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Applying the global RCP–SSP–SPA scenario framework at sub-national scale: A multi-scale and participatory scenario approach

Abiy S. Kebede [a,*], Robert J. Nicholls [a], Andrew Allan [b], Iñaki Arto [c], Ignacio Cazcarro [c,d], Jose A. Fernandes [e,f], Chris T. Hill [g], Craig W. Hutton [g], Susan Kay [f], Attila N. Lázár [a], Ian Macadam [h], Matthew Palmer [h], Natalie Suckall [i], Emma L. Tompkins [i], Katharine Vincent [j], Paul W. Whitehead [k]

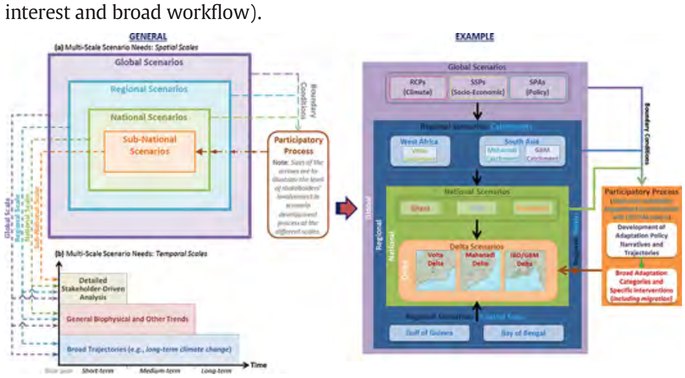
[a] Faculty of Engineering and the Environment, Tyndall Centre for Climate Change Research, University of Southampton, Southampton SO17 1BJ, UK
[b] Centre for Water Law, Policy, and Science, University of Dundee, Dundee DD1 HN, UK
[c] Basque Centre for Climate Change, Alameda Urquijo 4, 48008 Bilbao, Spain
[d] ARAID (Aragonese Agency for Research and Development), University of Zaragoza, Gran Vía, 2, 50005 Zaragoza, Spain
[e] AZTI, Herrera Kaia, Portualdea, z/g., Pasaia, Gipuzkoa 20110, Spain
[f] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK
[g] GeoData, Geography and Environment, University of Southampton, Southampton SO17 1BJ, UK
[h] Met Office, FitzRoy Road, Exeter EX1 3PB, UK
[i] Geography and Environment, University of Southampton, Southampton SO17 1BJ, UK
[j] Kulima Integrated Development Solutions (Pty) Ltd, South Africa
[k] School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK

HIGHLIGHTS

- We develop a framework for applying the global RCP-SSP-SPA scenario framework at sub-national scales.
- The framework is applied and tested for deltas to explore migration and adaptation.
- We demonstrated the benefits of a multi-dimensional approach to capture different drivers of change.
- Highlighted the need to integrate the best science and stakeholder views.
- The concept, methods, processes are transferrable to other sub-national settings with multi-scale challenges.

GRAPHICAL ABSTRACT

An integrated scenario framework for applying the global RCP–SSP–SPA scenario framework at sub-national scale: A multi-scale and participatory approach. The generic framework (left) is applied and demonstrated within the DECCMA project to explore migration and adaptation in deltas (right, showing the various scales of interest and broad workflow).



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ABSTRACT

To better anticipate potential impacts of climate change, diverse information about the future is required, including climate, society and economy, and adaptation and mitigation. To address this need, a global RCP (Representative Concentration Pathways), SSP (Shared Socio-economic Pathways), and SPA (Shared climate Policy Assumptions) (RCP–SSP–SPA) scenario framework has been developed by the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC-AR5). Application of this full global framework at sub-national scales introduces two key challenges: added complexity in capturing the multiple dimensions of change, and issues of

* Corresponding author.
E-mail address: ask2g08@soton.ac.uk (A.S. Kebede).

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scale. Perhaps for this reason, there are few such applications of this new framework. Here, we present an integrated multi-scale hybrid scenario approach that combines both expert-based and participatory methods. The framework has been developed and applied within the DECCMA[1] project with the purpose of exploring migration and adaptation in three deltas across West Africa and South Asia: (i) the Volta delta (Ghana), (ii) the Mahanadi delta (India), and (iii) the Ganges-Brahmaputra-Meghna (GBM) delta (Bangladesh/India). Using a climate scenario that encompasses a wide range of impacts (RCP8.5) combined with three SSP-based socio-economic scenarios (SSP2, SSP3, SSP5), we generate highly divergent and challenging scenario contexts across multiple scales against which robustness of the human and natural systems within the deltas are tested. In addition, we consider four distinct adaptation policy trajectories: *Minimum intervention*, *Economic capacity expansion*, *System efficiency enhancement*, and *System restructuring*, which describe alternative future bundles of adaptation actions/measures under different socio-economic trajectories. The paper highlights the importance of multi-scale (combined top-down and bottom-up) and participatory (joint expert-stakeholder) scenario methods for addressing uncertainty in adaptation decision-making. The framework facilitates improved integrated assessments of the potential impacts and plausible adaptation policy choices (including migration) under uncertain future changing conditions. The concept, methods, and processes presented are transferable to other sub-national socio-ecological settings with multi-scale challenges.

1. Introduction

Scenario analysis has long been identified as a strategic management tool to explore future changes and associated impacts for supporting adaptation decision-making under uncertainty. Scenarios represent coherent, internally consistent, and plausible descriptions of possible trajectories of changing conditions based on 'if, then' assertion to develop self-consistent storylines or images of the future (e.g., Moss et al., 2010; O'Neill et al., 2014). They are generally developed to investigate the implications of long-term climatic, environmental, and anthropogenic futures for designing robust policies in an environment of interacting-complex systems and uncertainty (e.g., Evans et al., 2004; Hall et al., 2016; Harrison et al., 2015). Representing scenarios is complex due to multiple dimensions of change. In climate analysis, initially scenarios focussed strongly on climate change, and little on other factors (e.g., Hulme et al., 1999). The Special Report on Emission Scenarios of the Intergovernmental Panel on Climate Change (IPCC) addressed this deficiency by considering both climate and socio-economic changes (Arnell et al., 2004; Nakicenovic and Swart, 2000). The Fifth Assessment Report (IPCC AR5) extends this further to consider climate, socio-economic, and policy dimensions of change through the new global RCP–SSP–SPA scenario framework (Representative Concentration Pathways; van Vuuren et al., 2011, Shared Socio-economic Pathways; O'Neill et al., 2014, and Shared climate Policy Assumptions; Kriegler et al., 2014) (see Fig. 1). The framework provides a foundation for an improved integrated assessment of climate change impacts and adaptation and mitigation needs under a range of climate and socio-economic scenarios, and adaptation and mitigation policy assumptions. However, as more dimensions are added, application becomes more difficult and there are few full applications of a climate-socio-economic-policy framework like the RCP–SSP–SPA approach.

Scale poses an additional challenge in climate change assessment. Coarse resolution (e.g., global, regional, national) scenarios are widely available, but site-specific and policy-relevant integrated assessments need information at finer resolution (e.g., local, sub-national). Applying the global RCP–SSP–SPA scenario framework at sub-national scale requires a multi-scale approach that captures both scientific inputs and stakeholder views. Combining expert-based and participatory methods facilitates hybrid top-down and bottom-up approaches for developing consistent scenarios across the multiple scales of interest, ranging from global to sub-national and short- to long-term (e.g., van Ruijven et al., 2014). This paper presents a conceptual framework, methods, and processes adopted for applying the global RCP–SSP–SPA scenario framework at a sub-national scale. The examples used here are coastal deltas as analysed in the DECCMA[1] project. The paper is structured as follows: Section 2 presents the concept, methods and development process of the integrated scenario framework, and describes application and testing of the framework within the DECCMA context. Sections 3 to 5 discuss the global, regional, and national scale scenario representations of the various exogenous and endogenous drivers, while Section 6 outlines the delta-scale scenarios and the participatory process adopted for development of alternative adaptation policy trajectories. Finally, the key messages are discussed and conclusions are drawn in Section 7.

2. Integrated scenario framework: a multi-scale and participatory approach

Mid- and low-latitude deltas are home for over half a billion people globally, and they have been identified as one of the most vulnerable coastal environments (De Souza et al., 2015; Ericson et al., 2006; Syvitski et al., 2009). They are susceptible to multiple climatic and environmental drivers (e.g., sea-level rise, natural subsidence, storm surges, changes in temperature and precipitation) as well as socio-economic challenges (e.g., catchment management, human-induced subsidence, population and GDP growth). These drivers of change also operate at multiple scales, ranging from local to global and short- to long-term.

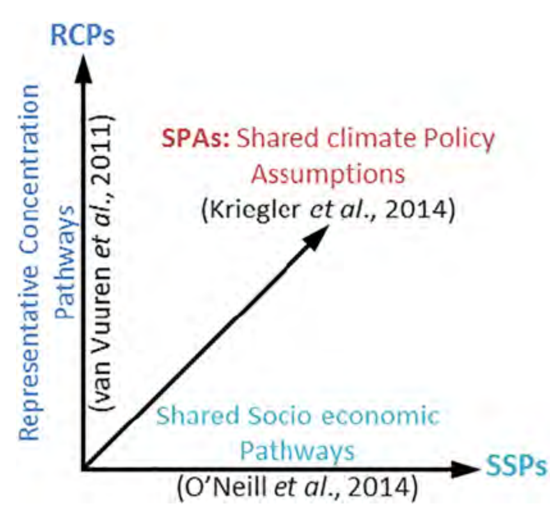


Fig. 1. Simplified schematic of the latest global RCP–SSP–SPA scenario framework of the IPCC AR5 (adapted from IPCC, 2012).

