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# 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 21<sup>st</sup>-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

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

37

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

40

## 41 **1. Introduction**

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

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

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

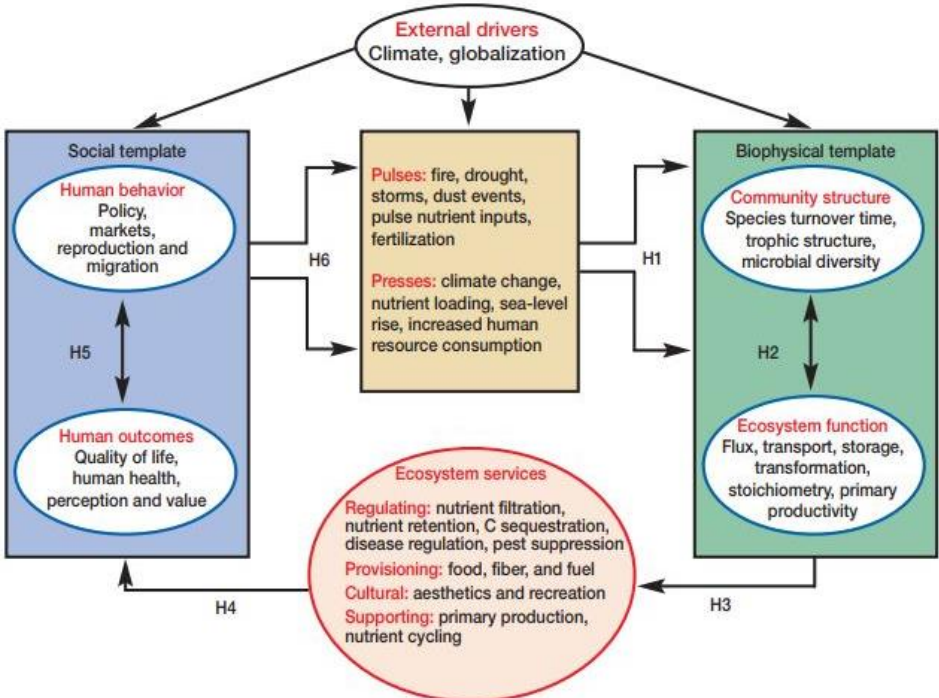
64 Notwithstanding their value to human wellbeing, coastal ecosystems are under threat from an  
65 increasing population, resource exploitation, and global environmental change (e.g., climate  
66 change) (MEA 2005; Lotze et al. 2006). In recent times, coastal SES is experiencing intense  
67 social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

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

78 Considering the wide range of drivers and pressures in coastal SES, it has been recognized  
79 as overdeveloped, overcrowded, and overexploited (Hinrichsen 1998), as well as over-exposure  
80 to global environmental changes (Hossain et al. 2020). A better understanding of coupled social-  
81 ecological interactions within the coastal system is vital for implementing developmental  
82 strategies that will optimize human well-being and sustain ecosystems and the resources they  
83 generate (Rangel-Buitrago et al., 2015; Willcock et al. 2016; Guerrero et al., 2018; Gain et al.  
84 2019). Coastal systems comprising both social and ecological components, with inherent  
85 interdependencies across multiple scales can be conceptualized as an SES (Gain et al. 2020).  
86 Various frameworks have been developed and used for the adaptive management of SES (Gari  
87 et al., 2015). For example, the Outcome Approach was used to evaluate the progress of  
88 Integrated Coastal Management (ICM; Olsen, 2003). The Millennium Ecosystem Assessment  
89 (MEA, 2005) applied a framework connecting drivers, ecosystem services and human well-being.  
90 Ostrom (2009) developed a general framework for evaluating SESs. A Systems Approach  
91 Framework (SAF) is equally developed and applied to complex coastal systems in facilitating the  
92 European environmental policies implementation for sustainable development (Newton, 2012).

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

102 Since Collins et al. (2011) SES framework can represent the various phenomena and  
 103 interactions occurring on coasts, we hypothesized that it can be deployed to develop coastal  
 104 scenarios of change. Developing a scenario means all important information should be  
 105 considered, both at the boundaries of the system and inside it. To test the possibility of  
 106 constructing a complete scenario using the framework, we seek to apply such an approach to the  
 107 West Africa coastal (WAC) areas.  
 108



109  
 110 Figure 1. The *press-pulse dynamics* (PPD) framework of Collins et al. (2011). Framework hypotheses: H1  
 111 - long-term press disturbances and short-term pulse disturbances interact to alter ecosystem structure and  
 112 function; H2 - biotic structure is both a cause and a consequence of ecological fluxes of energy and matter;  
 113 H3 - altered ecosystem dynamics negatively affect most ecosystem services; H4 - changes in vital  
 114 ecosystem services alter human outcomes; H5 - changes in human outcomes, such as quality of life or  
 115 perceptions, affect human behaviour; H6 - predictable and unpredictable human behavioural responses  
 116 influence the frequency, magnitude, or form of press and pulse disturbance regimes across ecosystems  
 117 (Collin et al., 2011).

118  
 119 **2. West Africa coastal areas case study**

120 **2.1 The WAC Settings**

121 The West African coast (WAC) covers 12 mainland countries, from Mauritania to Nigeria (and the  
 122 main focus of this study; Fig. 2), and two archipelagos of Sao Tome and Principe and Cape Verde.  
 123 The mainland WAC can be categorized into three major sectors based on their geo-environmental

124 properties and metocean driving forces (Alves et al., 2020; Ibe and Awosika, 1991). The  
125 Northwest sector (from Mauritania to Guinea Bissau), the muddy and sandy West coast (from  
126 Guinea-Bissau to Sierra Leone) and the Gulf of Guinea sector (from Liberia to Nigeria). This coast  
127 presents a unique coastal geomorphic variability. Starting with the narrow continental shelf, sandy  
128 dune-bound coasts of Mauritania, Senegal and Gambia, and their commonly narrow spits  
129 bounding estuaries. It continues to the transitional muddy Guinea-Guinea Bissau-northern Sierra  
130 Leone sector. Here, the cliff-bound coasts and mangrove-rich open estuaries are favoured owing  
131 to the strong wave dampening effect and tidal range amplification caused by widening continental  
132 shelf related to geological offsetting of the shelf by the Guinea and Sierra Leone fracture zones.  
133 And finally, to the narrow shelf, bounded by massive rectilinear sandy beach-ridge complexes  
134 with diverted river systems and back-barrier lagoons from southern Sierra Leone to the Niger  
135 Delta (Anthony and Blivi, 1999; Feka and Morrison, 2017; Alves et al., 2020).

136 The climate along the WAC is equatorial, with considerable differences in the amount and  
137 seasonal distribution of the precipitation. It is characterized by the interchange of two important  
138 drivers: the Atlantic Ocean and the Sahara. In the first order, both temperature and precipitation  
139 and their annual cycle depend on how the air masses associated with the dry and hot desert  
140 interior and the humid ocean to the south and the west, interact (Lewis and Buontempo, 2016).  
141 In terms of hydrology, the WAC is strongly influenced by the river basin drainages. The most  
142 important rivers include the Niger, which drains an area of over 1 million km<sup>2</sup>; the Volta, with a  
143 drainage basin of 390,000 km<sup>2</sup>; and the Senegal River, the second-longest river in West Africa,  
144 with a catchment area of nearly 450,000 km<sup>2</sup> (Diop et al., 2014; Anthony, 2015; Anthony et al.,  
145 2016). However, the hydrology and sediment flow of these rivers have been significantly altered  
146 due to river damming, thereby limiting sediment supply to the coast (Anthony, 2015; Anthony et  
147 al., 2016, 2019; Dada et al., 2015, 2016a, 2018; Diop et al., 2014; Ly, 1980).

