Towards West African coastal social-ecosystems sustainability : Interdisciplinary approaches

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Abstract

The coastal system can be regarded as co-evolving socio-economic and ecological systems undergoing intense environmental pressures owing to the mechanisms of change exerted by human activities against a background of natural change. Understanding and managing ecological responses to these changes in the coastal areas require interdisciplinary approaches. Here, we develop a new approach to coastal socio-ecological systems (CSES) based on earlier work on the press-pulse dynamics (PPD) socio-ecological systems. To show the relevance of the modified (mPPD) framework, we applied it to two unique features (mangroves and beach systems) of the western African coastal (WAC) systems. Then, we constructed plausible 21st-century coastal systems scenarios at the coast based on a set of descriptive indicators (population growth, economic development, environmental quality, governance, technological advancement and climate change) for a better understanding and sustainable management planning of WAC systems.

We found that different indicators characterizing each scenario will exert different pressures on the WAC systems, under the forms of the long-term press and short-term pulse events. The cross-cutting narratives of the different future scenarios in the face of climate change using the mPPD framework offer valuable insight into the development of WAC management strategies, policies and other agendas. It helps to define the plausible implications of following, or not, a particular management path. The inconsistencies between the aspirations of different resource users and lack of coordination of human activities taking place on land and in the coastal zone, partly due to fragmentation of institutions and weak coastal governance are revealed. In this context, the mPPD-CSES framework can be used to investigate how ecosystems can experience different (intensities of) press as well as different frequencies of the pulse. Thus, its

adaptability to construct future coastal vulnerability scenarios adds to its usefulness as a robust and dependable integrated coastal zone management tool.

Keywords: *Sustainable development, integrated coastal management, social-ecological system, sustainability science, West African coastal vulnerability*

1. Introduction

The coastal system constitutes only 5% of the earth's surface, but about 17% of the global population live in areas less than 10 m above sea level (MEA 2005). Besides, around two-thirds of the global population lives within 100 km of the coast (Hossain et al., 2020). The coastal system holds some of the most valuable and distinct ecosystems in the world, therefore providing a broad range of ecosystem services estimated at US 12 USD trillion/yr (Costanza et al. 1997, 2014). These ecosystem services include provisioning (e.g., food, shelter), supporting (e.g., protecting the coastal population from storm and erosion), regulating (e.g., storing carbon) and cultural (e.g., tourism) services (MEA 2005). According to IPCC (2014), the coastal system needs to be conceptualized in connection with both its social and ecological subsystems.

Social-ecological systems (Binder et al., 2013; Petrosillo et al., 2015) or socio-ecological systems (Gallopín, 1991) or human-environment systems (Turner et al., 2003) are complex adaptive and intrinsically coupled systems, having a lot of feedbacks and connections between the ecological and the social system components. Separating the social and the ecological system is unsuitable evidenced-based solutions to SES issues.

The coastal ecological system contains sub-sets of ecosystems like estuaries, deltas, wetlands, coral reefs in addition to other distinct features like rocky coasts, beaches, mudflats, and dunes (Hossain et al., 2020). While built environments (e.g., settlements, ports, seawalls), means of livelihood (e.g., fisheries, tourism), and coastal-relevant institutions (e.g., policies, laws, customs, culture) are key features of a coastal social system (Hossain et al., 2020). The coastal system does not only contain discrete ecological and social subsystems but also involve interdependencies between the two subsystems (de Andrés et al. 2018; Schlüter et al., 2019), forming a coupled SES (Hossain et al. 2020).

Notwithstanding their value to human wellbeing, coastal ecosystems are under threat from an increasing population, resource exploitation, and global environmental change (e.g., climate change) (MEA 2005; Lotze et al. 2006). In recent times, coastal SES is experiencing intense social and ecological pressures which have damaging societal impacts in coastal areas. It has been estimated that globally 0.8–1.1 million people per year are flooded (Hinkel et al. 2014) and

US$ 1407 billion economic losses have been incurred since 1942 owing to tropical cyclones (Hossain et al. 2020). Coastal erosion, flooding and sea-level rise are also threatening coastal SES. In addition to these environmental changes, anthropogenic pressures such as habitat loss due to development-related pressures, population growth, overexploitation of resources, and land degradation are compromising the ability of coastal SES to sustainably provide ecosystem services (MEA 2005). These challenges will be amplified by climate change (IPCC 2014). The ecological, social, and economic importance of coastal SES and the increasing human and environmental pressures on them has led to several national and global initiatives towards sustainable coastal SES.

Considering the wide range of drivers and pressures in coastal SES, it has been recognized as overdeveloped, overcrowded, and overexploited (Hinrichsen 1998), as well as over-exposure to global environmental changes (Hossain et al. 2020). A better understanding of coupled social-ecological interactions within the coastal system is vital for implementing developmental strategies that will optimize human well-being and sustain ecosystems and the resources they generate (Rangel-Buitrago et al., 2015; Willcock et al. 2016; Guerrero et al., 2018; Gain et al. 2019). Coastal systems comprising both social and ecological components, with inherent interdependencies across multiple scales can be conceptualized as an SES (Gain et al. 2020). Various frameworks have been developed and used for the adaptive management of SES (Gari et al., 2015). For example, the Outcome Approach was used to evaluate the progress of Integrated Coastal Management (ICM; Olsen, 2003). The Millennium Ecosystem Assessment (MEA, 2005) applied a framework connecting drivers, ecosystem services and human well-being. Ostrom (2009) developed a general framework for evaluating SESs. A Systems Approach Framework (SAF) is equally developed and applied to complex coastal systems in facilitating the European environmental policies implementation for sustainable development (Newton, 2012).

Recently, a social-ecological system framework called “Press-Pulse Dynamics (PPD)” was developed by Collins et al. (2011). The framework (Fig. 1) is a coherent system in which biogeophysical, and social factors regularly interact in a resilient and sustained manner. It links external drivers (e.g. climate, globalization and demography), presses (subtle, long-term events, e.g. climate change, sea-level rise, natural resources overexploitation), pulses (sudden, short-term events, e.g. storm, flood, drought), the biogeophysical (ecological) system in its structure and functions, ecosystem services that connect biogeophysical systems to human outcomes and behaviours, institutional, community and individual components of the social system, including quality of life, health, perceptions and values aspects (Fig. 1).

Since Collins et al. (2011) SES framework can represent the various phenomena and interactions occurring on coasts, we hypothesized that it can be deployed to develop coastal scenarios of change. Developing a scenario means all important information should be considered, both at the boundaries of the system and inside it. To test the possibility of constructing a complete scenario using the framework, we seek to apply such an approach to the West Africa coastal (WAC) areas.

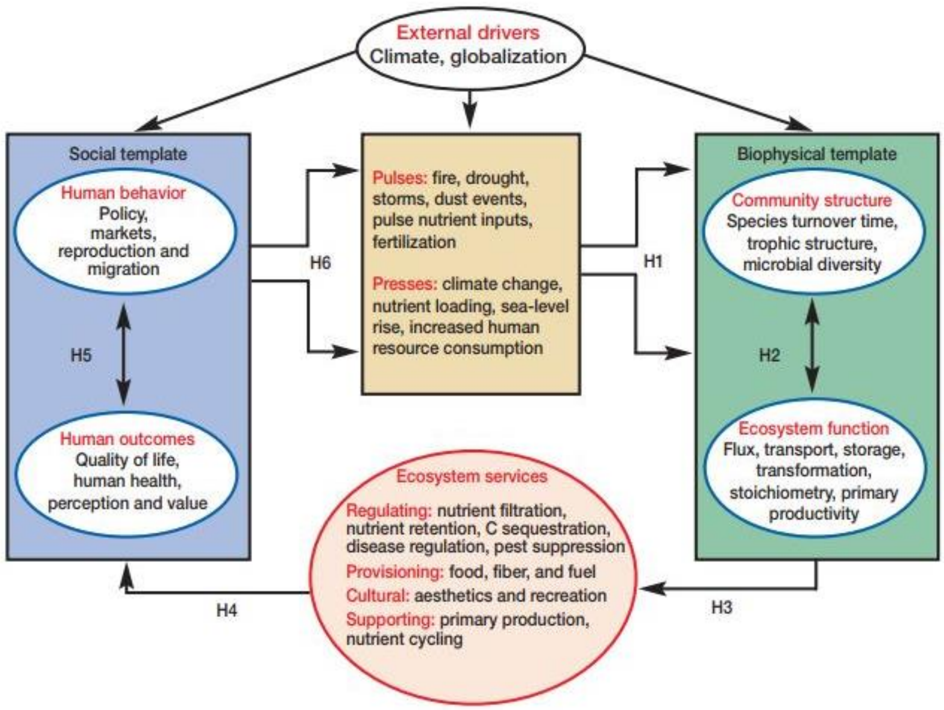

Figure 1. The *press-pulse dynamics (*PPD) framework of Collins et al. (2011). Framework hypotheses: H1 - long-term press disturbances and short-term pulse disturbances interact to alter ecosystem structure and function; H2 - biotic structure is both a cause and a consequence of ecological fluxes of energy and matter; H3 - altered ecosystem dynamics negatively affect most ecosystem services; H4 - changes in vital ecosystem services alter human outcomes; H5 - changes in human outcomes, such as quality of life or perceptions, affect human behaviour; H6 - predictable and unpredictable human behavioural responses influence the frequency, magnitude, or form of press and pulse disturbance regimes across ecosystems (Collin et al., 2011).

2. West Africa coastal areas case study

2.1 The WAC Settings

The West African coast (WAC) covers 12 mainland countries, from Mauritania to Nigeria (and the main focus of this study; Fig. 2), and two archipelagos of Sao Tome and Principe and Cape Verde. The mainland WAC can be categorized into three major sectors based on their geo-environmental properties and metocean driving forces (Alves et al., 2020; Ibe and Awosika, 1991). The Northwest sector (from Mauritania to Guinea Bissau), the muddy and sandy West coast (from Guinea-Bissau to Sierra Leone) and the Gulf of Guinea sector (from Liberia to Nigeria). This coast presents a unique coastal geomorphic variability. Starting with the narrow continental shelf, sandy dune-bound coasts of Mauritania, Senegal and Gambia, and their commonly narrow spits bounding estuaries. It continues to the transitional muddy Guinea-Guinea Bissau-northern Sierra Leone sector. Here, the cliff-bound coasts and mangrove-rich open estuaries are favoured owing to the strong wave dampening effect and tidal range amplification caused by widening continental shelf related to geological offsetting of the shelf by the Guinea and Sierra Leone fracture zones. And finally, to the narrow shelf, bounded by massive rectilinear sandy beach-ridge complexes with diverted river systems and back-barrier lagoons from southern Sierra Leone to the Niger Delta (Anthony and Blivi, 1999; Feka and Morrison, 2017; Alves et al., 2020).

The climate along the WAC is equatorial, with considerable differences in the amount and seasonal distribution of the precipitation. It is characterized by the interchange of two important drivers: the Atlantic Ocean and the Sahara. In the first order, both temperature and precipitation and their annual cycle depend on how the air masses associated with the dry and hot desert interior and the humid ocean to the south and the west, interact (Lewis and Buontempo, 2016). In terms of hydrology, the WAC is strongly influenced by the river basin drainages. The most important rivers include the Niger, which drains an area of over 1 million km^2; the Volta, with a drainage basin of 390,000 km^2; and the Senegal River, the second-longest river in West Africa, with a catchment area of nearly 450,000 km^2 (Diop et al., 2014; Anthony, 2015; Anthony et al., 2016). However, the hydrology and sediment flow of these rivers have been significantly altered due to river damming, thereby limiting sediment supply to the coast (Anthony, 2015; Anthony et al., 2016, 2019; Dada et al., 2015, 2016a, 2018; Diop et al., 2014; Ly, 1980).

