Wetlands Ecol Manage
DOI 10.1007/s11273-015-9417-3

ORIGINAL PAPER

Procedures for quantification of belowground biomass of three mangrove tree species

Marco Andrew Njana · Tron Eid · Eliakimu Zahabu · Rogers Malimbwi

Received: 10 June 2014 / Accepted: 24 February 2015

Abstract A review of studies on belowground biomass (BGB) of mangroves revealed that procedures for excavation and determination of dry weight are insufficiently documented. The main objective of this study was therefore to describe procedures for quantification of tree BGB for *Avicennia marina* (Forssk.), *Sonneratia alba* J. Smith and *Rhizophora mucronata* Lam. The study covered four sites in Tanzania where 30 trees were sampled (10 for each species). A new root sampling procedure applied for *A. marina* and *S. alba* seemed to work adequately. Dry to fresh weight ratios (DF-ratios) varied between tree species, between tree sizes and between root components. Therefore, for each tree species, tree- and root component-specific DF-ratios were applied for dry weight determination. For *A. marina* and *S. alba* trees, a significant proportion of total tree BGB is stored in the root crown (34 and 10 % respectively). Future studies should therefore ensure inclusion of root crown when accounting for total tree BGB. Tests of previously developed models on our data revealed large prediction errors, partly due to differences in site conditions and partly due to incomprehensive excavation procedures applied when these models were developed. Local tree BGB models for mangroves should therefore be developed.

Keywords *Avicenia–Rhizophora–Sonneratia* · Root biomass · Root sampling · Tanzania

M. A. Njana (✉) · E. Zahabu · R. Malimbwi
Department of Forest Mensuration and Management, Sokoine University of Agriculture, P. O. Box 3013, Morogoro, Tanzania
e-mail: marconjana2002@yahoo.com; njanama@gmail.com

T. Eid
Department of Ecology and Natural Resources Management, Norwegian University of Life Sciences, P. O. Box 5003, 1432 Ås, Norway

Introduction

Mangroves are an important and productive ecosystem. Among other functions, mangroves store large amounts of carbon per unit area (e.g. Murdiyarso et al. 2009; Donato et al. 2011; Kauffman et al. 2011). Large proportions of carbon in mangroves is also stored belowground, which are highly vulnerable to disturbances whose consequences include the release of greenhouse gasses (Hutchings and Saenger 1987; Komiyama et al. 2000; Kauffman and Donato 2012). In Tanzania mainland, mangroves cover about 108,000 ha (Wang et al. 2003). In total there are ten tree species, and among them *Avicenia marina* (Forssk.) Vierh, *Sonneratia alba* J. Smith and *Rhizophora mucronata* Lam. are dominant (Wang et al. 2003; Luoga et al. 2004; Nshare et al. 2007). Despite their importance, mangroves are threatened by deforestation and forest degradation in Tanzania (e.g. Wang

Published online: 04 March 2015

et al. 2003) and in different parts of the globe (e.g. Valiela et al. 2001; FAO 2007).

Various methods may be employed to quantify forest carbon stock. The most common and accurate approach involve the use of models for prediction of tree dry weight, from which carbon stock may be derived (e.g. Brown 1997; Chave et al. 2005, 2014). Development of models requires destructive sampling of trees, where aboveground biomass (AGB) and belowground biomass (BGB) are first determined for fresh weight. Subsequently dry weight is determined by using oven-dry to fresh weight ratio (DF-ratio) derived from sub-samples. Finally, models predicting dry weight biomass based on tree parameters such as diameter breast height (dbh) and total tree height (ht) are developed.

The diversity of tree forms among mangrove species, especially their unusual root systems, along with the growing conditions and changing tides, salinity levels and muddy soils, pose many challenges in field surveys of mangrove forests. In spite of this, quantification of biomass in mangroves has attracted much attention. A review by Komiyama et al. (2008) identified 72 published articles related to biomass and tree allometry. Most of these studies focused on AGB and were largely carried out in Asia while only two were carried out in Africa (Steinke et al. 1995; Slim et al. 1996). Besides, additional studies on biomass and allometry of mangroves by Kirui et al. (2006), Tamooh et al. (2008), Kairo et al. (2008, 2009), Cohen et al. (2013), Lang'at et al. (2013) and Sitoe et al. (2014) carried out in Africa exist. Studies on BGB particularly on allometry are however fewer in number compared to AGB for mangroves. Among the studies from Africa, Steinke et al. (1995), Tamooh et al. (2008), Kairo et al. (2008) and Lang'at et al. (2013) dealt with BGB issues while Kirui et al. (2006) and Kairo et al. (2009) dealt with allometry of BGB for *R. mucronata*. However, the latter two studies sampled the aboveground part of stilt roots only while the belowground part of stilt roots was not considered.

The relatively few studies on BGB of mangroves are obviously due to difficult and tedious excavation conditions. A number of different excavation methods have been applied, however. Some studies have applied full excavation of all roots on small sample plots (e.g. Steinke et al. 1995) or used soil core samples distributed randomly on plots (e.g. Lang'at et al. 2013). With these methods, however, it is not possible to link BGB to a particular tree. Thus, the development of models predicting BGB based on tree variables such as dbh and ht is not possible.

Based on previous literature, we identified four BGB sampling methods where the link between BGB and tree variables exists. The methods include (i) "trench method" (e.g. Komiyama et al. 1987, 2000), (ii) "root ball method" (e.g. Comley and McGuinness 2005), (iii) "pull up method" (e.g. Tamai et al. 1986) and (iv) "total excavation method" (e.g. Ong et al. 2004). The "trench method" is based on the establishment of a trench of a certain size in length, width and depth starting at the base of the subject tree while for the "root ball method" all roots surrounding the subject tree within a limited radius are excavated. For none of these two methods, however, roots are traced to their terminal end. The "pull up method" involves pulling up the roots of individual trees physically. In soft soils and for small trees, loss of root biomass with this method is probably relatively small. However, for large trees, where machinery is required, most likely larger roots will snap and remain unmeasured. The "total excavation method" assumes that all roots belonging to the subject tree are excavated. Although total excavation generally should give the most accurate BGB, probably some parts of the medium sized and fine roots in the deeper zones are lost even with this method.

In addition to the loss of biomass, the main challenge related to all the described methods is the amount of work involved. As a compromise between these two partly conflicting factors, i.e. work load and loss of biomass, one could consider, at least for some of the mangrove species, a "root sampling method" as an alternative. For this method, a few sample roots of different sizes for each tree are traced to their terminal end and weighed for fresh weight. Based on sampled roots from many trees, regression models predicting biomass from the basal diameter of the roots are developed. Finally, these models are used to predict biomass of all roots not excavated based on measurement of basal diameter of the root originating from the root crown. To our knowledge this method has never been applied for mangroves, but has proved successful for tropical dry forests (e.g. Mugasha et al. 2013).

The review of studies on BGB of mangroves also revealed that both excavation procedures and procedures for determining dry weight quite often are imprecisely or insufficiently documented. One

example of insufficient documentation is related to the procedures applied for conversion of fresh weight to dry weight by means of dry to fresh weight ratios (DF-ratios) from sub-samples. The studies however failed to mention whether the DF-ratios are based on the average of the sub-samples from the whole tree, from all belowground parts only or from different root components (e.g. root crown, roots, above- and belowground stilt roots) (e.g. Komiyama et al. 1987). It is obvious that if conversion of fresh to dry weight is not done appropriately, the final estimates of BGB are subject to uncertainty.

The present study focused on the three dominant mangrove species in Tanzania; *A. marina*, *S. alba* and *R. mucronata*. The aims were to (i) describe procedures for excavation of tree BGB, (ii) document procedures for determination of tree BGB, (iii) provide basic information on tree BGB quantities and (iv) test relevant previously developed models for predicting tree BGB.

Materials and methods

Site and tree species descriptions

The study was conducted in four sites distributed along the Tanzanian coastline from north (border with Kenya) to south (border with Mozambique). Study sites included (i) Pangani, (ii) Bagamoyo, (iii) Rufiji and (iv) Lindi–Mtwara (Fig. 1). The study sites represent different soil types and climatic conditions (Table 1). The spring tidal range along the Tanzanian coastline vary from 2 to 4 m (Richmond 1997). The elevations from sea to inland were from 1 to 16 m and from river to inland 2–18 m.

The sites are located in the largest continuous naturally growing mangrove forests along the coastline and are characterised by the dominating three mangrove species in Tanzania, i.e. *A. marina*, *S. alba* and *R. mucronata* (MNRT 1991; Luoga et al. 2004; Nshare et al. 2007). The tree species are structurally distinct and adapted to different environments. For example, while *A. marina* tolerate salinity levels ranging from 12 to 31 ‰, *S. alba* and *R. mucronata* grow best at around 2 and 30 ‰, respectively (Ball and Pidsley 1995; Joshi and Ghose 2003). All three species are ever-green and may exist as single or multi-stemmed trees.

