MANGROVES FACING CLIMATE CHANGE: LANDWARD MIGRATION POTENTIAL IN RESPONSE TO PROJECTED SCENARIOS OF SEA LEVEL RISE.

Di Nitto D.[1*], G. Neukermans[1], N. Koedam[1], H. Defever[1], F. Pattyn[3,4], J.G. Kairo[5] and F. Dahdouh-Guebas[1,2]

1 Biocomplexity Research Focus c/o Laboratory of Plant Biology and Nature Management, Mangrove Management Group, Vrije Universiteit Brussel - VUB, Pleinlaan 2, B-1050 Brussels, Belgium.

2 Laboratoire d'Écologie des Systèmes et Gestion des Ressources, Département de Biologie des Organismes, Faculté des Sciences, Université Libre de Bruxelles - ULB, CP 169,Avenue F.D. Roosevelt 50, B-1050 Bruxelles, Belgium.

3 Laboratory of Physical Geography, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium.

4 Unité de Recherche Sciences de la Terre,Université libre de Bruxelles, Brussels, Belgium.

5 Kenya Marine and Fisheries Research Institute, PO Box 81651, Mombasa, Kenya.

* Corresponding author: diana.dinitto@gmail.com

ABSTRACT

Mangrove forests prominently occupy an intertidal boundary position where the effects of sea level rise will be fast and well visible. This study in East Africa (Gazi Bay, Kenya) addresses the question whether mangroves can be resilient to a rise in sea level by focusing on their potential to migrate towards landwards areas. The combinatory analysis between remote sensing, DGPS-based ground truth and digital terrain models (DTM) unveils how real vegetation assemblages can shift under different projected [minimum (+9cm), relative (+20cm), average (+48cm) and maximum (+88cm)] scenarios of sea level rise (SLR). Under SLR scenarios up to 48 cm by the year 2100, the landward extension remarkably implies an area increase for each of the dominant mangrove assemblages, except for *Avicennia marina* and *Ceriops tagal*, both on the landward side. On one hand, the increase of most species in the first 3 scenarios, including the socio-economically most important species in this area, *Rhizophora mucronata* and *C. tagal* on the seaward side, strongly depends on the colonisation rate of these species. On the other hand, a SLR scenario of +88 cm by the year 2100 indicates that the area flooded only by equinoctial tides strongly decreases due to the topographical settings at the edge of the inhabited area. Consequently, the landward *Avicennia*-dominated assemblages will further decrease as a formation if they fail to adapt to a more frequent inundation. The topography is site-specific; however non-invadable areas can be typical for many mangrove settings.

Keywords: Sea Level Rise – Mangroves – Topography – DTM - Gazi Bay – Inundation – Landward migration – GIS

1. INTRODUCTION

Inhabiting the interface between land and sea, mangroves are amongst one of the most at-risk ecosystems when sea level rises (McLeod and Salm 2006). Throughout the Quaternary, mangroves have shown high resilience to disruptions from large sea level fluctuations over historic time scales (Woodroffe 1990). However, adaptation probabilities strongly depend on the rates of SLR and sediment supplies in combination with subsurface processes that affect sediment elevation (Gilman E. et al. 2007, Gilman E. L. et al. 2006, McLeod and Salm 2006, Wolanski and Chappell 1996, Woodroffe 1990). Ellison and Stoddart (1991) suggested that mangroves are stressed by SLRs between 9 and 12 cm over 100 years and concluded that faster rates could seriously threaten mangrove ecosystems. This view has been challenged by Snedaker *et al.* (1994) who cite historical records showing mangrove expansion under relative sea level changes nearly twice that high, however hard scientific data or SLR simulations are not available.

As mangrove ecosystems are very dynamic, the ability of these forests to migrate to more landward zones is a very important aspect when considering the effect of SLR on mangroves. If the possibility poses, mangroves will adjust to a SLR by expanding landward or laterally into areas of higher elevation, or even by growing upward in place (McLeod and Salm 2006). However, mangroves areas situated in a physiographic setting that limits landward migration due to obstacles or steep gradients and with a net decrease in sediment elevation or sediment accretion that is insufficient to keep up with SLR, are most vulnerable (Gilman E. L. et al. 2008). On a species level, adaptation can occur through landward migration at different speeds as mangrove species maintain their preferred hydroperiod or by sediment accretion (Gilman E. L. et al. 2008). Mangrove species composition can strongly affect mangrove's resistance and resilience to SLR given that on the one hand individual species have varying tolerances of the period, frequency, and depth of inundation, and on the other hand different vegetation zones have different rates of change in sedimentation elevation (Krauss et al. 2003, McKee et al. 2007, Rogers et al. 2005). Furthermore, several scientists have also investigated how different functional root types of several mangrove species respond to changes in elevation in order to determine the vulnerability to SLR (Ellison and Stoddart 1991, Vincente 1989).

Species-specific competition may allow some species to outcompete others and to become more dominant within the newly formed species composition (Lovelock and Ellison 2007). Establishment and dispersal play a significant role in these processes. They are however different for various species and strongly dependent on many biotic factors like buoyancy, period of obligate dispersal, longevity and period of establishment (Allen and Krauss 2006, Clarke et al. 2001, Drexler 2001, Tomlinson 1986), whilst wind and hydrodynamics of tides and currents can be equally important abiotic factors (Stieglitz and Ridd 2001). Additionally, factors like microtopography, top soil type and root structures can also have a significant effect on the fate of propagules once released from their parental trees, as can human induced degradation, like tree cutting (Di Nitto et al. 2008).

To date, mangroves have been subjected to non-climate related anthropogenic stressors which have accounted for most of the global average annual rate of mangrove loss, estimated to be 1-2%, with losses during the last quarter century ranging from 35 to 86% (Alongi 2002, Duke et al. 2007, FAO 2003, 2007, Valiela et al. 2001). So far, relative SLR has been a smaller threat to mangroves. However, it may constitute a substantial proportion of predicted losses (about 10-20% of total estimated losses) as several studies have already shown that many mangrove areas have not been keeping pace with current rates of relative SLR (Cahoon et al. 2006, Gilman E. et al. 2007, McKee et al. 2007). We would like to emphasize the importance of understanding mangrove responses to SLR as these ecosystems provide tremendous social, economic and ecological value (Barbier 2003, Dahdouh-Guebas F. et al. 2005, Mumby et al. 2004, Nagelkerken et al. 2008, Walters et al. 2008, Wells et al. 2006).

This study focuses on the critical factor 'tidal range' in order to investigate the potential for landward migration of mangrove vegetation assemblages in Gazi Bay (Kenya) under different SLR scenarios. As mangroves species have their preferred hydroperiod, the vegetation distribution in the different inundation classes at present is extrapolated towards future SLR scenarios based on a static mangrove surface elevation. Digital terrain modelling is derived from differential GPS field measurements and used to simulate water levels in a GIS environment. In combination with a mangrove species map, preliminary results are generated regarding the effect of SLR in the study site in Gazi Bay (Kenya). The focus resides on individual mangrove species and their possible colonization of back-mangrove areas that become accessible when sea level rises. We deliberately adopt a reductionistic approach by taking abstraction of alterations in sedimentation and elevation and to other consequences of global change such as increases in temperature, CO_2 concentration and storm frequency and possible shifts in seasonal periods (Pernetta 1993, UNEP 1994, Woodroffe 1990, Woodroffe and Grime 1999). However we feel that, in this context, relevant conclusions can be made. First of all, this study represents the first attempt to simulate the effect of SLR based on a large amount of detailed information on topography and vegetation covering the whole bay. Secondly, many researchers have already gathered valuable information within this study area on diverse subjects like regeneration, vegetation structure dynamics, human impacts and propagule dispersal (e.g. Abuodha and Kairo 2001, Bosire J. O. et al. 2003, Bosire J. O. et al. 2008b, Dahdouh-Guebas Farid and Koedam 2006, Dahdouh-Guebas F. et al. 2002a, Di Nitto et al. 2008, Kairo J. G. et al. 2001, Kirui et al. 2008, Neukermans et al. 2008). The latter gives us the opportunity to draw preliminary conclusions on the potential for landward migration of mangroves in Gazi Bay and to create some views on the future vegetation structure dynamics, which can contribute to their resilience to SLR. Resilience here understood as the survival of the formation, even if displaced in space.

