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Full Length Research Paper

Allometric equations for estimating biomass in naturally established *Prosopis* stands in Kenya

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Forty five *Prosopis* stems of 2.5-18.0 cm diameter at breast height (DBH) were sampled at Nadapal along the Turkwel riverine forest for development of biomass and volume prediction equations for naturally established stands. Basal diameter (D_{30}), DBH and heights were measured, felled trees and their volumes, fresh and dry weights determined. Linear and power models were evaluated for volume and biomass prediction through regression analysis of measured tree parameters. Power models yielded better results than linear models in volume and biomass prediction, with D_{30} and DBH being more reliable than height. Validation of models at two sites in Marigat and Bura, revealed strong significant correlations between predicted and measured tree biomass and volumes, suggesting effectiveness of the models in biomass prediction across sites. Subsequently, model development and model validation data were pooled to develop national models. Basal diameter was found to be the best variable in the development of power models for biomass and volume prediction across the country. When logarithmically transformed, biomass and volume per tree had strong significant linear relationship with basal diameter, and are accordingly recommended for quick biomass and volume estimation in the field.

Key words: Biomass, Bura, Marigat, Nadapal, Turkwel, power models, linear models.

INTRODUCTION

Wood biomass is the main source of energy in Kenya, with notable localized deficits (Kirubi et al., 2000; Okello et al., 2001; Ng'etich et al., 2009). Provision of wood fuel was one of the main objectives of *Prosopis* species introduction in the country (Mwangi and Swallow, 2008). This objective is not yet fully realized, despite the successful establishment of the species in the initial trials (Maghembe et al., 1983; Olukoye et al., 2003) and their subsequent spread into other unintended areas, as a result of natural seed dispersal by livestock, wild animals and water (Mwangi and Swallow, 2008; Mworia et al., 2011). Recently, the government gave a policy direction for utilization of *Prosopis* species to control their further spread in areas where they are invasive (GOK, 2007). Exploitation of the species for wood fuel, as initially intended, provides excellent opportunities for invasion control and reducing wood biomass energy deficits.

However, management guidelines, particularly for biomass quantification are yet to be developed. The species composition of natural stands is also poorly understood because introduced species such *Prosopis chilensis* Stunz, *Prosopis juliflora* (Sw.) and *Prosopis pallida* Kunth are difficult to differentiate because of similar morphology and formation of hybrids of intermediate phenotypes (Saidman et al., 1996; Pasieznik et al., 2001; Landeras et al., 2006). These species could be coexisting in any of the natural stands.

Allometric equations are used to predict tree and stand biomass, based on easily measured tree variables such height, diameters and crown. Normally, developed equations are specific to species, sites, tree age and management (Lott et al., 2000; Claesson et al., 2001; Kairo et al., 2009), thus limiting their generalized transferability.

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Although biomass prediction models were developed in the early stages of *Prosopis* species introduction, the models were for localized use in *P. juliflora* plantation trial (Maghembe et al., 1983) and comparison of species growth within species screening trials (Rosenschein et al., 1999). Therefore, their application in naturally established *Prosopis* species stands is limited by species composition, sites variations and the lack of any prescribed management in the naturally established stands.

Basal or stump diameter, height, crown area and depth are the commonly used biomass predictors in young trees and multistemmed trees and shrubs (Maghembe et al., 1983; Eshete and Stahl, 1998; Kariuki et al., 2007; Kaonga and Bayliss-Smith, 2010; Zeng et al., 2010). For *Prosopis* species, basal diameter is one of the most commonly used variable for biomass prediction (Maghembe et al., 1983; Elfadl et al., 1989; Duff et al., 1994) and height inclusion found to improve biomass prediction models (Padron and Navarro, 2004). Although basal diameter is not always specified in literature (Maghembe et al., 1983; Duff et al., 1994), diameter measured at 30 cm above the ground (D_{30}) is more frequently used as basal diameter (Eshete and Stahl, 1998, Padron and Navarro, 2004; Kariuki et al., 2007) and was thus adopted for this study. Furthermore, accurate tree height and crown measurement may not be feasible in naturally established dense *Prosopis* stands, because of interlocking tree canopies. The objective of this study was therefore to evaluate the suitability of diameters (D_{30} and DBH) as variables for biomass estimation in naturally established *Prosopis* stands.

