RESEARCH ARTICLE

Litter Fall Dynamics of Restored Mangroves (*Rhizophora mucronata* Lamk. and *Sonneratia alba* Sm.) in Kenya

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Abstract

Mangrove forests are active carbon sinks and important for nutrient cycling in coastal ecosystems. Restoration of degraded mangrove habitats enhances return of ecosystem goods and services, including carbon sequestration. Our objective was to assess the restoration of primary productivity of reforested mangrove stands in comparison with natural reference stands in Gazi Bay, Kenya. Litter fall data were collected in nine *Rhizophora mucronata* and *Sonneratia alba* monospecific stands by use of litter traps over 2 years. Litter was emptied monthly, dried, sorted, and weighed. The reforested and natural stands showed seasonality patterns only in the production of reproductive material. Leaves constituted the highest percentage to total litter fall. Litter productivity rates for the *R. mucronata* stands were not significantly different and ranged from 6.61–10.15 to 8.36–11.02 t ha^{-1} yr^{-1} for the restored and natural stands, respectively. The productivity of 5 years *R. mucronata* stands reached 5.22 t ha^{-1} yr^{-1} and was significantly different from other stands. Litter productivity rates for *S. alba* stands was 7.77–7.85 for the restored stands and 10.15 t ha^{-1} yr^{-1} for the natural stand but differences were not significant. Our results indicate that plantations of at least 11 years have attained litter productivity rates comparable to the natural forests. This suggests that productivity of replanted mangroves is likely to reach complete recovery by this age under the prevailing environmental conditions.

Key words: Kenya, litter fall, mangrove productivity, reforested stands, seasonality.

Introduction

Mangrove forests are considered to be productive ecosystems with a high rate of primary productivity, significantly contributing to detrital-based food webs (Odum & Heald 1972; Boto & Bunt 1981; Komiyama et al. 2008). Aksornkoae (1996) suggested that the high productivity in mangroves is a result of high litter fall and rapid breakdown of the detritus. More recently mangrove forests have been found to be highly efficient carbon sinks and carbon rich forests in the tropics (Komiyama et al. 2008; Donato et al. 2011). However, recent estimates indicate that world mangrove area has declined to 137,760 km^2 (Giri et al. 2011) compared to earlier estimates of slightly over 150,000 km^2 (Spalding et al. 2011), suggesting a world without mangroves in coming decades (Duke et al. 2007).

Losses and degradation of mangrove forests deprive communities of ecosystem goods and services and could result in carbon emissions of 0.02–0.12 Pg carbon per year (Donato et al. 2011). It also deprives the mangrove ecosystem of litter, thus compromising ecosystem productivity and functioning in general. To restore the provision of ecosystem goods and services, mangrove reforestation has been carried out worldwide (e.g. Aksornkoae 1996; Qureshi 1996; Kairo et al. 2001; Saenger 2011). In South East Asia and elsewhere, mangrove reforestation has been used as a tool to control shoreline erosion, increase fishery production, as well as transforming degraded mangroves to uniform stands of higher productivity (Bosire et al. 2008).

A successfully restored mangrove forest is expected to be similar to a natural forest in terms of structure and function, a case which is not likely to be realized especially where initial conditions of the forest have changed with time (McKee & Faulkner 2000). Following reforestation of degraded mangrove forests, it is necessary to assess restoration success of the rehabilitated forest. Ellison (2000) reports various attributes that could be used in the assessment of restoration success, including: vegetation structure, secondary succession, and primary productivity. Assessment of biogeochemical functions and nitrogen fixation has also been used to evaluate restoration success of reforested mangrove forests (McKee & Faulkner

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2000; Vovides et al. 2011). However, no single project has the ability to carry out complete assessment of restoration success of replanted forest, due to timing and budgetary constraints of such projects (SER 2004). In Kenya, for instance, restoration success of mangrove reforestation has been evaluated through monitoring of floral and faunal secondary succession (Bosire et al. 2003, 2004), nutrient dynamics (Bosire et al. 2005), and structural development of replanted areas (Kairo et al. 2008).