2. MATERIAL AND METHODS

2.1. Study area

Gazi Bay (4° 26' S, 39° 30' E) is a shallow tropical water system situated circa 40km south of the historic port (Kilindini) of Mombasa (Figure 1). The mangrove forest covers an area of approximately 6.5 km^2 and is drained by two tidal creeks. The tidal regime within the bay is semi-diurnal with a macro-tidal range of 3.5 m and an ebb dominant asymmetry (Kitheka 1996, 1997). Ten East African mangrove species are present within this bay fringed with mangrove forests, seagrass beds, and coral reefs, more specifically *Avicennia marina* (Forssk.) Vierh., *Bruguiera gymnorrhiza* (L.) Lam., *Ceriops tagal* (Perr.) C. B. Robinson, *Heritiera littoralis* Dryand., Lumnitzera racemosa Willd., *Rhizophora mucronata* Lam., Sonneratia alba Sm., *Xylocarpus granatum* Koen, a second yet unidentified *Xylocarpus* species, and *Pemphis acidula* Forst. (Gallin et al. 1989) (nomenclature according to Tomlinson (1986)). Topographical measurements (see 2.2) were conducted throughout the western part of the bay during two dry periods (July-August 2003 and 2005).

Mangrove species distribution within this study area was obtained by Neukermans *et al.* (2008). A classification of a Standard QuickBird multispectral satellite image was performed in combination with ground truthing based on vegetation transects by the Point-Centered-Quarter Method (PCQM+) of Dahdouh-Guebas and Koedam (2006). The two socio-economically most important species within this study area, *R. mucronata* and *C. tagal* (Dahdouh-Guebas F. et al. 2000, Dahdouh-Guebas F. et al. 2004a), are mapped with User's Accuracies above 85 percent, whereas all four dominant mangrove species (*A. marina* (on the seaward side (Sw) and the landwards side (Lw)), *S. alba, R. mucronata* and *C. tagal* (Sw and Lw)) are mapped with an Overall Accuracy (OA) of 72 percent.

2.2. Topographical field survey and construction of a DTM

The aim of the topographical field surveys was to construct a digital terrain model (DTM) in order to simulate water levels at present and for different Intergovernmental Panel on Climate Change (IPCC) scenarios of SLR (for explanation on IPCC scenarios, see 2.3). Measurements were carried out using a Leica GPS-AT302 which is a centimeter-precise differential global positioning system (DGPS) with a fixed reference station and a mobile rover station. Since a dense mangrove cover disrupts the DGPS signal, a stratified design was applied targeting the low-cover mangroves, back-mangrove areas, tidal mudflats and creeks. Resolution of the DTM varies from 1m in the topographically 'rough' areas to 50m in areas characterized by a relatively flat and even surface. All DGPS points were post-processed in SKI (Static Kinematic Program) and after converting these geographical coordinates into projected coordinates (WGS 1984, UTM zone 37S) and assigning their absolute height, a thorough knowledge of the field was used to add extra points and breaklines in order to eventually optimize the

constructed DTM. As the height measurements of these points are relative, we followed the high water line of a chosen spring tide on two consecutive days and collected the X-Y-Z data of 116 points using the DGPS. Based on the Kilindini tide tables (Kenya Ports Authority, KPA) the approximated absolute height of the water was calculated, and the relative elevations in the DTM converted to approximate absolute field topography. We recognize a temporal delay in tides between Mombasa and Gazi Bay, however this does not influence our study.
The final coordinates resulting from the topographical measurements were inserted into a geographical information system (GIS) and served as an input to create a triangular irregular network (TIN) of the area. The TIN was based on the (non-constrained) Delaunay triangulation of the original set of points by use of Voronoi diagrams, a theory for which we refer to Raper (1990). In this paper it is not the intention to investigate in-depth the impact of these elevation errors through Principal Component Analysis (Lopez 1997) but we give an estimation of the absolute mean error and the standard deviation in densely covered and less densely covered areas. After extracting 30 points respectively from each of the latter areas, the TIN was reconstructed and height values were re-assessed for these particular points.

2.3. Spatial analyses

IPCC has predicted several SLR scenarios [+ 9cm (minimum), +20cm (relative), +48 cm (average) and + 88 cm (maximum)] by the year 2100 (IPCC 2001)[1] based on atmosphere-ocean general circulation models and emission scenarios incorporating uncertainties regarding changes in terrestrial ice, permafrost and sediment deposition. The main purpose of the spatial analyses is to predict possible changes in vegetation assemblages under these different scenarios of SLR.

This modelling exercise mainly focuses on the potential of mangroves to migrate towards landward areas, but it is solely based on sea level rise relative to a static mangrove surface elevation. In this stage, data on sediment related changes are not available, however we do not underestimate the importance of sediment in mangrove vegetation dynamics in view of SLR.

The modelling exercise started with an assessment of the current species related zonation or spatial structure present in Gazi Bay. First of all, the height boundaries for each inundation class according to Watson (1928) (Table 1) was defined based on the combination of the tide tables (July 2003-July 2004) published by the KPA and the monthly inundation frequencies per class (Table 1). In further analysis, inundation frequencies higher than those of 'class 1' will be referred to as 'class 0'. Using ArcGIS 8.2, these boundaries were classified into

[1] We based our analysis on SLR scenarios of the IPCC Third Assessment Report (TAR) (2001) and not on those of the Fourth Assessment Report (AR4) (2007), which respectively forecast a range from 9cm - 88cm by 2100 and a range from 18cm-59cm by 2090-2099. The reason is the following: due to lacking of published literature, AR4 models do not include uncertainties in climate-carbon cycle feedback nor do they include the full effects of changes in ice sheet flow. The AR4 projections however include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed for 1993-2003, but these flow rates could increase or decrease in the future. The AR4 could have similar ranges to those of TAR if uncertainties were treated in the same way.

inundation classes based on the DTM for the current scenario versus different IPCC scenarios of eustatic SLR. The relative scenario of +20 cm coincides with the current trend of SLR within the long-term dataset (1985-2003) obtained from gauge measurements by the Kenya Marine and Fisheries Research Institute at the Kilindini Port in Mombasa. This initiative is part of the 'Global Sea Level Observing System' (GLOSS) founded by the Intergovernmental Oceanographic Commission (IOC) of the UNESCO.

Secondly, an overlay between the vegetation map and the current inundation classes (Figure 2-B) gives an estimation of the vegetation surface of each species within each inundation class. To review the accuracy of the DTM and/or the classification of the vegetation, it is important to investigate whether the distribution of the species within the inundation classes deviate from a random distribution. To perform the statistical analyses, the complete area was divided into 10 equally sized blocks. Within each block the areal coverage (ha) was calculated of each species in all inundation classes of the current situation. Secondly, a Kolmogorov-Smirnov test was performed to compare the observed cumulative distribution function to a theoretical normal distribution, whereafter Kruskal-Wallis tests were completed to investigate if the vegetation distribution within the inundation classes is random. Since the species concerned are not randomly distributed, extrapolations of the vegetation structure towards future IPCC scenarios of SLR were performed. The area increase (%) of each inundation class within each scenario was calculated in relation to the current situation where after these percentages were multiplied by the current vegetation area (ha).

