DECCMA

Working Paper

The DECCMA Integrated Scenario Framework: A Multi-Scale and Participatory Approach to Explore Migration and Adaptation in Deltas

Authors: R.J. Nicholls[1], A.S. Kebede[1] A. Allan[2], I. Arto[3], I. Cazcarro[3], J.A. Fernandes[4], C.T. Hill[5], C.W. Hutton[5], S. Kay[4], V. Lauria[6], J. Lawn[1], A.N. Lázár[1], I. Macadam[7], M. Palmer[7], N. Suckall[5], E.L. Tompkins[5], K. Vincent[8], P. Whitehead[9]

Affiliations:
[1] *Faculty of Engineering and the Environment, University of Southampton, UK*
[2] *Centre for Water Law, Policy and Science, University of Dundee, UK*
[3] *Basque Centre for Climate Change (BC3), Spain*
[4] *Plymouth Marine Laboratory, UK*
[5] *Geography and Environment, University of Southampton, UK*
[6] *Institute for Coastal Marine Environment (IAMC),National Research Council (CNR), Italy*
[7] *Met Office, UK*
[8] *Kulima Integrated Development Solutions (Pty) Ltd, South Africa*
[9] *School of Geography and the Environment, University of Oxford, UK*

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About DECCMA Working Papers

This series is based on the work of the Deltas, Vulnerability and Climate Change: Migration and Adaptation (DECCMA) project, funded by Canada's International Development Research Centre (IDRC) and the UK's Department for International Development (DFID) through the **Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA)**. CARIAA aims to build the resilience of vulnerable populations and their livelihoods in three climate change hot spots in Africa and Asia. The program supports collaborative research to inform adaptation policy and practice.

Titles in this series are intended to share initial findings and lessons from research studies commissioned by the program. Papers are intended to foster exchange and dialogue within science and policy circles concerned with climate change adaptation in vulnerability hotspots. As an interim output of the DECCMA project, they have not undergone an external review process. Opinions stated are those of the author(s) and do not necessarily reflect the policies or opinions of IDRC, DFID, or partners. Feedback is welcomed as a means to strengthen these works: some may later be revised for peer-reviewed publication.

Contact
Prof. Robert J. Nicholls
Email: R.J.Nicholls@soton.ac.uk

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ACRONYMS AND ABBREVIATIONS

AR5	*IPCC 5th Assessment Report*
CanESM2	*Canadian Earth System Model (2nd generation)*
CNRM-CM5	*Centre National de Recherches Météorologiques – Climate Model version 5*
CM	*Climate Modelling*
DECCMA	*Deltas, Vulnerability & Climate Change: Migration & Adaptation*
ΔDIEM	*Delta Dynamic Integrated Emulator Models*
ESPA	*Ecosystem Services for Poverty Alleviation*
GBM	*Ganges-Brahmaputra-Meghna delta*
GCM	*Global Climate Models*
GDP	*Gross Domestic Product*
GFDL-CM3	*Geophysical Fluid Dynamics Laboratory – Climate Model version 3*
GHGs	*Greenhouse Gases*
HadGEM2-ES	*Headley Global Environment Model 2 – Earth System*
IA	*Integrated Assessment*
IAM	*Integrated Assessment Modelling*
IIASA	*International Institute for Applied Systems Analysis*

INCA	*Integrated Catchment Model*
IPCC	*Intergovernmental Panel on Climate Change*
RCM	*Regional Climate Models*
RCP	*Representative Concentration Pathways*
SPA	*Shared climate Policy Assumptions*
SRES	*Special Report Emission Scenarios*
SSP	*Shared Socioeconomic Pathways*
VIA	*Vulnerability, Impacts and Adaptation*

ACKNOWLEDGEMENT

SUMMARY

To better anticipate potential impacts of climate change, integrated information about the future is required, including: climate, society and economy, and adaptation and mitigation policy scenarios. This working paper describes the overall scenario framework, methods and processes adopted for the development of scenarios in the DECCMA project across the multiple scales of interest (from local to global and short- to long-term). The paper particularly focuses on recent advances in scenario development exercises, within the broader context of the latest global RCP–SSP–SPA[1] scenario framework developed for the recent IPCC AR5[2] report.

The DECCMA project is analysing the future of three contrasting deltas in South Asia and West Africa: (i) the Ganges–Brahmaputra–Meghna (GBM) delta (Bangladesh/India); (ii) the Mahanadi delta (India); and (iii) the Volta delta (Ghana). This includes comparisons between these three deltas. Hence, the integrated scenario framework presented here comprises a multi-scale hybrid approach for producing appropriate and consistent endogenous and exogenous scenarios to analyse each delta. It includes and combines model-based and participatory approaches as appropriate, and provides an improved specification of the role of scenarios to analyse the future state of migration and adaptation across the three case study deltas. The framework has six discrete levels of scenario considerations from the global to the delta scale, although these levels are coupled. It considers the global scale scenario narratives, the regional (catchments, coastal seas, and political conditions) and national scale scenario projections as boundary conditions for development of more specific delta-scale scenarios and future adaptation policy trajectories for each delta.

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 provides a challenging yet plausible scenario context against which to test robustness of the human and natural systems and adaptation policies. Up to 2050, the RCP8.5 climate scenario can be combined with any socio-economic (SSP) scenario, while after 2050 only SSP3 and SSP5 have consistent emissions, although SSP2 is close. In DECCMA, we have identified three SSP-based scenario narratives: (i) Medium (middle of the road) scenario (~SSP2), (ii) Medium+ scenario of high economic and low population growth, and high level of urbanisation (~SSP5), and (iii) Medium– scenario of low economic and high population growth, and low level of urbanisation (~SSP3) scenarios that are consistent, and can be combined, with the RCP8.5 climate scenario for up to 2050. Beyond 2050, we combine the RCP8.5 climate and SSP5 socio-economic scenarios, which provide continuity for pre- and post-2050 analysis. This forms the focus of the long-term biophysical assessment, which is more exploratory in nature. Based on these global climate and socio-economic scenario narratives, downscaled climate and socio-economic scenarios are considered at the regional (catchments and coastal seas) and national scales based on downscaled simulations (e.g., RCM simulations) 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 distinct adaptation policy trajectories (APTs) (i.e., *minimum intervention*, *economic capacity expansion*, *system efficiency enhancement*, and *system restructuring*), which describe alternative future bundles of adaptation actions and measures under different economic and social trajectories. 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 across the multiple scales. The overall concept, methods and processes presented here are transferable to other deltas, and potentially to other coastal areas and sub-national socio-ecological settings with multi-scale challenges.

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[1] *Representative Concentration Pathways (RCPs) – Shared Socio-economic Pathways (SSPs) – Shared climate Policy Assumptions (SPAs).*
[2] *The Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC).*

DECCMA

The DECCMA Integrated Scenario Framework: A Multi-Scale and Participatory Approach to Explore Migration and Adaptation in Deltas

R.J. Nicholls, A.S. Kebede *et al.* (2017)

1. INTRODUCTION

Mid- and low-latitude delta systems around the world have been identified as some of the most vulnerable coastal environments during the 21st Century (Ericson *et al*. 2006; Syvitski *et al*. 2009). They are susceptible to multiple climatic and environmental drivers (e.g., sea-level rise/subsidence, storm surges, temperature and precipitation changes, etc.) and socio-economic factors (e.g., human-induced subsidence, upstream catchment management, changes in population, GDP growth, urbanisation, etc.). These drivers of change also operate at multiple scales from local to global and short- to long-term, highlighting the need for linking global scale impacts to local scale issues/processes and developing multi-scale scenarios (e.g., Alcamo *et al*. 2006). With over half a billion people estimated to be living within deltas globally, the scale of the challenge is immense. In many narratives of the future of deltas, they are the source of large numbers of environmental refugees forced to leave due to sea-level rise and subsidence (e.g., Milliman *et al*. 1989; Myers 2001; Ericson *et al*. 2006), although this process has received limited exploratory study. 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 livelihood of large (often poor) population under changing conditions (e.g., Day *et al*. 2016; Szabo *et al*. 2016; Tessler *et al*. 2016). A holistic understanding of these challenges and the potential impacts of and vulnerabilities to future climate and socio-economic changes is central for devising robust adaptation policies (e.g., Chapman *et al*. 2016; Haasnoot *et al*. 2012, 2013; Kwakkle *et al*. 2015).

