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Title: Patterns of mangrove forest disturbance and biomass removal due to small-scale harvesting in southwestern Madagascar

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Abstract

Informal small-scale mangrove wood harvesting has received limited attention, though it is a widespread threat to mangroves in many parts of the tropics. We investigated wood use and the impacts of harvesting on mangrove forests in the Bay of Assassins in southwest Madagascar. We measured forest structure, composition, and harvesting across 60 vegetation plots and investigated human uses of the mangroves through Rapid Rural Appraisal techniques. We found that unlike other mangroves in the region, those in the Bay of Assassins are dominated by *Ceriops tagal*. Tree harvesting rates are high, with a mean of 28.7% (SD 19.4) of trees harvested per plot. This is similar to heavily harvested mangroves in other parts of the tropics. A comparison of tree versus sapling importance of the different mangrove tree species indicates that the composition of the mangrove forest is changing, with *C. tagal* becoming more important. Livelihood activities drive the harvesting of certain species and size classes. Mangrove wood is used mainly for the construction of traditional housing and fencing. There are also emerging uses of mangrove wood, including seaweed (*Kappaphycus alvarezii)* aquaculture and the production of 'sokay', a lime render made by burning sea shells in mangrove wood kilns and used to improve the durability of houses. Small-scale selective harvesting of mangrove wood is important for local livelihoods but may have wide-ranging impacts on forest composition and structure. Demand for mangrove wood has grown in relation to new commodity chains for marine products, demonstrating the need for integrated landscape management that considers wetland, terrestrial and marine resources together.

1. Introduction

Intertidal mangrove forests are globally threatened (Polidoro et al. 2010, Hamilton & Casey 2016) by a range of pressures such as aquaculture and agriculture, urban development, harvesting for paper pulp, fuelwood, charcoal and construction materials, changes in hydrology and sediment budgets, and sea-level rise (UNEP 2014). There is considerable geographical variation in the processes that lead to mangrove deforestation and degradation, with threats differing in both scale and type. Aquaculture has been the most important human activity leading to mangrove loss globally (Thomas et al. 2017), particularly driving mangrove change in Southeast Asia and Latin America (Walters et al. 2008, Richards & Friess 2016). In sub-Saharan Africa, harvesting for fuelwood and charcoal production are growing threats (Feka and Ajonina 2011, UNEP 2014; Feka, 2015).

Mangrove deforestation and degradation in low-income nations is of particular concern, as poor rural communities rely heavily on a wide range of ecosystem services provided by mangrove forests. These include the direct provisioning of building materials, fuelwood, charcoal, animal fodder, (shell)fish and non-timber forest products (Bandaranayake 1998, Dahdouh-Guebas et al. 2000, Walters 2005a, Barbier et al. 2011, Lau & Scales 2016), alongside the benefits that these communities gain from regulating services (e.g., coastal protection) and cultural services (e.g., recreation, aesthetic and spiritual values).

While communities benefit from ecosystem services, the extraction of provisioning services can have negative impacts on the system providing them. Informal small-scale wood harvesting is one of the most widespread forms of resource use in mangrove forests (e.g. Rajkaran et al. 2004, Walters 2005a, Walters 2005b, Walters et al. 2008). This is especially the case in sub-Saharan Africa (Feka & Ajonina 2011). However, few studies of informal mangrove harvesting have been published. Furthermore, research on the impacts of mangrove harvesting has mostly focused on measuring mangrove cover loss through forest clearance rather than looking at other forms of human use and disturbance. This is in part because, unlike forest clearance, more cryptic forms of

degradation caused by harvesting and other small-scale forest disturbances can be difficult to detect using remote sensing methods (Dahdouh-Guebas et al. 2005). Inaccessibility and poor infrastructure make mangrove monitoring through field surveys difficult and time-consuming (Feka & Morrison 2017).

Madagascar has 2% of the total global mangrove forest cover by area (Giri & Mulhausen 2008). With a mean per capita daily income of $1.50, it is one of the poorest countries in the world (World Bank 2016). As a result, rural communities are heavily reliant on the provisioning services of ecosystems, including mangroves, for their basic needs (Harris 2011). This potentially has implications for the long-term sustainability of these ecosystems, and highlights the importance of sustainable forest management.

We take a multidisciplinary approach to investigate the patterns and use of small-scale harvesting on mangrove forests in the Bay of Assassins in southwestern Madagascar, a remote region where mangroves are used by poor, largely subsistence-based, artisanal fishing communities (Scales et al. 2018). First, we characterize mangrove forest composition and structure throughout the Bay. Second, we quantify patterns of harvesting pressure on the mangrove system and the volume of biomass removed. Third, we investigate household use of mangrove wood. We finish by considering the management implications of current mangrove uses and their impacts in the Bay of Assassins.

2. Methods

2.1 Study site description

Madagascar's mangroves covered an area of 2797 km^2 in 2005 (Giri & Mulhausen 2008), distributed primarily in bays and inlets along the sheltered west coast. Madagascar is home to nine species of mangrove tree (Spalding et al. 2010). A substantial rainfall gradient exists along the western coast, with the arid southwest of Madagascar receiving approximately 400 mm of rainfall per year, and the wetter northwest coast receiving approximately 2000 mm per year. This influences

mangrove forest structure along the coast, with trees of larger stature found in mangroves in the northwest bays of Ambaro, Ambanja and Mahajamba compared to the southwest (Hutchison et al. 2014; Jones et al. 2016). Mangrove biomass carbon averages 146.8 Mg C ha^{-1} in the northwest (Jones et al. 2014), but only 46.2-73.9 Mg C ha^{-1} in the southwest (Benson et al. 2017).