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



158 The tidal ranges along the WAC are wide, exceeding 5 m in some places, with the average  
 159 for the whole coastal area being considered in the order of 1 m. The highest tidal ranges recorded  
 160 in the region are in Guinea-Bissau, Guinea, and Sierra Leone (from 2.8–4.7 m; [Diop et al., 2014](#)).  
 161 Three distinct and relatively persistent oceanic current systems are of importance to the WAC  
 162 ecosystems ([Fig. 2](#)) are: (a) The cold Canary Current, (b) The North Equatorial Countercurrent;  
 163 and (c) The Guinea Current ([Diop et al., 2014](#)). The Canary Current itself transports cool waters  
 164 toward the Equator and has current speeds of approximately 20 cm.s<sup>-1</sup>. The cool and richer  
 165 upwelling waters prevail along the northwestern part and at limited parts of the northern parts of  
 166 the Gulf of Guinea.  
 167



168  
 169 **Figure 2.** The West Africa coast (WAC) showing main coastal cities and population, ports and harbours,  
 170 rivers and marine currents, and the two case studies areas (modified after [Diop et al., 2014](#)).  
 171

172 **2. 2 The WAC present state and trends**

173 In WAC areas, socio-economic activities are increasingly affecting the coastal and marine  
 174 environment. Over-exploitation of coastal resources and ecosystems is currently a serious and  
 175 accelerating phenomenon in the region ([Fig. 3](#)). Many coastal communities depend on coastal  
 176 resources for their livelihoods, mostly for food, fuel, shelter, and income ([Diop et al., 2011](#)). Owing  
 177 to increasing population pressures and a lack of alternative resources to sustain populations,

178 resource exploitation is becoming unsustainable. In many coastal areas, important coastal  
179 habitats, such as mangrove forests, seagrass beds, and coral reefs, are degraded or destroyed,  
180 making way for agriculture, aquaculture, port/ harbour development, hydropower dam and urban  
181 development (Diop et al., 2011).

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

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

203 Throughout the region, the shorelines are retreating (Almar et al., 2015, 2019; Andrieu,  
204 2018; Anthony et al. 2016, 2019; Anthony and Blivi, 1999; Appeaning-Addo, 2009; Appeaning  
205 Addo et al., 2009, 2013; Angnuureng et al., 2013, 2017; Dada et al., 2015, 2016a, b, 2018, 2019;  
206 de Boer et al., 2019; Laibi et al., 2014; Ozer et al., 2017; Sadio et al 2017; Giardino et al., 2018;  
207 Ndour et al., 2018) and the major contributing factors are the construction of ports and harbours  
208 (de Boer et al., 2019, Almar et al., 2015, Anthony et al. 2016, 2019), coastal engineering defence  
209 (Appeaning Addo et al., 2013; Angnuureng et al., 2013), and recreational facilities, which have  
210 led to the clearing of important coastal vegetation, including mangrove forests (Andrieu, 2018;

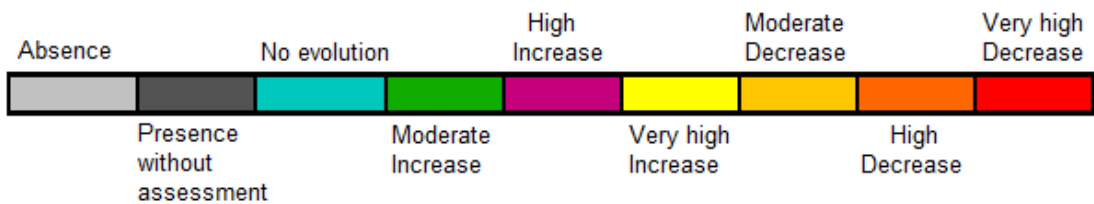


211 [Andrieu and Mering, 2008](#); [Boone et al., 2016](#)), and the reclamation of coastal wetlands ([Giardino](#)  
212 [et al., 2018](#); [Güneralp et al., 2017](#)).

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

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

Country	Location	Beaches	Mangroves	Mudflats	Sea grasses	Forests	Estuarine channels	Rocky bottoms	Coral reefs
Gambia	Baobolon	Yellow	Yellow	Yellow	Grey	Grey	Cyan	Grey	Grey
	Niumi	Yellow	Yellow	Yellow	Grey	Green	Green	Grey	Grey
	Tanbi	Yellow	Yellow	Yellow	Grey	Grey	Cyan	Grey	Grey
	Tanji	Yellow	Yellow	Yellow	Grey	Grey	Cyan	Grey	Grey
Guinea	Alcatraz	Cyan	Cyan	Yellow	Grey	Cyan	Grey	Grey	Grey
	Iles de Loos	Yellow	Orange	Yellow	Yellow	Yellow	Yellow	Yellow	Orange
	Tristao	Cyan	Cyan	Yellow	Grey	Cyan	Grey	Grey	Grey
Guinea Bissau	Cacheu	Grey	Green	Grey	Grey	Magenta	Grey	Grey	Grey
	Cantanhez	Yellow	Yellow	Yellow	Grey	Green	Grey	Grey	Grey
	Joao Vieira Poilao	Yellow	Yellow	Yellow	Grey	Green	Grey	Grey	Grey
	Urok	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
Senegal	Abene	Orange	Green	Yellow	Grey	Orange	Grey	Grey	Green
	Bamboung	Grey	Yellow	Green	Grey	Yellow	Grey	Grey	Grey
	Cayar	Yellow	Grey	Grey	Grey	Grey	Grey	Grey	Grey
	Gandoul	Grey	Yellow	Yellow	Grey	Yellow	Yellow	Grey	Grey
	Iles de la Madeleine	Orange	Grey	Grey	Grey	Green	Grey	Grey	Grey
	Joal-Fadiouth	Yellow	Yellow	Grey	Grey	Grey	Grey	Grey	Grey
	Kawawana	Grey	Grey	Grey	Grey	Grey	Grey	Grey	Grey
	Langue de Barbarie	Orange	Green	Yellow	Grey	Yellow	Red	Grey	Grey
	Palmarin	Yellow	Dark Green	Orange	Grey	Dark Green	Yellow	Grey	Grey
	Popenguine	Light Green	Grey	Grey	Green	Dark Green	Grey	Grey	Grey
	Saint-Loius	Orange	Orange	Orange	Grey	Orange	Orange	Yellow	Grey
	Sangomar	Yellow	Yellow	Grey	Grey	Yellow	Grey	Grey	Grey
	Somone	Yellow	Magenta	Orange	Grey	Grey	Orange	Grey	Grey



235

236 Fig. 3. Summary of the evolution of the WAC ecosystems in marine protected areas in the last 10 years  
 237 (Adapted from Failler et al., 2020a).  
 238