Scenario analysis has long been identified as a strategic management tool to address future uncertainties in order to support robust adaptation decision-making under changing climate/ environmental and socio-economic conditions (e.g., van Vuuren *et al*. 2014; Star *et al*. 2016). Scenarios represent coherent, internally consistent, and plausible descriptions of possible trajectories of future conditions based on 'if, then' assertion to develop self-consistent storylines or images of the future (Moss *et al*. 2010; O'Neill *et al*. 2014). They are generally developed to investigate long-term futures for the exercise of decision-making in an environment of interacting-complex systems and uncertainty (e.g., Hall *et al*. 2016; Hickford *et al*. 2015). They can be used to explore a range of plausible future conditions and their challenges.

The DECCMA project is analysing the future of deltas as they have been identified as a hotspot where climate change, and sea-level rise in particular, may have major adverse effects for development (de Souza *et al*. 2015). Three delta case studies in south Asia and Africa are considered: the Ganges-Brahmaputra-Meghna (GBM) delta (Bangladesh/India); the Mahanadi delta (India); and the Volta delta (Ghana). There is a focus on understanding migration and other adaptation and the policy implications for the future of these deltas. The analysis includes comparisons between these three deltas and hence the methods and scenarios need to be consistent across the deltas.

A major challenge in delta-level climate change impact, adaptation and vulnerability assessment is the differences in spatial scale between available coarser-resolution scenario projections and the growing demand for policy-relevant information on finer-resolution site-specific variations of socio-economic drivers of changes, such as population, Gross Domestic Product (GDP), land-use, and urbanisation, and other non-climatic drivers. For instance, when analysing global change, spatial scales play an important role – where some changes (such as global warming) can be investigated at a coarser scale (e.g., global level), while other regional/local scale changes (such as land-use, potential climate change impacts and adaptation needs) require spatially-finer assessments (van Vuuren *et al*. 2010).

In integrated assessment, climate scenarios need to be coupled with appropriate socio-economic scenarios – which depend on factors such as demographic and socio-economic development, and

technological and environmental changes (Arnell *et al*. 2004; Carter *et al*. 2007; Moss *et al*. 2010). Various studies have applied different socio-economic, land-use and technology scenarios at a regional and country level based on the global scenarios developed in the IPCC SRES and more recently the SSP scenario storylines. However, large regional socio-economic variations (such as population, income and technological development differences) can produce sharp contrasts in images of the future in terms of exposure and vulnerability of social and economic systems to climate change and adaptive capacity (Carter *et al*. 2007). This implies the limited local applicability of a coarser and single characterisation of the images of the future; and hence, the need for a range of plausible representations of what the future might unfold to adequately characterise the potential changes of non-climatic drivers of changes (such as demography, socio-economic and technological changes). Nicholls *et al*. (2008) and Nicholls *et al*. (2012) also illustrate the importance and development of scenarios of plausible futures of relevant climate and non-climate drivers that can be used for coastal vulnerability analysis.

The evaluation of global scenarios and appropriate downscaling to, and development of locally-relevant, finer-spatial scale scenarios is therefore an important step when representing the future and analysing associated uncertainties (e.g., Wollenberg *et al.* 2000). As such, the development of a self-consistent and appropriate socio-economic scenario for climate change impact, adaptation and vulnerability assessment requires a rational and representative image of the long-term future throughout the century – reflecting the possible changes in socio-economic and technological characteristics. This highlights the need for a combined bottom-up and top-down approach for developing scenarios across scales (van Ruijven *et al*. 2014).

The purpose of this working paper is to outline the process and methods implemented in the development of the scenarios for the DECCMA project. The paper is structured as follows: Section 2 outlines the DECCMA scenario development process and method used, discusses the scenario framework, and highlights how it advances current methods and process. This section also considers the scenario framework of the ESPA Delta's project (Allan and Barbour 2015) and describes the different components of the framework across the various scales of interest in DECCMA, including the structure of the delta-scale scenario participatory process. Section 3 presents the lessons learned from the scenario development process in terms of the concept and methods used as well as the multi-scale and participatory approach implemented. Finally, concluding remarks and future research directions are presented in Section 4.

2. THE DECCMA SCENARIO FRAMEWORK: A MULTI-SCALE APPROACH

2.1 The ESPA Deltas Experience and Scenario Needs in DECCMA

The ESPA Deltas[3] project aimed to support Bangladeshi decision makers with knowledge and tools on the cause-effect relationships of ecosystem services and poverty and health by considering climate and environmental change in the world's largest and most dynamic deltas: the Ganges-Brahmaputra-Meghna (GBM) delta (see Nicholls *et al*. 2015; 2016). The project developed an integrated approach, which combined expert and stakeholder knowledge through continuous engagement and iterative learning: learning about interacting drivers and processes (Figure 1a), scenario development and quantification, governance and stakeholder analysis, socio-economic analysis, household surveys, and detailed biophysical modelling. Stakeholders played a key role in shaping the research focus, the scenario development and implementation. In addition, stakeholders were part of an iterative learning process in which project results are disseminated, discussed and new model runs designed (Figure 1b).

