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Biomass Prediction Equation for *Colophospermum mopane* (Mopane) in Botswana

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Abstract

This study aimed to develop a biomass equation for estimating the total above-ground biomass for *Colophospermum mopane* (mopane) based on the pooled data from three study sites. The mopane woodlands in Botswana represent 14.6% of Botswana's total area. The woodlands directly or indirectly support the livelihood of the majority of the rural population by providing wood and non-wood products. However, there is limited information on the pattern, trends and distribution of woody biomass production and their primary, environmental, and climatic determinants in different parts of Botswana. All the data were collected by destructive sampling from three study sites in Botswana. Stratified random sampling was based on the stem diameter at breast height (1.3 m from the ground or Diameter at Breast Height (DBH)). A total of 30 sample trees at each study site were measured, felled and weighed. The data from the three sites were pooled together, and the study employed regression analysis to examine the nature of relationships between total above-ground biomass (dependent variable) and five independent variables: 1) total tree height; 2) crown diameter; 3) stem diameters at 0.15 m; 1.3 m (DBH) and 3 m from the ground respectively. There were significant relationships between all the independent variables and the dependent variable. However, DBH emerged as the strongest predictor of total tree above-ground biomass for mopane. The equation $\ln Biomass = -1.163 + 2.190 \ln DBH$ was adopted for use in the indirect estimation of total tree above-ground biomass for mopane in Botswana.

Keywords

Botswana, *Colophospermum mopane*, Crown Diameter, Stem Diameter,

Total Above-Ground Biomass

1. Introduction

Colophospermum mopane (Kirk ex Benth) Kirk ex J. Léonard Syn *Copaifera mopane* commonly known as mopane is the only species in the genus *Colophospermum*, which belongs to the Detarieae tribe of the sub-family Caesalpinioideae in the Fabaceae (Leguminosae) family (Mapaure, 1994; Timberlake, 1995). Other sub-families in the family are the Mimosoideae and the Papilionoideae. At the same time, Timberlake (1995) states that the generic name comes from the Greek word meaning "resinous seed", an illusion of the numerous scattered resin glands that cover the seeds while De Winter et al. (1966) state that the word comes from the Greek word meaning "seeds inhabiting the light".

Mopane is indigenous to Southern Africa, where it is found in Angola, Botswana, Malawi, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe. The natural range of mopane woodland is distributed in the low-lying areas of southern Africa's savannahs between latitudes 9˚S and 25˚S (Makhado et al., 2018). The mopane woodland covers an area of about 550,000 km^2, about 35% of the total area of 1.5 million km^2 of savannah woodlands in southern Africa (Makhado et al., 2014; Makhado et al., 2018). The mopane woodlands in Botswana are 85,000 km^2, representing 14.6% of Botswana's total area of 581,730 km^2 (Teketay et al., 2018).

The phenomenon of mopane occurring in both tree and shrub forms is well known. When made up of very tall trees reaching heights of 16 - 20 m, it is colloquially termed "cathedral mopane" (Palgrave, 2002; Timberlake, 1995). This type is generally found on old and deep clay-rich alluvium. When soil conditions are not favourable, and the plants remain stunted (2 - 6 m), such as on many *karoo* sediments and on sodium-rich or on cracking clays, the mopane vegetation is referred to as "mopane scrub" (Palgrave, 2002; Timberlake, 1995). Although mopane is a halophytic plant within its range in southern Africa (Henning & White, 1974), it will grow best in areas where there are no physical and chemical constraints (Lewis, 1991). Under these conditions, however, competing species are favoured and may exclude mopane. On the other hand, where soils have restricted rooting depth, high sodium content, low infiltration rates, and high-water holding capacity, mopane tends to dominate (Lewis, 1991; Mlambo, Nyathi, & Mapaure, 2005).

There are three distinct structural forms of mopane in Botswana, where it occurs: 1) mopane woodland with tall and large trees of up to 20 m high, which are usually found in the deep soils in the northern part of the country and on the periphery of the Okavango delta where non-alkaline freely drained sandy soils overlie medium textured sub-soils of higher water holding capacity; 2) mopane savannah with small to medium-sized trees usually ranging between 5 and 12 m tall, which are mostly found in the north-eastern parts of the country; and 3) mopane scrubland with shrubs of up to 3 m high. These are mostly found in the eastern part of the country where non-alkaline freely drained sands do not overlie medium textured sub-soils of higher water holding capacity. The shrub mopane differs from the other two forms in that the stem is not developed, and unlike the mopane trees, they do not produce fruits.

The mopane woodlands directly or indirectly support the livelihood of the majority of the rural population in its natural range through the provision of wood and non-wood products that contribute significantly to the livelihood of the rural communities adjacent to them. In mopane woodland areas, people who use fuelwood as the primary source of energy for cooking and heating would prefer to use mopane tree because it has high energy content and emits less smoke when it is dry (Makhado et al., 2012). It is also preferred for the construction of traditional structures because of its durability, termite resistance and relative straightness (Makhado et al., 2012; Teketay et al., 2018).

There has been an increased utilization of biomass as a unit of measure in forestry mainly for the following reasons: 1) climate change and carbon sequestration; 2) determination of ecosystems dynamics; and 3) renewable energy as an alternative for fossil fuels (Angombe et al., 2020; Kebede & Soromessa, 2018; Phiri et al., 2015; Picard et al., 2012). Forests, in particular, have a major role in mitigating climate change through carbon sequestration. Because of interest in the global Carbon (C) cycle, estimating aboveground biomass with sufficient accuracy to establish the increments or decrements of C stored in forests is increasingly important (Gibbs et al., 2007). Therefore, in the context of Reducing Emissions from Deforestation and Forest Degradation (REDD+) and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks, precise and accurate estimation of carbon stocks becomes increasingly necessary as part of national forest monitoring systems (Pothong et al., 2021). However, there is limited information on the pattern, trends and distribution of woody biomass production and their primary environmental and climatic determinants in different parts of Botswana. So, this has hindered the development of techniques for enhancing woody biomass production for natural woodlands.

The limited information has also hindered the formulation of management strategies for comprehensive forest management and conservation policies by the government. The information gap covers the production and physiological ecology of woody vegetation and extends to the whole of the arid and semi-arid savannahs of southern Africa. Efforts to improve the situation are quite limited despite the heavy reliance in Botswana of a large proportion of the population on woody biomass resources for energy and other household requirements.

