Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove forests with Landsat ETM+ and Shuttle Radar Topography Mission elevation data

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[1] Mangroves are salt tolerant plants that grow within the intertidal zone along tropical and subtropical coasts. They are important barriers for mitigating coastal disturbances, provide habitat for over 1300 animal species and are one of the most productive ecosystems. Mozambique's mangroves extend along 2700 km and cover one of the largest areas in Africa. The purpose of this study was to determine the countrywide mean tree height spatial distribution and biomass of Mozambique's mangrove forests using Landsat ETM+ and Shuttle Radar Topography Mission (SRTM) data. The SRTM data were calibrated using the Landsat derived land-cover map and height calibration equations. Stand-specific canopy height-biomass allometric equations developed from field measurements and published height-biomass equations were used to calculate aboveground biomass of the mangrove forests on a landscape scale. The results showed that mangrove forests covered a total of 2909 km^2 in Mozambique, a 27% smaller area than previously estimated. The SRTM calibration indicated that average tree heights changed with geographical settings. Even though the coast of Mozambique spans across 16 degrees latitude, we did not find a relationship between latitude and biomass. These results confirm that geological setting has a greater influence than latitude alone on mangrove production. The total mangrove dry aboveground biomass in Mozambique was 23.6 million tons and the total carbon was 11.8 million tons.

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1. Introduction

[2] Mangrove forests are the dominant coastal ecosystem in tropical and subtropical regions. They form an important link between aquatic and terrestrial ecosystems. Although mangroves grow in difficult environments regularly inundated by saltwater, their primary productivity of 2.5 g carbon m^{-2} day^{-1} makes them the most productive aquatic ecosystem [*Jennerjahn and Ittekot*, 2002]. The constant tidal outwelling of mangrove litter provides large amounts of carbon (C) to coastal and offshore marine ecosystems and contributes over 10% of the dissolved organic C (DOC) to ocean sediments worldwide [*Cintrón and Shaeffer-Novelli*, 1984; *Dittmar et al.*, 2006]. Mangroves also act as coastal buffer zones, by accumulating sediment and protecting coastal areas from wave action, erosion, storms and tidal waves [*Cintrón and Shaeffer-Novelli*, 1984]. As keystone species, mangroves provide habitat, food and nutrients for 1300 animal species, many of which are commercially important fish and shrimp [*Duke*, 1992]. Despite these known benefits, mangrove areas are being altered and destroyed by anthropogenic impacts and their cover has decreased by 35% in the past 20 years [*Valiela et al.*, 2001; *Alongi*, 2002]. Because of their ecological and economical importance mangrove forests have been estimated at 200,000 USD/km^2 to 900,000 USD/km^2 per year by the United Nations Environment Programme World Conservation Monitoring Center [*UNEP-WCMC*, 2006] for the ecological services they provide. In addition, through the adoption of clean development mechanisms (CDM) and Forest Carbon Credits, developing nations will receive income to maintain their forest resources as carbon storage to mitigate carbon (C) emissions of developed nations [*Laurance*, 2007]. Given the threats to this ecosystem it is crucial to determine landscape-scale extent, distribution and biomass of mangroves accurately from scientific, management and economical perspectives.

[3] In this paper we focus on the mangroves of Mozambique. Mangrove-dependent fisheries represent 40% of Mozambique's Gross National Product. Prawn fishery alone

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is responsible for 55.4 million U.S. Dollars per year based on numbers from the Ministry of Cooperation and Environmental Action [*MICOA*, 1998]. Rural coastal populations use mangrove wood as building material, fuel and food harvesting grounds [*Spalding et al.*, 1995; *Barbosa et al.*, 2001]. The economy and people's livelihoods in Mozambique are therefore directly dependent on mangroves.

[4] In Mozambique, mangroves are found along the entire 2770 km coast, spanning over 16 degrees latitude from 10°20′S to 26°50′S latitude. They constitute the 3rd largest mangrove area in Africa, and have the highest species diversity on the continent with 10 species [*Spalding et al.*, 1995; *Barbosa et al.*, 2001]. The coast has three major geographical settings: sandy coastlines in the Southern regions, estuaries in the Central regions and coralline limestone areas in the Northern regions [*Barbosa et al.*, 2001]. Estimates of mangrove area in Mozambique vary greatly [*FAO*, 1981; *Hughes and Hughes*, 1992; *IGNFI-CENACARTA*, 1999; *FAO*, 2003], but the generally accepted, most recent estimate of mangrove area is 396,080 ha for 1990 [*Saket and Matusse*, 1994; *Barbosa et al.*, 2001].

[5] It is generally believed that species diversity, biomass and C turnover rates are at their highest close to the equator and as latitude increases, these rates decrease. This relationship was confirmed for mangroves by *Saenger and Snedaker* [1993], in a review of 43 papers describing the aboveground biomass of mangrove forests around the world. However, these papers are all based on small-scale, plot-based studies and may be affected by site selection biases. The particular growth form of tidally inundated, high-density forests, with dense aboveground roots has made it difficult to assess mangrove structure and biomass on a large scale in the field [*Alongi*, 2002; *Ellison*, 2002]. Thus, remote sensing is the only effective way to systematically measure forest extent and biomass at a large scale.

[6] Optical Remote Sensing techniques have proven a reliable tool for the estimation of mangrove forest area, productivity and species distribution [*Aschbacher et al.*, 1995; *Smith et al.*, 1998; *Dahdouh-Guebas et al.*, 2000; *Kovacs et al.*, 2001; *Satyanarayana et al.*, 2001; *Dahdouh-Guebas et al.*, 2002; *Sulong et al.*, 2002; *Cohen and Lara*, 2003; *Dahdouh-Guebas et al.*, 2004; *Gesche et al.*, 2004; *Wang et al.*, 2004]. The combination of optical and radar remote sensing is a technique that can provide greater insight into mangrove structure estimations [*Rasolofoharinoro et al.*, 1998; *Pasqualini et al.*, 1999; *Held et al.*, 2003; *Simard et al.*, 2006]. Data from the Shuttle Radar Topography Mission (SRTM) has proven particularly well suited, due to its accuracy and worldwide coverage [*Simard et al.*, 2006; *Rodriguez et al.*, 2006]. The Shuttle Radar Topography Mission was flown aboard the space shuttle Endeavor from February 11th to 22nd 2000. The mission used dual-antennae, C-band (5.6 cm wavelength) Interferometric Synthetic Aperture Radar (INSAR) which covered areas from 56°S′ and 60°N′ and provides the most accurate, globally consistent digital elevation model (DEM) for over 80% of the world's landmasses [*Rodriguez et al.*, 2006]. The DEM is freely available at 1-arcsecond resolution for the United States and 3-arcsecond resolution worldwide, making it a great data set for developing nations. In forested areas, the radar elevation estimate (or phase center) is biased by radar scattering within the canopy, enabling the estimation of tree canopy height. Studies in tropical and temperate forests have shown that SRTM can be used to estimate forest height and biomass [*Kellndorfer et al.*, 2004; *Gillespie et al.*, 2006; *Heo et al.*, 2006; *Simard et al.*, 2006]. Because mangroves grow in tidally inundated areas, underlying topography is negligible and forest structure can be accurately measured on large scales using SRTM elevation data. Lidar and field measures are two ways of calibrating the SRTM data for greater accuracy [*Carabajal and Harding*, 2005; *Carabajal and Harding*, 2006; *Hofton et al.*, 2006] and previous studies in Florida and Columbia using airborne lidar and ICEsat GLAS waveforms have provided calibration equations for mangrove tree height estimations from SRTM data [*Simard et al.*, 2008].

