models, but no effect on the slope. Normand and Lauri (2012) suggested that this effect resulted from differences among genotypes in the allocation of biomass within the branch and between the branch components, stem and leaves. Slopes of the models developed for 74-158, 74-148 and 74-54 genotypes were significant ($p<0.05$), but their intercept showed no significant difference ($p>0.05$) (Appendixes8).

Table 13. Slopes of the model (Y=ax+b) estimating branch biomass using branch cross-sectional area of eight genotypes of Arabica coffee at three locations. Differences in slopes and intercepts of the models between location and genotypes were tested using *ANCOVA.*

Genotype	Location	Model Y=ax+b			Common Model for each genotype at all location					
		Slope	Intercept	R^2	Slope	Intercept	MSE	RMSE	CV	R^2
74-112	Buture	81.119	-5.7174	**0.9444**	71.9678	-4.56759	1.24	1.11	20.14	**0.8760**
	Gembe	75.208	-5.2013	**0.8878**						
	Degalu	43.843	-1.0842	**0.7652**						
74-165	Buture	86.594	-5.1028	**0.8185**	81.4397	-4.20550	1.61	1.27	20.54	**0.8506**
	Gembe	90.209	-5.1093	**0.9542**						
	Degalu	47.835	-0.4633	**0.6149**						
75-225	Buture	99.845	-8.6704	**0.8665**	91.4027	-7.27587	2.80	1.67	24.52	**0.8599**
	Gembe	103.8	-8.6607	**0.9342**						
	Degalu	81.35	-5.6839	**0.7762**						
74-1	Buture	69.286	-2.8499	**0.9436**	58.8946	-1.07387	2.31	1.52	22.99	**0.8220**
	Gembe	69.563	-3.0572	**0.7805**						
	Degalu	41.922	1.3375	**0.6707**						
74-140	Buture	62.146	0.5654	**0.7145**	53.0459	0.90402	1.47	1.21	14.58	**0.9068**
	Gembe	46.018	0.9697	**0.9028**						
	Degalu	61.111	0.6904	**0.7652**						
74-158	Buture	54.026	-0.8014	**0.9202**	56.1546	-0.76202	1.35	1.16	19.34	**0.9294**
	Gembe	51.874	-1.3163	**0.699**						
	Degalu	64.094	-0.447	**0.7728**						
74-148	Buture	88.918	-7.0085	**0.7429**	83.8409	-5.03603	3.54	1.88	25.57	**0.8031**
	Gembe	80.877	-4.2211	**0.9068**						
	Degalu	109.45	-8.3483	**0.8865**						
74-54	Buture	64.211	-5.5485	**0.875**	51.5984	-2.35512	1.29	1.13	22.53	**0.8135**
	Gembe	67.324	-5.25	**0.9293**						
	Degalu	62.491	-2.7008	**0.7708**						

Data from all genotypes at all locations were pooled and a single regression model was developed. Single regression model or common model which was fitted to the combined data of all genotypes (BM=62.059x-2.0532) has smaller coefficient of determination (R^2) and low precision (high SE) in relation to the genotype-specific models (Table 5).

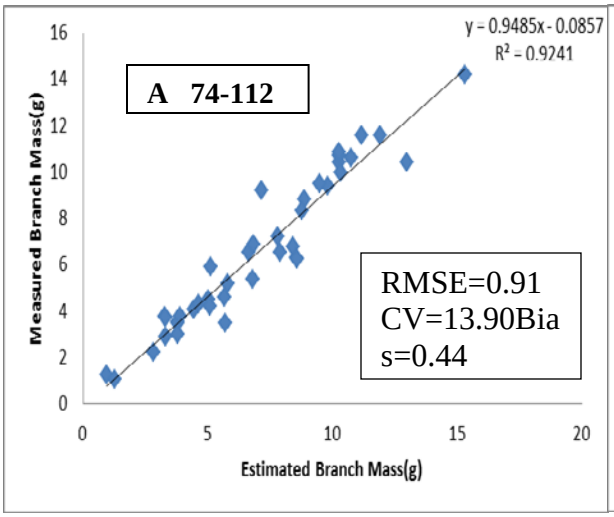
Table 14. Common Model for branch biomass estimation for all genotypes at all location