One widely used indicator for mangrove productivity of particular relevance for ecological restoration is annual litter fall (Clough & Attiwill 1982). This aspect estimates the amounts of litter fall and contribution of the mangrove forest to the local food web and near shore environments (Kristensen et al. 2008). Ehrenfeld and Toth (1997) underscore the need for net primary production assessment as a measure of detritus material available to consumers and decomposers. This would in return influence restoration of faunal communities within the forest floor. Studies carried out in reforested plantations show that young reforested stands are important in the production of leaf litter while mature stands are significant in propagule production (Clough et al. 2000; Nga et al. 2005). Biomass accumulation rates of reforested stands have also been reported to be higher than in natural forests (Putz & Chan 1986; Kairo et al. 2008). Various authors have reported on litter fall of reforested mangrove forests in Asia (Sukardjo & Yamada 1992; Clough et al. 2000; Nga et al. 2005; Chen et al. 2009).

To our knowledge, no litter fall studies have been conducted on reforested mangrove plantations in Africa region although litter fall is a good proxy for stand development. The aim of our study was, therefore, to assess litter production and seasonality in monocultures of *Rhizophora mucronata* Lamk. and *Sonneratia alba* Sm., the two principal mangrove species in Kenya. Compared to other mangrove trees in Kenya, *S. alba* is the fastest growing species with a rate exceeding 1.0 m/year (Kairo et al. 2001). *Sonneratia* fringes the sea margin and is the first species likely to experience effects of climate change through sea level rise (Gallin et al. 1989; Kairo et al. 2001; Kathiresan et al. 2010). Cultivation of *Sonneratia* is complicated by small size of seeds with high pre-establishment mortality (Kairo et al. 2001). On the other hand, *R. mucronata* occupy the mid zone with deep sediment deposition. The species grows at an average of 0.8 m/year, and because of its wide utilization in firewood and construction industry *Rhizophora* is the most preferred species in many restoration projects in Kenya.

In this study, we addressed the following questions: (1) Are there differences in seasonality of litter fall in restored versus natural mangrove forests? (2) Are productivity rates comparable between reforested and natural stands? (3) Is there a relationship between stand age and litter productivity?

Methods

Study Area

The study was conducted in Gazi Bay (4°25′S, 39°30′E), located 50 km from Mombasa at Kenya's south coast (Fig. 1). Total embayment of the area is 18 km², with a mangrove cover of 6.6 km² (Slim et al. 1996). Similar to most parts along the Kenya coast, the climate at Gazi is influenced by the monsoon winds that bring about a bimodal pattern of rainfall (GOK 2009). Long rains are experienced from April to July while short rains occur from October to December.

All nine mangrove species recorded in the Western Indian Ocean are found in Gazi Bay. The dominant species in Gazi is *Rhizophora mucronata*, which constitutes 70% of mangrove forest formation in the area. *Rhizophora* is the most preferred mangrove species for firewood and building because it grows tall, straight, and is resistant from termite attacks (Kairo et al. 2001). *Sonneratia alba* has a relatively limited areal extent and occupies an important frontline position toward the open water (Neukermans et al. 2008). The species is used for making ceilings as well as ribs for traditional boats. Average rainfall in Gazi during the 2005–2006 study period was 848 and 1,580 mm, respectively, whereas mean annual temperature was 28.1 and 30°C.

Description of the Study Sites

The study was carried out in nine monospecific stands of natural and reforested stands of *R. mucronata* and *S. alba*. The reforested sites were replanted in the 1990s in an effort to restore degraded mangroves of Gazi Bay (Kairo 1995). Study sites for *R. mucronata* were located in the eastern and western plots at Kinondo and Gazi, respectively, which are separated by a creek. Kinondo site (S1) included two reforested stands aged 11 years of which one of the stands had been pruned prior to the start of this study. The Gazi site included two reforested stands of *R. mucronata* aged 5 and 12 years old (S2) and two of *S. alba* aged 11 (S3) and 13 years (S4). In all cases, adjacent natural stands were used as references to minimize any confounding factors.