[7] This study uses a combination of Landsat ETM+ and SRTM data, similar to the method introduced in *Simard et al.* [2006], to produce landscape-scale maps and estimates of mangrove cover, height, biomass and C for the entire coast of Mozambique. The main objectives of this study are: (1) To describe the current extent of mangrove forest areas across Mozambique based on Landsat ETM + data; (2) To determine the total aboveground biomass and C contained in mangrove forests based on height estimations extracted from SRTM data; and (3) To establish whether the theory of decreasing mangrove biomass with increasing latitude can be confirmed using remote sensing-based estimations.

2. Methods

2.1. Forest Composition Data

[8] In September–October 2005, we conducted field measurements of mangrove structure and composition on Inhaca Island. Inhaca is located in the Maputo Province, at the Southern end of Mozambique and mangroves are one of the main vegetation types on the Island (Figure 1). They cover almost 11% of Inhaca's land area and approximately 50% of the entire island coastline [*Kalk*, 1995; *Barbosa et al.*, 2001]. In total, we established 51 plots of 15 m diameter were along eight 300 m long transects. Within each plot, we identified the species, and measured the diameter at breast height [DBH] and canopy height of every tree with a DBH over 2.5 cm using the generalized methods described by *Cintrón and Shaeffer Novelli* [1984]. The five species of mangrove present on Inhaca were *Avicennia marina* (Forskal) Vierh., *Rhizophora mucronata* Lamarck., *Bruguieria gymnorrhiza* (L.) Lamarck., *Ceriops tagal* (Perr.) C.B., and *Lumnitzera racemosa* Willd.

[9] The patterns of species zonation and composition on Inhaca are comparable to the qualitative descriptions of mangrove forests across Mozambique [*Beilfuss et al.*, 2000; *Barbosa et al.*, 2001], with tall *Avicennia marina* (and *Sonneratia. alba* further North) acting as pioneer species on fringing mudflats and coastal beaches, followed by *Rhizophora mucronata* - *Ceriops tagal* - *Bruguiera gymnorrhiza* communities and scrub *A. marina* communities on the landward border of the forest. Mangroves in general have a low diversity and are closer in species composition and forest structure than other tropical forests. Because tree biodiversity is low and the forest patterns on Inhaca are similar throughout Mozambique, we believe that the composition, structure and biomass measured on Inhaca are a good indicator of mangrove forests throughout Mozambique.

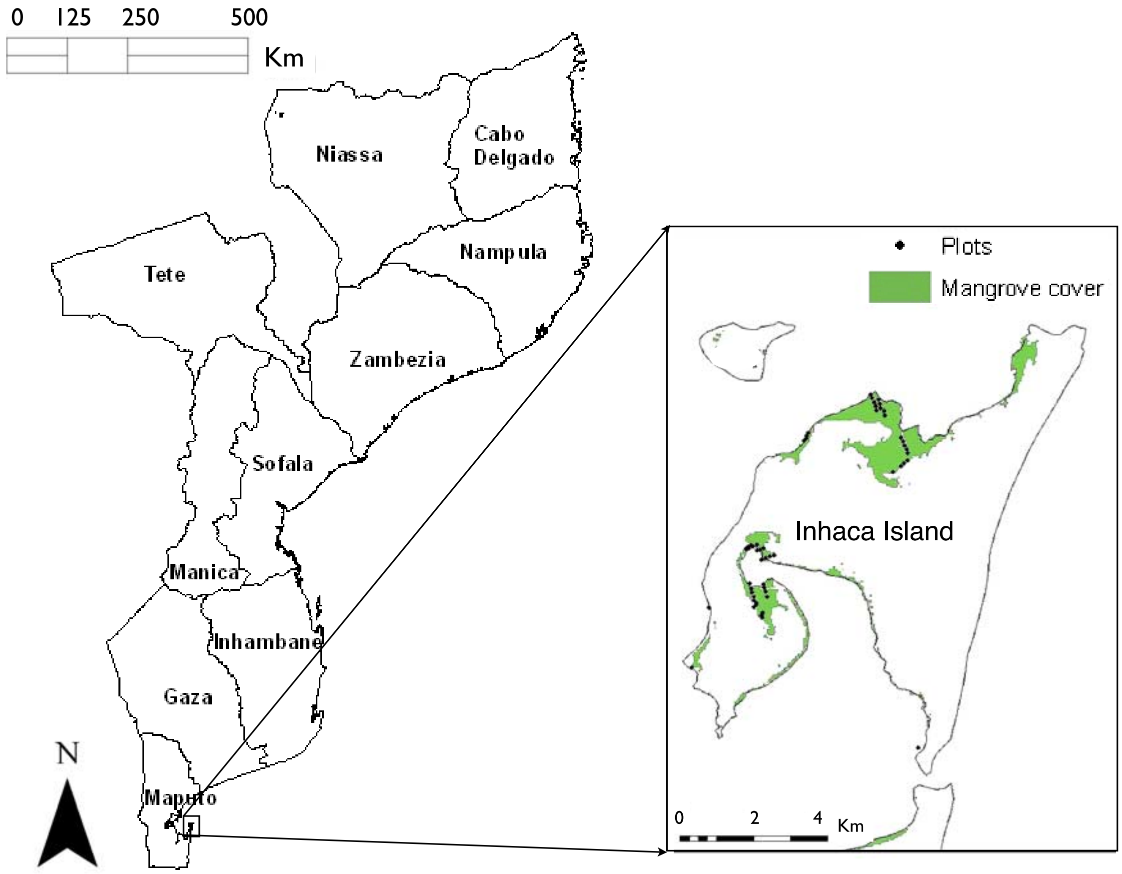

Figure 1. Map of Mozambique with all provinces outlined and map of Inhaca Island with the location of the mangrove forests in green (based on *Spalding et al.* [1995]) and field plots as black dots.

2.2. Remote Sensing Methods

[10] Sixteen orthorectified Landsat 7 ETM+ scenes with a resolution of 30 × 30 m were acquired (Table 1) from the Global Land Cover Facility [http://glcf.umiacs.umd.edu] and re-projected into Lat/Long grid, WGS84 projection and datum. Three SRTM version 3 tiles, covering the entire Mozambican coastline, were obtained from the Consultative Group on International Agricultural Research (CGIAR) [www.cgiar.com] and mosaiqued to form a single image in Lat/Long grid, WGS84 projection and datum.

2.2.1. Landcover Map

[11] Assuming that mangrove forest canopies in Mozambique do not grow over 35 m in height [*Barbosa et al.*, 2001], we masked all areas on the Landsat images that were taller than 35 m based on the SRTM DEM. By eliminating areas that we know are not mangroves based on their height, we were able to decrease the number of pixels of non-mangrove areas that could be misclassified as mangroves. We applied a Maximum Likelihood classification to the masked Landsat images, using training classes determined with help from GPS points, a landcover map provided by MICOA-CENACARTA and Google Earth software. The resulting classes were merged into 3 final classes (mangrove, nonmangrove and water) by visual interpretation, expert knowledge of the area and high-resolution images in Google Earth software to produce the final mangrove cover map.