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

240 *3.1 The process of developing a conceptual framework for the WAC systems*

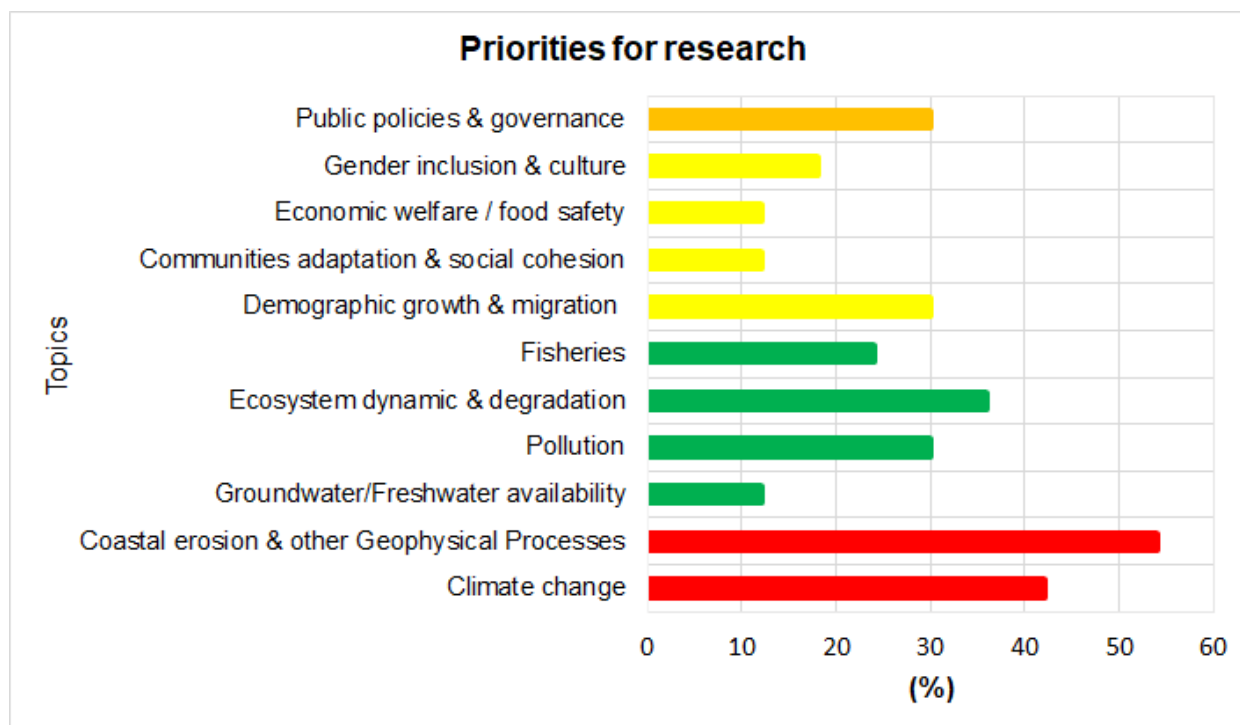
241 As a consequence of the issues mentioned above, an interdisciplinary workshop was organized  
 242 by the Interdisciplinary Partnership Programmes (PSIP) research group of the French National  
 243 Research Institute for Sustainable Development (IRD) in March 2019 at Saint Louis, Senegal.

244 The meeting focused on finding a solution to the vulnerability of coastal areas in West Africa in

245 the context of global change. It was well-attended by over 60 African and non-African experts and  
 246 other stakeholders with expertise in different fields that ranged from marine ecology, physical  
 247 oceanography, coastal dynamics and modelling, geography, social sciences, economics, political  
 248 science, coastal remote sensing, coastal ecosystems and adaptation, regional sea level, coastal  
 249 impacts, coastal evolution, meteorology and climate dynamics, hydrogeology, geophysics,  
 250 coastal and marine geology, atmospheric sciences, etc. Representatives of relevant WA  
 251 government ministries and financial institutions like the French Development Agency (AFD)  
 252 group funds and the World Bank were in attendance.

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

261



262 Fig. 4. Types of drivers, pressures and other phenomena to be addressed as priorities for research  
 263 according to the participants of the Saint-Louis workshop (% of people)  
 264  
 265

### 266 3.2 Key features of the modified press-pulse dynamics (mPPD) Framework

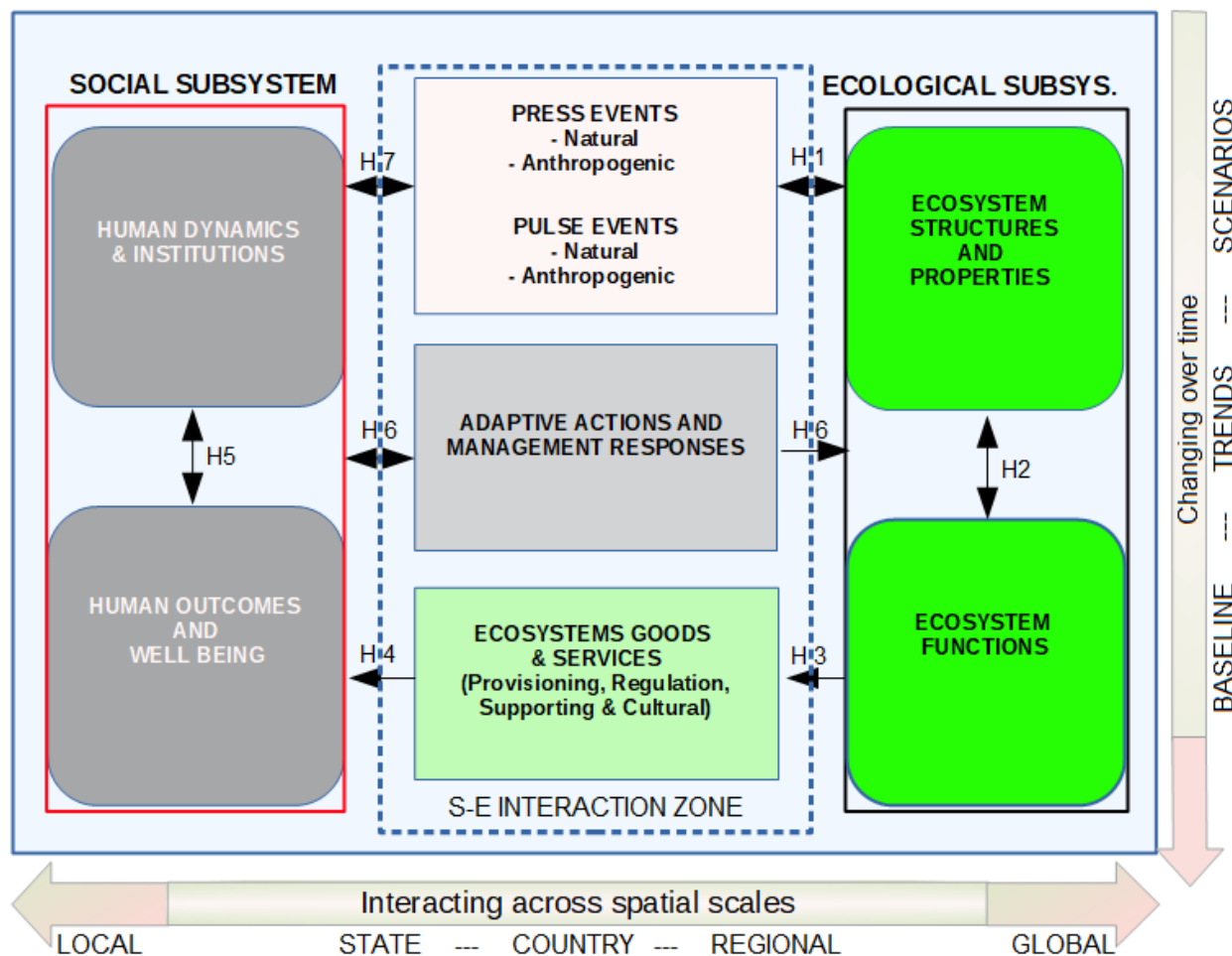
267 The traditional PPD framework (Fig. 1) by Collins et al. (2011) has four interlinked core  
268 components (press-pulse events, ecological subsystem, ecosystems goods and services, and  
269 social subsystem). We modified the framework (hereafter refers to as mPPD) to achieve our  
270 desired objective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

