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Perennial Biomass Production in Arid Mangrove Systems on the Red Sea Coast of Saudi Arabia

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Abstract: Above and below biomass production were estimated in two *Avicennia marina* mangrove stands in Yanbu and Shuaiba regions on the Red sea coast of Saudi Arabia. Allometric equations were used to estimate above ground biomasses including stem, branches, leaves and total biomass while aerial and fine roots were estimated using ground plots and random coring, respectively. Linear relationships on log-log scale with tree DBH and height as predictor parameters best described the biomass variations. The total aboveground biomass in Shuaiba, (18.58 ha^{-1}) was significantly higher than that of Yanbu (10.77 t ha^{-1}) ($p<0.05$). Shuaiba also had significantly higher aerial and fine roots (23.7 and 96.42 t ha^{-1}) than Yanbu (10.1 and 39.1 t ha^{-1}, respectively) ($p<0.05$). Overall, aboveground biomass of the two sites was 14.77 t ha^{-1} while belowground fine roots was 67.8 t ha^{-1} and a shoot to root ratio of 0.22 indicating high biomass allocation to roots. These findings are the first reported for the Red sea mangroves and were comparable to estimates reported in other locations at similar extreme environmental conditions. In addition, these finding can serve as a baseline study for monitoring annual biomass increment as a function of site productivity and health.

Key words: Allometric equations, *Avicennia marina*, biomass estimation, mangrove, Red sea, Saudia Arabia

INTRODUCTION

Mangroves represent an important source of primary production in coastal regions providing a source of nutrients for the associated biota. They supply organic carbon into the sediment and have a direct impact on the health and function of the marine food web (Saenger *et al*., 1983; Alongi, 2002). In Saudi Arabia, the *Avicennia marina* mangrove forest is the dominant coastal habitat on the Red sea coast with high economic and ecological significance. Mangrove forests are used for fishing, the wood from mangroves is used as fuel wood and their timber is used in house construction and making fishing boats while the mangrove leaves are used as animal fodder (PERSGA, 2004; FAO, 2005). In addition, the mangrove forests serve as nesting grounds for many bird species and a source of food and refuge for many aquatic animals (Al-Maslamani, 2006; Kumar *et al*., 2010). Mangrove production mainly involves estimates of annual litterfall and the annual increase in perennial biomass. Estimating biomass in mangrove system is crucial for:

- Eimating primary productivity of mangrove systems
- Determining storage and cycling of elements (i.e., organic matter, nutrients and heavy metals)
- Understanding the condition of the system (i.e., degree of maturity, structural development and stress level) to aid in determining restoration levels in degraded areas
- Indicating the response of mangrove to several experiments (i.e., fertilization, stress, climate and management)
- Evaluating commercial-valued biomass for wood companies and for silvicultural practices

Perennial biomass productivity estimates involve measurements of the amount of living material (i.e., leaves, branches, stems and roots) produced by a mangrove

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community over a specified time. There are three main methods to estimate perennial biomass production (above and belowground) namely: tree clear cutting, mean-tree biomass and allometric equations. In the clear cut method, a tree is destructively sampled and thus frequent assessment of biomass increase is not possible. While the mean-tree biomass method requires even aged trees with homogeneous tree size and thus cannot be applied in natural forest (Komiyama *et al*., 2008). The allometric equations involve estimating the whole or partial weight of a tree from easily measured tree parameters such as Diameter at Breast Height (DBH), tree height, Basal Diameter (BD). This method is considered robust and non-destructive allowing estimation of temporal changes in forest biomass (Brown *et al*., 1989) thus commonly used for perennial biomass production estimation.

Mangrove trees have relatively higher root to shoot ratio when compared to terrestrial forests, this ratio increases in extreme (i.e., arid hyper saline and nutrient deficient) environment (Iwasa and Roughgarden, 1984). Although, representing a significant biomass component, estimations of belowground biomass in mangroves are scarce. Most biomass studies on mangrove trees have neglected estimating the belowground component mainly due to several difficulties associated with quantitative sampling in intertidal habitats such as time wastage, equipment transportation and handling (Clough and Attiwill, 1982; Snedaker and Snedaker, 1984).

The environment of the Red sea is considered a limiting factor for the development and growth of mangroves (Edwards and Head, 1987). The mangrove trees are growing in hyper saline conditions reaching 41% salinity mainly as a result of low rates of rainfall and high evaporation. The area is also characterized by limited nutrient availability evident in the absence of rivers, estuaries and direct influx of water from the Indian ocean. Mangroves are also exposed to wide ranges of air temperature. Shore air temperature is elevated to rates that are sometimes higher than desert temperatures (Edwards and Head, 1987). In addition, the Red sea mangroves are growing on shallow sedimentation (averaging <1 m depth) which limits the growth and development of the trees (IUCN/MEPA, 1986).