This study was conducted in the Bay of Assassins (Helodrano Fagnemotse in Malagasy), a coastal inlet in southwestern Madagascar (22° 12' S, 43° 16'N), 180 km north of the regional capital of Toliara (Figure 1). The climate is semi-arid, with approximately 400 mm rainfall per year. The inlet is fringed by c. 1300 ha of mangrove forest (Jones et al. 2016). There are 10 villages around the bay, with a total population of approximately 3000 (Peabody & Jones 2013). With an average daily per capita income of less than US$1.50, fishing communities in southwestern Madagascar are some of the country's most isolated and marginalized (Harris 2011). Small-scale fishing generates over 80% of household income in these communities and provides the majority of dietary protein (Barnes-Mauthe et al. 2013).
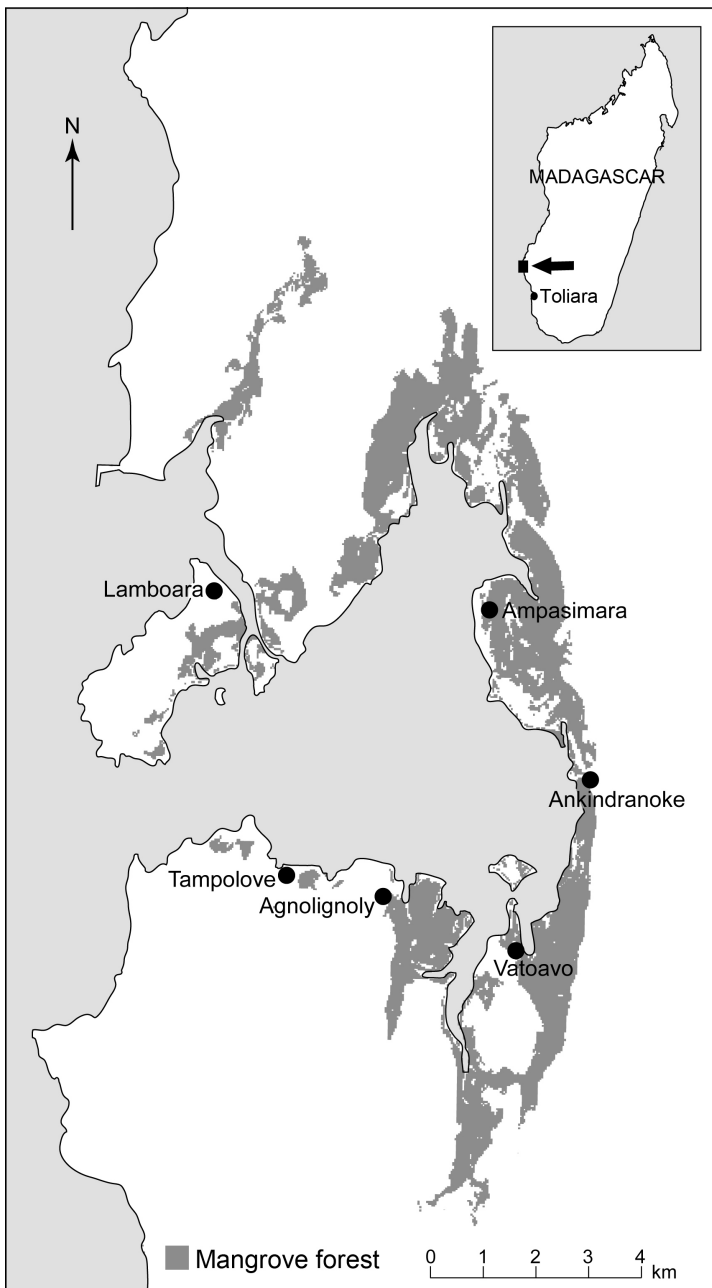
Figure 1. The Bay of Assassins, southwestern Madagascar showing mangrove forest cover (dark grey)

2.2 Field measurements of forest characteristics and harvested status

Our vegetation survey was based on a modified version of a mangrove forest structure and biomass assessment protocol set out by Kauffman & Donato (2012). We conducted measurements of mangrove canopy cover, species composition, forest structure, and harvesting in 60 circular plots with a seven metre radius (covering an area of 153.94 m^2). Plot locations were randomly selected

around the Bay of Assassins to minimize sampling biases due to edge effects or distance from human habitation. A random number generator was used to select distances and angles between sampling points. This sampling design also ensured that we randomly covered all representative forest types across the bay.

We recorded the latitude and longitude of each plot using a handheld Global Positioning System. The Euclidean distance of each plot to the forest edge and the nearest settlement were calculated in ArcGIS. We estimated canopy cover in four cardinal directions at the centre of each plot using a concave spherical canopy densitometer (Lemmon 1956). In each plot we counted and identified all trees (non-harvested and harvested) to species level, as well as measured diameter at breast height (DBH). We defined trees as woody mangrove vegetation with a DBH of at least 5 cm and defined saplings as woody mangrove vegetation with a diameter greater than 1 cm but less than 5 cm. We counted and identified to species level every sapling in the plot. We also counted all seedlings within a nested circular plot of 2 m radius around each plot centre. The DBH of live trees was measured at a height of 1.3 m above the ground surface, or 30 cm above the highest root if the root was higher than 1.3 m (e.g., for *Rhizophora mucronata*). For multi-stemmed trees, the DBHs of all stems were measured, though this accounted for a small percentage of the total number of measured trees. The DBH of harvested trees was measured either at a height of 1.3 m, or immediately below the cut location if mangroves were harvested at a height lower than 1.3 m. We assessed harvested status by recording the way trees had been harvested. Trees were recorded as either harvested at the ground surface (1); harvested below 1.3 m height (2); harvested above 1.3 m (3); or harvested by branch only (4).

2.3 Calculation of statistics, forest composition and structure indices

We calculated the tree basal area (TBA) for each tree using the following equation: TBA (m^2) = (DBH/200)^2 x 3.142 m^2. For each species, we calculated: i) the absolute frequency (the percentage of plots in which a species was recorded); ii) the absolute density (the number of trees per hectare);

and iii) the absolute cover (the total basal area of all trees per hectare). We converted absolute measures into relative measures by expressing the absolute measure for each species as a percentage of the total of the absolute measures for all trees across all species. We then calculated the importance value for each species by adding together relative frequency, relative density and relative cover (Mueller-Dombois et al. 1974). We calculated relative importance values by dividing the importance values of each species by the total importance values of all species and multiplying by 100. We repeated this for saplings. We calculated the regeneration rate for each species by dividing the number of saplings by the number of trees and multiplying by 100.

2.4 Calculations of biomass

The living aboveground biomass (AGB) and belowground biomass (BGB) of mangroves trees was estimated using published, species-specific allometric equations, in line with previous biomass studies and accepted international protocols (e.g., Kauffman and Donato 2012). In contrast to previous studies that utilize a standard mangrove allometric equation (e.g., Abino et al. 2014; Rahman et al. 2015; Portillo et al. 2017), we used species-specific allometric equations (where available) to increase the robustness of our biomass estimates. Where an equation for a particular species was not available, it was substituted for a similar species, e.g., *Rhizophora apiculata* (Putz & Chan 1986) in place of *R. mucronata.* In place of an equation for *Ceriops tagal* we used an equation for *C. australis* (Comley and McGuinness 2005); while *C. australis* and *C. tagal* are genetically distinct species they are botanically very similar, and until recently were considered the same species. We also chose published equations from locations that most closely matched the forest characteristics and local geomorphology of our study site where possible (Table 1). We could not easily control for biogeographic region because of a lack of suitable robust studies of allometry for African mangroves. However, regional differences in allometry are not generally considered significant (Chave et al. 2014).