There have, however, been increasing efforts in recent years to improve the situation (Knoop & Walker, 1985; Sekhwela, 2000). For energy planning purposes, attempts have been made to estimate the amount of woody biomass available in Botswana forests and woodland savannahs using remote sensing techniques (Tietema, 1993). However, owing to a lack of understanding of the relation between on-the-ground biomass and spectral reflection measured by various satellites, the results of these studies were generally too inaccurate to be used for forest management purposes (Ringrose, Matheson, & Dube, 1987).

Moreover, weighing the actual tree biomass in the field is undoubtedly the most accurate method to determine tree biomass; however, it is generally a time-consuming and destructive method that is usually restricted to small areas and small tree sample sizes (Xiao & Ceulemans, 2004). Therefore, the use of allometric relationships, which yield a non-destructive and indirect measurement of biomass compartments, is often the preferred approach since it is less time-consuming and less expensive than direct measurements (Crow, 1978; Montès et al., 2000; Parresol, 1999; Xiao & Ceulemans, 2004; Chave et al., 2004, 2005, 2014; Pati et al., 2022).

Hence, this study focuses on building a biomass prediction model for mopane and determining the factors contributing to appropriate information concerning woody biomass production in Botswana. Furthermore, as this study is based on direct field measurements, it avoids the problems experienced in previous studies in Botswana that were based on remote sensing techniques. This paper aims to support the conservation and management of mopane woodlands by examining the variation in woody biomass in three *Colophospermum mopane* (mopane) woodland types prevalent in Botswana and the southern African region. The objectives of this study are: 1) To determine the relationship between total above-ground tree biomass and the following five variables: a) stem diameter at 0.15 m; b) stem diameter at 1.3 m; c) stem diameter at 3 m from the ground; d) crown diameter; and e) total tree height; and 2) To provide an allometric equation that will predict the total tree above-ground biomass (stem plus branches and foliage) for individual mopane trees in Botswana.

2. Materials and Methods

2.1. Study Site Description

The three study sites of Serule, Sexaxa, and Tamacha are located in Botswana and were selected in terms of their mean annual rainfall and temperature ranges. The study sites also have slightly different soil types. The soil group in Serule is composed of small units of *regosols* and *leptosols* on hillcrests and upper slopes, while the lower slopes comprise larger-scale units of *lixisols* and/or *chromic luvisols*. On the other hand, the predominant soils in Sexaxa and Tamacha are the *eutric arenosols*. The presence among the dominant woody species of the economically important mopane was also critical in the site selection in order to allow comparison between the study sites. **Table 1** shows the study sites' geographical coordinates, climatic and vegetation characteristics, while **Figure 1** shows the location of the study sites.

Table 1. Characteristics of the study sites.

Characteristics	Study sites		
	Serule	*Sexaxa*	*Tamacha*
Location (Geographical coordinates)	21˚56'S 27˚31'E	19˚54'S 23˚46'E	18˚48'S 22˚04'E
Altitude (metres above sea level)	892	945	1023
Mean maximum temperature (˚C)	29	31	31
Mean minimum temperature (˚C)	15	29	29
Average rainfall (mm)	370	430	520
Vegetation	Mopane scrub	Deciduous savannah woodland	Monotypic mopane woodland

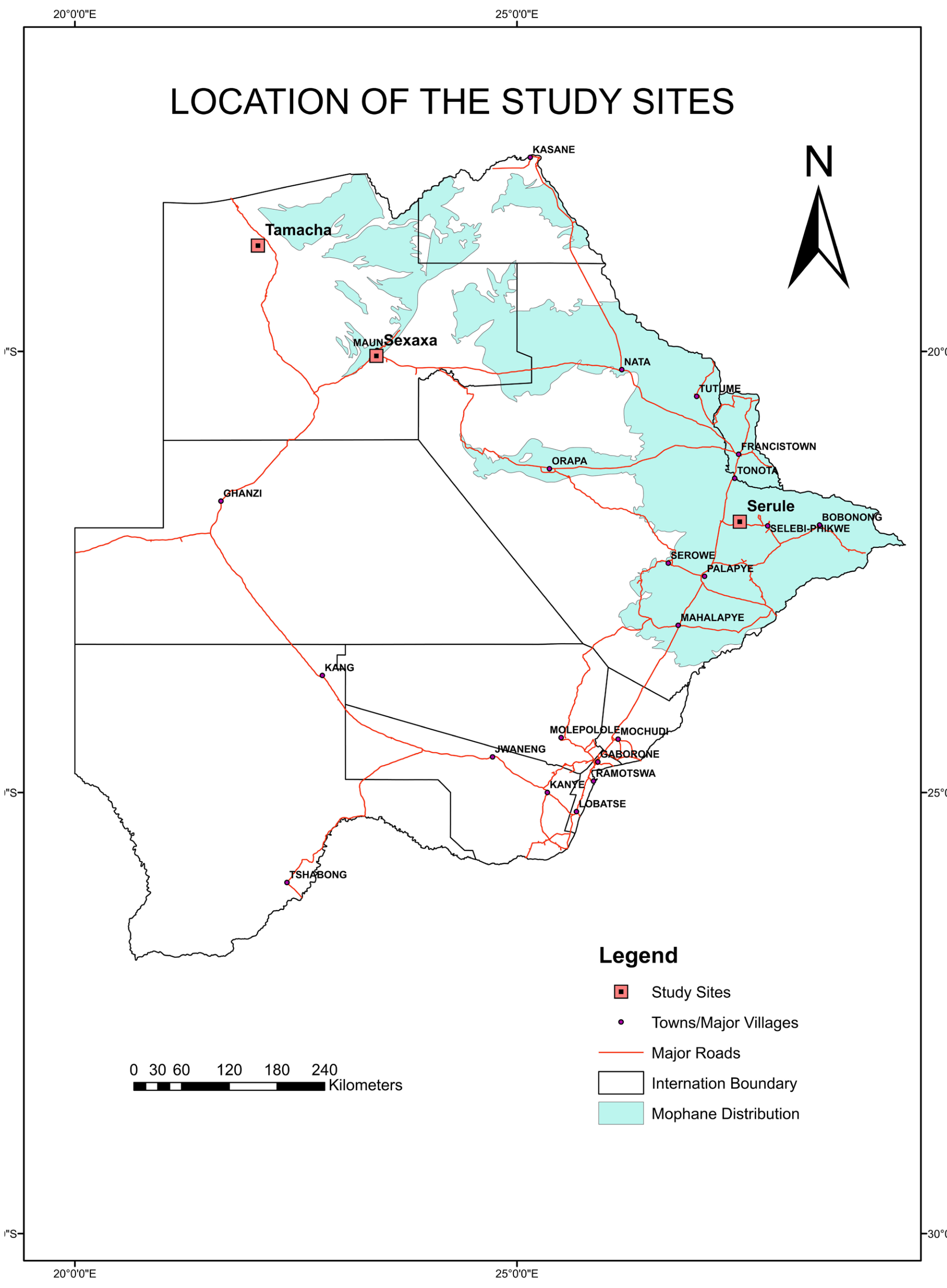

Figure 1. Location of study sites.