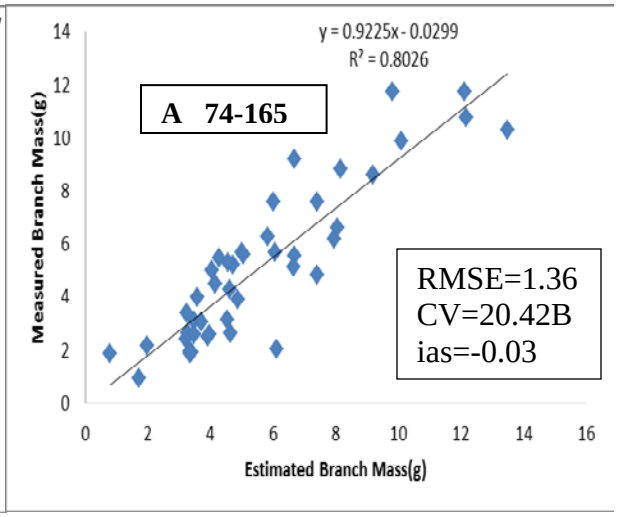
Model (Y=ax+b)			SE	RMSE	R^2	Equation
Regression coefficients	**Slope**	62.059	1.45026	1.90	**0.7605**	**BM=62.059x-2.0532**
	Intercept	-2.0532	0.21505			

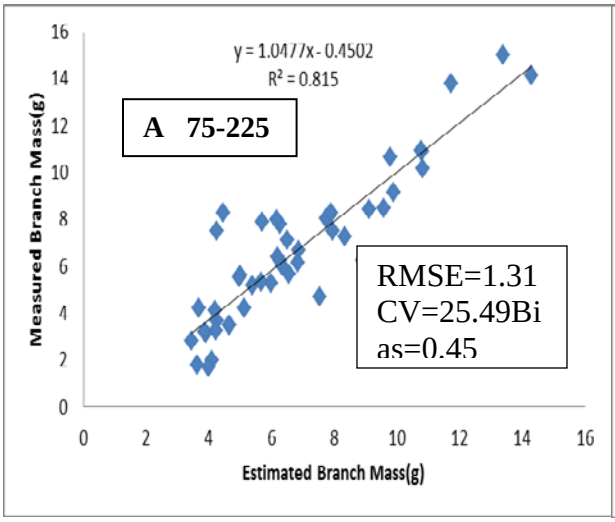
4.4. Model validation for Branch biomass estimation

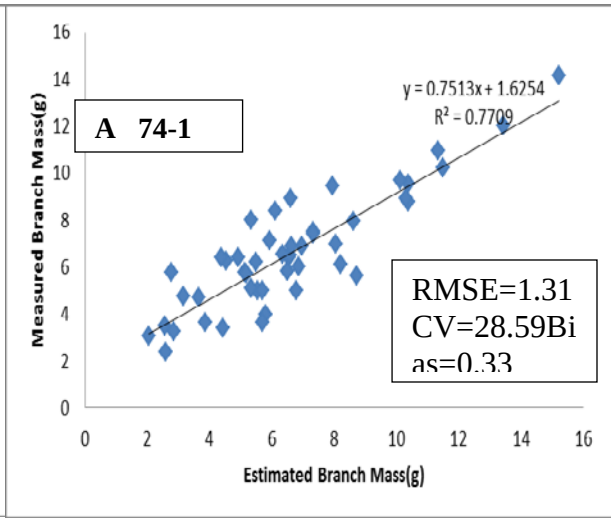
The relationship between measured branch biomass and estimated branch biomass using genotype specific and general model shows strong correlation ($r = 0.96$, for both $P < 0.01$, $r = 0.90$, for both $P < 0.01$, $r = 0.90$, for both $P < 0.01$, $r = 0.88$, for both $P < 0.01$, $r = 0.84$, for both $P < 0.01$, $r = 0.84$, for both $P < 0.01$, $r = 0.92$, for both $P < 0.01$, $r = 0.83$, for both $P < 0.01$)for 74-112, 74-165, 75-225, 74-1 ,74-140,74-158,74-148 and 74-54 genotypes respectively. No significant difference ($P>0.01$) was obtained between the slopes of the regressions between measured branch biomass and estimated branch biomass from the 1:1 relationship for all of the eight *Coffea arabica* genotypes. (Figure 2 and 3).Genotype specific models over estimates branch biomass of the six genotypes 74-112 ,74-165, 74-140,74-158, 74-148, 74-54 with 6.8%,7.8%,5.6%,4.6%, 4.8% and 6.9% respectively. But Genotype specific models developed for 75-225 and 74-1 under estimates with 0.6% and 0.3 % respectively. The general model over estimates branch biomass of all eight genotypes 74-112,74-165,75-225,74-1,74-140,74-158, 74-148, 74-54 with 20.8%,13.8%,9.2%, 4.3%,2.6%,4.6%,0.8% and 38.0% respectively.