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

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

297 An adaptive management approach is especially important for coastal planning due to the  
298 uncertainty and complexity associated with planning across sectors. Some sources of uncertainty  
299 are our limited knowledge of coastal system interactions and dynamics, lag times between

300 implementation of actions and measurable results, and difficulties in predicting climate change,  
 301 land-use change, and their potential impacts on coastal ecosystems (Álvarez-Romero et al., 2011;  
 302 Broderick, 2008). The “adaptive actions/management responses” component is set at the centre  
 303 of the framework to create links between the social and ecological subsystems, which should be  
 304 developed by the coastal managers to directly influence the stakeholders’ actions towards  
 305 environmental-friendly activities/behaviours.  
 306  
 307



308  
 309 Fig. 5. The mPPD framework. The left-hand side represents the human subsystem, and the right represents  
 310 the ecological subsystem. The two subsystems are connected by pulse and press events indirectly caused  
 311 or influenced by human behaviour. Then, the ecosystem goods and services that are made available to  
 312 humans may eventually trigger management responses that influence the frequency, magnitude, or form  
 313 of press and pulse events across ecosystems, if not satisfactory. Note: The horizontal double arrow  
 314 illustrates the required varying spatial resolutions used to build our assessments at the regional scale. The  
 315 vertical double arrow indicates the baseline, trends and scenarios as a function of time scale.  
 316

317 *3.3 Building futures Scenarios with mPPD framework*

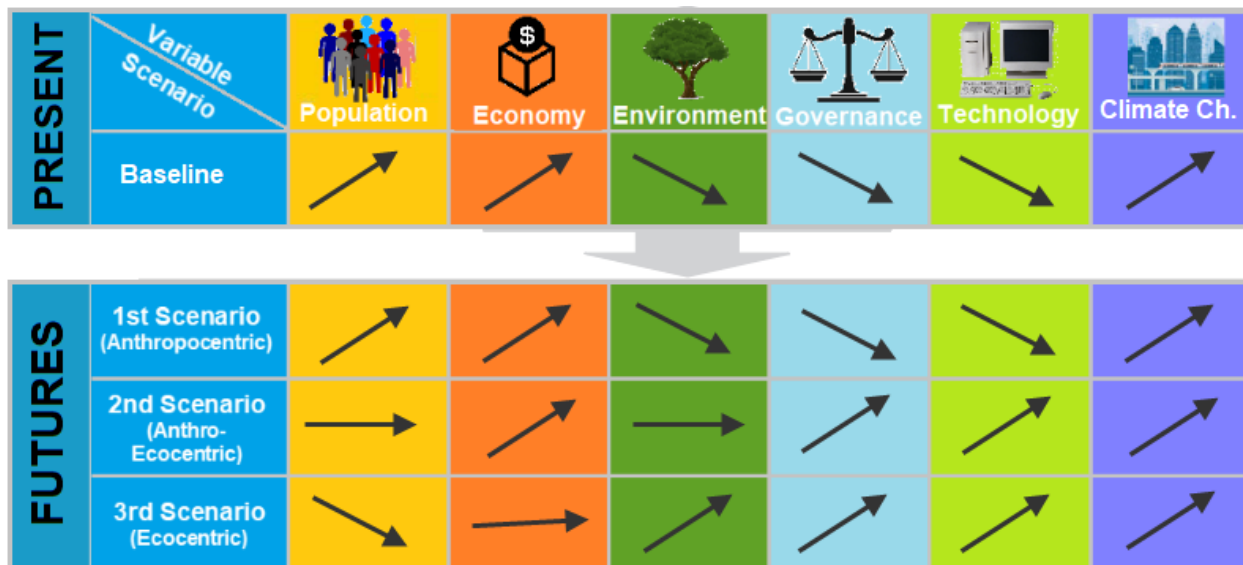


318 In attempts to get beyond the analytical constraints posed by the formal integrated models, a  
319 scenario formulation is one of the approaches that can be used to tell stories, in words and  
320 numbers, of plausible development that may arise in the future (Ruttan, 1999). They are  
321 constructed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

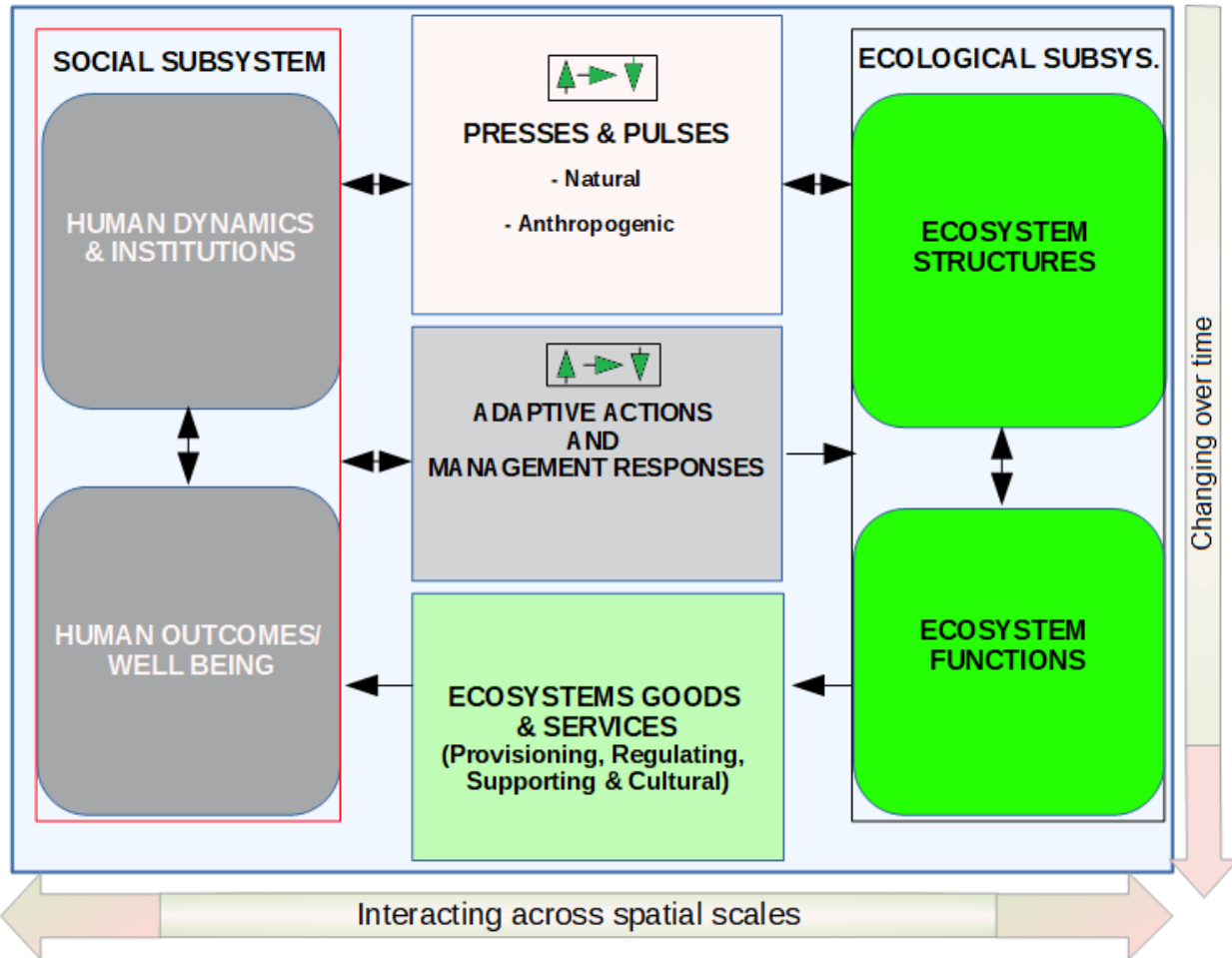
331 As shown in Fig. 6, the three different social-economic scenarios constructed can be  
332 employed to understand the dynamics and intrinsic vulnerabilities of the 21st-century coast  
333 anywhere in the world, but here deployed to the WAC region. The narrative of these scenarios is  
334 based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

