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Colonization of non-planted mangrove species into restored mangrove stands in Gazi Bay, Kenya

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Abstract

Recruitment of non-planted mangrove species into *Rhizophora mucronata*, *Sonneratia alba* and *Avicennia marina* reforested stands (all of them 5 years old) was investigated to assess possibilities for natural colonization. Corresponding bare (denuded or open without mangroves) and natural (relatively undisturbed) sites were used as controls. Interstitial water salinity and temperature (measured at low tide) were lower, whereas sediment organic matter content was higher in the areas with mangrove cover. Also, the bare sites were more sandy, whereas those with mangrove cover had more clay and silt. There was no apparent recruitment of non-planted mangrove species into the bare areas, but the reforested stands of *S. alba*, *A. marina*, and *R. mucronata* had 5400, 4000 and 700 recruits ha^{-1}, respectively of different mangrove species. The results therefore suggest that mangrove reforestation has facilitated natural colonization of sites, most likely by altering local hydrodynamics.

Keywords: Mangrove reforestation; Colonization; Non-planted species; Environmental variables; Kenya

1. Introduction

Mangrove forests are among the most productive ecosystems and offer a wide range of resources and services including shoreline stabilization (Teas, 1977; Snedaker, 1987; Field, 1995), habitat, nursery and breeding ground for many fish species and other fauna (Teas, 1977; Collete, 1983; Ahmad, 1984; Kurian, 1984; Robertson and Duke, 1987; Ngoile

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and Shunula, 1992; Sasekumar et al., 1992; Rönnbäck, 2001), wood for fuelwood, timber, poles, boats (Ahmad, 1984; Burbridge, 1984; Fredericks and Lampe, 1984; Aksornkoae, 1987; Hirsh and Mauser, 1992; Dahdouh-Guebas et al., 2000) among other products. Unfortunately, development and demographic pressure in many areas have led to widespread overexploitation of the world's mangrove forests, at a rate faster than they are being regenerated (Field, 1999). In Kenya in particular, mangroves were heavily exploited in the 1970s due to indiscriminate cutting of trees leading to extensive bare lands in some areas along the coastline (Kairo, 1992, 1995; Bosire, 1996).

The realization that in some parts of the world mangrove ecosystems are being destroyed, with a consequent loss of inherent services has prompted an upsurge in the number of rehabilitation projects (Field, 2000). Examples of such mangrove rehabilitation projects are reported from, e.g. Thailand (Aksornkoae, 1996), Pakistan (Qureshi, 1996), Australia (Saenger, 1996), Bangladesh (Siddiqi and Khan, 1996), Sri Lanka (SFFL, 1997) and Kenya (Kairo, 1995). However, monitoring of such replantation sites has been restricted to assessment of early development and growth performance and consequently very little is known about concomitant natural developments in these stands, such as re-colonization by non-planted mangrove species. Walters (2000), for example found no post-planting recruitment of non-planted mangrove species into reforested stands of 50 and 60 years old in The Philippines.

The purpose of this study was to assess the potential of reforested mangrove stands for re-colonization of non-planted mangrove species, using bare mangrove areas (denuded or open without mangroves) and natural stands (relatively undisturbed) as controls. We quantified several physico-chemical parameters and determined the density of non-planted mangroves in reforested monospecific stands as compared to bare and natural mangrove areas.

2. Study area

The study was conducted at Gazi (Maftaha) Bay (Fig. 1), on the southern coast of Kenya about 50 km from Mombasa in Kwale district (4°25′S and 39°30′E). The Bay is sheltered from strong waves by the presence of the Chale peninsula to the east and a fringing coral reef to the south. The mangrove is not continuously under direct influence of fresh water because the two rivers (Kidogoweni in the north and Mkurumji in the south) draining into the Bay are seasonal and temporal depending on the amount of rainfall inland. Groundwater seepage is also restricted to a few points (Tack and Polk, 1999). Generally freshwater influx via rivers and direct rainfall in the Bay accounts for a volume of 305 000 m^3 per year of which 20% is lost due to evapotranspiration, which is also responsible for a salinity maximum zone of 38 PSU in the upper region of the Bay covered by mangroves (Kitheka, 1997). High tidal flushing rates are coupled with short residence times (3–4 h), which are a function of wide shallow entrance, lack of topographic controls and the orientation of the bay with respect to dominant water circulation patterns. River discharge is important during the wet season, which enhances weak stratification in the upper parts of Kidogoweni, whereas in the dry season, well mixed homogenous water is found in most regions of the Bay (Kitheka, 1996, 1997). All the nine mangrove species occurring in Kenya are found in this Bay: *Avicennia*