Considered a storm-free environment, the WAC zone is dominated by the North Atlantic swells (Almar et al., 2019; Sadio et al 2017). Wave regime along the Gulf of Guinea sector is mostly influenced by the extratropical South Atlantic Southern Annular Mode (SAM) and its natural variability (Almar et al., 2015). The SAM strongly affects sea level variability (Abessolo Ondoa et al., 2020; Melet et al., 2016) and the longshore sediment transport (Almar et al., 2015), both of which drive significant coastal changes at this sector of WAC (Anthony et al., 2019). The morpho-sedimentary evolution of the West African sandy coast is controlled by a strong longshore sediment drift resulting from oblique waves (Anthony et al., 2019; Laibi et al 2014). Given the magnitude of longshore sediment transport rates, small changes in alongshore gradients can result in massive local erosion or accretion (Almar et al., 2019).

The tidal ranges along the WAC are wide, exceeding 5 m in some places, with the average for the whole coastal area being considered in the order of 1 m. The highest tidal ranges recorded in the region are in Guinea-Bissau, Guinea, and Sierra Leone (from 2.8–4.7 m; Diop et al., 2014). Three distinct and relatively persistent oceanic current systems are of importance to the WAC ecosystems (Fig. 2) are: (a) The cold Canary Current, (b) The North Equatorial Countercurrent; and (c) The Guinea Current (Diop et al., 2014). The Canary Current itself transports cool waters toward the Equator and has current speeds of approximately 20 cm.s^{-1}. The cool and richer upwelling waters prevail along the northwestern part and at limited parts of the northern parts of the Gulf of Guinea.

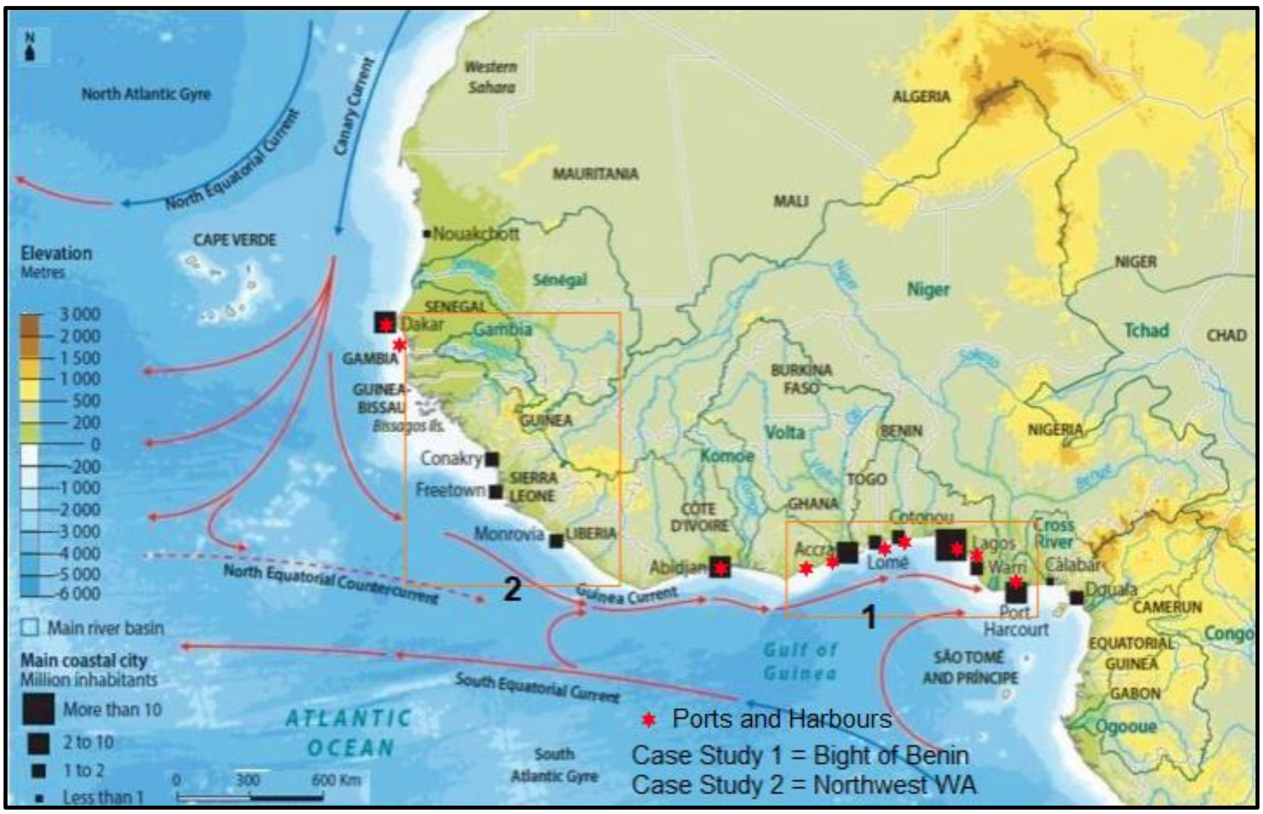

Figure 2. The West Africa coast (WAC) showing main coastal cities and population, ports and harbours, rivers and marine currents, and the two case studies areas (modified after Diop et al., 2014).

2. 2 The WAC present state and trends

In WAC areas, socio-economic activities are increasingly affecting the coastal and marine environment. Over-exploitation of coastal resources and ecosystems is currently a serious and accelerating phenomenon in the region (Fig. 3). Many coastal communities depend on coastal resources for their livelihoods, mostly for food, fuel, shelter, and income (Diop et al., 2011). Owing to increasing population pressures and a lack of alternative resources to sustain populations, resource exploitation is becoming unsustainable. In many coastal areas, important coastal habitats, such as mangrove forests, seagrass beds, and coral reefs, are degraded or destroyed, making way for agriculture, aquaculture, port/ harbour development, hydropower dam and urban development (Diop et al., 2011).

The migration of people to coastal areas, in particular to coastal cities, is a long-term trend and presents one of the greatest challenges to the management of coastal resources. The most striking development is the rapid expansion of West African (WA) towns and cities. The population of town dwellers has risen from 13% in 1960 to 40% in 1990. Migration is taking place against the background of a rapidly growing population. WA's population accounts for about 30% of Africa's population and most of this population is concentrated along the WAC (Denis and Moriconi-Ebrard, 2009). The coastal fringe accounts for about 56% of the gross domestic product (GDP) of the WA and there is a possibility of accelerating economic growth at rates exceeding 5% over the long-term in the region (UEMOA, 2011; Goussard and Ducrocq, 2014). The prospects of such rapid population growth should be a major concern in light of the increasing pressures on the ecosystem and its resources. Urbanization within the region, both through migration from the rural hinterlands and by growth within cities, is leading to classic urban sprawl, testing the carrying capacity of the coastal ecosystems (Diop et al., 2011).

The highest population density hotspots are located in some key cities along the coast, including Dakar, Abidjan, Accra-Tema, Lome, Cotonou, Lagos, and Port Harcourt (Fig. 2). The pressures in some countries have been exacerbated in recent years by human conflict and political instability. Local fisheries resources have been overexploited and cutting of mangroves and other resource extraction activities are severely degrading coastal habitats. Pollution from sewage and industry is degrading coastal ecosystems and causing health issues, and coastal groundwater resources are becoming depleted through unsustainable groundwater abstraction and the consequent intrusion of seawater (Diop et al., 2011).

Throughout the region, the shorelines are retreating (Almar et al., 2015, 2019; Andrieu, 2018; Anthony et al. 2016, 2019; Anthony and Blivi, 1999; Appeaning-Addo, 2009; Appeaning Addo et al., 2009, 2013; Angnuureng et al., 2013, 2017; Dada et al., 2015, 2016a, b, 2018, 2019; de Boer et al., 2019; Laibi et al., 2014; Ozer et al., 2017; Sadio et al 2017; Giardino et al., 2018; Ndour et al., 2018) and the major contributing factors are the construction of ports and harbours (de Boer et al., 2019, Almar et al., 2015, Anthony et al. 2016, 2019), coastal engineering defence (Appeaning Addo et al., 2013; Angnuureng et al., 2013), and recreational facilities, which have led to the clearing of important coastal vegetation, including mangrove forests (Andrieu, 2018;

Andrieu and Mering, 2008; Boone et al., 2016), and the reclamation of coastal wetlands (Giardino et al., 2018; Güneralp et al., 2017).

Besides, an increase in sediment loads, and discharges of often inadequately treated sewage and solid waste (Diop et al., 2014) have deteriorated water quality and degraded coastal habitats (Diop et al., 2011; Diop et al., 2014; World Bank, 2020; Croitoru et al., 2019). For example, subsidence and mangrove clearance have increased erosion to about -30 $m.yr^{-1}$ along the exposed Nigerian Transgressive Muddy coast northwest of the Niger Delta (Ebisemiju 1987; Dada et al., 2019; Anthony et al., 2019). The accelerated rate of coastal degradation in this mud coast is further complicated by extreme seasonal coastal flooding events due to changing climate (Dada et al., 2020).

The WAC is already threatened by the expected effects of climate change. Sea-level rise and changes in the frequency and power of extreme meteorological events are increasing the impact on coastal flooding and erosion by the acceleration of land loss (see Fig. 3; World Bank, 2020; Marti et al., 2019; Appeaning Addo, 2015; Appeaning Addo et al., 2011; Dada et al., 2020; Failler et al., 2020a). The WA low-lying coastal zones, estuaries and deltas are most vulnerable to coastal flooding related to mean sea level rise (World Bank, 2020; Nicholls and Tol, 2006). This rise in sea level, coupled with the increasing intensity or frequency of extreme events, will have serious effects on the development of the coastal areas (IPCC, 2018). Along the WAC, a rise greater than the global average is expected (World Bank, 2020). This could bring dramatic consequences for certain coastal areas, like Nouakchott, Mauritania that is already below sea level. Major WAC cities are greatly at risk Ouikotan, 2017). Unfortunately, there is significant insufficient information about SLR to generate future projections with high confidence in the region. Also, very few regional climate models or empirical downscaling have been constructed to assess climate change scenarios on the WA coast (World Bank, 2020).

