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DISCUSSION PAPER ON EXPOSURE OF MANGROVES TO ENVIRONMENTAL CHANGES IN THE WESTERN INDIAN OCEAN.

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Discussion paper: Exposure of mangroves to environmental changes in the Western Indian Ocean

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Background

This working paper presents analyses of the exposure of mangroves to environmental change in the Western Indian Ocean (WIO). Analyses employ systems approach to understanding the relative spatial exposure of mangroves ecosystems to environmental stress in the WIO. These analyses draw on the ecological understanding of how mangroves are impacted by various environmental pressures, and how they respond to those pressures, i.e. the impact response mechanism. This work is a culmination of multidisciplinary team effort and it showcases the diverse set of skills, or representation of disciplines necessary for a successful vulnerability analyses for any system. The team here includes ecologists, socio-economists, and geospatial analysts among others. In considering the interactions among multiple factors within a mangrove ecosystem, it is essential as a first step to define a boundary of the system enclosing key factors that will be represented in the analyses. Designating factors membership as within or outside the idealized system boundary takes into account the available data, time and other resources as necessary. Consequently, one of the main tasks at the onset of these analyses was to explicitly define the system boundary and the membership of various mechanisms in a mangrove ecosystem as within or outside the system. In addition to generating knowledge on the relative exposure of mangroves to climate change and local human pressures, outputs of this work can be applied to support decisions on the climate change adaptation and management strategies that would promote the survival of mangrove ecosystems.

Defining the system

In a mangrove socioecological system, geophysical, biological and social components of the system can interact in many ways. The interaction can be either beneficial or detrimental to the ecosystem. When the interaction is antagonistic, the net effect on a system is stress moderation and increased survival while in a synergistic interaction, stress on the ecosystem is reinforced or amplified thus undermining the resilience of mangrove ecosystems. For example, while there is a general consensus that sea level rise will impact on mangroves by inundating low lying coastal areas (Gilman et al. 2008, Krauss et al. 2011, IPCC 2007, McLeod and Salim 2006), availability of migration corridors and gentle topography can facilitate landward mangrove transgression as a response to increasing sea level, thus moderating potential impact of the primary stressor. However, land use and land-use change, and unsuitable geomorphology (steep topographies) will negate this migration and thus act as impediment to mangrove's resilience. Gradual sediment input will also enable mangroves to accrete sediments and "build" land to keep pace with increasing sea level (McKee et al. 2007, Krauss et al. 2011, McLeod and Salim 2006), subject to the above conditions, thus having a reducing effect. Massive episodic sediment input however, shocks the system and has immediate deleterious effects normally resulting in mangrove diebacks (Thampanya et al. 2003, Kitheka et. 2002, Bosire et al. 2006). Unfortunately, thresholds (especially upper critical levels) for many environmental stressors on mangroves including sedimentation have not been determined, and this becomes more complicated with interaction and cumulative impacts of multiple stressors (Halpern et al. 2008, Maina et al. 2011). While this is a critical knowledge gap, it shouldn't derail efforts for vulnerability assessments. Workarounds, such as those employed in this case study provide avenues of circumventing the lack of data on key thresholds.

Data and methods

Essential ocean and ecosystem variables for mangroves - In a participatory process involving mangrove experts drawn from all countries in the WIO, a suite of essential variables (EVs) were developed to represent the biophysical conditions within the defined system boundary. EV's represent both environmental stimuli known to influence the integrity of mangrove ecosystems, and the ecological condition of mangroves. Using geo-statistical techniques, EV's were derived from satellite data and spatial databases and aggregated for mangrove locations in the region, and within the key mangrove sectors as defined by the experts (Annex figure 1). A brief description of some of the EVs included in our system boundary is provided below.

Land-use and erosion - To represent the impacts of land-use conversion and soil erosion on mangroves, we derived two EVs, the Land Development Intensity, and (ii) watershed erosion.