2.2. Sampling

At each study site, stratified random sampling procedures were applied, and a sample of 30[1] trees was selected per site, stratified within the stem diameter classes of each study site. Natural forests such as those found in the study sites are uneven-aged and, therefore, highly variable (Fang et al., 2006; Chaturvedi & Raghubanshi, 2013). Nevertheless, predictions of mopane biomass from a few sample trees could be more accurate than in most natural woodland types because mopane woodland is usually composed of even-sized stands that generally make up 90% of the total biomass, with only 3% - 7% of total mopane biomass being browse (leaves and twigs) (Timberlake, 1996).

The stem diameter strata of the study sites were determined from the data collected from permanent sample plots previously laid out on the study sites for vegetation studies by Kemoreile, Sekhwela and Mutakela (2004). The Diameter at Breast Height (DBH) of all mopane trees in each permanent sample plot was measured, and the trees were classified according to their respective diameter classes. Thus, at each of the study sites, five mopane sample trees were randomly selected for felling from each of the following six *DBH* classes: Class 1 (≥25.1 cm); Class 2 (20.1 - 25.0 cm); Class 3 (15.1 - 20.0 cm); Class 4 (10.1 - 15.0 cm); Class 5 (5.1 - 10.0 cm); and Class 6 (≤5.0 cm).

2.3. Baseline Data

The stem diameters for all the sample trees were measured at 0.15 m, 1.3, and 3 m from the ground. The crown diameter and total tree height for each of the sample trees were also measured. The crown diameter was measured at two perpendicular axes; the longest axis of the crown diameter and the axis perpendicular to the longest axis were measured. The average of the two measurements was taken as the crown diameter measurement (Chave et al., 2005).

The crown diameter was measured using a 50 m measuring tape, while diameter tapes were used for measuring the *DBH*, and the stem diameter was 0.15 m. The stem diameter at 3 m was measured using a Finnish calliper while the total tree height was measured using a *Haga* hypsometer for trees over 5 m tall and a 5 m telescopic measuring pole for trees/shrubs less than 5 m tall.

2.4. Biomass Data

After measuring the baseline data of the sample trees, the trees were felled to determine their fresh weight. They were cut 15 cm from the ground using a chainsaw. Each felled sample tree was partitioned into the crown (leaves, twigs, and small branches with a branch butt diameter ≤ 2 cm); large branches (branch butt diameter ≥ 2.1 cm); and stem. These methods are similar to those described by Bernardo et al. (1998); Chamshama et al. (2004); Chidumayo (1990); Fuwape, Onyekwelu, Adekunle (2001); Djomo and Chimi (2017); Wang et al. (1995) and

[1]Due to resource constraints for the collection of field data for this study, it was only possible to fell 30 sample trees at each study site.

Chaturvedi and Raghubanshi (2013). The total length of the stem was measured up to 2 cm in top diameter, and the part smaller than 2 cm was included as part of the crown (Bernardo et al., 1998). The middle diameter of the stem and its utilizable length was then measured before the stem was cross-cut into 1 m billets for biomass determination. A diameter and a 50 m measuring tape were used for measuring the stem's middle diameter and utilizable length, respectively. The utilizable stem length was considered the straight part of the stem that could be used as poles or building rafters. The length of each branch and its utilizable length, if any, were also similarly measured.

The stem and branch components were then cross-cut into 1 m billets, each of which was weighed to determine its fresh weight using a 100 kg spring-dial hoist scale balance mounted on a neighbouring tree. Thereafter, the total fresh weight of each sample tree was calculated by summing the fresh weights of the components (Fonseca et al., 2012).

2.5. Sampling for Oven-Dry Weight Determination

In order to reduce bias when randomly selecting a sample tree for oven-dry weight determination, the five sample trees in each diameter class were numbered from 1 - 5, and the five numbers representing the sample trees were placed in a cotton bag, after which one number was drawn from the cotton bag. The samples for oven-dry weight determination were collected from the sample tree represented by the drawn number.

One wood disc sample about 2 cm thick was cut from the stem at 0.15 m, 1.3 m and the top diameter (2 cm) of a randomly selected stem in each diameter class (Chamshama et al., 2004). Each wood disc sample was immediately weighed on a 5 kg kitchen scale to determine its fresh weight. A further sample of three wood discs (2 cm thick each) was randomly selected and cut from the branches (≥2 cm butt diameter) of the randomly selected sample tree. All the branches of the sample tree were numbered, after which the numbers were placed in a cotton bag. Three numbers were then successfully drawn from the cotton bag without replacement of the drawn number so that one number stood only one chance of being drawn. Wood discs were cut from the branches represented by randomly drawn numbers. The wood discs were weighed on a 5 kg kitchen scale to determine their fresh weight.

From the crown, a sample of four twigs (15 cm length) from the small branches (≤2 cm butt diameter) were selected in such a way that they represented the largest and the smallest twigs (one each) and two from the intermediate branch sizes (Chidumayo, 1990; Fuwape et al., 2001). The random selection of these samples was made by measuring the butt diameters of all the branches to determine the range of the butt diameter distribution. The branches were divided into three diameter classes representing the largest, intermediate, and small branches. All the branches in each diameter class were numbered, after which all the numbers that represented the branches from each diameter class were placed in one cotton bag, such that there were three cotton bags for the three branch diameter classes. Thereafter, one number was drawn from each of the two cotton bags that contained the numbers for the largest and smallest branches, while for the intermediate-sized branches, two numbers were successively drawn without replacement of the drawn number. The fresh weight of the wood discs was determined by weighing them on a 5 kg kitchen scale.

The fresh weight of the leaves of the sample tree was determined by filling a 2-litre bucket with uncompressed fresh leaves collected from the sample tree. The leaves were then transferred to a cotton bag, and their weight was determined using a 5 kg kitchen scale. A leaf was considered fresh when the whole leaf was completely green and did not have any patches of discolouration.