2.4. Sensitivity analysis

A source of uncertainty in the input data is the DTM's absolute height which was calibrated using Kilindini port gauge measurements. To address the sensitivity of the model to the absolute height uncertainty of the DTM, we investigated the impact of changes in the height boundaries of the inundation classes. Upper and lower height boundaries are slightly altered at a time and in a systematic manner, more specifically by an increase and decrease of these boundary intervals with 5, 10 and 15% corresponding to 4, 6 and 8cm. The comparison between the reference map (Figure 2-C1) and the output maps after altering the height boundaries was assessed with an error matrix, giving Overall (OA), User's (UA) and Producer's Accuracies (PA) (calculations see Appendix A).

3. RESULTS

3.1. Construction and validation of the Digital Terrain Model

The DTM of the study area is shown in Fig. 2-A. After post-processing in SKI, 4105 points were accepted with an average error on X, Y and Z of respectively 1.16 cm, 2.08 cm and 0.89 cm, whereafter several breaklines and 82 extra points were manually added to optimize the DTM. Breaklines along the creek banks are however crucial and had to be added as estimates (based on measurements within the creek) due to high mangrove coverage. Absolute mean error and standard deviation for densely covered and less densely covered areas are respectively 0.013m ± 0.106 and 0.089m ± 0.374.

3.2. Simulation of Sea Level Rise scenarios

The current situation covers a total (studied) area of 423.43ha, of which the regularly flooded area and the non-flooded area respectively encompass 386.53ha and 36.90ha. When looking at the inundation classes within the different scenarios (Figure 2-C1 to C5), we can conclude that there is an overall trend of transgression into the terrestrial areas. Especially the maximum scenario (+88cm) represents a significant area increase of 'class 0' and 'class1 (AHT)' (for abbreviations see Figure 2-C). More specifically, the % area increase of these 2 classes from the current situation towards the maximum scenario of SLR is respectively 245 and 103%. After calculating the extent of each mangrove species within each current inundation class, Kolmogorov-Smirnov tests were completed with results showing significance values < 0.05 for each species. The vegetation distribution is therefore not normal and nonparametric techniques have to be used for further analyses. The following Kruskal-Wallis test proved that the distribution of the vegetation within the inundation classes is not random; all significance values are < 0.05. Each species evaluated within the area has a preference for certain inundation classes confirming the occurrence of a specific zonation or spatial structure in Gazi Bay and therefore also an adequate accuracy of the field measurements.

Due to the errors on the classification of the vegetation map (see 2.1 and Neukermans et al. 2008)and the topographical measurements, the total area (ha) occupied by each mangrove species within the whole study area (TMA) does not fully coincide with the total area (ha) occupied by each mangrove species within the inundation classes at present (TMAI). This however does not exceed values between 2 and 12 (Table 2), except for *Sonneratia alba* which mainly occurs in 'class 0' (38%) & 'class 1 (AHT)' (35%), consequently being the only species with a high difference between TMA and TMAI of 61%. The high discrepancy between TMA and TMAI for *S. alba* could be explained by a possible lower accuracy of the DTM at the breaklines marking the creek bank.

All other species appear to have an adequate distribution within the whole study area: *Avicennia marina* Sw (seaward) mainly resides in 'class 1 (AHT)' (26%) & 'class 2 (MHT)' (45%), *Rhizophora mucronata* mainly appears in respectively 'class 2 (MHT)' (53%) and 'class 3 (NHT)' (22%), whilst *Ceriops tagal*, which is an inner mangrove, occupies the areas in several mid classes. *A. marina* Lw (landward) dominates the landward classes with 35% 'in class 4 (SHT)'. An extrapolation of changes in vegetation assemblages towards future scenarios (Figure 3-A) demonstrates that, in comparison to the average scenario of SLR (+48cm), all species will decrease in the maximum scenario (+88cm), resulting in a decline of 13% in 100 years. Although throughout the minimum, relative and average scenario most species show a possible area increase, this is not the case for *A. marina* Lw as this species will diminish throughout all scenarios with a highest decrease of 60% in the maximum scenario. When considering the two socio-economically most important species *R. mucronata* and *C. tagal* in the most probable relative scenario of +20cm SLR, an area increase of 15% occurs in comparison to the current situation. Finally, the area proportions between the total mangrove area, the non-flooded area and 'class 0' are shown in Fig. 3-B as % increase or decrease compared to the current situation. The maximum scenario shows a considerable decrease in total mangrove area of 13% whereas for the relative scenario this area increases with 4%. Most remarkable increase is for the area 'class 0', namely 245% in comparison to the current situation.

3.3. Sensitivity analysis and error matrix for map comparison or accuracy assessment

Table B.1. (see Appendix B) shows the results of the error matrices for map comparison or accuracy assessment. When comparing the vegetation distribution within adjusted height boundaries for each inundation class, the outcome appears to be relatively sensitive to an increase or decrease of 15%. The overall accuracy, with a comparable outcome for Khat , fluctuates between 87.34 to 65.88 % when considering an increase or decrease up to 10 %, yet strongly declines towards 53.61 to 48.02% when height boundaries of each inundation class are adjusted with 15%. As the applied vegetation classification confirms the occurrence of a specific zonation or spatial structure in Gazi Bay, which is highly related to inundation patterns, we can conclude that sensitivity to alterations in topography can be significant from a certain limit and should therefore be aligned to vegetation distributions when data is available.

4. DISCUSSION

This study was to investigate whether mangrove assemblages in Gazi Bay have the potential to migrate to more landward areas, which can contribute to their resilience to SLR (Figure 4), understood as the survival of the formation within the site. Although the focus of this study was mainly on tidal range, we emphasize the importance of sediment supply, especially for scenarios of SLR higher than 20cm/100y (relative scenario). Whether mangroves can be resilient to SLR strongly depends on the physiographic setting in which these ecosystems occur, human activities that are carried out in the wetland and on how species-specific competition and adaptation will unfold. There is no clear-cut answer that can be applied to global mangrove coverage, yet by studying this particular mangrove area with a macrotidal regime and a common vegetation zonation along a gentle slope gradient from land to sea, extrapolations can be made to areas with similar characteristics.

4.1. Vegetation dynamics of mangrove assemblages under different scenarios of SLR

Bearing in mind the reductionistic approach, the extent of the most common assemblages, apart from *Avicennia marina* and *Ceriops tagal* on the landward side (Lw), are forecasted to increase in surface under the different scenarios of SLR (except for the maximum scenario of +88cm). This forecast is in line with a few earlier reports that current sea-level rise rates do not pose a threat to mangrove ecosystems (e.g. McKee et al. 2007, Snedaker et al. 1994, Tan and Zhang 1997), but contradicts many others (e.g. Ellison and Stoddart 1991, Fujimoto and Miyagi 1990, Parkinson et al. 1994, Pernetta 1993). However, considering the uncertainties regarding the impact of global change on mangrove growth and development, such contradictions are not unexpected. In addition, our reductionistic approach focuses on tidal range and the possible dispersal range of propagules, but it does not take into account the biogeomorphological capacity to maintain or to protect a mangrove forest.

Landward migration of mangroves in Gazi Bay appears to be limited under the maximum scenario as the highest intertidal inundation class strongly decreases due to the topographical settings at the edge of the inhabited area. Consequently, the landward *Avicennia*-dominated assemblages will continue to decrease if they fail to adapt to a more frequent inundation or if competition with other species will prevail. Dahdouh-Guebas *et al.* (2004a) made a prediction of future vegetation structure in Gazi Bay based on retrospective remote sensing, social surveys and tree distribution and results show that the surface extent of *A. marina* on the landward side has been reducing since 1972. Furthermore, the current situation in Gazi Bay is characterized by large bare and sandy sites on the landward side which have remained in the same state for a substantial time, at least, no colonization was observed for ca.16 yrs (*pers. obs*). When landward areas are accessible during SLR, dispersal and early growth become important stages in a plant life that fundamentally determine community structure and population dynamics (Clarke et al. 2001, Sousa et al. 2007). These processes are very complex. A dense mangrove forest can provide an adequate propagule supply for dispersal towards newly colonisable areas, but (1) as Clarke *et al.* (2001) stated, establishment of young trees is mainly related to the presence of parental trees while this is not so much the case for juveniles and the hydrochorous dispersal of propagules, and (2) suitability for stranding or self-planting of propagules is strongly dependent on the presence of root structures (which can facilitate the entanglement of propagules) and the compactness of the soil (clay or silt dominated) (Di Nitto et al. 2008).