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

347



348  
 349 **Fig. 6.** Typical (anthropocentric, anthro-ecocentric and ecocentric) scenarios illustrating plausible future of  
 350 WAC. All three scenarios are developed over time along the six indicators (i.e., population growth, economic  
 351 development, environmental quality, governance and institution, technological change, and climate  
 352 change), which are interdependent. Note: The arrows (up = strong, down = weak, and horizontal =  
 353 moderate) are projected as uneven representations of just possible patterns of change in the WAC.  
 354  
 355



356  
 357 **Figure 7.** A generic future scenario for the coastal social-ecological system (CSES) in the 21<sup>st</sup> century. The  
 358 ecosystems will experience different (intensities of) pressures, and, consequently, different impacts on their  
 359 integrity and functionality, thus implying different environmental risk for society. Note: The green arrows  
 360 under “presses and pulses” and “adaptive action and management responses” panels illustrate varying  
 361 levels of effect: up arrow = strong, down arrow = weak, and horizontal arrow = moderate.  
 362  
 363

364 **4. Application of the framework**

365 We applied the mPPD framework to the Bight of Benin and the WA mangrove system (Fig. 8, Fig.  
 366 9; Table 1). Then, we used it to conceptualize the 21<sup>st</sup> CSES scenarios (Fig. 10). The case studies  
 367 are based on previous literature and expert’s judgement.  
 368

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

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

Shoreline Retreat (Bight of Benin; 1990-2015)	Climate change <sup>1,2</sup> ; sea-level rise <sup>3,4</sup> ; seaport development <sup>5,6</sup> ; river dams <sup>7,8</sup> ; engineering structure/ installation <sup>9,10</sup> ; coastal development <sup>11,12</sup> ; harbour construction with breakwaters <sup>13,14</sup> ; urbanization <sup>11,12</sup> ; land use/ conversion <sup>15,16</sup> .	Increasing extreme events <sup>17,18</sup> ; wave climate <sup>19,20</sup> ; rainfall variability <sup>21,22</sup> ; storm surge <sup>23</sup> ; sand mining <sup>7,24</sup> ; river mouth and channel dredging <sup>25</sup> .	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 <sup>25</sup> , sea-level rise <sup>26</sup> , increasing sea surface temperature <sup>27</sup> , land use/ conversion <sup>28,29</sup> , oil spill/ pollution <sup>30,31</sup> , coastal development <sup>31,32</sup> ,	Woodcutting/ harvesting <sup>31</sup> , aquaculture <sup>32</sup> , drought/ rainfall <sup>22,33</sup> , extreme weather events <sup>34</sup> ; Rice cultivation <sup>31</sup> ; Dam construction <sup>35</sup>	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, reseedling/ replanting, marine and coastal policy formulation, public sensitization and awareness, community engagement, monitoring & regulation

372 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);  
373 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);  
374 11: Badmos et al. (2018); 12: Denis & Moriconi-Ebrand (2009); 13: Kaki et al. (2011); 14: Giardino et al. (2018); 15: Andrieu  
375 (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);  
376 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  
377 & Awosika (1991); 27: Biasutti (2019); 28: Andrieu & Mering (2008); 29: Boone et al. (2016); 30: Feka & Ajonina (2011); 31:  
378 Ekundayo & Obuekwe (2001); 32: Diop et al. (2011); 33: Nicholson (2013); 34: Taylor et al. (2017); 35: Tendeg et al. (2016).  
379

#### 380 **4.1 Application to the vulnerability of low-lying West African coastal ecosystems**

##### 381 **Case study 1: The response of the Bight of Benin coastline to anthropogenic and natural** 382 **forcing (Fig. 8; Table 1; adapted from Anthony et al., 2019)**

383 The Bight of Benin in the Gulf of Guinea (Fig. 2) forms an embayment between the Volta River  
384 Delta in the west (Ghana) and the Niger River Delta (Nigeria) in the east (ecological subsystem).  
385 The Bight coast comprises sandy beaches backed by Holocene beach-ridge barriers (ecological  
386 subsystem). Incident swell waves, beach face gradient and the unidirectional longshore sand  
387 transport from west to east are intimately linked, generating a classic example of a strongly wave-

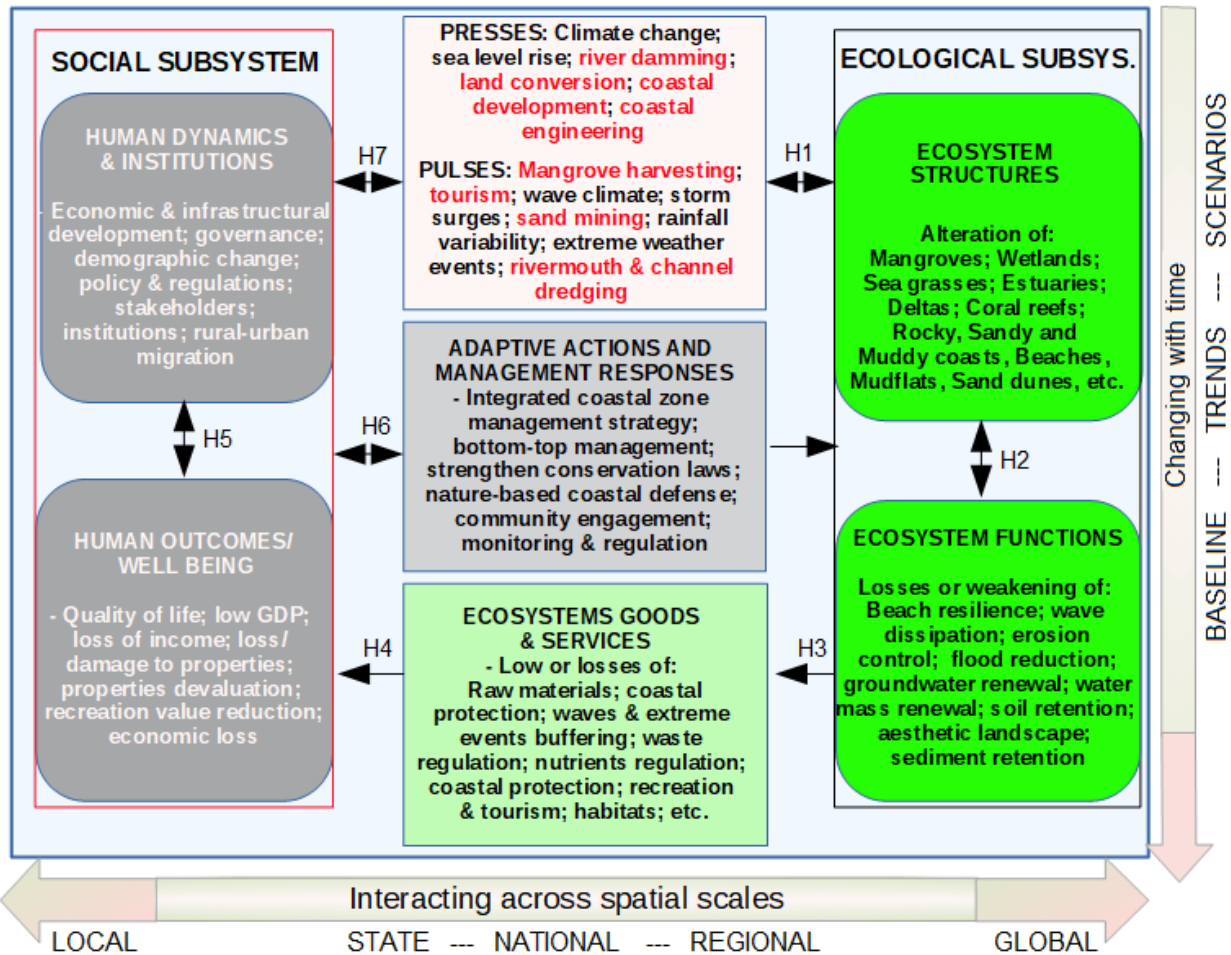
388 dominated drift-aligned coast (ecological subsystem). The stability of this coast, which hosts  
389 several major cities in addition to three large international deep-water ports, has been strongly  
390 affected by human activities (social subsystem as highlighted in Fig. 8), including the three ports  
391 (H7), and by natural and human-altered shoreline dynamics (H1) related to the Volta River Delta  
392 and distributaries at the northwestern flank of the Niger Delta. The combination of these factors  
393 has impacted alongshore sediment redistribution by segmenting the previously unrestrained  
394 longshore transport of sand that prevailed along this open coast (H2, H3).