2.6. Moisture Content Determination

In the laboratory, the initial fresh weight of all the samples from the stem, branches, and crown was taken before the samples were placed in Manila drying paper for drying in an oven at 90˚C (Chamshama et al., 2004; Fuwape et al., 2001; Sekhwela, 2000) until the constant dry weight was attained. Wood (stem and branch) samples were cut into small pieces, and the fresh weight of the individual smaller samples was recorded before being dried to determine their oven-dry weight. The samples were weighed every 24 hours. To reduce moisture re-absorption by the samples when they were removed from the oven for re-weighing, the samples were placed in a desiccator containing silica gel.

The total dry weight of the sample tree was then calculated by applying the ratio of fresh weight to dry weight observed in the sample tree to the corresponding total fresh weight of the component parts; the total dry weight can be calculated as follows:

$$tdw = \frac{dws}{fws}(tfw), \tag{1}$$

where *tdw* indicates the total dry weight of the sample tree, *dws* is the total dry weight of the component sample, *fws* denotes the total fresh weight of the component sample, and *tfw* denotes the total fresh weight of the sample tree.

2.7. Data Analysis

The collected data were analysed according to Scolforo (2005), and the collected data (stem diameter at 0.15 m; stem diameter at 1.3 m; stem diameter at 3.0 m; crown diameter; total tree height; and total tree above-ground biomass) were all transformed to their natural logarithms in an attempt to reduce heteroscedasticity[2] often associated with most volume or biomass data (Philip, 1994)

The relationship between the variables is expressed as an equation for a regression line in which the coefficients are estimated from the sample. Hence, we chose the equation that best fits the scatter diagram.

During the regression analysis, the coefficient of determination (R^2) and mean

[2]One of the assumptions of regression and/or Analysis of Variance (ANOVA) is that the variance of the error term should be constant. Thus, heteroscedasticity refers to the inconstant variance of the error term.

square error (*MSE*) were calculated and used to determine the goodness of fit. However, these statistics were used with caution because equations with different dependent and independent variables and different numbers of estimated parameters cannot be readily compared.

To compare the prediction ability of the different equations, the percentage of the bias and Standard Error of Estimate (*SEE*) were calculated. The bias and *SEE* percentage values are reported in terms of the real dependent variables and not the transformed dependent variables used in the regression analysis.

3. Results and Discussion

3.1. Distribution of Sample Trees

The range of *DBH* sizes for the sampled trees is shown in **Figure 2**. Although there are distinct differences between the growing sites, it is clear that the data from the sampled sites in **Figure 3** follow a similar *DBH*-total tree above-ground biomass trend and appear like samples from a single population. This *DBH*-total tree above-ground biomass trend shows that the stem diameter of mopane is positively correlated to total biomass, irrespective of site. This was to be expected because, generally, tree biomass or volume increases with increased stem diameter. Furthermore, **Figure 3** shows that there appears to be very little variability in the *DBH* measurements of the sample trees across the three sites. This may be because the assumptions of random sampling were deliberately violated by possibly introducing personal bias through the subjective selection of the sample trees to fit the prescribed *DBH* classes.

3.2. Mean tree Biomass

The mean tree fresh biomass per *DBH* class was found to be greatest at Tamacha (**Figure 4**). Sexaxa and Tamacha had the greatest biomass in *DBH* classes 1 and

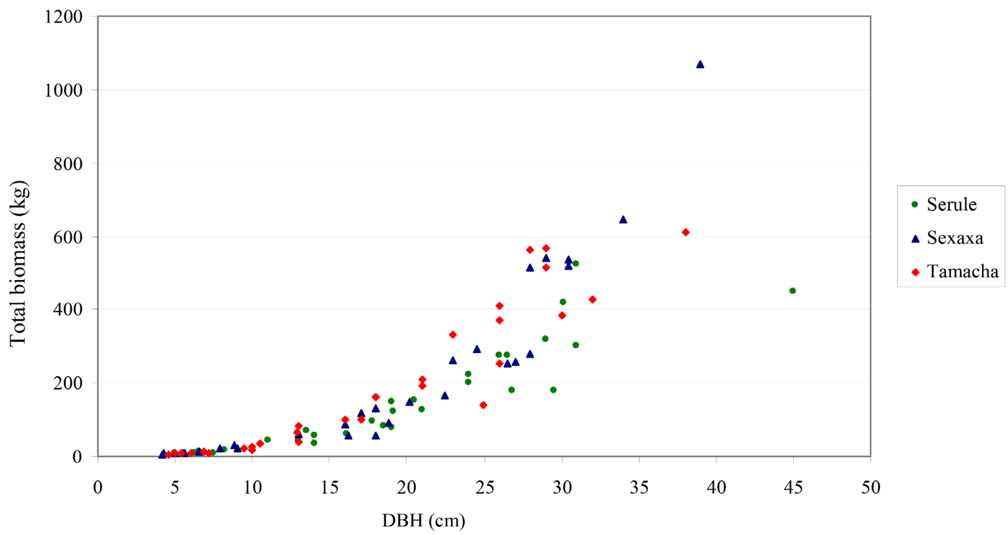

Figure 2. Distribution of sample trees across the Diameter at Breast Height-total tree above-ground biomass range.

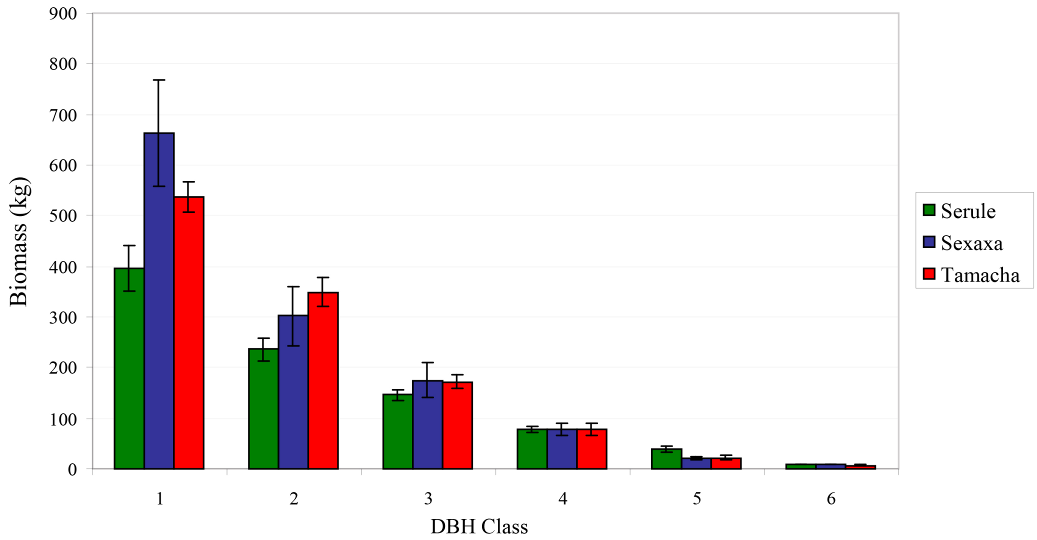

Figure 3. Mean tree biomass per Diameter at Breast Height class.