As in other transitional systems, plant establishment and community succession is driven by tolerance to physiological stress and plant-plant interactions (Bertness 1991, Milbrandt and Tinsley 2006), hence species-specific competition could signify a natural blockage for landward migration of mangroves. Yet, in several cases facilitation is a common mechanism of succession in terrestrial habitats, meaning that an early colonizer changes the abiotic conditions in a way that allows an entry and finally a displacement of a second species to a previous intolerable habitat (Connell and Slayter 1977). This was f.i. the case for (1) saltwort (*Batis maritima* L.) as it was identified as an abundant initial colonizer of an extensive black mangrove (*Avicennia germinans* L.) die-off area (Milbrandt & Rinsley, 2006) and (2) saltmarsh cordgrass (*Spartina alterniflora* Loisel.) being a potential initial soil stabilizer creating successional stages firstly for *Laguncularia racemosa* (L.) C.F. Gaertn which is secondly outshaded and replaced by *Avicennia schaueriana* Stapf & Leechm. ex Mold. (Cunha-Lignon et al. 2009).

The reported forecasts can also have an important socio-ecological implication. Although the forest adjacent to the village has long been over-exploited for wood and decreased in area, anthropogenic disturbance has diminished over the last years and some mangrove assemblages have ever expanded (Dahdouh-Guebas F. et al. 2004a). An increase in mangrove area under different scenarios of SLR, provided that it does not go at the expense of qualitative degradation, may imply an increase in anthropogenic threats like f.i. traditional utilisation (McLeod and Salm 2006). Clear felling of mangroves species can have severe consequences for future vegetation dynamics. Furthermore, most mangrove creeks (as the case in Gazi Bay) are characterized by the occurrence of time-velocity asymmetry in which ebb flow is more dominant than flood flow (Kitheka 1997, 1998, Kitheka et al. 2002). Sediment trapping occurs during incoming flood tides and there is no significant export of sediments during ebb tide (Furukawa and Wolanski 1996, Wattayakorn et al. 1990), however degradation of mangroves can lower trapping efficiency (Kitheka et al. 2002), consequently increasing vulnerability to sea level rise.

4.2. Vegetation dynamics of individual species under different scenarios of SLR

When landward areas become accessible for the migration and colonization of mangrove species, we have to ask the same question as Alongi (p4, 2008): "Are trends in mangrove forest replacement in response to catastrophic disturbances the result of somewhat deterministic sequences as in terrestrial forests, or are they the result of a stochastic, 'first come, first served' opportunistic response or neither?". Empirical data supports the idea that recovery is stochastic with distinct succession stages, yet early sequences of species replacement are greatly influenced by species present at initial recovery (Alongi 2008, Clarke et al. 2001, Sousa et al. 2007). Within this study the extrapolation of the present vegetation distribution towards scenarios under a rising sea level is based on species-specific preference for certain inundation frequencies. The survival of these species in their shift in a more landward direction is strongly dependent on their colonisation rate and interspecific competition. The most seaward mangrove species *Sonneratia alba* appears in vegetation zones that are daily inundated and are never submitted to large salinity variations (Tomlinson 1986). When sea level rises, this species is forecasted to increase in area (except under the maximum scenario), yet as investigated by Dahdouh-Guebas *et al.* (2004a) the juvenile layer within these *S. alba* stands is limited and propagule establishment is hampered by currents that are generally known to be strongest along the seaward side (Diop et al. 2001). The distribution of the young individuals of *S. alba* is more related to the adult trees, whereas juveniles are generally spread over a wider area (Dahdouh-Guebas F. et al. 2004a). The latter also applies for the species *Avicennia marina* on the seaward side (Sw). Furthermore, Imai *et al.* (2006) verified that *S. alba* seedlings and saplings, which require sunny conditions for their growth, were more abundant in gaps than in the understorey. Competition with a more landward species as *Rhizophora mucronata* might demonstrate that an area increase of *S. alba* could be overestimated by our analyses. However, colonisation by *S. alba* on seaward sand banks has occurred throughout the years. Additionally, bearing in mind the site-specific rates of sea level rise and sediment input rates, Ellison & Stoddart (1991) claimed that mangrove ecosystems can keep pace with SLR of 8-9cm per 100 year making seaward expansion and colonisation of these daily inundated areas possible. Rates of 9-12cm per 100 year cause stress and adjustment to higher rates is unlikely. The minimum scenario of SLR (+9cm) could in fact provide an additional and suitable habitat for *S. alba* and *A. marina* (Sw).

R. mucronata and *Ceriops tagal* are two economically valuable pioneer species that will most likely increase as predicted, unless anthropogenic impact rises. Multivariate vegetation structure analysis showed that *C. tagal* is very abundant in the understorey of assemblages dominated by other mangroves, which could camouflage a dynamic shift (Dahdouh-Guebas F. et al. 2004a). *R. mucronata* and *C. tagal* already occupy the mid zone within the mangrove area and knowledge on the dispersal of their propagules indicates that prop roots and pencil roots clearly have the ability to entangle propagules and that preference of propagule dispersal goes to flat areas and substrates with a more compact soil structure (clay, silt) (Di Nitto et al. 2008). One disadvantage for *R. mucronata* could however be represented by a further siltation along the seaward sand bank creating a patch of arid conditions and higher light intensity more favourable for *A. marina* (Dahdouh-Guebas F. et al. 2004a).

Avicennia marina (Lw) will have to adapt to longer inundation frequencies. It is known that this species can tolerate high salinity variation, so could the double zonation of this species on the landward side versus the same species on the seaward side support the idea of dynamic adaptation? Genetic analyses based on 48 RAPD (Randomly Amplified Polymorphic DNA) loci have demonstrated that 4 DNA fragments show a slight differentiation in allelic frequency between the two *A. marina* stands in spite of their short distance separation (Dahdouh-Guebas F. et al. 2004b). This indicates that there is less genetic exchange between the disjunctive stands than within one stand, consequently suggesting that an ecological or physical barrier might exists. Tidal range might facilitate the dispersal of propagules in both directions however obstruction by complex root structures can prevent this exchange. Additionally, interspecific competition with the adjacent species *C. tagal* could disadvantage *A. marina* as McCusker (1977) confirms that a salinity increase causes a reduction in water use efficiency for the seedlings of *Rhizophora*, but not for *Ceriops*. Furthermore, an elevated CO_2 level will enhance the efficiency of water use (UNEP 1994), however this advantage is lost when salinity becomes too high for instance at low inundation frequency areas at the landward side. Another drawback for *A. marina* is an increase of temperature, since this species has lowest optimal temperature for leaf development (Hutchings and Saenger 1987).

There are several well-established physiologic mechanisms influencing mangrove community composition (Duke et al. 1998, McKee 1995), yet research is needed on interspecies interactions influencing mangrove forest regeneration in post-disturbance mangrove communities.

4.3. Recommendation for further research and management strategies

In the light of mangrove ecosystem stresses caused by climate change, managers face the dual challenge of selecting and implementing conservation strategies in order to maintain and restore resilient mangrove forests.

In this study the emphasis resides on tidal range and not on sediment supply, however, we give a preliminary vulnerability assessment of this mangrove area based on a slightly adjusted decision tree (Figure 5) to aid resilient site selection for mangroves by McLeod & Salm (2006). This decision tree was applied after appointing Gazi Bay as a high biodiversity candidate site based on biological and environmental criteria (Table C.1, see Appendix C). Decisions were made based on available literature involving the mangrove area in Gazi Bay and the relative SLR scenario of +20 cm, which coincides with the current trend along the Kenyan Coast.