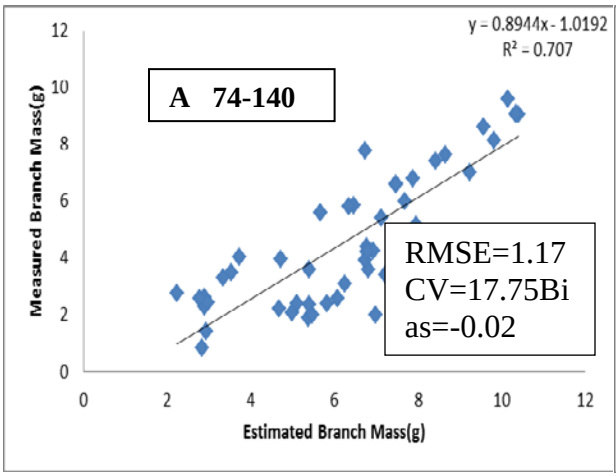
This result shows relatively good estimation of the branch biomass could be obtained for the seven genotypes 74-112,74-165, 74-140, 74-158, 74-54, 75-225 and 74-1 by using Genotype specific models but good estimation of branch biomass for 74-1,74-140,74-158, and 74-148 could be obtained by using general model. The result obtained was similar with (Segura, *et al* 2006) for shade trees and coffee bushes grown together (Grote, 2002) and Castelan-Estrada *et al*., 2002). They found linear model for vitis venifera and deciduous tree species respectively.

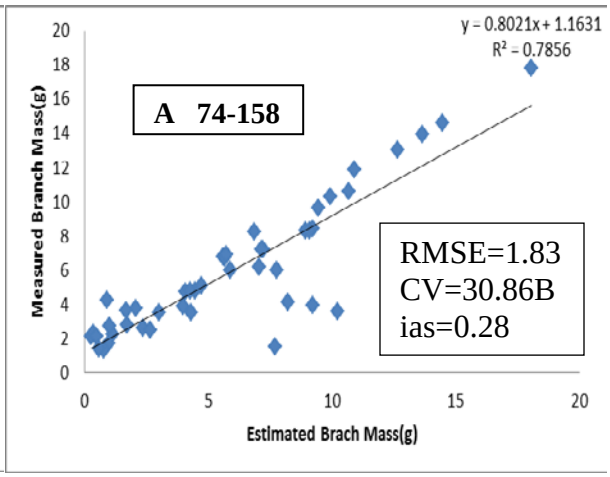

y = 0.9485x - 0.0857
R² = 0.9241
A 74-112
RMSE=0.91
CV=13.90Bias=0.44
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 0.9225x - 0.0299
R² = 0.8026
A 74-165
RMSE=1.36
CV=20.42Bias=-0.03
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 1.0477x - 0.4502
R² = 0.815
A 75-225
RMSE=1.31
CV=25.49Bias=0.45
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 0.7513x + 1.6254
R² = 0.7709
A 74-1
RMSE=1.31
CV=28.59Bias=0.33
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 0.8944x - 1.0192
R² = 0.707
A 74-140
RMSE=1.17
CV=17.75Bias=-0.02
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 0.8021x + 1.1631
R² = 0.7856
A 74-158
RMSE=1.83
CV=30.86Bias=0.28
Measured Branch Mass(g)
Estimated Brach Mass(g)