[12] Sieving and clumping of classes were then applied to the images resulting from both classifications to remove isolated pixels and to add spatial coherency to the classes. The accuracy of the area and distribution of mangroves in the two classifications were compared to coordinates of known mangrove areas from field measures using confusion matrices. Mangrove cover was analyzed first on a country-wide and then on a province wide level, starting with the

Table 1. Path, Row and Date of All Landsat ETM+ Scenes Used in Land Cover Map

Path	Row	Date	Provinces
167	78	7-May-2001	Maputo and Gaza
167	77	7-May-2001	Gaza and Inhambane
167	75	7-May-2001	Inhambane, Gaza, Sofala and Manica
167	74	7-May-2001	Inhambane, Sofala and Manica
166	77	1-Jun-2001	Gaza and Inhambane
166	76	1-Jun-2001	Inhambane
166	75	6-Jul-2002	Inhambane
166	73	16-Jul-2000	Sofala and Zambézia
166	72	27-Apr-2000	Zambézia
165	72	24-Aug-2000	Zambézia and Nampula
164	72	7-Sep-2001	Zambézia and Nampula
164	71	5-Jul-2001	Nampula
164	70	2-May-2001	Nampula and Cabo Delgado
164	69	31-May-2000	Cabo Delgado
164	68	7-Dec-1999	Cabo Delgado
164	67	18-May-2001	Cabo Delgado

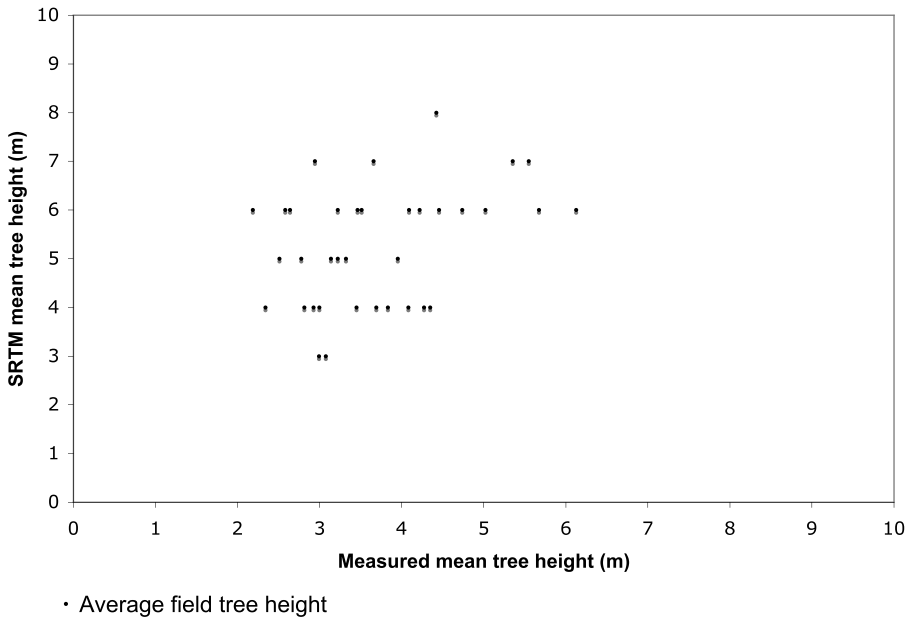

Figure 2. Comparison of canopy height estimates using SRTM with equation from *Simard et al.* [2006] and field measurements. We found a bias of −0.01 m with an RMSE of 1.5 m. These values indicate this equation is appropriate for this region.

southernmost province of Maputo and ending with the northernmost province of Cabo Delgado.

2.2.2. Height Map

[13] Using the mangrove landcover map, we masked all areas on the SRTM that were not within the mangrove area. Mangroves only grow in tidally inundated areas, at sea level. In Mozambique the tidal range is below 3.3 m, which may cause systematic errors in our SRTM tree height estimates. For this study, we assumed that all forests grow at sea level and therefore topography was not taken into account. Height data for mangrove forests in areas other than Inhaca Island was not available; therefore we made the assumption that the calibration equation (1) from the Caribbean [*Simard et al.*, 2006] could be applied to the mangrove forests of Mozambique. This assumption was based on the low tree biodiversity and similar structural and zonation patterns that are observed in mangroves worldwide [*Chapman*, 1944; *Chapman*, 1970; *Lugo and Snedaker*, 1974; *Smith*, 1992].

[14] We compared SRTM tree height estimates calculated from equation (1) with the field measurements to estimate systematic (bias) and random error. We found a bias of −0.01 and a RMSE of 1.5 m (Figure 2). The bias for the range of canopy height of our field data is well below measurement error, thus we consider SRTM well calibrated. Finally, we used equation (1) to calibrate the SRTM elevation to estimate mangrove canopy height of the entire coastline.

$$H = -2.19 + 1.12 \times H_{SRTM} \quad \text{RMSE} \quad 1.5 \quad \text{m} \qquad (1)$$

2.3. Biomass Estimation

[15] The field data from Inhaca Island was used as a sample to estimate the mangrove biomass of Mozambique. The biomasses of individual field-measured plots were calculated by applying allometric equations based on DBH of each individual tree in the plot. Several allometric equations were available for the species present in Mozambique (Table 2).

Table 2. Aboveground Biomass Equations for Nine Mangrove Species Present in Mozambique Based on the DBH[a]

Species	Equations	n	DBH (cm)	Location	Author
Avicennia marina	W = e^(5.551 + 2.153 ln (D))			Sri Lanka	3
Avicennia marina	W = 10^(−0.511) + D^(2.113)	22		Darwin Harbor, Australia	4
Bruguiera gymnorrhiza	W = 0.251 x 0.699 (D^2.46)	18	5.0–48.9	Thailand and Indonesia	1
Bruguiera gymnorrhiza	W = 10^(−0.7309) + D^2.3055	17	2.0–24.0	Queensland, Australia	2
Ceriops tagal	W = 0.251 x 0.746 (D^2.46)	6	5.0–48.9	Thailand and Indonesia	1
Ceriops tagal	W = 10^(−0.7247) + D^2.3379	26	2.0–18.0	Queensland, Australia	2
Ceriops tagal	W = 10^(−0.494) + D^(2.056)	12		Darwin Harbor, Australia	4
Rhizophora mucronata	W = e^(6.247 + 2.64 ln (D))			Sri Lanka	3
Rhizophora mucronata	W = 0.251 x 0.701 (D^2.46)	13	5.0–48.9	Thailand and Indonesia	1
Sonneratia alba	W = 0.251 x 0.475 (D^2.46)	13	5.0–48.9	Thailand and Indonesia	1
Xylocarpus granatum	W = 0.251 x 0.528 (D^2.46)	11	5.0–48.9	Thailand and Indonesia	1
Xylocarpus granatum	W = 10^(−1.0844) + D^2.5883	10	3.0–17.0	Queensland, Australia	2
Laguncularia racemosa	W = e^(1.095 + [0.659 x ln {D^2}] + [0.304 x ln {CW}])	43	2.5–8.8	Florida, USA	5

[a]Author list, 1: *Komiyama et al.* [2005], 2: *Comley and McGuinness* [2005], 3: *Amarasinghe and Balasubramianum*, 4: *Clough and Scott* [1989], 5: *Ross et al.* [2001].