Generally, the production estimate of mangrove litterfall for the Red sea coast is scarce) while its perennial biomass is completely absent (IUCN/MEPA, 1986; Edwards and Head, 1987; Sheppard *et al*., 1992). However, it has been assumed that the productivity is generally low owing to the harsh environmental conditions. Thus, accurate estimation of biomass is important for describing the current status of mangrove forests and for predicting the consequences of change (e.g., in age-size structure, species composition and disturbance).

The objectives of this study were to estimate above and belowground biomass of mangrove trees in two mangrove stands in the northern and southern regions of the Red sea using allometric relationships between biomass components and tree structural parameters, including DBH and height. The hypotheses tested were:

- The Red sea mangroves allocate greater biomass to belowground than aboveground
- Overall mangrove biomass of the Red sea is low when compared to global estimates
- Overall Red sea mangrove biomass is comparable to mangrove biomass in similar environmental conditions elsewhere

MATERIALS AND METHODS

Site description: The study was conducted in two mangrove stands in Yanbu city in the northern Red sea (38°09'46"E and 24°02'65"N) and in Shuaiba region in the southern Red sea (39°30'21"E and 20°46'2"N). Yanbu is situated at the mouth of the Farah valley which forms one of the widest deltas along the Red sea coast and contains the most extensive area of mangrove stands of *Avicennia marina* north of the Tropic of Cancer. Yanbu encompasses an area of approximately 185 km^2 in which mangrove trees cover an area of 0.9 km^2. Shuaiba is an old port laying at about 100 km south of the city of Jeddah. The region comprises of two lagoons extending for some 20 km from north to south with the greatest width being 5 km and each lagoon is connected to the sea through a small channel. Mangrove stands form a large basin population in the middle of the lagoons with an area of about 2 km^2.

The climate of the two sites is typical of the hot arid climate of the Red sea with very few millimetres of rain annually. In Shuaiba, temperature ranges from 18°C in February to 40°C in July with annual mean temperature of 29°C. The relative humidity in Shuaiba is 58% while mean annual precipitation is 15 mm. In Yanbu, the temperature ranges from 13°C in February to 41°C in August with an average annual temperature of 28°C. The mean annual precipitation is 10 mm and the relative humidity is 48%.

At Shuaiba site, a trend in tree density, size and height was found trees toward the eastern bank of the lagoons were bigger and denser than those toward the west. Based on those findings, four transects were set in North-South orientation perpendicular to the variation. Three permanent plots (50×50 m) were set at a distance of 100 m along each transect with a total of 12 plots. In Yanbu, it was found that trees were more homogenous in growth and density with no visual differences therefore, 12 plots (50×50 m) were randomly located on the site.

Tree measurement and sampling: In each site 120 trees were randomly selected and measured for DBH, height and density. It should be noted that *Avicennia marina* trees are well known for their multi-stemmed and irregular growth characteristics (Clough *et al*., 1997) (on average, there are 4-6 stems per tree). The following procedure described by Snedaker and Snedaker (1984) and English *et al.* (1997) was used for measuring DBH of individual trees in such cases: if a tree forks at or below breast height, each forked stem is measured separately. However if a tree forks at or slightly above breast height, DBH at breast height is measured. On the other hand if an irregular growth or swelling is present at breast height, DBH is taken just above or below the irregularity. However, in the current study, trees always forked at levels lower than breast height. Hence, all stems within a tree were measured for their DBH and then summed to obtain a DBH value per tree.

Tree population density was estimated by counting single trees within each of the study quadrates. The required number of trees to be sampled for biomass estimation was determined following Stain's two stage sampling procedure (Hedayat and Sinha, 1991; Steel *et al*., 1997) using DBH as an indicator for the population variance and following the equation:

$$n = \frac{1}{\frac{E^2}{t^2 s^2} + \frac{1}{N}}$$

Where:

n = Sample size
E^2 = $(0.1\ \mathrm{DBH}^{\bar{x}})^2$
S^2 = DBH variance
t = Tabulated t value from the t table at 0.05 probability level
N = Total number of trees in the pre-sampled population (120 tree)

From the pre-sampling, the estimated sample size was 16 and 10 trees in Shuaiba and Yanbu, respectively. These trees were randomly sampled in each site, measured for DBH and height and then felled. Tree components including stem, branches and leaves were separated and weighed. Sub samples from each tree component were taken for moisture content determination.

