Coping with Sea-Level Rise in African Protected Areas: Priorities for Action and Adaptation Measures

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Sea-level rise, a consequence of climate change, is progressively affecting coastal areas around the globe. In turn, protected areas are keystones for protecting coastal biodiversity and the ecosystems services ensuring sustainable livelihoods. Effective management and adaptation plans are needed to maintain ecological function and integrity. In the present article, we used a coastal digital elevation model to simulate inundation surfaces and a prioritization index for ranking management interventions in 278 coastal protected areas from 27 African countries. Of these, 15 areas and eight countries demonstrated a high need for proactive management actions because of high levels of biodiversity, international conservation relevance, and exposure to sea-level rise. From the array of management actions available, tailored solutions are being implemented according to the morphology and location of the areas. Concerted action by international, government, and local partners is required for successful protection of the areas, including implementation of adaptive plans and monitoring progress schemes.

Keywords: adaptation measures, Africa, protected areas, sea-level rise, socioeconomic development

Anthropogenic climate change is likely to become the major threat to natural and human systems in this century (Pecl et al. 2017). Since preindustrial times, emissions arising from human activities have already contributed in 1 degree Celsius (°C) to global warming and current estimates predict an increase of 1.5°C in global temperature by 2040, considering current warming rates (IPCC 2018). In addition, these emissions contribute to an increase in extreme events, changes in mean temperature, precipitation, sea-level rise (SLR), and drought events (IPCC 2018). Climate change will affect the structure, composition, and function of global ecosystems, imposing a challenge to achieving the 2030 United Nations Sustainable Development Goals (Pecl et al. 2017). Among the impacts of climate change, SLR places an extraordinary challenge for coastal areas. The end-of-century SLR projections for the worst-case emission scenario (representative concentration pathway 8.5) vary among the literature, ranging initially from 131 centimeters (cm) up to 243 cm in the latest projections (Mengel et al. 2016, Dangendorf et al. 2017). This long-term and possibly irreversible effect of climate change will affect on coastal and low-lying areas (Nicholls et al. 2018), resulting in the salinization of wetlands, increased flooding, and increased coastal erosion (Wong et al. 2014, Tully et al. 2019). Coastal areas concentrate the greatest density of human population (CIESIN 2018) and associated economic activities globally, because they provide substantial ecosystem services (Strauss et al. 2015). Simultaneously, they are highly vulnerable locations that will increasingly experience the adverse impacts of SLR, up to a level greater than previously thought (Kulp and Strauss 2019).

In Africa, coastal areas sustain large and growing human populations that are now highly vulnerable to SLR (Mo Ibrahim Foundation 2019). Coastal ecosystems provide services, such as food security and water supply, on which local economic growth and human development rely (Niang et al. 2014). For instance, coastal populations in East Africa are highly dependent on coral reefs for fishing activities that provide the main source of food in those regions (Niang et al. 2014). From species to biomes, Africa contains a large proportion of the remaining world's biodiversity (e.g., Jenkins et al. 2013). Coastal protected areas (PA) are the cornerstone to base the long-term protection of such diversity and simultaneously ensure sustainable livelihoods, especially in the fishing sector (UNEP-WCMC et al. 2018). African coastal PA, such as national parks, Ramsar sites or biosphere reserves, are key for ensuring biodiversity conservation and the protection of natural ecosystems, whereas world heritage sites retain historical legacy and cultural values of global importance (IUCN and UNEP-WCMC 2020). Recent SLR predictions show that many of the important coastal ecosystems in Africa will be flooded by the end of the century

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(Kulp and Strauss 2019). Management plans are needed to ensure that African coastal PA will maintain their ecological functions, such as the breeding and foraging habitats of many threatened species, as well as iconic and irreplaceable cultural resources.

Protected areas were created in response to human-related threats to natural and cultural values (UNEP-WCMC et al. 2018), but climate change and associated SLR are threatening their long-term effectiveness. Management plans and adaptation measures are basal to deal with the effects of SLR in coastal PA. Although SLR predictions suggest devastating impacts in coastal areas (Kulp and Strauss 2019), its effects will be progressively unfolding during this century (Wong et al. 2014). This time lag allows to anticipate SLR impacts and to develop proactive adaptation measures to minimize them. For instance, the United States is investing in engineering works designed to prevent flooding, such as shoreline armoring (e.g., seawalls, bulkheads, dams), and act against coastal erosion using beach and dune nourishment methods or artificial dune construction, or managing land anticipating retreat from current coastline (Schupp et al. 2015, Butler et al. 2016). These projects often come associated with high costs of implementation and maintenance (Beavers et al. 2016) that may be unsustainable in regions with few resources or capacities. Many countries in coastal Africa are developing nations with low Human Development Index (UNDP 2019) that are usually heavily dependent on local natural resources, making them vulnerable to climate change impacts. In addition, together with the lack of investment, resources, and infrastructures, the negative effects of SLR will potentially intensify socioeconomic inequities (Clarke and Dercon 2016).