(i) Landscape Development Intensity (LDI) - The LDI is a land-use based index for intensity of land use (Brown and Vivas, 2005). The LDI coefficient, which has been applied widely to demonstrate the impacts of land use development on ecosystems (e.g. Oliver *et.al.*, 2011) is based on the amount of non-renewable energy input received by each land-use type. To compute LDI for the region, we extracted watersheds from the elevation data and downloaded high resolution land use map at 20m grid over Africa. The land use classes were harmonized with those from Brown and Vivas (2005) and assigned the LDI coefficients. An area-weighted LDI, as devised by Brown and Vivas (2005), was calculated.

(ii) Watershed erosion - The Revised Universal Soil Loss Equation (RUSLE) calculates sheet and rill erosion from rainfall and the associated runoff for a landscape unit (Nam *et al.*, 2003). RUSLE is calculated using five parameters as follows: $A = K * R * LS * C * P$, where A = mass of annual soil erosion (tonnes km^{-2}); R = rainfall and runoff erosivity; K = soil erodibility (tonnes km^{-2} hour^{-1}); LS = slope parameter; C = soil and crop management; P = conservation practice. To estimate the exposure of mangroves as a result of land-use and erosion on the catchments, geo-statistical procedures were applied such that the single output map consists of values between 0-1, where 0 in relative terms represents no exposure and 1 high exposure high exposure to conditions represented by respective layers.

(iii) Human pressure/ Market access index - Human pressure index (HPI) was estimated using a mangrove accessibility map. The depletion of natural resources has become a major issue in many parts of the world, with the most accessible resources being most at risk. In both terrestrial and marine realms, resource depletion has classically been related to accessibility through road networks. Consequently, access to markets is used here as a proxy for human impact on mangrove ecosystems. A map that quantifies travel time to cities/markets at a spatial resolution of approximately one by one kilometre was developed by integrating several data layers that characterize factors affecting human movement rates and urban centers or towns within an established geospatial-modelling framework. The resulting travel time map for mangrove areas was standardized to generate values between 0-1 representing low and high human pressure respectively.

(iv) Sea-level Anomaly - Monthly climatologies of sea level anomaly (SLA) maps were downloaded from https://www.aviso.altimetry.fr for the years 1993 to 2017. Since SLA pixels only cover the ocean, near shore values were extrapolated to land using a 3x3 filter to overlay with the mangrove extent. For each grid, maximum of 12 climatology maps was calculated to generate a maximum SLA layer, which we used as a proxy for sea level rise. The optimal sea-level anomaly of 11.22m was calculated by taking the average sea level anomaly maps and adding 2SD (4.82 + 2*3.20). To develop an index for mangrove exposure to sea level rise, the maximum aggregated SLA layer was standardized between 0-1 using the increasing min-max function, with 1 representing maximum exposure and 0 representing no exposure.

(v) Inundation - Elevation and tidal data were used to determine the relative exposure of mangrove areas to flooding. To define the gradient of exposure of the elevation to flooding, we used the mangrove extent map and the elevation layers to compute the average elevation where mangroves are found, and the standard deviation. These statistics were then utilized to calculate the threshold elevation of 21.11m by adding the average to 2SD (8.89 + 2*6.11). This value was then incorporated into the decreasing min-max function where 21.11 was used as the minimum and zero as maximum in the standardization process. The output was an inundation map showing relative exposure of mangrove areas to flooding, based on elevation.

(vi) Land transgression - Slopes and land use types are some of the main factors affecting mangrove transgression. Hence, we utilized slope layer and land use map to define the suitability of land to mangrove transgression. Using slope layer and the mangrove extent layer, we calculated the optimal slope for mangroves by adding the mean of the slope of all areas where mangroves are found to twice the standard deviation. The result, 3.31 degrees, was used in an increasing min-max function to standardize the slope layer to values between 0 and 1. Further, we computed the suitability of land area for landward transgression by mangroves using land use map reclassified to 0 (land uses which would obstruct mangrove transgression) and 1 (land use types that would favour transgression). The land-use layer was first reclassified using a mask cropland map whereby all areas in the crop layer that had pixels with greater than 60% cultivation were used to assign cropland in the land-use layer. The modified land-use layer was then re-classed, with urban/artificial area assigned 0 (not favourable to mangrove transgression), while cropland, bare areas, forests and areas with permanently or semi-permanently submerged vegetation were classified as 1.