[1] DECCMA (*DEltas, vulnerability and Climate Change: Migration and Adaptation*) project is part of the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA), with financial support from the UK Government's Department for International Development (DFID) and the International Development Research Centre (IDRC), Canada. For more information, visit the project website: http://www.geodata.soton.ac.uk/deccma/.

Furthermore, deltas and low-elevation coastal zones are known for significant urbanisation trends and land use change (e.g., Meyer et al., 2016) and associated high levels of population mobility mainly due to economic reasons (e.g., Foresight, 2011). However, in many narratives of the future of deltas, they may also be the source of large numbers of environmental refugees forced to leave due to sea-level rise and subsidence (e.g., Ericson et al., 2006; Geisler and Currens, 2017; Milliman et al., 1989; Myers, 2002; Szabo et al., 2016a). For example, a 1 m sea-level rise impacts an area in Bangladesh with a present population of 25–30 million people, raising questions about home much migration this might cause. This highlights the complex challenges deltas face in terms of both their long-term sustainability as well as the well-being of their residents and health of ecosystems that support the livelihoods of large (often poor) populations under uncertain changing conditions (e.g., Day et al., 2016; Szabo et al., 2016b; Tessler et al., 2016). A holistic understanding of these challenges and the potential impacts of future climate and socio-economic changes is central for devising appropriate adaptation policies (e.g., Haasnoot et al., 2012, 2013; Kwakkle et al., 2015).

When analysing the potential implications of sea-level rise and climate change on migration and adaptation in deltas, it is important to envisage a coherent future world within which the deltas sit. At one level, climate change is a global phenomenon, which is the result of broad global-scale processes associated with collective greenhouse gas emissions and the earth system's response to this. However, these processes both occur within and impact a range of social and economic processes such as global food prices, markets, and other economic boundary conditions. At sub-global scales, deltas sit within the context of regional catchments and coastal seas and they are influenced by associated regional politics as well as national boundaries with particular socio-economic conditions. Hence, the deltas will be subjected to these higher/coarser scale changes (exogenous factors), but it is also important to consider drivers of changes within the deltas themselves (endogenous factors) and ultimately the interaction between these drivers. Hence, any multi-scale hybrid scenario framework needs to include the various scales at which the biophysical and socio-economic change drivers operate (e.g., Biggs et al., 2007; Schweizer and Kurniawan,

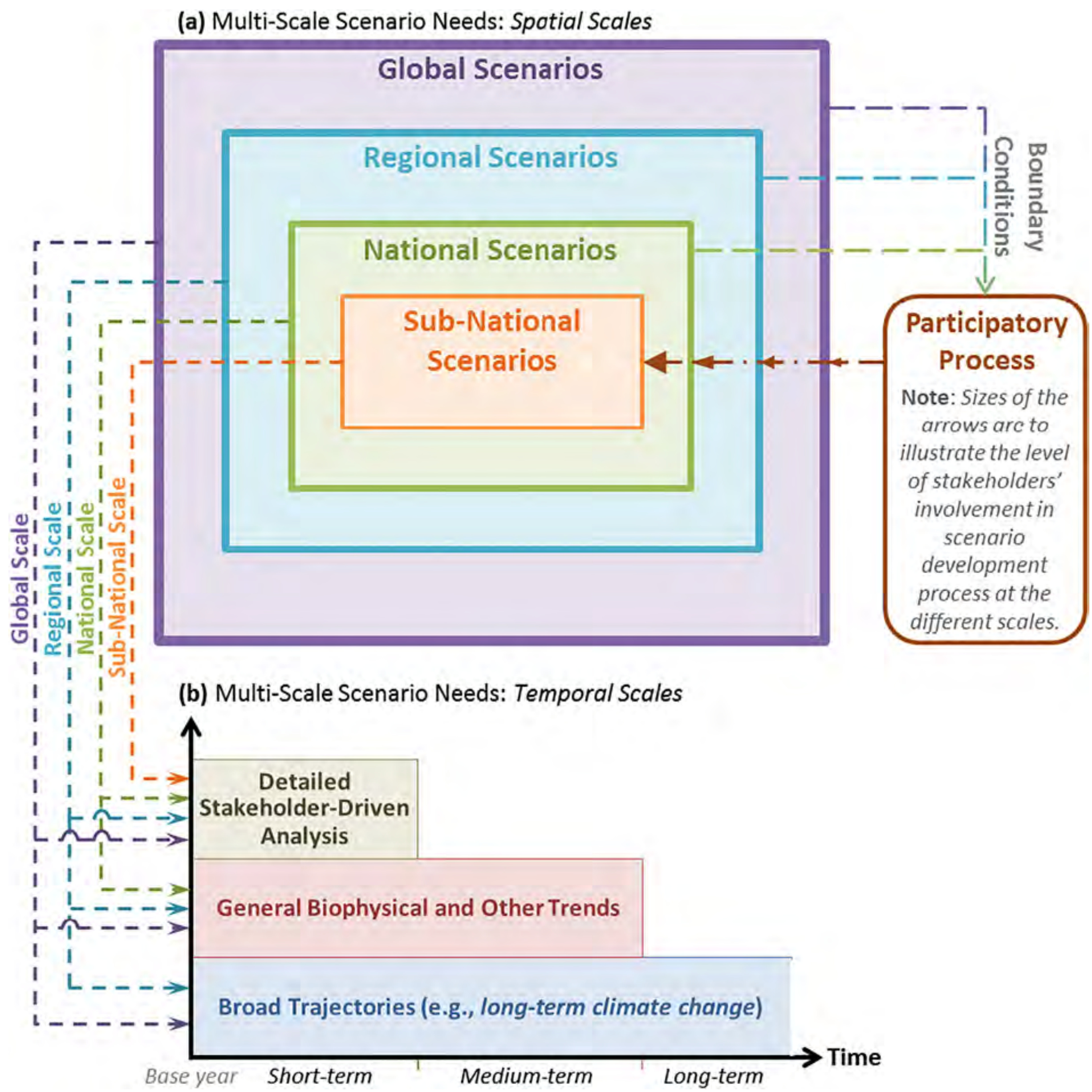
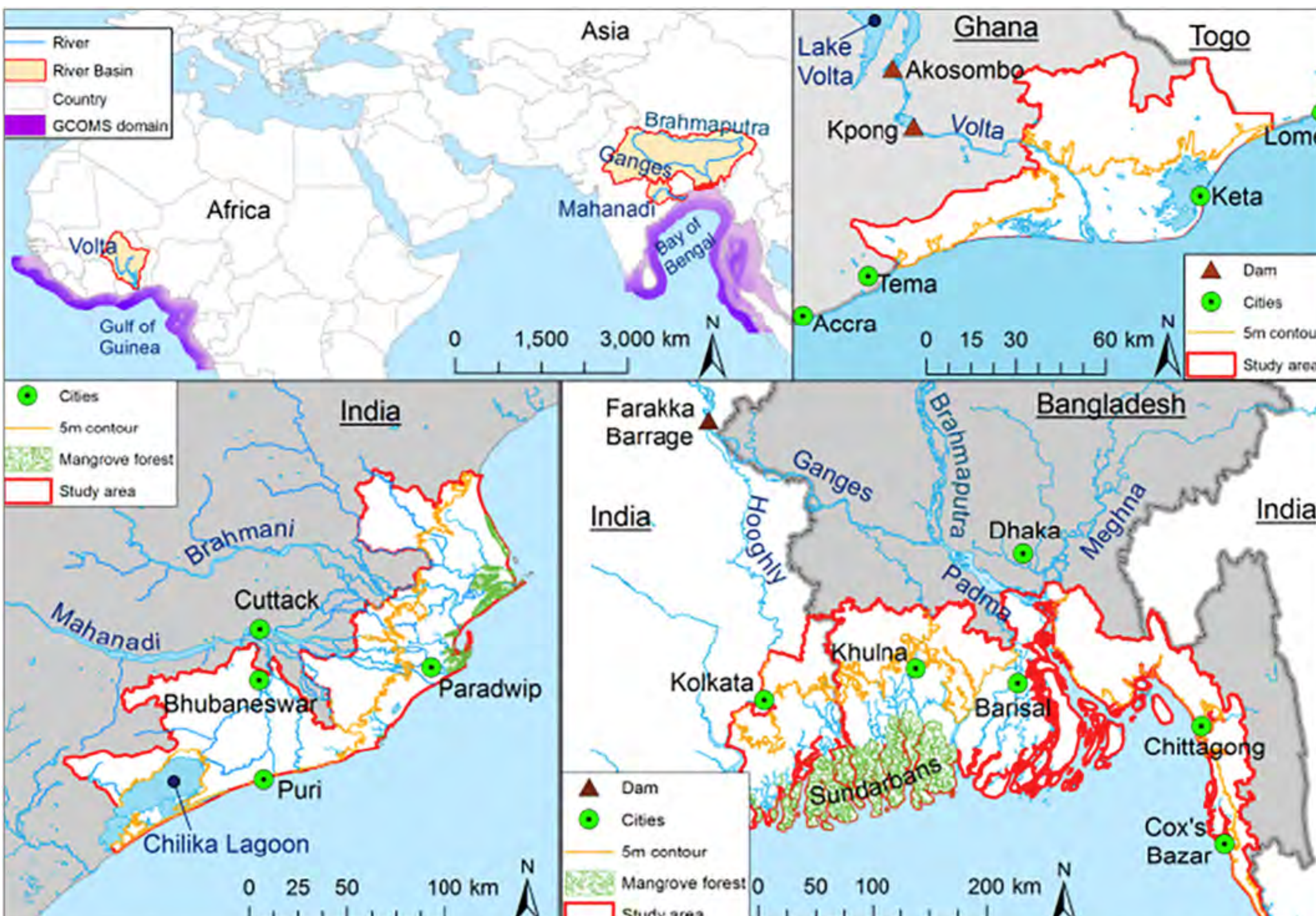


Fig. 2. An integrated scenario framework based on a multi-scale hybrid approach and combining expert-based and participatory methods. Short, medium and long-term are defined pragmatically and the boundaries are at roughly 30 and 80 years reflecting stakeholders' interest, credibility, and time horizon of climate change analysis.