Sampling and excavation procedures

Sample plots

In general, site conditions in mangroves vary transversely with reference to the sea/river (e.g. Dahdouh-Guebas et al. 2004; Lovelock et al. 2005). To cover as much variation as possible, a total of 37 transects were established perpendicular to the sea/rivers. Within these transects, a total of 120 plots were established. The first plot was located close to the edge of the sea/river and the remaining plots were located at fixed distances of 150–250 m depending on the total extension of the forest along transects. For some transects it was not possible to establish all plots because of impenetrable mangrove stand or inaccessibility due to rivers/streams. Therefore the number of plots sampled within transects varied from one to four. Among the 120 plots, 15, 45, 45 and 15 were measured in Pangani, Bagamoyo, Rufiji and Lindi–Mtwara, respectively. Initially the study targeted Bagamoyo only since mangroves in the site represent a large range of functional types of mangrove stands (Spalding et al. 2010). Later we decided to cover more variation by adding sites, and the largest number of plots was allocated to Rufiji since the site represents the largest single block of mangroves in the country.

We established a nested plot design with 2 and 10 m radius concentric plots. On each plot we measured diameter at breast height (dbh) (1.3 m above soil surface for *A. marina* and *S. alba* and 0.3 m above the highest stilt root for *R. mucronata*) for all trees with dbh larger than 1 and 5 cm within the 2 and 10 m radius plots, respectively. All trees were identified for species.

Tree selection

For each plot, one tree was selected for destructive sampling. A total of 120 trees were measured for AGB (not reported on in this study) and 30 out of these were excavated and measured for BGB. In addition to allocation of equal number of trees to each of the three tree species (40), the selection of trees was based on strata defined by five dbh classes; 1–10, 10.1–20, 20.1–30, 30.1–40 and >40 cm. The strata were established based on previous studies on mangrove structure in the country (Mattia 1997; Luoga et al. 2004; Nshare et al. 2007). In the selection of trees for excavation we also checked the conditions on each

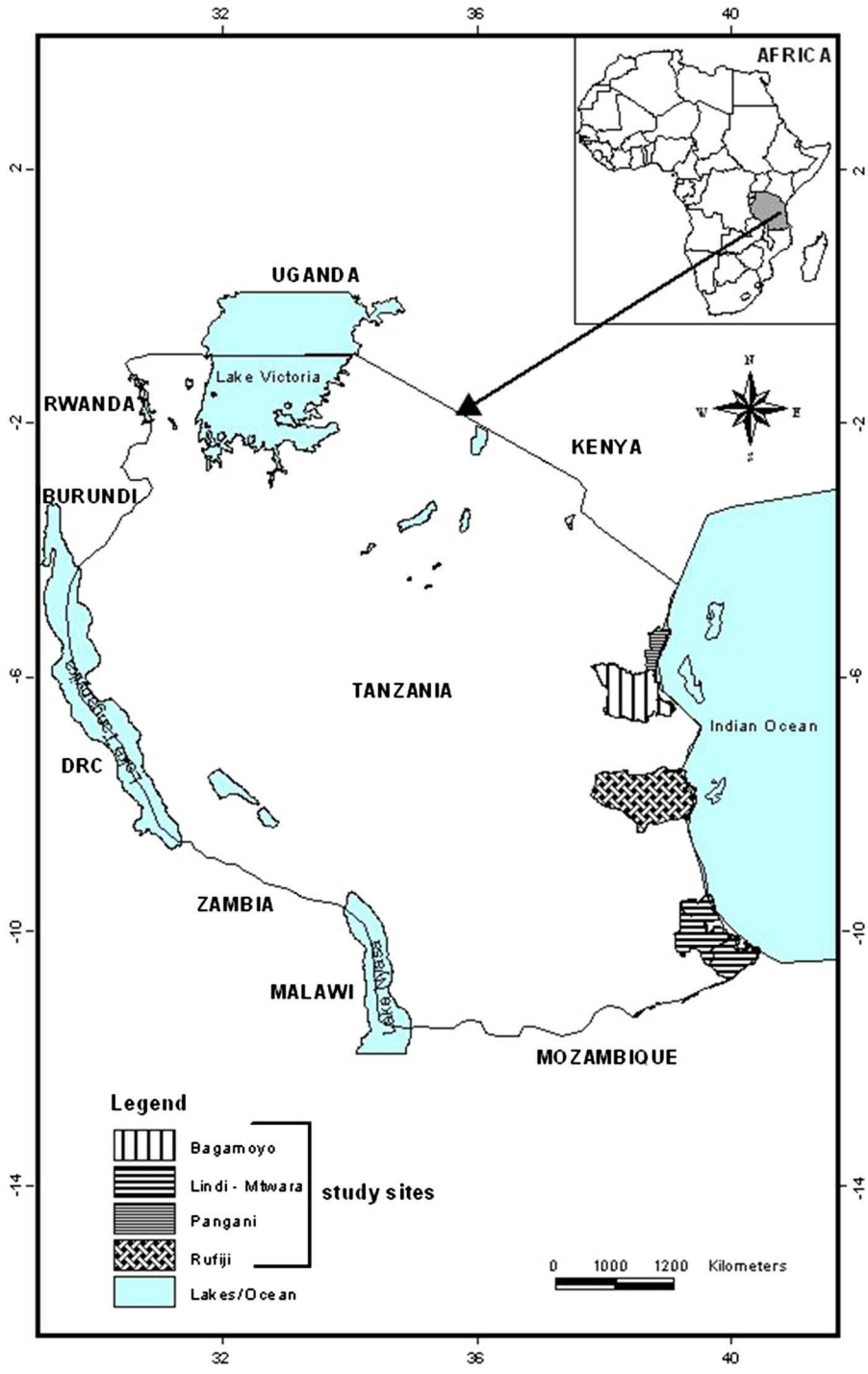

Fig. 1 Map of Tanzania showing the four study sites

plot in order to avoid root system interference and cross-over. Finally, this resulted in the excavation of 3, 15, 9 and 3 trees, respectively, for Pangani, Bagamoyo, Rufiji and Lindi–Mtwara.

For all sample trees belong to *A. marina* and *S. alba* we measured dbh, basal diameter (bd, diameter 15 cm above soil surface), total tree height (ht, distance from soil surface to highest point of the tree), bole height

Table 1 Site, location, dominant soil type, temperature and precipitation for the study sites

Site and location	Dominant soil type	Mean annual min. temperature (°C) Mean ± STD	Mean annual max. temperature (°C) Mean ± STD	Annual rainfall (mm) Mean ± STD
Pangani (5°24′S, 38°59′E)	Alluvial, clay and sandy soils	22.4 ± 0.7	30.8 ± 0.3	1240 ± 333
Bagamoyo (6°26′S, 38°54′E)	Alluvial and sandy soils	21.0 ± 1.5	30.7 ± 0.8	940 ± 239
Rufiji (7°49′S, 39°15′E)	Alluvial, silt and clay soils	23.7 ± 0.5	30.3 ± 0.3	879 ± 200
Lindi (10°2′S, 39°39′E)–Mtwara (10°15′S, 40°10′E)	Alluvial and sandy soils	21.1 ± 0.5	30.2 ± 0.4	1072 ± 249

Source Tanzania Meteorological Agency, rainfall and temperature data; Pangani and Lindi–Mtwara (1970–2012); Bagamoyo (1964–2013) and Rufiji (2005–2012)

(bht, distance from soil surface to first living branch) and crown diameter (crd, average of the longest crown diameter and diameter perpendicular to the longest crown diameter). Crown length (crl) was determined as the difference between total tree height and bole height. For *R. mucronata* we measured the same parameters, but bd was defined to be at the same level as the highest stilt root, while dbh was measured 30 cm above this level. Bole height and ht were measured from the level of the highest stilt root. Diameter at breast height and bd were measured using a diameter tape while crd was determined using a distance tape. Total tree height was measured using a distance tape for small trees and a Suunto hypsometer for larger trees. Three sample trees (*R. mucronata*) were multi-stemmed, i.e. two trees with two stems and one tree with three stems. For these trees, dbh, bd and ht were determined for each stem while crd, bht and crl were recorded for the main stem only (i.e. the stem with the largest dbh). The sample trees covered large variations regarding plot level conditions, i.e. number of trees (N) (trees ha^{-1}) and basal area (G) (m^2 ha^{-1}) for trees with dbh larger than 5 cm, and tree parameters (Table 2).