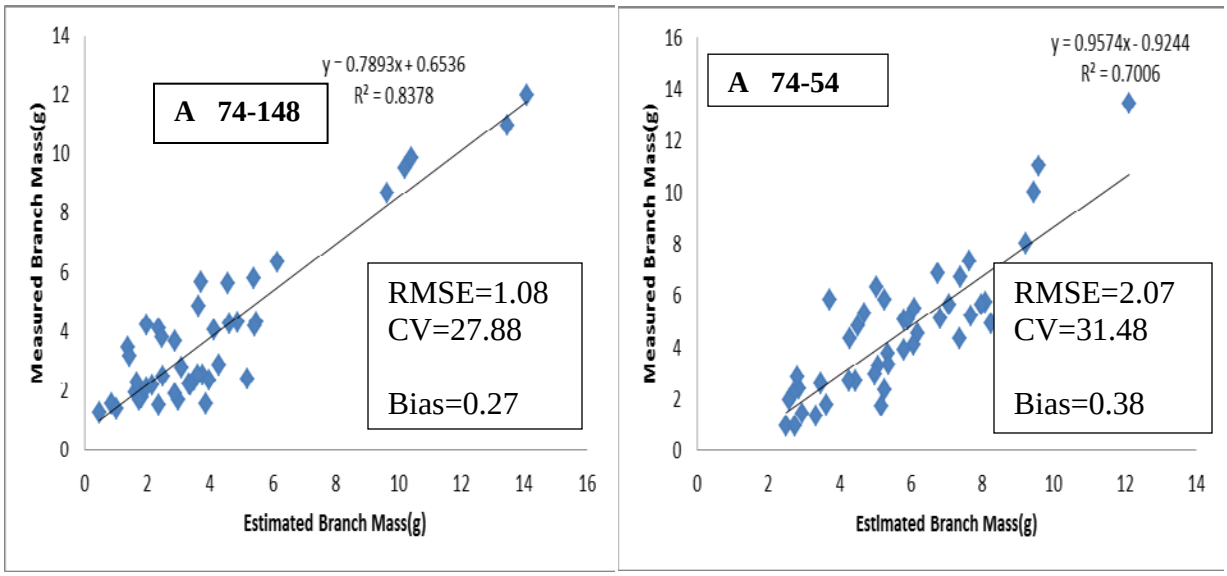
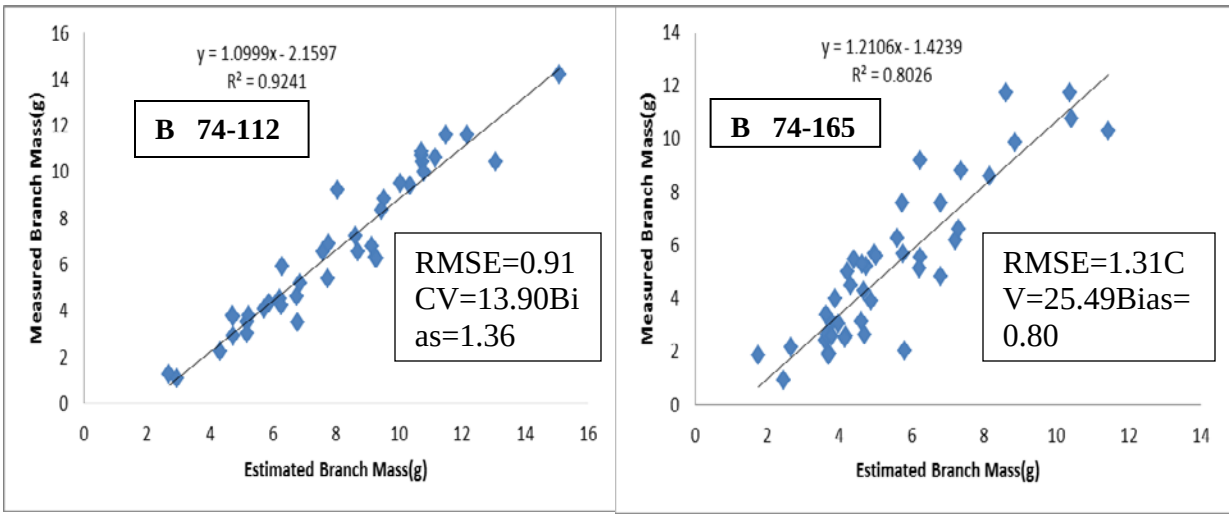