Root biomass estimation: Weight and density of aerial roots were estimated for each site, 1 m^2 quadrats were placed at distances of one, 2 and 3 m away from mangrove trees with a total of 108 quadrats were used in each site for aerial root estimation. All roots within quadrats were cut at ground level, separated from dead roots, counted and weighted on site. Subsamples of roots were taken for moisture content determination which was later used to derive dry weight.

Fine roots biomass estimation was carried out using random coring. Core samples were taken at 1 and 2.5 m away from trees. For each distance, core samples were taken and sectioned by depths into 0-10, 10-20, 20-30, 30-40 and 40-50 cm depths. A total of 24 core samples were taken from each site. Fine roots (<2 mm) from core samples were washed from sediments, separated from coarse roots, oven dried at 70°C for 24 h, weighed and expressed in tonnes per hectare basis.

Statistical analysis: Biomass data were processed and analysed using SPSS ver. 14 statistical software (2005). Levene's test of equal variance and normal P-P plots were used to test for data normality. Least square regression analysis was used to find the best fit model for the biomass components. Linear regression equations were used to find models that best fit the biomass data using height and DBH as predictor variables.

RESULTS

Tree biomass characteristics: Mangrove trees in Shuaiba reached a mean height of 3 m with mean DBH of 16.7 cm and density of 1040 trees ha^{-1}. While at Yanbu, mangroves reached a height of 2.57 m with DBH of 9.3 cm and density of 1337 trees ha^{-1}. The felled trees in Shuaiba had a mean DBH of 10.44 cm and a mean height of 3.18 m. The stem accounts for 51% of the above ground biomass compared to 31 and 17% of the biomass allocated to branches and leaves, respectively. In Yanbu, there was a mean DBH of 7.52 and a mean height of 2.72 m (Table 1).

Aboveground biomass estimation: In Shuaiba, all biomass components were best predicted in a log (biomass)-log (parameter) form. The regression equation used to predict stem biomass was in the form of:

$$\log\text{Stem biomass} = a + b_1 \log\text{Ht} + b_2 \log\text{DBH}$$

Table 1: Means of tree parameters and dry weight biomass of trees harvested in Shuaiba and Yanbu regions, Saudi Arabia (±denotes standard deviations)

Variables	Shuaiba (n = 16)	Yanbu (n = 10)
DBH (cm)	10.44±5.18	7.52±2.03
Height (m)	3.18±0.42	2.72±0.23
Stem biomass (kg)	8.10±5.10	2.69±1.79
Branch biomass (kg)	6.31±6.59	3.79±3.06
Leaf biomass (kg)	2.93±2.53	1.56±0.72
Total biomass (kg)	17.34±13.39	8.05±4.97
Stem biomass (%)	51	40
Branch biomass (%)	31	44
Leaf biomass (%)	17	16

Table 2: Allometric models of above ground biomass components in Shuaiba and overall (Shuaiba+Yanbu) for *Avicennia marina* mangroves grown on the Red sea coast, Saudi Arabia

Sites	Components	Equations	r^2	F	p
Shuaiba	Stem	$\text{logbiomass} = -1.607+2.026\text{logHt}+0.552\text{logDBH}$	0.57	8.54	**
	Branch	$\text{logbiomass} = -1.621+0.542\text{logDBH}^2\text{Ht}$	0.36	8.02	*
	Leaves	$\text{logbiomass} = -2.841+1.585\text{logHt}+0.838\text{logDBH}$	0.55	8.03	**
	Total	$\text{logbiomass} = -1.145+1.793\text{logHt}+0.777\text{logDBH}$	0.54	7.76	**
Overall	Stem	$\text{logbiomass} = -3.550+3.242\text{logHt}+0.725\text{log DBH}$	0.62	19.07	***
	Branch	$\text{Biomass} = -14.092+4.900\text{Ht}+0.506\text{DBH}$	0.34	6.00	**
	Leaves	$\text{Biomass} = 1.059+0.004\text{DBH}^2\text{Ht}$	0.47	21.66	***
	Total	$\text{Biomass} = -38.299+13.483\text{Ht}+1.242\text{DBH}$	0.52	12.45	***