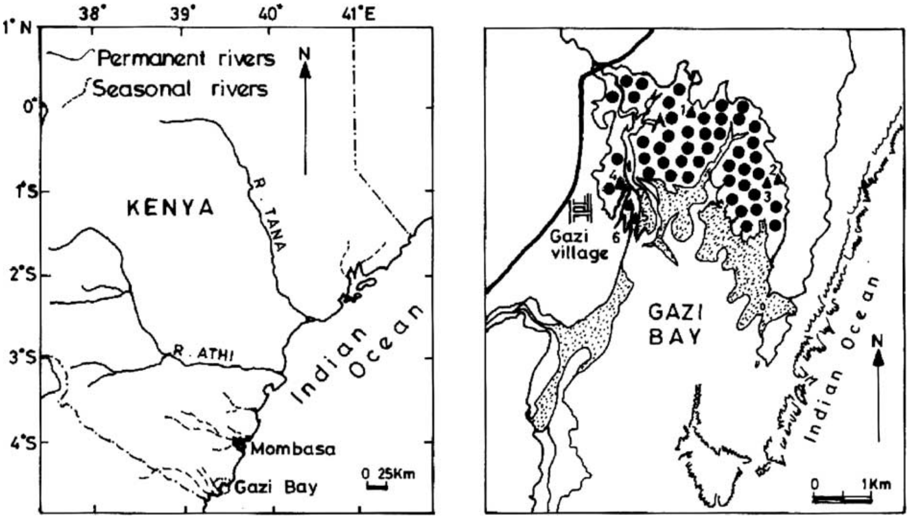

Fig. 1. Map of the Kenyan coast showing the study area (Gazi Bay) and the location of the bare, reforested and natural sites of the *R. mucronata*, *A. marina* and *S. alba* forests (Ruwa, 1997 and Dahdouh-Guebas et al., 2001). KEY: (●) mangroves, (▲) sampling sites, (1) *R. mucronata* bare site, (2) *R. mucronata* natural site, (3) *R. mucronata* reforested site, (4) *S. alba* bare and reforested sites, (5) *S. alba* natural site and (6) *A. marina* bare, reforested and natural sites.

marina (Forsk.) Vierh., *Bruguiera gymnorrhiza* (L.) Lamk., *Ceriops tagal* (Perr.) C.B. Rob., *Heritiera littoralis* Dryand., *Lumnitzera racemosa* Willd., *Rhizophora mucronata* Lamk., *Sonneratia alba* J. Smith, *Xylocarpus granatum* Koen. and *Xylocarpus moluccencis* (Lamk.) Roem. (nomenclature after Tomlinson, 1986).

The climate in Gazi is typical of the Kenyan coast and principally influenced by monsoon winds. Total annual precipitation varies between 1000 and 1600 mm showing a bimodal pattern of distribution. The long rains fall from April to August under the influence of the southeast monsoon winds, while the short rains fall between October and November under the influence of the northeast monsoon winds. It is normally hot and humid with an average annual air temperature of about 28 °C with little seasonal variation. Air temperature in Gazi Bay varies between 24 and 39 °C (data recorded by the Meteorological Department). Relative humidity is about 95% due to the close proximity to the sea.