2016; Zurek and Henrichs, 2007) in the delta scale scenarios development process. In addition, to develop locally-relevant scenarios, a participatory process is required to include stakeholders' expertise and interest (e.g., Allan and Barbour, 2015; Allan et al., 2018; Barbour et al., 2018; Scolobig and Lilliestam, 2016).

Furthermore, small-scale processes (such as human responses) have different (often shorter) time scales than larger-scale biophysical processes (such as global sea-level rise). Consequently, detailed stakeholder-led sub-national scale scenarios and policy choices can be most meaningful for about 30 years (up to 2050). At longer timescales (e.g., to 2100), only global, e.g., downscaled SSP-based and biophysical scenarios (e.g., for regional or national scale assessments) can be considered with an element of confidence. For a century or more, only long-term trajectories (e.g., global climate change and sea-level rise scenarios) can be explored using broad-scale impact indicators/metrics. This also highlights that scenario assumptions become broader and simpler with increasing time scale and the associated results become more generalised. As a result, these scale issues suggest the need for a multi-scale (combined bottom-up and top-down) approach and participatory (joint expert-stakeholder) methods for developing appropriate scenarios across scales (both spatial and temporal). These assumptions lie at the heart of the DECCMA scenario development process. Here, we develop an integrated scenario framework to address these multi-scale scenario needs and challenges (as outlined in Fig. 2). The framework provides a structure for a systematic representation of the various exogenous (external) and endogenous (internal) drivers of change across the multiple scales of interest that need to be taken into account when assessing climate change at a sub-national scale, such as deltas.

The generic framework is demonstrated through its application within the DECCMA context. The main aims of DECCMA are to: (i) evaluate the effectiveness of adaptation options in deltas, (ii) assess migration as an adaptation in deltaic environments under a changing climate, and (iii) deliver policy support on sustainable adaptation in deltaic areas (Hill et al., this issue). These are explored focusing on three contrasting coastal deltas in South Asia and West Africa: (i) the Volta (small-scale) delta (Ghana), (ii) the Mahanadi (medium-scale) delta (India), and (iii) the Ganges-Brahmaputra-Meghna (GBM) (large-scale) delta (Bangladesh/India). Fig. 3 shows the location of the study domains and key characteristics of the three case study deltas.



Key Statistics	Volta Delta	Mahanadi Delta	GBM Delta
Area (km^2)	4,562	13,054	51,486
Population (million)	0.85	8.1	56.7
Population density (people/km^2)	186	620	1101

Fig. 3. Locations and key characteristics of the case study deltas in West Africa and South Asia.

The study includes assessment and comparisons of the implications of future climatic, environmental, and socio-economic changes, within and across the three deltas, in terms of: (i) the short- to medium-term (i.e., up to 2050) socio-economic impacts (e.g., on migration, well-being and livelihoods, etc.), (ii) the long-term (i.e., up to 2100) biophysical changes (e.g., in river flows and nutrient fluxes, fisheries, etc.), and (iii) simulations of the implications of sea-level rise over a very long-time period (i.e., beyond 2100) (e.g., area at risk of flooding). This framework allows us to articulate how we assume the world will evolve, in addition to the associated sub-national and local changes within and across the three case study deltas. This allows comparison with existing climate change, environmental change studies and adaptation and migration research and compares future adaptation needs across the three deltas investigated.

In order to achieve these objectives, the multi-scale hybrid approach within the context of the proposed integrated scenario framework (Fig. 2) includes six levels of scenario considerations: (i) global climate change (e.g., changes in global temperature, precipitation, and sea-level rise) and socio-economic processes (e.g., changes in global population and other macro-economic boundaries); (ii) regional catchments (e.g., changing river flow and water quality issues), (iii) regional coastal seas (e.g., fisheries), (iv) regional politics (e.g., transboundary issues), (v) national socio-economics (e.g., population, GDP growth and urbanisation trends), and (vi) delta-scale scenario conditions (e.g., adaptation and migration policies). Furthermore, the scenario process includes and combines expert-based and participatory (stakeholder engagement) approaches for providing improved specification of the role of scenarios in the development of alternative adaptation policy trajectories for the deltas. This is important for the development of appropriate and consistent exogenous and endogenous scenario futures: (i) at the scale of each delta, and (ii) across all deltas, taking into account the higher scale boundary conditions (global, regional and national). Fig. 4 outlines application of the integrated scenario framework in more detail, highlighting the broad workflow across the multiple scales of interest. The framework facilitates consistency of the modelling process across the various scales and sub-components. This is particularly important in facilitating consistent integration across the biophysical and vulnerability hotspot modelling and the overall integrated assessment of future migration and adaptation within and across the three case study deltas (e.g., Lazar et al., 2015).

The following sections present the key assumptions and procedures considered for the various scenario components at the global, regional, national, and sub-national (delta) scales.

3. Global scenarios: RCPs, SSPs and SPAs

At the global scale, the key factors are greenhouse gas emissions (and hence climate change) and socio-economic factors about the

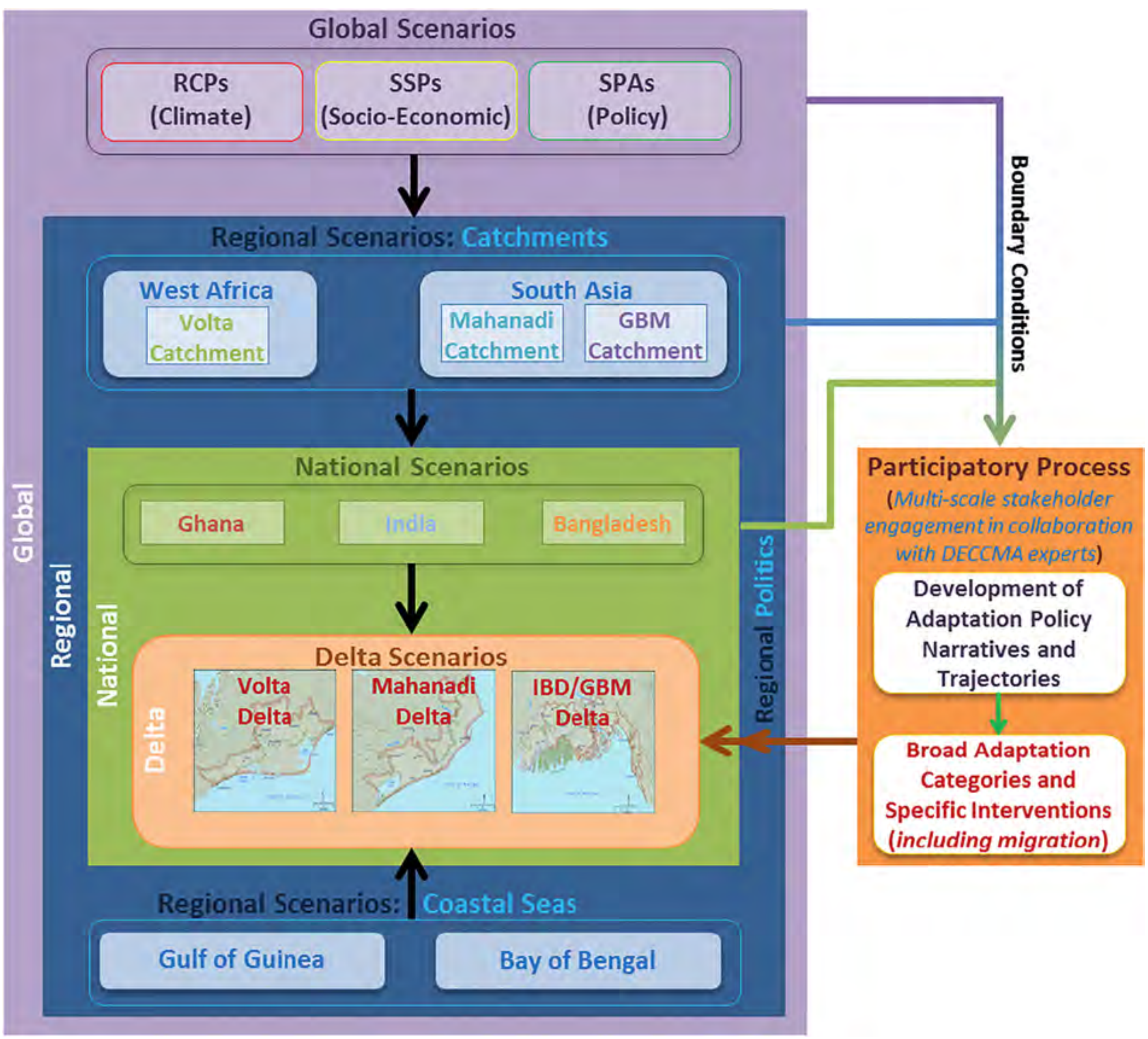


Fig. 4. Application of the integrated scenario framework (Fig. 2) in DECCMA, illustrating the various scales of interest and broad workflow.