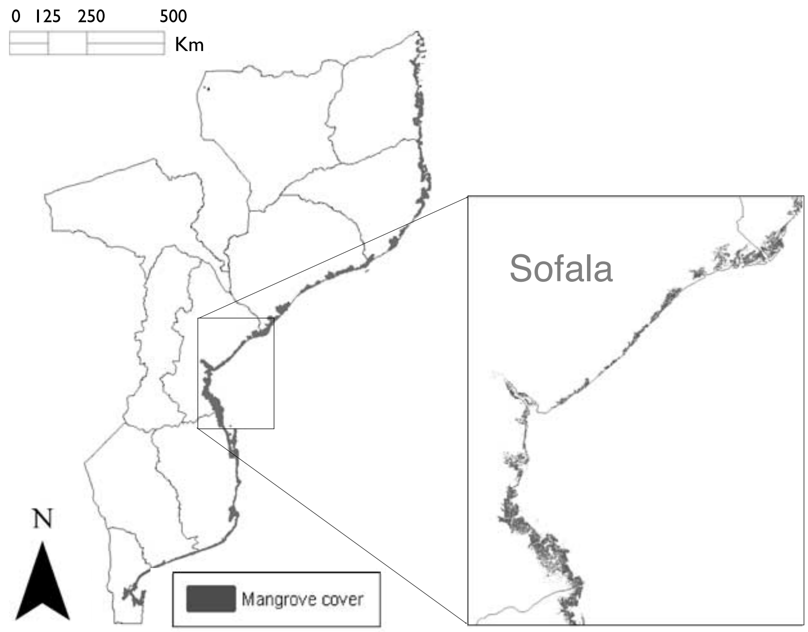

Figure 3. Mangrove cover of Mozambique. The largest mangrove areas are present in the central regions, particularly Sofala and Zambézia provinces, as shown in the magnification.

We selected the allometric equations based on the range of DBH that encompassed the range of our field measurements. For *R. mucronata* we used an allometric equation derived for Gazi Bay, Kenya [*Slim et al.*, 1996], because of its geographical proximity to the site and comparable range of DBH's. For *A. marina*, equations derived by *Comley and McGuinness* [2005] for Darwin Harbor, Australia were used, as they had a similar range of DBH's as trees on Inhaca. For *C. tagal*, we used equations from *Clough and Scott* [1989] for Australia, rather than those from *Slim et al.* [1996] from Kenya, because the size range reported for Australia was larger and closer to the range found on Inhaca. For *B. gymnorrhiza*, we chose to use equations developed for Australia [*Clough and Scott*, 1989], rather than equations derived for Thailand [*Komiyama et al.*, 2005], as they had the same range of sizes as found on Inhaca and they were closer latitudinally. However, we could not find any allometric equations for *Lumnitzera racemosa*. As *Lumnitzera racemosa* and *Laguncularia racemosa* are in the same family, we used allometric equations derived for *Laguncularia* from Southern Florida [*Ross et al.*, 2001].

[16] We applied the field data from Inhaca Island to derive a single height-biomass regression (equation (2)). In a previous study, *Saenger and Snedaker* [1993] obtained a global mangrove height-biomass relationship (equation (3)) for mangrove forests worldwide based on a review of 43 articles and reports on mangrove biomass.

$$B = 50.7 \times H - 117.5 \quad R^2 = 0.64 \text{ RMSE } 35.5, n = 51 \tag{2}$$

$$B = 10.8 \times H + 34.9 \ R^2 = 0.77 \text{ RMSE } 43.8, n = 43 \tag{3}$$

where B is aboveground dry mangrove biomass in Mg/ha and H is average tree height in m.

[17] The equation obtained from their study varies substantially from the one obtained in the field in Mozambique, as the slope of the equation derived for Mozambique is about 5 times that of the one derived for the whole world.

Table 3. Confusion Matrix of Landsat ETM+ Classification[a]

			Ground Truth (%)					
Class	Mangrove	Dune	Rural Area	Mudflats	Forest	Urban Area	Water	Seagrass
Unclassified	0.29	0.75	0.06	0.17	0.17	0.21	0.00	0.14
Mangrove	90.86	8.66	0.49	1.00	0.10	0.05	0.00	0.00
Dunes	0.71	64.55	0.90	0.56	6.65	0.75	0.00	0.00
Rural Area	3.34	9.93	79.11	0.25	17.29	10.70	0.00	0.00
Mudflats	3.97	1.42	0.06	72.21	0.02	0.08	0.37	0.57
Forest	0.02	10.82	13.24	0.45	68.40	4.45	0.00	0.00
Urban area	0.53	3.13	6.13	2.76	7.37	83.73	0.01	0.00
Water	0.36	0.00	0.00	1.00	0.00	0.00	99.62	0.00
Seagrass	0.22	0.75	0.00	21.61	0.00	0.01	0.00	99.28
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[a]The overall accuracy was 93.91%, and the Kappa coefficient was 0.8703.