*p = <0.05, **p = <0.01, ***p = <0.001

and was significant ($p<0.01$) explaining 57% of the biomass variance ($r^2 = 0.57$). Similarly for branches, biomass was best predicted using the regression model:

$$\text{logbiomass} = a+b_1\text{logDBH}^2\text{Ht}$$

($p<0.05$; $r^2 = 0.36$). The regression equation for leaf biomass was:

$$\text{logLeaf biomass} = a+b_1\text{logHt}+b_2\text{logDBH}$$

($p<0.01$; $r^2 = 0.55$). And for the total aboveground biomass, the regression equation:

$$\text{logbiomass} = a+b_1\text{logHt}+b_2\text{logDBH}$$

was significant ($p<0.01$) explaining 54% of the total biomass variance ($r^2 = 0.54$) (Table 2). In Yanbu, no significant relationship was found between the biomass components and the tree parameters and all tree components had an r^2 value of <0.3. As such prediction equations for biomass were not obtained, site biomass in Yanbu was calculated using mean biomass values of the 10 sampled trees and using site tree density of 1337.3 tree ha^{-1}.

Overall biomass (Shuaiba and Yanbu) of each tree component (stem, branches and leaves) were pooled to find the best fit biomass model. The idea of pooling the result is to have a model that can predict overall mangrove biomass (since, the two sites are typical topmost of mangrove stands on the Red sea. The generalised model is to be used only if an overall biomass estimate is needed. It cannot be used for either Shuaiba or Yanbu separately. For stem biomass, the best overall predicting model was a linear log-log regression equation in the form of:

$$\text{logbiomass} = a+b_1\text{logHt}+b_2\text{logDBH}$$

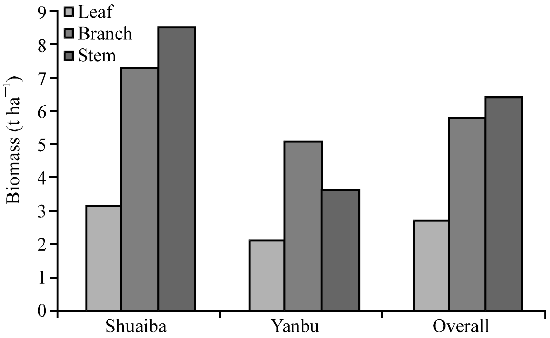

Fig. 1: Biomass estimation (t ha^{-1}) of mangrove tree components in Shuaiba and Yanbu regions, Saudi Arabia (±standard deviation)

The log-log regression equation was significant ($p<0.001$) explaining 62% of stem biomass variance ($r^2 = 0.62$). Overall branches were best predicted using the linear regression:

$$\text{Biomass} = a+b_1\text{Ht}+b_2\text{DBH}$$

($r^2 = 0.34$, $p<0.01$) and the leaves were best predicted using the equation:

$$\text{Biomass} = a+b_1\text{DBH}^2\text{Ht}$$

($r^2 = 0.47$, $p<0.001$) while the overall total biomass was predicted using the equation:

$$\text{Biomass} = a+b_1\text{Ht}+b_2\text{DBH}$$

($r^2 = 0.52$, $p<0.001$) (Table 2). Using the generated prediction models, site biomass (t ha^{-1}) for each of the biomass components and for the total biomass was calculated. The biomass values for Shuaiba components were 3.14, 7.27 and 8.47 t ha^{-1} for leaves, branches and stem, respectively. In Yanbu, the biomass values were 2.09, 5.07 and 3.6 t ha^{-1} for leaves, branches and stem, respectively (Fig. 1). Since, a model that could best predict Yanbu biomass was not achieved, the mean values of the sampled trees biomass along with site tree density was used to generate Yanbu site biomass values. When biomass of both sites was pooled together, the overall biomass obtained from the regression equation yielded values of 2.70, 5.77 and 6.40 t ha^{-1} for leaves, branches and stem, respectively (Fig. 1).

Table 3: Aerial root density and biomass of *Avicennia marina* mangroves in Shuaiba and Yanbu regions, Saudi Arabia (±standard deviations)

	Shuaiba		Yanbu	
Distances (m)	Density (m^{-2})	Biomass ($t\ ha^{-1}$)	Density (m^{-2})	Biomass ($t\ ha^{-1}$)
1	128.78±21.41	23.5±4.4	141.1±48.500	11.4±3.5
2	133.94±21.23	25.0±4.6	136.8±52.610	10.0±3.7
3	122.36±17.54	22.6±4.0	107.74±43.27	9.0±2.5
Mean	128.36±5.800	23.7±1.2	128.54±18.10	10.1±1.2