Table 1
Global scenarios for selected climate and socio-economic variables.

	Global scenarios	
Climate scenarios[a] (relative to 1986–2005 across all RCPs):	2045–2065	2081–2100
Temperature (°C)	0.4–2.6	0.3–4.8
Sea-level rise (cm)	17–38	26–82
Socio-economic scenarios[b] (across all SSPs):	2050	2100
Population (billions)	8.5–10	6.9–12.7
Urban share (% of population)	55–78	58–93
GDPppp (trillion US$2005/year)	177–360	278–1014

[a] IPCC (2013)
[b] IIASA (2016) - SSP Database, available at: https://tntcat.iiasa.ac.at/SspDb

world economy. In addition, the climate policy assumptions on the aims, instruments and limits on implementing mitigation and adaptation measures are key for linking the socio-economic futures with radiative forcings and climate outcomes. Here, we considered selected scenario combinations taking into account the global climate (RCP), socio-economic (SSP) and policy (SPA) narratives. The RCPs (Representative Concentration Pathways) "provide information on possible development trajectories for the main forcing agents of climate change" (van Vuuren et al., 2011). They comprise a set of global climate scenarios accounting for emissions of greenhouse gases and other air pollutants and changes in land use. They include trajectories for "radiative forcing" of the global climate system, a measure of the effect on the energy balance of the system of changes in the composition of atmosphere, such as due to emissions of greenhouse gases. Radiative forcing is usually expressed as a change relative to pre-industrial times in net energy flux into the climate system per unit of area. Each of the four RCPs has a different forcing at the end of the 21st century and is named according to its forcing level in 2100: RCP2.6 (~490 ppm CO_2 eq.), RCP4.5 (~650 ppm CO_2 eq.), RCP6.0 (~850 ppm CO_2 eq.), and RCP8.5 (~1370 ppm CO_2 eq.). On the other hand, the SSPs (Shared Socio-economic Pathways) are "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies" (O'Neill et al., 2014). They outline five plausible social, economic and technical narratives and alternative development pathways that humankind could follow over the next century, in terms of, for example, the level of international co-operation, market freedom, regional equality, and technological development. They also represent the different levels of challenges to mitigation and adaptation: SSP1 (Sustainability – low mitigation and adaptation challenges); SSP2 (Middle of the road – intermediate mitigation and adaptation challenges); SSP3 (Fragmentation/regional rivalry – high mitigation and adaptation challenges); SSP4 (Inequality – high adaptation and low mitigation challenges); and SSP5 (Conventional/fossil-fuelled development – high mitigation and low adaptation challenges). Table 1 presents a summary of the global climate and socio-economic scenarios across the various RCPs and SSPs.

Each paired RCP and SSP scenario combination represents a family of macro-scale scenarios. However, scenario pathways designed to achieve a particular radiative forcing level requires consideration of appropriate mitigation and adaptation policies to achieve the specified emission levels and cope with the resulting climate change (Ebi et al., 2014). The SPAs (Shared climate Policy Assumptions) represent the last component (third dimension) of the global scenario framework. They "capture key policy attributes such as the goals, instruments and obstacles of mitigation and adaptation measures" (Kriegler et al., 2014). They play a key role in linking the RCPs and SSPs and provide a platform for devising common assumptions across a range of studies to assess the consequences of specified adaptation and/or mitigation policy approaches. However, the detailed specification and global level narratives and quantifications of the SPAs are still less developed. Furthermore, the RCPs, SSPs and SPAs are not entirely independent, while in theory possible, only certain combinations are plausible (Riahi et al., 2017). For example, only SSP5 (associated with the highest economic growth) could be fully compatible with RCP8.5 and lead to emission levels that are consistent with RCP8.5, while RCP2.6 emission levels could not be attained under an SSP3 world. Similarly, consideration of the SPAs for linking a particular RCP/SSP combination depends on the aims, instruments and limits for implementing appropriate mitigation and adaptation policies under the climate and socio-economic change scenarios considered. For example, this may depend on regional cooperation and national participation and adaptation needs, and such policy assumptions need to be developed through a participatory process at multiple scales. These limitations are recognised and considered within the integrated framework and the scenario combinations selection process adopted within DECCMA as discussed below.

In this study, we focus on the global RCP8.5 scenario in order to consider the strongest climate signal, with the greatest atmospheric greenhouse gas concentrations in the late 21st century. This maximises the sampling of uncertainty in future climate changes and provides a challenging yet plausible scenario context against which to test the robustness of human and natural systems and climate change adaptation measures. Furthermore, it was recognised that up to 2050, practically any RCP (including RCP8.5) can be combined with any SSP, as high divergence of forcings from the different RCPs occur mainly beyond 2050s. However, after 2050 only SSP3 and SSP5 can produce the required emissions, although SSP2 is close. In DECCMA, three SSP-based

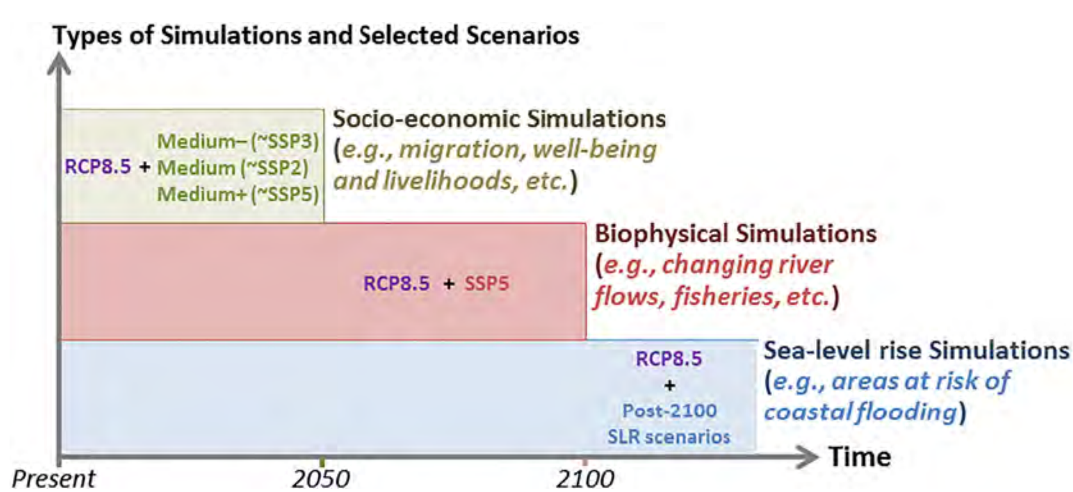


Fig. 5. Summary of the DECCMA RCP and SSP scenarios for the different types of simulations over the three respective time horizons (see Nicholls et al., 2017 for further details on the selection process).

scenario narratives are identified for up to 2050: Medium (~SSP2), Medium– (~SSP3) and Medium+ (~SSP5) that are consistent with the RCP8.5 climate scenario. The Medium– and Medium+ scenarios represent: low economic growth, high population growth and low level of urbanisation; and high economic growth, low population growth and high level of urbanisation, respectively. These narratives are then used to downscale the global projections to regional and national levels. The narratives also inform development of the participatory-based delta-scale scenarios and adaptation policy trajectories for up to 2050. Beyond 2050, SSP5 is considered, as it is compatible with RCP8.5 and will provide continuity for pre- and post-2050 analysis. The post-2050 analysis based on the combination of RCP8.5 and SSP5 forms the focus of the long-term biophysical assessment, which is more exploratory in nature and does not include stakeholder-driven scenarios. Fig. 5 presents a summary of the selected RCP and SSP scenario combinations and associated time horizons considered for assessing different socio-economic and biophysical components of the delta systems investigated within DECCMA.

4. Regional scenarios: catchments, coastal seas and regional politics

We consider three regional catchments: (i) the Volta catchment in Ghana, (ii) the Mahanadi catchment in India, and (iii) the GBM catchment in India and Bangladesh; and two regional coastal seas: (i) the Gulf of Guinea and (ii) the Bay of Bengal (which the Mahanadi and GBM deltas share). The catchments study includes river flow and nutrient modelling for the River Volta system, and catchment water quality modelling for the Mahanadi and GBM catchments, using the Integrated Catchment Model, INCA (Whitehead et al., 2015a, 2015b). The coastal sea study includes oceanographic/fisheries modelling using combined POLCOMS-ERSEM and fish species-based (SS-DBEM) and size-spectrum models (Fernandes et al., 2013, 2016, 2017; Mullon et al., 2016). The primary drivers for these models are the global and regional climate models. Four Global Climate Models (GCMs) and two Regional Climate Models (RCMs) are used to generate downscaled climate data for the study regions (catchments and coastal seas) under the RCP8.5