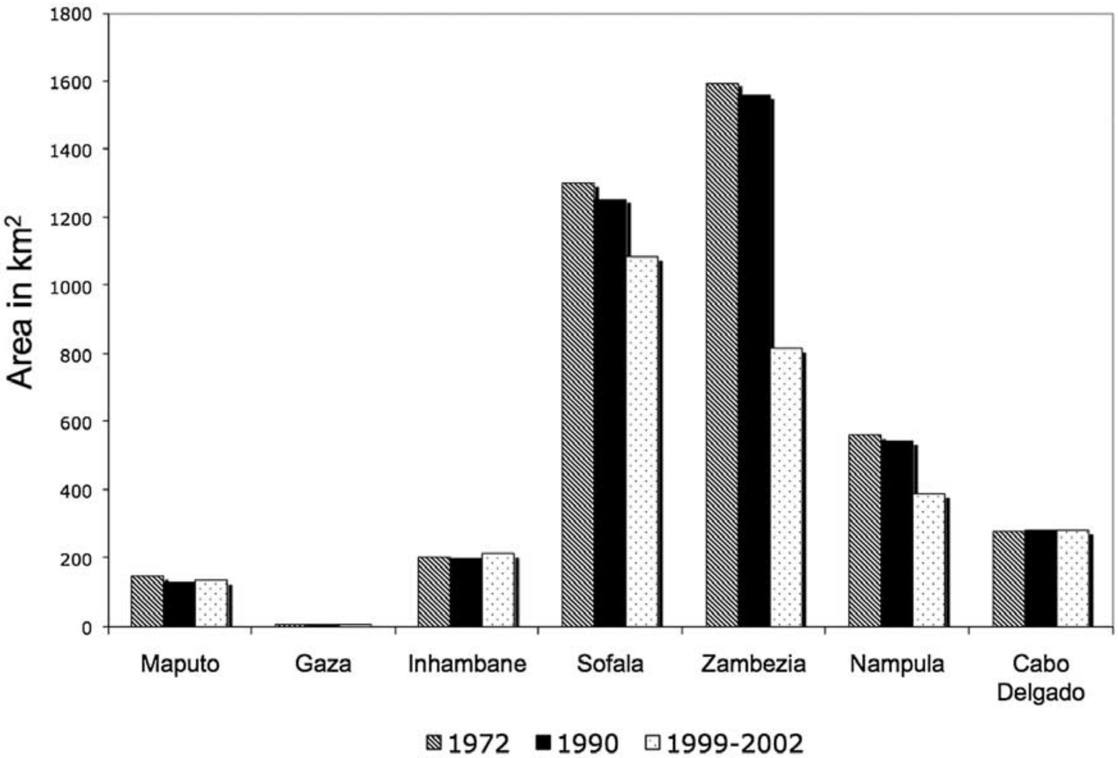

Figure 4. Histogram of mangrove cover in km^2 in Mozambique for 1972, 1990 and 1999–2002, showing that mangrove cover overall has been decreasing, especially in Sofala, Zambézia and Nampula provinces, while mangrove cover in Maputo, Inhambane, Gaza and Cabo Delgado has been relatively constant.

However, equation (2) only applies for forests with average heights ranging from 2.3 m to 6.4 m, whereas equation (3) applies to forests up to 40 m in height. We therefore used the worldwide biomass-height relationship (equation (3)) derived by *Saenger and Snedaker* [1993] to calibrate average tree heights. The amount of C was then estimated as 50% of the biomass [*Lieth and Whitaker*, 1975; *Piao et al.*, 2005]. In the last published estimates of mangrove area, *Saket and Matusse* [1994] reported mangrove area broken down by province. To facilitate comparison with this estimate, we described mangrove area by province as well. Finally, we extracted all heights and biomasses and plotted them against latitude to determine whether there is a relationship between these factors.

3. Results

3.1. Land Cover Map

[18] The total area of mangrove cover in Mozambique was 2909 km^2 with 93% accuracy (Table 3 and Figure 3). When the Landsat data was classified without applying the SRTM mask, the classification accuracy is much lower, at 71%. The final area estimate is 27% lower than previous estimates by *Saket and Matusse* [1994] of 3960 km^2, which was based on the interpretation of 16 printed Landsat images from 1973 and 1992. The largest mangrove areas are found in the Save-Zambezi River complex in Sofala and Zambézia provinces with a total mangrove area of 1900 km^2 and the smallest forest is found in the Limpopo Estuary in Gaza province with a total area of 3.5 km^2.

[19] Mangrove cover changed greatly throughout the country and the differences since 1978 and 1990 are illustrated in Figure 4. Based on the classification, the largest changes in mangrove area were observed in Zambézia province, with a difference of 745 km^2, representing almost half of its mangrove cover. Both Maputo and Inhambane Provinces registered a slight increase in mangrove cover of 6 and 13 km^2 respectively and Cabo Delgado is the only province in which mangrove cover was stable at 2790 ha.

3.2. Height and Biomass Estimations

[20] The SRTM height and aboveground biomass map of Mozambique is presented in Figure 5 and a geographical breakdown of height and biomass distribution in the provinces is in Table 4. Mangrove heights ranged from 1 m to 27 m, with an average of 5.8 m throughout the country. Average biomass in the provinces ranged from 72 Mg/ha to 207 Mg/ha with an average of 81 Mg/ha. Inhaca data included transects going from the shore to inland, thus representing the canopy structure as whole. Furthermore, the height class distributions for Inhaca obtained from SRTM and field measurements both exhibit the same inverse J-shape distribution with a majority of small trees and few tall trees. Even though SRTM has a larger range in heights than the field data, 86% of average tree heights on Inhaca Island measured by SRTM are shorter than or equal to 7 m, which is the maximum average height measured in the field. As the field measurements comprise almost 90%

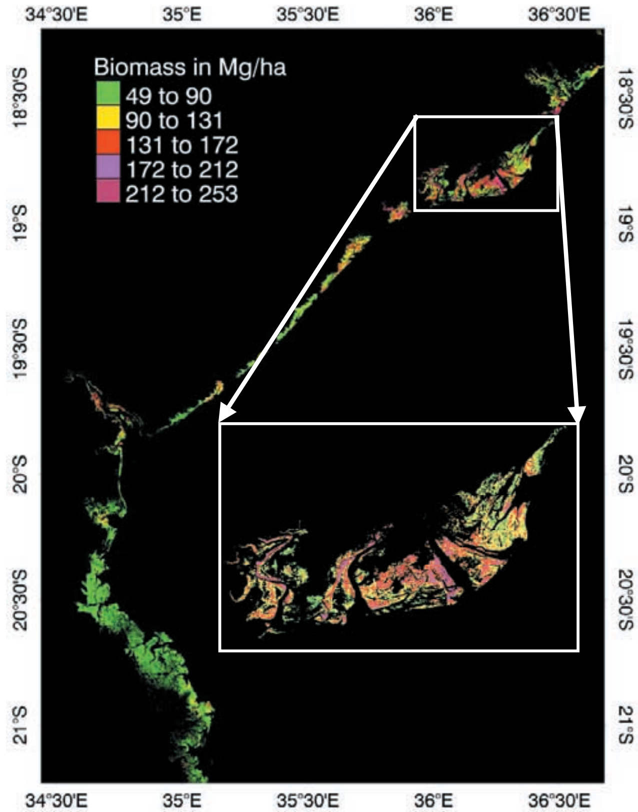

Figure 5. Example of the spatial distribution of mangrove forest biomass in the Sofala-Zambezi complex based on SRTM data, showing that there is a high spatial heterogeneity.

of the height range the field measurements are a good representative sample of the complete range in forest structure on Inhaca Island.

[21] The tallest mangroves in the country are found in Gaza and Zambézia provinces where riverine forests attain up to 27 m and 18 m height respectively. These areas also have high average biomasses per hectare values of 207 Mg/ha and 97 Mg/ha. It was previously believed that the forests of the Zambezi delta harbored the tallest mangroves in the country [*Barbosa et al.*, 2001]; however, Gaza has the largest proportion of tall trees throughout the country with an average height of 15.9 m ± 7 7.9 m. All provinces except for Gaza exhibit J-curve diametric distributions typically described for mature forests [*Obade et al.*, 2004], with 90% of trees under 9 m. The mangroves of Gaza province, exhibit a bimodal distribution, with few small trees (<5 m) and only 50% of trees in the province under 14 m. While a majority of the trees are short, a majority of the biomass, in each state and throughout the country, is contained in larger trees - between 9 m and 15 m.

[22] When comparing the average biomass per average tree height of the mangroves measured in the field on Inhaca Island, we found that short forests have larger biomasses than in most areas that were used to derive the worldwide biomass-height regression. A patch of forest with an average height of 4.4 m on Inhaca Island has an average biomass of 106 Mg/ha, whereas the biomass of a neotropical mangrove forest of the same height would be about 45 Mg/ha and that of an Australian forest would be 22 Mg/ha, for example. The biomasses of mangrove forests in Sri Lanka however, are similar to those found on Inhaca Island. Thus, the differences in biomass/height relationships between the field equation and the worldwide equation might lead to underestimations in biomass.