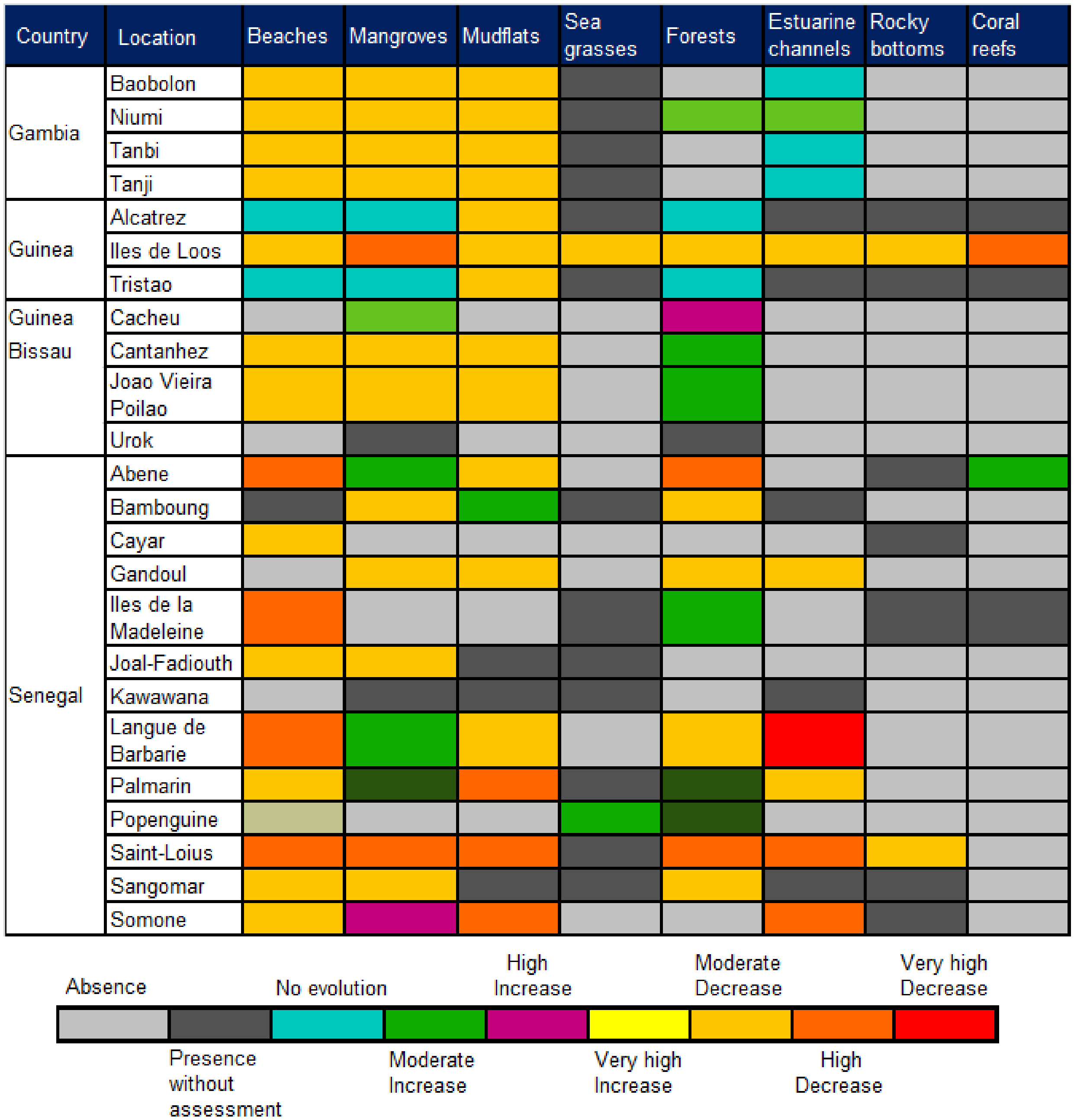

Fig. 3. Summary of the evolution of the WAC ecosystems in marine protected areas in the last 10 years (Adapted from Failler et al., 2020a).

3. Designing the SES framework for W.A. coastal areas

3.1 The process of developing a conceptual framework for the WAC systems

As a consequence of the issues mentioned above, an interdisciplinary workshop was organized by the Interdisciplinary Partnership Programmes (PSIP) research group of the French National Research Institute for Sustainable Development (IRD) in March 2019 at Saint Louis, Senegal. The meeting focused on finding a solution to the vulnerability of coastal areas in West Africa in the context of global change. It was well-attended by over 60 African and non-African experts and other stakeholders with expertise in different fields that ranged from marine ecology, physical oceanography, coastal dynamics and modelling, geography, social sciences, economics, political science, coastal remote sensing, coastal ecosystems and adaptation, regional sea level, coastal impacts, coastal evolution, meteorology and climate dynamics, hydrogeology, geophysics, coastal and marine geology, atmospheric sciences, etc. Representatives of relevant WA government ministries and financial institutions like the French Development Agency (AFD) group funds and the World Bank were in attendance.

As illustrated in Figure 4, the participants were asked about the drivers, pressures, impacts and other phenomena to be addressed as priorities by research according to their importance in the dynamic of the WAC areas (several responses allowed). The participants mentioned a wide range of issues, going from physical hazards and processes to social and policy aspects. This finding suggests a need to adopt a comprehensive approach when studying the evolution of WAC areas. The outcome of the workshop encouraged the development of an integrative conceptual framework that encompasses phenomena ranging from geophysical to societal and policymaking. To achieve this objective, we build on the PPD framework (Fig. 1), because of its robustness.

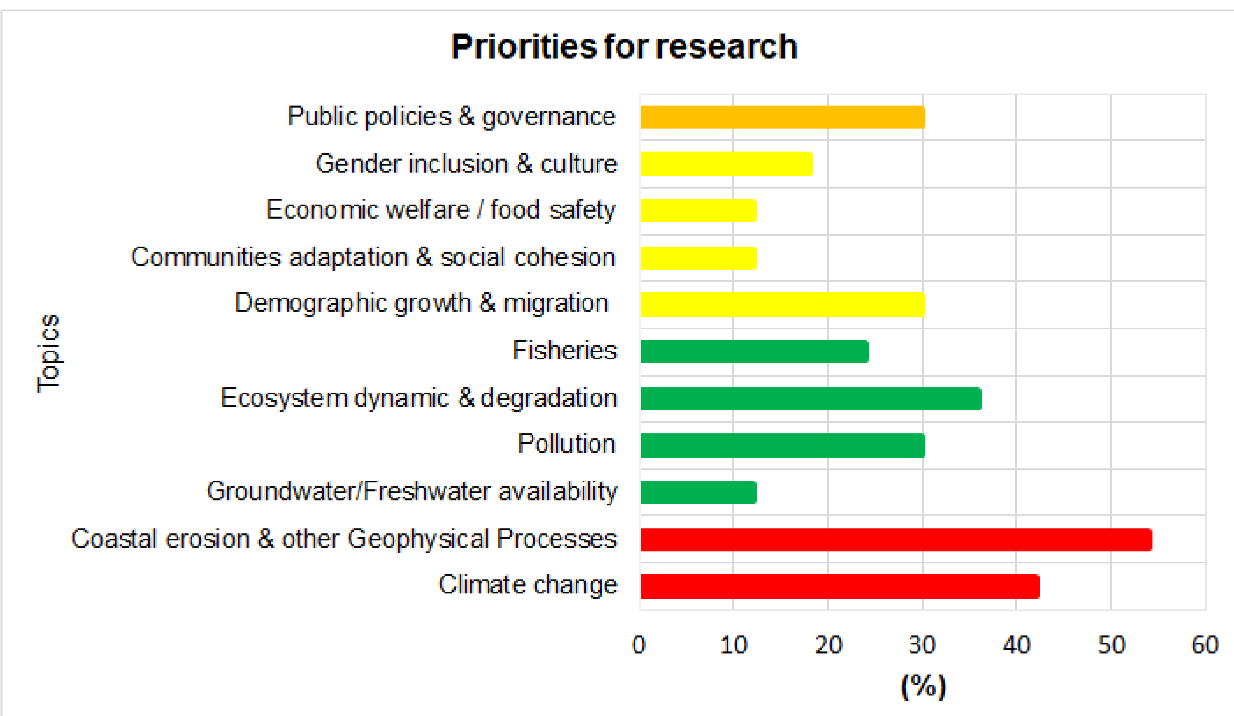

Fig. 4. Types of drivers, pressures and other phenomena to be addressed as priorities for research according to the participants of the Saint-Louis workshop (% of people)

3.2 Key features of the modified press-pulse dynamics (mPPD) Framework

The traditional PPD framework (Fig. 1) by Collins et al. (2011) has four interlinked core components (press-pulse events, ecological subsystem, ecosystems goods and services, and social subsystem). We modified the framework (hereafter refers to as mPPD) to achieve our desired objective of including the governance and management aspects (Fig. 5): we extended the original concept by integrating a new component named 'adaptive actions/management responses'. This component represents the management decisions/actions that could be taken to address the disturbances and the impact within the social-ecological system (SES). Thus, the mPPD framework contains five main components: (1) press and pulse events, (2) the ecological subsystem, (3) ecosystem goods and services, (4) a social subsystem, and (5) adaptive actions/management responses. The SES (i.e., the entire coastal system) represents the conventional disciplinary research theories that define processes within each subsystem (Fig. 5). In our modified framework, press and pulse events, ecosystem goods and services and adaptive actions/management responses are classified forms of impacts/responses that explain the linkages between the social and ecological subsystem in form of their interdependencies. We referred to this central section as the social-ecological interactions zone (Fig.5). These include human involvement and as its 'counterpart' in the delivery of ecosystem services.

The processes or interactions described above are taking place and interacting at different scales and management levels (as shown by the thick arrows outside the central panel of Fig. 5). The external horizontal and vertical thick arrows are pointing to how the ecosystem's benefits to people can be delivered, utilized, evaluated and managed at different spatial and temporal scales. They also explain interactions and feedback from many factors that can as well operate on more than one scale. Consequently, the mPPD can be concurrently applied locally, nationally, regionally and globally, i.e., at different scales of ecological processes and of potential drivers of change.

In the mPPD framework, an adaptive management approach is shown by the feedback with the social subsystem and indicates the iterative nature of planning. Feedbacks requiring reconsideration of earlier parts of the process may be necessary. For instance, anthropogenic changes to the ecological subsystem, altered social-economic conditions, new information or dataset, and monitoring of the effectiveness of conservation efforts (Álvarez-Romero et al., 2011; Sarkar et al. 2006).

An adaptive management approach is especially important for coastal planning due to the uncertainty and complexity associated with planning across sectors. Some sources of uncertainty are our limited knowledge of coastal system interactions and dynamics, lag times between implementation of actions and measurable results, and difficulties in predicting climate change, land-use change, and their potential impacts on coastal ecosystems (Álvarez-Romero et al., 2011; Broderick, 2008). The "adaptive actions/management responses" component is set at the centre of the framework to create links between the social and ecological subsystems, which should be developed by the coastal managers to directly influence the stakeholders' actions towards environmental-friendly activities/behaviours.

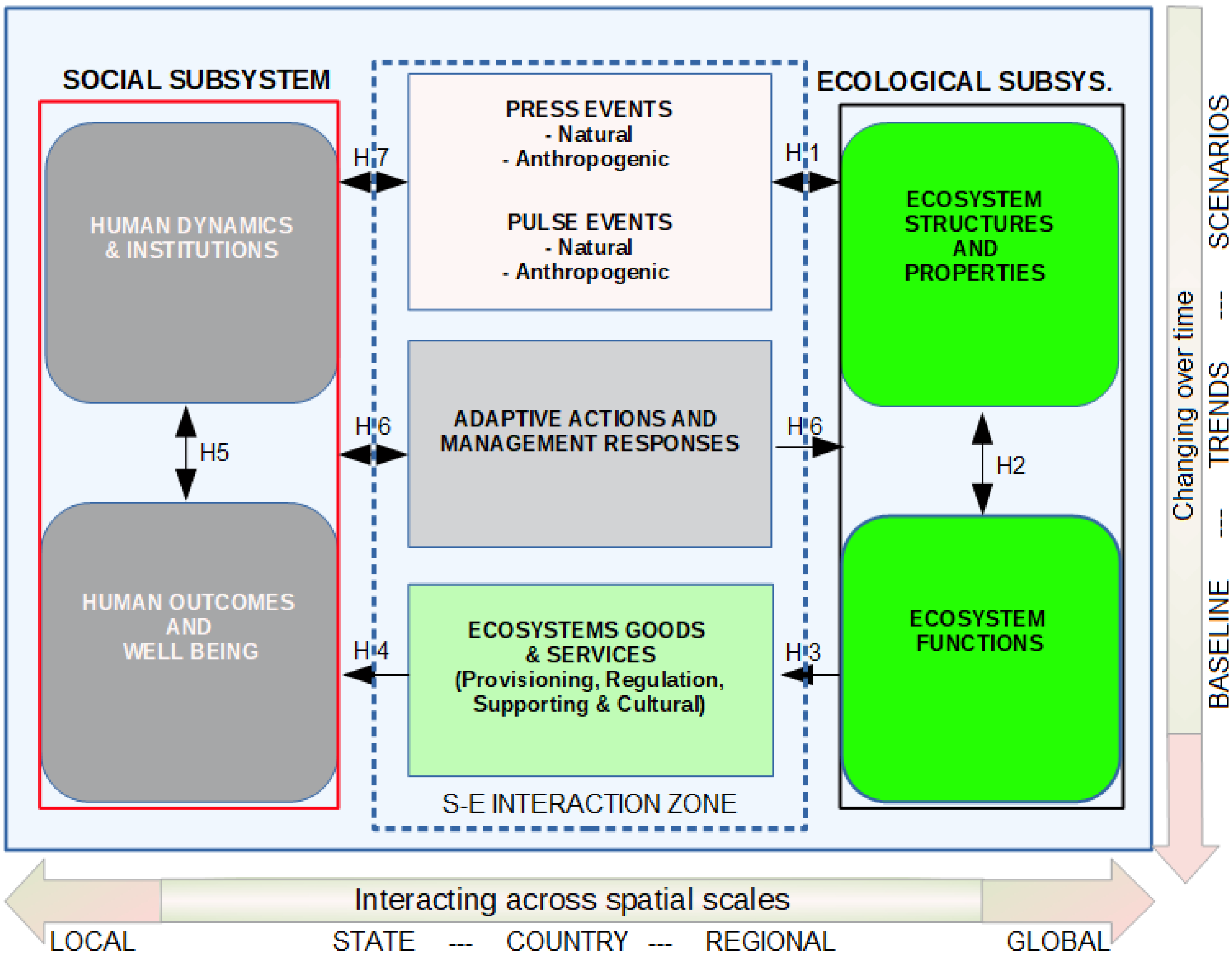

Fig. 5. The mPPD framework. The left-hand side represents the human subsystem, and the right represents the ecological subsystem. The two subsystems are connected by pulse and press events indirectly caused or influenced by human behaviour. Then, the ecosystem goods and services that are made available to humans may eventually trigger management responses that influence the frequency, magnitude, or form of press and pulse events across ecosystems, if not satisfactory. Note: The horizontal double arrow illustrates the required varying spatial resolutions used to build our assessments at the regional scale. The vertical double arrow indicates the baseline, trends and scenarios as a function of time scale.