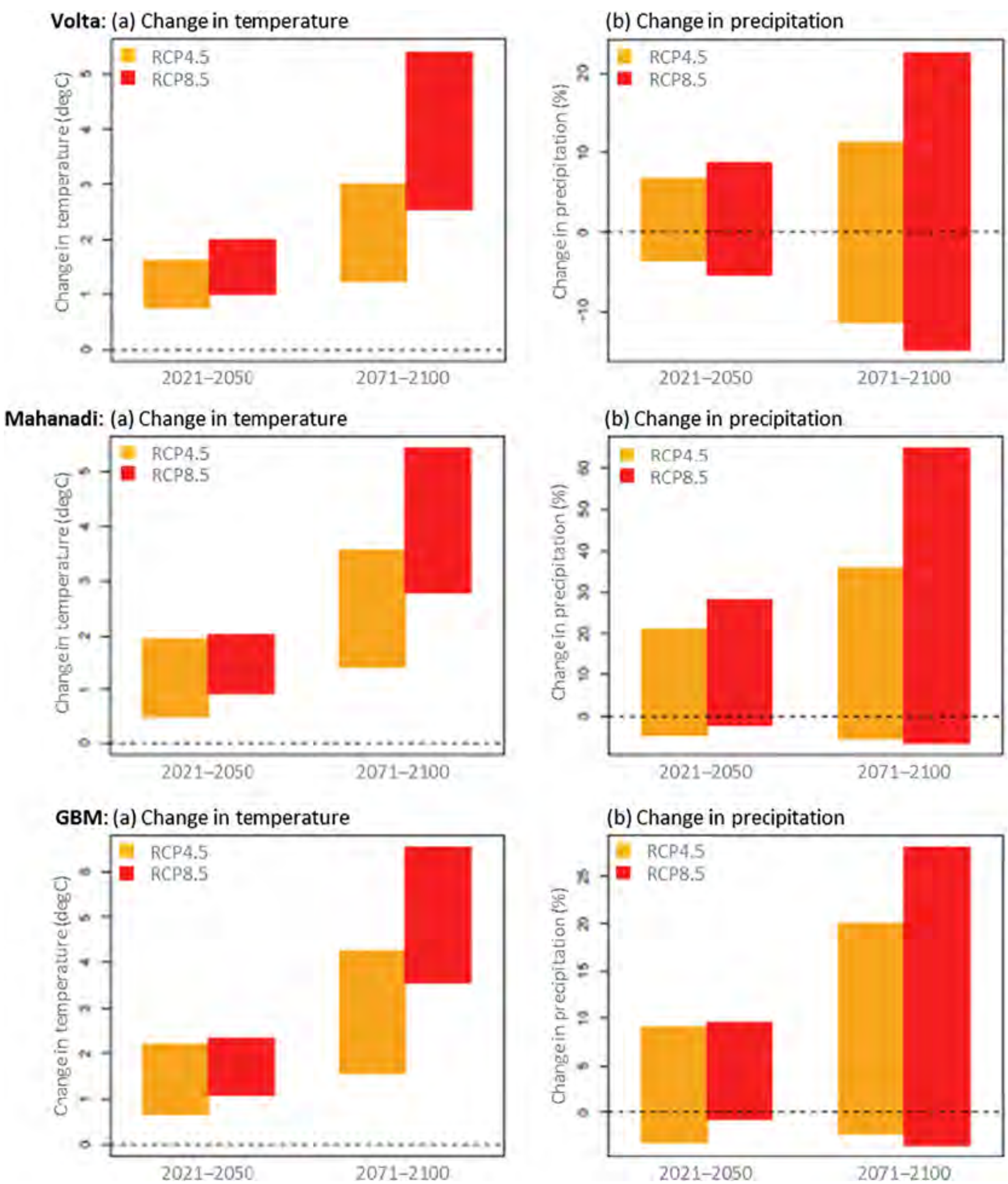


Fig. 6. Changes in annual mean temperature and precipitation (relative to 1971–2000 levels) under the RCP8.5 scenario used in this study (the RCP4.5 data is shown for comparison). Changes shown are for regions around the Volta (−10 to 5°E, 0 to 15°N), Mahanadi (75 to 90°E, 15 to 30°N) and GBM (70 to 100°E, 20 to 35°N) catchments. Note: the scales (in y-axes) differ between catchments for display purposes.

Table 2
Catchment scenarios for selected socio-economic variables (as % change relative to 2010; see Jin et al., this issue; Whitehead et al., this issue for further details).

	Catchments			
	Volta catchment		GBM and Mahanadi catchments	
	2050s	2090s	2050s	2090s
Population:				
Medium− (~SSP3)	63	67	16	−8.4
Medium (~SSP2)	92	138	33	29
Medium+ (~SSP5)	129	254	58	108
Intensive agricultural land use:				
Medium− (~SSP3)	94	68	4	6
Medium (~SSP2)	78	85	5	7
Medium+ (~SSP5)	130	175	7	10
STP[a] effluent discharge (given urban % change):				
Medium− (~SSP3)	45	67	16	−8.4
Medium (~SSP2)	60	138	33	29
Medium+ (~SSP5)	70	150	58	108
Reach irrigation water demand:				
Medium− (~SSP3)	94	68	18	18
Medium (~SSP2)	77	85	22	22
Medium+ (~SSP5)	130	75	25	30

[a] STP: Sewage treatment plant discharge.

scenario. These are: (i) CORDEX Africa dataset based on the CNRM-CM5, CanESM2, and HadGEM2-ES GCMs and the RCA4 RCM, and (ii) PRECIS South Asia dataset based on the CNRM-CM5, GFDL-CM3 and HadGEM2-ES GCMs and HadRM3P RCM (Janes and Macadam, 2016; Macadam, 2017). The GCMs were selected to attempt to span the uncertainty in future changes in the climatic factors (e.g., mean temperature and rainfall) simulated by the full range of CMIP5 GCMs (see Macadam et al., this issue. for more information). Fig. 6 presents the regional climate projections for the three catchments under two RCP scenarios downscaled from simulations of 38 CMIP5 GCM (Global Climate Model) outputs, using Regional Climate Model (RCM) simulations.

At the catchment scale, the downscaled daily precipitation and temperature data for the three catchments are used to drive the INCA model (Whitehead et al., 2015a, 2015b). The simulations from the catchment models are then provided for the downstream coastal sea models. Socio-economic scenarios also affect water quality in that changes to industry, agriculture and population levels will affect nutrients (N and P) and these changes in nutrient fluxes are likely to affect coastal systems (Jin et al., 2015). In addition, the catchments' modelling takes into account socio-economic scenarios as a means of integrating social aspects of future changes. The catchment scale socio-economic scenarios are defined based on the three SSP socio-economic development pathways and scenario narratives that are compatible with the RCP8.5 scenario (as outlined in Fig. 5). There are many factors that affect the socio-economic conditions and potential futures in the catchments from a flow and a water quantity perspective. These include: population change, effluent discharge, water demand for irrigation and public supply, land use change, atmospheric deposition, and water transfer plans, which are defined under each scenario (see Jin et al., this issue; Whitehead et al., this issue). Table 2 summarizes the scenarios of selected socio-economic drivers for the three study catchments.

For the coastal sea modelling, the GCMs provide physical and biogeochemical data at the ocean boundary of the sea models, while the RCMs provide physical data at the air-sea boundary. River flow and nutrient data provide an additional input to the regional sea models and for the Volta, GBM and Mahanadi, these are taken from the INCA catchment model, with the medium SSP scenario used for the nutrients. Overall, the RCPs are the primary drivers of the regional sea modelling; SSPs have only a minor effect through river nutrient levels. Table 3 summarizes future projections of the key regional sea climate drivers for the Gulf of Guinea and Bay of Bengal regions.

For fisheries modelling, total fish productivity is derived from the regional sea models and uses the same scenarios (Blanchard et al., 2012). The species-based fisheries model allows considering a further anthropogenic pressure via fishing effort scenarios, focussing on the key species that provide the largest marine catches in the two regional coastal seas (Fernandes et al., 2013, 2016, 2017). The fishing scenarios are considered based on the concept of Maximum Sustainable Yield (MSY), which is defined as the highest average theoretical equilibrium catch that can be continuously taken from a stock under average environmental conditions (Hilborn and Walters, 1992; Fernandes et al., 2016). The three scenarios considered for providing fish catch and biomass projections are:

(i) Sustainable management: effort consistent with average fishing at MSY level. This is the value that results in maximum catches while maintaining the population at their productivity peak,
(ii) Business as usual: Fishing mortality consistent with the average of recent estimates of fishing mortality, and
(iii) Exploitation: Corresponds to a scenario where management is not a constraint to the fishery. A generalised over-exploitation scenario of three times MSY is considered for all the species studied.

Table 4 shows the two scenarios of fishing mortality and the level of exploitation considered for different fish species in the Gulf of Guinea and Bay of Bengal regional coastal seas.

5. National scenarios: Ghana, Bangladesh and India

At the national scale, the socio-economic scenarios for the three countries (Ghana, India, and Bangladesh) are based on the *SSP Public*

Table 3
Future climate projections of the three deltas and the wider areas of the Gulf of Guinea and Bay of Bengal, change from present-day conditions under the RCP8.5 scenario.