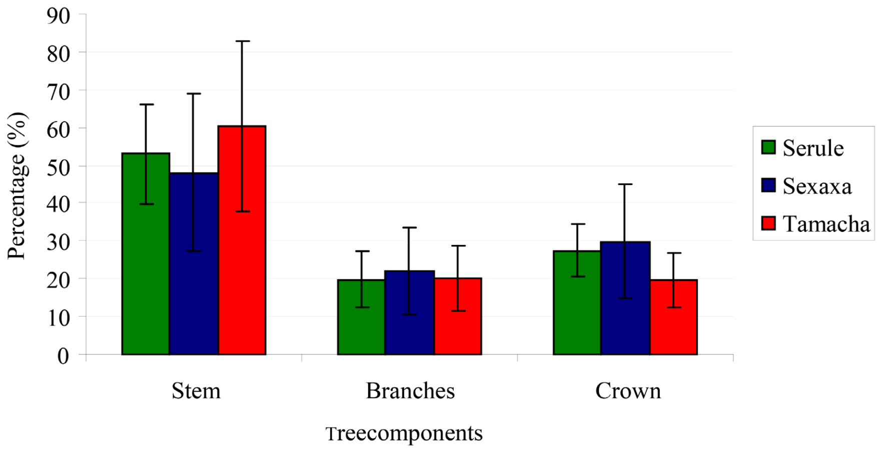

Figure 4. Mean tree biomass allocation per site.

2, respectively. Serule may have had the greatest biomass in *DBH* class 5 because the mopane in the smaller *DBH* classes at Serule mainly occurs as multi-stemmed shrubs with an increased number of stems per plant, hence the increased tree biomass per plant. At Sexaxa, the large mopane trees in *DBH* class 1 are also multi-stemmed, and this increased the biomass per tree considerably. The multiple stems that are characteristic of this type of woodland cause difficulties in statistical analysis. The individual stems could have been analysed separately. Still, in such analysis, each observation was not genetically independent from the next, thus violating one of the assumptions for ANOVA and linear regression (Snedecor & Cochran, 1967). Therefore, all of the *DBH*s and total tree heights of the stems per stool were combined and treated as one (1) record for use in the development of biomass prediction equations (Grundy, 1995).

3.3. Mean Biomass Allocation

The mean biomass allocation per tree is shown per site in **Figure 4**. The stem biomass allocation which was found to be greater at Tamacha (60% ± 22.6%), followed by Serule (53% ± 13.4%) and Sexaxa (48% ± 21%) was not significantly different ($p > 0.05$).

The mean for the primary branches was greater at Sexaxa (22% ± 11.3%) followed by Tamacha (20% ± 8.5%) and Serule (20% ± 7.3%). The differences in the biomass allocation for the primary branches were also not significantly different ($p > 0.05$). The mean allocation for the crown (including secondary branches) per tree was found to be greater at Sexaxa (30% ± 15.2%), while Serule and Tamacha had 27% ± 6.9% and 20% ± 7.2% respectively. A one-way ANOVA revealed no significant differences ($p > 0.05$) in the crown biomass allocation. The findings are consistent with those by Fuwape et al. (2001) on *Gmelina arborea* and *Nauclea diderrichii* in Nigeria, and those by Fuwape and Akindele (1997) on 7-year old *Gmelina arborea* and *Leucaena leucocephala* also in Nigeria. This biomass allocation is also consistent with other species such as *Acacia luederitzii* and *A. mellifera* which produced more stem than branch components in the higher rainfall areas in Botswana (Sekhwela, Yates, & Lamb, 2000).

The consequence here is that communities in different rainfall areas will have different availability of products. The higher rainfall areas will yield more timber from the stem while the low rainfall areas will yield more of poles and browse from the branches and crown respectively. This may form the basis of selective harvesting of various wood products which has been observed in southern Africa (Grundy et al., 1993). The differences in the yield of different wood components are important in the consideration of the possible kind of management and desirable products in view of the needs of a given community, type of woodland, existing land use, and environmental and climatic factors. However, the interaction between climatic and environmental factors affecting the growth and subsequent production levels of trees need comprehensive understanding in order to develop suitable management systems.

3.4. Biomass Prediction Equations

The measurements of the stem diameter at 0.15 m; stem diameter at 1.3 m; and stem diameter at 3 m above the ground; tree crown diameter, and total tree height which were transformed to their natural logarithms, were used in the development of a biomass equation that could be used to predict total tree aboveground biomass also transformed to the natural logarithm. The best fitting regression type was found to be an equation of the linear form:

$$y = \beta_0 + \beta_1 x \quad (2)$$

where:

y = value of the dependent variable;

x = value of the independent variable;

β_0 = an estimate of the intercept of the regression line;

β_1 = estimates of the slope of the regression line.

A biomass prediction equation for total tree above-ground biomass as a function of both *DBH* and total tree height was not included in this study because the incorporation of tree height in addition to stem diameter as independent variables does not necessarily increase the R^2 value (Chamshama, Mugasha, & Zahabu, 2004; Guy, 1981). This is further confirmed by Guy (Guy, 1981; Chaturvedi & Raghubanshi, 2013; Morataya et al., 1999; Pérez Cordero & Kanninen, 2002) who found that for a large number of shrubs, stem diameter was the best predictor of above-ground biomass, and that the incorporation of tree height into the equation did not significantly improve the accuracy of the prediction. In Malawi, the inclusion of the logarithm of total height as a second parameter in miombo woodland only improved the R^2 value by 0.5% - 2% (Abbot et al., 1997).