Assessment of Forest Structure

Study plots of 10 × 10 m were established in each of the natural and reforested mangrove stands at Gazi and Kinondo. All trees with diameter at breast height (dbh) of ≥2.5 cm were counted and their height measured. The dbh and tree height was measured with forest calipers and a Suunto hypsometer (or a graduated rod where the forest was thick), respectively.

Litter Fall Collection

Inside the 10 × 10 m² plots, 10 litter traps with a mouth of 0.25 m² were randomly placed below the crown canopy but above the highest tide mark to avoid litter submergence during high waters. Litter was emptied monthly from January 2005 to December 2006. In the laboratory, litter from each respective trap was dried at 80°C for 72 hour until a constant dry weight was reached. It was then sorted into leaves, reproductive parts (buds and flowers), propagules/fruits and woody twigs, and weighed. Owing to logistical challenges, data collection for *R. mucronata* in Kinondo was delayed till the end of April 2005. Interfering of litter traps by mangrove cutters in the pruned plots of Kinondo affected data collection beyond October 2006.
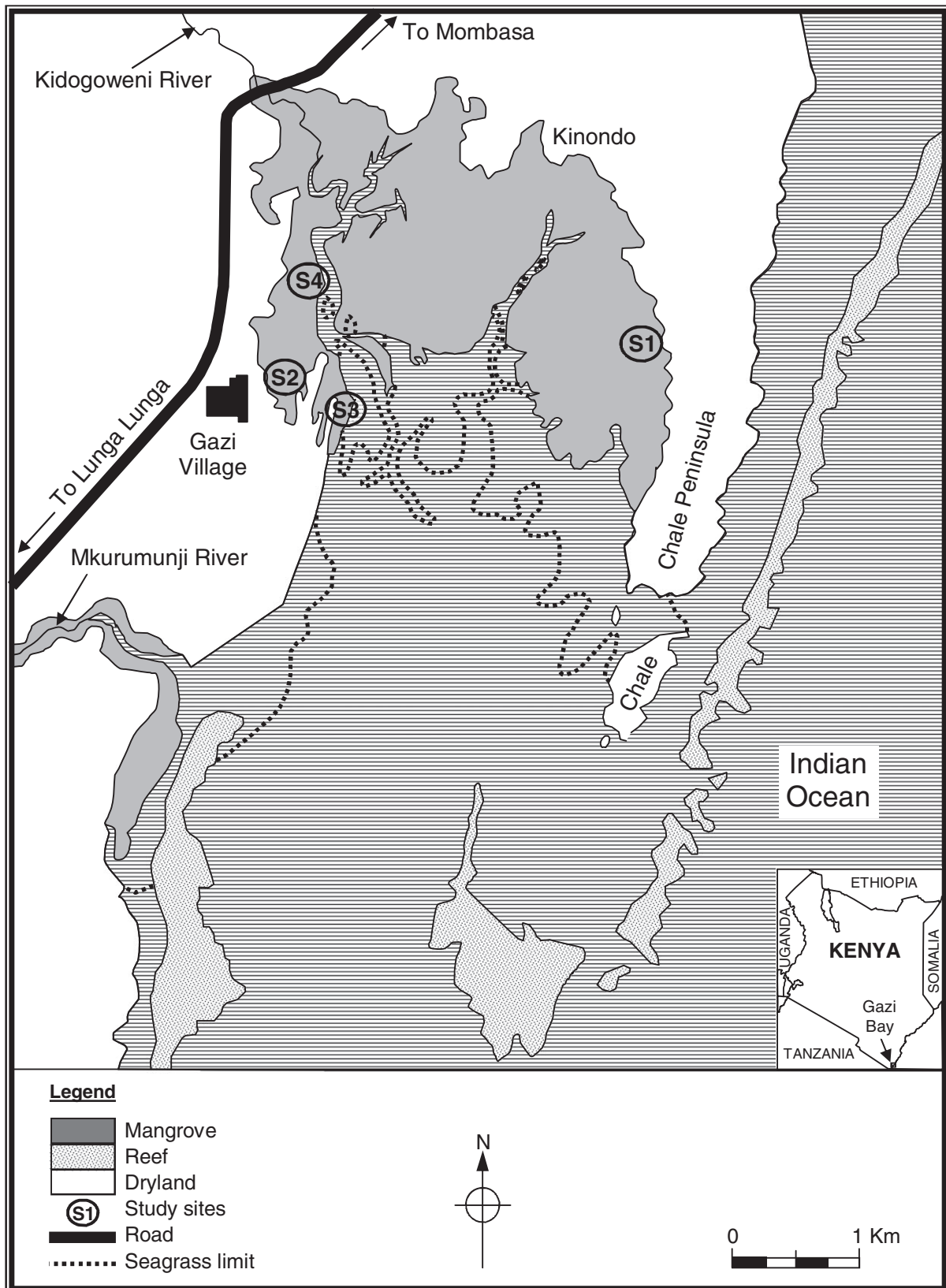
Figure 1. Map of the Kenyan Coast showing the study area of Gazi Bay with study sites encircled (modified from Dahdouh-Guebas et al. 2002 and Bosire et al. 2004). S1, Kinondo site; *Rhizophora mucronata* stands; S2, Gazi site; *R. mucronata* stands; S3 and S4, Gazi site *Sonneratia alba* stands.