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

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

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**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.

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

438 As displayed in Figures 3, 9 and Table 1, the mPPD framework is used here to illustrate the  
439 dynamics and vulnerability of the mangrove coastal ecosystems of the WA, specifically in the  
440 northwest, The extraordinary pulse event of severe drought (H1) in the Sahel in the 1970s  
441 (Descroix et al., 2015; Nicholson et al., 2000; Nicholson, 2005, 2013; Nielsen and Reenberg,  
442 2010) affected the Sahelian coastal ecological services, especially that of mangrove ecosystems,  
443 like provisioning, supporting, regulating and culture (H2-H3). This period was followed by  
444 abundant rainfall of the 1990s (Cormier-Salem, 1999; Diop et al., 1997; Spalding et al., 2010;  
445 Valiela et al., 2001). The anthropogenic factors also played a role (H7-H1). Until 1990, traditional  
446 wood cutting (for wood and oyster harvesting) was practised by the local population (H7-H1).

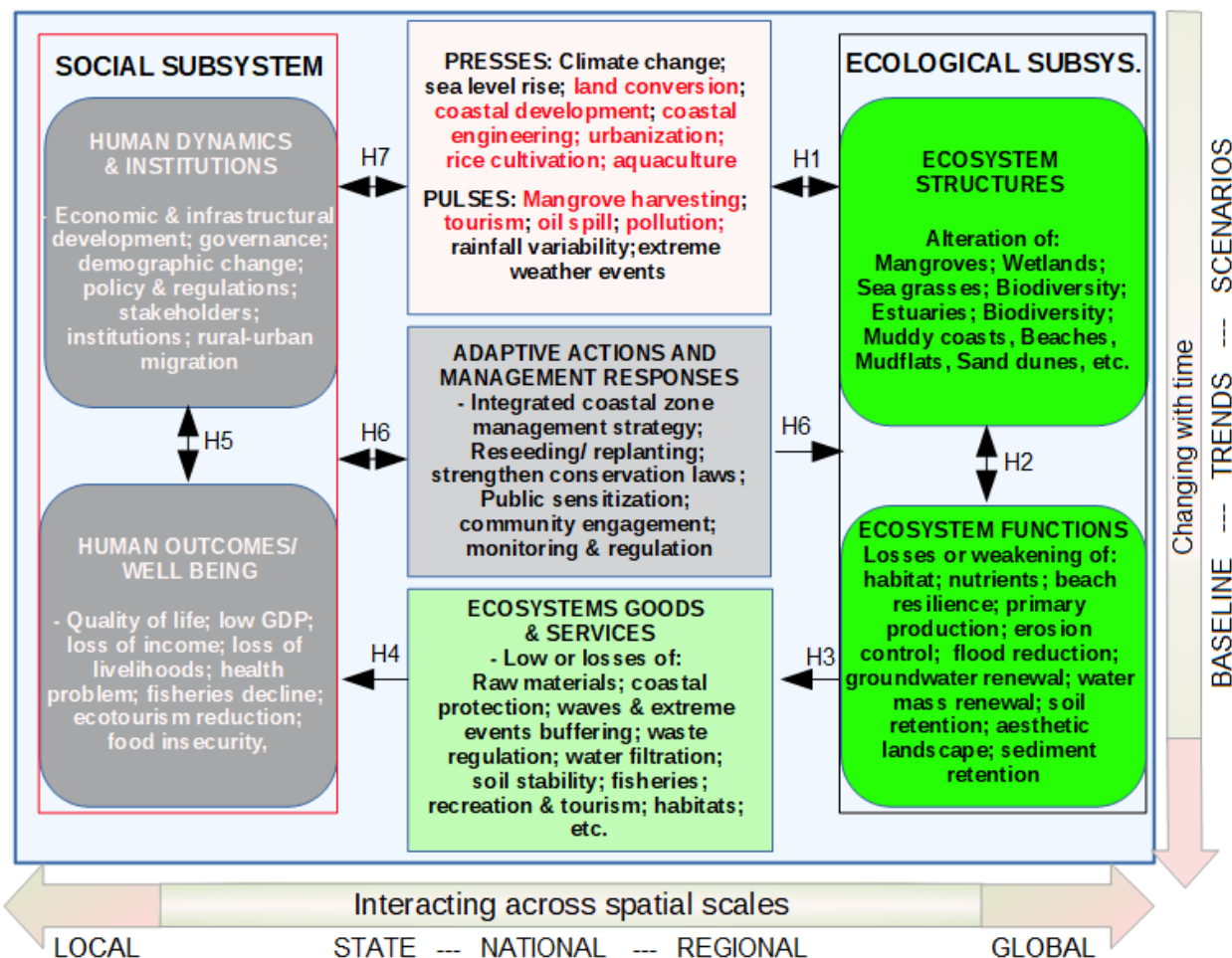
447 The adverse climatic changes (H1) can be viewed as the major causation of the coastal  
448 social-ecological systems dynamism at this section of the WAC. It affected the entire structures  
449 and functioning of ecological subsystems (H2-H3) of this particular coastal region (Dieye et al.,  
450 2013), which in turn, indirectly altered the provisioning, supporting, regulating of the ecological  
451 services, such as food resources, and finally the quality of human outcome and well-being of the  
452 coastal indigenous communities (H4-H5; Fig. 9). This situation prompted diverse  
453 human/management responses ((H-6-H7; Barry, 2009; Dieye et al., 2013).

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

461 The second reason is most likely the enforcement of regulations, the management  
462 improvement of the mangrove ecosystems (H6-H7) since the beginning of the 2000s (Andrieu  
463 2018; Andrieu et al., 2019, 2020; Failler et al., 2020a, b; Gallup et al., 2019; Gautier et al., 2016).  
464 The non-government organizations' conservation efforts in WA to prioritize mangrove forests of  
465 ecological significance and strategically seek their protection also played a key role in these  
466 changes (Andrieu 2018; Andrieu et al., 2019, 2020; Conchedda et al., 2011; Cormier-Salem,  
467 2016; Dieye et al., 2013; Fent et al., 2019; Temudo and Cabral, 2017). These combined actions  
468 reduced mangrove degradation as can be seen in the model (Fig. 9).