Excavation procedures

In addition to the root crown, the root systems of *A. marina* and *S. alba* trees may be divided into four parts; cable roots (lateral growth), pneumatophores (vertical upward growth), feeder roots and anchor roots (Fig. 2). For *A. marina*, the pneumatophores are pencil-like, on average about 8 mm thick and peak to about 20 cm above ground level while for *S. alba* are conical-like, about 50 mm thick and peak to about 30 cm above ground level. The root system of *R. mucronata* (Fig. 3) comprises of root crown and above- and belowground stilt roots. Since the three tree species are structurally distinct, procedures for BGB destructive sampling are described separately. To quantify tree BGB we applied root sampling (i.e. not all roots for a given tree were excavated (e.g. Mugasha et al. 2013)) for *A. marina* and *S. alba*. For *R. mucronata* we applied total root excavation (e.g. Ong et al. 2004).

(1) Destructive sampling of BGB for *A. marina*

Trees were cut at 15 cm above ground level using a chain saw (Fig. 2). The cut-off point was guided by National Forest Resources Monitoring and Assessment (NAFORMA) of Tanzania definition of a stump (URT 2010). Then the root crown was excavated while at the same time the main cable roots originating from root crown were partially exposed up to about 0.5 m away from the stump. Finally, the main cable roots were cut from the crown at the point where root begin to swell abruptly. The approach of cutting and immediate felling, followed by excavation of the root crown, however, appeared to be laborious. We therefore employed a new strategy, where the tree was left un-cut while we excavated the root crown and exposed the main cable roots around the base of the tree. This approach proved to be efficient since the weight of the tree, with the help of pushing or wind, aided significantly in unearthing the root crown.

After felling, the root crown was fully excavated. We used a combination of pickaxes, hand hoes, machetes and spades. Subsequently, for each tree, one or two main cable roots including feeder and anchor roots were selected and traced to their terminal end. The root selection for each tree considered inclusion of small and large roots in order to cover a wide cable

Table 2 Statistical summary of sample tree parameters and plot variables

	A. marina ($n = 10$)			*S. alba* ($n = 10$)			*R. mucronata* ($n = 10$)[a]		
	Mean ± STD	Min.	Max.	Mean ± STD	Min.	Max.	Mean ± STD	Min.	Max.
Plot variables									
N (trees ha^{-1})	420 ± 290	0	892	602 ± 532	96	1719	343 ± 319	0	1083
G (m^2 ha^{-1})	10.3 ± 11.0	0	35.6	8.8 ± 6.1	0.3	19.3	9.4 ± 7.1	0	24.2
Tree parameters									
dbh (cm)	17.6 ± 13.2	3.0	38.6	17.1 ± 10.5	6.5	33.8	17.5 ± 10.7	1.4	32.6
bd (cm)	21.4 ± 14.3	4.1	45.4	24.7 ± 15.1	8.2	51.7	16.6 ± 12.2	1.9	39.1
ht (m)	9.6 ± 5.4	3.1	21.5	9.5 ± 4.7	4.0	20.9	7.4 ± 6.4	0.8	18.7
bht(m)	4.2 ± 3.4	0.8	11.0	2.9 ± 2.9	1.1	10.0	4.2 ± 4.9	0.2	12.5
crd (m)	5.2 ± 3.8	1.4	11.9	4.9 ± 3.3	0.7	10.1	4.3 ± 2.5	0.8	8.1
crl (m)	5.4 ± 3.2	1.2	10.2	6.6 ± 2.3	2.8	10.9	5.2 ± 3.1	0.6	9.7

[a] For *R. mucronata*, sample size (n) for all variables was 10 except for dhh, bd and ht where it was 14 because the stems for multi-stemmed trees were regarded as individual trees

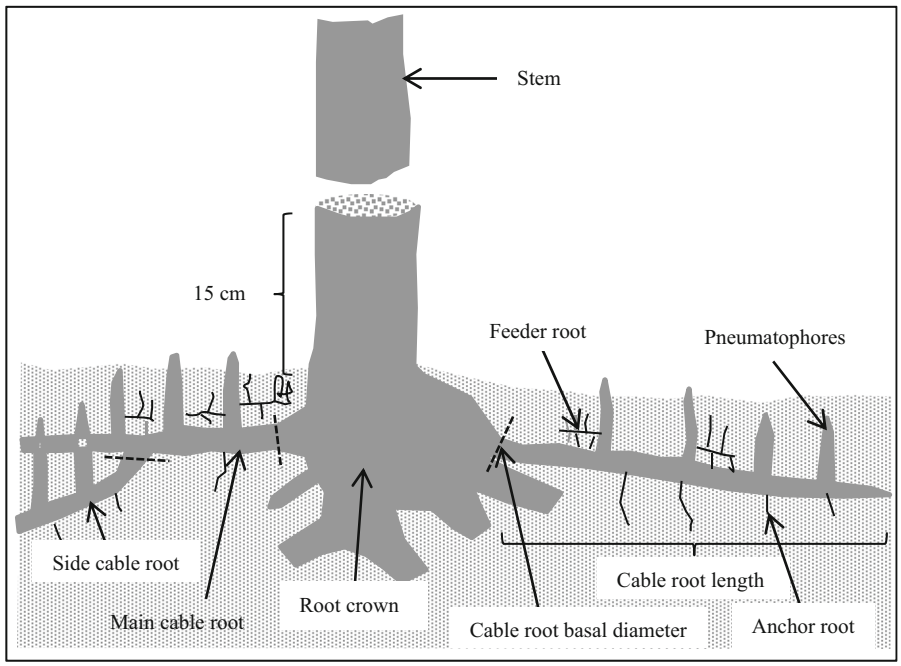

Fig. 2 *Avicennia marina and S. alba* tree root system (modified from Purnobasuki 2013), the *dashed lines* indicate cut-off point between root crown and main cable roots and between main cable roots and side cable roots

root size ranges. Basal diameter of both excavated and unexcavated main and side cable roots (Fig. 2) were measured. Finally, the root crown and all selected cable roots were carefully washed and their fresh weights determined by means of a spring balance (0.1 kg accuracy). In total 20 main cable roots and 22 side cable roots were selected for *A. marina*. Basal diameter of excavated side cable roots ranged from 0.52 to 1.98 cm with a mean of 1.19 cm (the unexcavated roots had a mean basal diameter of 1.23 cm) while for main cable roots basal diameter ranged from 1.02 to 13.53 cm with a mean of 4.33 cm (the unexcavated roots had a mean basal diameter of 2.57 cm).

Excavation pits for exposing roots ranged from 0.2 to 1.4 m in depth while length of traced cable roots

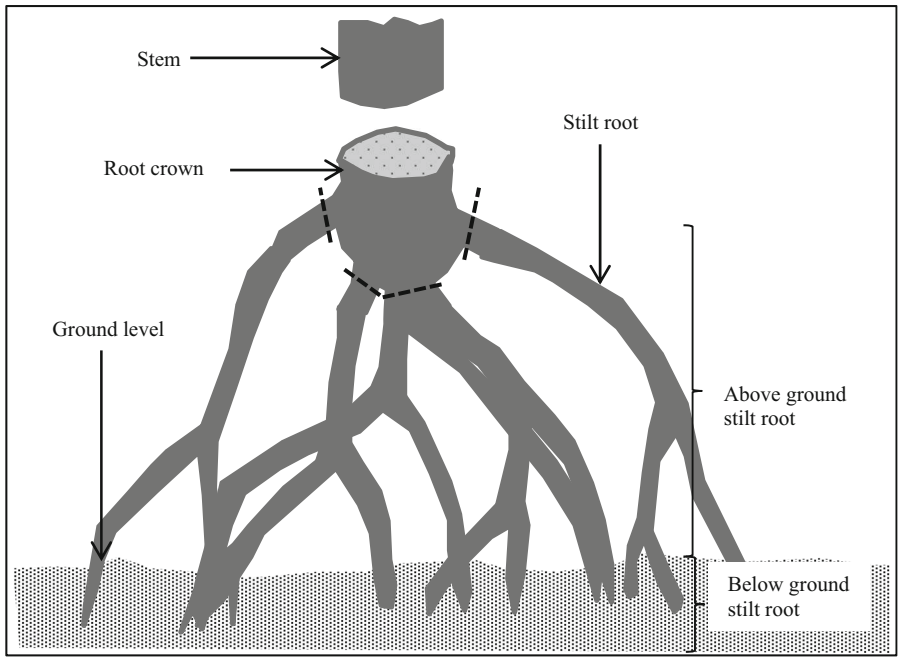

Fig. 3 *Rhizophora mucronata* tree root system, the *dashed lines* indicate cut-off point between root crown and stilt roots

ranged from 1.4 to 16.1 m. Since *A. marina* constitute numerous pneumatophores, it was not possible to identify which ones belonging to which root for those located close to the stump. Pneumatophores located up to about 0.5 m from the stump were therefore excluded. However, beyond 0.5 m around the stump, adequate care was taken to identify and gather all pneumatophores from the main and side cable roots being traced.