Table 1. Structural attributes of reforested and natural mangrove stands at Gazi bay.

Species	Stand Age (Years)	n	Height (m)	dbh (cm)	Density (Stems/ha)
Rhizophora mucronata (G)	5	58	2.3 ± 0.02	3.2 ± 0.1	5,800
	12	35	4.3 ± 0.1	4.2 ± 0.1	3,500
	Natural	44	4.9 ± 0.1	5.9 ± 0.4	4,400
R. mucronata (K)	11 (pruned)	38	8.5 ± 0.2	7.9 ± 0.7	3,800
	11	38	8.5 ± 0.2	7.9 ± 0.7	3,800
	Natural	36	10.5 ± 0.1	6.5 ± 0.0	3,600
Sonneratia alba	11	146	5.4 ± 0.2	5.1 ± 0.1	14,600
	13	98	7.5 ± 0.4	5.8 ± 02	9,800
	Natural	80	11.5 ± 0.7	8.0 ± 0.4	8,000

G, Gazi site; K, Kinondo site.
Means ± SE; n = number of trees in 10×10 m plot with a dbh ≥ 2.5 cm.

Statistical Analysis

Data were analyzed using STATISTICA (Statsoft, Tulsa, OK, U.S.A.) package. Kruskal–Wallis ANOVA and non-parametric multiple comparison of means was used to determine litter productivity differences within and among the stands.

Results

Forest Structure

Stand densities of *Rhizophora mucronata* and *Sonneratia alba* stands were higher in replanted than in natural stands except for the 12-year-old *R. mucronata* natural stand in Gazi (Table 1). The average stand density in reforested stands was 6,883 stems/ha, as compared to 5,333 stems/ha for natural stands. Mean tree height and dbh was also higher in the natural stands than in restored stands except for the *R. mucronata* stand in Kinondo where mean dbh was slightly lower.