3.3 Building futures Scenarios with mPPD framework

In attempts to get beyond the analytical constraints posed by the formal integrated models, a scenario formulation is one of the approaches that can be used to tell stories, in words and numbers, of plausible development that may arise in the future (Ruttan, 1999). They are constructed to provide insight into drivers of change, unveil the consequences of present trajectories, and reveal options for action. They describe futures that could be rather than futures that will be (Peterson et al., 2003). Scenarios tell “plausible stories about what may happen in the future. Whether using qualitative and/or quantitative models and information on present and past conditions; they are a useful tool for exploring key uncertainties that may shape the future of social-ecological systems” (Biggs et al., 2007). SES scenarios can be used to assess the adaptation and vulnerability of the coastal ecosystem (Ledoux et al., 2004; Turner, 2005). Here, we constructed the 21^{st}-century coastal systems scenarios based on the literature reviews (e.g., Gallopin and Raskin, 1998) and the experience the authors have garnered in the study area over time.

As shown in Fig. 6, the three different social-economic scenarios constructed can be employed to understand the dynamics and intrinsic vulnerabilities of the 21st-century coast anywhere in the world, but here deployed to the WAC region. The narrative of these scenarios is based on a set of descriptive variables like population growth, economic development, environmental quality, governance, technological advancement at the coast (Fig. 6). They are categorized as the (a) anthropocentric (i.e., human activity-focused), (b) anthro-ecocentric (i.e., human-environment focused), and (c) ecocentric (i.e., environment focused) coastal scenarios. These set of indicators or variables represent the attributes of the coastal system while the differences in the attributes, from one scenario to another, are what reveal the differences between the scenarios. The scenarios (Fig. 6) were synthetically incorporated into the mPPD framework (Fig. 7).

In addition, for future climate change, we assumed the worst-case scenario is constant across the board. We used the upper RCP 8.5 scenario (IPCC, 2018), characterized by a sea-level rise (+1 m by 2100), temperature (6° by 2100), extreme wave events (up to 3% and a clockwise rotation up to 2°) and rainfall (20% increase for 2100, since temperature increases). This future climatic condition was also considered by Giardino et al. (2018) in the study area.

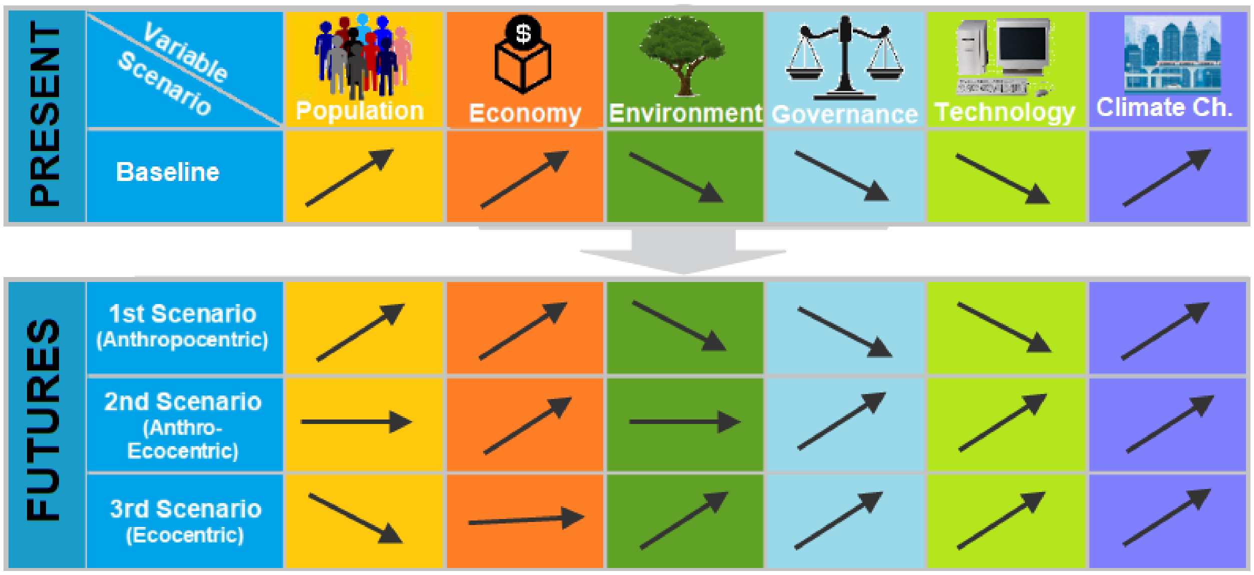

Fig. 6. Typical (anthropocentric, anthro-ecocentric and ecocentric) scenarios illustrating plausible future of WAC. All three scenarios are developed over time along the six indicators (i.e., population growth, economic development, environmental quality, governance and institution, technological change, and climate change), which are interdependent. Note: The arrows (up = strong, down = weak, and horizontal = moderate) are projected as uneven representations of just possible patterns of change in the WAC.

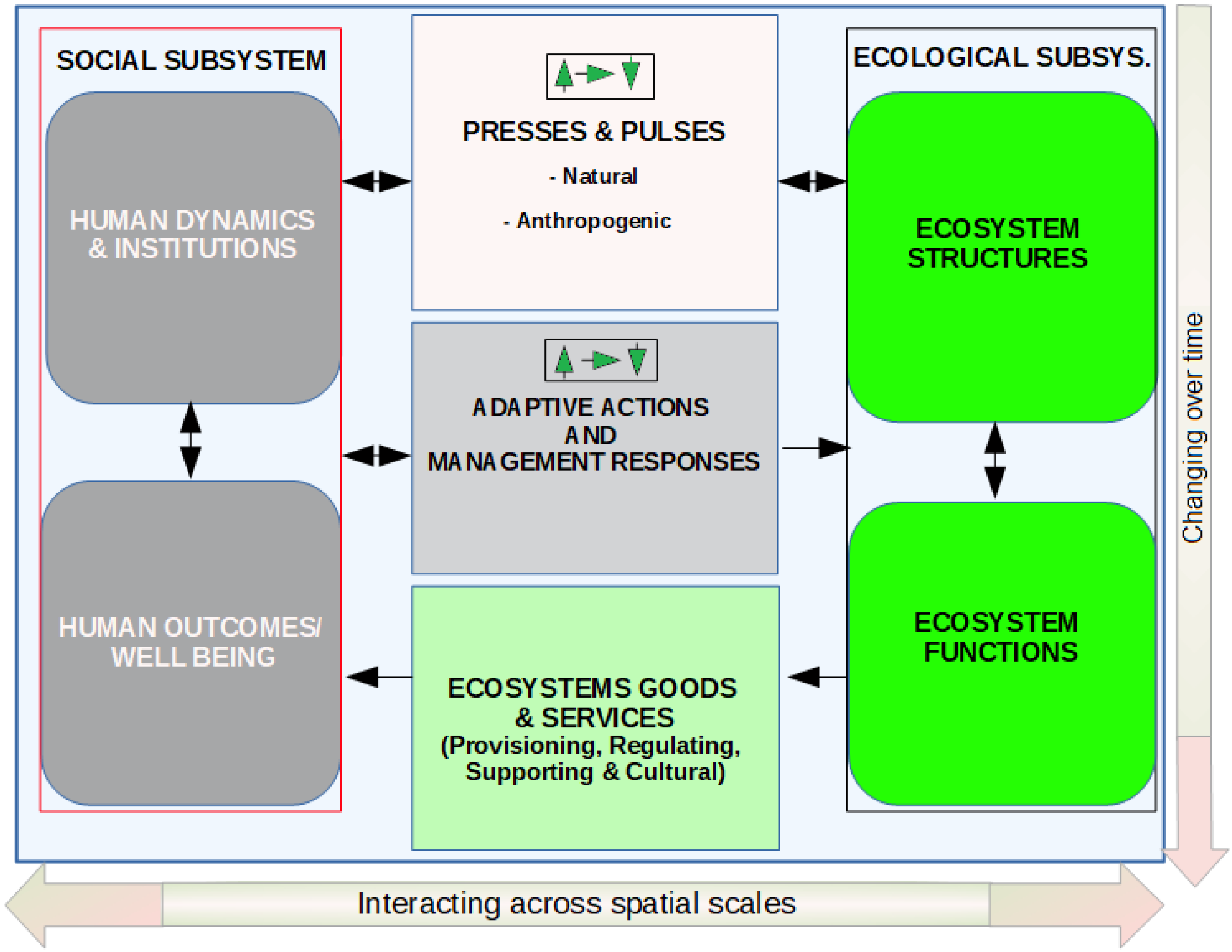

Figure 7. A generic future scenario for the coastal social-ecological system (CSES) in the 21st century. The ecosystems will experience different (intensities of) pressures, and, consequently, different impacts on their integrity and functionality, thus implying different environmental risk for society. Note: The green arrows under "presses and pulses" and "adaptive action and management responses" panels illustrate varying levels of effect: up arrow = strong, down arrow = weak, and horizontal arrow = moderate.

4. Application of the framework

We applied the mPPD framework to the Bight of Benin and the WA mangrove system (Fig. 8, Fig. 9; Table 1). Then, we used it to conceptualize the 21st CSES scenarios (Fig. 10). The case studies are based on previous literature and expert's judgement.