Following this decision tree, the mangrove area in Gazi Bay appears to be adequately resilient for at least 100 years and can most likely be appointed as a Marine Protected Area (MPA). However we do not intend to focus only on MPA's, yet we want to anticipate to a future scenario of sea level rise and indicate gaps in on the one hand scientific and on the other hand site-specific knowledge that necessitates further research. Given (1) the macrotidal regime and permanent rivers and creeks that provide freshwater and sediment (mainly during wet season), (2) the knowledge that the drainage basin of both Mkurumuji and Kidogoweni rivers, which extend into the coastal ranges of the Nature Reserve 'Shimba Hills', has limited anthropogenic pressures with respect to the intactness of the hydrological regime, and (3) that landward migration in Gazi Bay is possible under the relative scenario of sea level rise, the decision tree leads us towards the question whether recruitment is strong. The answer is definitely 'yes', however we feel that the possibility of a shift in vegetation structure needs to be implemented, rendering Gazi Bay into a site that is 'Maybe OK for MPA'. According to McLeod & Salm (2006) the decision tree would have led towards 'Good choice for MPA'.

The recommendations for further research and management strategies, which can be applied globally, are the following: 1) identifying an early colonizer to promote early establishment of mangrove seedlings, 2) measuring changes in elevation by means of Surface Elevation Tables (SETs), 3) Assuring the possibility of landward migration and (4) investigating propagule dispersal by combined hydrodynamic and ecological behaviour modeling.

Appendix A: Calculation of an error matrix for map comparison or accuracy assessment

Map 1= raster grid of *n* classes as a model output

Map 2= raster grid of *n* classes from an alternative model or comparison reference layer.

Producer's accuracy (PA)

Takes into account the accuracy of individual classes and therefore indicates the probability of the cell value in Map 2 being the same as in Map 1.

$= x_{ii} / x_{+i} * 100\%$

x_{ii}= total number of correct cells in a class

x_{+i}= sum of cell values in the column

User's accuracy (UA)

Takes into account the accuracy of individual classes but indicates the probability of the cell value in Map 1 being the same as in Map 2.

$= x_{ii} / x_{i+} * 100\%$

x_{ii}= total number of correct cells in a class

x_{i+}= sum of cell values in the row

Overall Accuracy (OA)

Summarizes the total agreement / disagreement between the maps and incorporates the major diagonal while excluding the omission and the commission errors.

$= D/ N * 100\%$

D= total number correct cells as summed along the major diagonal

N= total number of cells in the error matrix

K_{hat}

Measure of agreement or accuracy based on KAPPA analysis to compare maps of similar categories in order to determine if they are significantly different

$=N ((\Sigma^{r}_{i=1} x_{ii} - \Sigma^{r}_{i=1} (x_{i+} * x_{+i})) / (N^2 - \Sigma^{r}_{i=1} (x_{i+} * x_{+i})))$

r= number of rows in the matrix

x_{ii}= total number correct cells in a class (*i.e.* value in row i and column i)

x_{i+}= total for row i

x_{+i}= total for column i

N= total number of cells in the error matrix

Appendix B

Input parameter	Adjustments in input criteria	Comparison of vegetation distributions within the adjusted inundation classes	
		Overall accuracy (%)	K_{hat} (%)
Inundation classes (height boundaries)	+5%	87.34	85.34
	+10%	76.67	75.3 1
	+15%	48.02	49.61
	-5%	78.09	75.28
	-10%	65.88	65.39
	-15%	53.61	50.72

Table B.1: Results of the error matrices for map comparison or accuracy assessment when comparing the vegetation distribution within adjusted height boundaries for the inundation classes. Values represent the overall accuracy and K_{hat} in percentages.

Appendix C: Mangrove resilience factors: Case study: Gazi Bay, Kenya

Factors that allow for peat building to keep up with sea-level rise	Applicable to Gazi Bay Yes / No	Literature available per factor
Association with drainage systems including permanent rivers and creeks that provide freshwater and sediment	Yes	(e.g. Dahdouh-Guebas F. et al. 2004a, Kitheka 1996, 1997, Njambuya 2006, Obade et al. 2004, Ohowa et al. 1997)
Sediment rich-macrotidal environments to facilitate sediment redistribution and accretion	Yes	
Actively prograding coast and delta	Yes	

Natural features (bays, barrier islands, beaches, sandbars, reefs) that reduce wave erosion and storm surge	Yes	
Factors that allow for landward migration		
Mangroves backed by low-lying retreat areas (for example, salt flats, marshes, coastal plains) which may provide suitable habitat for colonization and landward movement of mangroves as sea level rises	No/Yes in certain places	(e.g. Di Nitto et al. 2008, Neukermans et al. 2008, Obade et al. 2004)
Mangroves in remote areas and distant from human settlements and agriculture, aquaculture, and salt production developments	Yes	

Mangroves in areas where abandoned alternate land use provides opportunities for restoration, for example, flooded villages, tsunami-prone land, unproductive ponds	Yes, unmanaged coconut plantations	
Factors that enhance sediment distribution and propagule dispersal		
Unencumbered tidal creeks and areas with a large tidal range to improve flushing, reduce ponding and stagnation, and enhance sediment distribution and propagule dispersal	Yes	(e.g. De Ryck 2009, Di Nitto et al. 2008, Kitheka 1996, 1997, Ohowa et al. 1997)
Areas with a large tidal range may be better able to adjust to increases in sea level due to stress tolerance	Yes	

Permanent strong currents to redistribute sediment and maintain open channels	Yes	
Factors that indicate survival over time		
Diverse species assemblage and clear zonation over range of elevation (intertidal to dry land)	Yes	(e.g. Beeckman et al. 1989, Bosire J. et al. 2008a, Bosire J. O. et al. 2006, Dahdouh-Guebas F. et al. 2002a, Dahdouh-Guebas F. et al. 2004a, Dahdouh-Guebas F. et al. 2002b, Kairo J.G. 2001, Kairo J.
Range in size from new recruits to maximum size class (location and species dependent)	Yes	
Tidal creek and channel banks consolidated by continuous dense mangrove forest (which will keep these channels open)	Yes	
Healthy mangrove systems in areas which have been exposed to	No	

large increases in sea level due to climate induced sea-level rise and tectonic subsidence		G. et al. 2001, Neukermans et al. 2008, Tack et al. 1992, Van Tendeloo 2004)
Factors that indicate strong recovery potential		
Access to healthy supply of propagules, either internally or from adjacent mangrove areas	Yes	
Strong mangrove recruitment indicated by the presence, variety, and abundance of established mangrove propagules	Yes	
Close proximity and connectivity to neighbouring stands of healthy	Yes	

mangroves		
Access to sediment and freshwater	Yes	
Limited anthropogenic stress	Yes, no major residential area in the vicinity, selected as a fairly pristine East African site in the EU PUMPSEA project: http://www.pumpsea.icat.fc.ul.pt	
Unimpeded or easily restorable hydrological regime	Yes	
Effective management regime in place such as the control of usual	Yes	

threats like dredging and filling, conversion to aquaculture ponds, construction of dams, roads, and dikes that disrupt hydrological regime etc.			
Integrated Coastal Management Plan or Protected Area Management Plan implemented	Yes/No		

1 **Table C.1: Mangrove resilience factors that inform site selection (according to McLeod & Salm, 2006) Case study: Gazi Bay, Kenya**

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Table 1: Inundation classes and monthly inundation frequency according to Watson (1928). Height boundaries (m above datum) of present and future inundation classes are presented: a minimum (+9cm), relative scenario (+20cm), average (+48cm) and maximum (+88cm) scenario is based on IPCC eustatic SLR scenarios for the year 2100. In further analysis, inundation frequencies higher than those of 'class 1' will be referred to as 'class 0'.