		Gulf of Guinea		Bay of Bengal		
		Volta delta	Wider area	GBM delta	Mahanadi delta	Wider area
Surface temperature (°C)	Mid-century	+1.0 to +1.7	+1.0 to +1.8	+0.9 to +4.2	+0.8 to +4.2	+0.9 to +4.4
	End-century	+2.5 to +3.6	+2.5 to +3.6	+2.6 to +6.6	+2.6 to +6.3	+2.6 to +6.5
Precipitation (%)	Mid-century	−30 to +2	−1 to +2	−3 to +4	−8 to +25	−2 to +20
	End-Century	−25 to +40	−4 to +13	−45 to +2	−25 to +4	−10 to −2
Maximum wind speed (ms^{-1})[a]	Mid-century	+0.1 to +0.2	−0.6 to +0.1	−0.3 to +0.5	−0.5 to +0.4	−0.2 to +0.3
	End-century	+0.3 to +0.6	−0.7 to +0.4	−0.2 to +1.3	0 to +1.3	−0.3 to +0.1
Frequency of high wind events (days per decade)[b]	Mid-century	+4 to +9	−10 to +2	−5 to +10	−37 to +13	−1 to +4
	End-century	+27 to +34	−11 to +5	−50 to +30	−65 to +55	−6 to +5
Sea-level rise[c] (m, relative to 2000 baseline)	Mid-century	+0.21 to +0.36		+0.18 to +0.33		
	End-century	+0.55 to +1.1		+0.49 to +1.0		

[a] Maximum wind speed is defined as the 98th percentile of the daily mean wind speed.
[b] High wind events are defined as daily mean wind speed exceeding 8 ms^{-1} for the Gulf of Guinea and 13 ms^{-1} for the Bay of Bengal.
[c] These are based on thermal expansion and ice melt only, and they do not include local subsidence.

Table 4
Fishing management scenarios for selected species in the Gulf of Guinea and Bay of Bengal regions.

	Species	Source	Fisheries Scenarios (as a factor of msy)	
			Business as usual	Sustainable management
Gulf of Guinea	*Brachydeuterus auritus*	Bannerman et al. (2001)	1.43	0.39
	Ilisha Africana	Francis and Samuel (2010)	1.34	1.09
Bay of Bengal	*Tenualosa ilisha*	Fernandes et al. (2016)	1.86	0.61
	Harpadon nehereus	Khan et al. (1992)	3.78	0.66
	Rastrelliger kanagurta	Mansor and Abdullah (1995)	0.73	1.02

Database Version 1.1 (IIASA, 2016). This data provides historic trends and future projections of the changes in population, urban share (as % of total population in urban areas), and GDPppp through the 21st century for each country under the five SSP scenarios (Fig. 7). Together, these data are used as one of the boundary conditions to inform the delta-specific scenarios and adaptation policies development process. This is facilitated by providing the relevant stakeholders with a summary of these national level future socio-economic conditions to provide a context for the deltas under the selected SSP scenarios.

6. Delta scenarios: adaptation policies and the participatory process

6.1. Scenarios and adaptation policies

At the delta scale, there are endogenous and exogenous environmental and socio-economic change drivers. As discussed above, the climate, environmental and socio-economic change drivers that operate at higher/coarser spatial scales (e.g., national, regional, global) represent the exogenous drivers. They define the boundary conditions for the delta scale scenario and adaptation policy narratives and trajectories

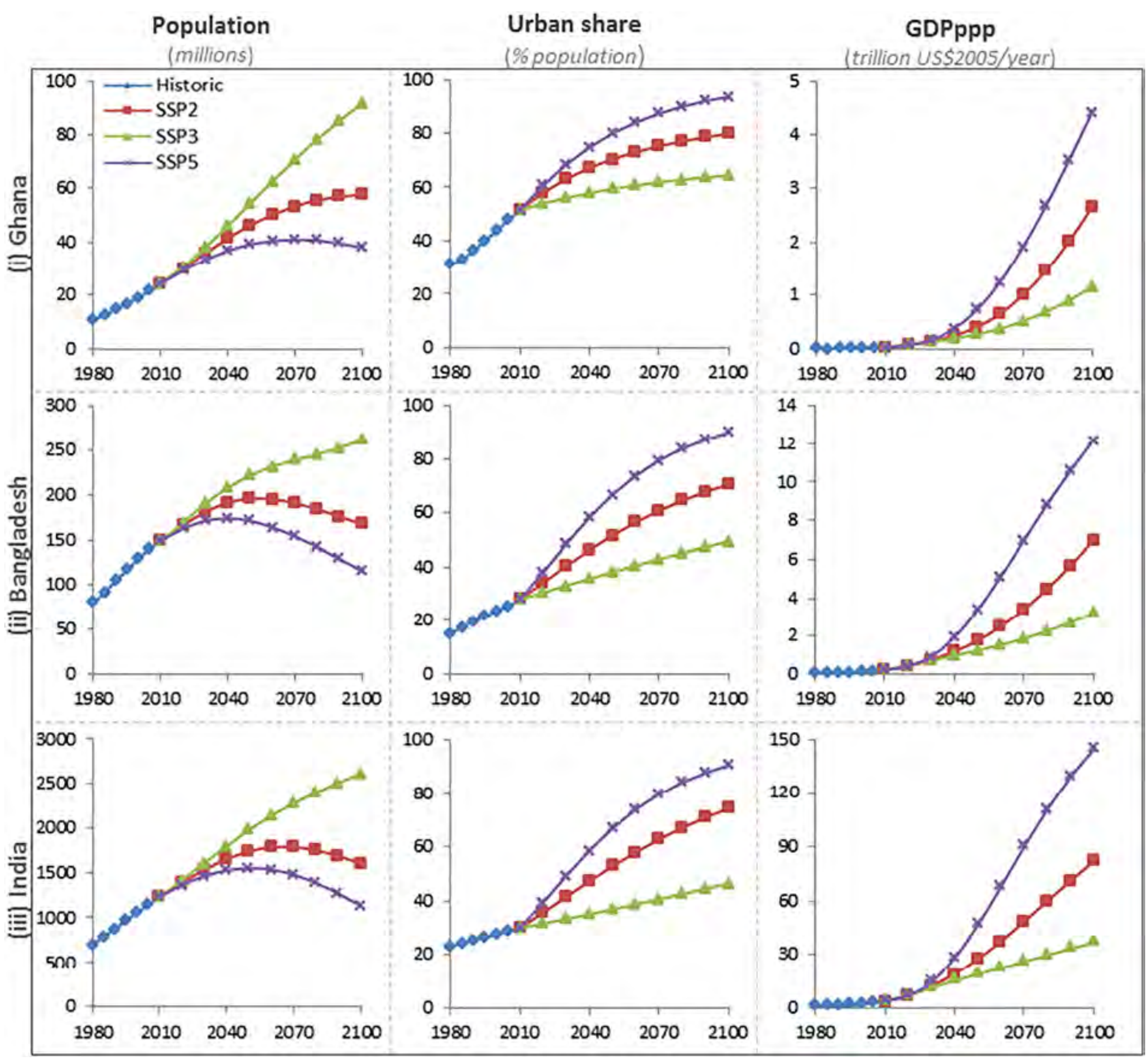


Fig. 7. National level historic trends and future projections of population, urbanisation, and GDPppp in Ghana, Bangladesh, and India under the selected three SSP scenarios. Note: the scales (in y-axes) differ between countries for display purposes.
(Source: IIASA, 2016).

(see Fig. 4). Global climate change/sea-level rise and markets and food prices are examples of mainly exogenous pressures, while local human-induced subsidence (e.g., due to groundwater extraction), local political economy and socio-economic/ecological conditions are examples of endogenous drivers.

In this analysis, each case study delta is considered as a distinct socio-ecological system for which there are endogenous and exogenous pressures that are identified and defined as scenarios accordingly. Fig. 8 shows examples of delta-level scenario projections of population and GDP. For population, SSP-based projections are obtained from spatially explicit data available from Jones and O'Neill (2016). In addition, the Component Population Projection Method is used to develop medium delta-scale projections for each case study delta (see Codjoe et al., in prep. for further information). On the other hand, an expert-based questionnaire was used in order to obtain expert judgment and visions on the future economic conditions providing GDP projections and associated sectoral shares for each delta (see Arto et al., in prep. and Cazcarro et al., 2018 for further information).

The climate and socio-economic scenarios at the various scales (outlined above) provide divergent and challenging scenarios contexts investigated in this study. They are used for testing the robustness of the human and natural systems within the deltas by considering alternative adaptation policies. The overall conceptual framework, scenario matrix architecture, and the participatory process employed for development of the alternative adaptation policy options explored are outlined below (see Fig. 9).

As part of the participatory process, a set of procedures are considered through which stakeholders and experts collaborate to develop, test, and/or validate the scenarios and adaptation policy trajectories for each delta (see Section 6.2). Building on the ESPA Deltas experiences (see Allan and Barbour, 2015; Nicholls et al., 2016), the main purpose of the participatory process is to integrate inputs and views of different interested groups as appropriate. The participatory process was facilitated by a systematic conceptualisation of the links between the global climate (RCPs) and socio-economic (SSPs) scenario narratives and policy assumptions (SPAs) for developing appropriate national level adaptation policy trajectories and associated specific interventions for each delta.

Few studies have systematically considered different high-level adaptation futures consistent with the SPA concept. One successful example is Hall et al. (2016) who analysed national infrastructure under a range of future conditions, including policy trajectories (see also Hickford et al., 2015) (Table 5). Their four-fold policy approach provides a high-level expression of policy choices and has been adopted here (Chapman et al., 2016; Suckall et al., 2018). Drawing on Hall et al. (2016), four distinct visions of future adaptation choices (Adaptation Policy Trajectories – APTs) are proposed here. These are considered to be visionary but realistic in addressing potential future changes.