Table 1. *Descriptions of the aboveground biomass (AGB) and belowground biomass (BGB) allometric equations used in this study.*

Species	Allometric Equation	Reference
Avicennia marina	$AGB = 0.308DBH^{2.11}$ $BGB = 1.28DBH^{1.17}$	Comley & McGuinness (2005)
Bruguiera gymnorhiza	$AGB = 0.186DBH^{2.31}$ $BGB = 0.199*\rho^{0.899}*DBH^{2.22}$	Clough & Scott (1989) Komiyama et al. (2008)
Ceriops tagal	$AGB = 0.32DBH^{2.056}$ $BGB = 0.158DBH^{1.95}$	Comley & McGuinness (2005) Comley & McGuinness (2005)
Rhizophora mucronata	$AGB = 0.1709DBH^{2.516}$ $BGB = 0.00698DBH^{2.61}$	Putz & Chan (1986) Ong et al. (2004)
Xylocarpus granatum	$AGB = 0.08233DBH^{2.5883}$ $BGB = 0.199*\rho^{0.899}*DBH^{2.22}$	Clough & Scott (1989) Komiyama et al. (2008)

2.5 Surveys of mangrove wood use

To investigate mangrove wood use by local communities we used Rapid Rural Appraisal (RRA) techniques (McCracken et al. 1988, Chambers 1992, Pratt and Loizos 1992, Newing 2011). RRA covers a broad range of methods devised to identify the problems and strategies of households, groups and communities in a limited time span that precludes in-depth ethnographic fieldwork or quantitative household surveys (Pratt and Loizos 1992, Newing 2011). The core principle of RRA is triangulation, where data from different techniques and informants are compared against each other to reduce various forms of individual bias in responses (e.g. according to age, gender or socio-economic class) and arrive at a rigorous understanding of major similarities and differences in resource use.

Our RRA was based on a literature review (including data from household surveys carried out by an environmental non-governmental organization); interviews with local experts working for environmental non-environmental organizations; focus group discussions in five villages; and semi-structured interviews and transect walks with 15 key informants. We selected these informants purposively to provide further information on specific aspects of mangrove use. Our informants included fishermen, individuals involved in gleaning, and individuals involved in mangrove wood

harvesting for various purposes (e.g. house construction and lime kiln construction). We interviewed both men and women to ensure information on the widest possible range of household uses and (often gender-specific) livelihood activities relating to mangroves. Interviews lasted between 30 minutes and an hour. Transect walks involved walking with informants along a path covering major aspects of the landscape (villages, livestock pens, farms, mangrove forests, and dry forests) and resource uses (e.g. fishing, gleaning, and aquaculture).

3. Results

3.1 The composition and structure of live mangroves in the Bay of Assassins

While six species of mangrove tree have been recorded in the Bay of Assassins (Benson et al. 2017), we recorded only five species in our vegetation surveys: *Avicennia marina* (afiafy in the local Malagasy dialect), *Bruguiera gymnorhiza* (tangampoly), *C. tagal* (tangambavy), *R. mucronata* (tangandahy), and a single individual of *Xylocarpus granatum*. We also came across a small number of *Sonneratia alba* trees outside our plots. *X. granatum* is rarely found in Malagasy mangroves (Gaudian et al. 1995). We measured a total of 2667 live trees, 4861 live saplings and 1058 seedlings across the 60 plots.

The mean tree basal area for live trees across the 60 plots was 19.37 m^2 ha^{-1} (SD = 9.24). Our plots had a mean canopy cover of 73.5% (SD = 23.07). Table 2 shows that the most important species in the mangroves of the Bay of Assassins are *C. tagal* and *R. mucronata*. *C. tagal* dominates, with the highest frequency (100%), relative frequency (39.47%), relative density (59.1%), relative basal area cover (52.17%), and relative importance value (50.25%). Figure 2 shows that mangrove stands in the Bay of Assassins are dominated by small trees with DBHs smaller than 10 cm, with the diameter class distribution for all four major species in the Bay of Assassins heavily skewed towards smaller trees.

Table 2. Frequency, density, cover and importance of live trees of the five mangrove species recorded in sample plots

| Species	Absolute frequency (% of plots)	Relative frequency	Absolute density (trees ha^{-1})	Relative density	Absolute cover (m^2 ha^{-1})	Relative cover	Importance value	Relative importance
A. marina	13.33	5.23	75.79	2.63	1.31	6.74	14.60	4.87
B. gymnorhiza	60.00	23.53	277.16	9.62	2.03	10.49	43.64	14.55
C. tagal	100.00	39.22	1701.96	59.10	10.10	52.12	150.41	50.14
R. mucronata	80.00	31.37	825.00	28.65	5.92	30.55	90.56	30.19
X. granatum	1.67	0.65	1.08	0.04	0.02	0.10	0.80	0.27
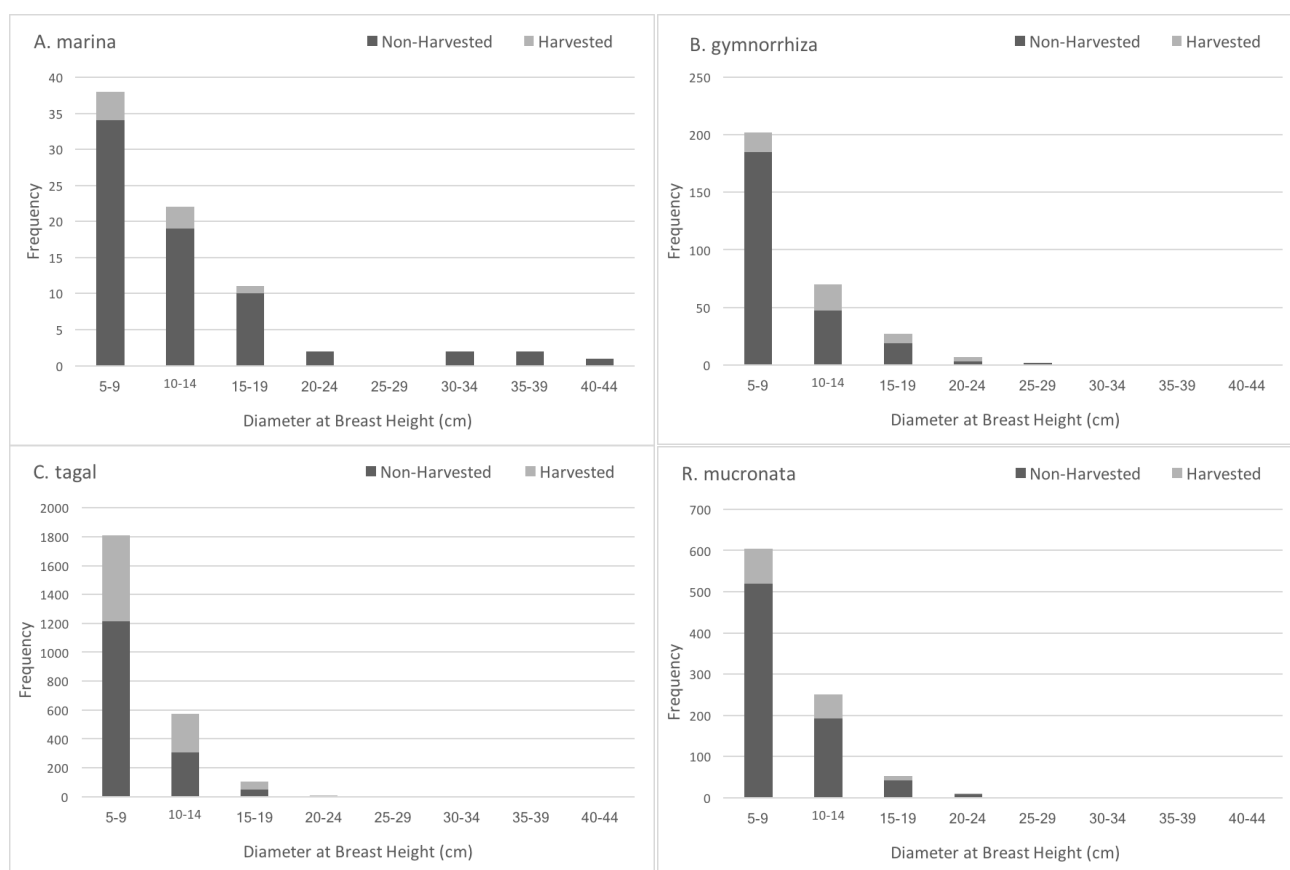
Figure 2. Frequency distributions of the DBH (cm) of non-harvested and harvested trees of the four major species found in the Bay of Assassins