MATERIALS AND METHODS

Sites descriptions

Sites for this study were identified at Katilu and Nadapal during a related study on prediction of *Prosopis* species invasion in Kenya (Muturi et al., 2010). The structure of DBH for *Prosopis* stands in the two sites was evaluated using sixteen intensive sample plots (Barnett and Stohlgren, 2003). Subsequently, Nadapal site was selected for allometric models development. Two more sites: - Marigat and Bura were selected for validation of the developed models. All the sites are within arid areas of Kenya that are characterized by low erratic rainfall, high temperatures and high evapotranspiration potentials, leading to high soil moisture deficits (Sombroek et al., 1982). However, Nadapal and Bura are riverine sites where microclimate is modified by forests, periodic flooding and river flow. Rainfall in all the sites is bimodal with peaks around April and November. Mean annual rainfall along the Turkwel riverine forest ranges from 500 mm upstream to less than 200 mm downstream, with high inter-annual variations (Reid and Ellis, 1995; Stave et al., 2005). The mean rainfall at Katilu is higher (≈ 350 mm) than at Nadapal (≈ 200 mm). Temperatures in the vast arid areas adjacent to Turkwel riverine forest ranges from 28-40°C. At Marigat, the mean annual rainfall is estimated at ≈500 mm with mean temperatures of 24-34°C (Ekaya et al., 2001; Kipkorir et al., 2002). Bura has a mean annual rainfall of 370 mm and mean daily temperature of 28°C (Maingi and Marsh, 2006). The geographical locations of the sites are shown in Figure 1.

Tree sampling

Thirty trees from the site selected for allometric equations development were randomly sampled and their height, diameters (D_{30} and DBH), fresh weight and volumes measured in the field. The trees were sampled to represent the known range of diameters for the species in the area, at specified intervals of 2 - 3 cm classes. Tree height was measured with a measuring rod, while diameters were measured using a diameter tape. The choice of basal diameter measurement point (30 cm from ground surface) was influenced by the multistemming of stumps, as most *Prosopis* trees were found to branch at beyond 30 cm from the ground. As the number of merchantable stems (DBH ≥2.5 cm) per stump were occasionally greater than 1, the number of stems used in model development was 45. Each measured tree or merchantable stem was felled and branches for volume and biomass measurement cut off at diameters of ≥1.5 cm (the lower limit for woody material considered suitable for use as fuel wood). Several tree discs or segments totaling about 1kg were sampled at 2.5 m intervals from the base of each tree upwards for dry weight determination. For multistemmed trees, only one stem was sampled and uniformity of tree characteristics assumed for the other stems. The actual weight of all the sampled tree components was then determined with a spring balance and sample volumes determined immediately using water displacement method. In this method, a bucket was placed in a large container, water filled to the brim and tree samples submerged in water. Displaced water was collected in the container where the bucket was placed and the volume of water displaced by each sample measured with graduated containers.

For determination of whole tree weight and volume, trees were cut into small sizes immediately after felling, depending on the depth of the bucket used in water displacement. Tree segments of weights that could be easily lifted were fastened together with a sisal twine and weighed with a spring balance until the entire tree materials were exhausted; and their volumes determined using the aforementioned water displacement method. Volumes and weights were then recorded separately for each tree or merchantable stem.

Samples collected for moisture content determination were kept under field conditions while in field, and at room temperature after each day, until the field sampling was complete. Samples were then taken to KEFRI laboratory, weighed and oven dried at 105°C for 72 hours and re-weighed daily until constants weight was achieved for each sample as previously described (Maghembe et al., 1983; Padron and Navarro, 2004). Percentage dry weight of the samples was determined after the drying process and the values obtained for each tree sample used to convert fresh weight into dry weight for the respective tree. The procedure was repeated for trees sampled at Marigat and Bura for model validation. The characteristics of trees in the three sites are summarized in Table 1.