2.1. Site history

The mangrove forests of Gazi have been exploited for many years especially for wood used for industrial fuel (in the calcium and brick industries in the 1970s) and building poles (Kairo, 1995; Dahdouh-Guebas et al., 2000). The clear-felling due to the industrial extraction left some areas along the coastline completely denuded. Experimental reforestation (plantation trials) was initiated at Gazi Bay in 1991 (Kairo, 1995) where five sites were selected and saplings of *S. alba*, *R. mucronata*, and *C. tagal* were replanted. Results (in terms of growth and survival rates) obtained after 3 years indicated that the performance of the replanted mangroves depended on planting material type (saplings/propagules), elevation (height above datum) of the forests and the size of the saplings during transplanting. Saplings did better than propagules and as for elevation, *Rhizophora* did better at inundation classes 3 and 4 than at classes 1, 6 and 7. Submergence and excessive drought thus were major constraints. In inundation class 1, profuse barnacle infestation also caused high mortality of saplings. *Ceriops* did best in inundation class 5 compared to saplings in class 1 which died after 2–3 months due to long hours of submergence. The information obtained was used in an extended experimental reforestation program in 1994, which was done through community participatory forestry in the rehabilitation of deforested mangrove areas of Gazi. During this replanting, saplings of *R. mucronata*, *B. gymnorrhiza*, *A. marina*, *S. alba* and *C. tagal* were planted in denuded mangrove areas of Gazi Bay from March to May 1994 in monospecific stands. The sites which were replanted had been clear-felled in the 1970s and did not show any natural regeneration almost 25 years later when the reforestation was done (Kairo, 1995). The reforested stands (among those planted above) used in this study had *R. mucronata* (6.74 ha), *S. alba* (0.4 ha) and *A. marina* (0.25 ha). The three stands were of the same age (5 years).

The bare and natural sites used as controls were chosen based on physical proximity, tidal inundation and similarity in site history as the criteria, so as to minimize environmental variation and maximize paired matching. The denuded controls for reforested *S. alba* and *R. mucronata* stands, were of the same inundation classes following Watson (1928), i.e. class 1 (at 2 m above datum, with the "zero" datum level at the lowest astronomical tide level for the Kenyan coast as a reference) and class 2 (2.5 m above datum), respectively, were also clear-felled in the 1970s (Kairo, 1995) and were closest to the respective reforested sites. The control site for the *S. alba* forest was just adjacent, whereas that of the *R. mucronata* forest was about 1 km away but it was the closest site of the same inundation class and site history. The control site for the *A. marina* forest was also of the same inundation class (class 2) as the reforested site but had no mangroves before they were planted. The natural control sites were adjacent to the reforested stands in all cases.

3. Materials and methods

3.1. Environmental factors

Sediment interstitial water samples were randomly collected by digging a hole into the soil of 10–15 cm (depending on the inundation class, 10 cm for class 1 and 15 cm for class 2) using a machete. Salinity was measured using an optical refractometer (Atago brand), whereas temperature and pH were taken using a pH meter (WTW pH 320/set-1). Three subsamples were taken per quadrat for three 10 m × 10 m quadrats randomly chosen per site. The same experimental protocol was repeated for the controls (bare and natural sites). All measurements were taken at low tide. Sediment samples were taken down to a depth of 5 cm using a hand corer. Three replicates were taken per site (one replicate per quadrat). These samples were oven-dried at 80 °C for about 3 days until constant dry weight was obtained and stored in labeled plastic bottles for granulometric analysis. About 20 g was weighed for each sample and transferred into their prelabeled beakers. The organic matter in the samples was removed by digestion using an excess of 30% diluted technical H_2O_2 as an oxidising agent after which the samples were rinsed with demineralised water until a more or less stable suspension was obtained (Wartel et al., 1995). The samples were then re-dried for 24 h at 105 °C and weighed. The difference in weight gave an estimate of the organic matter content. Grain size analysis was done using a combination of dry sieving and sedigraph method as outlined by Wartel et al. (1995). The sedigraph determines the size distribution of particles dispersed in a liquid assuming settling of particles according to Stokes' law (Arnold, 1986). For grain size ranges, the unified soil classification system was used (Robert et al., 1997).