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[3] *The Ecosystem Services for Poverty Alleviation (ESPA) Deltas Project ("Assessing Health, Livelihoods, Ecosystem Services and Poverty Alleviation in Populous Deltas, 2012 – 2016") (see Nicholls et al. 2015; 2016; Allan and Barbour 2016)*
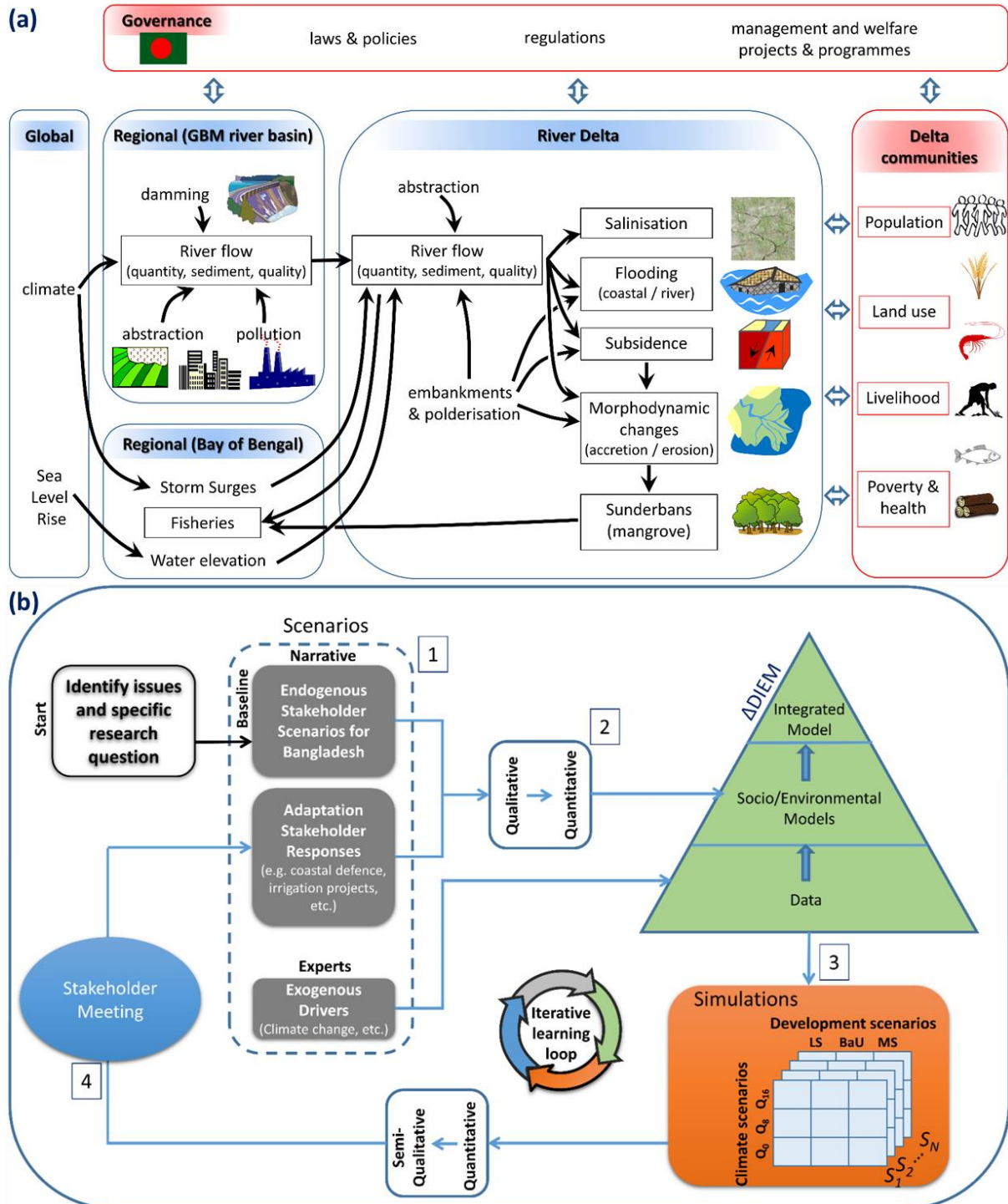
Figure 1: *Schematic illustration of (a) the scales of analysis in the ESPA Deltas project and (b) the iterative qualitative-quantitative (Q2Q) stakeholder engagement process (Source: Nicholls et al. 2016).*

The DECCMA project is more ambitious by considering the future of three deltas in South Asia and Africa: (i) the Ganges-Brahmaputra-Meghna delta (Bangladesh/India), (ii) the Mahanadi delta (India), and (iii) the Volta delta (Ghana) (Figure 2). The scenario development process in DECCMA builds on the ESPA Delta's experience that demonstrated the key function of the scenario development process in linking the concerns and priorities of relevant stakeholders with integrated models (see Allan and Barbour 2015), while recognising the more complex scenario space requirement in DECCMA. In addition, the scenario purpose in DECCMA aims at (i) producing consistent futures at the delta scale across all the three deltas,

as well as (ii) maintaining consistency with the other CARIAA projects (to the maximum possible extent) and with wider climate change, environmental change and migration research.
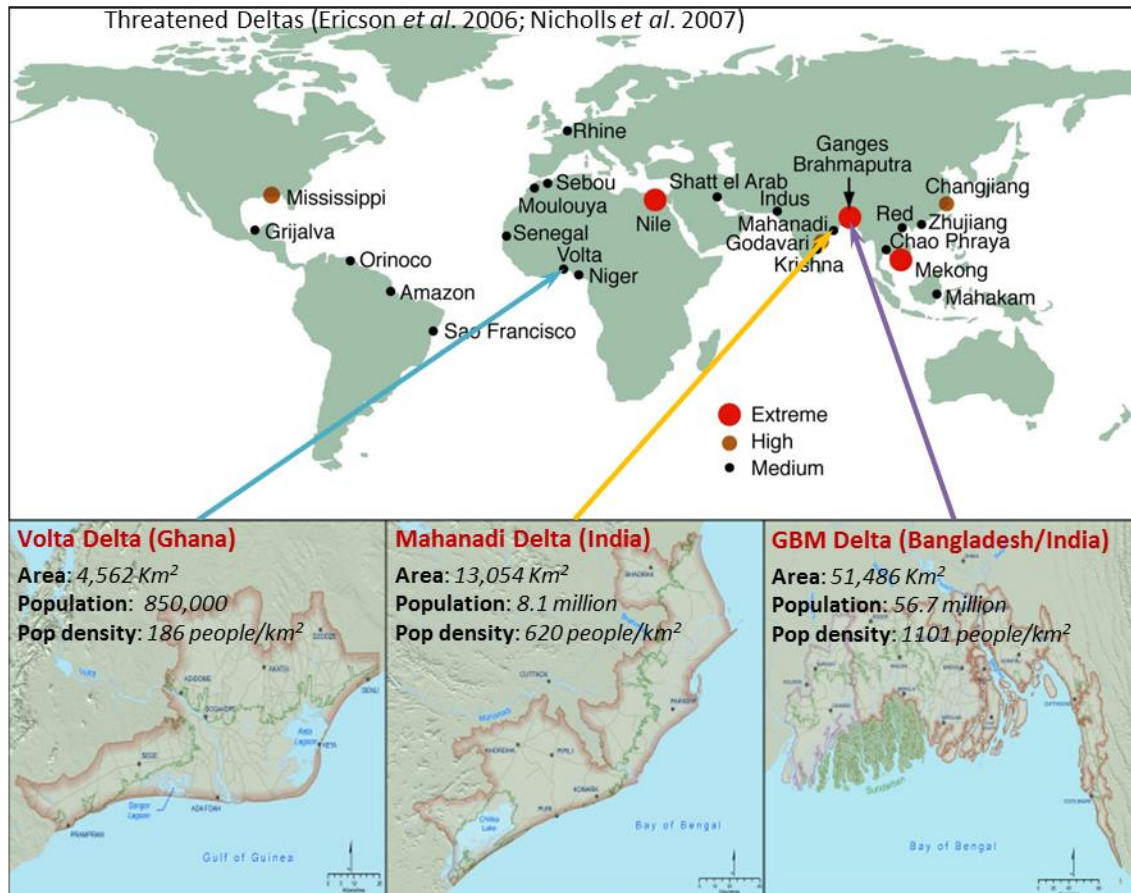
Figure 2: *Locations and key characteristics of the DECCMA case study deltas.*