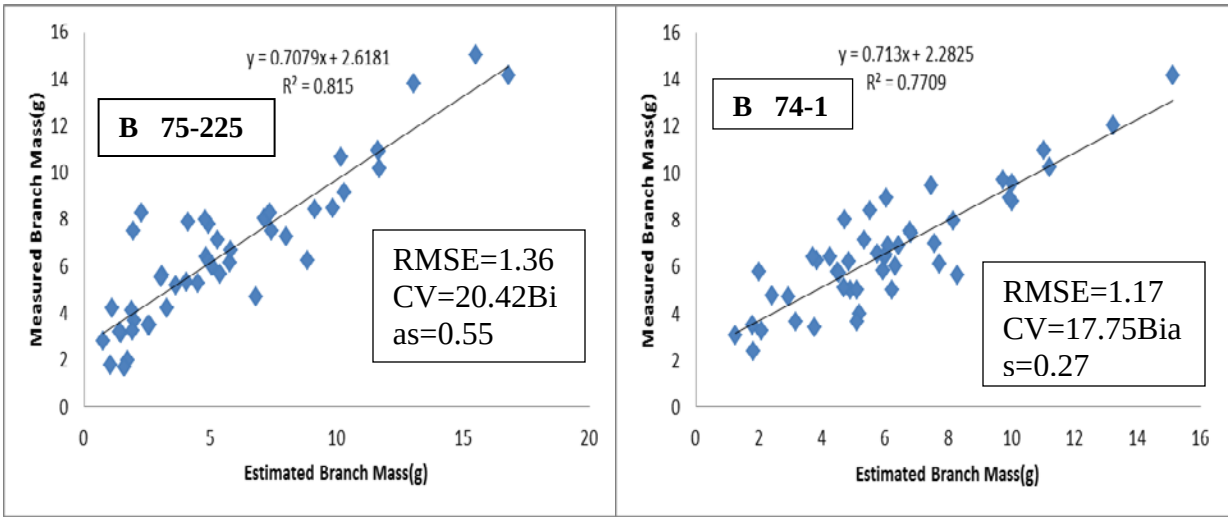
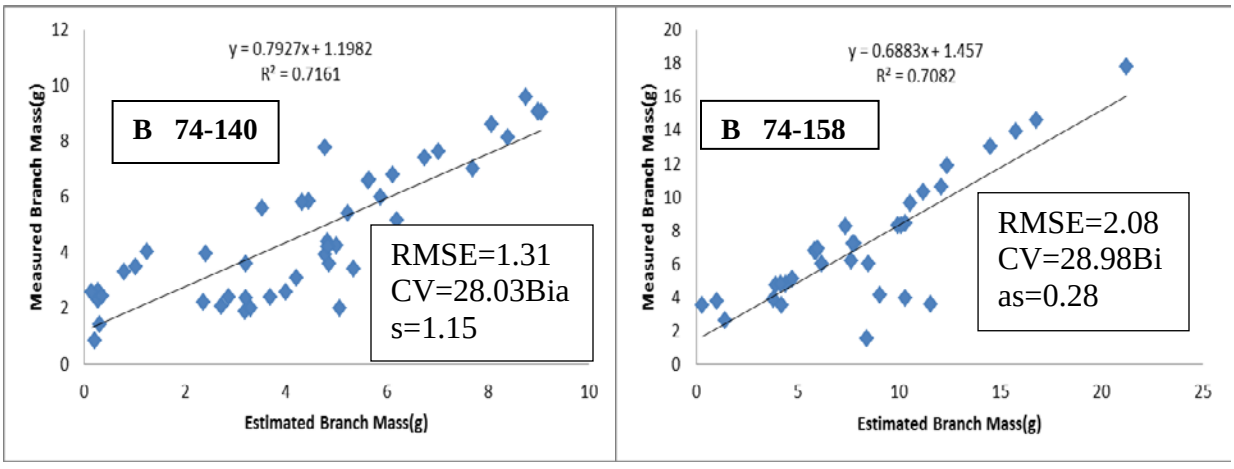


