

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

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Abstract

This study was aimed at establishing allometric models for estimating LA (Leaf Area) of eight *Coffea arabica* genotypes in Mana district of Jimma Zone Oromia Regional State, South Western Ethiopia (7°46'N, 36°0'E). Many Methodologies and instruments have been devised to facilitate measurement of leaf area. However, these methods are destructive, laborious and expensive. For modeling leaf area, leaf width, leaf length and leaf area of 1200 leaves (50 leaves for each genotype) was measured for model calibration and the respective measurements on 960 leaves were used for model validation. Linear measurement was taken from leaves and branch diameters 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. Linear and non-linear models were tested for their accuracy to predict leaf area 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. Therefore, 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 was 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. Hence, 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 *C. arabica* at different altitudes accurately.

Keywords

Coffea arabica L., Modeling, Leaf Area 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 [1]. 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 [1] [2].

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 [3] [4] [5] [6]. It strongly affects light interception, physiology as well as productivity of the plant. It also affects photosynthesis, evapotranspiration, and response to fertilizer and irrigation [4] [5] [7] [8]. Therefore, the knowledge of leaf area is vital and employed as key trait for Eco physiological and agronomic studies [4] [9] [10]. For this reason, quantifying Leaf Area is fundamental for assessing plant primary productivity [4] and as a functional component of crop modeling [11].

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 [12] and these methods may or may not be destructive [13]). 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 [11]. 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 [6] [10] [12] [14]. In certain cases, when the number of leaves to be assessed is high, quantification of LA is costly in time and resources [7]. Non-destructive methods, such as the use of a portable scanning planimeter, can be fast and precise [15] but are only feasible on small plants with few leaves [16]. Alternatively, analysis of images using software is also fast and precise [17] but may be limited by not being user-friendly.

An essential aspect of studies on plant growth and reproduction is the accu-

rate 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 [9]. These models are based on statistical relationships between a key variable of interest and one or several variables that are easy to measure [18]. 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 [19].

Allometric models have mainly been developed for their application for *Coffea 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 has been developed by many authors and for different coffee genotypes such [7] coffee (*Coffea arabica* and *Coffea canephora*), [20] for genotypes of conilon coffee and [21] (*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 [22]. 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 Coffee 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 to develop simple and reliable model for nondestructive leaf area estimation of eight *Coffea arabica* L. genotypes grown at three different altitudes of Mana District, Jimma Zone.

2. Materials and Methods

2.1. 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°C and 11.2°C, respectively with the coldest month being December [23]. 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

2.2. 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 × 10 m in 2 m × 2 m spacing giving a density of 2500 plants per hectare and planting depth of 0.6 m × 0.6 m. Crop management practices were similar for all locations.

2.3. 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

2.4. Sampling Method and Data Collection

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 genotype at each location were collected using method of [5]. Fifty leaves were collected for each genotype per location for model development (five plants × 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 × ten leaves).

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

2.5. Measuring of Leaf Dimensions

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 [13]. 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 (cm²).

2.6. Model Development and Validation

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 (cm²), L = Length (cm), W = Width (cm), a = Slope and b = intercept (cm²). 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 [24]. 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.

$$RMSE = \sqrt{\sum_{i=1}^n (Y_i - Y_o)^2 / n} \quad (1)$$

$$Bias = \sum \frac{(Y_i - Y_o)}{n} \quad (2)$$

where “n” is the number of observations, “ Y_i ” and “ Y_o ” 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:

$$CV(\%) = RMSE \times 100/x \quad (3)$$

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

where “x” is the mean observed values.

Equality of a set of regression models between each location for each geno-

type, 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 [25] were calculated to detect collinearity in two-dimensional models as follows:

$$VIF = 1/(1 - r^2) \quad (5)$$

$$T = 1/VIF \quad (6)$$

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 [2] [26].

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 1:1 correspondence line methods used by (Dent and Blackie, 1979 cited in [27]).

2.7. 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.

3. Results and Discussion

3.1. 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 ($L \times W$) were tested for estimating leaf area by using different equations. 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. 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. 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 *Coffea arabica* L. genotypes.

The models, power ($Y = ax^b$), logarithmic ($Y = a\ln x + b$) 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 (**Tables 2-4**). However, a better fit was achieved using $L * W$ without intercept ($Y = aLW$) than using $L * W$ with intercept ($Y = aLW + b$) for all of the eight *Coffea arabica* genotypes tested (**Tables 2-4**).