Given these limited resources, data, and a framework for prioritizing investments in PA are needed. In the present article, we evaluate the prevalence, geographic distribution, and main characteristics of affected coastal PA in 27 African countries. Then, on the basis of the global conservation importance, biodiversity levels, and exposure to SLR effects, we identify the coastal PA and countries that are of high priority to develop management actions to counteract SLR impacts. We then address relationships between national governance and development indicators in African coastal countries and the high priorities for management actions. Finally, we examine which management actions are available and which ones are being discussed and implemented by African coastal countries. We answer two basic questions that must be addressed: Which are the highest priority coastal PA for which proactive management actions are most needed? And which countries potentially have the best governance and development conditions to successfully implement those actions?

To address these questions, we first simulated inundation surfaces of continental Africa and adjacent islands and islets using as baseline the highest spatial precision available (approximately 90 meters) coastal digital elevation model (CDEM; Kulp and Strauss 2018). We used the K17 global sea-level projection that considers a SLR of up to 243 cm by the year 2100 (Dangendorf et al. 2017) and applied this threshold to the coastal elevation model to simulate inundation surfaces above current sea level (supplemental file S1). We then identified 278 terrestrial PA that intersect the coastline (from IUCN and UNEP-WCMC 2020) and characterized them according to their additional international conservation interest (Ramsar sites, important bird areas, world heritage sites, biosphere reserves), the location in Biodiversity Hotspots, the richness in species of mammals, birds, and amphibians (Jenkins et al. 2013), the dominant biomes and ecoregions (Dinerstein et al. 2017), and the predicted extent area affected by SLR (supplemental file S2). Then, we built an index to identify which coastal PA and countries are of the highest priority for developing management actions (IPRA) to address SLR impacts on the basis of three partial indices that weighted the international conservation relevance (ICRE), the importance for biodiversity conservation and representation of terrestrial biomes and ecoregions (IBDV), and the potential exposure to SLR (ISLR) based in the predicted surfaces of inundation by 2100 in relation to the areas of PA and countries (supplemental file S3). We then determined relationships between national governance (voice and accountability, political stability and absence of violence or terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption) and development indicators (high funding for biodiversity conservation, and human development) in African coastal countries using a principal component (PC) analysis (supplemental file S4). Next, we plotted the factor scores in the first PC axes to identify main patterns of clustering among countries and symbol sizes of each country were made proportional to the IPRA results to identify the high priority countries for developing management actions to address SLR in relation to multidimensional governance and development variability. Finally, we reviewed the management actions currently available to mitigate the effects of SLR on biodiversity and focused on which coastal adaptation options are being implemented in African coastal PA to face the accelerating the impacts of SLR.

Number, distribution, and characteristics of protected areas affected by SLR

All 278 coastal PA examined will be potentially affected by distinct levels of SLR (see details below) by the year 2100 and these PA are distributed in 27 out of the 33 African coastal countries (figure 1; supplemental file S5, table S3). Within countries, there is large variation in the number of PA potentially affected, from a single PA in four countries up to 115 PA in South Africa. The latter, together with Egypt, Morocco, and Tunisia, accumulate 65% of the coastal PA potentially affected. There are several reasons for the large variations recorded in the number of PA affected by country: In Benin and Togo, no coastal PA have been implemented, probably