3.2. Vegetation structure and recruitment

Three quadrats of 10 m × 10 m randomly taken in each of the natural and reforested forests were measured giving a total of nine quadrats for the reforested sites and a similar number for the natural controls. Tree height and the diameter D130 (Brokaw and Thompson, 2000; formerly referred to as DBH, the diameter at breast height) for all the trees greater than 2.5 cm diameter were measured using a Suunto hypsometer (or a graduated rod where the forest was thick) and forest calipers, respectively. Density, basal area and absolute frequency (presence of a mangrove species in quadrats within a site) were then computed. From these three parameters, relative density ((density of individual species/total density of all species) × 100), relative dominance ((dominance of a species/dominance of all species) × 100) and relative frequency (absolute frequency of a species/total absolute frequency of the stand) were computed and the latter three then summed respectively to get the importance value (IV) of every mangrove species for all the stands according to Cintron and Schaeffer-Novelli (1984). This IV combines the three absolute indices (density, basal area and absolute frequency) from which the relative values are derived to show which mangrove species contributes relatively more to the structure of a stand. A complexity index was calculated according to Holdridge et al. (1971). This index combines all the measured stand structural attributes (stem density, DBH calculated into basal area, height and number of a species) to show how complex or structurally developed a stand is. The density of juveniles (seedlings less than 2.5 cm in diameter and less than 1 m in height) recruited into the reforested and natural stands were also counted. All juveniles in the reforested stands were less than 1 m in height. Important to emphasize is that there was no natural regeneration at the reforested sites during mangrove replanting and thus the areas were completely bare at that time (Kairo, 1995).

3.3. Statistical analysis

Statistical analyses of environmental factors, vegetation structural indices and juvenile densities data were done using two-way ANOVA (fixed effect with replication). Multiple comparisons were done using Tukey's Honest Significant Difference (HSD) test. In all cases, the quadrats mentioned above were treated as replicates and the three sites (bare, reforested and natural) within forests as treatments.

Table 1
Two-way ANOVA of the sediment characteristics in *A. marina*, *R. mucronata* and *S. alba* forests (stands)

Variable	Factor	d.f.	SS (%)	*P*
Organic matter	Mangrove stand	2	21	0.01
	Cover type	2	37	0.01
	Interaction	4	16	0.06
	Error	18	26	
Salinity	Mangrove stand	2	11	0.09
	Cover type	2	32	0.01
	Interaction	4	22	0.06
	Error	18	36	
Temperature	Mangrove stand	2	4	0.19
	Cover type	2	66	0.01
	Interaction	4	8	0.21
	Error	18	21	
pH	Mangrove stand	2	23	0.04
	Cover type	2	1	0.82
	Interaction	4	21	0.19
	Error	18	56	
Clay	Mangrove stand	2	47	0.01
	Cover type	2	15	0.01
	Interaction	4	5	0.65
	Error	18	33	

The different cover types (bare, reforested and natural) were used as treatments.

4. Results

4.1. Environmental factors

With the exception of the *S. alba* forest, the bare sites in the other forests had higher interstitial salinities ($P < 0.05$) than the corresponding reforested and natural sites (Tables 1 and 2). Salinity was similar in all sites of the *S. alba* forest. pH did not vary significantly among sites in all the forests. In *A. marina* and *R. mucronata* forests, interstitial temperature was highest ($P < 0.05$) at bare sites and lowest at natural sites. However, in the *S. alba* forest, the bare and reforested sites had similar ($P > 0.5$) and higher temperature than the natural site. The bare sites had the lowest organic matter content and higher proportion of sand than the reforested and natural sites The clay content was not significantly different among sites within respective mangrove stands.

4.2. Vegetation structure and recruitment

Within its natural stand, *R. mucronata* was the most dominant (Table 3) compared to the other species (*X. granatum* and *B. gymnorrhiza*). All the reforested sites were monospecific for the adult trees. The natural stand of *S. alba* was also monospecific. The natural stand of *A. marina* had the highest number of mangrove species with *A. marina* mostly being

Table 2
Site averages (mean ± S.E.) of sediment characteristics in plots with matched natural and reforested (Ref.) stands as well as bare controls for *A. marina*, *R. mucronata* and *S. alba* forests