Modeling

Square and log transformed (Duff et al., 1994; Padron and Navarro, 2004; Alvarez et al., 2011) and untransformed (Maghembe et al., 1983; Padron and Navarro, 2004) basal diameters have been used for *Prosopis* biomass prediction depending on the species and nature of the stand studied. Therefore, transformed and untransformed data were evaluated for model development in the current study, using linear and power regression between tree height, D_{30} and DBH as the independent variables and tree volume or biomass as the dependent variables. Goodness of fit and model comparisons were evaluated using coefficient of determination (R^2), the standard error (SE) and F values (Sokal and Rohlf, 1981). Models with high R^2, low se and high F value were selected and used to predict volume and tree biomass for trees sampled at Marigat and Bura. Subsequently, linear regression was used to test the effectiveness of selected models in predicting tree volume and

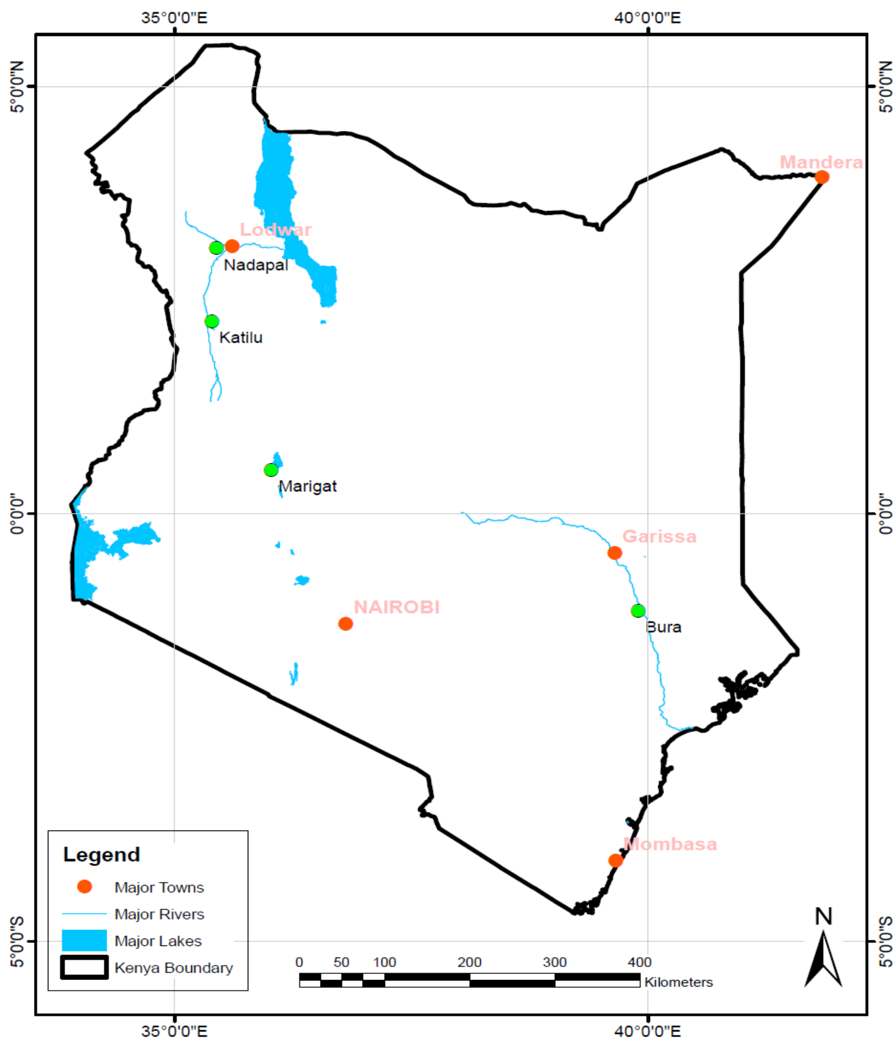

Figure 1. Approximate geographical locations of data collection sites (circular symbols) in Kenya. Nadapal, Katilu and Bura are riverine sites, whereas Marigat is a flat low lying site that receives seasonal runoff.

Table 1. Summary of tree variables measured at the three sites.