Seasonality in Litter Fall

Litter production patterns for the two species were comparable, with peak leaf litter production occurring in the same period irrespective of the site and stand ages (Figs. 2–4). Leaf litter production occurred every month during the study for *R. mucronata* and *S. alba*. Several peaks in leaf litter were observed with maximum fall for all species coinciding with dry seasons from November to January. There was relatively low fall in woody twigs compared to leaf litter in *Rhizophora*, with peaks recorded in November and December period. Generally for *Rhizophora* plantations, fall of reproductive parts (buds and flowers) was observed in April–May with propagules falling from March to May. For the natural stands, however, prolonged propagule fall of 3–4 months was observed as opposed to a single month in the reforested stands. In *S. alba* stands fall of leaf and twig litter occurred throughout the study period; however, inconsistent peaks were observed in March and May for twigs. In *Sonneratia*, production of reproductive parts peaked in July in 2005 and
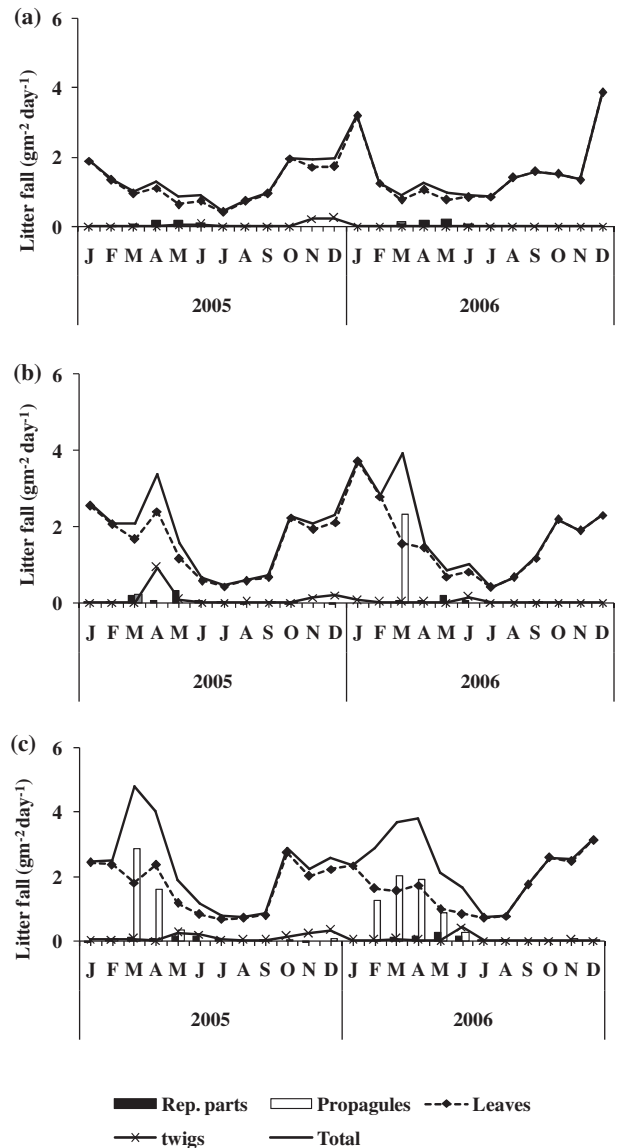

Figure 2. Mean monthly litter production patterns for *Rhizophora mucronata* stands in Gazi Bay: (a) 5 years. (b) 12 years. (c) Natural.

shifted to September in 2006. Fruit fall in *S. alba* was observed in October and November in 2005 and shifted to a month earlier in 2006, respectively.

Litter Productivity Rates

In all species, leaf litter contributed the highest percentage to total litter fall (Table 2). In *R. mucronata* leaves accounted for 73–97% of the total litter fall, while twigs, reproductive parts, and propagules contributed 2–7, 1–3, and 0.2–17%, respectively. Leaf litter accounted for 80–91% of the total litter fall in *S. alba*, whereas twigs, reproductive parts, and fruits contributed 7–13, 0.7–2, and 0.2–6%, respectively. Mean annual total litter fall was higher in *R. mucronata* stands in Kinondo than in Gazi. The 5 years *R. mucronata* stand in Gazi showed a
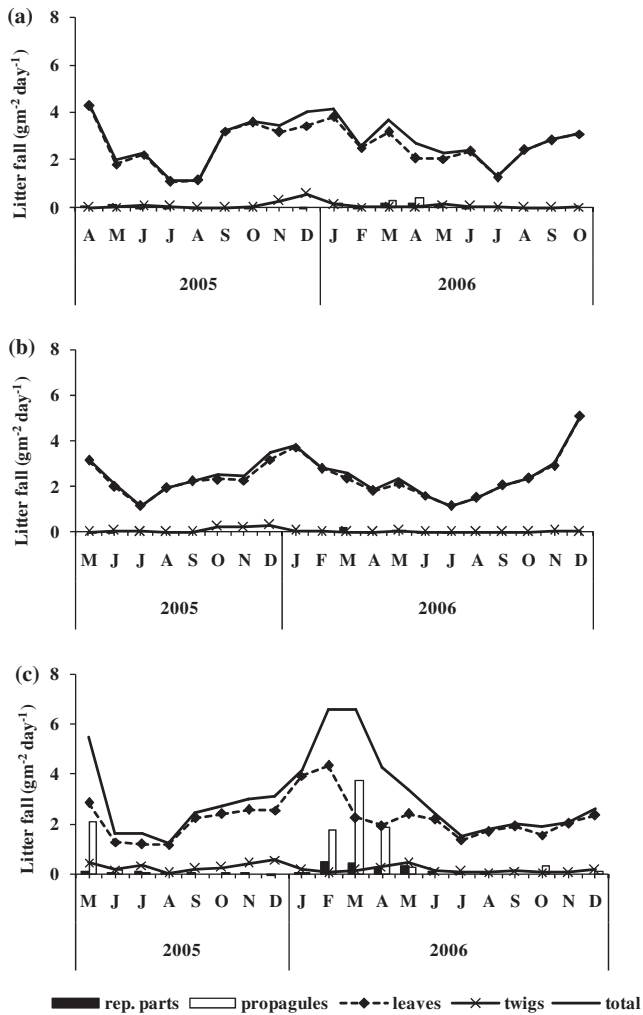
Figure 3. Mean monthly litter production patterns for *Rhizophora mucronata* stands in Kinondo: (a) 11 years pruned. (b) 11 years. (c) Natural.