Parameter	*A. marina*			*R. mucronata*			*S. alba*		
	Bare	Ref.	Natural	Bare	Ref.	Natural	Bare	Ref.	Natural
Salinity (‰)	43 ± 1 a	38 ± 1 b	35 ± 0.7 c	44 ± 3 a	34 ± 0.6 b	35 ± 0.6 b	35 ± 0.5 a	36 ± 0.4 a	35 ± 0.4 a
pH	7 ± 0	7 ± 0	7 ± 0.1	7 ± 0.1	7 ± 0.1	7 ± 0.1	8 ± 0.1	8 ± 0.1	7 ± 0
Temperature (°C)	30 ± 0.4 a	27 ± 0.1 b	26 ± 0.3 c	30 ± 0.6 a	27 ± 0.2 b	26 ± 0.1 c	30 ± 0.3 a	29 ± 0.7 a	27 ± 0.1 b
Organic matter (%)	3 ± 0.2 a	19 ± 8 b	25 ± 11 b	4 ± 0.1 a	20 ± 4 b	40 ± 2 c	1 ± 0.3 a	11 ± 2 b	5 ± 1 b
Clay (%)	7 ± 3	23 ± 13	20 ± 9	17 ± 4	37 ± 8	42 ± 9	0	5 ± 2	5 ± 2

Tukey multiple comparisons within each forest are also presented. Sites within forests bearing same letters were not significantly different. pH and percent clay did not differ significantly among sites within forest stands, hence no letters were assigned to them ($n = 3$).

Table 3
Absolute (and relative) adult tree density, basal area (and derived % dominance) and absolute (as well as relative) frequency of mangrove species in natural and reforested stands of *A. marina*, *R. mucronata* and *S. alba* forests

Stand	Site	Species	Abs. density (rel.) (n ha^{-1})	Basal area (dom.) (m^2 ha^{-1})	Abs. frequency (rel.) (%)	IV	Mean stand height (m)	Complexity index[a]
A. marina	Natural	*A. marina*	3530 ± 730 (83)	26 ± 0.4 (96)	100 (43)	222		
		C. tagal	430 ± 26 (11)	1 ± 0.1 (3)	67 (29)	43		
		R. mucronata	130 ± 13 (4)	0 (1)	33 (14)	19		
		S. alba	70 ± 60 (2)	0 (1)	33 (14)	17	6.1 ± 0.1	27.4
	Reforested	*A. marina*	4530 ± 420 (100)	8 ± 0.1 (100)	100 (100)	300	4.5 ± 0.1	1.6
R. mucronata	Natural	*R. mucronata*	2570 ± 410 (69)	34 ± 0.3 (80)	100 (43)	192		
		B. gymnorrhiza	1130 ± 410 (29)	8 ± 0.3 (20)	100 (43)	92		
		X. granatum	70 ± 61 (2)	0 (0)	33 (14)	16	7.5 ± 0.2	35.6
	Reforested	*R. mucronata*	3330 ± 921 (100)	3 ± 0.1 (100)	100 (100)	300	2.9 ± 0.1	0.3
S. alba	Natural	*S. alba*	4300 ± 1221 (100)	35 ± 0.9 (100)	100 (100)	300	8.3 ± 0.6	12.5
	Reforested	*S. alba*	7640 ± 600 (100)	12 ± 0.3 (100)	100 (100)	300	2.6 ± 0.04	2.4

The relative values are expressed as percentage, while averages are given as mean ± S.E.

[a] Complexity index is the product of number of species, stem density, mean stand height and basal area divided by 10^5 (Holdridge et al., 1971).

Table 4
Density (n ha^{-1}) of juvenile mangrove trees in plots within sites of the reforested and natural stands of *A. marina*, *R. mucronata* and *S. alba* given as mean ± S.E.

Stands	Recruits					Total
	A. marina	*S. alba*	*R. mucronata*	*C. tagal*	*B. gymnorrhiza*	
Reforested stands						
S. alba	600	1700	1600	1200	300	5400 ± 1100
R. mucronata	0	100	100	100	400	700 ± 100
A. marina	1800	0	600	1200	400	4000 ± 300
Natural stands						
S. alba	400	0	1000	100	0	1500 ± 300
R. mucronata	2000	0	4900	1100	0	7000 ± 300
A. marina	2600	0	4000	100	0	6700 ± 200

Table 5
Two-way ANOVA of juvenile densities in the reforested and natural sites of the *A. marina, R. mucronata* and *S. alba* forests (stands)

Factor	d.f.	SS (%)	*P*
Mangrove stand	2	11	0.01
Cover type	1	12	0.00
Interaction	2	70	0.00
Error	12	8	

dominant. Due to their higher mean heights and basal areas, all the natural stands had higher complexity indices than their respective reforested stands (Table 3).