Furthermore, on practical grounds alone, it is preferable to estimate biomass from stem measurements (particularly *DBH*) because height and crown diameter are often difficult to measure with high accuracy, particularly in closed forests (Abbot et al., 1997; Guy, 1981; Segura & Kanninen, 2005). Furthermore, the use of equations where tree biomass is determined from *DBH* has a practical advantage because most of the inventories include *DBH* measurements which are easy to carry out accurately in the field (Abbot et al., 1997; Segura & Kanninen, 2005).

The simplest way to analyze data from the three (3) study sites would be to pool the data from all of them and derive a single regression line that best describes all the data together. The coefficients and fit statistics from fitting cross-site biomass prediction equations for the estimation of total tree above-ground biomass from each independent variable are presented in **Table 2**.

Table 2. Coefficients and fit statistics from fitting cross-site prediction equations for the estimation of total tree above-ground biomass.

Dependent variable	Independent variable	Regression coefficients ± standard errors and *p*-values (in brackets)			R^2 values (%)	*p*-values for regression equation	*MSE*	Normality test (*p*-values)	Equality of variances (*p*-values)	*n*
		b_0	b_1	b_2						
$ln(TTAB)$	$ln(D_{0.15})$	−1.903 ± 0.15 (<0.0001)	2.313 ± 0.05 (<0.0001)		96.0	<0.0001	0.090	<0.005	0.860	87
$ln(TTAB)$	$ln(D_{1.3})$	−1.163 ± 0.09 (<0.0001)	2.190 ± 0.04 (<0.0001)		97.5	<0.0001	0.050	<0.005	0.821	88
$ln(TTAB)$	$ln(D_{3.0})$	1.619 ± 0.11 (<0.0001)	1.450 ± 0.05 (<0.0001)		93.3	<0.0001	0.150	<0.005	0.320	85
$ln(TTAB)$	$ln(CD)$	0.822 ± 0.16 (<0.0001)	2.631 ± 0.11 (<0.0001)		92.0	<0.0001	0.180	<0.005	0.287	83
$ln(TTAB)$	$ln(Ht)$	−0.277 ± 0.35 (<0.0001)	2.461 ± 0.20 (<0.0001)		64.7	<0.0001	0.770	<0.005	0.604	89

1) *TTAB* is the total tree above-ground biomass, 2) $D_{0.15}$ is the stem diameter at 0.15 m, 3) $D_{1.3}$ is the stem diameter at 1.3 m 4), $D_{3.0}$ is the stem diameter at 3.0 m, 5) *CD* is the crown diameter, 6) *Ht* is the total tree height, 7) *ln* is the natural logarithm.

The *p*-values for the Anderson-Darling normality test are shown in **Table 2**. The *p*-values are less than the chosen α-level of 0.05. Thus, there is not enough evidence to suggest that the pooled data follow a normal distribution. This was not surprising in view of the great range of size from the smallest to the largest measurements at the three study sites. This means that if all the three study sites are analyzed together, one of the assumptions in regression analysis would be violated, and it therefore provides justification for treating each site separately. However, the coefficients and fit statistics from fitting the linear equations to the data give sufficiently good fits and adequate biomass predictions to preclude the need for further data transformation more so that the data had already been transformed to their natural logarithms.

The test for the equality of variance shows that the *p*-values are greater than the α-level of 0.05. Thus, the null hypothesis was not rejected: there is no difference between the variances. The *p*-values for the Levene's test for equal variances are also shown in **Table 2**. The Levene's test was used instead of the Bartlett's test because the Anderson-Darling normality test indicated that there was not enough evidence to suggest that the data follow a normal distribution.

In terms of the stem diameter at 0.15m, the coefficients and fit statistics from fitting the biomass prediction equation to the logarithm of the pooled data show that the *p*-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (**Table 2**). The *p*-value for the overall fit of the biomass prediction equation to the pooled data is also significant ($p < 0.0001$). Thus, there is a positive linear relationship between the pooled data of the total tree above-ground biomass and the pooled data of the stem diameter at 0.15 m.

The R^2 value of the relationship between the logarithm of the total tree above-ground biomass and the logarithm of the upper stem at 1.3 m is 97.5%. Based on the R^2 value, this is the best cross-site biomass prediction equation. An R^2 value of 97.5% is very close to 100%, and it indicates that the biomass prediction equation provides a good fit to the data. The diagnostic tests indicated that there were no influential observations in the data set.

The coefficients and fit statistics from fitting the biomass prediction equation to the pooled data show that the *p*-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (**Table 2**). The *p*-value for the overall fit of the biomass prediction equation to the pooled data is also significant ($p < 0.0001$). Thus, there is a positive linear relationship between the pooled data for the logarithm of the total tree above-ground biomass and the pooled data for the logarithm of the stem diameter at 1.3 m.

The results pertaining to the stem diameter at 3 m show that the coefficients and fit statistics from fitting the biomass prediction equation indicate that the *p*-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (**Table 2**). The *p*-value for the regression equation is also significantly different from zero ($p < 0.0001$), which indicates that there is a positive linear relationship between total tree above ground biomass and the stem diameter at 3 m above the ground. The R^2 value of this relationship is 93.3%.

The linear equation for the logarithm of the total tree above-ground biomass against the logarithm of the crown diameter has accounted for 92% of the variability in the sample data. Based on the R^2 value (92%), the biomass prediction equation also provides a good fit to the sample data. The coefficients and fit statistics from fitting the biomass prediction equation indicate that the p-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (**Table 2**). The p-value for the regression equation is also significantly different from zero ($p < 0.0001$), which indicates that there is a positive linear relationship between the total tree above ground biomass and the crown diameter.

Finally, the linear equation of the pooled data for the logarithm of the total tree above-ground biomass against the pooled data for the logarithm of the total tree height has accounted for 64.7% of the variability in the sample data. The coefficients and fit statistics from fitting the biomass prediction equation indicate that the p-values for the intercept and the slope are significantly different from zero ($p < 0.0001$) (**Table 2**). The p-value for the regression equation is also significantly different from zero ($p < 0.0001$), which indicates that there is a positive linear relationship between total tree above ground biomass and total tree height. However, compared with the other four (4) variables, this relationship has the lowest R^2 value.

3.5. Assessment of Predictive Ability of the Biomass Equation

It must be noted that the R^2 value alone cannot be used to determine the goodness of fit of the biomass prediction equations. The R^2 values just show the proportion of variability that has been accounted for by the regression and in general are poor criteria for selection of equations. Therefore, the use of the R^2 value to determine the goodness of fit has to be complemented by the use of other criteria such as the bias percentage and the standard error of estimates to determine the predictive ability of the biomass prediction equations, and the testing of the significance of the slope and intercept. Therefore, in order to assess the predictive ability of the cross-site biomass prediction equations, the percentage of their bias were calculated and are presented in **Figure 5**.