While DECCMA is considering adaptation and migration to sea-level rise and climate change at the scale of deltas, it is important to envisage a coherent future world within which each delta sits. At one level, climate change is a global phenomenon which is the result of broad global-scale processes – collective greenhouse gas emissions. These also reflect a range of social and economic processes and these worlds will influence non-climate factors such as global food prices and other economic boundary conditions. At sub-global scales, the deltas sit in catchments (e.g., river flow modelling) and regional seas (e.g., oceanographic/fisheries modelling) as well as national scale socio-economic conditions (e.g., relevant for input-output analysis), which will be subject to climate and non-climate changes. The deltas will be subject to these changes, but we will also need to consider changes within the delta. This highlights the need for a multi-scale framework within DECCMA. Figure 3 shows a schematic illustration of the various scales at which the biophysical and socio-economic change drivers operate, which need to be captured in the DECCMA scenario development process at the delta scale.
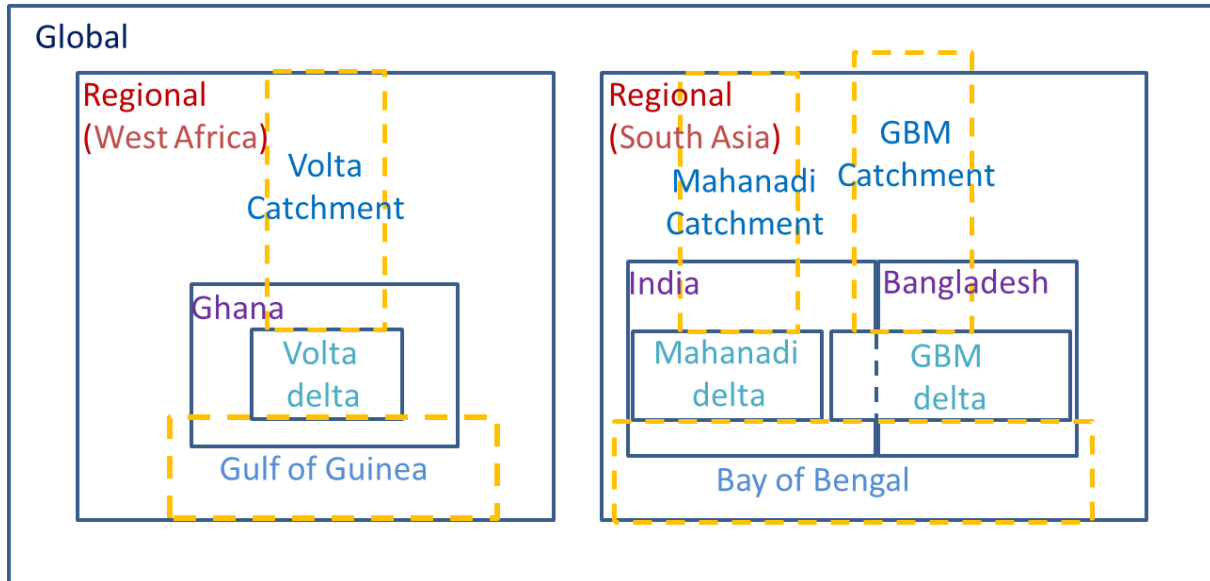
Figure 3: *The range of scenario scales in DECCMA. Six spatial levels are recognised: (1) global, (2) regional (politics), (3) catchments, (4) regional seas, (5) national, and (6) delta.*

Hence, to analyse these systems a range of consistent scenarios (or plausible futures) are required at a range of scales, including: (1) global (e.g., population and GDP for economic modelling), (2) regional (e.g., catchment climate and catchment modelling for river modelling or regional sea climate for oceanographic/fisheries modelling or regional land-use/land cover change modelling), (3) national scale for socio-economic factors relevant to input-output modelling, and (4) the delta scale itself for a wide range of disciplinary analyses. It is imperative that consistent scenarios are used across these scales so that we can articulate how we assume that the world is evolving, in addition to the associated regional and local changes. Importantly, this will allow us to reference our results to other climate change studies and make comparative statements between the analyses of the different deltas being considered. Table 1 elaborates the DECCMA scenario needs by scale together with examples of potential data sources.

Table 1: *DECCMA multi-scale scenario needs and example data sources.*

Scales	Example Factors	Example Sources
Global	*Greenhouse gas emissions and CO_2 concentrations*	*RCP narrative (RCP8.5)*
	Socio-economic situation	*SSP narrative (SSP5)*
Regional (Political)	*Inter-state cooperation and development, or trans-boundary disputes, other factors such as geopolitical context, hydro-politics, etc.?*	*International treaties; literature on environmental governance, etc.?*
Regional (Catchments)	*Downscaled climate scenarios*	*Regional Climate Model (RCM) simulations or library (e.g., downscaling of selected GCM simulations and application of bias correction)*
	Changing land cover	*SSP projections, e.g., Popp et al. (2016, GEC)*
Regional (Coastal seas)	*Downscaled climate scenarios*	*Regional Climate Model (RCM) simulations or library (e.g., downscaling of selected GCM simulations)*
	Regional sea-level rise scenarios	*Regionalisation of the IPCC AR5 sea-level rise scenarios (see Palmer et al. in prep.)*
National	*Socio-economic scenarios*	*Downscaled SSP scenarios, e.g., IIASA; Jones & O'Neill (2016, ERL)*
Delta	*Adaptation choices*	*Experts and participatory process (e.g., stakeholder workshops)*

In terms of the temporal scale, delta-scale stakeholder scenarios can be considered reasonably robust up to 2050, after which only biophysical and downscaled SSP-based scenarios can be used with greater confidence. Post-2100, only sea-level rise scenarios can be explored (see Figure 4). Hence, the scenario needs become simpler with increasing time scale and the analysis results become more generalised.
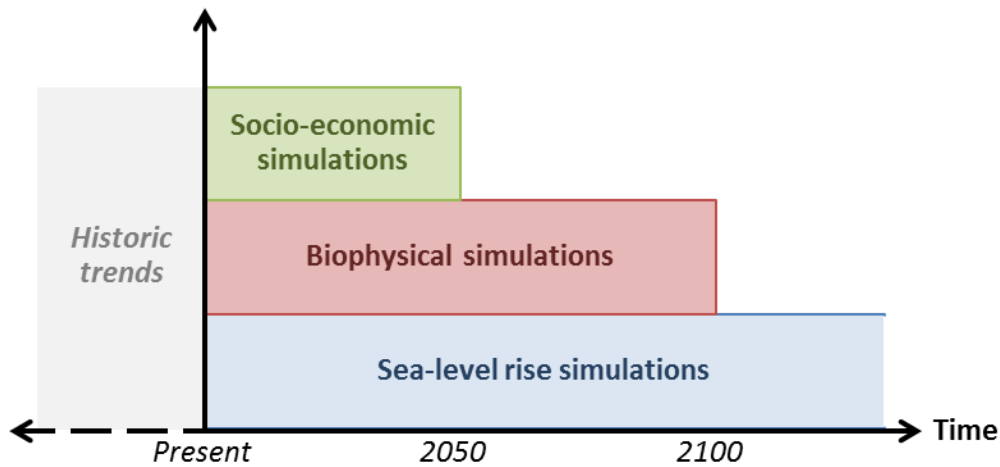
Figure 4: *Schematic illustration of the temporal scales in scenario needs.*