(vii) Ecological Conditions – We utilized the Normalized Difference Vegetation Index (NDVI) as a proxy for ecological condition, such that high vegetation signals as observed from satellite images indicate lack of fragmentation and good ecological condition, and vice versa. MODIS 13 NDVI product of 16-day composites at 250 m resolution (NASA LPDACC, 2006) was obtained for the years from July 2000 to December 2018. The data was pre-processed and clipped to the mangrove extent to calculate the monthly and yearly averages. Statistical summaries were computed for each month and for the entire time series. NDVI values range from 0-1, with 0 indicating bare soil or no vegetation condition, and 1 indicating high vegetation. To reflect the ecological condition, we converted the average NDVI layer such that 1 represented high exposure due to ecological condition and 0 represented low exposure as a result of high NDVI values.

(viii) Climate extreme events - Climate variables influence mangroves through a range of direct and indirect pathways. Here, we considered exposure path-ways to include the physical exposure as represented by temperature extremes events. Temperature extreme events may influence mangroves physiology, phenology and survival. Consequently, understanding the nature of potential changes in the probability of extreme events in the context of global warming is important for the assessment of ecosystem consequences (Christensen et al. 2007). To analyze changes in the frequency of extreme temperature, we used a published database of historical and future climate indices computed using a consistent methodology across different modeled and observational data by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al. 2011). ETCCDI has defined 21 indices that represent extreme events of temperature and rainfall, as part of the efforts to facilitate the understanding of the observed and projected climate change (Sillmann et al. 2013a, b). Among these, an air temperature index that represents extreme conditions/heatwaves, i.e. the exceedance in rates (%) above the 90 of temperature (TX90p) for the period 2050-2060 is used here for two climate change scenarios (RCP45 and RCP85). This was used to develop a layer representing exposure to heatwaves using the methods described above.

Exposure analysis – Geostatistical techniques were then applied with all the partial exposure maps as the input to generate the overall mangrove exposure estimates for WIO. The overall exposure map was then summarized for each sector as mean and standard deviation (Annex Table 2).

Results - Exposure maps from the seven EV's considered indicate variability within and among the mangrove sectors in the region (Annex Table 1). Mangroves in different sectors showed great variability in terms of their exposure to the EV's. For example, human pressure is highest in the southern parts of Tanzania and Northern Mozambique, while the lowest values were recorded in Southern Mozambique. The exposure to sea level rise suggests a north to south latitudinal gradient, with sectors in the lower latitudes less exposed than sectors in the higher latitudes. Based on the 18-year ecological condition, mangroves in Mozambique and in Northern Madagascar appear to be in relatively better condition than in other sectors. Overall, sectors with extreme overall exposure values include Kilifi, Pemba, Tanga, Rufiji and Mombasa, while least exposed sectors were found in southern Mozambique.

Management implications

The knowledge generated on the partial and overall exposure of mangroves in the region can be used to target management strategies spatially adaptively. For example, mangroves that have little chance of land ward migration may require a different management strategy than those that can migrate inland. Likewise, the spatial gradient in exposure human pressure can in form the management on which are a may need protection from human pressure due to ease of access.

Recommendations

Technical recommendations: *The Secretariat is urged to produce an assessment report on the exposure of mangroves to environmental changes in the Western Indian Ocean*

Policy recommendations*: The Secretariat as part of implementing the Convention climate change strategy, work with partners to produce a climate change vulnerability* *assessment toolkit for major ecosystems (coral reefs, mangroves and seagrass beds) in the region*

Policy recommendations*: The Secretariat as part of implementing the Convention climate change strategy, work with partners to build capacity on climate change vulnerability assessment for major ecosystems (coral reefs, mangroves and seagrass beds) in the region.*