469 For instance, in the Somone Estuary, Senegal (Sakho et al., 2011), since 1992, a  
470 modification of mangrove logging and a new reforestation policy (H6-H7) resulted in an

471 exponential increase of mangrove area (see Fig. 3) progressively replacing intertidal mudflats  
 472 (H2-H3). Such success in the restoration of the ecosystem reforestation is supported by  
 473 favourable environmental conditions: tidal flooding, groundwater influence, rainfall during the wet  
 474 season, low net accretion rate of about 0.2-0.3 cm.yr<sup>-1</sup>, (H1) and a ban on the cutting of mangrove  
 475 wood (H6-H7). The rate of mangrove loss from 1946 to 1978 was 44,000 m<sup>2</sup>.yr<sup>-1</sup>, but this has  
 476 been offset by restoration efforts resulting in an increase in mangrove area from 1992 to 2006 of  
 477 63,000 m<sup>2</sup>.yr<sup>-1</sup> (H2-H3).  
 478



479  
 480 Fig. 9. The WA mangroves ecosystem response to changes in trajectories of long-term presses and short-  
 481 term pulses as a result of natural and human dynamics. Note: The horizontal spatial scale arrow (external)  
 482 indicates that, although our assessments take place at the regional scale (scope), they will in part build on  
 483 properties and relationships at finer- national-, state- and local scales (resolution, to a minimum discernible  
 484 unit). While the vertical arrow (external) indicates the baseline, trends and scenarios will be used. Presses  
 485 and pulses in red denote human-induced activities.  
 486

487 **4.2 The 21<sup>st</sup>-century scenarios for WAC ecosystems**

488           **The first (Anthropocentric, i.e., human activity focused) coastal scenario.** This is a  
489 future WAC in which prevailing trends is allowed to continue without major interventions (Fig.  
490 10A). High economic activities and infrastructural development associated with demographic  
491 pressure together with weak governance, institutions and policy have a deleterious effect on the  
492 environment (coastal ecosystems).

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

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

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

518           Coastal protection works are prioritized in areas with higher socio-economic values that  
519 lead to inequality in areas with lower socio-economic values, where people are at bigger risk of  
520 the social effects of displacement. As a result, political and social tensions are on the increase.  
521 Also, losses of properties are arising because coastal protection works are failing. Likewise, the

522 values or prices of the properties are declining, and property owners are finding it difficult to get  
523 insurance or mortgages for their properties. WAC communities depending on coastal tourism as  
524 a means of livelihoods are experiencing a decrease in income. The reduced productivity of  
525 businesses that rely on infrastructures that are affected by coastal degradation or incur costs in  
526 its mitigation, will have a knock-on effect on the local economy.

527 Without adaptation, more intense and frequent extreme sea level (ESL) events, together  
528 with trends in coastal development will increase expected annual flood damages by 2-3 orders of  
529 magnitude by 2100 (Oppenheimer et al., 2019). Coastal processes and associated land-use  
530 changes continue as “business as usual” toward a negative ‘facing the wall’ situation with too  
531 much risk (flooding/ erosion/ pollution) for a dense rather poor unprotected population. Coastal  
532 scenario 1 can be tied with the occurrences straddle between the Shared Socioeconomic  
533 Pathways (SSP) 3 and 4 used by IPCC (Merkens et al., 2016; Moss et al., 2010; O’Neill et al.,  
534 2020).

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

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

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

550 The hybrid solutions are retrofitted onto existing infrastructures in most of the coastal  
551 urban cities like Lagos, Dakar, Cotonou, Abidjan, Accra, Lome. These cities are densely  
552 populated and there is insufficient space to use only natural infrastructure for coastal defence.  
553 Although the hybrid system provides some co-benefits besides coastal protection, it does not  
554 provide all the same benefits that natural systems provide owing to the built component that has  
555 some negative impacts on ecological diversity (Sutton-Grier et al., 2015). They negatively



556 influence economic interests and human health and wellbeing that rely on ecological goods such  
557 as ecotourism, recreation and fisheries, clean air and abundant freshwater, and ecological  
558 services like air and water purification, biodiversity maintenance, waste decomposition, soil and  
559 vegetation generation and renewal, groundwater recharge, greenhouse gas mitigation, and  
560 aesthetically landscapes.

561 Also, with the SLR, the heights of the hard structures will need to be raised to remain  
562 effective. This is an expensive endeavour that ultimately may prove unaffordable and  
563 unachievable. Even with well-designed hard protection, the risk of possibly catastrophic effects in  
564 the event of failure of defenses cannot be overruled (Oppenheimer et al., 2019). Coastal scenario  
565 2 portrays many similarities with SSP 2 (Merkens et al., 2016; Moss et al., 2010; O'Neill et al.,  
566 2020).

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

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

581 The scenario is the most radical of the three and assumes a general shift in attitudes of  
582 the stakeholders and policymakers towards more environmentally sound ways of life (Fig. 10C).  
583 The coast tends toward a wilder scenario owing to sustainable policies implementation and  
584 enforcement (e.g., widespread adoption of managed realignment or abandonment policy). This  
585 may be due to a “do-nothing approach” in which the disturbed area is left alone to recover naturally  
586 without any management intervention. It could also be a situation whereby nature (risk e.g.,  
587 natural hazards) forces people to leave the coast because of too much risk. In such a situation,  
588 less pressure is on the ecosystems. Hence the coastal ecosystems are more resilient to face and

589 adapt to natural events and extreme climatic conditions. By this means, providing the best  
590 benefits/services that can be obtained from the ecosystems (e.g., natural protections and  
591 decontamination of wetlands, flooding protection of wide beaches and dunes, resilience abilities  
592 of the buffer coastal zone to extremes, fisheries, beautiful wild coasts for tourism, etc.).