significant difference in total litter production ($H_{5,203} = 27.24$; $p \leq 0.0001$) than other *R. mucronata* stands. There was no significant difference in litter productivity ($p < 0.5$) between the pruned and un-pruned reforested mangrove stands in Kinondo. Similarly, annual total litter production was not significantly different among *S. alba* stands. However, there was a significant difference ($H_{2,72} = 27.24$; $p \leq 0.0001$) in twig production between the natural and the reforested stands of *S. alba*.

Discussion

At the end of any forest restoration program, it is important to empirically determine the return of ecosystem services following rehabilitation activities. In mangroves, stand productivity is an important indicator of ecosystem health. Healthy and recovered systems are bound to show enhanced structural productivity as compared to degraded systems. Additionally, mangrove forests have been found to play critical role in climate change
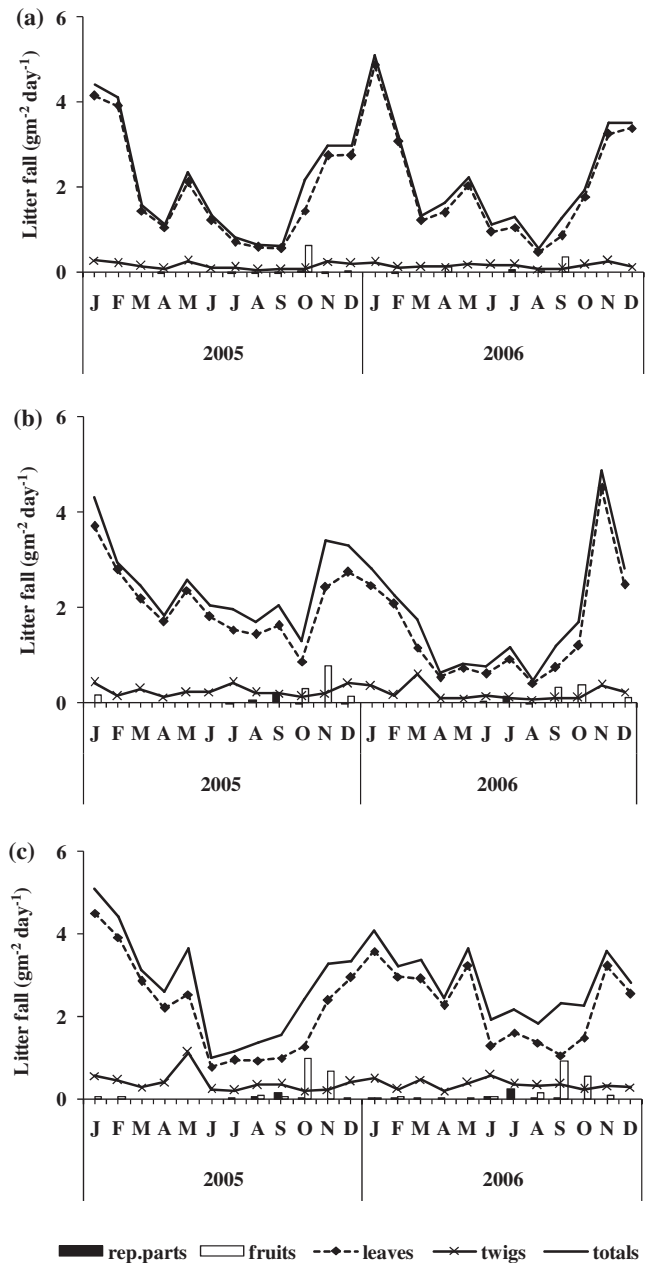