3.2 Mangrove regeneration

We found a mean seedling density of 14,039 seedlings ha^{-1} (SD = 16,089) and a live sapling density of 4554 saplings ha^{-1} (SD = 5901). Table 3 shows that there is considerable variation between species in sapling frequency, density and importance. *C. tagal* has the highest sapling frequency, density and importance. Comparing trees to saplings, the overall pattern is the same, with *C. tagal* the dominant species. However, compared to trees above 5 cm DBH, *C. tagal* saplings have a higher relative importance (59.47 compared to 50.14) and *R. mucronata* saplings have a lower relative importance (21.00 compared to 30.19).

Table 3. Live sapling frequency, density and regeneration rate for each species

Species	Absolute frequency (% of plots)	Relative frequency	Absolute density (saplings ha^{-1})	Relative density	Importance (relative frequency + relative density)	Relative importance	Regeneration rate
A. marina	3.33	1.52	12.99	0.29	1.81	0.90	13.95
B. gymnorhiza	65.00	29.55	350.79	7.72	37.27	18.63	102.76
C. tagal	85.00	38.64	3647.53	80.31	118.95	59.47	153.70
R. mucronata	66.70	30.30	530.51	11.68	41.98	21.00	124.76

3.3 Mangrove harvesting characteristics

A total of 1146 harvested trees (1241 trees ha^{-1}) and 665 harvested saplings (720 saplings ha^{-1}) were sampled over the 60 plots. The mean tree harvesting rate per plot was 28.7% (SD = 19.4), and the mean sapling harvesting rate was 18.7% (SD = 23.1). Every plot sampled contained harvested trees, with plots ranging in harvesting rate from 1.5% to 71.4%.

Harvest pressure differed between species; *C. tagal* was the most harvested species, contributing 81.2% of all harvested trees, followed by *R. mucronata* (13.6%), *B. gymnorhiza* (4.6%) and *A. marina* (0.7%). Of all *C. tagal* trees measured, 35.8% were harvested, compared to 16.3% of *R. mucronata* trees, 16% of *B. gymnorhiza* trees and 9.3% of *A. marina* trees. The large majority of trees (92.7%) were harvested by cutting the tree at the trunk rather than cutting branches.

The mean DBH of harvested trees was 9.21 cm (SD = 3.67). Looking at all species together, the most harvested size class was 5-9 cm DBH. These accounted for 61.59% of all harvested stems. Table 4 compares the mean DBH of non-harvested and harvested trees for each species. It shows that for every species apart from *A. marina*, the mean DBH of harvested species was significantly greater (p = <0.05) than the mean DBH of non-harvested trees, indicating that harvesters are preferentially selecting trees that are larger than the average size.

Table 4. Comparison of the mean DBH in cm (with standard deviations) of non-harvested and harvested trees

	Mean DBH (cm) of non-harvested trees	Mean DBH (cm) of harvested trees	t	p
All trees	8.53 (3.55)	9.21 (3.67)	-5.26	<0.001
A. marina	12.48 (8.03)	10.66 (3.53)	1.16	0.26
B. gymnorhiza	9.20 (3.98)	11.81 (4.64)	-4.38	<0.001
C. tagal	8.16 (2.97)	8.96 (3.62)	-5.70	<0.001
R. mucronata	8.85 (3.59)	9.74 (3.21)	-3.09	0.002

The AGB for all our plots averaged 161.9 Mg ha^{-1} (SD = 68.6 Mg ha^{-1}). However, harvesting pressure means that this average is below the potential AGB that is available at this site. A mean AGB of 46.7 Mg ha^{-1} was removed through harvesting, though a large standard deviation (42.4 Mg ha^{-1}) is reflective of the substantial variation in total harvested AGB across the 60 plots, ranging from 0 to 163.3 Mg ha^{-1}. This means that the site AGB is 22.4% lower than the potential AGB available at this site.

C. tagal was the preferred species to be harvested, accounting for 72.9% of the total AGB of harvested wood (Table 5). This was followed by *R. mucronata* (20.3% of all harvested wood). Size classes were also differentially harvested. Trees with a DBH between 5.0 cm and 9.9 cm accounted

for an average of 27.9% of all harvested trees. This is a disproportionate contribution, considering the small individual volume of trees in this smaller size class, compared to the larger trees harvested. Similar to the overall volumes, *C. tagal* was strongly preferred as a smaller pole, alone accounting for 21.4% of all AGB harvested. We discuss the uses of the different species and size classes in section 3.5.