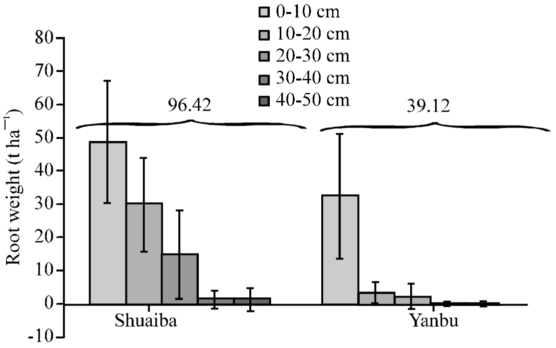

Fig. 2: Fine root biomass of *Avicennia marina* mangroves in Shuaiba and Yanbu region, Saudi Arabia (error bars are standard deviations; different letters denote significant differences (bracket values are total biomass in t ha^{-1})

Aerial root biomass estimation: In Shuaiba, the number of aerial roots was 129, 134 and 122 roots m^{-2} at 1, 2 and 3 m away from the trees, respectively. Their respective biomass was 23.5, 25 and 23 t ha^{-1}, respectively. On the other hand, the number of aerial roots in Yanbu was 141, 137 and 108 roots m^{-2} at 1, 2 and 3 m away from the trees, respectively and their respective biomass was 11.4, 10 and 10 t ha^{-1} (Table 3). No significant differences were found in aerial root density or biomass at any distance for any site ($p>0.05$). Generally, root density at Shuaiba (128.36 roots m^{-2}) was not significantly different from that at Yanbu (128.54 roots m^{-2}) ($p>0.05$). However, aerial root biomass for Shuaiba (24 t ha^{-1}) was significantly higher than that for Yanbu (10 t ha^{-1}) ($p>0.001$).

Belowground biomass estimation: Almost all fine root biomass appeared at the top 30 cm profile (Fig. 2). In Shuaiba, 97% of fine roots were concentrated in the top 30 cm profile (93.47 t ha^{-1}) with 52% of that concentrated in the top 10 cm profile. In Yanbu, 98% of roots were concentrated in the top 30 cm profile (38.34 t ha^{-1}). However, 83% of that was concentrated in the top 10 cm profile. In addition, when the top 10 cm profile was compared between sites, it was found that fine root biomass in Shuaiba was significantly higher than that in Yanbu ($p<0.05$). Similarly, Shuaiba had higher total fine root biomass of the two sites 96.42 vs. 39.12 t ha^{-1} for Shuaiba and Yanbu, respectively (Fig. 2).

DISCUSSION

Site specific biomass characteristics: *Avicennia marina* are trees that can grow in wide environmental ranges including those of extreme high temperature and salinity levels in Saudi Arabian coasts thus represent the dominant species in the country. In addition, the multi-stemmed feature of *A. marina* can cause difficulties in distinguishing between stems and branches and therefore, resulted in inaccurate estimations of biomass components (Clough *et al*., 1997). Shuaiba trees had most of the biomass allocated to stem compared to the other components where in Yanbu, the largest biomass proportions were allocated to branches rather than stem and leaves (42 vs. 37 and 21% for branches and leaves, respectively). In Shuaiba, the mangrove trees were larger and vertical in shape making it easier to define stems from branches while in Yanbu, the trees were smaller and more multi-stemmed. As a result, the trees did not show a clear definition between stems and branches most of the time in fact, this problem had led previous researchers to conclude that differentiating between stems and branches of a tree in such conditions is difficult and is largely influenced by personal judgment (Clough *et al*., 1997). This difficulty may have led to measuring error in the current study as a result of including stem-like branches as branch components.

Shuaiba trees were taller and bigger in diameter than Yanbu but the population density was lower. The considerable differences in the tree parameters between sites reflect how biomass of the same species may vary from site to site depending on the environmental conditions and possibly plantation age. Shuaiba mangroves which are characteristic of basin soft bottom mangroves, grow in well developed sediments reaching a depth of approximately 1.8 m, this allows space for stabilization, vertical growth and biomass increase. Moreover the basin nature of the Shuaiba mangroves allow for the trees to be spaced and thus minimizing competition and allowing for bigger diameter growth. On the other hand, Yanbu mangroves are fringe growing in a narrow belt parallel to the shore line; they are characterized as hard bottom mangroves because they grow on dead coral beds covered with a shallow sediment layer typically <60 cm under mangrove stands. This had

Table 4: Comparisons of aboveground biomass (t ha^{-1}) of Avicennia mangrove systems around the world (*mean values)