Figure 2. Plot of Predicted Branch Biomass (PBM) using (A) **Genotype Specific Model** for each genotype at all location versus measured values of Branch Biomass (MBB) for eight *Coffea arabica* L. genotypes (Table 5, 6 and 7). Dotted lines represent the 1:1 relationship between the predicted and measured values.


y = 1.0999x - 2.1597
R² = 0.9241
B 74-112
RMSE=0.91
CV=13.90Bi
as=1.36
Measured Branch Mass(g)
Estimated Branch Mass(g)
y = 1.2106x - 1.4239
R² = 0.8026
B 74-165
RMSE=1.31C
V=25.49Bias=
0.80
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 0.7079x + 2.6181
R² = 0.815
B 75-225
RMSE=1.36
CV=20.42Bi
as=0.55
Measured Branch Mass(g)
Estimated Branch Mass(g)
y = 0.713x + 2.2825
R² = 0.7709
B 74-1
RMSE=1.17
CV=17.75Bia
s=0.27
Measured Branch Mass(g)
Estimated Branch Mass(g)


y = 0.7927x + 1.1982
R² = 0.7161
B 74-140
RMSE=1.31
CV=28.03Bia
s=1.15
Measured Branch Mass(g)
Estimated Branch Mass(g)
y = 0.6883x + 1.457
R² = 0.7082
B 74-158
RMSE=2.08
CV=28.98Bi
as=0.28
Measured Branch Mass(g)
Estimated Branch Mass(g)

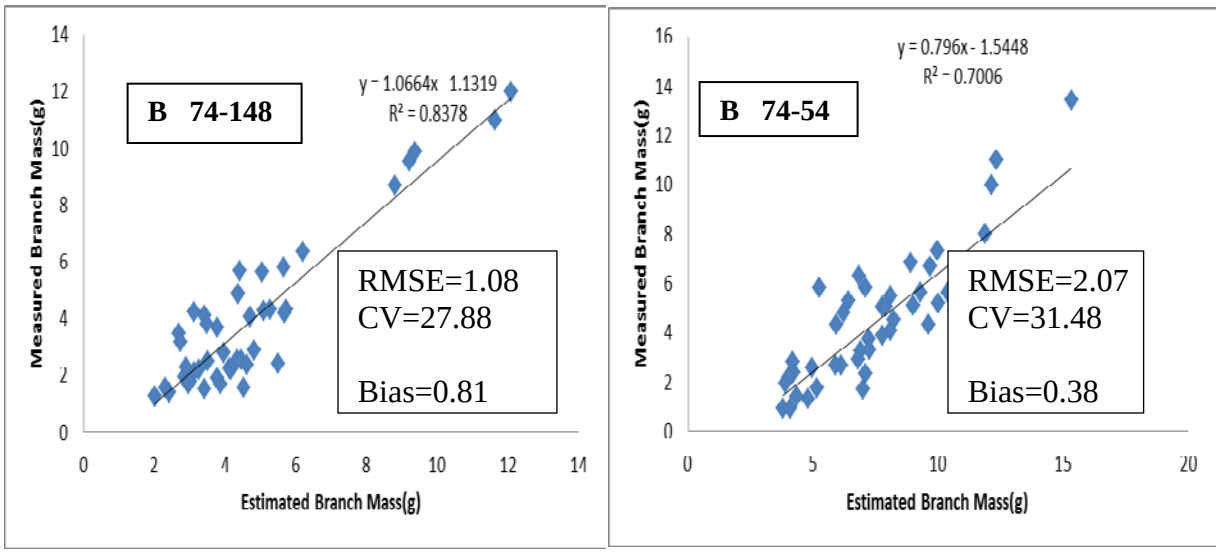


Figure 3.Plot of Predicted Branch Biomass (PBB) using Common Model for all genotypes at all location versus measured values of Branch Biomass (MBB) for eight *Coffea arabica* L. genotypes (Table 5, 6 and 7). Dotted lines represent the 1:1 relationship between the predicted and measured values.