Sub-samples from different parts of the root system were taken for laboratory analyses. One sub-sample was taken from each root crown by slicing them from the top down towards the tap root so as to secure an appropriate vertical representation. In addition, sub-samples were taken randomly along the lengths of the selected side or main cable roots. In total for all *A. marina* trees, 10 and 19 sub-samples were taken from root crowns and roots, respectively. All sub-samples were labelled and measured for fresh weight using a digital balance (0.01 g accuracy). On average, the sub-samples added up to about 450 g fresh weight per tree.

(2) Destructive sampling of BGB for *S. alba*

The same approach for excavation and destructive sampling as described for *A. marina* was applied for *S. alba*. In total, 20 main cable roots and 13 side cable roots were selected. Furthermore, 10 and 19 sub-samples were taken from root crown and roots, respectively. Excavated pits ranged from 0.2 to 1.8 m in depth and lengths of root tracing ranged from 1.3 to 14.5 m. The basal diameters ranged from 0.83 to 4.43 cm with a mean of 1.82 cm for the excavated side cable roots (the unexcavated roots had a mean basal diameter of 1.79 cm) and from 1.43 to 10.48 cm with a mean of 5.32 cm for the excavated main cable roots (the unexcavated roots had a mean basal diameter of 3.60 cm).

(3) Destructive sampling of BGB for *R. mucronata*

The excavated BGB for *R. mucronata* included root crown and stilt roots from both above and below the ground level (Fig. 3). This conform with IPCC (2006, 2013) guidelines stating that BGB should include all live roots. The same procedure was followed by Komiyama et al. (2005) for *R. mucronata*, Ong et al. (2004) for *Rhizophora apiculata* and Comley and McGuinness (2005) for *Rhizophora stylosa*. Although contrary to our approach, for example, Tamai et al. (1986) and Kairo et al. (2009) excluded the below-ground stilt roots when sampling BGB for *R. mucronata*.

The stilt roots of *R. mucronata* trees are numerously stocked within a limited area (Fig. 3) and are densely entangled, which made it impossible to trace

individual roots. Instead we performed a total excavation of all roots. After taking tree measurements, the tree was cut just above the root crown (i.e. above the highest stilt root) and felled. Subsequently, the stilt roots were cut approximately at 0.3 m above ground level while the stilt root stumps were marked in order to avoid mixing roots of the subject tree with those of neighbouring trees. Then all belowground stilt roots were completely excavated. The excavation pits ranged from 0.3 to 1.0 m in depth and from 1.6 to 5.1 m in width.

For multi-stemmed *R. mucronata* trees, roots were partitioned based on the proportion of the individual stem basal areas, and each stem was assumed to be a stand-alone tree. For the 10 trees, we therefore have a total of 14 observations for BGB (see also Table 2). A similar procedure is detailed by Clough et al. (1997).

During field work, the different root components of *R. mucronata*, i.e. root crown, above- and belowground stilt roots, were mixed together because initially the study aimed at quantifying total BGB rather than individual component biomass. Despite this, sub-samples from root crown, and above- and belowground stilt roots were extracted separately, weighed for fresh weight, labelled and brought to laboratory for dry weight determination. A total of 7 (from 7 trees), 17 (from 9 trees) and 19 (from 10 trees) sub-samples were extracted from root crowns, and above- and belowground stilt roots, respectively.

Dry weight determination procedures

All sub-samples were taken to laboratory and oven-dried at 105 °C to constant weight. Dry weights of all sub-samples (kg) were determined by using a digital balance.

For *A. marina* and *S. alba,* dry weights of the belowground components, i.e. side and main cable roots and root crown, were determined by multiplying fresh weights and tree- and component-specific DF-ratios derived from the sub-samples. This resulted into individual cable root dry weight (kg root^{-1}) as well as root crown dry weight (kg tree^{-1}). The procedure for determination of total tree BGB (kg tree^{-1}) for *A. marina* and *S. alba* trees was as follows;

(1) From the dry weight of excavated side cable roots (B_{side_excav}), we developed regression models for prediction of dry weight of individual unexcavated side cable roots ($B_{side\_unexcav}$) based on basal side root diameter as predictor variable.
(2) Total dry weight of side cable roots (B_{side}) belonging to an individual main cable root was then determined by adding all predicted dry weights of unexcavated side cable roots to dry weights of excavated side cable roots; $B_{side} = \Sigma\, B_{side\_excav} + \Sigma\, B_{side\_unexcav}$.
(3) Total dry weight of the individual sample main cable roots (B_{main}) was determined by adding dry weight of excavated main cable roots (B_{main_excav}) and dry weight from all side cable roots; $B_{main} = B_{main\_excav} + B_{side}$.
(4) From the dry weight of individual sample main cable roots, we developed regression models for prediction of dry weight of unexcavated main cable roots ($B_{main\_unexcav}$) based on basal main root diameter as predictor variable.
(5) Total tree root dry weight (B_{roots}) was determined by adding dry weights of excavated main cable roots (B_{main}) and dry weights of predicted main cable roots not excavated ($B_{main\_unexcav}$); $B_{roots} = \Sigma\, B_{main} + \Sigma\, B_{main\_unexcav}$.
(6) Total tree BGB was finally determined by adding total tree root dry weight (B_{roots}) and root crown dry weight (B_{rcrown}); $BGB = B_{roots} + B_{rcrown}$.

Since the *R. mucronata* trees were totally excavated and since we did not separate the root components (root crown, and above- and belowground stilt roots) when determining fresh weight in the field, dry weight determination procedure for this species was straightforward; we applied tree-specific DF-ratios without differentiating between the root components to convert fresh weight into total tree BGB.

Analyses

Statistical data analyses

All statistical analyses were carried out in R software version 2.8.0 (R Core Team 2013). Prior to dry weight determination, DF-ratios were subjected to analysis of covariance (ANCOVA) to determine differences between species, between individual trees within the same species and between root components within trees following general linear model (GLM) procedures. When analysing difference in DF-ratio between

species, the root component DF-ratios were summarised to tree level all components (i.e. root crown and root) average or simply tree average. When the differences were significant we applied Bonferroni post hoc tests. Diameter at breast height (dbh) served as a covariate in the analyses and significance levels of 0.1, 1 and 5 % were applied. Since DF-ratios varied between species, between individual trees within the same species and between root components, dry weights of *A. marina* and *S. alba* (as described above) were determined by multiplying fresh weight and tree- and component-specific DF-ratios derived from subsamples. ANCOVA was also applied when testing differences in total tree BGB between the tree species.

During explorative data analysis, we found that the relationships between main and side cable root dry weights and basal diameter were nonlinear. We therefore initially tested several options to describe the nonlinear relationships (e.g. second order polynomial functions and exponential functions) but found the power function as the best. The power function has also been widely used to describe biomass relationships (e.g. Niklas 2004; Komiyama et al. 2008). The model form was as follows:

$$B = \beta_0 \times x^{\beta_1} + \varepsilon$$

where B = root dry weight of main/side cable roots (kg root^{-1}), x = main/side cable root basal diameter (cm), β_0 and β_1 are model parameters and ε is an additive error term.

The model fitting was done by using 'nls2' function in R software (R Core Team 2013). Both ordinary and weighted nonlinear least squares methods were employed in estimation of model parameters. Regression assumptions on homoscedasticity and normal distribution of residuals were examined by means of graphical plots (plots not displayed in results). Where heteroscedastic error distributions were observed, nonlinear weighted least squares were employed to compensate for violation of homoscedasticity and allocate less weight to extreme observations. Root mean square error (*RMSE*) and mean prediction error (*MPE (%)*) for the models were computed as follows:

$$RMSE = \sqrt{\frac{\sum e^2}{n}}$$

where e = residuals, i.e. differences between predicted and observed dry weights (kg) and n = number of observations, and

$$MPE\,(\%) = \left(\frac{\sum (e)/n}{MB_{obs}}\right) \times 100$$

where MB_{obs} = mean observed dry weight (kg). Two-tailed paired *t*-tests were employed to determine the significance of *MPE (%)*.

Relationships between BGB and tree variables were determined using Spearman correlation tests. Significance levels of 0.1, 1 and 5 % were applied.