[23] We identified three sources of systematic error which apply to the province-wide biomass estimate that should be studied in more detail in future research: (1) errors in the classification, (2) errors in the ground elevation estimate and (3) errors in the biomass fit. The potential systematic error in the classification is due to omissions and commissions of mangrove pixels in the classification. The commissions were of 3.6% and the omissions of 10.6%, with a total error of 7.0%. The systematic error from the ground elevation could arise if the all mangroves do not grow exactly at sea level, but below and above sea level as well. However, if the amount of mangroves above sea level is the same as below sea level, there is no bias. The field data from Inhaca was a sample of all vegetation structures, including trees that may grow below and above sea level, and thus the systematic height estimate error for Inhaca is negligible. For the continental mangrove forests, the distribution of mangroves along the height profile might be different, and a bias may be expected, however this bias could not be over the 1.5 m tidal range, as tidal influence is necessary for mangrove growth. The error estimates based on the classification error, the elevation error and the biomass error were calculated from equation (4) and are shown in Table 4.

$$E_s = \sqrt{\left(E_c^2 + E_{eb}^2 + E_b^2\right)} \quad (4)$$

where E_s is systematic error, E_c is classification error, E_e is the elevation error and E_b is biomass error. As the error of

Table 4. Breakdown of Mangrove Forest Height and Biomass by Province

Province	Average Height (m)	Standard Deviation of Height (m)	Biomass (Mg/ha)	Total Biomass (Mg)	Random Error (Mg)	Systematic error (Mg)
Maputo	3.7	2.7	72	964,101	6,318	273,128
Gaza	15.9	7.9	207	70,810	1,015	8,444
Inhambane	4	4.4	67	2,238,038	7,978	450,141
Sofala	4.8	3.3	84	9,187,137	18,081	2,260,888
Zambezia	5.8	3.2	97	7,874,952	15,663	1,717,545
Nampula	4.7	2.5	84	3,247,788	10,802	806,410
Cabo Delgado	6.3	2.9	102	2,841,468	9,166	591,514
Total	5.8	3.9	81	23,582,826	29,624	6,048,089

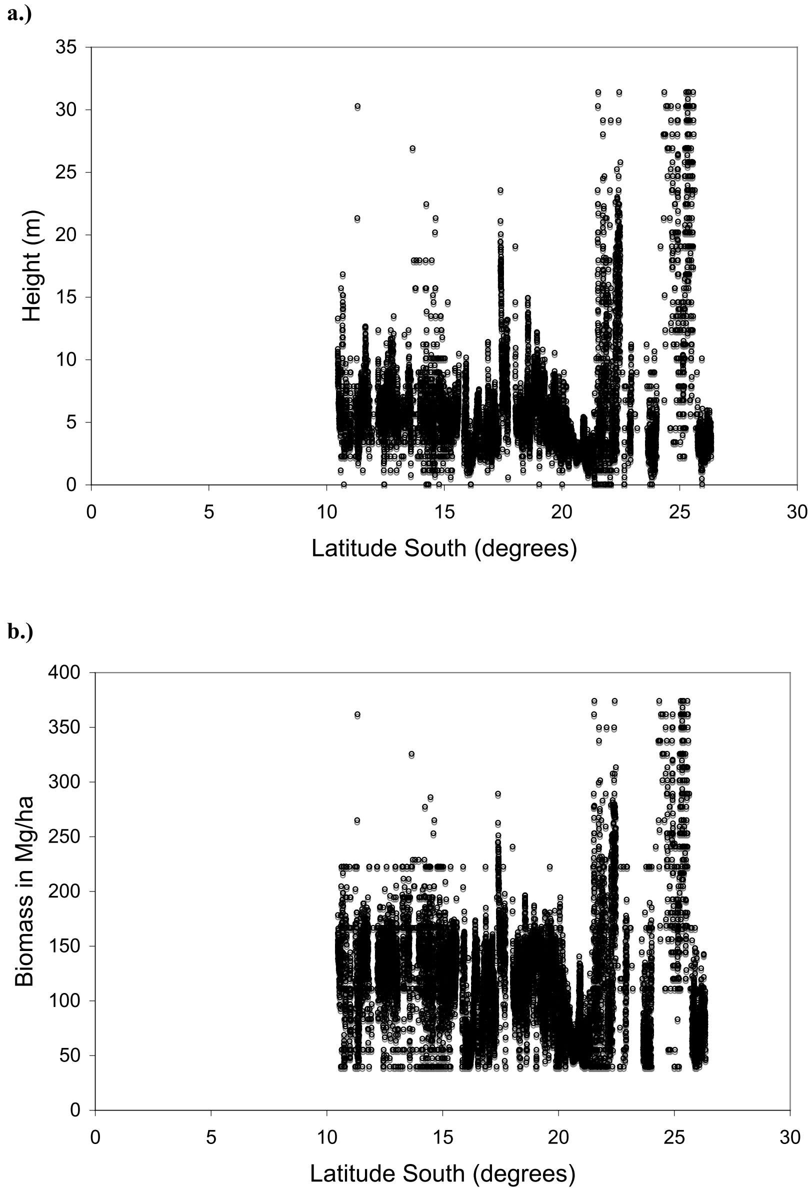

Figure 6. (a) Plot of the variation of average canopy height in Mozambique. There was no significant correlation between height and latitude across the whole country, indicating that factors other than latitude have a stronger influence on the height of mangrove forests in Mozambique. (b) Plot of the variation of total biomass with latitude in Mozambique. There was no significant correlation between biomass and latitude across the whole country, indicating that factors other than latitude have a stronger influence on the biomass of mangrove forests in Mozambique.

the biomass-height relationship was not reported in the *Saenger and Snedaker* [1993] paper, we neglected it in our calculations, however the estimation of the biomass error should be included in our future work.

3.3. Latitudinal Gradient

[24] Finally we investigated whether there was an increase in tree height and biomass from the South to the North of the country. We extracted all heights and biomasses throughout Mozambique and plotted them against latitude (Figure 6). We found no significant relationship - neither for average height nor for average biomass - with latitude. In fact, as stated above, the tallest mangrove forests were found in the Zambezi Delta, in central Mozambique, where trees were up to 18 m tall with an average of 5.8 m ± 3.3.2 m, and in the Limpopo Estuary, Southern Mozambique, where mangroves were up to 27 m tall, with an average height of 15.9 m ± 7.9 m. The northern provinces of Cabo Delgado and Nampula did have some of the tallest mangroves in the country, with average height of 6.3 m ± 2.9 m and 4.7 m ± 2.5 m, but the range of heights, total area with large trees

and average biomass were not as large as in Gaza and Zambézia provinces.