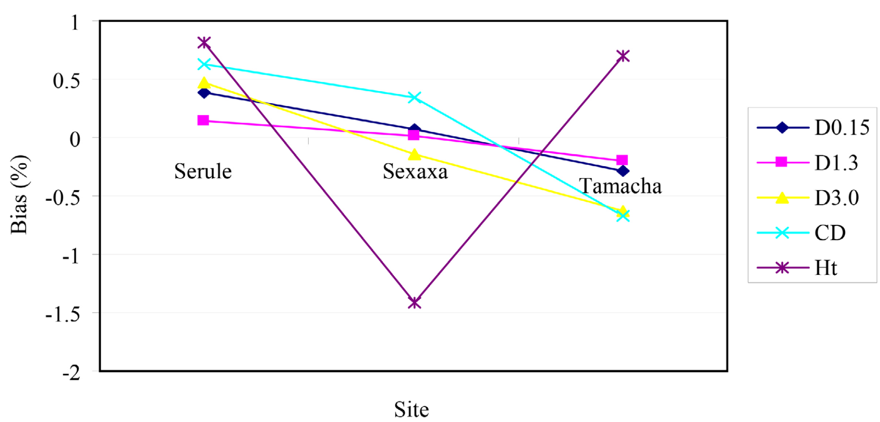

Figure 5. Bias (%) of the cross-site equations to predict total tree above-ground biomass at the study sites.

By studying the values in Figure 5, the following conclusions can be made: the prediction equation based on the stem diameter at 1.3 m to predict total tree above-ground biomass is the most accurate because of the least bias percentage. The other biomass prediction equations based on the stem diameter at 0.15 m, stem diameter at 3 m and crown diameter show similar, but less accurate capabilities. The biomass prediction equation based on total tree height is the least accurate and shows a pattern that is different from the other four (4) biomass predictions equations at the Sexaxa and Tamacha sites. This biomass prediction equation provides the least accurate predictive ability with a bias percentage of about −1.5 percent. This may be attributed to the highly variable total tree height of the mopane at the Sexaxa site.

The standard errors of estimates were calculated and are presented in Figure 6. The results further show that the biomass prediction equation based on total tree height is the least accurate and shows a pattern that is different from the other four (4) biomass predictions equations at the Sexaxa and Tamacha sites. The prediction equation based on total tree height to predict total tree above-ground biomass at the Sexaxa site provides the least accurate predictive ability with a standard error of estimates of about 8 percent. The results for the percentage of the standard error of estimates for the cross-site biomass prediction equations are consistent with the results that show the bias percentage.

The results from Figure 6 also show that the biomass prediction equation based on the stem diameter at 1.3 m to predict total tree above-ground biomass is the most accurate. The other biomass prediction equations based on the stem diameter at 0.15 m, stem diameter at 3 m and crown diameter show similar, but less accurate capabilities.

A common requirement in biological experiments is the comparison of the regression lines. The biomass prediction equation based on the stem diameter at 1.3 m was tested to verify its superior performance over the other biomass prediction equations and to test whether it can be used as a biomass prediction equation for all the sites. The biomass prediction equation that was tested is:

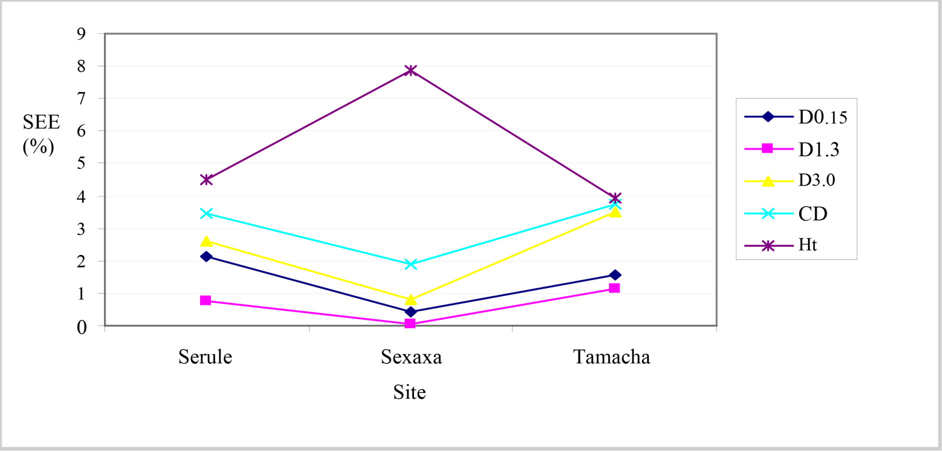

Figure 6. SEE (%) of the cross-site equations to predict total tree above-ground biomass at the study sites.

$$\ln biomass = -1.163 + 2.190 \ln DBH. \quad (3)$$

The analysis of covariance showed that the intercepts of the three (3) sites are not significantly different from each other because of a *p*-value that is greater than the α-level of 0.05 ($p = 0.059$). Therefore, the hypothesis that all the sites have the same intercept/origin can be accepted. The *p*-values for the slopes show that all the three sites have slopes that are not significantly different from each other ($p = 0.061$) and zero ($p = 0.052$) at the α-level of 0.05. Therefore, the two hypotheses that there is no difference in the slopes and that the slopes are not significantly different from zero can be accepted. The conclusion is that it is possible to pool the data and use the cross-site biomass prediction equation based on the stem diameter at 1.3 m.

The plot of the data and the line of best fit together with the 95% confidence interval are shown in Figure 7. The confidence interval shows the range in which the estimated mean total tree above-ground biomass is expected to fall.

The equations in this study apply to mopane trees within the range of *DBH* measured (2.7 cm - 35.2 cm). Extrapolation beyond the limits of the range of diameters is not recommended, since the predictions are likely to be inaccurate. The trees measured in this study represent the average range of stem sizes encountered in the mopane woodlands in Botswana. However, trees that grow much taller and reach stem diameters of 50 cm and more do occur in some parts of Botswana but are becoming increasingly rare. Site characteristics are a determining factor in the growth of these trees (Sekhwela, 2000) and therefore, the equations are also only likely to apply to mopane growing under similar conditions. Therefore, further destructive sampling over a range of different sites is needed to develop equations for more widespread use.