Site	Number of trees	D_{30} (cm)	DBH (cm)	Height (m)	Dry weight (kg/tree)
Nadapal	30(45)	2.8 - 18.5	2.5 - 18.0	3.6 - 10.4	0.50 - 180.1
Marigat	11	3.6 - 18.0	2.5 - 17.5	3.9 - 12.0	1.10 - 148.8
Bura	10	2.6 - 18.0	2.5 - 16.8	6.3 - 11.5	0.76 - 134.0

Range of basal diameter (D_{30}), diameter at breast height (DBH) and dry weight of *Prosopis* trees sampled at Nadapal, Marigat and Bura. At Nadapal, 30 trees were sampled but individual stems were 45 because some trees multistemmed.

biomass using measured volumes and weights as the independent variables and those predicted as the dependent variables. The best models based on R^2 and standard error were selected, the data from the three sites pooled and variables in the selected models used to develop overall models for predicting tree biomass and volumes in naturally established stands. The selected models were tested in predicting tree biomass along the Turkwel using data collected from the DBH structure evaluation plots. Statistical variation of selected models was evaluated with paired t-test, using predicted tree weights or volume for diameter models (D_{30} and DBH) and diameters and multiplicative (H*D) models. All statistical analyses were carried out using SPSS.

RESULTS

The DBH distribution structures for stands at Katilu revealed

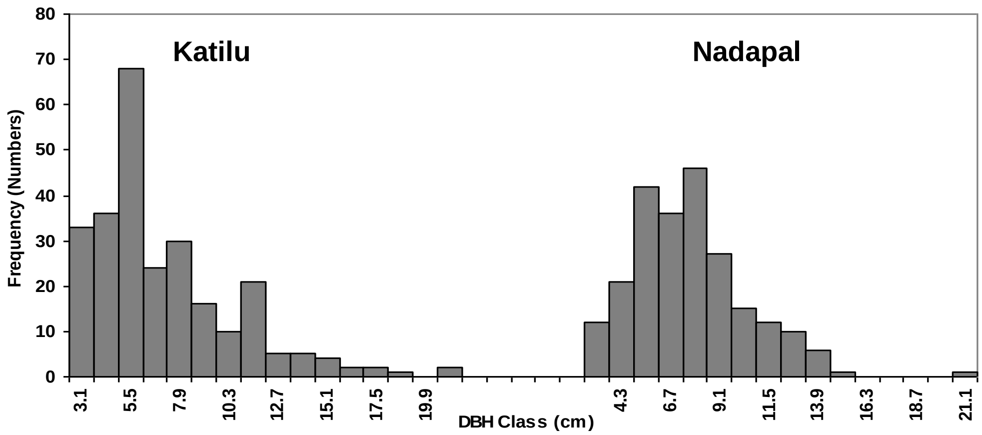

Figure 2. Structure of *Prosopis* diameter at breast height (DBH) at Katilu and Nadapal.The dbh structure at Nadapal was a near normal distribution compared to the dbh at Katilu, hence a stand at Nadapal was selected for biomass and volume prediction models development.

a mixed trend while a near normal distribution trend was found at Nadapal (Figure 2). The Nadapal site was therefore considered more suitable for model development. Preliminary evaluation of model development using transformed and untransformed data could not justify data transformation as reliable models were obtained with untransformed data. Untransformed data was therefore used for allometric equations development. Power models ($y = aX^b \pm e$) were stronger than linear models ($y = aX + b \pm e$) in relating tree volumes, fresh weight and dry weights to tree diameters and height (Table 2). This fact is exemplified by comparison of height and D_{30} multiplicative power ($Y = aHD_{30}^b$) and linear ($Y = aHD_{30} + b$) models for fresh weight, volume and dry weight (Table 2). From this comparison, both R^2 and F values were higher in power than in linear models, while a contrary trend was observed for standard error. Compared to diameter models, height models were weak on all comparison attributes (Table 2). Statistical comparisons of predicted tree biomass and volumes revealed insignificant differences between diameters models and between comparable diameter and multiplicative models (t-test data not shown).

The diameter and multiplicative models selected for validation at Marigat and Bura were all effective in correlating predicted and measured tree weights and volumes, with DBH model yielding the best results (Table 3). Multiplicative models revealed mixed results (Table 3).

Prediction was slightly better at Bura than Marigat, when models parameters were compared between the two sites (Table 3). However, this was statistically insignificant as exemplified by the overlapping linear models fitted between predicted and measured dry weight and volume, using D_{30} models (Figure 3).

Results for models developed using pooled data from all sites is shown in Table 4. From the table, D_{30} models were superior to DBH models according to model evaluation parameters (R^2, F value and SE), and compared favourably with the corresponding multiplicative models. Linear D_{30} models were therefore developed using log transformations for biomass and volumes estimation in the field (Figure 4), while the power dry weight model was used to estimate dry biomass in plots used for DBH structure evaluation. The predicted biomass ranged from 769 to 18,953 Kg per ha, depending on variation of mean plot basal diameter.