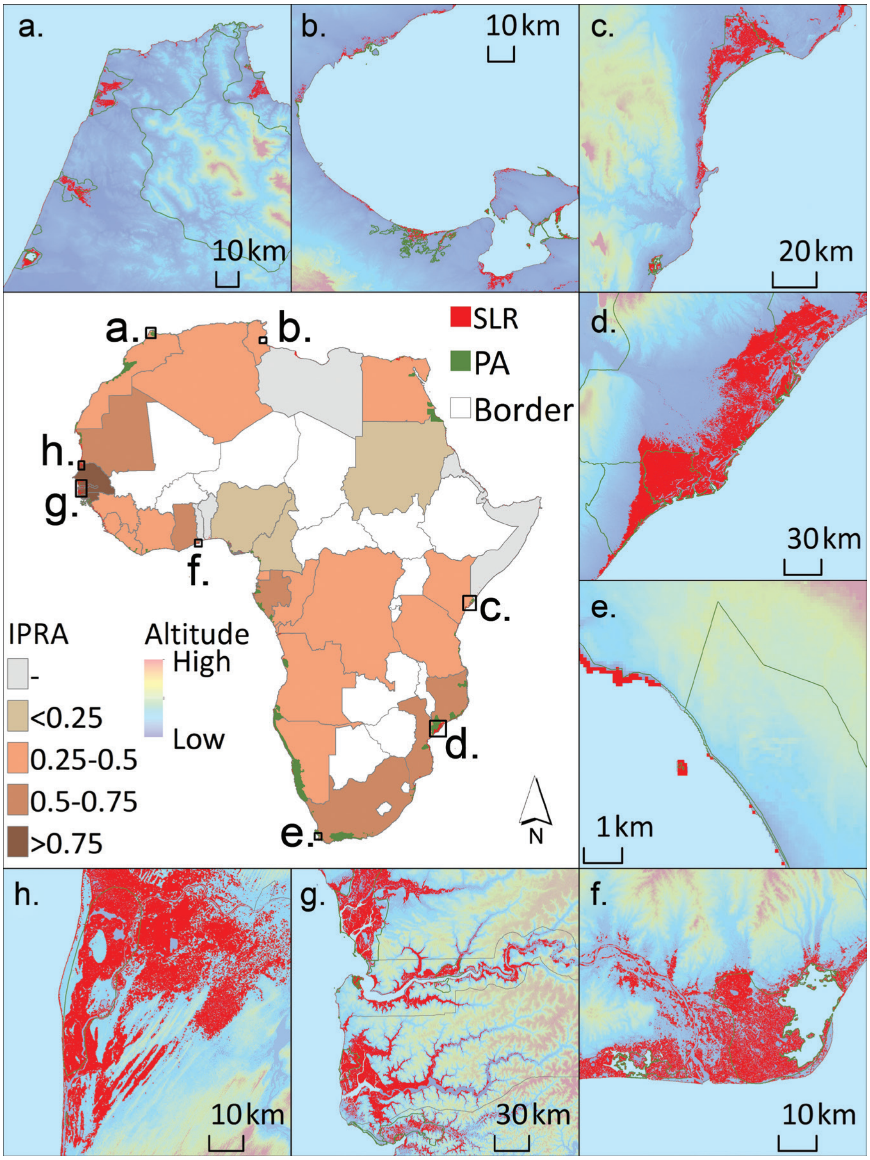

Figure 1. Distribution of African coastal protected areas (PA) potentially affected by sea-level rise (SLR) and selected zooms on relevant areas depicting the simulation of inundation surfaces (SLR, red pixels). Coastal African countries are color coded according to the index for priority for action (IPRA). Grey represents countries not included in analyses (see the text for details). White represents landlocked countries. (a) Merja Zerga lake (Ramsar site), Larache and Tahaddart rivers, and Intercontinental Mediterranean (biosphere reserve) in Morocco; (b) Chott el Guetayate wetland complex, Boughrara lagoon and other Ramsar Sites in Tunisia; (c) Watamu Marine protected area and Lower Tana Delta in Kenya; (d) Zambezi delta (Ramsar Site) and Marromeu and Coutada Oficial no. 10 Game Reserves in Mozambique; (e) Seal Ledges and Koeberg Nature Reserves in South Africa; (f) Songor biosphere reserve and Anlo-Keta Ramsar site in Ghana; (g) Delta du Saloum national park and Kalissaye Ramsar site in Senegal, Tanbi Wetland and Niumi National Parks and Baobolon Wetland Reserve in Gambia, and Mangroves du Fleuve Cacheu National Park in Guinea-Bissau; (h) Diawling National Park in Mauritania and Leybar Forest in Senegal.

as a consequence of the massive human population density and associated habitat changes along the coastlines of these countries (CIESIN 2018). In Djibouti and Eritrea, implemented coastal PA are strictly marine, so they were excluded from this analysis (supplemental file S2). And in Libya and Somalia, the only information about implemented coastal PA was strictly available as point data in the Word Database of Protected Areas (WDPA; IUCN and UNEP-WCMC 2020). Such PA were excluded from the analyses because we considered that creating artificial PA boundaries with buffering methods would produce unacceptable uncertainties in PA location and extension (supplemental file S2). This problem affected full countries (Libya and Somalia) and several PA in many other countries (e.g., Chat Tboul and Cape Blanc in Mauritania). There are additional sources of biases in the estimations made. For instance, confronting the list of Ramsar sites (Ramsar Convention 2020), which in theory are included in the WDPA, shows that several sites (e.g., Ad-Dakhla Bay and Bokkoyas Coast in Morocco) are absent from the WDPA data set, so they were not considered in these analyses. Also, coastal PA were defined as those PA for which the boundary intersected at least in one point in space with the coastline (although we considered a 500-meter buffer to account for potential georeferencing errors in PA limits; see supplemental file S2). This implies that PA near the coastline that do not actually intersect the coastline were excluded from the analyses. However, we verified that some of these PA will also be strongly affected by SLR (e.g., Djoudj National Park in Senegal). As such, the estimation in the present article presented on SLR impacts in the number of PA and countries affected clearly underestimate the magnitude of the problem and should be taken as a best-case scenario.