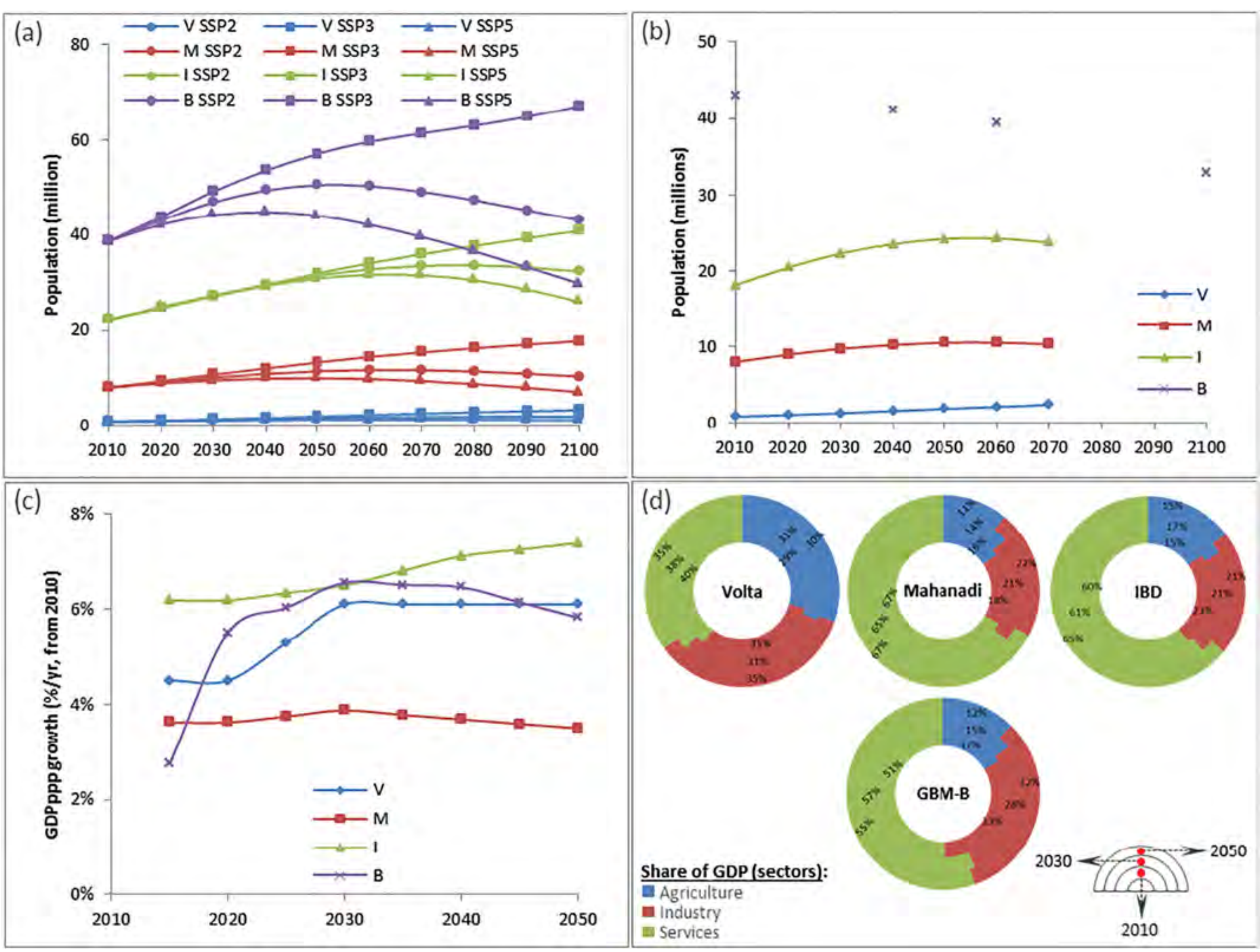


Fig. 8. Examples of delta-level scenarios of (a) SSP-based and (b) Cohort-Component based population projections, and (c) projections and (d) compositions of GDP. (The GDP data are developed based on a participatory process with country economic experts; see Arto et al., in prep. for more detail and maybe subject to revision). Note: the 'V', 'M', 'I' and 'B' stands for Volta, Mahanadi, and IBD, GBM (Bangladesh) deltas, respectively.

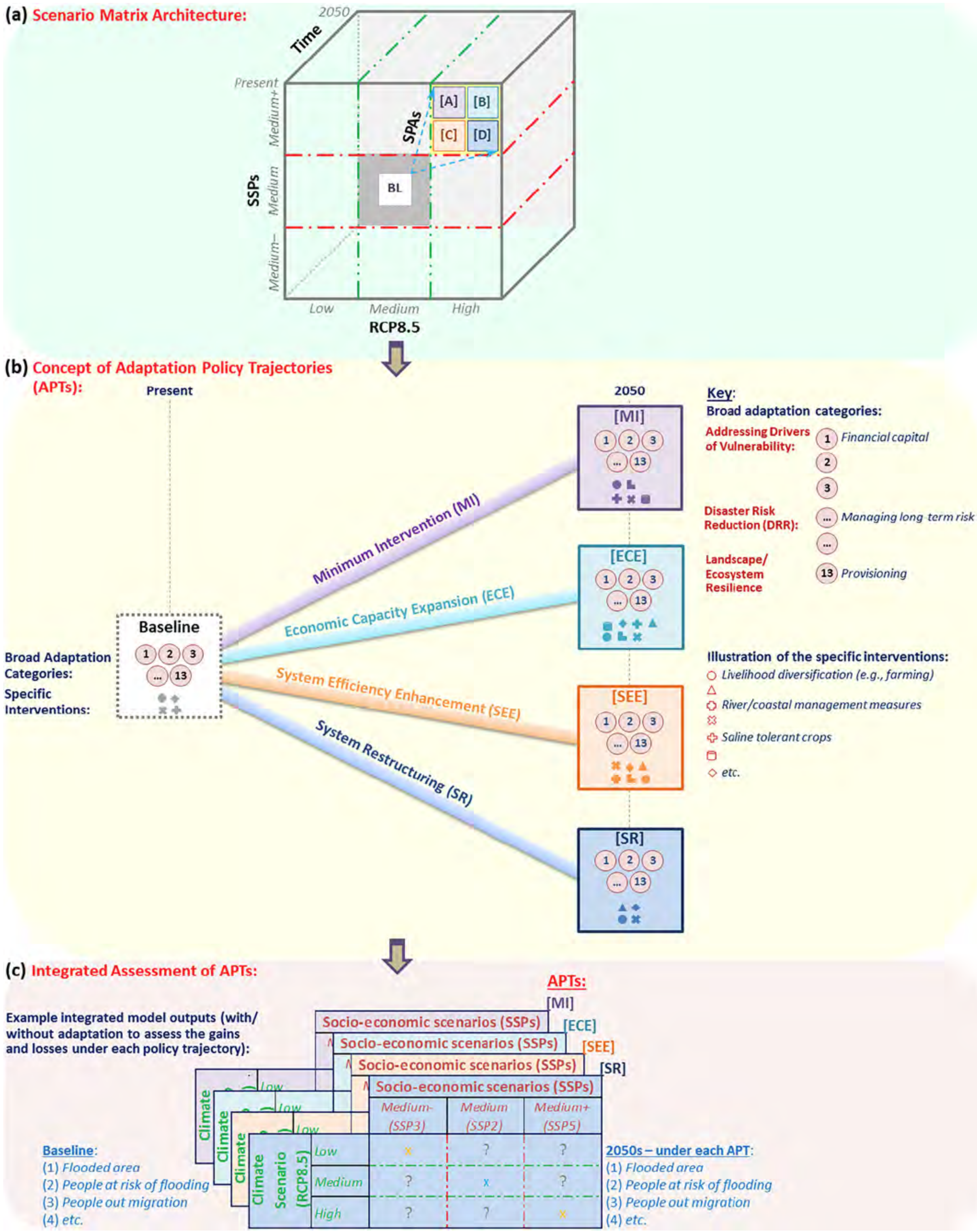


Fig. 9. Schematic illustration of the concept used for linking the climate (RCPs) and socio-economic (SSPs) scenarios and policy assumptions (APTs) and the overall scenario matrix architecture investigated in DECCMA.

Each APT is tested by taking into account the higher-scale scenario boundary conditions, historic trends and baseline conditions (e.g., based on household survey, adaptation inventory and policy reports analysis conducted within DECCMA). The four APTs are defined in Table 5 and compared to the ITRC study (Hall et al., 2016) (see Chapman et al., 2016; Suckall et al., 2018 for further details). They encourage thinking of different portfolios of responses, which may include radical change compared to current practice (especially under System Restructuring).

The narratives and key characteristics of the four APTs are defined based on a set of broad adaptation categories and description of how they are projected to evolve over time (between now and 2050) under each trajectory. To this end, thirteen broad categories are defined based on three main theoretically-derived adaptation policy components as outlined in Fig. 10.

Each APT contains specific national level adaptation interventions (within the thirteen categories), some of which are delta specific. Examples (one per category under the three main components) include I. *livelihood diversification*, *use of climate resilient farming techniques*, *use of co-operatives*, *access to markets*, and *land re-distribution to the poor*; II. *river/coastal management infrastructure*, *community training in disaster risk reduction*, *use of high land during flood time*, and *relocation of households*; and III. *use of saline tolerant crops*, *mangrove forest planting*, *promoting protecting green spaces*, and *wildlife conservation in natural heritage sites*. The gains and losses associated with each APT under the various scenarios can be assessed by focusing on the quantified interventions for each of the four policy trajectories.