Source	Species	Leaves (t ha^{-1})	Branches (t ha^{-1})	Stem (t ha^{-1})	Total (t ha^{-1})	DBH range (cm)	Height (m)	Environmetal condition	Region
Current study	*A. marina*	2.70	5.77	6.40	14.77	3.3-20.2	2.5-3.8	Arid	Saudi Arabia
Kairo *et al.* (2009)	*A. marina*	1.38	4.20	6.10	11.70	>5	-	Hot and humid	Kenya
Medeiros and Sampio (2008)	*A. schaueriana*	-	-	-	2.76	3.4-10.2	3.1-7.5	Saline	Brazil
Saintilan (1997a, b)	*A. marina*	-	-	-	56.10	-	0.5-2.0	Hyper saline	Australia
Tam *et al.* (1995)	*A. marina*	0.62	4.90	2.90	8.50	8.3-14.3	3.1-5.6	Humid	China
Mackey (1993)	*A. marina*	-	-	-	341.00	-	1.4*	Subtropical	Australia
Woodroffe (1985)	*A. marina*	-	-	-	6.80	-	>1	Temperate	New Zeland
Woodroffe (1985)	*A. marina*	-	-	-	23.70	-	1-2.5	Temperate	New Zeland
Murray (1985)	*A. marina*	-	-	-	21.70	4.4*	4.3*	Humid	Australia
Davie (1984)	*A. marina*	-	-	-	30.00	-	-	Temperate	Australia
Clough and Attiwill (1975)	*A. marina*	-	-	-	86.00	-	-	Temperate	Australia
Briggs (1977)	*A. marina*	-	-	-	128.00	58.1*	7.34*	Temperate	Australia

possibly contributed in limiting vertical tree growth. Moreover, the narrow growth space of the fringe Yanbu mangroves had possibly resulted in the denser tree growth and thus minimized diameter growth.

Aboveground biomass estimation

Site specific biomass estimation: As mentioned earlier, *Avicennia marina* trees were noticeably multi-stemmed and growth-irregular more in Yanbu than in Shuaiba and stems were branching at very low levels of the tree trunk. And in some cases may start below the soil surface making it very difficult to differentiate stems from branches. These characteristics could have caused errors in estimating stem and branch biomass which may have contributed to the insignificant prediction. Similar errors in estimating *A. marina* aboveground biomass using stem DBH were encountered in the literature (Tam *et al.*, 1995; Clough *et al.*, 1997). Tam *et al.* (1995) working on stunted, irregular *A. marina* trees in China found no significant relationships between the tree parameters (DBH and height) and any biomass component. A more recent study by Kairo *et al.* (2009) studying aboveground biomass in Gazi bay, Kenya of several species among which is *A. marina* has also found no simple relationships between DBH and any biomass component.

Although, no simple model describing the tree biomass for Yanbu was achieved, similar cases have been reported in literature for *Avicennia* species (Tam *et al.*, 1995; Kairo *et al.*, 2009). In which a straightforward relationship between biomass and tree parameters was not found or when compared to other species had low coefficient of determinations.

In Shuaiba site, stem biomass was the component that best predicted by allometric equations while leaf biomass was the least, this might be due to the fact that leaves are susceptible to seasonal variations and thus may cause variation in biomass sampling. Moreover, leaves are more vulnerable to environmental conditions such as wind and rain (Robertson and Alongi, 1992) and thus could lead to errors in biomass estimations. In addition such low leaf biomass prediction has been frequently reported in the literature (Komiyama *et al.*, 2000; Sherman *et al.*, 2003; Ong *et al.*, 2004; Soares and Schaeffer-Novelli, 2005; Smith and Whelan, 2006; Medeiros and Sampio, 2008).

It should be noted that most of the published biomass estimations in mangrove ecosystems were of species other than *A. marina* particularly for species that yield higher biomass such as *Rhizophora mangle*. This might be due to the low biomass of *A. marina* trees compared to other species. The multi-stemmed and growth irregularity features are other factors that could have made working with *A. marina* less attractive.

In similar cases where stems are forking close to the surface level, it would be of great interest to use individual stem diameter (per tree) just above the stem junction and if present, the girth of common butts where stems arose from. Clough *et al.* (1997) attained regression equations for *A. marina* and *Rhizophora stylosa* using individual stem girths and common butts as biomass predictors, the technique they used involved taking stem girths at 10-15 cm above stem junction and in case where stems arose from a common butt at height of >20 cm above the ground, the butt girth was also recorded. All stems, branches, leaves and total biomass were best predicted using these parameters with high significant correlation ($r^2 = 0.97$ for total biomass). Another study by Comley and McGuinness (2005) working on *A. marina* and following the same procedure as Clough *et al.* (1997) also attained similar accuracy ($r^2 = 0.94$ for total biomass). Moreover, crown diameter is sometime used in conjunction with DBH as other predictor for biomass (Ross *et al.*, 2001; Coronado-Molina *et al.*, 2004; Soares and Schaeffer-Novelli, 2005). In other studies, allometric equations of different species gave a better prediction when wood specific gravity of each species was considered. Moreover, Komiyama *et al.* (2005) reached a common allometric equation using $DBH^2 \cdot Ht$ as biomass predictor.