Table 2. 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	$Y = 0.6506(x)$
	$y = a\ln x + b$	32.349	-92.732	0.9318	$Y = 32.349\ln(x) - 92.732$
	$y = ax^b$	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	$Y = 0.6477(x)$
	$y = a\ln x + b$	29.894	-83.318	0.9481	$Y = 29.894\ln(x) - 83.318$
	$y = ax^b$	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	$Y = 0.6471(x)$
	$y = a\ln x + b$	27.018	-73.436	0.9543	$Y = 27.018\ln(x) - 73.436$
	$y = ax^b$	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	$Y = 0.6347(x)$
	$y = a\ln x + b$	23.77	-61.769	0.9602	$Y = 23.77\ln(x) - 61.769$
	$y = ax^b$	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	$Y = 0.6450(x)$
	$y = a\ln x + b$	25.309	-66.765	0.972	$Y = 25.309\ln(x) - 66.765$
	$y = ax^b$	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	$Y = 0.6563(x)$
	$y = a\ln x + b$	30.633	-86351	0.9465	$Y = 30.633\ln(x) - 86351$
	$y = ax^b$	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	$Y = 0.6351(x)$
	$y = a\ln x + b$	26.651	-72.52	0.9116	$Y = 26.651\ln(x) - 72.52$
	$y = ax^b$	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	$Y = 0.6357(x)$
	$y = a\ln x + b$	22.17	-56.026	0.9532	$Y = 22.17\ln(x) - 56.026$
	$y = ax^b$	0.7456	0.9563	0.9758	$Y = 0.7456(x)^{0.9563}$