Inundation classes	Flooded by	Monthly inundation frequency	Present situation (m)	Minimum scenario, +9cm (m)	Relative scenario, +20cm (m)	Average scenario, +48cm (m)	Maximum scenario, +88cm (m)
1	*All high tides (AHT)*	56-62	2.10-2.60	2.19-2.69	2.30-2.80	2.58-3.08	2.98-3.48
2	*Medium high tides(MHT)*	45-56	2.60-3.10	2.69-3.19	2.80-3.30	3.08-3.58	3.48-3.98
3	*Normal high tides (NHT)*	20-45	3.10-3.50	3.19-3.59	3.30-3.70	3.58-3.98	3.98-4.38
4	*Spring high tides (SHT)*	2-20	3.50-3.80	3.59-3.89	3.70-4.10	3.98-4.28	4.38-4.68
5	*Abnormal (equinoctial tides) (EHT)*	0-2	3.80-4.20	3.89-4.29	4.10-4.40	4.28-4.68	4.68-5.08

Table 2: Presentation of the total area (ha) occupied by each mangrove species with the whole studied area (TMA) and the total area occupied by each mangrove species within the inundation classes at present (TMAI). Sw= seaward side and Lw= landward side.

Species	TMA	TMAI	Difference %
Avicennia marina Sw	46.59	41.65	11.86
Avicennia marina Lw	32.34	29.53	9.52
Ceriops tagal Lw	37.99	36.53	3.99
Ceriops tagal Sw	13.50	13.27	1.76
Rhizophora mucronata	109.42	105.50	3.71
Sonneratia alba	7.96	4.95	60.89

Figure 1: Representation of (A) the Kenyan coast (Dahdouh-Guebas F. et al. 2000) and (B) Gazi Bay. The satellite image (Quickbird) shows the whole bay of Gazi ; however this research focuses on the western part as encompassed by the overlaid vegetation map. *S. alba = Sonneratia alba, R. mucronata= Rhizophora mucronata, C. tagal* Lw*= Ceriops tagal* on the landward side*, C. tagal* Sw*= Ceriops tagal* on the seaward side *A. marina* Lw*= Avicennia marina* on the landward side and *A. marina* Sw*= Avicennia marina* on the landward side. Classification of the mangrove species coverage was obtained by Neukermans *et al.* (2008).

Figure 2: (A) Presentation of the DTM, (B) 3D presentation of the combination between (B1) inundation classes, (B2) vegetation map and (B3) Quickbird image, (C) Presentation of the inundation classes: (C1) Current situation, (C2) Scenario +9cm, (C3) Scenario +20cm, (C4) Scenario +48cm, (C5) Scenario +88 cm. AHT= all high tides, MHT= medium high tides, NHT= normal high tides, SHT= spring high tides and EHT= equinoctial high tides. Inundation frequencies higher than those of 'class 1' will be referred to as 'class 0'.

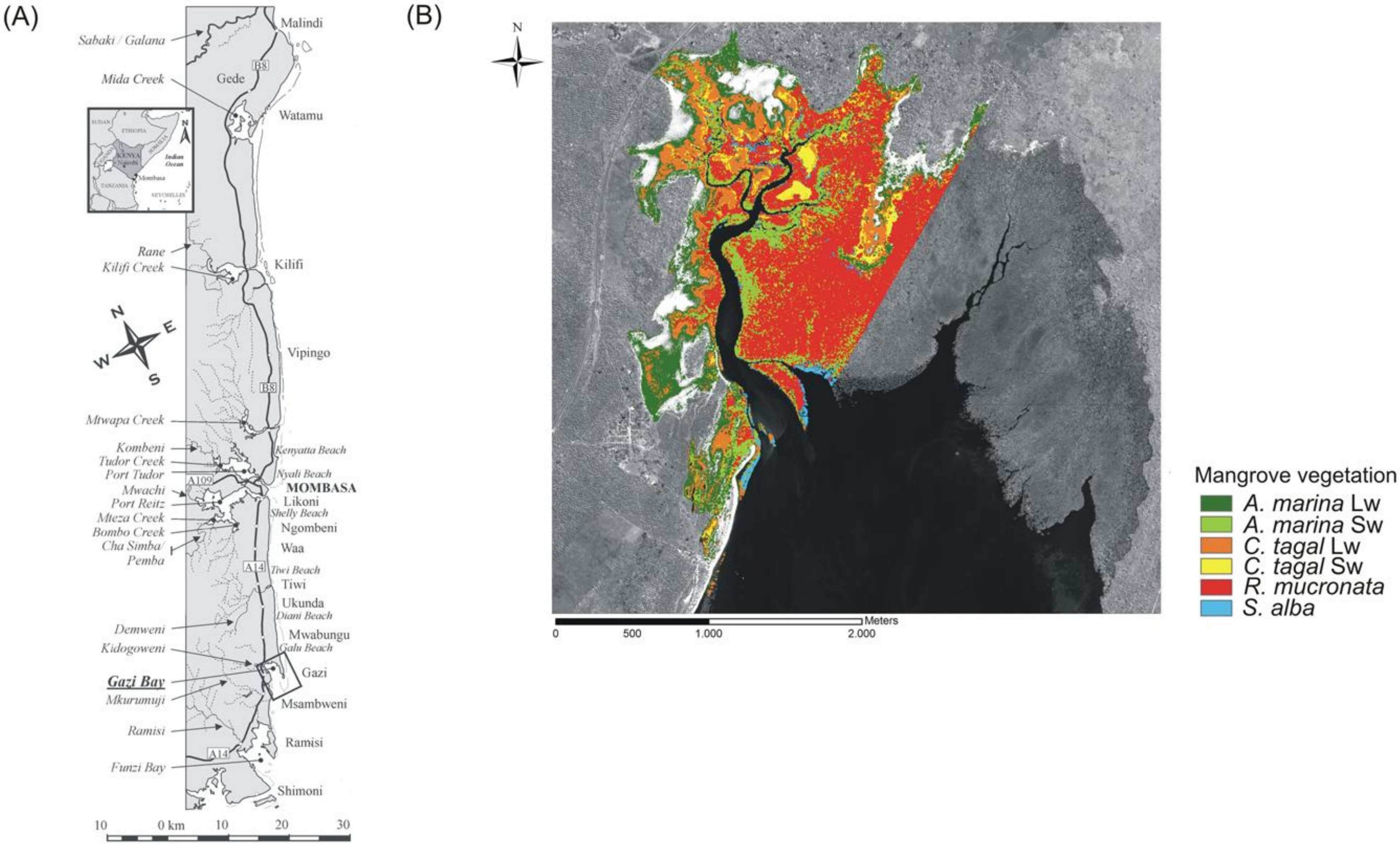
Figure 3: (A) Graph of the total area (ha) per species within the 4 SLR scenarios, (B) Future prediction of the dynamics of mangroves, non-flooded area and 'class 0'.

Figure 4: Overview scheme summarizing the discussion on resilience of mangroves facing sea level rise, more specifically concerning the case study in Gazi Bay (Kenya).

Figure 5:

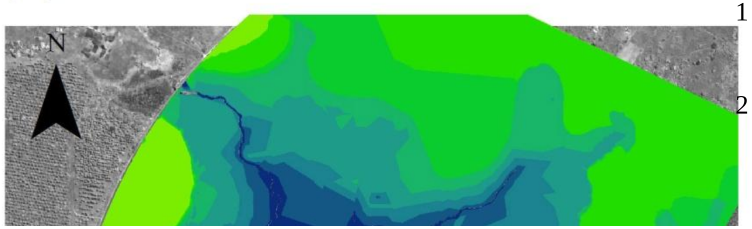
Figure 6: Decision tree to aid resilient site selection for mangroves according to McLeod & Salm (2006). The latter can be applied once candidate sites of high biodiversity have been selected using biological criteria f.i. *factors that indicate strong recovery potential (see

Appendix, Table A.2). This decision tree was adjusted (**) to implement the possibility of a shift in vegetation structure. MPA= Marine Protected Area.