DISCUSSION

Prosopis stands in Kenya can be described as very dynamic in terms of diameter distribution structures (Figure 2). This observation may be associated with invasion trends, a spontaneous process that can vary with site conditions. For example, Katilu is an irrigated agriculture area, where invasion is primarily driven by continuous farm abandonment unlike Nadapal where abandonment was incidental, according to local informants and a previous study (Muturi et al., 2010). From the current study, it was apparent that basal diameter was consistently the best variable for predicting both tree volume, and tree biomass, a finding that was consistent with previous studies on *Prosopis* allometric models (Maghembe et al., 1983, Elfadl et al., 1989, Duff *et al.,* 1994). Although multiplicative models were slightly better than basal diameter models (Table 2), multiplicative models lead to a higher error in models validation (Table 3), a factor that can be attributed to the challenges of accurate height measurement in closed canopy *Prosopis* stands. Since DBH models were also highly effective in biomass and volume prediction, the study confirms the suitability of diameters in volume and biomass prediction in naturally established *Prosopis* stands where canopy and height cannot be accurately measured.

Table 2. Models for tree volumes and weight prediction for tree samples collected at Nadapal.

Equation	R^2	SE	F	P-|value
Fresh weight equation				
$Fw = 0.0004H^{5.9471}$	0.76	0.64	138.6	<0.01
$Fw = 0.1283D_{30}^{2.5194}$	0.97	0.21	1641.3	<0.01
$Fw = 0.2772DBH^{2.3624}$	0.94	0.33	646.1	<0.01
$\mathbf{Fw = 0.0134H*D_{30}^{1.9096}}$	0.98	0.17	2589.5	<0.01
$Fw = 0.0276H*DBH^{1.812}$	0.95	0.29	847.3	<0.01
$\mathbf{Fw = 1.3554H*D_{30} - 37.071}$	**0.92**	**16.3**	**494.0**	**<0.01**
Volume equation				
$V = 0.0002H^{6.3337}$	0.74	0.72	122.7	<0.01
$V = 0.0664D_{30}^{2.7308}$	0.98	0.20	2047.0	<0.01
$V = 0.1578DBH^{2.5446}$	0.93	0.37	576.8	<0.01
$\mathbf{V = 0.0059H*D_{30}^{2.0608}}$	**0.98**	**0.20**	**2116.4**	**<0.01**
$V = 0.0134H*DBH^{1.9464}$	0.93	0.35	666.9	<0.01
$\mathbf{V = 1.1298\ H*D_{30} - 29.898}$	**0.94**	**11.7**	**666.4**	**<0.01**
Dry weight equation				
$Dw = 0.0001H^{6.3237}$	0.75	0.70	131.3	<0.01
$Dw = 0.0483D_{30}^{2.6906}$	0.97	0.24	1398.7	<0.01
$Dw = 0.1114DBH^{2.5164}$	0.93	0.38	559.6	<0.01
$Dw = 0.0044H*D_{30}^{2.0372}$	**0.98**	**0.21**	**1844.2**	**<0.01**
$Dw = 0.0096H*DBH^{1.9293}$	0.94	0.34	695.9	<0.01
$\mathbf{Dw = 0.7833H*D_{30} - 21.619}$	**0.89**	**10.7**	**381.9**	**<0.01**

Power models were better than linear models based coefficient of determination (R^2), standard error (SE) and F value (F), as exemplified by HD_{30} models (in bold) for fresh weight, volume and dry weight prediction.