Table 5. Percentage of above-ground biomass (AGB, Mg Ha^{-1}) harvested by species and size class. Total = 100%.

	DBH >5.0 <10.0 cm	DBH >10 cm
A. marina	0.20%	0.58%
B. gymnorhiza	0.56%	5.21%
C. tagal	21.40%	51.52%
R. mucronata	5.77%	14.53%
A. marina	0.00%	0.23%

3.4 *Spatial patterns of mangrove harvesting*

The plots we sampled were a mean distance of 1159 m (SD = 606) from the nearest settlement, with a minimum of 233 m and a maximum of 2801 m. Plots were a mean distance of 92 m from the nearest mangrove edge (SD = 62), with a minimum of 15 m and a maximum of 352 m. Table 6 shows the results of correlations conducted between distances of the plots from the nearest human settlement; distances of the plots from the nearest mangrove edge; and various measures of mangrove harvesting.

Table 6. Correlation coefficients for relationship between distance from the nearest human settlement and distance from the nearest mangrove edge

	Distance from nearest human settlement (m)		Distance from nearest mangrove edge (m)	
	r	p	r	p
Percentage of trees harvested	-0.43	<0.001	-0.21	0.10
Percentage of saplings harvested	0.08	0.53	-0.03	0.80
Percentage of trees 5-9 cm DBH harvested	-0.42	<0.001	-0.23	0.07
Percentage of trees 10-14 cm DBH harvested	-0.39	0.002	-0.12	0.37
Percentage of trees 15-19 cm DBH harvested	-0.13	0.36	0.18	0.22
Percentage of trees ≥20 cm DBH harvested	-0.09	0.71	0.36	0.10
Percentage of *A. marina* trees harvested	-0.40	0.37	-0.12	0.80
Percentage of *B. gymnorhiza* trees harvested	-0.38	0.02	-0.09	0.56
Percentage of *C. tagal* trees harvested	-0.47	<0.001	-0.29	0.03
Percentage of *R. mucronata* trees harvested	-0.23	0.11	-0.18	0.21

The results show that there are significant inverse correlations (p = <0.05) between the distance from the nearest human settlement and the percentage of trees harvested; the percentage of 5-9 cm and 10-14 cm DBH trees harvested; and the percentage of *B. gymnorhiza* and *C. tagal* harvested. However, there was no significant correlation between distance from the nearest human settlement and the percentage of *A. marina* or *R. mucronata* harvested. None of the correlations between distance from the nearest mangrove edge and tree harvesting were significant. These results show that mangrove forests are more heavily harvested closer to human settlements but that distance from the mangrove edge (and thus access from the sea or land) does not seem to influence harvesting pressure.

3.5 Human uses of harvested mangrove wood

The Rapid Rural Appraisal showed that mangrove trees in the Bay of Assassins were harvested: i) as fuelwood for domestic cooking; ii) as a building material for housing and fencing; iii) as a building material for seaweed aquaculture; and iv) for the construction of lime kilns. Respondents suggested that the use of mangrove wood in lime kilns and in seaweed aquaculture are recent, having only developed over the last ten years. Mangrove wood was also recently used in sea cucumber (*Holothuria scabra*) aquaculture to construct growing-out enclosures. However, mangrove wood has now been replaced with stronger and more durable steel rods for this use.

With regards to domestic fuelwood, saplings and trees less than 10 cm DBH were sometimes used but wood from neighbouring terrestrial dry forests was preferentially used as a fuel as it is usually drier and more easily combustible. The most frequent use of mangrove wood was for house and fence construction. These activities almost exclusively use mangrove wood rather than wood from terrestrial forests. Larger poles (between 10 cm and 20 cm diameter) were used to build the frames of houses (Figure 4A), with smaller poles (5 to 10 cm diameter) used to support wall and roof material. Respondents generally favoured *R. mucronata* for the construction of house frames because of its resistance to decay.

Poles of *C. tagal* were used in the construction of fencing around houses (background of Figure 4B) and to construct livestock enclosures. Fences are particularly important due to high incidences of banditry in the region. Fence poles were used in large quantities due to frequent maintenance and replacement requirements, with poles lasting two or three years. Our informants told us that fence construction was the most common reason for harvesting mangrove wood. This is supported by the vegetation survey (*Section 3.4*), which showed that a disproportionate volume of harvested AGB was *C. tagal* stems with a DBH of between 5 and 9.9 cm (the preferred species and size class for fencing).

A more recent use of mangrove wood in the Bay of Assassins involves seaweed (*Kappaphycus alvarezii*) aquaculture. Saplings and trees with a DBH of 5 to 9 cm and a length of

approximately 1 m were used as stakes for seaweed farming. The stakes provide anchor points for ropes on which the algae grow, but needed replacing every 6-24 months. Mangrove poles were also used to build tables to dry the seaweed (Figure 4B).
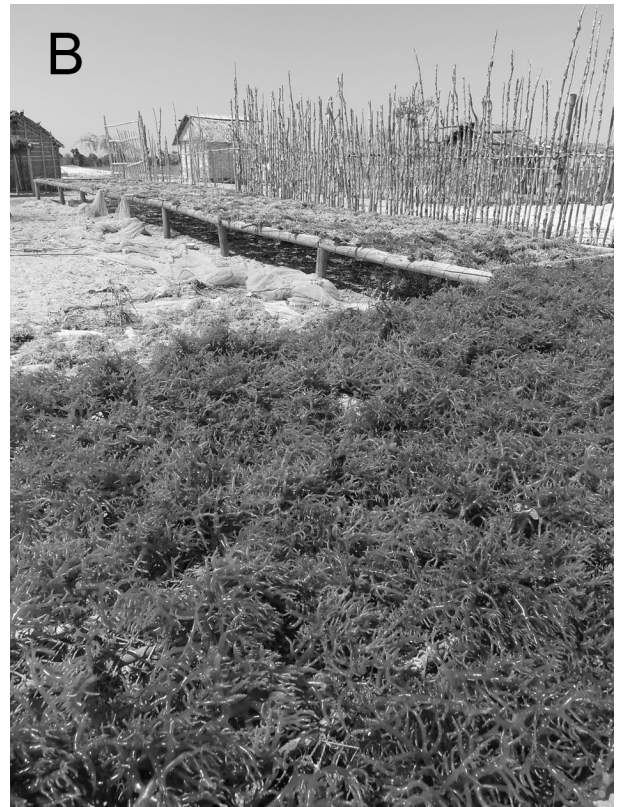
Figure 4. Examples of the use of mangrove wood: saplings and trees used in house construction (A); saplings used as fencing (background of B); trees used to construct seaweed drying racks (foreground of B); and large trees used to construct kilns (C) which produce lime render for houses (D)

Another more recent use of mangrove wood in the Bay of Assassins involved the construction of lime kilns (Figure 4C). These were used to produce 'sokay', a sea-shell based lime render used to improve the durability of house walls (Figure 4D). To construct a kiln, layers of sea shells are sandwiched between layers of mangrove wood. Burning the shells converts calcium carbonate ($CaCO_3$) to calcium oxide (CaO). Water is added to the resulting powder and the paste is then applied to house walls. Lime render was the preferred wall material because of its relative durability compared to the mangrove saplings and reeds used in traditional houses (Figure 4B). Madagascar regularly experiences tropical cyclones with strong winds and heavy rain, and respondents reported that lime rendered walls are more resistant to cyclone damage.