2.2 The DECCMA Scenario Framework

Figure 5 presents a simplified version of the DECCMA scenario framework, illustrating the board workflow across the various scales of interest (more detailed version of the framework is presented in Figure 6). The framework provides a structure highlighting representation of the various exogenous (external) and endogenous (internal) drivers and the participatory (stakeholder engagement) aspects considered for the development of the delta-scale scenario projections and adaptation policy trajectories. The framework facilitates consistency of the modelling process across the various scales and components, as well as in the three case study deltas. This is particularly important in facilitating consistency in the modelling process across the DECCMA project, such as the biophysical and vulnerability hotspot modelling (e.g., Payo *et al*. 2015) and the integrated modelling (e.g., Lazar *et al*. 2015).
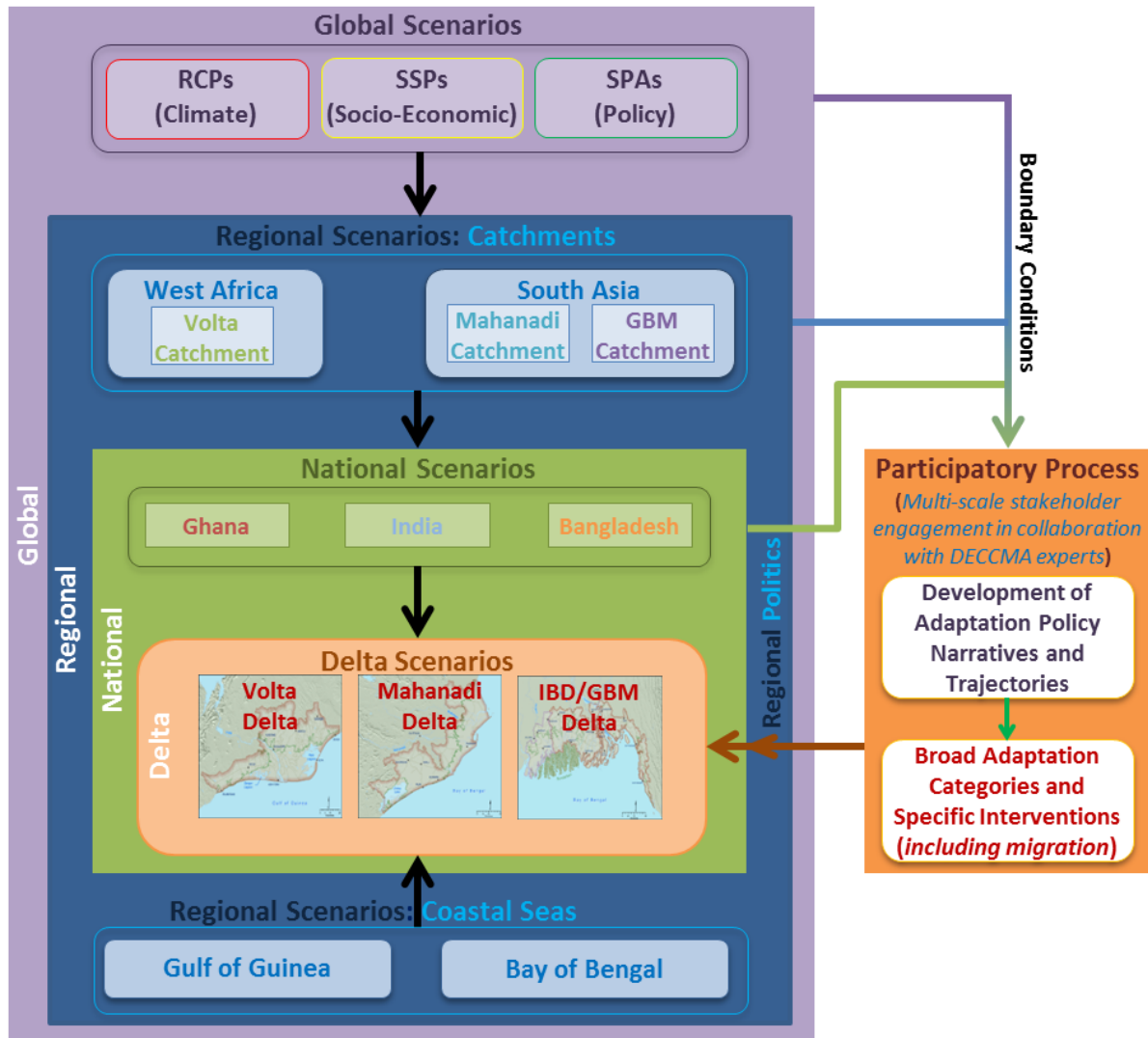
Figure 5: *A simplified version of the DECCMA scenario framework illustrating the various scales of interest and the broad workflow. A detailed version of the framework is presented in Figure 6.*
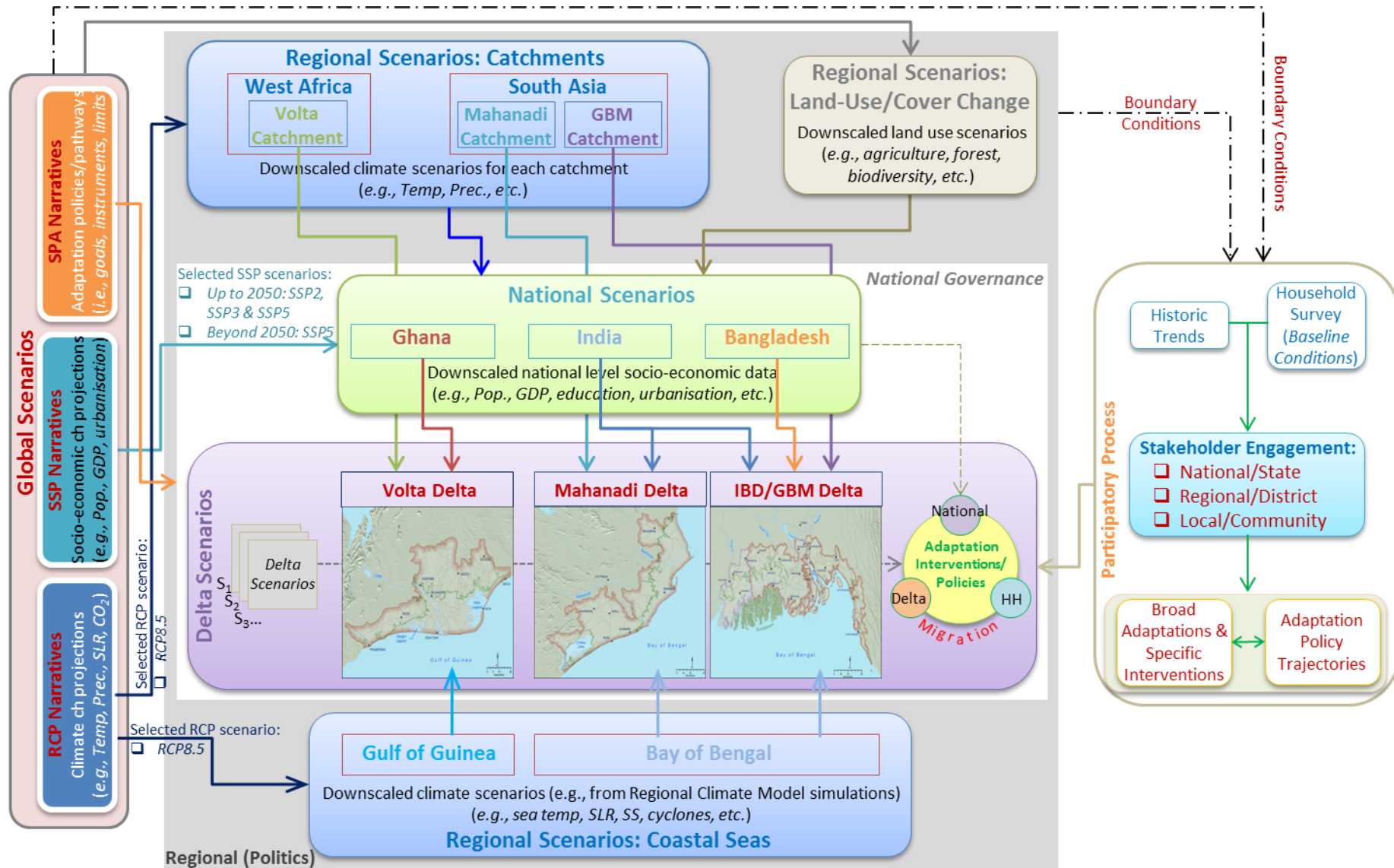
Figure 6: *A detailed version of the DECCMA scenario framework: a multi-scale and participatory approach. Up to 2050, the full framework operates and afterwards, a simplified approach, excluding stakeholder engagement, will be used as discussed in the text.*

At the global scale, the key factors are both greenhouse gas emissions, and hence climate change and socio-economic assumptions about the world economy, reflecting the scenario work of the Met Office on climate and BC3 on global economics (this contrasts with the ESPA Deltas scenarios approach where the only common global factor was an emissions, and resulting climate change, scenario). There are four RCPs and five SSPs, providing 20 possible broad-scale combinations. The number of possible combinations could also increase significantly if different scenarios (e.g., low, medium, high) of the climate sensitivity aspect are also to be considered for each RCP scenario. While recognising the potential benefits of considering as many of these combinations as possible, in DECCMA we focus on nine selected RCP and SSP scenario combinations to make the set of scenarios manageable (see Section 2.3.3).