Overall aboveground biomass estimation: Although, reaching a model that can predict Yanbu's biomass was not achieved, a combined biomass (Table 4) of the two sites was predictable by allometric models which were compared with biomass estimations of *Avicennia* species worldwide. According to Saenger and Snedaker (1993), the global estimations for mangrove biomass are between 6.8 and 436 t ha^{-1}. *A. marina* species fall in the lower half of that wide range. The lowest reported estimation came from New Zealand (6.8 t ha^{-1}) and the highest estimation came from Australia (341 t ha^{-1}). High biomass accumulations occur in tropical humid conditions where temperature and environmental conditions are favourable. In extreme conditions such as arid and temperate environments where temperature, salinity and nutrient enrichment are limiting factors, few species can thrive and such areas are often mono-specific. Mangroves growing in such environments need to spend much of their energy production in mechanisms that help to cope with the environmental stresses reducing availability for biomass accumulation (Robertson and Alongi, 1992). Such mechanisms would include physiological adaptations such as salt filtration and extrusion, thick waxy leaf surfaces and morphological adaptations such as aerial and anchoring root systems.

The current study of mangrove systems was conducted in one of the most extreme environment worldwide in fact the Red sea represent the northern growth limits of any mangrove species worldwide (Por *et al.*, 1977; EEAA, 1998; Edwards and Head, 1987) thus *A. marina* species accounts for 90% of mangroves on the Red sea. The current biomass estimations are comparable to those estimations in extreme environments; the estimation of the Red sea mangrove of 14.8 t ha^{-1} slightly higher than those reported in the closest region of Gazi bay, Kenya (11.7 t ha^{-1}) (Kairo *et al.*, 2009) and sometimes higher than other regions (8.5 t ha^{-1} in China and 6.8 t ha^{-1} in New Zealand). To the best of the knowledge, this is the first study that has provided a quantitative estimation of aboveground biomass in the Red sea as previous research on mangrove productivity has mainly focused on annual litterfall estimations and tree mensuration (Saifullah *et al.*, 1989; Khafaji*et al.*, 1991; Mandura, 1997, 1998). Therefore, the current biomass estimation can serve as baseline information that can be utilized when conducting biomass estimations in other parts of the Red sea and for future comparisons.

Belowground biomass estimation

Site specific belowground biomass estimation: Mangrove belowground biomass estimation is scarce and most of the biomass studies have neglected estimating the belowground part of mangrove trees. This is mainly due to several difficulties associated with quantitative sampling in intertidal habitats such as time consumption, equipment transportation and handling (Clough and Attiwill, 1982; Snedaker and Snedaker, 1984). In the present study, both Shuaiba and Yanbu had similar aerial root densities, this might be related to the shallow and extensive underground cable root system of *A. marina*, this root system has to be very dense in order to not only stabilize the tree but also by dispersing tree weight over a large area, to keep the trees from sinking into the mud (Komiyama *et al.*, 2008). Although, not different in density, Shuaiba had a higher aerial root biomass than Yanbu, this might be attributed to the substrate, sedimentation and tree density of each site. Shuaiba's mangroves are basin with many in plantation lakes and deep sedimentation (reaching approximately 1.8 m depth). This provides space and allow for higher root growth and biomass. On the other hand, Yanbu's mangroves are fringe with higher tree density and shallow sedimentation (reaching approximately 60 cm depth) offering very little for root biomass.

The top 10 cm soil profile contains >50% of the fine root biomass such high fine root biomass in top soil profiles is commonly reported in literature. Lauff (1967) found that most of *A. marina* roots are concentrated at the top 30 cm below the ground level. Moreover, Tamooh *et al.* (2008) working also on *A. marina* in Kenya has found that 65% of fine roots is concentrated in the top 20 cm soil profile. In addition, Komiyama *et al.* (2000) working on *Ceriops tagal* mangroves has found few roots present below that same depth. The high fine root biomass in the top 10 cm profile obtained from the current study may be attributed to the mangrove adaptive mechanism for living in soft, saline and sometimes, hot dry sediments (Briggs, 1977; Komiyama *et al.*, 2008). In addition, the high root biomass in the upper profile may also be attributed to the anoxic environment that halts root growth into deeper soil profiles (Stafford-Deitsch, 1996). The concentrated amount of roots in the top profile would also facilitate efficient uptake of water and nutrients in the sediment layers which are characterized by accumulated organic matter and relatively large amount of available nutrients as in terrestrial forests (Claus and George, 2005).