There is large variation in the potential flooded areas of PA, from less than 10 square kilometers (km^2) in five countries up to more than 1,000 km^2 in Mauritania, Mozambique, Namibia, and Senegal, adding a total of nearly 15,000 km^2

(supplemental file S5, table S3). These four countries concentrated 74% of total potential flooded area of PA. There is also large variation in the potential impact of SLR in the current network of PA, ranging from less than 2% of the area of coastal PA predicted to be flooded in 13 countries up to more than 50% in Gambia, Ghana, and Senegal. Our estimations of inundation surfaces were projected directly from the CDEM and discarded the potential additional effects caused by mean sea level and tidal amplitude (supplemental file S1). Although this simplified approach provided estimations of inundation surfaces rather identical to projections that consider the spatial and temporal dynamics of inundation (supplemental file S1, figure S1; Kulp and Strauss 2019), they underestimated the full potential effects of SLR. As such, the magnitude of the predicted flooding of PA presented in the present article should be taken as a minimum estimation of SLR effects.

The 278 coastal PA potentially affected by SLR accumulate up to 349 categories of international conservation interest (supplemental file S5, tables S4 and S5), and the categories important bird area and Ramsar site are the ones most affected, especially in Morocco, South Africa, and Tunisia (supplemental file S5, table S3). From the eight categories of biodiversity hotspots present in Africa, coastal PA potentially affected are distributed in six of them and the Cape Floristic Region, the Mediterranean Basin, and Maputaland–Pondoland–Albany are the ones most affected, adding up to 77% of the 217 coastal PA included in Biodiversity Hotspots (supplemental file S6, figure S2). From the nine biomes and 112 ecoregions present in Africa, coastal PA potentially affected are distributed in six biomes (67%) and 37 ecoregions (33%). Coastal PA in Mediterranean forests, woodlands and scrub, tropical and subtropical moist broadleaf forests, and deserts, and xeric shrublands are potentially the biomes most affected (81% of the 278 coastal PA), whereas the ecoregions Fynbos shrubland, Mediterranean woodlands and forests, and Albany thickets are potentially the ones most affected (43%). Most of the costal PA affected are in the land regions of Northern and Southern Africa (69%), and in the marine regions of Atlantic and Indic Oceans (84%). These patterns are mostly related with the large number of PA affected located in Egypt, Morocco, South Africa, and Tunisia (adding 65% of 278 PA), which tend to absorb the most frequent traits in terms of additional conservation categories, biodiversity hotspots, biomes, ecoregions, and land or marine regions.

Priorities for the development of management actions to address SLR impacts

The distribution of PA rankings identified a group of 15 PA that scored above .75 in the index for priority for the development of management actions (IPRA), and above .50 in at least one of the partial indices targeting international conservation relevance (ICRE), importance for biodiversity conservation (IBDV) or exposure to SLR (ISLR; table 1, supplemental file S6, figure S3). These 15 topmost PA are mostly distributed in Gambia, Senegal, and Tunisia (60%). Although the largest numbers of PA affected are located in Southern and Northern Africa (Egypt, Morocco, South Africa, and Tunisia), when considering the IPRA, 50% of the topmost PA are located in Western Africa (Gambia, Ghana, Guinea-Bissau, Mauritania, and Senegal). These 15 topmost PA exhibit the high levels of biodiversity and eight of them accumulate up to three or four international conservation categories, such as the Delta du Saloum National Park (Senegal). In 14 of these PA, the potential flooding will affect more than 50% of the area of the PA, and more than 90% in four of them. A detailed description of the 15 topmost PA and additional PA that scored high in any of the partial indices is provided (supplemental file S5, tables S6 and S7, respectively), including the main landscape features of PA, emblematic fauna and flora and their conservation status, main threats placed by SLR to landscapes and biodiversity, and other additional threats, and management actions developed to mitigate SLR effects.

The IPRA of countries ranked Gambia, Guinea-Bissau, and Senegal with scores above .75 (figure 1; supplemental file S5, table S3; supplemental file S6, figure S4). Together with Gabon, Ghana, Mauritania, Mozambique, and South Africa, they form a group of eight countries where the development of actions to counteract SLR effects is most priority. Each of these countries always scored above .50 in at least two of the partial indices ICRE, IBDV, and ISLR (figure 2).