(A)
Malindi
Sabaki / Galana
Mida Creek
Gede
Watamu
Rane
Kilifi Creek
Kilifi
Vipingo
Mtwapa Creek
Kombeni
Tudor Creek
Port Tudor
Mwachi
Port Reitz
Mteza Creek
Bombo Creek
Cha Simba/ Pemba
Kenyatta Beach
Nyali Beach
MOMBASA
Likoni
Shelly Beach
Ngombeni
Waa
Tiwi Beach
Tiwi
Ukunda
Diani Beach
Demweni
Kidogoweni
Mwabungu
Galu Beach
Gazi Bay
Gazi
Mkurumuji
Msambweni
Ramisi
Funzi Bay
Shimoni
10 0 km 10 20 30
(B)
N
Mangrove vegetation
A. marina Lw
A. marina Sw
C. tagal Lw
C. tagal Sw
R. mucronata
S. alba
Meters
0 500 1.000 2.000

1 **Figure 1**

(A) Presentation of the DTM



(B) 3D presentation of the combination between
(B1) inundation classes,
(B2) vegetation map
(B3) Quickbird image

(C) Presentation of the inundation classes (SLR scenarios):
(C1) Current situation, (C2) Scenario +9cm, (C3) Scenario +20cm, (C4) Scenario +48cm, (C5) Scenario +88 cm.

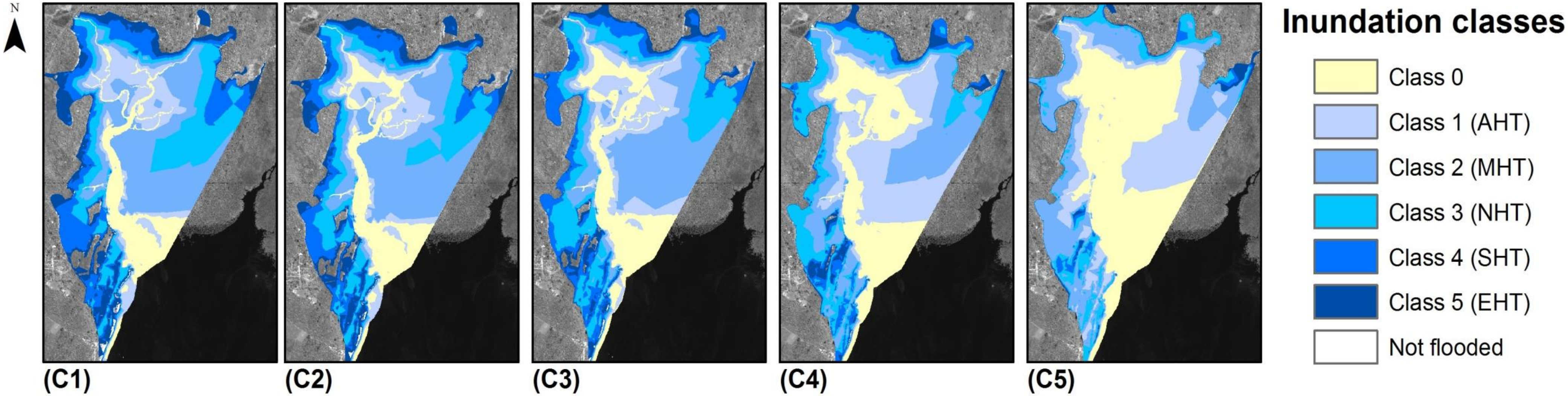
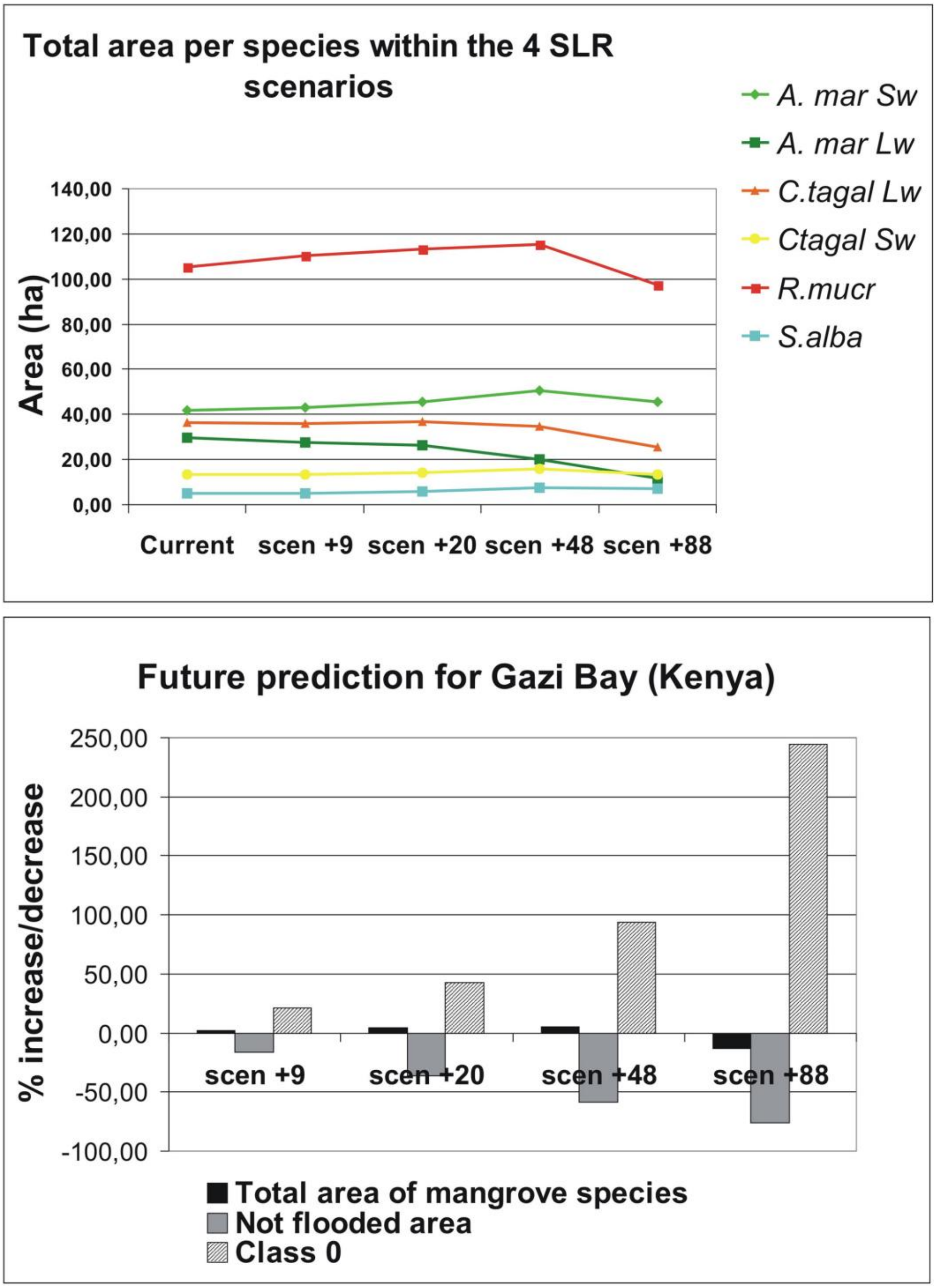


Figure 3

(A) (B)