Evaluation of existing models

Based on literature, we found four models for prediction of tree BGB relevant for testing on our data. The models included a common model developed by Komiyama et al. (2005) (model 1), a species-specific model for *A. marina* developed by Comley and McGuinness (2005) (model 2) and two species-specific models for *R. mucronata* developed by Tamai et al. (1986) (model 3) and Kairo et al. (2009) (model 4);

$$BGB = 0.199 \times \left(\rho^{0.899}\right) \times \left(dbh^{2.22}\right), \left(R^2 = 0.95,\ \mathrm{SE} = 1.81\right) \quad (1)$$

$$BGB = 1.28 \times \left(\mathrm{dbh}^{1.171}\right), \left(R^2 = 0.80,\ \mathrm{RMSE} = 0.268\right) \quad (2)$$

$$BGB = 0.00974\left(\mathrm{dbh}^2 \times ht\right)^{1.0525} \quad (3)$$

$$\log_{10}(BGB) = -1.3010 + 2.4044 \times \log_{10}(dbh),\ \left(R^2 = 0.70,\ \mathrm{SE} = 0.37\right) \quad (4)$$

where BGB = total tree belowground dry weight (kg), ρ = wood density (gcm^{-3}), dbh = diameter at breast height (cm) and ht = total tree height (m). The model reported by Komiyama et al. (2005) requires wood density as a predictor variable. However, wood density values for mangrove species are lacking in Tanzania and Africa in general. We therefore used data from the global wood density (GWD) database (Zanne et al. 2009; Chave et al. 2009). Since we found more than one wood density value for *A. marina*, *S. alba* and *R. mucronata* in GWD database and the values were variable, we applied species-specific mean values, i.e. 0.648 for *A. marina*, 0. 508 for *S. alba* and 0.814 for *R. mucronata.*

Results

Dry to fresh weight ratios (DF-ratios) varied between the tree species and root components (Table 3). The

results based on the ANCOVA test showed that for all components DF-ratio varied significantly between tree species ($F_{(2,\ 26)} = 11.866$, $p < 0.001$). The Bonferroni post hoc tests showed that all components DF-ratio for *S. alba* (0.387 ± 0.027 (STD)) was significantly lower than those of *A. marina* (0.490 ± 0.041 (STD)) and *R. mucronata* (0.470 ± 0.040 (STD)) ($p < 0.01$). All components DF-ratios for *A. marina* and *R. mucronata* were not statistically different ($p > 0.05$). For all the three species, DF-ratios also varied significantly between the belowground components: *A. marina* ($F_{(1,\ 17)} = 22.603$, $p < 0.001$), *S. alba* ($F_{(1,\ 17)} = 5.562, p < 0.05$) and *R. mucronata* ($F_{(2,\ 22)} = 15.163$, $p < 0.001$). The Bonferroni post hoc tests showed that for *A. marina* and *S. alba*, root crown DF-ratios were significantly larger than their corresponding root DF-ratios ($p < 0.05$) while for *R. mucronata*, root crown and aboveground stilt root DF-ratios were significantly larger than the belowground stilt root DF-ratio.

The tree level root component DF-ratios varied with tree size (dbh) (Fig. 4). The variation is explained by linear (*S. alba* roots and *R. mucronata*) and second order polynomial functions (*A. marina* and *S. alba* root crown). With the exception of root crown DF-ratio for *A. marina* ($R^2 = 0.49$, $p > 0.05$) and belowground stilt root DF-ratio for *R. mucronata* ($R^2 = 0.003$, $p > 0.05$), the variations were significant ($p < 0.05$).

Models for prediction of side and main cable roots dry weight were developed (Table 4; Fig. 5). Generally, the *A. marina* models showed better fit (lower RMSE values and higher R^2 values) than *S. alba* models. All models revealed non-significant ($p > 0.05$) MPE (%) values. For all models, the distributions of residuals were approximately normally distributed although the residuals slightly increased with increasing basal diameter of the roots.

Mean total tree BGB for *A. marina* (n = 10), *S. alba* (n = 10) and *R. mucronata* (n = 14) were 100.5 ± 93.7 (STD) kg, 273.2 ± 346.7 (STD) kg and 166.0 ± 160.9 (STD) kg, respectively. Despite similarities in tree size (mean dbh of 17.6, 17.1 and 17.5 for *A. marina, S. alba* and *R. mucronata*, respectively, see Table 2) and root size (cable root diameters (~up to 13 m) and root lengths (~up to 16 m)), the ANCOVA test showed tree BGB was significantly different between species ($F_{(2,\ 30)} = 3.41, p < 0.05$). Accordingly, Boferroni post-hoc tests revealed that, tree BGB was significantly different between *A. marina* and *S. alba* while for the remaining pairs the differences were not statistically significant ($p > 0.05$). On average for *A. marina*, the root crown contributed 34 % (34.0 ± 35.5 (STD) kg) of the total tree BGB while 66 % (66.5 ± 61.0 (STD) kg) came from the roots. The corresponding proportions were 90 % (246.0 ± 329.6 (STD) kg) and 10 % (27.6 ± 38.1 (STD) kg) for *S. alba*. This paper however, provides no information on biomass for the root components of *R. mucronata*.

Spearman correlation coefficients described the relationships between total tree BGB and different tree variables (Table 5). All tree variables, except bole height (bht) for *S. alba*, correlated positively with tree BGB. The correlations were generally strong (ranging from 0.85 to 0.99) and statistically significant ($p < 0.05$), for dbh, basal diameter (bd) and crown diameter (crd). Total tree height (ht) and crown length (crl) correlated poorly with tree BGB for *A. marina* and S. *alba* and the relationships were statistically non-significant ($p > 0.05$). However, the

Table 3 Descriptive statistics on distribution of DF-ratios

Species	Belowground component	*n*	Mean ± STD	Min.	Max.
A. marina	-Root crown	*10*	0.536 ± 0.040	0.442	0.580
	-Root	*10*	0.444 ± 0.051	0.336	0.515
	All components	*10*	*0.490 ± 0.041*	*0.389*	*0.540*
S. alba	-Root crown	*10*	0.424 ± 0.065	0.334	0.544
	-Root	*10*	0.350 ± 0.073	0.262	0.537
	All components	*10*	*0.387 ± 0.027*	*0.339*	*0.437*
R. mucronata	-Root crown	*7*	0.607 ± 0.048	0.551	0.680
	-Aboveground stilt root	*9*	0.535 ± 0.045	0.466	0.621
	-Belowground stilt root	*10*	0.363 ± 0.135	0.243	0.613
	All components	*10*	*0.470 ± 0.040*	*0.424*	*0.560*