It is critical to mention that several biases may affect IPRA indices, given the characteristics of the three partial indices that they include (supplemental file S3). First, the ISLR is most likely underestimated as explained above, although the underestimation is likely to be uniform across all coastal Africa. Still, regional differences in SLR estimate by 2100 (Fasullo and Nerem 2018) need to be better integrated for full assessment of prioritizations Second, the IBDV may be affected by geographical biases related to sampling efforts. For instance, deserts in general are poorly sampled in comparison to other biomes (Brito and Pleguezuelos 2020) and countries under long-term conflict or affected by conflicts until recently (e.g., Angola, Sierra Leone, Somalia) are naturally less well sampled, which may have affected the IBDV estimation in some PA or countries. Most importantly, the ICRE for PA and countries is highly affected by the willingness of countries in designating sites as of conservation value. For instance, considering the African coastal countries and their full territory extent (not only coastal areas), Angola and Somalia do not have a single Ramsar site designated (Ramsar Convention 2020), Djibouti, Guinea-Bissau, Liberia, Sierra Leone, and Somalia do not have a single world heritage site designated (UNESCO 2020a), and Angola, Liberia, Sierra Leone, and Somalia do not have a single biosphere reserve designated (UNESCO 2020b). On the contrary, and again considering the full territory extent, Algeria, Morocco, South Africa, and Tunisia have more than 25 Ramsar sites designated, Algeria, Egypt, Kenya, Morocco, Senegal, South Africa, Tanzania, and Tunisia have more than

Table 1. The 15 topmost African coastal protected areas priority for action concerning potential sea-level rise and their main conservation traits.

WDPA-Id	Country	Name	Percentage of area SLR	RAM	IBA	WHS	MAB	BH	IPRA	ICRE	IBDV	ISLR
866	SEN	Delta du Saloum National Park	58.5	Y	Y	Y	Y	–	1.000	***	***	**
903024	GAM	Tanbi Wetland National Park	92.8	Y	Y	–	–	–	.903	*	**	***
4649	MOZ	Marromeu Game Reserve	92.9	Y	Y	–	–	Y	.896	**	*	***
555624277	TUN	Boughrara lagoon Ramsar Site	89.9	Y	Y	–	–	Y	.855	**	*	***
903087	TUN	Sebkhat Soliman Ramsar Site	69.0	Y	Y	–	–	Y	.841	**	**	**
95349	MAU	Diawling National Park	65.3	Y	Y	–	Y	–	.837	**	**	**
145529	GAM	Baobolon Wetland Reserve	65.5	Y	Y	–	–	–	.815	*	***	**
903080	TUN	Lagune de Ghar el Melh et Delta de la Mejerda	79.6	Y	–	–	–	Y	.807	*	**	***
555621995	KEN	Watamu Marine National Reserve	63.5	–	Y	–	Y	Y	.801	**	**	**
555547583	GHA	Songor biosphere reserve	65.3	Y	Y	–	Y	–	.794	**	**	**
555547400	TUN	Sebkhet Halk El Manzel and Oued Essed Ramsar Site	57.5	Y	Y	–	–	Y	.785	**	**	**
555629212	SEN	Kalissaye Ramsar Site	70.8	Y	Y	–	–	–	.770	*	**	**
33046	GBA	Mangroves du Fleuve Cacheu National Park	30.7	Y	Y	–	–	–	.765	*	***	*
555629213	SEN	Somone Ramsar Site	77.3	Y	Y	–	–	–	.758	*	**	***
555564035	SAF	Seal Ledges Provincial Nature Reserve	100.0	–	–	–	Y	Y	.756	*	*	***

Abbreviations: BH, biodiversity hotspots; IBA, important bird area; IBDV, importance for biodiversity; ICRE, international conservation relevance; IPRA, index of priority action; ISLR, potential exposure to sea-level rise; MAB, UNESCO biosphere reserve; PA, protected areas; RAM, Ramsar site; SLR, sea-level rise; WDPA-Id, World Database of Protected Areas identifier; WHS, UNESCO world heritage site. Scores of the indices: – <.25. *.25–.50. **.50–.75. ***.75–1.00. Country codes as in supplemental file S5, table S3.