Table 3. 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
74-112	$y = ax + b$	0.6503	-0.8269	0.9785	$Y = 0.6503(x) - 0.8269$
	$y = ax$	0.6380	-	0.9987	$Y = 0.6380(x)$
	$y = a\text{Ln}x + b$	39.576	-122.6	0.9544	$Y = 39.576\ln(x) - 122.6$
	$y = ax^b$	0.5962	1.0157	0.9779	$Y = 0.5962(x)^{1.0157}$
74-165	$y = ax + b$	0.5942	1.3995	0.9806	$Y = 0.5942(x) + 1.3995$
	$y = ax$	0.6266	-	0.9991	$Y = 0.6266(x)$
	$y = a\text{Ln}x + b$	43.398	-64.257	0.9665	$Y = 43.398\ln(x) - 64.257$
	$y = ax^b$	0.7621	0.9482	0.9773	$Y = 0.7621(x)^{0.9482}$
75-225	$y = ax + b$	0.6607	-0.4945	0.9903	$Y = 0.6607(x) - 0.4945$
	$y = ax$	0.6514	-	0.9987	$Y = 0.6514(x)$
	$y = a\text{Ln}x + b$	31.615	-89.182	0.9165	$Y = 31.615\ln(x) - 89.182$
	$y = ax^b$	0.6391	1.004	0.9857	$Y = 0.6391(x)^{1.004}$
74-1	$y = ax + b$	0.666	-0.5462	0.9753	$Y = 0.666(x) - 0.5462$
	$y = ax$	0.6528	-	0.9975	$Y = 0.6528(x)$
	$y = a\text{Ln}x + b$	24.901	-64.635	0.9235	$Y = 24.901\ln(x) - 64.635$
	$y = ax^b$	0.6652	0.9933	0.9508	$Y = 0.6652(x)^{0.9933}$
74-140	$y = ax + b$	0.6280	1.0732	0.9891	$Y = 0.628(x) + 1.0732$
	$y = ax$	0.6503	-	0.9982	$Y = 0.6503(x)$
	$y = a\text{Ln}x + b$	26.879	-70.756	0.9574	$Y = 26.879\ln(x) - 70.756$
	$y = ax^b$	0.7568	0.9613	0.9837	$Y = 0.7568(x)^{0.9613}$
74-158	$y = ax + b$	0.6272	0.7945	0.9898	$Y = 0.62729(x) + 0.7945$
	$y = ax$	0.6442	-	0.9988	$Y = 0.6442(x)$
	$y = a\text{Ln}x + b$	25.22	-66.153	0.9628	$Y = 25.22\ln(x) - 66.153$
	$y = ax^b$	0.6886	0.9829	0.9827	$Y = 0.6886(x)^{0.9829}$
74-148	$y = ax + b$	0.6323	0.1912	0.9865	$Y = 0.6323(x) + 0.1912$
	$y = ax$	0.6365	-	0.9988	$Y = 0.6365(x)$
	$y = a\text{Ln}x + b$	28.342	-77.998	0.9712	$Y = 28.342\ln(x) - 77.998$
	$y = ax^b$	0.6181	1.0079	0.9810	$Y = 0.6181(x)^{1.0079}$
74-54	$y = ax + b$	0.6312	0.7028	0.9841	$Y = 0.6312(x) + 0.7028$
	$y = ax$	0.6439	-	0.9978	$Y = 0.6439(x)$
	$y = a\text{Ln}x + b$	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 4. 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
74-112	$y = ax + b$	0.6372	-0.3045	0.9766	$Y = 0.6372(x) - 0.3045$
	$y = ax$	0.6339	-	0.9985	$Y = 0.6339(x)$
	$y = a\ln x + b$	41.096	-129.31	0.9321	$Y = 41.096\ln(x) - 129.31$
	$y = ax^b$	0.6876	0.9803	0.9704	$Y = 0.6876(x)^{0.9803}$
74-165	$y = ax + b$	0.636	-0.0565	0.9886	$Y = 0.636(x) - 0.0565$
	$y = ax$	0.6348	-	0.9993	$Y = 0.6348(x)$
	$y = a\ln x + b$	26.641	-72.013	0.9668	$Y = 26.641\ln(x) - 72.013$
	$y = ax^b$	0.6351	0.9997	0.9881	$Y = 0.6351(x)^{0.9997}$
75-225	$y = ax + b$	0.6577	-0.5511	0.9848	$Y = 0.6577(x) - 0.5511$
	$y = ax$	0.6499	-	0.9981	$Y = 0.6499(x)$
	$y = a\ln x + b$	42.081	-130.36	0.9540	$Y = 42.081\ln(x) - 130.36$
	$y = ax^b$	0.5961	0.02	0.9840	$Y = 0.5961(x)^{0.02}$
74-1	$y = ax + b$	0.6516	-0.0844	0.9784	$Y = 0.6516(x) - 0.0844$
	$y = ax$	0.6499	-	0.9982	$Y = 0.6499(x)$
	$y = a\ln x + b$	30.745	-86.382	0.9522	$Y = 30.745\ln(x) - 86.382$
	$y = ax^b$	0.6365	1.005	0.9774	$Y = 0.6365(x)^{1.005}$
74-140	$y = ax + b$	0.6193	1.7383	0.9844	$Y = 0.6193(x) + 1.7383$
	$y = ax$	0.6539	-	0.9982	$Y = 0.6539(x)$
	$y = a\ln x + b$	28.413	-76.989	0.9535	$Y = 28.413\ln(x) - 76.989$
	$y = ax^b$	0.7518	0.9654	0.9838	$Y = 0.7518(x)^{0.9654}$
74-158	$y = ax + b$	0.6104	1.3566	0.9821	$Y = 0.6104(x) + 1.3566$
	$y = ax$	0.6388	-	0.9979	$Y = 0.6388(x)$
	$y = a\ln x + b$	24.776	-64.464	0.9429	$Y = 24.776\ln(x) - 64.464$
	$y = ax^b$	0.791	0.9448	0.9754	$Y = 0.791(x)^{0.9448}$
74-148	$y = ax + b$	0.6127	2.1606	0.9722	$Y = 0.6127(x) + 2.1606$
	$y = ax$	0.6447	-	0.9980	$Y = 0.6447(x)$
	$y = a\ln x + b$	35.269	-103.89	0.9531	$Y = 35.269\ln(x) - 103.89$
	$y = ax^b$	0.7916	0.9515	0.960	$Y = 0.7916(x)^{0.9515}$
74-54	$y = ax + b$	0.6361	0.4031	0.9881	$Y = 0.6361(x) + 0.4031$
	$y = ax$	0.6433	-	0.9985	$Y = 0.6433(x)$
	$y = a\ln x + b$	31.839	-91.613	0.9517	$Y = 31.839\ln(x) - 91.613$
	$y = ax^b$	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 5**). Then the data were pooled and a single regression model was developed for each genotype at all locations (**Table 6**). Slopes of the models developed for each genotype at all location also showed no significant difference ($P > 0.05$) among the three locations.