We found, based on measurements of 10 kilns found in five villages, that a typical lime kiln measures c. 2.6 m in length, 2.3 m in width and 1.2 m in height, using mangrove poles of c.10-15 cm diameter. Kiln construction requires c. 120 poles of mangrove wood, with a total volume of c. 2.4 m^3. Respondents stated that their preferred species of mangrove wood for kiln construction was *R. mucronata* because it burns hotter than other mangrove and terrestrial forest tree species, producing a purer lime powder. However, in our village surveys and observations of the kilns we noted that other species, particularly *C. tagal* and *B. gymnorhiza* were also used, presumably due to availability. Kiln builders stated that the ideal size class for mangrove trees to build kilns was between 10 cm and 15 cm DBH. Trees over 20 cm DBH were too large for an individual to carry out of the mangroves, and as such are harvested infrequently.

4. Discussion

4.1 Forest structure, composition and regeneration

The mix of species in the Bay of Assassins is typical of southwest Madagascar's mangroves, with five species recorded in our plots, compared to a total of six species known to be present in the Bay (Benson et al. 2017). However, in comparison to other sites in southwest Madagascar, the mangroves of the Bay of Assassins are unusual in that they are strongly dominated by *C. tagal*. In our survey this species was found in all plots and was the dominant species in 65% of plots, accounting for 65.52% of all trees sampled. In comparison, the mangroves of the Mangoky River Delta, located approximately 80 km north of the Bay of Assassins, are dominated by *R. mucronata* and *A. marina* (Rakotomavo & Fromard 2010), as are the mangroves of the Tulear Lagoon, 180 km to the south of our study site (Laroche et al. 1997).

It is possible that geomorphology plays a role in the differences between these different sites, since mangrove species distribution is heavily influenced by abiotic factors such as inundation frequency (Leong et al., 2018). However, information on the geomorphic setting of these locations is not available. The dominance of *C. tagal* in the Bay of Assassins may also be driven by historical harvesting pressure on *R. mucronata*, coupled with *C. tagal* being the dominant regeneration species (as suggested by its higher importance values). Other East African case studies have shown that the preferential harvesting of *R. mucronata* (due to its high density and calorific value) leads to a change in mangrove community dominated by *C. tagal* over time (Kairo et al. 2002). However, a lack of historical data on harvesting or vegetation structure at this sites means we are unable to test this hypothesis in the Bay of Assassins.

We also found that for all four mangrove tree species commonly found in the Bay of Assassins (*A. marina, B. gymnorhiza, C. tagal, and R. mucronata*), mangrove forests were dominated by small trees that were <10 cm DBH. This could be due to a combination of climatic pressures and harvesting pressure. Mangrove growth rates and biomass accumulation are often linked to climatic variables such as cyclone frequency (Simard et al., 2019) and, more importantly,

long term distribution of rainfall (Krauss et al. 2007, Sanders et al. 2016). Arid conditions (such as those in our study site) are associated with high soil salinities, which may restrict mangrove growth (Cintron et al. 1978) and cause them to allocate greater biomass to the below-ground fraction to minimize salinity gradients around the roots and aid in water uptake (Clough et al. 1997, Alongi et al. 2005). This would lead to lower biomass partitioning (and DBH) above ground. Extreme aridity has thus been suggested as a reason for low biomass and small DBH for mangroves along the arid coast of western Australia (Clough et al. 1997), though other studies in Australia show different results (Comley & McGuiness 2005). Thus, harvesting pressure probably also plays a role in controlling size classes. In general, harvested trees were significantly larger than non-harvested trees (with the exception of *A. marina,* which is not preferred as harvested material to the same degree as the species of Rhizophoraceae), with the mean DBH of remaining non-harvested trees being an average of <9 cm.

4.2 Harvesting pressure and patterns in the Bay of Assassins

Unlike many other parts of Madagascar (cf. Jones et al. 2014, Giri and Mulhausen 2008), the clear cutting of mangroves is, at present, relatively rare in the Bay of Assassins. The region experienced a rate of mangrove cover loss of 0.27% per year between 2002 and 2014 (Benson et al. 2017), compared to 1.19% per year for mangrove in northwestern Madagascar between 1990 and 2010 (Jones et al. 2014); 0.85% per year between 1951 and 2000 in the Mangoky River delta (Rakotomavo & Fromard 2010); and 0.52% per year for the whole of Madagascar between 2000 and 2005 (Giri & Mulhausen 2008). Thus, mangrove forests in the Bay of Assassins are not, at present, facing the large-scale deforestation threats that other mangrove forests in Madagascar are experiencing. In other parts of Madagascar, mangrove deforestation has been driven primarily by clearance for agriculture, large-scale commercial shrimp aquaculture, and commercial charcoal production (Giri & Mulhausen 2008, Rakotomavo & Fromard 2010, Jones et al. 2016), none of which are currently resource uses found in the Bay of Assassins. This is possibly because the Bay

of Assassins is too arid and currently too inaccessible from major markets for these alternative land uses to be financially viable.

During the vegetation survey we only came across one instance of clear cutting, which was outside our randomly-assigned vegetation plots and was related to a large order for lime render. Instead, the ecological impacts of mangrove wood harvesting are more cryptic (Dahdouh-Guebas et al. 2005). We did not come across a single unharvested plot during our extensive survey. Thus, the main stressor on the Bay of Assassins system is selective harvesting for a range of household construction activities, particularly fencing. However, even with harvesting, mean canopy cover was high (73.5%, SD = 23.07).

Comparison with the small number of mangrove harvesting studies conducted across the tropics (Table 7) suggests that mangrove harvesting pressure is high in the Bay of Assassins. With a mean of 28.7% of trees harvested, the magnitude is similar to the figure of 31.7% reported for a heavily harvested site in the Phillipines (Walters 2005b). In a study of various sites in Micronesia, the overall harvest pressure was found to be 10%, with a removal of mangrove wood equivalent to 11% of the standing volume (Hauff et al. 2006).