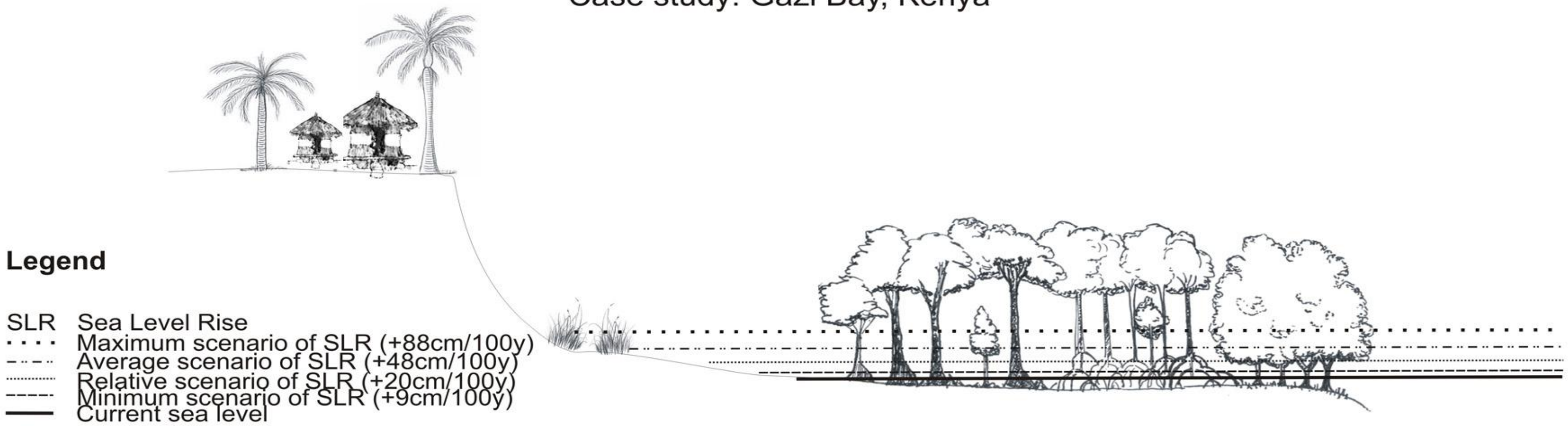


Total area per species within the 4 SLR scenarios
A. mar Sw
A. mar Lw
C.tagal Lw
Ctagal Sw
R.mucr
S.alba
140,00
120,00
100,00
80,00
60,00
40,00
20,00
0,00
Area (ha)
Current
scen +9
scen +20
scen +48
scen +88
Future prediction for Gazi Bay (Kenya)
250,00
200,00
150,00
100,00
50,00
0,00
-50,00
-100,00
% increase/decrease
scen +9
scen +20
scen +48
scen +88
Total area of mangrove species
Not flooded area
Class 0

Figure 4

MANGROVES FACING SEA LEVEL RISE

Case study: Gazi Bay, Kenya



Are mangroves resilient to sea level rise?

	Land inwards	Mangrove ecosystem
Certainties	Current **topography**:steep slope Bare, sandy areas: **no colonisation** for ca. 16 years	Current **topography**: gentle slope from sea to land Current **vegetation** distribution and past changes **Colonisation** by *Sonneratia alba* on seaward sand bank

⟹ Maximum scenario of SLR (+88cm)= **limitation of landward migration** due to topographical setting

	Land inwards	Mangrove ecosystem
Uncertainties	Future **human activities** Potential initial colonizer for **facilitation** of mangroves? **Sediment** supply and processes	Future **human activities** **Colonisation** rate and species-specific **competition** **Sediment** supply and processes

⟹ Educated guess: possibility exists for adaptation to SLR

⟹ Need for **ADAPTIVE CONSERVATION MANAGEMENT** on a regional scale

Figure 5

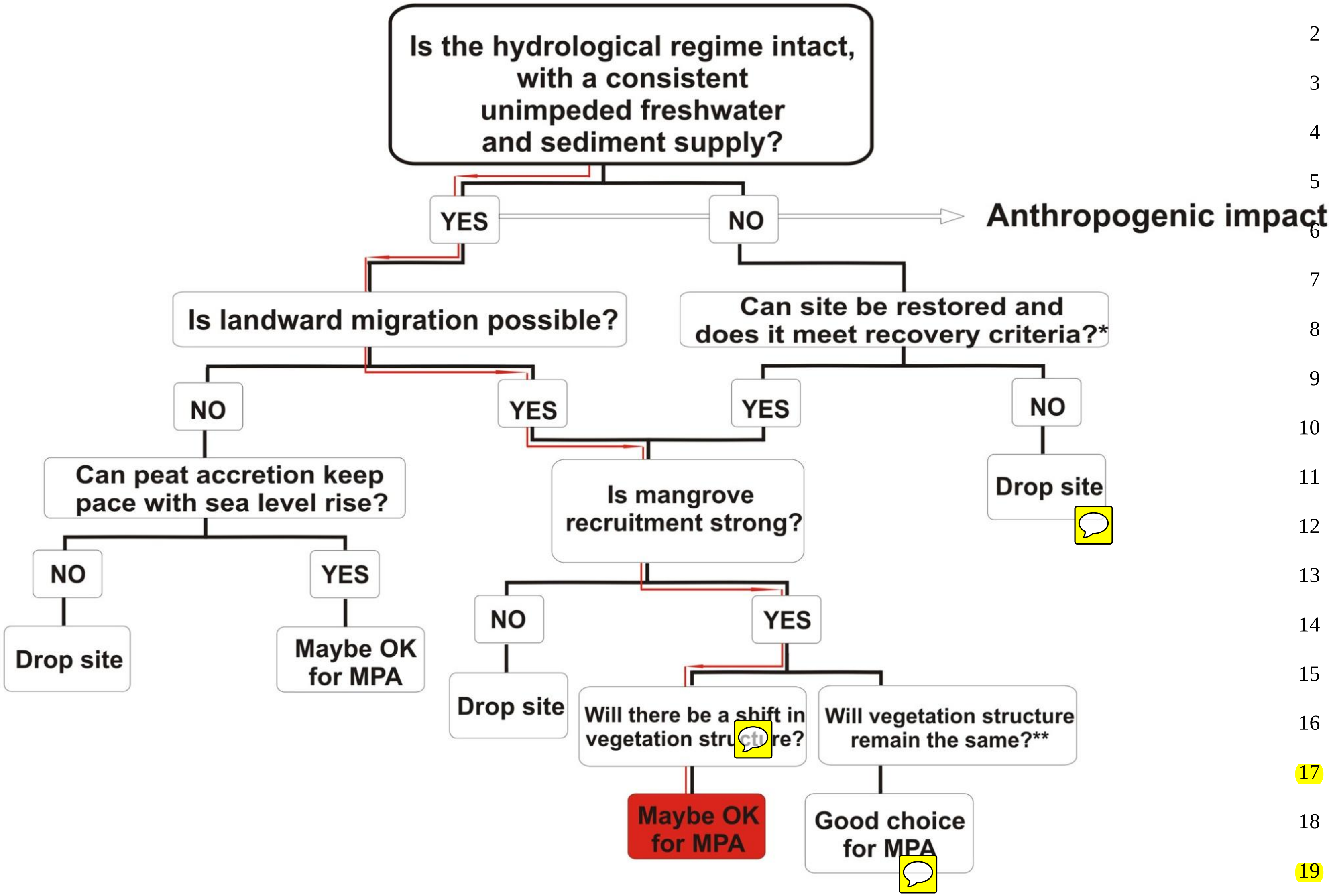

Is the hydrological regime intact, with a consistent unimpeded freshwater and sediment supply?
YES
NO
Anthropogenic impact
Is landward migration possible?
Can site be restored and does it meet recovery criteria?*
NO
YES
YES
NO
Can peat accretion keep pace with sea level rise?
Is mangrove recruitment strong?
Drop site
NO
YES
NO
YES
Drop site
Maybe OK for MPA
Drop site
Will there be a shift in vegetation structure?
Will vegetation structure remain the same?**
Maybe OK for MPA
Good choice for MPA

Figure 6