Figure 4. Mean monthly litter production patterns for *Sonneratia alba* stands in Gazi: (a) 11 years. (b) 13 years. (c) Natural.

mitigation through carbon capture and storage (Mcleod et al. 2011). On area basis, mangroves sequester 3–5 times more carbon than any productive terrestrial forests (Donato et al. 2011). This carbon is either produced within or outside the system. In the current study we used litter fall as a proxy to investigate stand productivity of reforested and natural mangrove stands in Kenya. In terms of litter fall data, our results indicate a progress toward complete recovery of formerly degraded mangroves. The production of propagules, however, was still higher in natural mangroves than in restored stands. Propagule production period was also prolonged in natural than reforested stands.

Table 2. Litter fall in replanted and natural mangrove stands of Gazi Bay. Means sharing the same superscript within site are not significant at 5% significance level.

	Leaves	Rep. Parts	Propagules	Twigs	Total Per Day (g m⁻² day⁻¹)	Total Per Year (t ha⁻¹ yr⁻¹)
Rhizophora mucronata (Gazi)						
5 years	1.36 ± 0.2^a	0.05 ± 0.01^a	$0.00 \pm 0.0^{a***}$	$0.02 \pm 0.01^{a*}$	$1.43 \pm 0.16^{a**}$	5.22
12 years	1.58 ± 0.18^a	0.05 ± 0.02^a	$0.11 \pm 0.00^{a*}$	0.07 ± 0.04^b	1.81 ± 0.20^b	6.61
Natural	1.69 ± 0.16^a	0.05 ± 0.02^a	0.47 ± 0.16^b	0.08 ± 0.02^b	2.29 ± 0.22^b	8.36
R. mucronata (Kinondo)						
11 years (pruned)	2.61 ± 0.18^a	0.04 ± 0.02^a	0.05 ± 0.02^a	$0.08 \pm 0.02^{a***}$	2.78 ± 0.20^a	10.15
11 years	2.38 ± 0.18^a	$0.02 \pm 0.0^{b***}$	$0.0 \pm 0.0^{a*}$	$0.06 \pm 0.02^{a***}$	2.45 ± 0.18^a	8.94
Natural	2.20 ± 0.16^a	0.10 ± 0.02^a	0.51 ± 0.20^b	0.20 ± 0.03^b	3.02 ± 0.33^a	11.02
Sonneratia alba (Gazi)						
11 years	1.96 ± 0.27^a	0.00 ± 0.0^a	0.05 ± 0.02^a	$0.15 \pm 0.02^{a***}$	2.15 ± 0.27^a	7.85
13 years	1.79 ± 0.2^a	0.02 ± 0.02^a	0.09 ± 0.04^a	$0.23 \pm 0.02^{a***}$	2.13 ± 0.22^a	7.77
Natural	2.24 ± 0.22^a	0.02 ± 0.02^a	0.15 ± 0.3^a	0.36 ± 0.04^b	2.78 ± 0.22^a	10.15

Rep. Parts, reproductive parts.
$*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