Table 5. Slopes of the model ($Y = aLW$) 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		Regression coefficients				
		$Y = aLW$						
		Slope	R^2	Slope	RMSE	MSE	CV	R^2
74-112	Buture	0.6506 ^a	0.9980					
	Degalu	0.6380 ^a	0.9987	0.6395 ^a	1.64	2.70	4.32	0.9983
	Gembe	0.63308 ^a	0.9985					
74-165	Buture	0.6471 ^a	0.9987					
	Degalu	0.6266 ^a	0.9991	0.6380 ^a	1.01	1.038	3.65	0.9995
	Gembe	0.6409 ^a	0.9993					
75-225	Buture	0.6471 ^a	0.9992					
	Degalu	0.65136 ^a	0.9987	0.6453 ^a	1.347	1.815	4.15	0.9995
	Gembe	0.6409 ^a	0.9982					
74-1	Buture	0.6347 ^a	0.9991					
	Degalu	0.6528 ^a	0.9975	0.6456 ^a	1.221	1.492	4.60	0.9993
	Gembe	0.6499 ^a	0.9981					
74-140	Buture	0.6429 ^a	0.9989					
	Degalu	0.6536 ^a	0.9982	0.6527 ^a	1.182	1.397	4.30	0.9992
	Gembe	0.6592 ^a	0.9982					
74-158	Buture	0.6563 ^a	0.9986					
	Degalu	0.6442 ^a	0.9988	0.6468 ^a	1.246	1.554	4.22	0.9993
	Gembe	0.6388 ^a	0.9979					
74-148	Buture	0.6351 ^a	0.9978					
	Degalu	0.6365 ^a	0.9988	0.6389 ^a	1.458	2.128	4.60	0.9993
	Gembe	0.6447 ^a	0.9980					
74-54	Buture	0.6357 ^a	0.9990					
	Degalu	0.6474 ^a	0.9978	0.6410 ^a	1.342	1.803	4.38	0.9994
	Gembe	0.6433 ^a	0.9985					

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

Table 6. 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	0.9993	Y = 0.6434LW
	0.6434	0.0008	1.2385		

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 6). 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 6). 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 6). This finding was in agreement with other finds that developed a linear model for leaf area estimation in perennial crops [28].

3.2. Model Validation

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, 74-148 and 74-54 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 [7] for *Coffea arabica* ($LA = 0.667LW$); [21] for *Coffea canephora* Pierre ex Froehner var. Conilon $LA = 0.6587 (LW)$ and $LA = 0.6533 (LW)$; [22], for (*Coffea arabica* L.) of the Castillo $LA = LW * 0.6612$). Many researchers also found similar results for other crops such as [29] for sweet cherry $LA = 0.690LW$; [30], for *Capsicum annum* L. $LA = 0.587 (L \times W)$; [28] for grapevine $LA = 0.587(L \times W)$.

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 [27] Kumar and Sharma (2010 and 2013) ($LA = -3.44 + 0.729LW$) for saffron (*Salvia sclarea* L.) and ($Y = 0.333 + 0.603LW$ for Picrorhizakurroa, respectively, which depending on length multiplied by width (LW) as