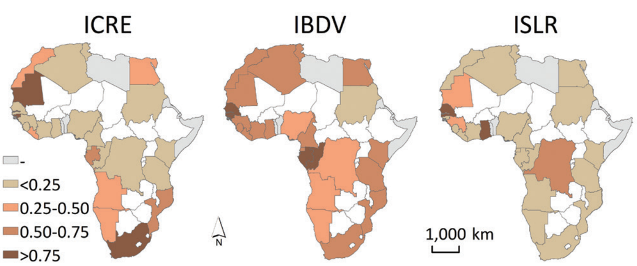

Figure 2. Coastal African countries color coded according to the indices of international conservation relevance (ICRE), biodiversity importance (IBDV), and potential exposure to sea-level rise (ISLR). Grey represents countries not included in analyses (see the text for details). White represents landlocked countries.

seven world heritage sites designated, and Algeria, Kenya, and South Africa have more than five biosphere reserves designated. The designation of sites under these three conservation categories requires national applications to the global body of institutions governing them (Ramsar Convention and UNESCO), and the latter group of countries are the ones who have developed efforts is preparing successful applications. Naturally, the ICRE will maximize the value of PA located in these countries, because these PA tend to accumulate additional conservation categories. Furthermore, there are strong geographical biases in the designation of sites as PA. For instance, Djibouti, Eritrea, Liberia, Libya, Mauritania, and Sudan have less than 5% of their territory extent covered by terrestrial PA (UNEP-WCMC et al. 2018). On the contrary, Congo, Gabon, Guinea-Conakry, Ivory Coast, Morocco, Mozambique, Namibia, Senegal, and Tanzania have more than 17% of their territory covered by PA. Again, the ICRE will maximize the value of countries that accumulate more PA with added conservation importance. Overall, we question that these asymmetries are the product of random patterns deriving from (e.g., low conservation importance of some regions or countries) but, rather, reflect national governance and development indicators, which ultimately affect the political willingness, capacities or resources of countries in designating sites of conservation importance. Despite variations, the same first six countries

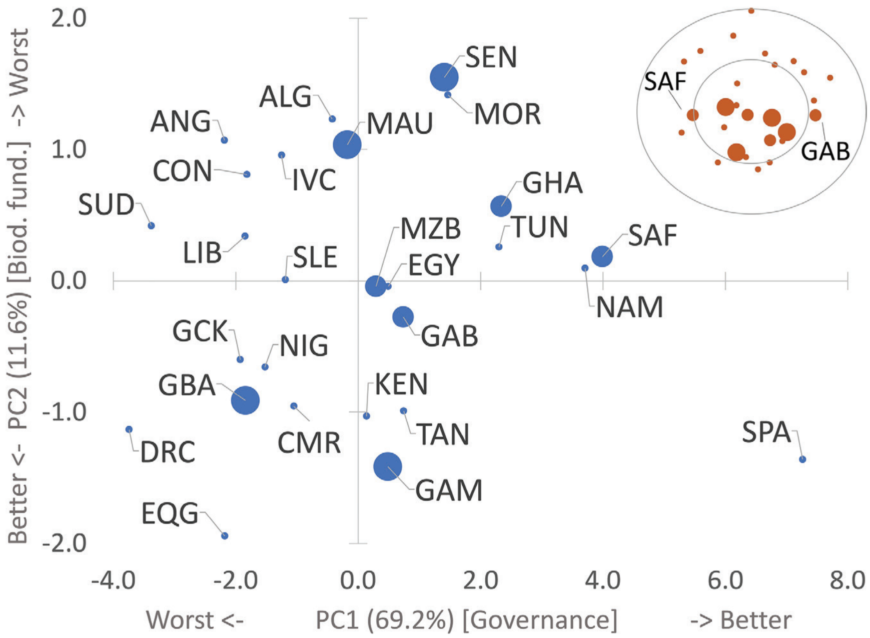

Figure 3. Factor scores of African countries containing coastal protected areas potentially affected by sea-level rise in the first and second axes of a principal component analysis based in governance and development indicators. The symbol sizes are proportional to the index of priority of action (IPRA): small, <0.50; medium, .50–.75; large, >.75. The scores in PC3 are depicted in the upper right inset, where values outside central circle indicate developed conditions, and the values inside central circle indicate developing conditions. The country codes are as in supplemental file S5, table S3.

ranked as of high priority by IPRA were identified also as of high ranking by all individual indices (supplemental file S6, figure S4).