In view of the R^2 values, the percentage of bias and the standard error of estimates, and the analysis of covariance, the stem diameter at 1.3 m provides the best fit to the data from the individual sites and cross-sites. Another reason for

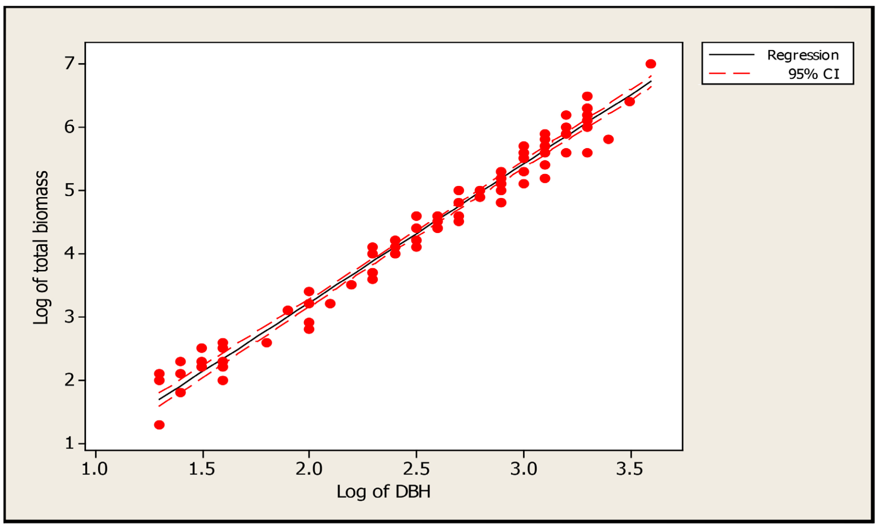

Figure 7. The cross-site plot and line of best fit together with the 95% confidence interval for total tree above-ground biomass estimated by logarithm of stem diameter at 1.3 m.

using *DBH* as an independent variable is that in most cases it avoids problems related to buttresses and other irregularities in the shape of the stem close to the ground; and it makes measurements easy, thereby reducing costs (Hofstad, 2005).

However, where the trees have been repeatedly cut and their taper and form at and around *DBH* has become irregular, stem diameter, which is measured at a height closer to the ground level than *DBH*, may be a better reference diameter than *DBH* for predicting tree or stand characteristics (Khatry Chhetri & Fowler, 1996). Furthermore, for low branching multi-stemmed trees such as the mopane that occurs at Serule, measuring stem diameter at ankle height is more feasible than measuring higher up the stem.

3.6. Comparison with Other Existing Equations

In general, the stem, and in particular *DBH*, is an important predictor of total tree biomass. Tree weight (stem, branches and leaves) increases with *DBH*. Guy (1981) found similar relations in mopane woodland in Zimbabwe. Chamshama, Mugasha and Zahabu (2004) found an R^2 value of 97% in miombo woodland species in Tanzania using the equation

$$\ln B = 0.01559 + 2.796 \ln DBH \tag{4}$$

where:

B = total tree biomass;

DBH = stem diameter at 1.3 m from the ground.

These findings suggest that *DBH* could be used as a reliable estimator of stem volume, stem weight and total weight for mopane and other species in areas of similar characteristics.

The stem component, which can be assessed independently for construction purposes, is supported by the good relationship depicted by the strong R^2 values. The relationship shows the potential for development of simple resource and product assessment techniques for quick resource evaluation. Most of the available forestry related resource evaluation techniques relate to industrial timber, and not to community needs, and hence there are few studies which have looked at the use of such techniques to assess resource availability for community needs.

The results show that crown diameter and total tree height are not as accurate as the stem to predict total tree above-ground biomass for mopane. The most probable reason is that the range of crown diameters and tree heights at the three sites is very wide. In addition, the shape of the mopane crown is irregular and highly variable at the three sites. This could be the reason why crown diameter and total tree height which have been used to predict tree biomass in other studies (Sekhwela, 2000; Stromgaard, 1985; Stromgaard, 1986; Ter-Mikaelian & Korzukhin, 1997) are apparently inadequate to predict mopane tree fresh biomass.

Guy (1981) used total tree height as a predictor of biomass but found that separate regressions were necessary to adequately describe all the species encountered. Although prediction equations that could be used to predict shrub and tree biomass from stem variables could therefore be developed, the difficulty involved in measuring shrub stem diameters and the numbers of shrubs often encountered in the field, make it tedious and time consuming to measure stem diameter. Thus, in such cases, the total tree height would be used in preference to stem diameter.

4. Conclusion

This work adds to the scant but growing number of studies which demonstrate good relationships between some stem characteristics and total woody biomass in mopane woodlands, from which reliable biomass tables can be developed.

The results from this study show that there is a strong positive relationship between total tree biomass and the stem at different heights from the ground level. The strongest relationship was between the total tree above-ground biomass and the stem diameter at 1.3 m from the ground. The R^2 value of the relationship was 97.5% for the pooled data and the biomass prediction equation was:

$$\ln Biomass = -1.163 + 2.190 \ln DBH \quad (5)$$

In order to predict total above-ground tree biomass at all the sites *DBH* would provide the most accurate estimation. Previous studies had also reported that when *DBH* is applied as an estimator in the allometric equations for estimating branch biomass, improved results are obtained (Pati et al., 2022; Dao et al., 2021). Total tree height was considered to be less suitable for indirect estimation of total tree biomass. Furthermore, in both cases of the crown diameter and total tree height, their unsuitability to predict total tree biomass is compounded by the difficulty of accurately determining height and crown diameters, particularly in dense populations. Moreover, crown dimensions are also influenced by stand density. However, tree height or crown dimensions may be considered for the estimation of total above-ground biomass for mopane where the mopane trees are multi-stemmed, and the measurement of such stems becomes tedious. The crown dimensions can also be used in non-destructive techniques (such as in 3-D photogrammetric analysis) for the estimation of total above-ground biomass as shown in studies by other researchers.

Finally, the biomass prediction equation presented here offers a realistic option of carrying out extensive surveys of standing total above-ground biomass for mopane in Botswana. This will be very important in determining the effect of mopane wood harvesting, establishing stand density and mean annual increments. The present study shows that to avoid destructive approach and subsequent reduction in regenerating phases, biomass of small diameter individuals can be precisely estimated using diameter and height through these allometric equations. The development of species-specific allometric equations to minimize errors in biomass and Carbon stock estimations is critical for accurate Carbon accounting.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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