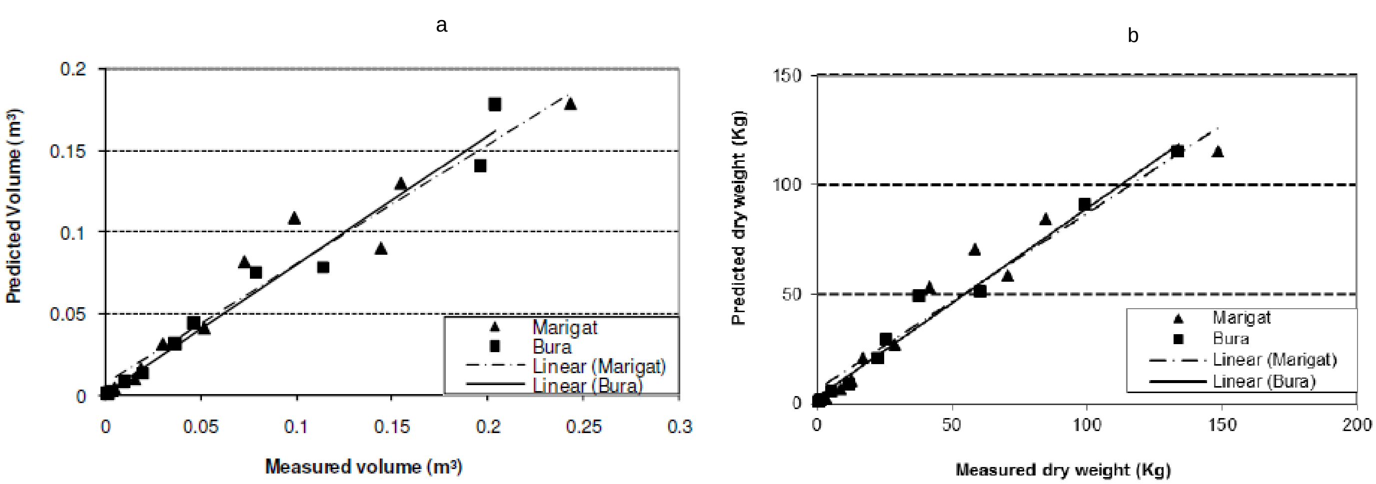

Figure 3. Scatter plots between measured and predicted tree volume (a) and tree dry weight (b). Scatter plots between measured and predicted tree volumes (a) and dry weight (b) for Marigat and Bura. Prediction was based on basal diameter (D_{30}) models. The fitted linear regression lines overlapped in both cases.

Trees sampled from Nadapal were representative of trees found in the other two *Prosopis* stands in Kenya, as evident from good model biomass and volumes prediction at Marigat and Bura (Table 3), despite the distance between the three sites (Figure 1). The slight difference in model validation outputs could be attributed to site variation, since models are sensitive to site conditions (Kairo et al., 2009), among other factors.