Table 1. Summary of the natural and anthropogenic presses and pulses associated with each case study, outlining the ecological or biogeophysical impacts, social consequences and recommended management responses

Case Study	Presses	Pulses	Biogeophysical Impacts		Social Consequences	Recommended management actions
			Biological	Physical		

Shoreline Retreat (Bight of Benin; 1990-2015)	Climate change[1,2]; sea-level rise[3,4]; seaport development[5,6]; river dams[7,8]; engineering structure/ installation[9,10]; coastal development[11,12]; harbour construction with breakwaters[13,14]; urbanization[11,12]; land use/ conversion[15,16].	Increasing extreme events[17,18]; wave climate[19,20]; rainfall variability[21,22]; storm surge[23]; sand mining[7,24]; river mouth and channel dredging[25].	Bio-diversity loss, habitat loss	Erosion, sediment deficit, water pollution, soil infertility, loss of scenic quality	Loss of income, loss or damage to property, property devaluation, recreation values reduction, social inequality, political and social tensions, loss of lives, and health, economic loss/ disruption, loss of livelihoods, decreasing purchasing and production power, mass migration, population displacement, economic growth and development decline, psychological impacts.	Development of integrated coastal zone management strategy, abandonment of risk zones, beach nourishment, nature-based coastal defence
WA Mangrove Ecosystem Decline (W.A: 1975-2013; Somone Estuary, Senegal:1946-2006)	Climate change[25], sea-level rise[26], increasing sea surface temperature[27], land use/ conversion[28,29], oil spill/ pollution[30,31], coastal development[31,32],	Woodcutting/ harvesting[31], aquaculture[32], drought/ rainfall[22,33], extreme weather events[34]; Rice cultivation[31]; Dam construction[35]	Mangrove dieback, mangrove habitat loss, population structure change, invasive species invasion, primary production loss, nursery habitat loss, biodiversity loss	Hyper-salinization of soil, coastline erosion, increased sedimentation, coastal flooding, water quality reduction	Declining fisheries and indigenous uses, loss of livelihood, food insecurity, low life quality	Adaptive strategies, reseeding/ replanting, marine and coastal policy formulation, public sensitization and awareness, community engagement, monitoring & regulation

1: Abessolo et al. (2020); 2: Appeaning Addo et al. (2011); 3: Angnuureng et al. (2017); 4: Marti et al. (2019); 5: Anthony et al. (2016); 6: de Boer et al. (2019); 7: Almar et al. (2015); 8: Dada et al. (2015); 9: Appeaning Addo et al. (2013); 10: Angnuureng et al. (2013); 11: Badmos et al. (2018) ; 12 : Denis & Moriconi-Ebrand (2009) ; 13 : Kaki et al. (2011) ; 14 : Giardino et al. (2018) ; 15 : Andrieu (2018) ; 16 : Dada et al. (2019) ; 17 : Almar et al. (2019); 18 : Gautier et al. (2016) ; 19 : Anthony et al. (2019); 20 : Dada et al. (2016b); 21 : Dada et al. (2018); 22 : Sakho et al. (2011) ; 23 : Jonah et al. (2015) ; 24 : Dada et al. (2016a); 25 : Dia Ibrahima (2012) ; 26 : Ibe & Awosika (1991) ; 27 : Biasutti (2019) ; 28 : Andrieu & Mering (2008) ; 29 : Boone et al. (2016); 30: Feka & Ajonina (2011); 31: Ekundayo & Obuekwe (2001); 32: Diop et al. (2011); 33: Nicholson (2013); 34: Taylor et al. (2017; 35: Tendeg et al. (2016).

4.1 Application to the vulnerability of low-lying West African coastal ecosystems

***Case study 1: The response of the Bight of Benin coastline to anthropogenic and natural forcing** (Fig. 8; Table 1; adapted from Anthony et al., 2019)*

The Bight of Benin in the Gulf of Guinea (Fig. 2) forms an embayment between the Volta River Delta in the west (Ghana) and the Niger River Delta (Nigeria) in the east (ecological subsystem). The Bight coast comprises sandy beaches backed by Holocene beach-ridge barriers (ecological subsystem). Incident swell waves, beach face gradient and the unidirectional longshore sand transport from west to east are intimately linked, generating a classic example of a strongly wave-dominated drift-aligned coast (ecological subsystem). The stability of this coast, which hosts several major cities in addition to three large international deep-water ports, has been strongly affected by human activities (social subsystem as highlighted in Fig. 8), including the three ports (H7), and by natural and human-altered shoreline dynamics (H1) related to the Volta River Delta and distributaries at the northwestern flank of the Niger Delta. The combination of these factors has impacted alongshore sediment redistribution by segmenting the previously unrestrained longshore transport of sand that prevailed along this open coast (H2, H3).

The result is a mixture of natural and artificial sediment cells increasingly dominated by shoreline stretches subject to erosion (H2, H3), endangering parts of the rapidly expanding port cities of Lomé (Togo), Cotonou (Benin) and Lagos (Nigeria), coastal roads and infrastructure, and numerous villages (H3, H4, H5). Post-2000, the entire Bight shoreline has undergone a significant decrease in accretion, which is attributed to an overall diminution of sand supply via the longshore transport system (H2, H3). This diminution is attributed to the progressive depletion of sand-sized bedload supplied to the coast (H2, H3) through the main Volta river channel downstream of the Akosombo dam (H7-H1), built between 1961 and 1965. Sand mining to cater for urban construction in Lomé, Cotonou and Lagos (H7-H1) also contributed locally to beach sediment budget depletion (H2, H3).

Although alongshore sediment supply from the Volta River has been the dominant source of sand (H2, H3) for the stability or progradation of the Bight of Benin coast (H3-H4), potential sand supply from the shoreface, and the future impacts of sea-level rise on this increasingly vulnerable coast are also important (H2-H3). The continued operation of the three ports and existing river dams, coupled with sea-level rise, will lead to sustained shoreline erosion along the Bight of Benin in the coming decades (H6-H7). Since the Volta Delta, Togo, Benin and Nigeria belong to the same littoral cell, an integrated approach that will address the issue at this scale of sediment cell is necessary. As indicated in Fig. 8 and Table 1, this justifies recommending integrated and adapted management actions.

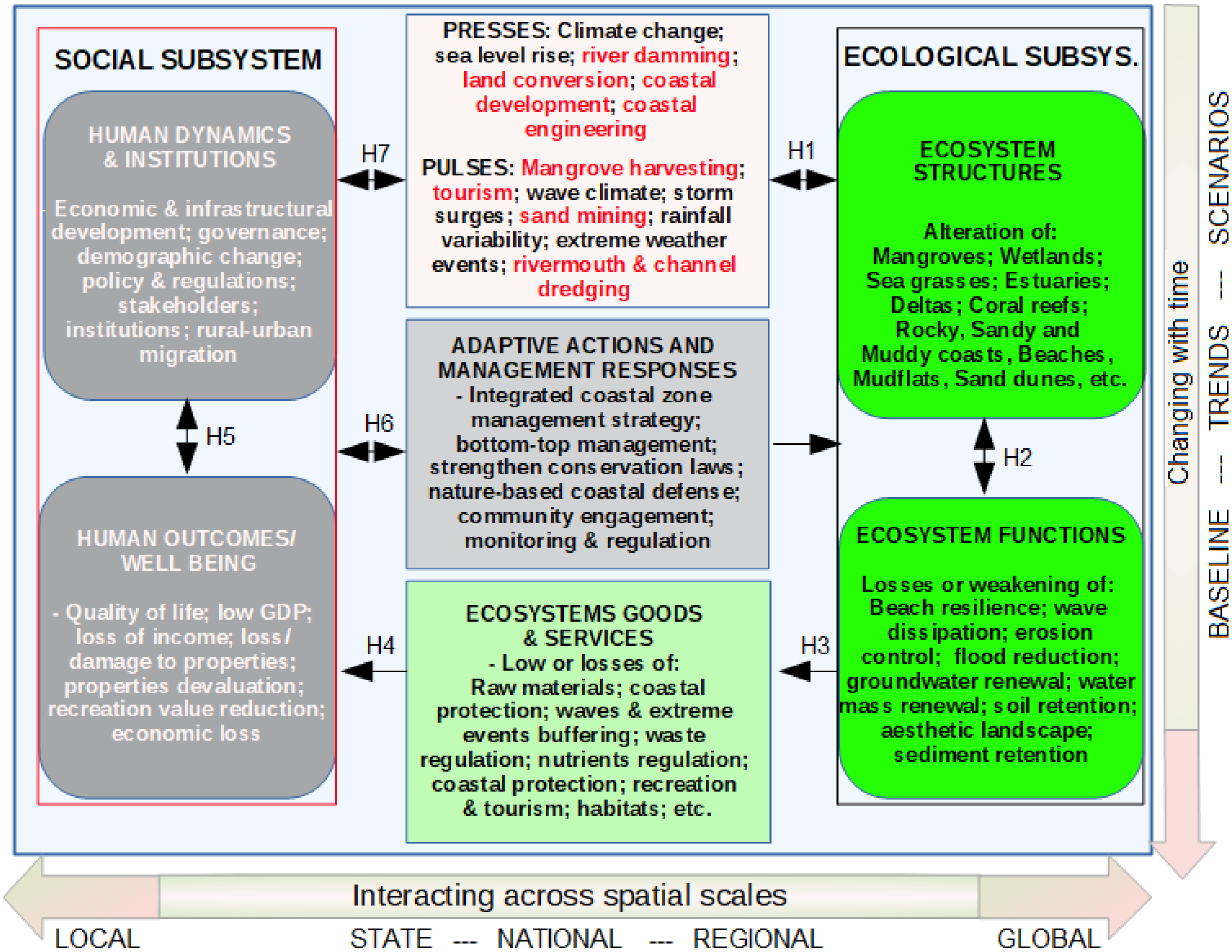

Figure 8. The shoreline vulnerability of the Bight of Benin section of the WAC response to changes in trajectories of long-term presses and short-term pulses as a result of natural and human dynamics. Application of the framework to assess the shoreline vulnerability of the Bight of Benin section of the WAC. The entire coastal system is changing over time and across spatial scales. The WAC SES are affected by both external (e.g., global climate, globalization, etc.) and internal (e.g., demographic changes, weak institution, policy, governance, economic activities, etc.) driving forces that generate disturbances (long-term press and short-term pulse). Both the long-term press and short-term pulse disturbances, in the form of continued operation of the three ports and existing river dams, and sea-level rise, elicited by these human behaviours altered the WA ecological system structures and functions negatively (e.g., coastline retreat, polluted groundwater, decreasing river load, nutrient reduction, biodiversity loss, etc.) and thereby influencing the ecosystem services delivery. The altered ecosystems services (e.g., decreasing coastline erosion control, coastal protection defence, water quality, waste regulation, etc.) in turn influence the human outcome and well-being (in terms of quality of life, human health, household incomes, etc.) that necessitate the proposed adaptive actions and management options. Note: The horizontal spatial scale arrow (external) indicates that, although our assessments take place at the regional scale (scope), they will in part build on properties and relationships at finer- national-, state- and local scales (resolution, to a minimum discernible unit). While the vertical arrow (external) indicates the baseline, trends and scenarios will be used. Presses and pulses in red denote human-induced activities.

Case study 2: The WAC *Mangrove ecosystem dynamics (Fig. 9, Table 1)*

As displayed in Figures 3, 9 and Table 1, the mPPD framework is used here to illustrate the dynamics and vulnerability of the mangrove coastal ecosystems of the WA, specifically in the northwest, The extraordinary pulse event of severe drought (H1) in the Sahel in the 1970s (Descroix et al., 2015; Nicholson et al., 2000; Nicholson, 2005, 2013; Nielsen and Reenberg, 2010) affected the Sahelian coastal ecological services, especially that of mangrove ecosystems, like provisioning, supporting, regulating and culture (H2-H3). This period was followed by abundant rainfall of the 1990s (Cormier-Salem, 1999; Diop et al., 1997; Spalding et al., 2010; Valiela et al., 2001). The anthropogenic factors also played a role (H7-H1). Until 1990, traditional wood cutting (for wood and oyster harvesting) was practised by the local population (H7-H1).

The adverse climatic changes (H1) can be viewed as the major causation of the coastal social-ecological systems dynamism at this section of the WAC. It affected the entire structures and functioning of ecological subsystems (H2-H3) of this particular coastal region (Dieye et al., 2013), which in turn, indirectly altered the provisioning, supporting, regulating of the ecological services, such as food resources, and finally the quality of human outcome and well-being of the coastal indigenous communities (H4-H5; Fig. 9). This situation prompted diverse human/management responses ((H-6-H7; Barry, 2009; Dieye et al., 2013).

This mangrove ecosystem has been in a recovery state since 1990 (Andrieu, 2018; Andrieu et al., 2019, 2020). It is among the few globally that is growing obviously (in the area and mass) since the beginning of the 1990s. This is probably owing to, primarily, a sequence of pulse events (H2) of higher frequency of the wet condition and more intense and intermittent seasonal rainfall rebound since 1990 (Biasutti, 2019; Conchedda et al., 2011; Nicholson, 2005; Nouaceur and Muraresccu, 2020; Ozer et al., 2003). This helped the dilution of hypersaline water in estuaries where salinity is much higher (up to 200 $g.l^{-1}$ in the 1980s).