4. Discussion

4.1. Methodology and Error

[25] The combined use of optical and radar satellite images provide an important tool for the estimation of forest cover and aboveground biomass. The use of Radar remote sensing is particularly effective for estimating biomasses in areas that are difficult to access, such as mangroves [*Pasqualini et al.*, 1999]. There have been multiple approaches to estimating mangrove cover and forest composition [*Dahdouh-Guebas et al.*, 2004; *Laba et al.*, 1997; *Kovacs et al.*, 2001] but many rely on costly high-resolution imagery and few cover large areas. *Dahdouh-Guebas et al.* [2004] used high resolution IKONOS (1m resolution) to map mangrove cover and differences between species in mangrove forests of Sri Lanka. *Held et al.* [2003] used a combination of high-resolution CASI airborne scanner (2.5 m resolution) images and AIRSAR polarimetric radar data to map mangrove cover in Northern Queensland, Australia. *Laba et al.* [1997] and *Kovacs et al.* [2001] used Landsat images to assess changes in mangrove cover over time. In our study, we applied methods that were specifically developed for mangrove biomass estimation by *Simard et al.* [2006] to estimate aboveground biomass for all of Mozambique with remotely sensed data and field estimates of biomass.

[26] Some uncertainties nevertheless exist in the mangrove area and biomass estimations using our method. While the landcover map did have a high accuracy of 93%, there was still some misclassification of mangrove areas as nonmangrove and vice versa, with 3.6% commissions and 10.6% omissions. Given the low bias found for the height measurements on Inhaca, we neglected all systematic error in the height measurements and assumed the remaining error was random. For the biomass estimate, we identified three sources of systematic error, which apply to the province-wide biomass estimate: classification, ground elevation and biomass fit. The potential error in the estimate calculated from the systematic error is large and should be further quantified.

[27] For the calibration of the biomass estimate, the field data used to derive the biomass-height regression did not include all ten-mangrove species present in Mozambique, and we were limited to a sample of five species. Another major sources of error in the estimation of the real total biomass of mangrove forests is below-ground biomass. Because of their extensive root systems, between 10% and 60% of mangrove biomass is stored belowground [*Slim et al.*, 1996]. Based on this knowledge, we believe that our biomass estimate is very conservative, and that the actual biomass is larger than we calculated. All of these uncertainties are difficult to quantify without access to more detailed mangrove data from Mozambique and therefore more research in this area is needed.

4.2. Description and Comparison of Mozambique's Mangrove Area Estimates

[28] Overall, we observed a 27% smaller mangrove area for Mozambique (2909 km^2), based on our classification using SRTM and Landsat data, than was described for 1990 by *Saket and Matusse* [1994] (3961 km^2), who carried out the most complete remote sensing study of mangrove cover in Mozambique. Other estimates of Mozambique's mangrove area ranged from 5000 km^2 to 1000 km^2 [*FAO*, 2003] for the 1990s, but the abovementioned study is presumed the most accurate because of the methods used. In their study, *Saket and Matusse* [1994] compiled the total mangrove area of Mozambique using manual interpretations of two sets of false-color Landsat MSS images from 1972 and 1990. The differences in area estimates between *Saket and Matusse's* [1994] and our study can be explained by differences in methodology, classification errors (9% error in our study) and changes in mangrove areas due to anthropogenic and environmental factors. The methodology employed by *Saket and Matusse* [1994] relied entirely on visual interpretation, some field calibration and comparison with aerial photographs, but the accuracy of the final map was not published and can therefore not be compared to our accuracy assessment.

[29] Since 1990, there have been great changes in land use and environmental factors across Mozambique. With the end of the civil war in 1993, Mozambique has had a high economic growth rate (7.9% for 2006) [*United States State Department*, 2007] and overall development has substantially increased. Coastal areas have been particularly altered, because of population pressure, diversion of freshwater, agricultural and urban development and a flourishing tourism industry [*de Boer*, 2002]. The major threats to mangroves in Mozambique are: (1) exploitation for firewood, charcoal and construction, (2) conversion to agricultural lands and salt pans, (3) pollution, (4) diminishing freshwater flow and other anthropogenic effects, in addition to natural environmental occurrences such as hurricanes and changes in water currents [*Saket and Matusse*, 1994; *Doddema*, 1997].

[30] Throughout Mozambique, the patterns of mangrove cover change vary greatly. Maputo province is the southernmost province of Mozambique. It has experienced the fastest development rate in the country because this is where the capital city Maputo is located. Despite this rapid development, the total mangrove area in the vicinity of the capital has increased by 5%, although this increase is nonuniform. This confirms the results of *de Boer* [2002], who found that, while the overall mangrove area in Maputo Province from 1958 to 1991 decreased by 8%, in the areas furthest away from urban areas, particularly on Inhaca Island, mangrove cover increased by 13%. *de Boer* [2002] attributed the decreases in cover to distance to urban areas and increased sediment accretion rates [*Salm*, 1976; *Young and Harvey*, 1996; *Furukawa et al.*, 1997], whereas increases in mean air and ocean temperatures lead to expanding mangrove forests [*Schumann et al.*, 1995]. While we did not observe a significant change in area of mangroves in Maputo province based on the classification, there has been substantial degradation of mangrove forests in certain areas of the Maputo Bay, notably in the Costa do Sol area, the estuary of the Espiritu Santo River and on Portuguese Island [*Hatton and Couto*, 1992; *de Boer*, 2002].

[31] In Gaza province, there has been a clear decrease in mangrove area since the major flooding event in 2000, which affected the entire southern region of the Limpopo

river basin following cyclone Eline and the subsequent opening of dams upstream [*Dyson*, 2000; *Smithers et al.*, 2001]. As a result of the floods, the shape of the Limpopo Estuary changed completely, with the inundation of a 1 km wide strip of land in front of the river mouth and the creation of a lagoon. The mangroves on the coast were completely destroyed by flooding and sand intrusion and cannot be recolonized since they are now exposed to strong waves and coastal winds. In Inhambane province, we observed a small increase in mangrove area despite the fact that Inhambane is a popular tourist destination. According to our classification, Sofala is the province with the single largest area of mangroves in all of Mozambique with over 100 000 ha. The Sofala mangroves benefit from large amounts of freshwater discharge and alluvium from about 18 rivers [*Barbosa et al.*, 2001]. However, there was a 14% decrease of mangrove cover from 1990 to 2000.

[32] The mangroves of the Zambezi Delta have been described by *Timberlake* [2000], who mapped coastal mangroves/saline mudflats/inland freshwater mangrove associates, and *Vilankulos and Marquez* [2000], who mapped section of delta mangrove using 1999 SPOT imagery. *Beilfuss et al.* [2001] also describe the changes in vegetation cover of the Zambezi delta since 1960. Based on a classification of the same image as the one used in this study, they found that mangroves and associated species stretch up to 35 km inland and that mangroves alone occupy about 100,000 ha. However, when based solely on the Landsat ETM+ image path 166 row 073 from 2000, we found 73,000 ha of mangrove, an area much lower than the 155,000 ha described by *Saket and Matusse* [1994] and the 100,000 ha by *Beilfuss et al.* [2000]. We attribute these large differences in estimates to classification differences and the inclusion of mudflats and mangrove associated species in the classifications by *Beilfuss et al.* [2000] and *Saket and Matusse* [1994]. In general, *Beilfuss et al.* [2000] found insignificant changes in overall mangrove area, but large shifts in mangrove distribution, whereas we found a large decrease in mangrove area. The construction of the Kariba Dam in 1960 and the Cahora Bassa Dam in 1975 have altered both the total flow of freshwater to the delta and the cyclical flooding of the floodplain, leading to the regression of the coast of the delta and the surrounding 200 km [*Tinley*, 1994], and possibly contributing to the mangrove die off. In the North of the country, saltpan production is particularly widespread, with up to 50% of mangrove area converted [*Barbosa et al.*, 2001]. We found a decrease of over 150 km^2 of mangrove area in Nampula Province from previous estimates. The northernmost province of Cabo Delgado is the only one that has not seen changes in mangrove area since 1972. This can be attributed to the difficulty of accessing the area, low population pressure and the fact that there were no major natural environmental changes.