Table 7. Comparison of selective harvesting pressures in mangroves across the tropics.

Harvesting pressure (%)	Species preferred	Use(s)	Location	Reference
7.7-33.4	*Rhizophora mangle, Laguncularia racemosa*	Construction	Río Limón, Venezuela	López-Hoffman et al. 2006
10	*Rhizophora apiculata* (fuelwood), *Bruguiera gymnorhiza* (fuelwood, construction)	Fuelwood, construction materials	Kosrae, Micronesia	Hauff et al. 2006
28.7 (SD = 19.3)	*Ceriops tagal, Rhizophora mucronata*	Construction materials	Bay of Assassins, Madagascar	*This study*
30.5-44.9	*Avicennia marina, Ceriops tagal*	Household use	Metinaro, Timor Leste	Calculated from Alongi and de Carvalho 2008
31.7	*Rhizophora* spp. (for construction)	Fuelwood, house construction, fence construction	Visayas, Philippines	Walters 2005b

All four of the major mangrove species were harvested. The principle method of harvesting, whereby trees are cut at the base of the trunk, has important management and sustainability implications. For both *C. tagal* and *R. mucronata* cutting in this way kills the tree, since members of the *Rhizophora* and *Ceriops* genera lack reserve meristems and do not coppice (Hamilton & Snedaker 1984). This means that for the two dominant and most harvested species in the mangroves of the Bay of Assassins regeneration is entirely dependent on replacement by new seedlings.

We found that for all species apart for *A. marina*, the mean DBH of harvested trees was significantly greater than that of non-harvested trees, indicating a preferential selection of larger than average trees. The results of our Rapid Rural Appraisal indicate a preference for large (>10cm DBH) *R. mucronata* trees, particularly for the construction of house frames and in the production of lime render. There was a correlation observed between distance from the nearest settlement and the percentage of *C. tagal* trees harvested, because this is a common species and can be harvested in many locations. In contrast, no such correlation was observed for *R. mucronata* trees. Our key

informants informed us that as large (>10cm DBH) *R. mucronata* trees are particularly desirable, resource users will travel further to extract them.

Taken together with the importance values of trees and saplings, these results suggest a shift in community composition and structure, with harvesting leading to a relative absence of large trees, and an increase in the importance of younger and smaller *C. tagal* trees. This is similar to other studies that have shown that harvesting pressure on *Rhizophora* spp. is not driven by distance; instead, resource users will travel to locations depending on resource availability (Dahdouh-Guebas et al. 2000, Palacios & Cantera, 2017). In South Africa, a study found that *R. mucronata* was heavily harvested while adjacent species such as *A. marina* were not (Rajkaran et al. 2004).

Rhizophora species have historically been preferred for harvest due to their resistance to insect pests when used as construction materials (e.g. de Puyt, 1868) and their high calorific value, which makes them ideal fuelwood for domestic purposes and, in the case of the Bay of Assassins, in the construction of lime kilns. They are still preferred by local communities for these reasons today (e.g. Dahdouh-Guebas et al. 2000). This fact has important implications for the spatial planning of potential management areas versus the spatial distribution of preferred species.

4.3 Contributions of mangrove harvesting to local livelihoods

Mangroves are often used for fuelwood and charcoal production in sub-Saharan Africa (Dahdouh-Guebas et al. 2000, Rajkaran et al. 2004) and other tropical coastal areas (e.g. Oo 2002, Sudtongkong & Webb 2008, Moriizumi et al. 2010), though this was not the case in the Bay of Assassins. Forest users instead prefer to use fuelwood resources collected from terrestrial spiny forest, which is itself heavily threatened (Sedden et al. 2000, Casse et al. 2004).

In the Bay of Assassins, mangrove wood is used primarily in the construction of houses and fences, where its ability to resist decay makes it a favoured material. Mangrove wood plays an important role in household security, as it is used to build fences to protect property (including livestock) from banditry. It is also used in the reinforcement of house walls (and thus protection

from cyclones) through the production of lime render. The harvesting of 5-9 cm trees, which are primarily used as fencing material, accounts for the majority of above-ground mangrove wood biomass removed.

We have also documented emerging uses of mangrove wood. The recent development of seaweed and sea cucumber aquaculture has created new demand for mangrove wood. In addition, the production of lime render using mangrove wood kilns is also creating demand for mangrove wood. Lime render has only recently been identified as a significant resource use associated with mangrove harvesting in the Bay of Assassins (Scales et al. 2018) and, to our knowledge, has not been recorded elsewhere in Madagascar or sub-Saharan Africa. Rendering the walls of an average house requires the lime produced by two kilns, which themselves require 4.8 m^3 of mangrove wood. To put this in perspective, the frame and un-rendered walls of a typical house in the region require 0.9 m^3 of wood (Rasolofo 1997). A rendered house uses approximately six times more mangrove wood than an un-rendered house.

4.4 Reconciling the ecology and management of the Bay of Assassins

This study highlights the strong dependence that local communities have on the mangrove forests in the Bay of Assassins, with provisioning ecosystem services such as seafood (Aina, 2010) and wood products (Scales et al. 2018; this study) making an important contribution to livelihoods and the local economy. It is crucial to manage these resources sustainably, so that they can continue to provide wood and fuel resources into the future without adverse ecological impact.

How sustainable are current mangrove harvesting practices? Extrapolating our data on harvested trees from the 60 vegetation plots (0.92 hectares) to the 1300 ha of mangroves in the Bay of Assassins indicates that there are approximately 2.76 million live trees in the Bay of Assassins with a DBH of 5-9 cm. A household survey carried out in seven of the ten villages in 2014 estimated that mangrove harvesting for fence poles accounted for approximately 50 stems per

person per year (Blue Ventures 2015). This translates a total of 150,000 stems per year, or 5.43% of the trees in the 5-9 cm size class, for all the villages in the Bay of Assassins.

Our study suggests that while mean canopy cover (73.5%) remains high and the mangroves of the Bay of Assassins are currently regenerating, ecological impact is apparent. Looking to the future, it is likely that human pressures on the mangroves of the Bay of Assassins will continue to increase. The human population in the region is growing. Data are scarce, but informants reported significant in-migration over the last five years. This is supported by Epps (2007), who found that <30% of inhabitants in Lamboara and Ampasilava were born in those settlements. Coastal areas in southwest Madagascar are experiencing rapid in-migration, as poor agricultural households move to the coast seeking more secure livelihoods (Bruggemann et al., 2012). A growing population means more demand for mangrove wood, especially for housing and fencing. The harvesting of 5-9 cm trees, which are primarily used as fencing material, accounts for a disproportionate percentage of above-ground mangrove wood biomass removed, considering their small individual volume, and those managing the mangroves of the Bay of Assassins may need to look for alternative fencing material if demand continues to grow.