The second reason is most likely the enforcement of regulations, the management improvement of the mangrove ecosystems (H6-H7) since the beginning of the 2000s (Andrieu 2018; Andrieu et al., 2019, 2020; Failler et al., 2020a, b; Gallup et al., 2019; Gautier et al., 2016). The non-government organizations' conservation efforts in WA to prioritize mangrove forests of ecological significance and strategically seek their protection also played a key role in these changes (Andrieu 2018; Andrieu et al., 2019, 2020; Conchedda et al., 2011; Cormier-Salem, 2016; Dieye et al., 2013; Fent et al., 2019; Temudo and Cabral, 2017). These combined actions reduced mangrove degradation as can be seen in the model (Fig. 9).

For instance, in the Somone Estuary, Senegal (Sakho et al., 2011), since 1992, a modification of mangrove logging and a new reforestation policy (H6-H7) resulted in an exponential increase of mangrove area (see Fig. 3) progressively replacing intertidal mudflats (H2-H3). Such success in the restoration of the ecosystem reforestation is supported by favourable environmental conditions: tidal flooding, groundwater influence, rainfall during the wet season, low net accretion rate of about 0.2-0.3 $cm.yr^{-1}$, (H1) and a ban on the cutting of mangrove wood (H6-H7). The rate of mangrove loss from 1946 to 1978 was 44,000 $m^2.yr^{-1}$, but this has been offset by restoration efforts resulting in an increase in mangrove area from 1992 to 2006 of 63,000 $m^2.yr^{-1}$ (H2-H3).

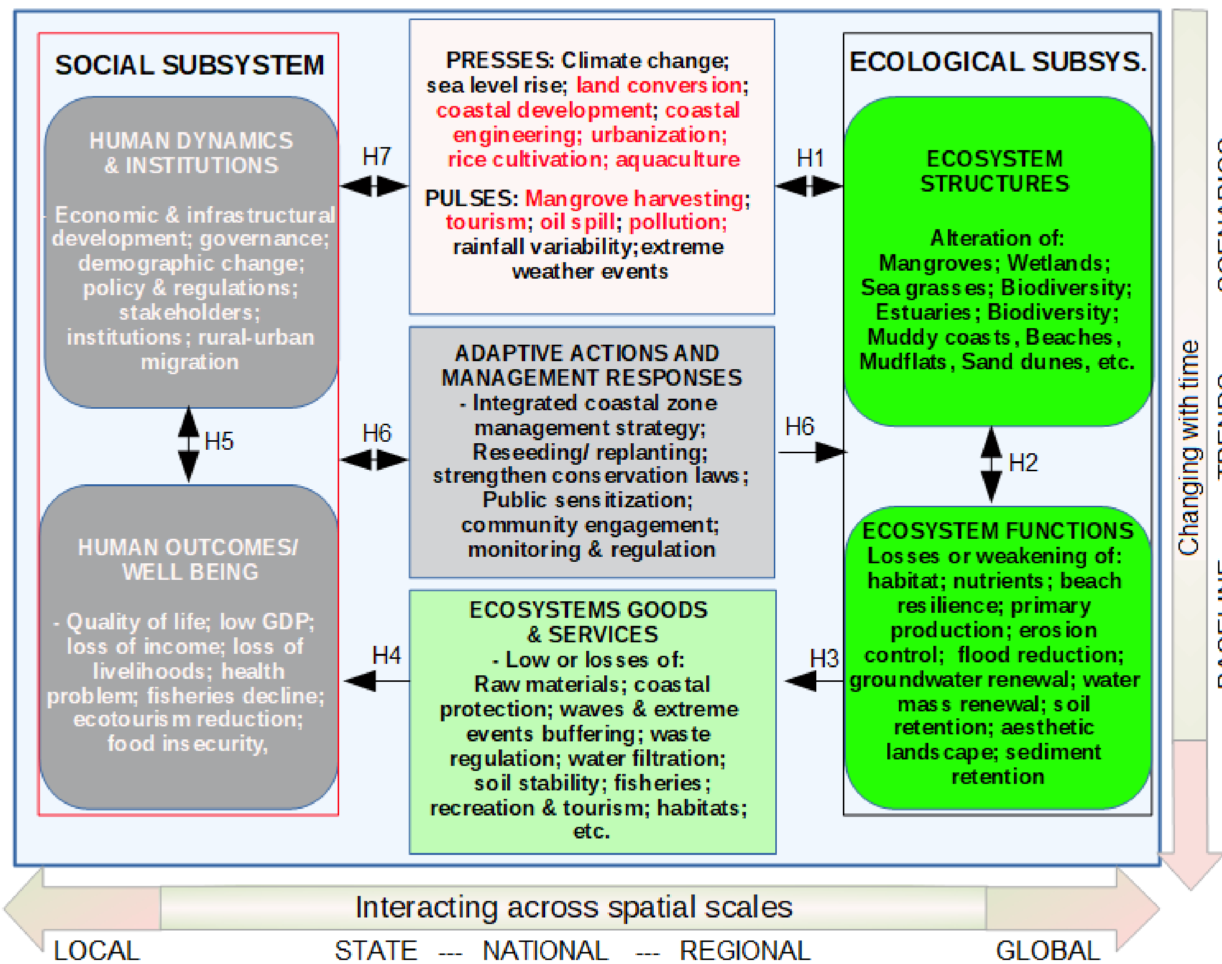

Fig. 9. The WA mangroves ecosystem response to changes in trajectories of long-term presses and short-term pulses as a result of natural and human dynamics. Note: The horizontal spatial scale arrow (external) indicates that, although our assessments take place at the regional scale (scope), they will in part build on properties and relationships at finer- national-, state- and local scales (resolution, to a minimum discernible unit). While the vertical arrow (external) indicates the baseline, trends and scenarios will be used. Presses and pulses in red denote human-induced activities.

4.2 The 21st-century scenarios for WAC ecosystems

The first (Anthropocentric, i.e., human activity focused) coastal scenario. This is a future WAC in which prevailing trends is allowed to continue without major interventions (Fig. 10A). High economic activities and infrastructural development associated with demographic pressure together with weak governance, institutions and policy have a deleterious effect on the environment (coastal ecosystems).

The existing failures in coastal governance and institutional structures at the local, state and national levels remain unattended, which the outcome is the continuing degradation of the WAC ecosystems. The major lingering governance issues are poor coordination by the governments of the WAC countries at different levels, the lack of understanding of the fragility of the environment and the importance of its protection amongst policymakers, inappropriate and weak legislation and inadequate institutional frameworks and capacities for managing coastal development pressures. The main concern is given to economic and infrastructural development and resources exploitation whereas environmental objectives are loosely implemented and enforced (Hofmann et al., 2005; Karageorgis et al., 2006). There is a continuing rise of slums in many Sub-Saharan African coastal cities owing to rural-urban migration and rapid urbanization without proper planning (Badmos et al., 2018).

Under this scenario, the general approach to ecosystem services is reactive, rather than proactive (Butler and Oluoch-Kosura, 2006; Carpenter et al., 2006). Thus, it may leave WAC communities vulnerable to frequent adverse surprises (e.g., flooding, ocean surge, pollution, coastal eutrophication, saline intrusion, climate change), which may be tardily recognized and ill-managed. Some of these adverse ecological surprises may surpass a threshold, overwhelming social capacity and, consequently, affect human well-being (Butler and Oluoch-Kosura, 2006).

The main management approach being the construction of sea dike systems to prevent erosion, flooding and salinization of the soil, and protect economic and wealthy residential areas and maintain agricultural productivity and aquaculture inside the dikes. Earthen dikes (rubble mound breakwaters) have mainly been constructed along with ancillary structures like groins, embankments and breakwaters. However, most time, this approach is confronted with poor technical standards and the challenge of protecting the entire coastline. Grey (human-engineered) infrastructure negatively impacts the WAC ecosystem and environment, and the high costs involved make it to be less widely applied, and consequently, the effectiveness is reduced.

Coastal protection works are prioritized in areas with higher socio-economic values that lead to inequality in areas with lower socio-economic values, where people are at bigger risk of the social effects of displacement. As a result, political and social tensions are on the increase. Also, losses of properties are arising because coastal protection works are failing. Likewise, the values or prices of the properties are declining, and property owners are finding it difficult to get insurance or mortgages for their properties. WAC communities depending on coastal tourism as a means of livelihoods are experiencing a decrease in income. The reduced productivity of businesses that rely on infrastructures that are affected by coastal degradation or incur costs in its mitigation, will have a knock-on effect on the local economy.

Without adaptation, more intense and frequent extreme sea level (ESL) events, together with trends in coastal development will increase expected annual flood damages by 2-3 orders of magnitude by 2100 (Oppenheimer et al., 2019). Coastal processes and associated land-use changes continue as "business as usual" toward a negative 'facing the wall' situation with too much risk (flooding/ erosion/ pollution) for a dense rather poor unprotected population. Coastal scenario 1 can be tied with the occurrences straddle between the Shared Socioeconomic Pathways (SSP) 3 and 4 used by IPCC (Merkens et al., 2016; Moss et al., 2010; O'Neill et al., 2020).

The second coastal (Anthro-ecocentric) scenario (Fig. 10B) is characterized by increasing population growth, infrastructural and economic development, and significant advancement in technology and also, a modest improvement in environmental quality as a result of improved governance.

Under this scenario, which could occur in the same global context as the previous one, there is no alternative but to adopt traditional sea defence and coastal protection schemes (both soft and hard engineering works) to protect those areas that are economically viable. Research in coastal risk management and capacity building with the help of foreign partners result in hybrid solutions that combine natural infrastructure with built infrastructure. Such adaptation measures are implemented along the WAC to adapt to SLR in the 21st century.

The goal is to preserve, restore, and enhance elements of the natural system that will enable natural ecosystems to function in conjunction with built infrastructure to maximize benefits and reduce the cost of adaptations. Using this approach, while the degraded coastal ecosystems are restored, built infrastructures are put in place to provide protection benefits as natural infrastructure becomes stronger.

The hybrid solutions are retrofitted onto existing infrastructures in most of the coastal urban cities like Lagos, Dakar, Cotonou, Abidjan, Accra, Lome. These cities are densely populated and there is insufficient space to use only natural infrastructure for coastal defence. Although the hybrid system provides some co-benefits besides coastal protection, it does not provide all the same benefits that natural systems provide owing to the built component that has some negative impacts on ecological diversity (Sutton-Grier et al., 2015). They negatively influence economic interests and human health and wellbeing that rely on ecological goods such as ecotourism, recreation and fisheries, clean air and abundant freshwater, and ecological services like air and water purification, biodiversity maintenance, waste decomposition, soil and vegetation generation and renewal, groundwater recharge, greenhouse gas mitigation, and aesthetically landscapes.

Also, with the SLR, the heights of the hard structures will need to be raised to remain effective. This is an expensive endeavour that ultimately may prove unaffordable and unachievable. Even with well-designed hard protection, the risk of possibly catastrophic effects in the event of failure of defenses cannot be overruled (Oppenheimer et al., 2019). Coastal scenario 2 portrays many similarities with SSP 2 (Merkens et al., 2016; Moss et al., 2010; O'Neill et al., 2020).

The third (Ecocentric) scenario (Fig. 10C), being environment-focused, is characterized by government incentives for environmental conservation, green energy, and land-use planning. More confidence is placed on the development of environmental engineering, climate and energy-friendly technology, and new ways of farming that incorporate provisioning with regulating and cultural ecosystem services (Butler and Oluoch-Kosura, 2006; Carpenter et al., 2006). Besides, ecological systems sustainability is promoted. Ecosystem-based approach policies are strengthened, ecotourism principles are supported, and environmental laws and regulations are strictly adhered to. The pace of population growth and economic development is wholly determined by environmental quality. There is also a considerable improvement in technological advancement.