All components = root crown and root

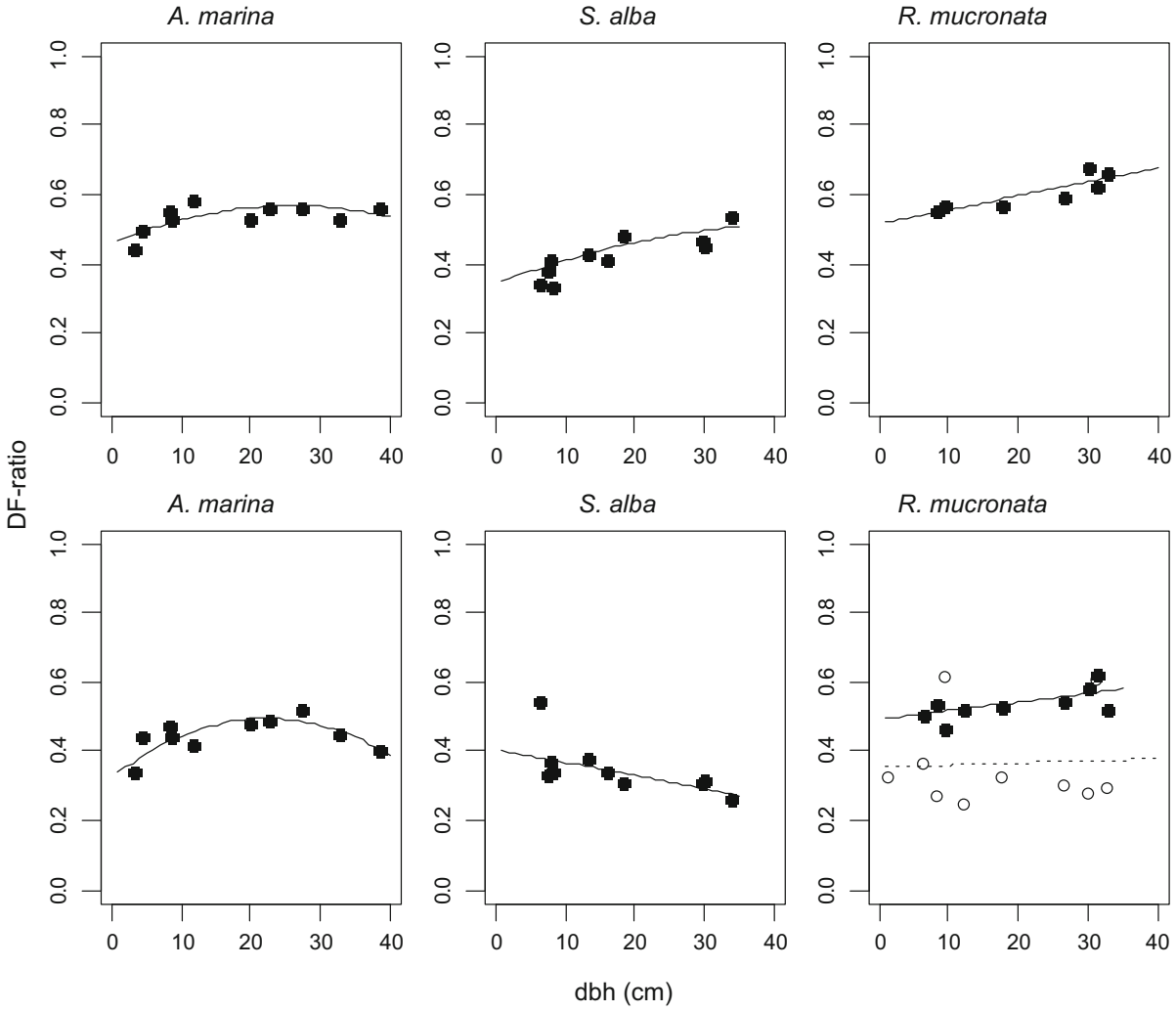

Fig. 4 Tree level DF-ratios over tree species and dbh for root crown (*upper panel*) and roots (*lower panel*). Individual tree DF-ratio values (*solid dots*) and trend lines for individual tree values (*solid line*). Roots for *R. mucronata* (*lower panel*) are divided into aboveground stilt roots (*solid dots*, *solid line*) and belowground stilt roots (*open dots*, *dotted line*)

Table 4 Models for side and main cable root dry weight prediction

Species	Model	*n*	Parameters		RMSE	R^2	MPE %
			β_0	β_1			
A. marina	Side cable root	*20*	0.10123***	2.60603***	0.085	0.76	−1.0
A. marina	Main cable root	*22*	0.20390**	1.60410***	0.321	0.73	+0.1
S. alba	Side cable root	*13*	0.46310**	1.60600***	0.519	0.45	+0.8
S. alba	Main cable root	*20*	0.01817*	3.48190***	2.814	0.63	−1.6

Model form; $B = \beta_0 \times x^{\beta_1} + \varepsilon$ where B = root dry weight (kg root^{-1}), x = side/main cable root basal diameter (cm), β_0 and β_1 are model parameters and ε is an additive error term

* Significant at 5 %, ** significant at 1 % and *** significant at 0.1 %

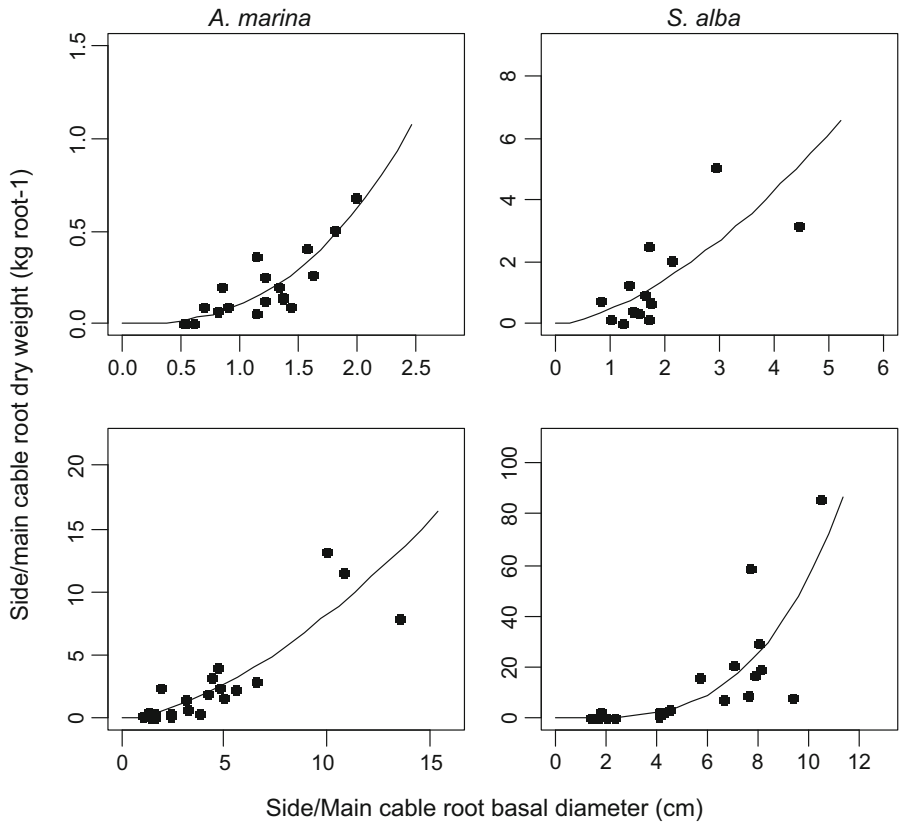

Fig. 5 Side (*upper panel*) and main (*lower panel*) cable root dry weight models (*solid line*) and observations (*solid dots*) for *A. marina* and *S. alba*

corresponding correlations were stronger for *R. mucronata*.

The prediction errors for the models selected from previous studies when tested on our data (Table 6). For all cases, except when the common model developed by Komiyama et al. (2005) was applied on *A. marina* data set, the models under-estimated tree BGB (not significant for *S. alba*). Where tested models under-estimated tree BGB, MPE values ranged from -56.1 ± 62.5 (STD) kg (-33.8 %) to -186.6 ± 290.4 (STD) kg (-68.3 %). When the common model developed by Komiyama et al. (2005) was applied on *A. marina* data set, the model over-estimated tree BGB by 26.2 ± 69.8 (STD) kg (26.1 %), although not statistically significant ($p > 0.05$).

Discussion

The basic task in any quantification of biomass dry weight is the determination of DF-ratio.

The DF-ratios varied significantly between the three species. Within species, DF-ratios also varied between root components and tree sizes. Based on our results we therefore suggest that future studies should avoid the use of mean DF-ratios across species, root components and trees. Instead, species-, tree- and root component-specific DF-ratios should be applied. Comparable results on DF-ratios for tree BGB of mangrove species are difficult to find in literature. Often DF-ratios are not reported (e.g. Tam et al. 1995; Komiyama et al. 2005; Comley and McGuinness 2005; Kairo et al. 2009). In addition, for the core sampling method (e.g. Tamooh et al. 2008) and the "trench method" (e.g. Komiyama et al. 1987), it is not clear how the root sub-samples for generation of DF-ratios were extracted, how the DF-ratios of roots from different species and tree sizes were distinguished and treated; and finally how they arrived at tree dry weight. Our study has clearly demonstrated that, unless the determination of DF-ratios is consciously and appropriately dealt with, the quantification of dry weight is subject to uncertainties.

The developed side and main cable root dry weight models for *A. marina* and *S. alba* generally showed strong relationships between basal diameter and dry

Table 5 Correlation between total BGB dry weight and tree variables

Variable	Total belowground dry weight (kg tree^{-1})		
	A. marina ($n = 10$)	*S. alba* ($n = 10$)	*R. mucronata* ($n = 10$)[a]
dbh (cm)	+0.99**	+0.87**	+0.93**
bd (cm)	+0.98**	+0.94**	+0.98**
ht (m)	+0.53^{NS}	+0.15^{NS}	+0.83**
bht (m)	+0.33^{NS}	−0.24^{NS}	+0.90**
crd (m)	+0.94**	+0.96**	+0.85**
crl (m)	+0.53^{NS}	+0.33^{NS}	+0.87**

Spearman correlation analysis (e.g. Crawley 2007)

[a] For dbh, bd and ht, $n = 14$, *NS* not significant at 5 %, * significant at 5 %, ** significant at 1 % and *** significant at 0.1 %

Table 6 Mean prediction errors of previously developed BGB models

Species	Model	Wood density	BGB (kg tree^{-1})		MPE	
			Pred.	Obs.	Mean ± STD (kg tree^{-1})	(%)[b]
A. marina ($n = 10$)	Common, Komiyama et al. (2005)	$\rho = 0.648$[a]	126.7	100.5	+26.2 ± 69.8	26.1^{NS}
	Species-specific, Comley and McGuinness (2005)	–	38.4	100.5	−62.8 ± 63.9	−62.5*
S. alba ($n = 10$)	Common, Komiyama et al. (2005)	$\rho = 0.508$[a]	86.6	273.2	−186.6 ± 290.4	−68.3^{NS}
R. mucronata ($n = 14$)	Common, Komiyama et al. (2005)	$\rho = 0.814$[a]	109.9	166.0	−56.1 ± 62.5	−33.8**
	Species-specific, Tamai et al.(1986)	–	75.0	166.0	−91.0 ± 75.5	−54.8**
	Species-specific, Kairo et al. (2009)	–	60.8	166.0	−105.2 ± 91.3	−63.4**

[a] Wood density based on global wood density database (Zanne et al. 2009; Chave et al. 2009)

[b] Two-tailed *t*-tests, *NS* not significant at 5 %, * significant at 5 %, ** significant at 1 % and *** significant at 0.1 %

weights. The mean prediction errors (MPE) for all models were statistically insignificant. It is, however, worth mentioning that main cable root residual variance increased with increasing root basal diameter. Although this pattern is normal for biomass regression models, this point at challenges concerning uncertainty when models are applied outside their data range, as is the case in the current study. For example, the largest basal diameter in the data used to develop the main cable root model for *A. marina* was 13.5 cm, while the largest basal diameter that we measured was 18.5 cm. Clearly when applying a root sampling procedure, like in the present study, extrapolation cannot be avoided. However, including as large data ranges as much as possible, when selecting sample roots, is vital to overcome such challenges. Selection of "one small and one big" root for each sample tree, as done in our study, was an attempt to include diverse root size covering a reasonable data range as a basis for the root dry weight models. Possibly the models would have improved if larger roots were included.