6.2. Participatory process

Arriving at these policy scenarios was based on a four-stage participatory process outlined below:

Stage 1: *Narratives of adaptation policy trajectories* (*Expert-led*)

- Preliminary expert-led story-telling to create a narrative for the APTs, and identification of adaptation interventions relevant to each APT for the chosen delta. Estimation of provisional trajectories of how these interventions will progress from baseline to 2050; followed by modelled projections of these trajectories.

Stage 2: *Evaluate and validate* (*Engaging stakeholders*)

- Stakeholder evaluation of modelled outputs of the APTs, along with the pre-identified adaptation interventions, and their trajectories under a medium scenario; coupled with comment on which of the APTs most closely resembles what they anticipate as their existing policy trajectory (i.e., Business as Usual, BaU, policy) and what tweaks need to be made to this APT to best align it with what their current policy vision for the future is. Stakeholder views on policy implementation and the factors influencing this are also sought.

Stage 3: *Revise and remodel* (*Expert-led*)

- Project re-modelling of amended APTs in the light of stakeholder comments and modifications to the BaU APT, with preparation of APT/RCP projections such that a representative spectrum of possibilities can be made available to stakeholders in stage 4.

Stage 4: *Refine and finalise* (*Re-engage stakeholders*)

- Stakeholders are presented with the newly revised and re-modelled results across the ranges of climate and socio-economic scenario uncertainties, with the opportunity to further adjust the BaU APT. In addition, stakeholders will give their views on how well society in 2050 is likely to respond to the increased impacts of climate change projected to occur between 2050 and 2100.

The four stages are discussed in greater detail in Nicholls et al. (2017).

7. Discussion and conclusions

The study highlights the important role of scenarios in understanding uncertainties in climate change adaptation policy decision-making. Scenarios provide alternative long-term future outlooks to explore implications of changes in climatic, environmental, and socio-economic conditions for devising robust policies. Historically, most climate change studies focussed on climatic drivers only. However, in integrated assessments, climate scenarios need to be coupled with appropriate socio-economic scenarios (Nakicenovic and Swart, 2000). A number of such scenarios and frameworks have been developed and applied recognising these limitations (e.g., Arnell et al., 2004; Carter et al., 2007; Mahmoud et al., 2009; Moss et al., 2010). This also highlights recent advances in scenario development exercise and techniques (e.g., Börjeson et al., 2006). Most notable is the latest global RCP–SSP–SPA scenario framework developed for the IPCC AR5, which integrates the climate, socio-economic, and policy components. However, full application of such global framework at sub-national scales raises two important challenges in integrated assessment of interacting human-natural systems under uncertain future changing conditions: (i) added complexity in capturing the multiple (i.e., climate-socio-economic-policy) dimensions of change, and (ii) issues of scale. Here, we present an integrated scenario framework that recognises these challenges based on a multi-scale (combined top-down and bottom-up approaches) and participatory (joint expert-stakeholder) scenario methods.

The paper demonstrates application of this global RCP–SSP–SPA scenario framework at sub-national scale using deltas as an example. It presents the overall scenario framework, methods, and processes adopted for the development of scenarios across the multiple scales of interest (from global to delta scales and short- to long-term changes) as developed and applied within the DECCMA project. DECCMA is analysing the future of three contrasting deltas across South Asia and West Africa: (i) the Volta delta (Ghana); (ii) the Mahanadi delta (India); and (iii) the Ganges–Brahmaputra–Meghna (GBM) delta (Bangladesh/

Table 5
The four adaptation policy trajectories (APTs) as defined in this study and compared to the ITRC study (Hall et al., 2016).

	Definition of the Four APTs	
	DECCMA	ITRC[a]
A.	Minimum intervention (MI): aims to minimise costs while protecting citizens from climate change impacts.	Minimum intervention (MI): takes a general approach of minimal intervention, reflecting historical levels of investment, continue maintenance and incremental change in the performance of the current system.
B.	Economic capacity expansion (ECE): focuses primarily on encouraging economic growth and utilizing the increased financial capacity it brings to protect the economic system from climate-induced harm.	Capacity expansion (CE): focuses on planning for the long-term by increasing investment in infrastructure capacity.
C.	System efficiency enhancement (SEE): focuses on promoting most efficient management and exploitation of the current system, looking at ways of distributing labour, balancing livelihood choices, and best utilizing ecosystem services to enhance livelihoods and wellbeing under climate change.	System efficiency (SE): focuses on deploying the full range of technological and policy interventions to optimise the performance and efficiency of the current system, targeting both supply and demand.
D.	System restructuring (SR): embraces pre-emptive fundamental change to the social and physical functioning of the delta system in response to serious threats to the delta's current socio-ecological system.	System restructuring (SR): focuses on fundamentally restructuring and redesigning the current mode of infrastructure service provision, deploying a combination of targeted centralisation and decentralisation approaches.

[a] ITRC: UK Infrastructure Transitions Research Consortium.

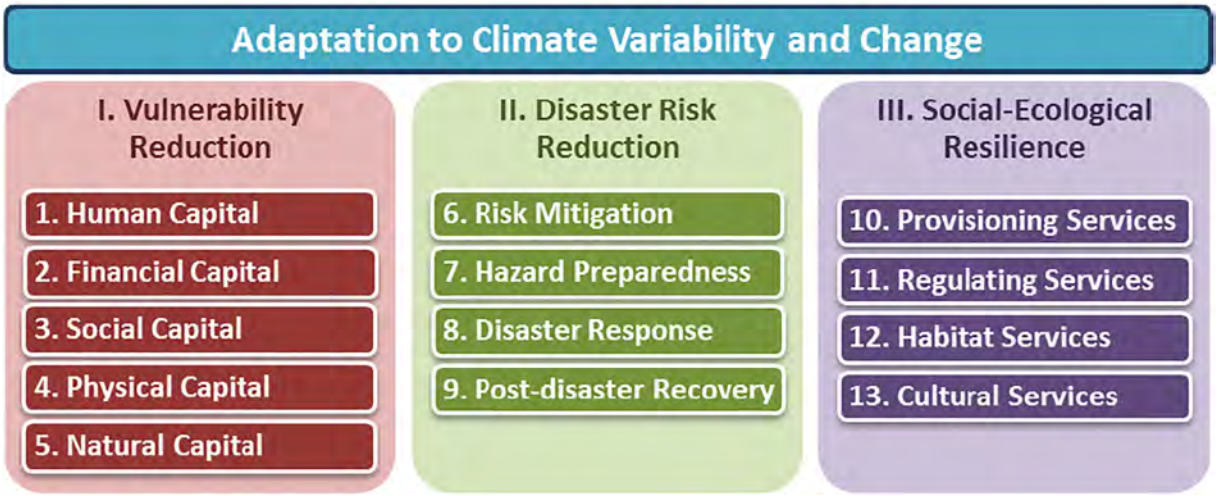


Fig. 10. The three main components and thirteen broad categories of the adaptation policy trajectories (adapted from Suckall et al., 2018).

India). This includes comparisons between these three deltas. The framework provides improved specification of the role of scenarios to analyse the future state of adaptation and migration across the case study deltas. To this end, six discrete levels of scenarios are considered: (i) global (climate change, e.g., sea-level rise and temperature change; and socio-economic assumptions, e.g., global food prices and markets); (ii) regional catchments (e.g., changing river flows), (iii) regional coastal seas (e.g., fisheries), (iv) regional politics (e.g., transboundary issues), (v) national socio-economic conditions (e.g., population and GDP growth), and (vi) delta scenarios (e.g., adaptation and migration policies).

At the global scale, the RCP8.5 climate scenario has been selected as the main focus in order to consider the strongest climate signal. It maximises the sampling of uncertainty in future climate changes and represents the most challenging scenario against which to test the robustness of the human and natural systems and adaptation policies in the deltas. Up to 2050, the RCP8.5 scenario can be combined with any socio-economic (SSP) scenario, while beyond 2050 only SSP3 and SSP5 have consistent emissions, although SSP2 is close. In this study, three SSP-based scenario narratives are identified: (i) Medium (middle of the road) scenario (~SSP2), (ii) Medium– scenario of low economic and high population growth, and low level of urbanisation (~SSP3), and (iii) Medium+ scenario of high economic and low population growth, and high level of urbanisation (~SSP5) scenarios that are consistent with the RCP8.5 scenario. For post-2050 analysis, we combine the RCP8.5 climate and SSP5 socio-economic scenarios, which will provide consistent temporal continuity (together with the Medium+ scenario). Based on these global scenario narratives, downscaled climate and socio-economic scenarios are considered at the regional (catchments and coastal seas) and national scales based on downscaled RCM simulations (e.g., Macadam et al., this issue) and open source databases (e.g., national SSP projections from IIASA). At the delta scale, a participatory process is used for the development of four alternative adaptation policy trajectories, APTs (i. *Minimum intervention*, ii. *Economic capacity expansion*, iii. *System efficiency enhancement*, and iv. *System restructuring*). Using a list of quantified specific adaptation interventions, the gains and losses under each APT are assessed for each delta taking into account uncertainties of the various future climatic, environmental, and socio-economic scenarios. The study demonstrates the benefits of a multi-dimensional scenario framework to capture the different drivers of change. It also recognises the need to use the best science and stakeholder engagement to deliver rigorous scenario development processes. Such an approach facilitates the development of appropriate and consistent endogenous and exogenous scenario futures across the multiple scales of interest. The lessons are transferable and the approach could be applied widely to other deltas, other coastal systems, and in fact to any sub-national problems with multiple drivers and scales.

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