The monospecific reforested *A. marina* and *R. mucronata* stands had seedling recruits of four species each, whereas in the *S. alba* stand we found five non-planted mangrove species (Table 4). The *S. alba* reforested stand had the highest density of newly recruited individuals (5400 recruits ha^{-1}), followed by the *A. marina* stand (4000 recruits ha^{-1}) and the *R. mucronata* stand (700 recruits ha^{-1}). All the three mangrove species recruited themselves with *A. marina* recruiting itself most, followed by *S. alba* and *R. mucronata* (1800, 1700 and 100 recruits ha^{-1}, respectively). A maximum of three mangrove species (*A. marina*, *R. mucronata* and *C. tagal*) was found growing in each of the natural stands. *R. mucronata* had the highest density of seedlings (7000 ha^{-1}), followed by *A. marina* (6700 ha^{-1}) and *S. alba* (1500 ha^{-1}) in natural stands. There were highly significant differences (Table 5) in seedling recruitment among the reforested and natural sites within respective forest stands ($P = 0.001$) and among the three forest stands ($P = 0.005$).

5. Discussion

We found no re-colonization in any of the bare sites, whereas a number of species had recruited into the comparable reforested and natural stands with tree cover. These findings suggest that mangrove regeneration has modified site conditions, in a way that facilitates settling and establishment of propagules.

Save for the *S. alba* forest, salinity and interstitial water temperature were lower in all reforested and natural sites as compared to bare sites probably due to the shading by the canopy above, as in Frith et al. (1976) and Frith and Brunnenmeister (1980). The similar salinity and temperature in the *S. alba* sites may be attributed to the fact that the forest is under water during all high tides (inundation class 1). Salinity was similar to that of seawater in this forest. The tree cover in the *Rhizophora* and *Avicennia* reforested sites has probably helped in reducing the effect of desiccation as a potential threat to propagule survival.

No colonization occurred in the *S. alba* bare site and yet this site had similar salinity and temperature as the comparable reforested and natural sites. Possible causes of this failure in seedling recruitment may include: a limited influx of propagules (FAO, 1994; Panapitukkul et al., 1998), propagule predation (Jones, 1984; Smith, 1988; Dahdouh-Guebas et al., 1997, 1998; Lee, 1998), high wave energies, hydrodynamic trapping or damage of propagules by floating debris (Walter, 1971; Snedaker, 1978; Cintron, 1996; Delgado et al., 2001; Stieglitz and Ridd, 2001; Thampanya et al., 2002), as well as the low tidal position of the sandflat, with associated strong tidal currents. However, with reproductive stands adjacent, propagule supply can be ruled out as a cause. Osborne and Smith (1990) found that propagules are more vulnerable to herbivores beneath closed canopies than in gaps, which may make propagule predation less probable as an important limiting factor. We suggest that daily tidal inundation exposes potential recruits to both wave action and tidal currents. The high sand content (100%) in this site may be indicative of the impact of these hydrodynamic processes.

Natural colonization varied among sites and mangrove species. The reforested *S. alba* stand had a higher number of recruits as compared to the natural stand, which may suggest a higher natural regeneration potential in the former. Even when compared with the other two natural stands, the natural *S. alba* stand had the lowest density of recruits. The low recruitment in this stand may be attributed to the harshness of the habitat for seedling survival due to exposure to stronger wave attack and higher tidal velocities. The higher densities of seedlings in the *A. marina* and *R. mucronata* natural stands can also be attributed to the presence of other adult tree species within these stands, which were the most likely propagule sources of the seedlings recruited contrary to the *S. alba* natural stand which was monospecific even for the adult trees.

6. Conclusion

The findings of this study suggest that clear-felling of mangroves greatly impairs natural regeneration most likely due to the resulting unfavourable site conditions. Mangrove reforestation however, appears to facilitate natural colonization of sites, most likely by altering local hydrodynamics and other physico-chemical factors. The aerial roots of established trees help in breaking waves, slowing tidal currents and trapping floating mangrove propagules assuring the establishment of a sapling bank (Ellison, 2000). With severely limited propagule retention, regeneration of any mangrove vegetation may not occur in the absence of human intervention.

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