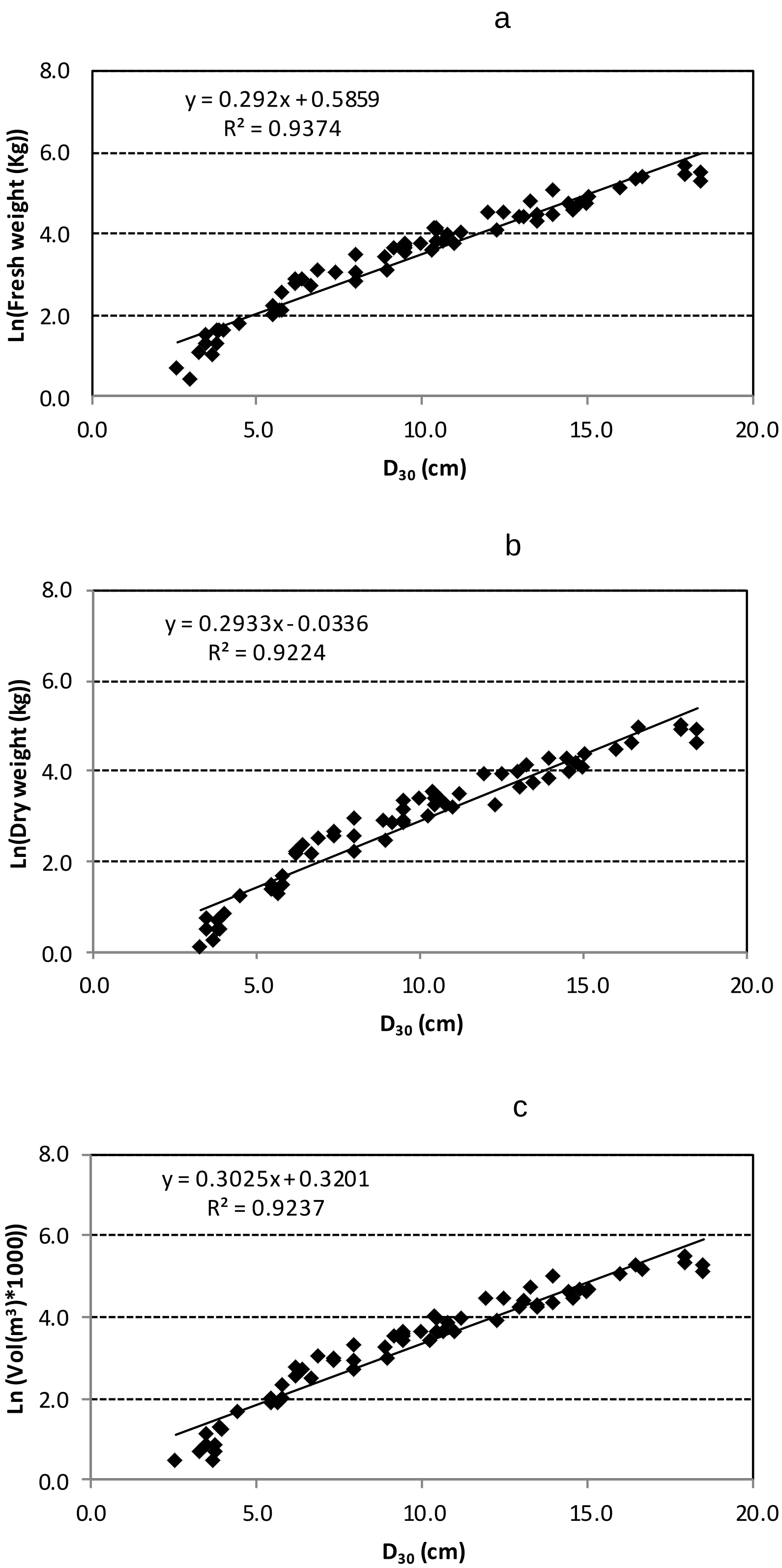

Figure 4. Relationship between basal diameter (D_{30}) and logarithmically transformed (Ln) fresh weight (a), dry weight (b) and volume (c), and basal diameter in *Prosopis* trees. For each case, a linear model (y=ax ±b) and coefficient of determination (R^2), and linear regression model lines are included in the scatterplot.

Table 3. Results of models validation at Marigat and Bura.

Parameter used	Marigat			Bura		
	R^2	SE	F	R^2	SE	F
Fresh weight (Kg)						
D_{30}	0.92	17.9	95.4	0.98	9.7	381.7
$H*D_{30}$	0.93	30.9	106.6	0.97	19.2	299.1
DBH	0.97	13.7	273.5	0.99	7.1	1010.0
H*DBH	0.92	36.3	105.6	0.98	17.0	463.3
Volume (m^3)						
D_{30}	0.93	16.1	109.0	0.97	10.4	304.9
$H*D_{30}$	0.89	38.6	65.3	0.96	24.6	172.7
DBH	0.98	10.9	403.6	0.99	8.1	707.9
H*DBH	0.89	44.7	67.5	0.97	23.0	240.1
Dry weight (Kg)						
D_{30}	0.94	10.1	116.2	0.98	5.9	402.8
$H*D_{30}$	0.94	18.4	130.2	0.99	8.8	602.9
DBH	0.98	8.0	318.8	0.99	5.3	700.9
H*DBH	0.94	22.4	120.5	0.99	7.2	1062.8

Coefficient of determination (R^2), standard error (SE) and F values (F) for linear regression between predicted and measured tree volumes and weights for samples collected at Marigat and Bura. The measured and predicted weight or volume were based on either D_{30}, $H*D_{30}$, DBH or H*DBH as the model variable. For all cases $P < 0.01$.

Compared to Marigat, Bura is a riverine site and sites conditions at Bura may compare favourably with those of Nadapal than site conditions between Marigat and Nadapal. However, the sensitivity of developed models to sites appeared negligible because of overlaps on fitted linear prediction models for both sites (Figure 3). Also site effects were mitigated by pooling all the data in development of final models (Table 4) and (Figure 3).