Overall belowground biomass estimation: Estimates of fine root biomassin *A. marina* range globally from 15-166 t ha^{-1} (Table 5). As mentioned earlier, studies

Table 5: A comparison of *Avicennia marina* fine root biomass (t ha^{-1}) from various sources

Source	Fine roots biomass (t ha^{-1})	Environmental conditions	Locations
Current study	67.77	Arid	Saudi Arabia
Tamooh *et al.* (2008)	41.4	Tropical	Kenya
Saintilan (1997a)	15-60	Hyper saline	Australia
Saintilan (1997b)	70.0-166	Subtropical	Australia
*Briggs (1977)	153.8	Temperate	Australia
*Mackey (1993)	118.6	Subtropical	Australia
Alongi (2002)	21.2	-	Australia

of belowground biomass worldwide are limited and most of reported studies were coming from Australia. The variations in the root biomass values reflect the dissimilarity in the environmental and regional conditions at the different sites. Overall, the fine root biomass of the current study was 67.8 t ha^{-1}, close to the limits reported in subtropical and hyper saline Australian environments (Saintilan, 1997a, b) and higher than those reported in Kenya of 41.1 t ha^{-1} (Tamooh *et al.*, 2008).

It should be noted that applying allometric equations for belowground biomass was not possible in the current study due to the web spreading nature of the root system which make assigning roots to specific trees impossible in addition a complete extraction of the root system is a difficult and inapplicable process (Komiyama *et al.*, 2008). The only estimate of *A. marina* belowground biomass using allometric equations was by Comley and McGuinness (2005) who reported estimates of roots at around 2 m radius since, it was impossible to trace roots to their final destination. This study partitioned percentage of common stem and common belowground biomass according to relative stem diameter. However, the study reported poor relationships between DBH and belowground root biomass owing to the limited root estimate to the 2 m radius around the tree and which underestimate the true belowground biomass. Thus, studies on the allometric relationship of mangrove roots are still needed due to the lack of study cases and to the differences in root extraction methods.

In the current study, the shoot to root ratio was 0.22 which could be one of the smallest reported in the literature. In his review research on mangrove biomass and productivity, Komiyama *et al.* (2008) reported shoot to root ratio of 12 mangrove stands ranging from 0.9-5 with *A. marina* ranging from 0.9-2.8. Mangroves are known to allocate a greater amount of their biomass to the belowground root system in order to cope with the unstable, soft, anoxic, hypersaline and nutrient deficient sediments they grow on and to ensure stabilization and anchoring of the tree (Komiyama *et al.*, 2008). This allocation of biomass into the root system can increases with aridity, light intensity and grazing rates (Iwasa and Roughgarden, 1984).

CONCLUSION

The regression equations developed in this study would facilitate future estimation of aboveground mangrove biomass in the Red sea. It is a valuable practical tool that estimates biomass from easily measured tree parameters. However, applying these equations must have the following considerations:

The regression equations are applicable when used within the DBH and height range reported in this study. Site specific equations should be only applicable at the same or similar sites only. The generalized equation can be used if an overall estimation of Red sea mangrove biomass is desired.

When applicable, it would be of interest to use parameters that were reported good biomass predictors such as girth at base, crown diameter, butt girth and wood density (in case of multiple species). Thus it is advisable to consider equation modification when necessary. In addition, the developed regression equation would aid in monitoring annual biomass increment as a function of site productivity and health. This is specifically important for sites similar to Shuaiba in the Southern Red sea regions where *A. marina* grows bigger and are mixed with other mangrove species.

The current investigation showed that *A. marina* belowground biomass was greater than those estimates obtained in East Africa and comparable to estimates obtained in similar environmental conditions. Thus, the current estimation will add a significant value to the regional estimates and to the global estimates of roots in similar environments. Moreover, The current belowground biomass estimates are one of the very few belowground estimates done on *A. marina* trees.

RECOMMENDATION

Therefore, there is a great need for studies addressing allometric relationships of roots due to the lack of reliable estimate and variations in the extraction methods.

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