In addition to population growth, the region is also experiencing economic change, which is increasing demand for mangrove wood. Over the last 10 years the region has become connected to global commodity chains of sea cucumber, seaweed and octopus (Aina 2010, Barnes-Mauthe et al. 2013). This has created new pressures on mangroves through the wood needed for aquaculture, for example to construct sea cucumber enclosures (although these are now made of steel rods), seaweed anchors and seaweed drying tables. Growing income from aquaculture has also led to increased demand for lime render for houses, as households who are able to benefit from the new commodity chains for marine products choose to improve the durability of their houses.

The harvesting of sea cucumber, seaweed and octopus have all increased over the last ten years (Aina 2010, Barnes-Mauthe et al. al 2013, Blue Ventures 2015). For example, the harvest of *K. alvarezii* in 2014 was over 55 tonnes, three times that of 2012. This has important implications

for the regions mangroves as three tonnes of mangrove wood are required to produce one tonne of dried seaweed (Blue Ventures 2015). Key informants also reported an increase in the use of lime render. This is supported by previous household surveys. In 2006, 28% of buildings in Lamboara village had walls covered in lime render (Epps, 2007). By 2014 this figure had gone up to 65% (Blue Ventures, 2015). Lime production is a time-consuming process, requiring men to find, cut, and carry heavy trees. Most households do not have the time to render their own walls, focusing their attention on fishing and gleaning. However, with a rise in income from aquaculture, wealthier households are paying others to produce lime. As a result, lime render is considered a status symbol. Demand for lime render, and thus for mangrove wood to use in lime kilns, is likely to grow with a growing population and / or rising incomes. Growing demand for large (>10 cm DBH) *R. mucronata* trees is occurring in a mangrove forest that is dominated by *C. tagal* trees below 10 cm DBH.

To date, efforts to manage natural resources in the Bay of Assassins have tended to focus on a single ecosystem or species, for example establishing closed seasons for octopus fisheries, introducing new techniques for sea cucumber aquaculture, and creating protected areas for mangrove forest where wood harvesting is forbidden (Andriamalala and Gardner 2010, Aina 2010, Benbow et al. 2014, Cripps and Gardner 2016). The key resource management lesson is that livelihoods in coastal communities cut across terrestrial, wetland and aquatic ecosystems. This means that mangroves are socio-ecologically linked to other ecosystems and must therefore be managed as part of broader landscape-based approaches. For example, increases in wealth from marine resources such as sea cucumber, algae and octopus are likely to lead to greater demand for more durable housing material which, unless alternatives are found, will lead to increased demand for lime render and thus place pressure on mangrove forests. Another potential cross-ecosystem linkage involves domestic fuelwood. While mangrove wood is the preferred material for construction, terrestrial dry forests are the preferred source of fuelwood. However, a reduction in terrestrial dry forest (for example due to forest clearance for agriculture or over-harvesting of

fuelwood), is likely to lead to more pressure on mangroves as households seek out alternative sources of domestic fuel. Therefore, management policies need to carefully model expected increases in demand for mangrove wood for different uses and consider developing alternative sources of domestic fuel and alternative ways to improve the durability of houses.

5. Conclusions

Small-scale wood harvesting by local communities can be a significant driver of degradation in many mangrove forests across the tropics (UNEP 2014). Given the importance of mangroves to the livelihoods of coastal communities in the tropics and the potential impact of human activities on mangrove cover, structure and composition, it is remarkable that so few studies of small-scale mangrove harvesting have been published. Our understanding of mangrove uses and their ecological impacts is hindered by a narrow focus on land cover change measured through remote sensing, which misses more cryptic forms of ecological change (Dahdouh-Guebas et al. 2005). There is thus a need for field surveys, combined with studies of human resource use, to reveal cryptic processes of ecological change that are not easily revealed through remote sensing.

This study, based on a combination of mangrove vegetation surveys and RRA techniques, has shown that poor coastal communities in southwest Madagascar use mangrove wood for both domestic and commercial purposes. We have shown high harvesting pressure. Our study also shows that harvesting is spatially variable and can have observable ecological impacts on multiple mangrove forest community characteristics. It also shows that the local community has clear intended uses, which drives the harvesting of particular species and size classes.

Environmental policy in the tropics often focuses on demographic change and the implications of population growth on resource use. There is a lack of understanding of the diverse ways in which low-income households, particularly in remote regions, rely on mangrove resources and a tendency to assume all poor households use natural resources in the same way (Angelsen & Wunder 2003, Belcher 2005). This study found that resource extraction, poverty and livelihoods are

interlinked, with increasing livelihood status changing the type of resource extracted (in this case *R. mucronata* wood for lime kiln construction). Thus, livelihood status is likely to impact the species preferred and the volume harvested. Even remote coastal regions such as the Bay of Assassins are increasingly linked to global commodity chains, leading to changes in resource use. More attention needs to be paid, through household surveys, to the quantities of mangrove wood used for different small-scale purposes, and how these vary according to socio-economic characteristics such as wealth and migration status, so that adverse ecological impacts on forest resources can be better quantified, anticipated and managed.

Finally, our study suggests that mangroves must be managed as part of broader landscape-based approaches. In the Bay of Assassins resource management policies have tended to focus on single species and ecosystems. For example, there have been efforts to improve the sustainability of marine resource use through the introduction of a closed season for octopus fisheries and new techniques for sea cucumber aquaculture. However, income from marine resources such as sea cucumber, seaweed and octopus has led to growing demand for lime render to improve the durability of houses. Lime render is made in mangrove wood kilns and growing demand has led to increased pressure on mangrove forests. In turn, the loss of mangroves has implications for natural coastal fisheries, due to their role in the life-cycle of fish and other marine fauna (Whitfield, 2017) that also play an important role in local livelihoods. Therefore, management plans must carefully consider how changes in the socio-ecological dynamics of one natural resource are likely to impact those of other resources that households depend on. Research has shown that governance decentralization and community mangrove management can improve mangrove condition if strong community institutions are present to enforcement common rules of natural resource management (Primavera 2001; Sudtongkong & Webb 2008; Damastuti & de Groot 2017). Community-based management approaches will therefore be of crucial importance in any attempt to manage mangroves as part of a broader landscape-based approach.

Acknowledgements

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