Furthermore, as the scale of analysis becomes smaller, the issue of consistency with the global scenarios allows a wider and wider range of consistent scenario values for the same SSP. Hence at the delta scale, in particular, there is some freedom to elaborate and quantify stakeholder-derived views in a participatory process, rather than just use downscaled numbers from global scenarios which may have little meaning to stakeholders at the delta scale. Ideally downscaled perspectives should inform a stakeholder process, but the stakeholder views should have primacy as it is critical that our analyses are credible with the delta-level and/or national policy processes, which will influence decisions concerning adaptation and migration. Hence, the ESPA Deltas scenario participatory method can be applied with stakeholders at the delta scale, but with the additional constraint that the scenario process must be comparable across deltas and linked in a narrative manner to the headline RCP/SSP assumptions and recognising the range of scenario scale (spatial and temporal) needs in DECCMA. This leads to a hybrid methodology which draws on the RCP–SSP–SPA framework on the global and regional scale, including global climate models and related global socio-economic futures and national projections linked in a number of natural steps to stakeholder-based approaches to create delta futures (cf. Figures 3–6). This in essence allows distinct and appropriate methods to develop the exogenous and endogenous scenarios within the DECCMA project.

2.3 Global Scenarios

The Representative Concentration Pathways (RCPs) (Moss *et al*. 2010; van Vuuren *et al*. 2011) – Shared Socio-economic Pathways (SSPs) (O'Neill *et al*. 2014) – Shared climate Policy Assumptions (SPAs) (Kriegler *et al*. 2014) framework (Figure 7) is a state-of-the-art global framework developed for the IPCC AR5 report. The framework supersedes the Special Report on Emissions Scenarios (SRES) framework (Nakicenovic and Swart 2000), and provides a foundation for an improved integrated assessment of climate change impacts and adaptation and mitigation needs. The following sub-sections discuss the RCP, SSP and SPA scenarios, and the development process and methods used, as well as the selected scenario combinations to be considered within the DECCMA project.
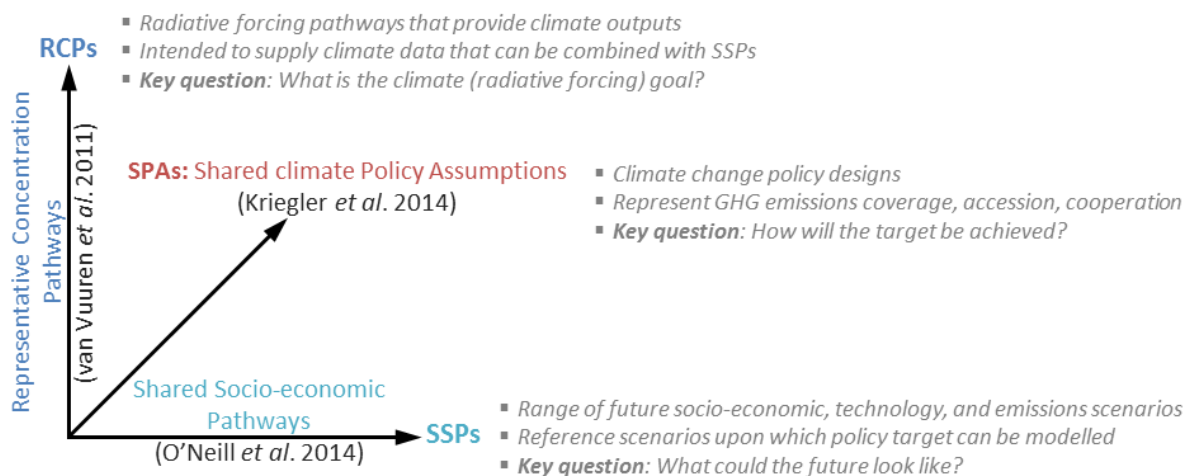
Figure 7: *Simplified schematic of the latest global RCP–SSP–SPA scenario framework of the IPCC AR5 (adapted from IPCC 2012).*

2.3.1 Representative Concentration Pathways (RCPs)

The RCPs "provide information on possible development trajectories for the main forcing agents of climate change" and comprise a set of four scenarios accounting for emissions of greenhouse gases and other air pollutants and changes in land use (van Vuuren *et al.* 2011). 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. Table 2 presents key characteristics of the four RCPs, including approximate atmospheric greenhouse gas concentrations expressed in terms of carbon dioxide equivalent (CO_2 eq.).

Table 2: *Characteristics of the four RCP scenario pathways (Source: van Vuuren et al. 2014).*

RCPs	Pathway Shape & Characteristics	Radiative Forcing and Approximate Atmospheric Greenhouse Gas Concentration in 2100
RCP8.5	Rising: *High emission scenario; a fast and high increase in emission up to around 2070, followed by a slow growth in emissions later in the century; rising and high radiative forcing throughout the century*	8.5 W/m^2 (~1370 ppm CO_2 eq.)
RCP6.0	Stabilisation without overshoot: *Emissions remain at current levels until 2030, which then peaks around 2080 before a sharp delayed reduction; radiative forcing stays below RCP4.5 up to 2060, followed by significant increase through the remaining part of the century*	6.0 W/m^2 (~850 ppm CO_2 eq.)
RCP4.5	Stabilisation without overshoot: *Moderate emission growth up to 2040 followed by gradual reduction before levelling around 2080; radiative forcing stabilises around 2060*	4.5 W/m^2 (650 ppm CO_2 eq.),
RCP2.6	Peak and decline: *Lowest overall emissions and forcing; strict emission abatement starts around 2020; peak in radiative forcing at 3 W/m^2 before mid-century; effective emissions are reduced to zero around 2080*	2.6 W/m^2 (~490 ppm CO_2 eq.)

The forcing information in the RCPs can serve as input data for climate model simulations to underpin projections of future climate conditions. The RCPs were used as input to the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor *et al.* 2012) Global Climate Models (GCM) simulations that formed the basis of the future climate projections presented in the IPCC AR5 report (IPCC 2013). Figure 8 shows the forcing trajectories and the IPCC AR5 projections of global mean temperature and associated sea-level rise for the 21st century for the RCPs.
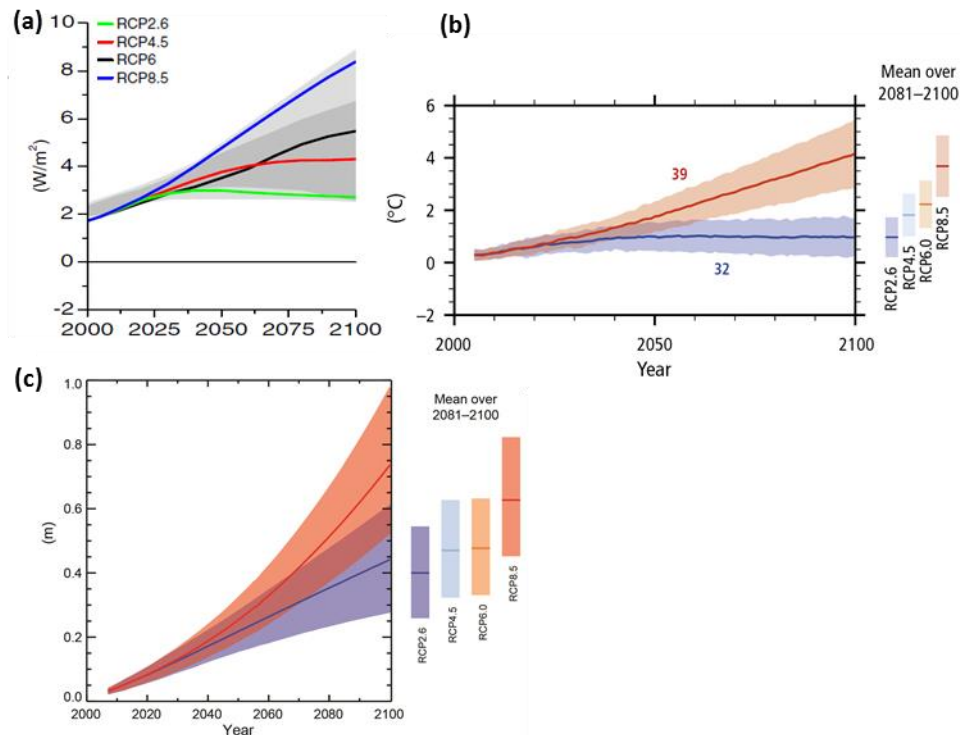
Figure 8: *Radiative forcing trends (a) (van Vuuren et al. 2011), and associated global mean surface temperature change (b) and sea-level rise (c) projections (relative to 1986–2005) under the four RCP scenarios (Source: IPCC 2013). Shading represents uncertainty.*