Relationships between national governance and development indicators

Under the context of potential SLR and focusing on the eight countries that scored the highest in the IPRA (figure 1), all except Guinea-Bissau and Mauritania exhibit positive values in the axis reflecting governance conditions (PC1; 69.2% of variation; supplemental file S4, table S2), Gabon, Gambia, Guinea-Bissau, and Mozambique display better conditions in the axis reflecting funding for biodiversity conservation (PC2; 11.6%), whereas in the axis reflecting human development (PC3; 9.1%) only Gabon and South Africa scored positive (figure 3). Taken together, these results indicate that from the eight countries that are a high priority for management actions and adaptive measure to counteract SLR effects, the ones possibly better able to do so given the current governance context are Gabon, Gambia, Mozambique, and South Africa. Still, Gambia and Mozambique need to promote the development of socioeconomic conditions, and South Africa needs to allocate additional funding to biodiversity conservation. The remaining countries exhibit several vulnerabilities that need to be addressed for effective implementation of measures, possibly requiring assistance from global funding mechanisms (e.g., World Bank, Global Environment Facility, European Development Fund, Economic Community of West African States, African Union). This is the case of Ghana and Senegal that need to improve funding allocated to biodiversity conservation and socioeconomic development, Guinea-Bissau needs better governance and socioeconomic development, whereas Mauritania requires support at all levels analyzed. Particularly Mauritania and Senegal are among the Top40 countries at global level most highly underfunded for biodiversity conservation (Waldron et al. 2013). Certainly, Senegal together with South Africa have shown a strong commitment in designating sites of conservation importance (explained above), which is a hopeful indication that they may display the willingness and capacities or resources to implement further action to address SLR impacts.

Management actions and adaptive measures to SLR effects

Depending on the PA morphology and the investment available, different management actions can be developed by countries to adapt to SLR effects (box 1). Those strategies ground on the development of hard and soft engineering and land management actions, which can act as adaptive, proactive or retreat measures to SLR impacts (Bollmann et al. 2010).

Regarding the eight priority countries, some may lack strong governance conditions allowing the implementation of strategies to adapt to SLR (explained above). For instance, Guinea-Bissau designed so far a single coastal plan for a PA (Varela National Park; UNFCCC 2008), but the rapid disappearance of other PA (e.g., the Bolama-Bijagós Archipelago biosphere reserve; Niang et al. 2012) stresses the need to develop management actions in this country. Contrarily, Gambia is one of the better prepared countries to act against SLR and, together with Senegal, they are designing strategies for both urban and protected areas to address SLR impacts (Niang et al. 2012, Drammeh 2013). Gabon also displays the best conditions to implement strategies, but until now no management actions were applied in PA (see examples in supplemental table S7). Some of these countries have designed so far strategies to protect urban areas from SLR or to safeguard tourism facilities, such as dune restoration activities in Nouakchott (Mauritania) and the creation of beach slopes and rock-filled gabions in Accra (Ghana), respectively (Niang et al. 2012). However, Ghana and Mauritania are among the most priority countries to

Box 1. Examples of management actions developed in coastal protected areas (PA) of Africa to counteract sea-level rise (SLR).

Actions are classified as adaptive (A), proactive (P), and retreat (R).

Hard engineering actions

Construction of breakwaters (P). Offshore structures parallel to the coast to reduce wave energy and prevent coastal erosion (Beavers et al. 2016). In Tunisia and Gambia, the construction of submerged breakwaters allowed to refill beaches, prevent costal erosion, and sand mining (APAL 2015, Mouloud 2015).

Construction of dikes (P). Structures to prevent flooding and protect inland wetlands from saltwater intrusion (Marijnissen et al. 2020). Dikes were built in Zambezi Delta in Mozambique to protect agricultural fields by acting against flooding but were not considered the most effective approach (Wesselinka et al. 2015).

Construction of groins (P). Perpendicular structures to the coastline to promote sand accumulation on the beach, usually used together with beach nourishment actions. The coastal protection project in Ghana prevented erosion near the Volta River estuary by constructing several groins along the coast (Niang et al. 2012).

Creation of beach slopes (P). Structures parallel to the coast using wave resistant materials to create a slope to protect inland areas (Niang et al. 2012). This technic has been applied in Tunisia to prevent flooding (MEET 2013).

Soft engineering actions

Beach nourishment (P). Mechanical dropping of granular sediment from the mainland along the coast to act against erosion (Niang et al. 2012). Beach nourishment activities in Tanji Bird Reserve in Gambia are preventing further coastal erosion (Komma 2019).

Dune restauration (A). Mechanical stabilization of sand dunes using reforestation technics to restore the habitat and stabilize coastlines (Niang et al. 2012). In Algeria and Gambia, dune fixation and rehabilitation are preventing coastal erosion through the plantation of native woodland vegetation (Mouloud 2015, Komma 2019). Native species should be prioritized, because exotic species such as Eucalyptus camaldulensis used in Senegal for this propose can have negative long-term impacts (Faye 2016).

Building living shoreline (A). Natural structures, such as vegetation and oyster reefs, used to stabilize coastal areas and prevent erosion (Beavers et al. 2016). In Tanzania, a multi-action project was developed to incorporate different coastal management activities, including shoreline rehabilitation using trees and grasses plantation (Yanda 2013).

Mangrove restoration (A). Reforestation and restoration of mangrove areas to promote ecosystem services and coastline stabilization (Niang et al. 2012). Several PA, such as the Niumi National Park in Gambia, the Sangomar Marine protected area in Senegal, and the Diawling National Park in Mauritania are developing mangrove restoration and protection actions to reduce coastal erosion and wave energy (UNFCCC 2008, Wicander et al. 2016).