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

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

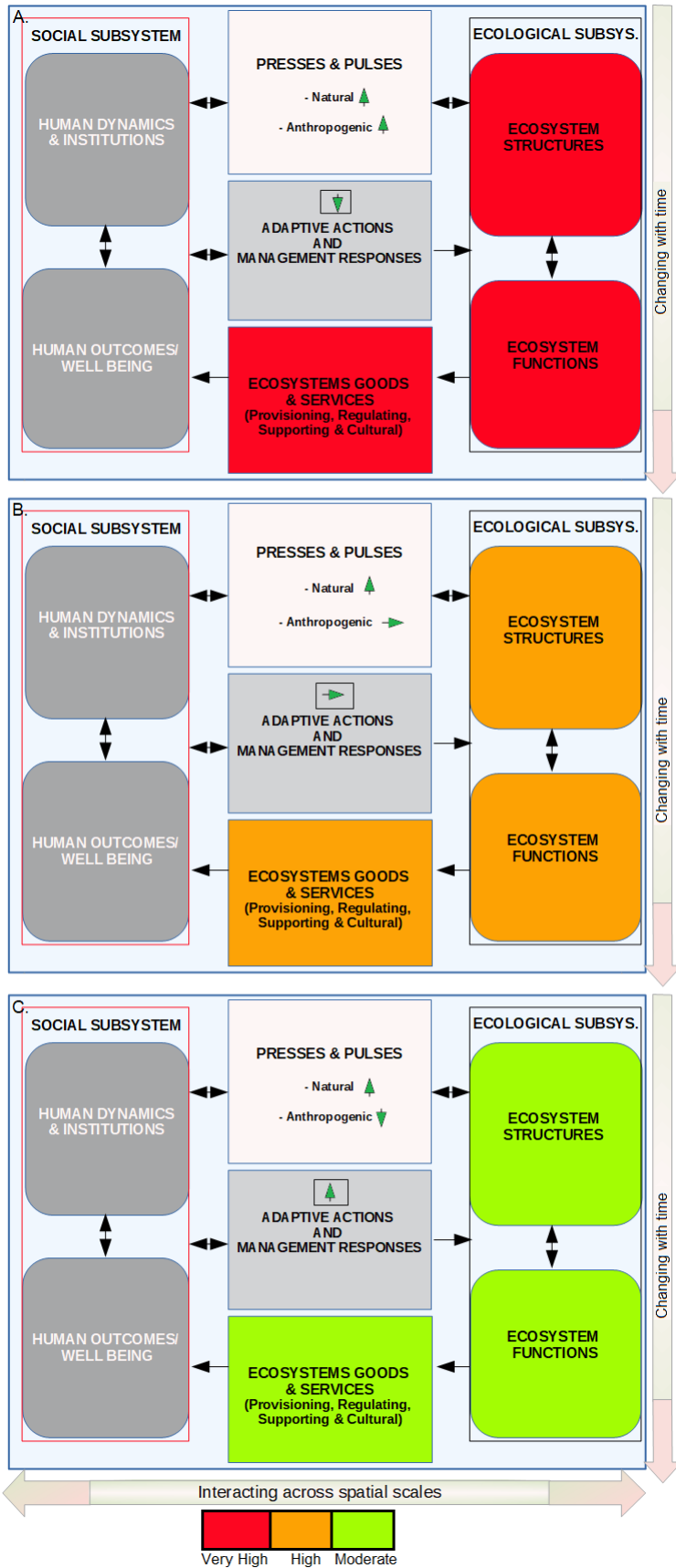
604 Policy responses at the coast embrace wholly integrated coastal management principles,  
605 and these principles are more effectively enabled because of voluntary partnerships across  
606 stakeholders and other participatory arrangements at the local level. This 'bottom-up' approach  
607 paves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

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

622 of continental precipitations, and the lagoons and estuary outlets are partially closed by the  
623 advance of sand spits, etc.

624         According to the most recent study, the restored coastal wetlands can trap more sediment  
625 ([Liu et al., 2021](#)). The effectiveness of this restoration is primarily driven by sediment availability,  
626 and not by wetland elevation, tidal range, local rates of SLR, and significant wave height. This  
627 suggests that nature-based solutions can mitigate coastal wetland vulnerability to SLR. Though  
628 they are most effective in coastal locals where there is abundant sediment supply ([Liu et al.,](#)  
629 [2021](#)). Further, restoration of vegetated coastal ecosystems, such as mangroves or tidal marshes  
630 (coastal “blue carbon” ecosystems), provide climate change mitigation through increased carbon  
631 uptake and storage of around 0.5% of current global emissions annually ([IPCC, 2019](#); [Ungera et](#)  
632 [al., 2020](#)).

633



635 **Figure 10 A-C.** The three constructed future scenarios for the W. African coastal social-ecological systems  
636 in the 21<sup>st</sup> century. Each scenario will exert different pressures on the 21<sup>st</sup> coastal systems. In this context,  
637 the ecosystems will experience different (intensities of) pressures, and, consequently, different impacts on  
638 their integrity and functionality, thus implying different environmental risk for society. Note: The green  
639 arrows illustrate varying levels of effect (up = strong, down = weak, and horizontal = moderate). The red,  
640 orange and green colours depict different levels of adverse impacts.  
641

## 642 **5. Discussion**

### 643 *5.1 Diagnosing sustainable coastal management and planning along the WAC*

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

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

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

664 The continued sectoral or piece-meal approaches to managing the WAC has continued to  
665 exacerbate coastal vulnerability. When this is combined with the implications of climate change  
666 due to global warming, it is likely to get worse (Oppenheimer et al., 2019). The rising and  
667 continuing human activities (in form of economic activities, urbanization, resources exploitation,  
668 tourism, land use and conversion, infrastructural development) call for new requirements for  
669 adaptation. So also, the challenges of new sources and forms of change (climate change, extreme  
670 wave events, storm surges, sea-level rise), and the increasing complexity of policy goals (e.g.,

671 related to the duplicity of responsibilities and acute multi-use conditions). New forms of adaptive  
672 governance that consider the coastal situation and the governance path is therefore necessary  
673 for the WAC.

674

## 675 *5.2 Strengthening integrated and sustainable management of WACA ecosystems*

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

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

699         This two-directional governance challenge can be achieved in the mPPD framework. First,  
700 in the mPPD, a wide range of crosscutting local, regional and global environmental issues  
701 occurring in a coastal system can be linked through the instrumentality of press and pulse  
702 dynamics (refers to Fig. 5). As shown in Figure 5, the mPPD interlinks the traditional four core  
703 PPD framework components (i.e., the press-pulse events, ecological subsystem, ecosystems  
704 goods and services, and social subsystem; see Fig. 1) of a complete earth system; and in our



705 case, the coastal system. Thus, the mPPD can be concurrently applied locally, nationally,  
706 regionally and globally, e.g., at different scales relevant for ecological processes and potential  
707 drivers of change. This shows there is no limit to the scale of application or analysis whether large  
708 or small.

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

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

722

### 723 *5.3 Management efforts at addressing coastal challenges along the WAC*

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

734 The WARCO has the mandate to monitor shoreline and reduce coastal risks in WA and  
735 disseminate good quality information among WA advisory and existing decision-making bodies.  
736 While the SDLAO is saddled with identifying coastal area issues and national coastal risks in a  
737 wide context, by emphasizing on inter-State's solidarity and reciprocity for shoreline management.  
738 Also, it has the responsibility to identify priority coastal issues and analyze the performance of the

739 government's existing instruments for the management of different issues. Shoreline  
740 Management Plans include the division of the entire WAC into 179 sectors based on the  
741 relationship between observed characteristics of coastal sensitivity and local communities' issues  
742 ([UEMOA, 2017](#)).

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

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

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

767 Besides, when it comes to coastal research and human capacity development, both WA  
768 and non-WA research institutions are involved. One of such non-WA research institutions is the  
769 Institut de Recherche pour le Développement (IRD; the French National Research Institute for  
770 Sustainable Development), an internationally recognized multidisciplinary French research  
771 organization. The PSIP research group under the IRD's Oceans, Climate and Resources  
772 (OCEANS) Department is training young researchers from WA institutions of which the first author

773 is a beneficiary. IRD is also jointly working with WB and UCC to develop a coastal Policy Brief for  
774 the WA policymakers.

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

787

#### 788 *5.4 The Way Forward- Interdisciplinary approaches*

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

797 Planning for the future use of the goods and services offered by the coastal ecosystems  
798 will continue to be influenced or disturbed by unpredictable events, whether within the social  
799 ecosystem or natural ecosystem. Adopting an exploratory and synthetic approach to the three  
800 pathways, uncertainties in future, especially drastic changes or surprises, may require greater  
801 resilience within the WAC systems. It will be beneficial to follow plausible future shocks and  
802 integrate anticipatory adaptive actions and dynamic, sustainable management policies in  
803 responses as the situation may require. There is a need to initiate a scenario-based approach  
804 within future science policy fora of the WACA Platform and WARCO regarding the management  
805 of WAC resources, to detail future anticipation using interdisciplinary approaches, to define the  
806 key challenges and risks facing policies, marine- and coastal-related interdisciplinary research

807 and development in the WAC region in the next century. This will allow more informed anticipation  
808 of the management, research and policy need in various sectors, over the medium and long terms.

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

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

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

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

841 **6. Conclusions and closing remarks**

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

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

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

868  
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