6. SUMMARY AND CONCLUSIONS

Allometric models to predict leaf area and branch biomass were calibrated and validated for eight *Coffea arabica* genotypes from the leaf width and leaf length and from the branch cross-sectional area, respectively. From the developed models, the simple linear regression models($Y= ax+b$) were more accurate than power($Y= ax^b$) and logarithmic ($Y= alnx+b$) regression models for both leaf area and branch biomass estimation based on the model selection criteria (high $R^2$and low RMSE and low SE).

The finding revealed that the effects of growing altitude and genotype on the models were negligible for leaf area estimation but there was a significant effect of growing altitude and genotype on the models for branch biomass estimation. One common linear model ($Y = 0.6434$ LW, $R^2= 0.9993$, RMSE= 1.2387, SE =0.0008) was developed for the eight genotypes of *Coffea arabica* grown at three different altitudes for leaf area estimation. This model gave accurate estimation of leaf area of the eight genotypes of *Coffea arabica* with an over or under estimation of less than 1.7%.Therefore this model can be proposed to be reliably used and with this developed model, researchers can estimate the leaf area of newly released eight genotypes of coffee Arabica at different altitudes accurately.

In developing the models for branch biomass estimation the slopes of the models developed for the five *Coffea arabica* genotypes (74-112, 74-165, 74-1, 74-225, 74-140) showed no significant difference ($p>0.05$) among the genotypes. However, their intercept showed significant difference ($p<0.05$).Slopes of the models developed for the rest three *Coffea arabica* genotypes (74-158, 74-148 and 74-54) showed significant effect ($p<0.05$) but their intercept showed no significant difference ($p>0.05$).Therefore, genotype specific models were developed for each genotype and one general model was developed for all the eight *Coffea arabica* genotypes to estimate branch biomass. From both models the genotype specific models gave relatively more accurate estimation of branch biomass with less than 7.8% of over or under estimation. The over estimation of the general model ranges from (13 to 38%) for three (74-165, 75-225 and 74-54) *Coffea arabica* genotypes but the over or under estimation for the rest five genotypes ranges from 0.8 to 9.2%.Therefore relatively good estimation of branch biomass of all the eight *Coffea arabica* genotypes was obtained with the genotype specific model.

7. RECOMMENDATIONS

In this work, predictive models (the L–W product linear model without intercept) were developed to estimate the leaf area of eight *Coffea arabica* L. genotypes. Irrespective of genotype and growth altitude, this model can be used as an excellent and non-destructive tool for measuring leaf area of *Coffea arabica* L genotypes. This is very important especially when successive Leaf Area (LA) measurements are needed. Such models can simply and accurately estimate leaf area without the use of expensive instruments such as LA meter, digital camera, and scanner with image measurement software.

Predictive linear models developed to estimate the branch mass of eight coffee Arabica genotypes using cross sectional area of the branch, showed a good result in estimating the branch biomass of the eight coffee Arabica genotypes.

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9. APPENDIX

1. For Leaf Area

Table 1. Analysis of Covariance (ANCOVA) table for difference between slope of the models developed for Eight coffee Arabica Genotype at three locations (Pr> F) values.

Parameters	74-112	74-165	75-225	74-1	74-140	74-158	74-148	74-54
LW	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Location	0.1200	0.3178	0.1239	0.1403	0.0553	0.7821	0.5620	0.8094
LW*Location	0.4401	0.1717	0.9689	0.1177	0.8088	0.2742	0.6520	0.6475
R-Square	0.9824	0.9853	0.9893	0.9802	0.9865	0.9746	0.9813	0.9784
C.V	4.0478	3.3684	4.1155	4.3977	4.2279	4.1375	4.60483	4.4216
MSE	5.8128	2.1588	4.2426	3.2694	3.1610	3.5572	5.1719	4.4425

Table 2. Analysis of Covariance (ANCOVA) table for difference between slope between the models developed for the Eight genotypes of *coffeaarabica*(Pr> F) values.