The mean total tree BGB for *A. marina* and *S. alba* were quite different. The larger pneumatophores of *S. alba* as compared to *A. marina* probably explains much of this difference. Larger side and main cable roots for *S. alba* could be another explanation for the observed differences in tree BGB between the two species. It is also worth mentioning that we found relatively large proportions of the total tree BGB for *A. marina* and *S. Alba* stored in root crowns. This suggest that sampling approaches such as root coring (e.g. Tamooh et al. 2008), where the sampling (coring) often is done around the subject tree without including root crown, leaves out an important part in accounting for total tree BGB. The total tree BGB for *R. mucronata* was determined, but unfortunately we do not have any information on the different components of the root system (root crown, above- and

belowground stilt roots) for this species. Obviously the excavation procedure for *R. mucronata* should be modified to accommodate separation of tree BGB into root components.

The strong and statistically significant relationships seen between basal diameter (bd), dbh and crown diameter (crd) and total tree BGB suggest that these variables may be important predictors in tree BGB models. It is worth mentioning that crd as a predictor variable may be of particular interest since the technology for assessment of biomass is advancing. Wannasiri et al. (2013) and Hirata et al. (2014), for example, used high resolution data based on Lidar and QuickBird, respectively, and estimated biomass of mangroves by using crd as predictor variable. Besides, tree height (ht) is usually an important predictor variable in biomass models (e.g. Chave et al. 2014). For our data, however, the relationships between this variable and tree BGB were relatively weak for *A. marina* and *S. alba,* yet stronger for *R. mucronata*.

When the common model developed by Komiyama et al. (2005) was tested on our data, tree BGB were over-estimated for *A. marina* and under-estimated for *S. alba* and *R. mucronata*. Since differences in forest structure, soil, salinity and climate may influence the results, it is generally not surprising that large prediction errors appear when this model is applied outside the data range from where it was developed. A common model is also supposed to work for all relevant tree species, but the data used by Komiyama et al. (2005) did not include *A. marina* (which was one of the target species for the test on our data). Excavation procedures may also have influenced the prediction errors. However, since Komiyama et al. (2005) partly applied full excavation we do not believe that the excavation procedure is a major factor here.

The tested species-specific models (Comley and McGuinness 2005; Tamai et al. 1986; Kairo et al. 2009) all significantly under-estimated tree BGB. The most likely explanation for such under-estimations is loss of biomass due to the excavation procedures applied when these models were developed. For *A. marina,* Comley and McGuinness (2005) applied the "root ball method". Irrespective of tree size; they limited excavation to a radius of 2 m from the subject tree. Since we in the present study sampled roots as far as 16 m from the tree base, it is quite obvious that models based on data from "root ball method" generally under-estimates tree BGB, and that the under-estimation increases with tree size. Similarly, when Tamai et al. (1986) and Kairo et al. (2009) developed their *R. mucronata* models they did not excavate the belowground stilt roots. Since we during field work observed that a significant proportion of the tree BGB originated from the belowground stilt roots, it is not surprising that the models developed by Tamai et al. (1986) and Kairo et al. (2009) under-estimated tree BGB.

According to Chave et al. (2005, 2014) and Komiyama et al. (2005) the prediction quality of biomass models is improved by including wood density as predictor variable.

However, various sources of information on wood density, including the GWD database (Zanne et al. 2009; Chave et al. 2009), show that species-specific wood density values are variable and that the reasons for such variation is not well documented. Wood density of *A. marina*, for example, varies from 0.520 to 0.732 in the GWD database. Wood density values for the three studied mangrove species based on sites from Tanzania and Africa are in general lacking in the database. In addition to differences in wood density between sites, within-tree differences are likely to be present (e.g. Nock et al. 2009; Santini et al. 2012). It is important that such differences are understood and taken into account when developing models for prediction of biomass. To our knowledge such issues have hardly been investigated for mangroves.

Biomass and carbon quantification are imperative for the implementation of reducing emission from deforestation and forest degradation (REDD) programs. To engage in such programs, Tanzania like other participating countries, need reliable assessment tools for biomass quantification in various forest types including mangroves. This is of particular importance for Tanzania since the country started the first national forest inventory in 2009 (URT 2010). Therefore, more research on mangroves is needed, not only on basic issues such as wood density, but also on the development of local tree BGB models.

Conclusions

The present study applied an excavation procedure involving root sampling when quantifying tree BGB for *A. marina* and *S. alba.* This procedure has never been applied to mangroves previously, but seemed to work adequately. Within a given budget, the

procedure facilitates more trees to be included in a sample compared to if all roots are excavated. DF-ratios varied between species, trees and root components. Therefore, species-, tree- and root component-specific DF-ratios were applied in conversion of fresh to dry weight biomass. For *A. marina* and *S. alba* trees, a significant proportion of total tree BGB is stored in the root crown. Future studies should therefore ensure inclusion of root crown in accounting for total tree BGB. Tests of previously developed models on our data revealed large prediction errors, partly due to differences in site conditions and partly due to incomprehensive excavation procedures applied when these models were developed. Local tree BGB models for mangroves should therefore be developed.

Acknowledgments This research work was financed by the Climate Change Impacts and Adaptation Mitigation (CCIAM) Programme under the cooperation between the Government of the United Republic of Tanzania and the Government of the Kingdom of Norway. We are also grateful for supplementary funding by the Project "Enhancing the Measuring, Reporting and Verification (MRV) of forests in Tanzania". Besides we are indebted to D. Mnyagi (Pangani), S.K. Nyabange (Bagamoyo), H. Mallya (Rufiji) and M.C. Mbago (Mtwara), working for Tanzania Forest Service, for logistical support during field work. The field assistants including boat drivers are also acknowledged for their hard work and courage throughout an intensive and tiresome data collection. The anonymous reviewers are appreciated for their valuable and critical comments.

Funding The work reported here was financed by the CCIAM Programme and Enhancing the measuring, reporting and verification (MRV) of forests in Tanzania Project both under the cooperation between the Government of United Republic of Tanzania and the Kingdom of Norway.

References

Ball MC, Pidsley SM (1995) Growth responses to salinity in relation to distribution of two mangrove species, *Sonneratia alba* and *S. lanceolata*, in northern Australia. Funct Ecol 9(1):77–85

Brown S (1997) Estimating biomass change of tropical forests: primer. FAO forestry paper 134. FAO, Rome

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B, Yamakura T (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99

Chave J, Coomes DA, Jansen S, Lewis SL, Swenson NG, Zanne AE (2009) Towards a worldwide wood economics spectrum. Ecol Lett 12:351–366

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martínez-Yrízar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Pélissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G (2014) Improved allometric models to estimate the aboveground biomass of tropical forests. Glob Chang Biol 20:3177–3190

Clough BF, Dixon P, Dalhaus O (1997) Allometric relationships for estimating biomass in multi-stemmed mangrove trees. Aust J Bot 45:1023–1031

Cohen R, Kairo J, Okello JA, Bosire JO, Kairo JG, Huxham M, Mencuccine M (2013) Propagating uncertainty to estimates of above-ground biomass for Kenyan mangroves: a scaling procedure from tree to landscape level. For Ecol Manag 310:968–982

Comley BWT, McGuinness KA (2005) Above- and below-ground biomass, and allometry of four common northern Australian mangroves. Aust J Bot 53:431–436