This is an ideal scenario for the WAC areas over the long term, but it is prefaced on parting with the past, which may induce some degree of strain in the short term. This may likely occur in the context of the global IPCC SRES B1-2 scenario (Rogelj et al., 2012) or the most recent scenario, the SSP 1 (Merkens et al., 2016; Moss et al., 2010; O'Neill et al., 2020).

The scenario is the most radical of the three and assumes a general shift in attitudes of the stakeholders and policymakers towards more environmentally sound ways of life (Fig. 10C). The coast tends toward a wilder scenario owing to sustainable policies implementation and enforcement (e.g., widespread adoption of managed realignment or abandonment policy). This may be due to a "do-nothing approach" in which the disturbed area is left alone to recover naturally without any management intervention. It could also be a situation whereby nature (risk e.g., natural hazards) forces people to leave the coast because of too much risk. In such a situation, less pressure is on the ecosystems. Hence the coastal ecosystems are more resilient to face and adapt to natural events and extreme climatic conditions. By this means, providing the best benefits/services that can be obtained from the ecosystems (e.g., natural protections and decontamination of wetlands, flooding protection of wide beaches and dunes, resilience abilities of the buffer coastal zone to extremes, fisheries, beautiful wild coasts for tourism, etc.).

Under this scenario, more importance is given to environmental issues and nature conservation. People are long-term, risk-averse planners, who attempt to minimize environmental risk, even at high costs (Hofmann et al., 2005; Karageorgis et al., 2006). It assumes a general shift in attitudes of the stakeholders and policymakers towards more environmentally sound ways of life.

Although SLR remains a problem, policy responses are more flexible, for example, abandonment and managed realignment approaches with compensation for victims. The built environment expansion is discontinued, and a major recovery and reconversion of lost habitats are initiated to ensure increases in biodiversity. Overall, most coasts move closer to integrated coastal management systems, while in others, basic coastal management measures are put in place and historical zoning plans revitalized.

Policy responses at the coast embrace wholly integrated coastal management principles, and these principles are more effectively enabled because of voluntary partnerships across stakeholders and other participatory arrangements at the local level. This ‘bottom-up’ approach paves way for the implementations of the coastal sustainable development agenda (Burdon et al., 2018). Noteworthy, managed realignment brings with it several positive externality impacts. It produces more habitat with potential biodiversity, amenity, and recreational values; a more far-reaching nutrient and contaminants storage capacity; and a carbon sequestration function. All these potential economic benefits are apart from its sea defence or coastal protection benefits with regards to increased resilience in response to SLR and climate change, and so reduced maintenance costs.

During this period, there is an SLR of 1 m, storms and extreme wave events that cause a significant elevation in the coastal hazards. First, reaching the WAC low-lying sandy coasts and mangroves, and also coastal zones that are composed of easily erodible materials. Then the major lagoon systems are affected, and the lowest-lying sectors are subjected to increasing erosion or temporary or permanent submersion. But because the natural coastal systems are not passive about the rise in sea level, and there are numerous threshold effects. The natural systems respond by adapting to the new configurations. For instance, in the case of submersion hazard, sediments are trapped by coastal plant formations, river flow rates are modified by the variability of continental precipitations, and the lagoons and estuary outlets are partially closed by the advance of sand spits, etc.

According to the most recent study, the restored coastal wetlands can trap more sediment (Liu et al., 2021). The effectiveness of this restoration is primarily driven by sediment availability, and not by wetland elevation, tidal range, local rates of SLR, and significant wave height. This suggests that nature-based solutions can mitigate coastal wetland vulnerability to SLR. Though they are most effective in coastal locals where there is abundant sediment supply (Liu et al., 2021). Further, restoration of vegetated coastal ecosystems, such as mangroves or tidal marshes (coastal "blue carbon" ecosystems), provide climate change mitigation through increased carbon uptake and storage of around 0.5% of current global emissions annually (IPCC, 2019; Ungera et al., 2020).

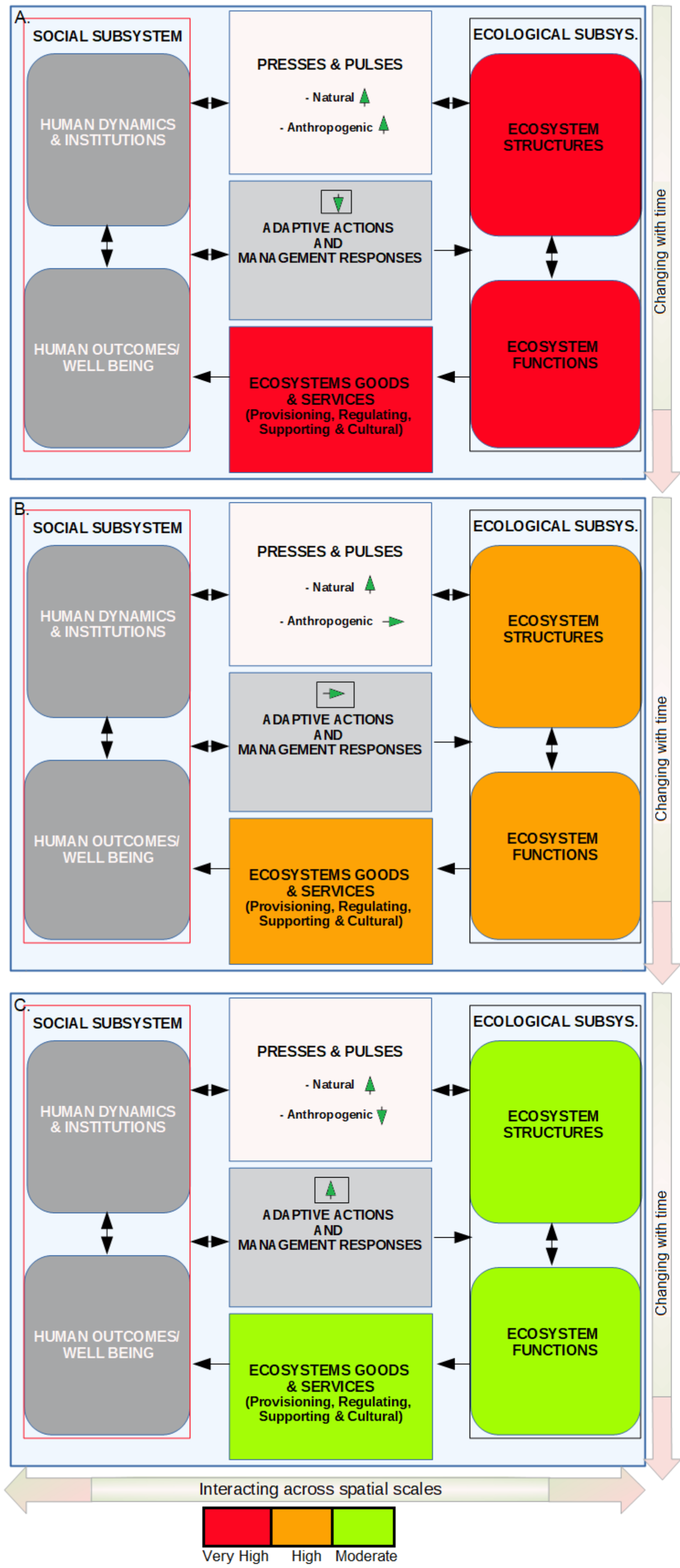
A.
SOCIAL SUBSYSTEM
HUMAN DYNAMICS & INSTITUTIONS
HUMAN OUTCOMES/ WELL BEING
PRESSES & PULSES
- Natural
- Anthropogenic
ADAPTIVE ACTIONS AND MANAGEMENT RESPONSES
ECOSYSTEMS GOODS & SERVICES (Provisioning, Regulating, Supporting & Cultural)
ECOLOGICAL SUBSYS.
ECOSYSTEM STRUCTURES
ECOSYSTEM FUNCTIONS
Changing with time
B.
SOCIAL SUBSYSTEM
HUMAN DYNAMICS & INSTITUTIONS
HUMAN OUTCOMES/ WELL BEING
PRESSES & PULSES
- Natural
- Anthropogenic
ADAPTIVE ACTIONS AND MANAGEMENT RESPONSES
ECOSYSTEMS GOODS & SERVICES (Provisioning, Regulating, Supporting & Cultural)
ECOLOGICAL SUBSYS.
ECOSYSTEM STRUCTURES
ECOSYSTEM FUNCTIONS
Changing with time
C.
SOCIAL SUBSYSTEM
HUMAN DYNAMICS & INSTITUTIONS
HUMAN OUTCOMES/ WELL BEING
PRESSES & PULSES
- Natural
- Anthropogenic
ADAPTIVE ACTIONS AND MANAGEMENT RESPONSES
ECOSYSTEMS GOODS & SERVICES (Provisioning, Regulating, Supporting & Cultural)
ECOLOGICAL SUBSYS.
ECOSYSTEM STRUCTURES
ECOSYSTEM FUNCTIONS
Changing with time
Interacting across spatial scales
Very High
High
Moderate

Figure 10 A-C. The three constructed future scenarios for the W. African coastal social-ecological systems in the 21st century. Each scenario will exert different pressures on the 21st coastal systems. In this context, the ecosystems will experience different (intensities of) pressures, and, consequently, different impacts on their integrity and functionality, thus implying different environmental risk for society. Note: The green arrows illustrate varying levels of effect (up = strong, down = weak, and horizontal = moderate). The red, orange and green colours depict different levels of adverse impacts.

5. Discussion

5.1 Diagnosing sustainable coastal management and planning along the WAC

In this study, we have presented an mPPD framework (Fig. 5) adapted to the integrated analysis of the coastal system that facilitates scenarios assessment (Fig. 10) under a range of plausible future climatic and socio-economic conditions to support decision-making. We evidenced that the vulnerabilities of the CSES are not independent, and it is inappropriate to consider a coastal issue in isolation. Rather, it requires analysis at a broader scale that accounts for interdependencies. Presently, this is generally not the case. For example, coastal flooding and erosion are usually assessed independently and the governance structures do not always match the scale at which management is required.

Our cross-cutting narratives of the different future scenarios using the mPPD framework offer valuable insight into the development of WAC management strategies, policies and other agendas. The scenarios analysis is to help in defining the plausible implications of following, or not, a particular management path. This also helps to highlight internal conflicts and inconsistencies, for example between the aspirations of different resource users or countries in the region.

The assessment of the WA coastal ecosystems using our framework (Figs 8, 9; Table 1) brings to the fore lack of coordination of various human activities taking place on land and in the coastal zone relating to their implications on the coastal ecosystems. This is partly due to the disconnection/fragmentation of institutions and weak coastal governance. And it is responsible for the conflict over the use of resources and forgoes opportunities for more sustainable coastal development planning along the WAC.

The continued sectoral or piece-meal approaches to managing the WAC has continued to exacerbate coastal vulnerability. When this is combined with the implications of climate change due to global warming, it is likely to get worse (Oppenheimer et al., 2019). The rising and continuing human activities (in form of economic activities, urbanization, resources exploitation, tourism, land use and conversion, infrastructural development) call for new requirements for adaptation. So also, the challenges of new sources and forms of change (climate change, extreme wave events, storm surges, sea-level rise), and the increasing complexity of policy goals (e.g., related to the duplicity of responsibilities and acute multi-use conditions). New forms of adaptive governance that consider the coastal situation and the governance path is therefore necessary for the WAC.

5.2 Strengthening integrated and sustainable management of WACA ecosystems

It has been argued that the traditional governance framework is inadequate to ensure the sustainable use of marine and coastal resources and to safeguard the global commons for human wellbeing and intergenerational equity (Borgese, 1999). Besides, more recent developments along global coasts, coupled with future scenarios, further challenge the governance mechanisms and the need for regionally, cross-border coordinated efforts. In the present study, the mPPD framework lays bare important information that helps to connect different processes that occur in the coastal system (Fig. 5). Consequent decoupling of different components of the coastal systems via case studies (Figs 8,9), followed by the construction of the plausible 21st coastal scenarios for the WAC (Figs 6,7,10) allows identification of the gaps and where management actions may be necessary. As earlier mentioned, the identified management actions or responses constitute an attempt at proffering solutions to those identified issues.