The above projections are based on many different GCMs (e.g., 39 GCMs for RCP8.5, 32 GCMs for RCP2.6) with different responses to forcing, resulting in a spread of trajectories for increases in global mean temperature for a given RCP. This contributes to the uncertainty represented by the shading in Figure 8(b). An additional component of this uncertainty is due to effect on global mean temperatures of unforced year-to-year and decade-to-decade climate variability (e.g., due to the El Nino Southern Oscillation). Hence, there is still some uncertainty in the projections for the early 21st century, where the forcing is relatively small (see Figure 8(a)). Uncertainties in the sea-level rise projections shown in Figure 8(c) arise from both uncertainties in future climate conditions and imperfections in the models used to derive sea levels from climate data. The IPCC AR5 projections are relatively similar for the different RCPs for the first half of the 21st century, but diverge significantly by the end of the century. For example, for the 2046–2065 period, the likely range for the increase in global average surface air temperature relative to 1986–2005 for RCP2.6 (0.4–1.6°C) overlaps the corresponding likely range for RCP8.5 (1.4–2.6°C). For this mid-century period, the likely range for global mean sea level is 17–38cm across the four RCP scenarios. For the 2081–2100 period, the likely range for the increase in global average surface air temperature for RCP2.6 (0.3–1.7°C) is similar to that for 2046–2065. However, the likely range for RCP8.5 for this period (2.6–4.8°C) is much greater. For this end-of-century period, the likely range for global mean sea level is 0.26–0.55cm for RCP2.6 and 0.45–0.82cm for RCP8.5.

2.3.2 Shared Socio-economic Pathways (SSPs)

The SSPs 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 possible socio-economic development trajectories that humans could follow over the next century. These pathways facilitate the work of the integrated assessment modelling (IAM) and the vulnerability, impacts and adaptation (VIA) communities.

The SSP scenario framework, when combined with the RCPs, provides a platform for assessing the impacts of climate change and measures for climate change adaptation and mitigation considering plausible futures that combine future forcing pathways and associated changes in climate together with alternative socio-economic development pathways (O'Neill *et al*. 2014; 2015). The new SSP scenario narratives provide five markedly different future socio-economic development pathways assuming no "explicit additional policies and measures to limit climate forcings or to enhance adaptive capacity" (Riahi *et al*. 2016). Figure 9 illustrates the five main steps for the development of the SSPs, including the socio-economic scenario narratives (i.e., the underlying scenario logic and qualitative descriptions of the characteristics and assumptions), the scenario drivers (i.e., the basic SSP elements such as demographic and economic drivers), and the SSP baseline and mitigation scenarios.
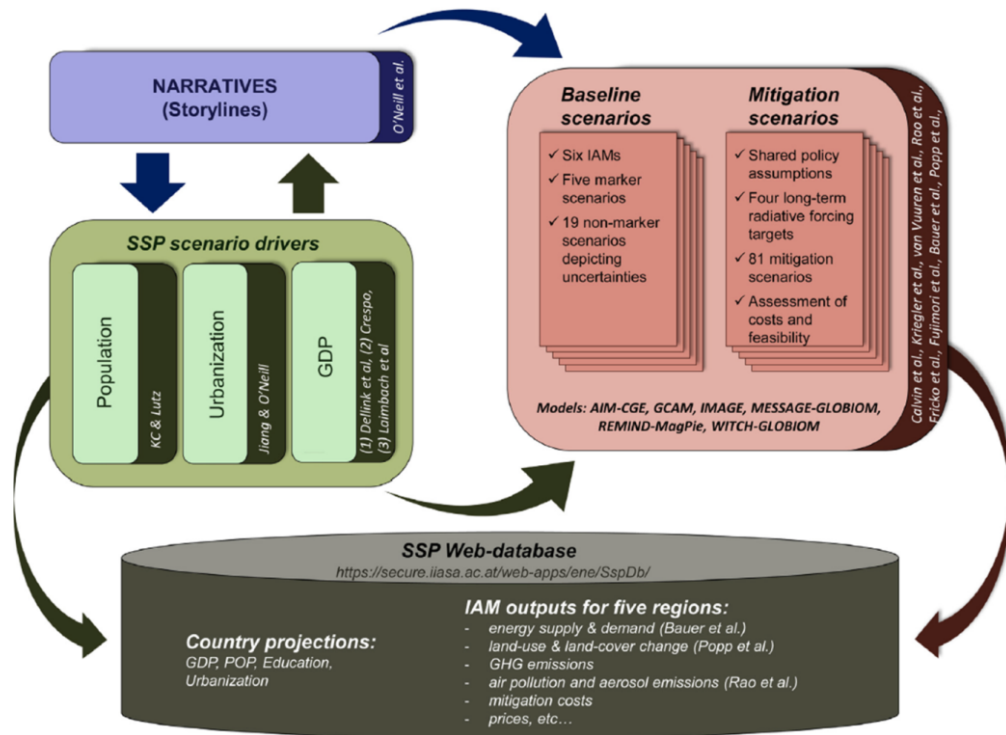
Figure 9: *Schematic illustration of the key steps in development of the SSP scenarios (Source: Riahi et al. 2016).*

Table 3 presents the new global IPCC AR5 SSP scenario narratives.