Crawley MJ (2007) The R book. Wiley, Chichester

Dahdouh-Guebas F, De Bondt R, Abeysinghe PD, Kairo JG, Cannicci S, Triest L, Koedam N (2004) Comparative study of the disjunct zonation pattern of the grey mangrove *Avicennia Marina* (Forsk.)Vierh. In Gazi Bay (Kenya). Bull Mar Sci 74:237–252

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M (2011) Mangroves among the most carbon-rich forests in the tropics. Nat Geosci 4:293–297

Food and Agriculture Organization of the United Nations (FAO) (2007) The World's mangroves 1980–2005. FAO forestry paper 153. FAO, Rome

Hirata Y, Tabuchi R, Patanaponpaiboon P, Poungparn S, Yoneda R, Fujioka Y (2014) Estimation of aboveground biomass in mangrove forests using high-resolution satellite data. J For Res 19:34–41

Hutchings P, Saenger P (1987) Ecology of mangroves. University of Queensland Press, Brisbone, p 388

IPCC (2006) Guidelines for national greenhouse gas inventories. Vol. 4: agriculture, forestry and other landuse. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) IPCC, Inter-governmental panel on climate change (IPCC). IPCC/IGES, Hayama

IPCC (2013) Revised supplementary methods and good practice guidance arising from the Kyoto protocol. In: Irving W, Zhou L (eds) Inter-governmental panel on climate change (IPCC). IPCC/IGES.3, Stockholm

Joshi H, Ghose M (2003) Forest structure and species distribution along soil salinity and pH gradient in mangrove swamps of the Sundarbans. Trop Ecol 44(2):197–206

Kairo JG, Joseph KSL, Dahdouh-Guebas F, Bosire J, Karachi M (2008) Structural development and productivity of replanted mangrove plantations in Kenya. For Ecol Manag 255:2670–2677

Kairo JG, Bosire J, Langat J, Kirui B, Koedam N (2009) Allometry and biomass distribution in replanted mangrove plantations at Gazi Bay, Kenya. Aquat Conserv 19:S63–S69

Kauffman JB, Donato DC (2012) Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working paper 86. CIFOR, Bogor

Kauffman JB, Heider C, Cole T, Dwire KA, Donato DC (2011) Ecosystem Carbon stocks of Micronesian mangrove

forests: implications of land use and climate change. Wetlands 31:343–352
Kirui B, Kairo JG, Karachi M (2006) Allometric equations for estimating aboveground biomass of *Rhizophora mucronata* mangroves at Gazi Bay Kenya. WIOJMS5 5(1):27–34
Komiyama A, Ogino K, Akisornkoae S, Sabhasri S (1987) Root biomass of a mangrove forest in Southern Thailand 1. Estimation by trench method and the zonal structure of root biomass. J Trop Ecol 3:97–108
Komiyama A, Havanond S, Srisawatt W, Mochida Y, Fujimoto K, Ohnishi T, Ishihara S, Miyagi T (2000) Top/root biomass ratio of a secondary mangrove (*Ceriops tagal* (Perr.) C.B. Rob.) forest. For Ecol Manag 39:127–134
Komiyama A, Poungparn S, Kato S (2005) Common allometric equations for estimating the tree weight of mangroves. J Trop Ecol 21:471–477
Komiyama A, Ong JE, Poungparn S (2008) Allometry, biomass, and productivity of mangrove forests: a review. Aquat Bot 89:128–137
Lang'at JKS, Kirui BKY, Skov MW, Kairo JG, Mencuccini M, Huxham M (2013) Species mixing boosts root yield in mangrove trees. Oecologia 172:271–278
Lovelock CE, Feller IC, McKee KL, Thompson R (2005) Variation in mangrove forest structure and sediment characteristics in Bocas del Toro, Panama. Caribb J Sci 41(3):456–464
Luoga EJ, Malimbwi RE, Kajembe GC, Zahabu E, Shemwetta DTK, Lyimo-Macha J Mtakwa P Mwaipopo CS (2004) Tree species composition and structures of Jasini Mwajuni Mangrove forest at Pangani, Tanzania. J TAF10: 42–47
Mattia SB (1997) Species and structural composition of natural mangrove forests: a case study of the Rufiji delta. Tanzania. Dissertation for award of MSc. Degree at Sokoine University of Agriculture, Morogoro, Tanzania
MNRT (Ministry of Natural Resources and Tourism) (1991) Management plan for the mangrove ecosystem of Rufiji District, mainland Tanzania, vol 7. Ministry of Tourism, Natural Resources and Environment (MTNRE), Forestry and Beekeeping Division, Catchment Forestry Project, Dar es Salaam
Mugasha WA, Eid T, Bollandsås OM, Malimbwi RE, Chamshama SAO, Zahabu E, Katani JZ (2013) Allometric models for prediction of above- and belowground biomass of trees in the miombo woodlands of Tanzania. Forest Ecol Manag 310:87–101
Murdiyarso D, Donato DC, Kauffman JB, Stidham M, Kurnianto S, Kanninen M (2009) Carbon storage in mangrove and peatland ecosystems in Indonesia—a preliminary account from plots in Indonesia. Working paper 48. Center for International Forest Research, Bogor
Niklas KJ (2004) Plant allometry: is there a ground unifying theory? Biol Rev 79:871–889
Nock CA, Geihofer D, Grabner M, Baker PJ, Bunyavejchewin S, Hietz P (2009) Wood density and its radial variation in six canopy tree species differing in shade-tolerance in western Thailand. Ann Bot 104:297–306
Nshare JS, Chitiki A, Malimbwi RE, Kinana BM, Zahabu E (2007) The current status of the mangrove forest along seashore at Salenda bridge, Dar es Salaam, Tanzania. J TAF 11:172–179
Ong JE, Gong WK, Wong CH (2004) Allometry and partitioning of the mangrove, *Rhizophora apiculata*. For Ecol Manag 88:395–408
Purnobasuki H (2013) Characteristics of root caps in four root types of *Avicennia marina* (Forsk.) Vierh. Am J P Sci 4:853–858
Richmond MD (ed) (1997) A guide to the sea shores of Eastern Africa and the Western Indian Ocean islands. Sida Department for Research Cooperation, SAREC, Stockholm
R Core Team (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. http://www.R-project.org/. Accessed 20 Nov 2013
Santini NS, Schmitz N, Lovelock CE (2012) Variation in wood density and anatomy in a widespread mangrove species. Trees 26:1555–1563
Sitoe AA, Mandlate LJC, Guedes BS (2014) Biomass and carbon stocks of Sofala Bay mangrove forests. Forests 5:1967–1981
Slim FJ, Gwada PM, Kodjo M, Hemminga MA (1996) Biomass and litterfall of *Ceriops tagal* and *Rhizophora mucronata* in the mangrove forest of Gazi Bay, Kenya. Mar Freshw Res 47:999–1007
Spalding M, Kainuma M, Collings L (2010) World atlas of mangroves. A collaborative project of ITTO, ISME, FAO, UNEP-WCMC, UNESCO-MAB, UNU-INWEH and TNC. Earthscan, London, p 319
Steinke TD, Ward CJ, Rajh A (1995) Forest structure and biomass of mangroves in the Mgeni estuary, South Africa. Hydrobiologia 295:159–166
Tam NFY, Wong YS, Lan CY, Chen GZ (1995) Community structure and standing crop biomass of a mangrove forest in Futian Nature Reserve, Shenzhen, China. Hydrobiologia 295:193–201
Tamai S, Nakasuga T, Tabuchi R, Ogino K (1986) Standing biomass of mangrove forests in southern Thailand. J Jpn For Soc 68:384–388
Tamooh F, Huxhamd M, Karachi M, Mencuccini M, Kairo JG, Kirui B (2008) Below-ground root yield and distribution in natural and replanted mangrove forests at Gazi Bay, Kenya. For Ecol Manag 256:1290–1297
United Republic of Tanzania (URT) (2010) National forest resources monitoring and assessment of Tanzania (NAFORMA). Field manual. Biophysical survey. NAFORMA document M01 – 2010, p 108
Valiela I, Bowen JL, York JK (2001) Mangrove forests: one of the world's threatened major tropical environments. Bioscience 51(10):807–815
Wang Y, Bonynge G, Nugranad J, Traber M, Ngusaru A, Tobey J, Hale L, Bowen R, Makota V (2003) Remote sensing of mangrove change along the Tanzania coast. Mar Geod 26:1–14
Wannasiri W, Nagai M, Honda K, Santitamnont P, Miphokasap P (2013) Extraction of mangrove biophysical parameters using airborne LiDAR. Remote Sens 5:1787–1808
Zanne AE, Lopez-Gonzalez G, Coomes DA, Ilic J, Jansen S, Lewis SL, Miller RB, Swenson NG, Wiemann MC, Chave J (2009) Global wood density database. Dryad. Identifier: http://hdl.handle.net/10255/dryad.235. Accessed 15 Dec 2013