Biomass and volumes of sampled trees were lower than what was recorded for trees of comparable basal diameters under plantation conditions at the early stages of *Prosopis* introduction to Kenya (Maghembe et al*.,* 1983), despite the use of a lower utilizable diameter branch limit in the current study. The possible explanation for this deviation could be variations in management, sites conditions, the species studied and lack of clarity in point of basal diameter measurement in the previous study. While the species studied under plantation condition was positively identified as *P. juliflora* and their initial management well prescribed (Maghembe et al*.,* 1983), the trees that were sampled in the current study could be a mixture of *P. chilensis, P. juliflora* and *P. pallida*, following multiple introductions of *Prosopis* species, subsequent seeds exchange and seed dispersal by livestock and wildlife (Barrow, 1980; Herlocker et al., 1980; Paetkau, 1980; Mworia et al., 2011). The naturally established stands are also not subjected to any management.

Compared to three sites where trees were sampled in this study, Mombasa has an annual rainfall ≈1200mm (Maghembe et al., 1983), which is higher than in the sites of the current study. It is likely therefore, that soil moisture in the study sites was more limiting to tree growth than in Mombasa.

Stands densities in plots sampled for DBH structure evaluation was within the range found in areas of *Prosopis* invasions (van Klinken et al., 2006). Although comparative studies of biomass in invaded riverine ecosystems is generally lacking, the potential contribution of *Prosopis* to biomass energy was evident from the observed dry weight range. The predicted biomass provides a basis for planned resource exploitation, by selecting trees and or stands that have best fuel wood based on stem diameters.

Conclusions

The trees selected for model development were representative enough for trees found in other *Prosopis* stands in Kenya, as evident from the capacity of developed models to predict tree weights and volume at Bura and Marigat, the distance between sites notwithstanding. By pooling the data for model development and validation, the potential for site sensitivity was mitigated. Therefore, the developed models have a wide application in predicting *Prosopis* biomass and volume in natural stands, particularly in Kenya. Since diameter models were better than height models and height inclusion in multiplicative models did not result to significant model

Table 4. Power models for biomass and volume prediction developed with pooled data from Nadapal, Marigat and Bura.

Predicted parameter	Allometric equation	R^2	SE	F	P Value
D_{30} (cm)					
Fresh weight (Kg)	$Y=0.132X^{2.5301}$	0.98	0.21	2457.6	<0.01
Volume (m^3)	$Y=0.00008X^{2.7058}$	0.98	0.23	2506.1	<0.01
Dry weight (Kg)	$Y=0.0507X^{2.6759}$	0.97	0.23	2418	<0.01
DBH (cm)					
Fresh weight (Kg)	$Y=0.2539X^{2.3909}$	0.96	0.28	1385.0	<0.01
Volume (m^3)	$Y=0002X^{2.5497}$	0.95	0.32	1236.3	<0.01
Dry weight (Kg)	$Y=0.1067X^{2.5142}$	0.95	0.33	1087.7	<0.01
HD_{30}					
Fresh weight (Kg)	$Y=0.01395X^{1.8855}$	0.98	0.19	2948.9	<0.01
Volume (m^3)	$Y= 0.000007X^{2.0147}$	0.98	0.21	2785.0	<0.01
Dry weight (Kg)	$Y= 0.005X^{1.9797}$	0.96	0.27	1714.5	<0.01

Coefficient of determination (R^2), standard error (Se) and F value (F) of allometric equations developed from pooled data that was collected at Nadapal, Marigat and Bura. The equations were derived with basal diameter (D_{30}), diameter at breast height (DBH) and both Height (H) and D_{30} (HD_{30}).

improvement, the use of diameter for biomass and volume prediction is recommended. A choice can be made between use of D_{30} and DBH in biomass and volume estimation, depending on stand characteristics, because the difference between models prediction outputs were insignificant between the two diameters. However, use of D_{30} is highly recommended based on model evaluation parameters. The logarithmic linear D_{30} models recommended for biomass and volume estimation in the field are:

(a) Ln(Fresh weight (Kg)) = $0.292D_{30} + 0.59$ ($R^2 = 0.94$),
(b) Ln(Dry weight (Kg)) = $0.2933D_{30} – 0.03$ ($R^2 = 0.92$) and
(c) Ln(Volume (m^3)*1000) = $0.3025D_{30} + 0.32$ ($R^2 = 0.92$).

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