4.3. SRTM Height Map

[33] We found that the mangrove mean canopy height in Mozambique ranged from 1 m to 27 m, with an average height of 5.8 m ± 3.9 m throughout the country. These results agree with the 2.4 m to 25 m range described by other studies of mangrove structure at the same latitudes [*Saenger and Snedaker*, 1993].

[34] The mangroves of the Limpopo Estuary present a particularly interesting case in Mozambique. Even though Gaza province has the smallest area of all provinces, it has the tallest trees measured by SRTM and therefore the highest biomass/ha. This can be attributed to optimal growing conditions due to the riverine location of the mangroves. In addition, the period from February 11th to 22nd, 2000 when SRTM was flown around the earth was also the exact time at which exceptionally heavy rains fell over Mozambique, North-East South Africa and Zimbabwe and resulted in the worst floods the region had witnessed in over 100 years [*Dyson*, 2000; *Smithers et al.*, 2001]. As the result of the heavy rains from cyclone Eline and the opening of upriver dams in South Africa, the Limpopo basin in particular was extremely heavily flooded. We believe that the floods resulted in the destruction of the smaller mangrove trees, while the taller, stronger trees survived, which explains why the size-class distribution of trees for Gaza province is characterized by a much larger proportion of tall trees than anywhere else in Mozambique.

[35] The total biomass of mangrove forests worldwide is estimated at 8.7 gigatons of dry weight [*Twilley et al.*, 1992; *Kathiresan and Bingham*, 2001]. We estimated the total dry Mangrove aboveground biomass of Mozambique at 23.6 million tons, with an average biomass of 81 Mg/ha and a RMSE of 44 Mg/ha. Assuming that 50% of the dry weight is C [*Lieth and Whitaker*, 1975], the standing stock of carbon stored in mangrove woody biomass is 11.8 million tons and 40.5 Mg C/ha. The average biomass of Mozambique of 81 Mg/ha of mangroves is relatively low compared to that of the mangroves of Indonesia and Malaysia with biomasses over 300 Mg/ha [*Ong et al.*, 1981; *Komiyama et al.*, 1988] but the range of 67 to 207 Mg/ha is similar to the biomasses found by other studies for the corresponding latitudes [*Saenger and Snedaker*, 1993]. As expected from the average height, Gaza province has the highest biomass Mg/ha, but Sofala and Zambézia provinces hold 72% of the mangrove biomass of the whole country. These are also the main regions for shrimp fishery and in addition to the knowledge of the direct relationship between total mangrove area and fishery catch [*Putz and Chan*, 1986], this data could now give more insight into the relationship between mangrove forest quality and fishery yield.

4.4. Relationship Between Biomass and Latitude

[36] It is generally believed that forest productivity is highest close to the equator, and decreases with increasing latitude. In a review of 43 papers on the structure, biomass and litterfall of mangrove forests around the world, *Saenger and Snedaker* [1993] confirmed that mangrove tree heights, aboveground biomass and litterfall followed this pattern of distribution. Using SRTM to estimate aboveground biomass in Mozambique presents a unique opportunity to test the results found by *Saenger and Snedaker* [1993], as it is the first study estimating total aboveground biomass using one method at this scale, covering over 16 degrees latitude.

[37] Contrary to the abovementioned findings, we did not find a significant correlation between biomass and height depending on latitude. Indeed, height (and biomass, which is directly proportional to height), was much more dependent on proximity to freshwater, with the riverine mangroves of the Limpopo at 25 degrees latitude and the deltaic

mangroves of the Zambezi at 18 degrees latitude growing the tallest. Mangrove growth is often limited by nutrient availability [*Lugo and Snedaker*, 1974; *Boto et al.*, 1984; *Clough*, 1992; *Twilley et al.*, 1992] and both the Zambezi delta and the Limpopo estuary receive large amounts of nutrient rich upstream sediments, leading to tall mangrove forests [*Barbosa et al.*, 2001; *Beilfuss et al.*, 2001].

[38] Mozambique has a variety of environmental settings, which have a stronger influence on mangrove growth, composition and therefore biomass, than latitude alone does. It would be interesting to carry out further studies of forest structure and biomass using SRTM on an even larger scale to verify whether it is possible to detect significant trends in mangrove biomass and productivity with latitude.

5. Conclusions

[39] Mangrove forests have been greatly degraded and destroyed throughout the world, despite their known ecological and economical importance. Because they form an ecosystem that is difficult to survey in the field and as they largely grow in developing nations for which data is often not available, large-scale studies of their structure and biomass have not been carried out. In this paper, a new method using Landsat-derived landcover maps and Shuttle Radar Topography mission data has been applied to estimate Mozambique's total mangrove area, as well as spatial height and biomass distribution. Since the coast of Mozambique covers a large range of latitudes, 10°20 'S to 26°50 'S, we were also able to test the biogeographical paradigm that mangrove biomass increases with proximity to the equator [*Saenger and Snedaker*, 1993].

[40] The mangrove map, developed from Landsat ETM+ data of Mozambique, showed that the total mangrove area of Mozambique is 2909 km^2 with an accuracy of 91%. The area of 2909 km^2 is 27% smaller than the previous estimate of 3600 km^2 [*Saket and Matusse*, 1994]. While the difference in area can be attributed to classification errors - the classification accuracy was increased by 22% by using the SRTM mask - we also believe that there has been a decrease in mangrove area throughout the country due to anthropogenic and environmental factors. Indeed, mangroves in Mozambique have suffered due to clearances for salt ponds, agriculture, use for firewood, construction of dams - which resulted in the diversion of freshwater - pollution and development of the land for tourism. In addition, major floods, coastal erosion and sand intrusion have also lead to the loss of mangrove forests, notably in Gaza province and in the Maputo Bay.

[41] The height map derived from the field data and SRTM data, showed that SRTM data is a good indicator of average mangrove tree height, with a RMSE of 1.5 m. There were substantial differences in height and biomass distributions throughout Mozambique. The average tree height in Mozambique was 5.8 m and tree heights measured with SRTM ranged from 1 m to 27 m. The tallest trees were found in the Zambezi Delta and in the Limpopo Estuary.

[42] In summary, our estimates of aboveground forest biomass and C storage are a good indicator of what the aboveground biomass of mangrove forests is in Mozambique. However, we do believe that more extensive ground measures of structure and biomass are needed. Subsequent research should consider the ground topography in mangrove forests and determine whether there is a bias in the height and biomass estimation. By determining the forest area and biomass of Mozambique, we were able to provide much needed data on Mozambique's natural resources and were able to prove that one of the most widespread theories in mangrove biogeography does not apply to this region.

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