Parameters	LW	Genotype	LW*Genotype	R-Square	C.V	MSE
	<.0001	0. 1060	0.1492	0.9840	4.2973	4.141

Appendix Table.3 Slope difference among genotypes for leaf area

Genotypes	74-112	74-165	75-225	74-1	74-140	74-158	74-148	74-54
74-112	-	0.3483	0.1341	0.4305	0.2207	0.4874	0.6614	0.8495
74-165			0.8009	0.0641	0.8237	0.8612	0.5856	0.4289
75-225				0.5865	0.2005	0.0940	0.0753	0.0922
74-1					0.0818	0.1360	0.2142	0.3172
74-140						0.7060	0.4261	0.2948
74-158							0.7442	0.5848
74-148								0.8104
74-54								-

2. For Branch Biomass.

AppendixTable.4. Analysis of Covariance (ANCOVA) table for, **Location slope** of Eight coffee Arabica Genotype of **Buture, Gembe and Degalu** (Pr> F) values.

Parameters	**74-112**	**74-165**	**75-225**	**74-1**	**74-140**	**74-158**	**74-148**	**74-54**
A	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Location	0.1900	0.3000	0.4339	0.1000	0.5437	0.7389	0.0618	0.3560
A*Location	0.1200	0.1000	0.3291	0.4500	0.1790	0.5848	0.0764	0.8490
R-Square	**0.9021**	**0.8964**	**0.8743**	**0.8747**	**0.9232**	**0.9579**	**0.85341**	**0.9054**
C.V	18.485	17.619	24.340	19.861	13.632	15.341	22.7075	16.5628
MSE	1.0504	1.1875	2.7597	1.7257	1.2924	0.8532	2.79059	0.7010

AppendixTable.5. Analysis of Covariance (ANCOVA) table for, LocationIntercept of Eight *Coffeaarabica* Genotype ofButure, Gembe and Degalu (Pr> F) values

Parameters	**74-112**	**74-165**	**75-225**	**74-1**	**74-140**	**74-158**	**74-148**	**74-54**
A	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Location	0.6805	0.1224	0.3323	0.0017	0.0094	<.0001	0.0005	<.0001
R-Square	**0.8775**	**0.8596**	**0.8671**	**0.8524**	**0.9190**	**0.9573**	**0.8418**	**0.9049**
C.V	20.344	20.204	24.4360	21.2377	13.7900	15.2418	23.2436	16.341
MSE	1.2723	1.5615	2.7816	1.9731	1.3224	0.8422	2.92390	0.6824

AppendixTable.6. Analysis of Covariance (ANCOVA) table for Eight *Coffeaarabica* Genotype of Buture, gembe and Degalu (Pr> F) values

Parameters	A	Genotype	A*Genotype	R-Square	C.V	MSE	
	<.0001	0.0001	0.0001	0. 8713	21.567	1.9702	

AppendixTable 7. Slope difference among genotype for branch biomass

Genotypes	**74-112**	**74-165**	**75-225**	**74-1**	**74-140**	**74-158**	**74-148**	**74-54**
74-112	-	0.0769	0.4465	0.1193	0.0601	<.0001	<.0001	<.0001
74-165			0.2582	0.7001	0.7201	<.0001	<.0001	<.0001
75-225				0.2055	0.2596	<.0001	<.0001	<.0001
74-1					0.1242	0.0010	<.0001	0.0098
74-140						<.0001	<.0001	<.0001
74-158							<.0001	<.0001
74-148								<.0001
74-54								-

AppendixTable 7.Intercept difference among genotype for branch biomass

Genotypes	74-112	74-165	75-225	74-1	74-140	74-158	74-148	74-54
74-112	-	<.0001	<.0001	<.0001	<.0001	0.2001	0.1400	0.1600
74-165			<.0001	0.0345	<.0001	0.2660	0.0683	0.5001
75-225				<.0001	<.0001	0.3001	0.4000	0.8000
74-1					<.0001	0.8697	0.1421	0.1000
74-140						0.8000	0.6201	0.1101
74-158							0.1940	0.1401
74-148								0.2301
74-54								-