Land management actions

Creation of buffer zones (A). Buffer zones delineated around PA to preserve their integrity (Niang et al. 2012). In Varela National Park in Guinea-Bissau, a buffer zone was created through tree plantation (UNFCCC 2008). In South Africa, buffer zones were created by implementing restriction areas to maintain habitats intact and protect against SLR and coastal erosion (Celliers et al. 2009).

Buy land to protect (R). Inland shifts and expansion of PA provide a long-term solution in remote locations, allowing the migration of ecosystems (Epanchin-Niell et al. 2017). However, this action depends on the landowner willingness to allow ecosystem migration and is not possible to implement in PA located in high population density regions (Field et al. 2017). Because of climate change effects, Namibia is already predicting the expansion of PA at risk (Turpie et al. 2010).

develop strategies to minimize SLR impacts, therefore they urgently need to invest on PA safeguarding. South Africa lies among the better prepared countries to act against SLR, however its high commitment until now has targeted urban areas, such as Cape Town, reinforcing the need to allocate additional funding to PA defense (EADP 2016). Likewise, Mozambique is investing on management actions to protect agricultural fields and cities, such as Maputo, because SLR is challenging food security and threatening human settlements (Junior 2009, Bucx et al. 2014), despite displaying good conditions regarding funding for biodiversity conservation.

Considering the 15 topmost PA priority for action, seven different strategies are being developed in Gambia, Mauritania, Mozambique, Senegal, and Tunisia (details on actions established in each PA are provided in supplemental file S5, table S6). The PA with extensive mangrove regions, such as the Delta du Saloum National Park in Senegal and in Diawling National Park in Mauritania, prioritize mangrove reforestation actions (UNFCCC 2008, Sadio et al. 2019). Because of the low cost and high positive impacts of mangrove reforestation (Niang et al. 2012), this action is being suggested in other priority PA, such as the Mangroves du Fleuve Cacheu National Park in Guinea-Bissau, Somone

Ramsar site in Senegal and Tanbi Wetland National Park in Gambia (Sakhoa et al. 2011, Drammeh 2013, García del Toro and Más-López 2019). Reforestation with other species, such as Acacia trees was implemented in the Sebkhet Halk El Manzel and Oued Essed Ramsar site in Tunisia to act against coastal erosion promoted by SLR (Ramsar Sites Information Service 2012). Although reforestation has been pointed as an effective method to stabilize dunes and prevent coastal erosion (Niang et al. 2012), plantation with exotic trees as the case of Eucalyptus plantations in the Delta du Saloum National Park in Senegal to protect villages may promote severe landscape changes (Faye 2016). Beach nourishment is a widely applied method and has been suggested to protect the Delta du Saloum National Park in Senegal from SLR, and was implemented in the Sebkhat Soliman Ramsar site in Tunisia (APAL 2015, Sadio et al. 2019), but without appropriate monitoring this action potentially entail negative environmental impacts (Peterson and Bishop 2005). In priority PA located in densely populated regions, such as the case of Sebkhat Soliman, the Ghar el Melh lagoon, and the Mejerda Delta Ramsar sites in Tunisia, hard engineering structures, such as breakwaters and beach slopes, are prioritized as their main objective is to prevent flooding (MEET 2013, APAL 2015), despite the high implementation costs and likely failure to act against coastal erosion (Niang et al. 2012). Other hard engineering structures, such as construction of dams and dikes, have been prioritized in Marromeu Game Reserve in Mozambique to protect agriculture and in Delta du Saloum National Park in Senegal (Bucx et al. 2014, Faye 2016). Because of the extreme morphology and location of some PA (e.g., rocky islands) the only possible actions require other hard engineering actions that may be unsustainable in face of the investment needed, such as Seal Ledges Provincial Nature Reserve in South Africa.

Adapting to SLR impacts is both challenging and ambitious goal but failing in taking proactive measures will likely result in the loss of critical natural resources, world heritage and already imperiled biodiversity. Our study identifies the critical African PA and countries where tailored measures need to be taken swiftly accordingly to PA morphology and location. Several countries will need international support to implement adaptive plans, incentives to PA management, and monitoring schemes of progress. The successful achievement of these objectives requires concerted action by international, government, and local partners, such as transnational sharing of efficient and ineffective experiences. The scale of climate change and SLR impacts opens for the first time the window for massive collaborative research. We should start now seizing this opportunity to ensure future benefits and accomplish the United Nations Sustainable Development Goals.

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Supplemental material

Supplemental data are available at *BIOSCI* online.

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