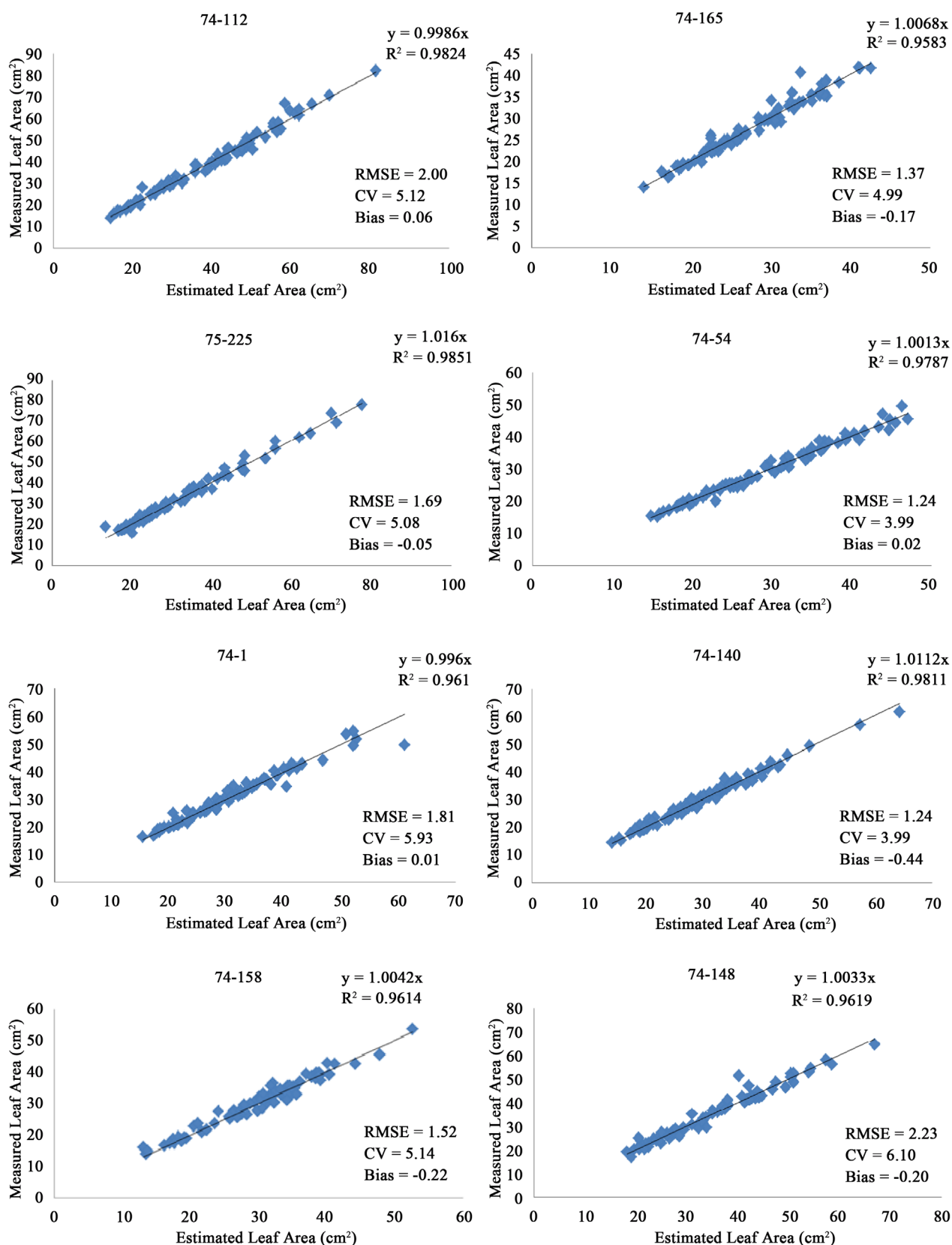


Figure 1. Plot of Estimated Leaf area (ELA) using best fitted model versus measured values of Leaf Areas (MLA) for eight *Coffea arabica* L. genotypes (See **Tables 5-7**). Dotted lines represent the 1:1 relationship between the predicted and measured values.

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 [25] $LA = 0.463 + 0.676WL$ *Vernonia ferruginea*; [12] $(LA = 0.03 + 0.71LW$ for raspberry, $LA = 1.72 + 0.69LW$ for redcurrant, $LA = 0.90 + 0.70LW$ for blackberry, $LA = 0.58 + 0.72LW$ for gooseberry, and $LA = 0.54 + 0.68LW$ for high bush blueberry, [27] hazelnut; [31] for faba bean (*Vicia faba* L.) and [32] for eggplant for developing simple and non-destructive models for estimating plant leaf area by using simple linear regression measurement. Also [33] 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 [7] $LA = 0.6626(LW)^{1.0116}$ and [34], $LA = 0.803 (LW)^{0.985}$ for *Coffea arabica* L and *Jatropha curcas* L respectively, which is not in agreement with this findings.

4. Summary and Conclusions

Allometric models to predict leaf area were calibrated and validated for eight *Coffea arabica* genotypes from the leaf width and leaf length. From the developed models, the simple linear regression models ($Y = ax + b$) were more accurate than power ($Y = ax^b$) and logarithmic ($Y = a \ln x + b$) regression models for leaf area 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. 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 *Coffea arabica* at different altitudes accurately. Allometric model for leaf area estimation for the rest *Coffea arabica* genotypes should be investigated.

5. 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.

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