Seasonal trends were observed in the production of reproductive materials (buds, flowers, propagules/fruits) in the natural and reforested stands of *Rhizophora mucronata* and *Sonneratia alba*. However, leaf and twig litter production occurred throughout the year, with peaks influenced by rain and dry periods. Other authors (e.g. Shunula & Whittick 1999; Nga et al. 2005; Bernini & Rezende 2010) have observed year round leaf fall, whereas Slim et al. (1996) and Arreola-Lizarraga et al. (2004) observed seasonal pattern in mangrove leaf fall, a factor associated with local climatic conditions. Differences in propagules production between reforested and natural mangroves could be due to a combination of age and management practices of the stands. A stand density of 2,500 stems/ha has been found to be sufficient to restock a degraded mangrove stand (FAO 1994). In this study, however, the replanted forest had a stocking rate exceeding 6,000 stems/ha. Such a density could shield the plant from photosynthetic active radiation and hence affect stand productivity. Productivity difference within replanted forests could be due to stand ages, with older plantations producing significantly more propagules that young stand. Similar results were observed by Nga et al. (2005), who reported higher propagule production in 17 and 24 years plantation than in 7 and 11-year-old stands of *Rhizophora apiculata* in Vietnam. These results have implications for the conservation and management of older mangrove stands as seed sources.

Leaf litter production rates did not differ between reforested and natural stands except for the 5 years *R. mucronata* stand that had lower values. Litter fall contributes to ecosystem productivity through detritus food web. This is supported by high secondary succession of benthic fauna in the replanted forests comparable to the natural stands in Kenya (Bosire et al. 2004, 2008). Vovides et al. (2011) reported restoration of nitrogen fixation functionality in a 12-year-old reforested mangrove stand in Mexico.

Monthly leaf litter production closely followed that of total litter fall and was similar in reforested and natural stands. Various authors (e.g. Duke 1988; Clough et al. 2000; Nga et al.

2005; Chen et al. 2009) reported similar observations in Asian and Australian mangroves. This indicates the high contribution of leaf litter to nutrient dynamics and mangrove food web. Leaf litter percentage of 81% has been reported for restored sites in comparison to natural sites Southwest Florida (McKee & Faulkner 2000).

In our study natural stands showed higher litter productivity rates. The higher productivity of *R. mucronata* stands in Kinondo compared to Gazi can partly be attributed to site fertility. Earlier studies reported high organic matter content in sediments in Kinondo plantations (Bosire et al. 2003; Kairo et al. 2008). Saenger and Snedaker (1993) reported site fertility as a factor contributing to stand development and hence litter production.

Litter productivity rates for *R. mucronata* reforested stands in Gazi Bay are within the 7.06–10.4 t ha⁻¹ yr⁻¹ reported for a 7 years *R. mucronata* stand in Indonesia (Sukardjo & Yamada 1992). Clough et al. (2000) reported litter productivity rates of 10.95, 9.41, and 18.79 t ha⁻¹ yr⁻¹ for the 6, 9, and 12 years *R. apiculata* stands in Vietnam. However, our litter productivity estimates for *S. alba* reforested stands is below the 15 t ha⁻¹ yr⁻¹ reported for 13 years *S. caseoralis* stands in China (Chen et al. 2009).

Most studies have largely focused on vegetation structure followed by ecological processes and ecosystem development in evaluating restoration success of reforested mangrove stands (Wortley et al. 2013). Although data on litter productivity of reforested stands in Africa are scarce our findings indicate that *R. mucronata* reforested stands in Gazi Bay compares well with the scanty global data available despite the geographical differences. This further emphasizes the need for assessment of litter productivity rates of reforested mangrove stands for the evaluation of restoration success of the rehabilitated mangrove forests worldwide.

In this study pruned reforested stands of *R. mucronata* had significantly higher overall production of reproductive material

and propagules. This underscores the need for forest management practices in replanted mangroves, including thinning and pruning. In restored monospecific stands actual periodic thinning is particularly recommended in forestry management in order to open up the forest canopy, reduce resource competition, and hopefully enhance general stand performance.

Implications for Practice

- Mangrove reforestation is a potential tool that could be used to restore deforested and degraded mangrove forests.
- Reforestation of degraded mangrove forests by planting native mangrove species is vital for the recovery of ecosystem services including carbon sequestration.
- Litter fall is a proxy that could be used to estimate productivity of a restored mangrove ecosystem.
- Mangrove reforestation should be part of integrated coastal zone management framework if we are to achieve the objectives of sustainable development in the coastal areas.

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