Given the importance of the coastal zone to WA populations and the economy of the region at large, there is an urgent need to adopt a long-term management paradigm that promotes sustainable and equitable utilization of coastal resources. However, to safeguard and achieve the sustainable use of the WAC resources, the future coastal governance of this region is faced with a two-directional challenge. The first is to integrate a range of crosscutting local to global environmental challenges. These are often associated with unsustainable exploitation and utilization of coastal resources, an increasing population as opposed to earthly diminishing resource, the weakening resilience of natural ecosystems, combined with anthropogenic climate change and variability. The second challenge rests on how to address the complexity of an already overburdened and fragmented coastal system governance. Many activities taking at several places on land have consequences on the coast, while the coastal areas are equally under the pressure of competing for land uses (Walsh and Döring, 2018).

This two-directional governance challenge can be achieved in the mPPD framework. First, in the mPPD, a wide range of crosscutting local, regional and global environmental issues occurring in a coastal system can be linked through the instrumentality of press and pulse dynamics (refers to Fig. 5). As shown in Figure 5, the mPPD interlinks the traditional four core PPD framework components (i.e., the press-pulse events, ecological subsystem, ecosystems goods and services, and social subsystem; see Fig. 1) of a complete earth system; and in our case, the coastal system. Thus, the mPPD can be concurrently applied locally, nationally, regionally and globally, e.g., at different scales relevant for ecological processes and potential drivers of change. This shows there is no limit to the scale of application or analysis whether large or small.

The second challenge, which dwells on how to address the complexity of an already overburdened and fragmented coastal system governance, is addressed by the mPPD with the coupling of an extra management component (i.e., adaptive actions/ management responses) to the traditional PPD (Fig. 1).

The mPPD can accommodate all activities taking at several places on land that have consequences on the coast, even those taking place within the coastal system. For example, the upland river damming. The framework advances understanding on coastal issues that come about, possibly, owing to inadequacy in coastal management apparatuses at governance levels or weak human and institutional capacity or lack of public awareness about coastal issues or low stakeholders' interest in the efficient and sustainable use of the coastal potential and resources. The coastal situation, from the mPPD management viewpoint, focuses on different forms of dependencies, observational complexity, and multiplicity of boundaries, supporting each other into a need for policy integration.

5.3 Management efforts at addressing coastal challenges along the WAC

While our study should be considered as a significant contribution towards providing decision-makers with some information and a tool to support integrated coastal zone management, key challenges remain, how to lessen the vulnerability of WAC populations to climate impacts and the implementation of appropriate governance processes for the management of a transition towards a more sustainable coast. Within the WA there are, however, moves to develop a more holistic approach to coastal risks management (UEMOA, 2017), and recently there has been a range of strategies, consultations and planning documents produced that impact the management of the WAC. Notable is the creation of the West African Coast Master Plan (SDLAO) which involves 12 countries (From Mauritania to Nigeria) and the establishment of the West African Regional Coastal Observation (WARCO).

The WARCO has the mandate to monitor shoreline and reduce coastal risks in WA and disseminate good quality information among WA advisory and existing decision-making bodies. While the SDLAO is saddled with identifying coastal area issues and national coastal risks in a wide context, by emphasizing on inter-State's solidarity and reciprocity for shoreline management. Also, it has the responsibility to identify priority coastal issues and analyze the performance of the government's existing instruments for the management of different issues. Shoreline Management Plans include the division of the entire WAC into 179 sectors based on the relationship between observed characteristics of coastal sensitivity and local communities' issues (UEMOA, 2017).

Other important initiatives include the establishment of the West Africa Coastal Areas Management Program (WACA) in 2015 by the World Bank Group as part of its long-term strategic engagement in the region. The program is designed to improve the livelihoods of WAC communities by reducing the vulnerability of its coastal areas and promoting climate-resilient integrated coastal management. It aims to work with the region's countries to create multi-year, multi-country coastal management initiatives that will be implemented in several stages, in collaboration with other development partners.

One of the projects under the WACA program is the $210 million WACA Resilience Investment Project (WACA ResIP) to address coastal erosion, floods and pollution problems in selected target areas of six WA countries of Benin, Cote d'Ivoire, Mauritania, Sao Tome and Principe, Senegal and Togo. The project was developed in collaboration with four regional institutions - the West African Economic and Monetary Union (WAEMU), the Abidjan Convention, the Dakar-based Center for Ecological Monitoring (CSE), and the International Union for Conservation of Nature (IUCN). It is jointly funded by the Nordic Development Fund, and the French Facility for Global Environment (FFEM). More partners are joining the effort through a new WACA Platform that has been set up to boost the transfer of knowledge, mobilize additional finance and foster political dialogue among countries, and protect the West African coast. The WACA Platform has created a coastal master plan through the exchange of knowledge, crowding in investments, and political dialogue among countries (World Bank, 2018).

Also, part of the WB's efforts is the setting up of the Africa Centre of Excellence in Coastal Resilience (ACECoR) hosted by the University of Cape Coast (UCC), Ghana to support the development of the technical and scientific capacity of young African professionals to develop integrated solutions to address coastal degradation through short- to long-term professional and academic training programmes.

Besides, when it comes to coastal research and human capacity development, both WA and non-WA research institutions are involved. One of such non-WA research institutions is the Institut de Recherche pour le Développement (IRD; the French National Research Institute for Sustainable Development), an internationally recognized multidisciplinary French research organization. The PSIP research group under the IRD's Oceans, Climate and Resources (OCEANS) Department is training young researchers from WA institutions of which the first author is a beneficiary. IRD is also jointly working with WB and UCC to develop a coastal Policy Brief for the WA policymakers.

The coastal countries in the region are also making other substantial efforts. For instance, in July 2019, the Environment Ministers to the Abidjan Convention met in Abidjan and deliberated on steps at achieving the conservation and sustainable management of marine and coastal ecosystems. The Abidjan Convention provides countries in the region with the tools and information they need to safeguard the fragile coastal ecosystems and the people and biodiversity that depend on them. The 18 Parties to the Convention signed four Protocols designed to improve the management of their respective and collective ocean and coastal zones. The four Protocols are the Pointe-Noire Protocol which provides sustainable approaches to Integrated Coastal Zone Management (ICZM). The Calabar Protocol provides a technical framework to ensure the sustainable management of mangroves. The Malabo Protocol determines minimum standards to combat the risks associated with pollution caused by oil and gas activities. While the Grand-Bassam Protocol focuses on regulating the land and atmospheric sources of pollution.

5.4 The Way Forward- Interdisciplinary approaches

Studies have shown that about 40% of the present WA's GDP is generated in coastal provinces, where one-third of the population resides (World Bank, 2018). This is bound to continue. So, whether resources provided by the ecosystem are exploited for local uses or exported, demand for ecosystems goods and services will continue to increase. This will result in overexploitation and activities that will cause further coastal degradation (in terms of erosion and flooding), habitat loss, pollution. Intensity from human use, coupled with the sea-level rise due to climate change, will either lead to moderate or very high or extreme impacts on the WAC ecosystems (Fig. 10).

Planning for the future use of the goods and services offered by the coastal ecosystems will continue to be influenced or disturbed by unpredictable events, whether within the social ecosystem or natural ecosystem. Adopting an exploratory and synthetic approach to the three pathways, uncertainties in future, especially drastic changes or surprises, may require greater resilience within the WAC systems. It will be beneficial to follow plausible future shocks and integrate anticipatory adaptive actions and dynamic, sustainable management policies in responses as the situation may require. There is a need to initiate a scenario-based approach within future science policy fora of the WACA Platform and WARCO regarding the management of WAC resources, to detail future anticipation using interdisciplinary approaches, to define the key challenges and risks facing policies, marine- and coastal-related interdisciplinary research and development in the WAC region in the next century. This will allow more informed anticipation of the management, research and policy need in various sectors, over the medium and long terms.

Most of the management efforts at addressing WAC challenges are sectoral-oriented and designed to address specific environmental problems. These management interventions are concentrated at the coastal zone, and their design and configuration do not usually account for linkages between the realms (land-coast interactions). To compound matter, most anthropogenic pressures, including land-based activities, that translate into ecological and socio-economic challenges at the coast are possibly located far from their source or in jurisdictional areas under different governance regimes. Yet these coastal-related activities are regulated and managed by sector-specific rules and bodies that are not designed to consider cumulative and transboundary impacts or cannot consider impacts on coastal ecosystems.

According to Wilson et al. (2005), the critical role of managing a natural environment in conservation management is to mitigate or prevent proximate threats. Coastal management involves the consideration of cross-system threats that can have significant impacts on coastal ecosystems. Incorporating cross-system threats into the coastal management plan entails identifying those threats that are most critical for coastal and marine conservation and mapping their sources and zones of influence, and also evaluating their magnitude and potential impacts (Álvarez-Romero et al., 2011). Thus, an assessment of both single-realm and cross-system threats is necessary for sustainable coastal management of the region. This may require strengthening collaboration among countries involved.

Our scenario analysis (Figs 6, 7, 10) identified ‘governance’ as the key driver to sustainable management and conservation planning of the WAC and its resources. Presently, the coastal governance and institutional structures at different levels in the region are weak and fragmented. This fragmentation is obvious in the sectoral institutions set up for the management of the different human activities and jurisdictional differences. While specialization of regulation is needed to manage specific sectors, the lack of coordination between sectoral approaches makes it difficult to achieve integrated management of pressures from various impacts and activities or to assess their cumulative effects. This also complicates the implementation of integrative horizontal policies for sustainable coastal development.

Therefore, strengthening and integrating coastal governance at all levels and across all actors is necessary to achieve sustainable management goals. All institutions and actors in the region should be adequately equipped to coordinate or cooperate across sectors and achieve effective measures, or to translate important sustainability principles, such as the ecosystem approach, or transparent and inclusive decision-making processes, into practice.

6. Conclusions and closing remarks

The mPPD-CSES framework presented in this study is a simplified representation of the links between human and overwhelmingly natural coastal ecosystems. It is grounded by the interdisciplinary and cross-cultural understanding crucial to bring together the information of a wide range of knowledge systems and stakeholders on the status, trends and vulnerabilities of the coastal ecological systems, what to do about them now and what to expect in the future.

We evidenced that by helping to identify the important components and interactions that are the causes of and solutions to detrimental changes in the CSES and subsequent loss of their ecological benefits to present and future generations, the mPPD framework has the potential to be useful with no limit to the scale of application or analysis, whether large or small. In this context, the mPPD-CSES framework can be used to investigate how the ecosystems can experience different (intensities of) press as well as different frequencies of pulse and, consequently, different impacts on their integrity and functionality, and articulate the plausible future reciprocal relationship between the natural- and social sub-systems within the coastal to understand changes and the pathways to successful coastal zone management and adaptation.

For the WAC ecosystems to be managed sustainably, there is a need to follow a plausible future pathway that integrates anticipatory adaptive actions and dynamic, and sustainable management policies in responses as the situation may require. There is also a need to initiate a scenario-based approach within future science policy fora of the WACA Platform and WARCO regarding the management of WAC resources, to detail future anticipation using interdisciplinary approaches, to define the key challenges and risks facing policies, marine- and coastal-related interdisciplinary research and development in the WAC region in the next century. This will allow more informed anticipation of the management, research and policy need in various sectors of the region, over the short, medium and long terms.

Acknowledgements

This work was carried out as part of the IRD PSIP-Littoral Project for the study of coastal vulnerability in West Africa through the construction of an interdisciplinary model and capacity building. The first author is grateful to the IRD for granting him a postdoctoral fellowship.

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