Table 3: *Global SSP scenario narratives (Source: O'Neill et al. 2015).*

SSPs	Description	Narratives (Storylines)
SSP 1	**Sustainability** (*Low mitigation and adaptation challenges*)	*Sustainable development proceeds at a reasonably high pace, inequalities are lessened, technological change is rapid and directed toward environmentally friendly processes, including lower carbon energy sources and high productivity of land.*
SSP 2	**Middle of the Road** (*Intermediate mitigation and adaptation challenges*)	*An intermediate case between SSP1 and SSP3.*
SSP 3	**Fragmentation/Regional Rivalry** (*High mitigation and adaptation challenges*)	*Unmitigated emissions are high due to moderate economic growth, a rapidly growing population, and slow technological change in the energy sector, making mitigation difficult. Investments in human capital are low, inequality is high, a regionalized world leads to reduced trade flows, and institutional development is unfavourable, leaving large numbers of people vulnerable to climate change and many parts of the world with low adaptive capacity.*
SSP 4	**Inequality** (*High adaptation*	*A mixed world, with relatively rapid technological development in low*

	and low mitigation challenges)	carbon energy sources in key emitting regions, leading to relatively large mitigative capacity in places where it mattered most to global emissions. However, in other regions development proceeds slowly, inequality remains high, and economies are relatively isolated, leaving these regions highly vulnerable to climate change with limited adaptive capacity.
SSP 5	**Conventional/Fossil-fueled Development** (*High mitigation and low adaptation challenges*)	*In the absence of climate policies, energy demand is high and most of this demand is met with carbon-based fuels. Investments in alternative energy technologies are low, and there are few readily available options for mitigation. Nonetheless, economic development is relatively rapid and itself is driven by high investments in human capital. Improved human capital also produces a more equitable distribution of resources, stronger institutions, and slower population growth, leading to a less vulnerable world better able to adapt to climate impacts.*
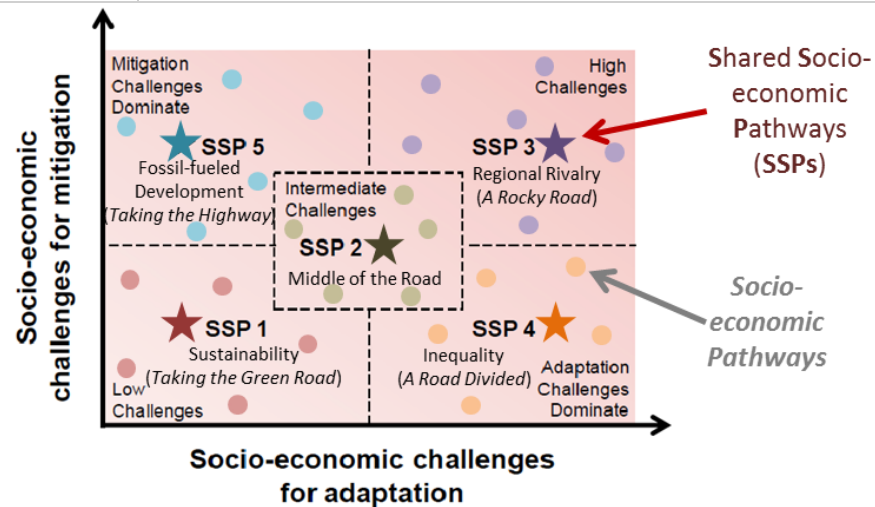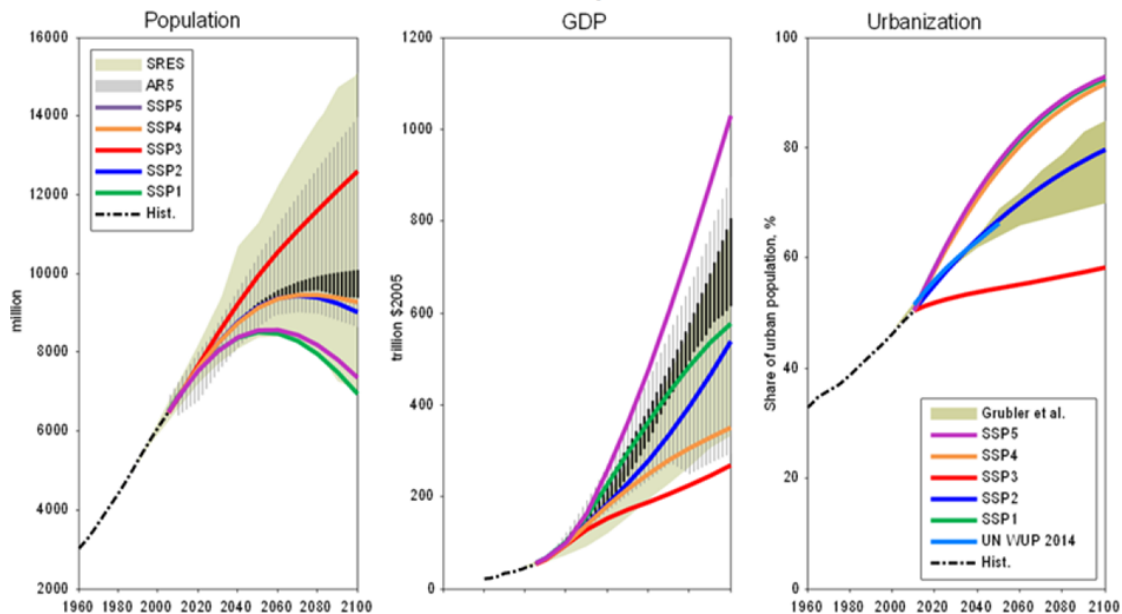
Figure 10: *(a) schematic illustration of the SSP scenario framework, and (b) the future global population, GDP, and urbanisation projections under the five SSP scenarios (Source: Riahi et al. 2016).*

The SSPs and their narratives reflect five different socio-economic development pathways and the challenges to adaptation and mitigation (Figure 10(a)). They qualitatively represent five different pathways in terms of, for example, the level of international co-operation, market freedom, regional equality, and technological development (see Table 3). Key quantitative indicators of the SSPs include population and other key demographic statistics (such as urbanisation, age, education) and economic

growth (GDP). Figure 10(b) presents projections of the global population, economic growth and urbanisation under the five SSP scenarios.

2.3.3 Selected RCP and SSP Scenario Combinations

The resources available to the DECCMA project precluded consideration of all RCP and SSP scenarios and so only a selection of scenarios were considered. Early in the DECCMA project, we decided to focus on the RCP8.5 scenario. There are a number of reasons for this:

a) To maximise the sampling of uncertainty in future climate changes - The selection of another RCP, with smaller forcing of the climate system, would result in simulated future changes in climate of smaller magnitude than those for RCP8.5. For climate changes where either an increase or decrease is indicated by the CMIP5 GCM ensemble in response to increasing atmospheric greenhouse gas concentrations, results for RCP8.5 will likely encompass those of the other RCPs. This is the case for the future changes in annual mean precipitation for the Volta, Mahanadi and GBM catchments shown in Figure 11. Therefore the DECCMA project is able to gain insights over a more substantial range of climatic change outcomes for RCP8.5 than for any other RCP.

b) To afford the best opportunity to investigate responses to increasing atmospheric greenhouse gas concentrations – Of the RCPs, RCP8.5 is consistent with the greatest increases in atmospheric greenhouse gas concentrations. The signal-to-noise ratio of climate changes resulting from radiative forcing to unforced climate variability would be less for an RCP with smaller radiative forcing. This effect will be particularly pronounced for the late 21st century, where there is the greatest difference between the radiative forcing levels for the different RCPs (see Figure 8(a)).

c) RCP 8.5 represents a challenging scenario against which to test the robustness of human and natural systems and climate change adaptation measures. Further, it provides greater extremes of climate outputs (see Figure 8), which provides a more dynamic range for the integrated modelling considered within the DECCMA project.

There are, however, some important implications of the selection of RCP8.5:

a) The global community has expressed an interest in limiting global warming to below 2°C above the pre-industrial global mean temperature (e.g. UNFCCC 2015). RCP8.5 is not consistent with this limit. According to IPCC AR5, RCP8.5 would likely result in an increase in global mean temperature of 2.6 to 4.8°C between 1986-2005 and 2081-2100 (IPCC 2013), in addition to the warming that has taken place prior to 1986-2005.

b) For the second half of the 21st century, it is possible that climate change impacts analysis based on RCP8.5 could produce such extreme impacts that only extreme, and possibly impractical, adaptation results would be robust to the climate scenarios considered. This may limit the relevance of the results of the project to less extreme climate scenarios for the late 21st century. However, this effect is expected to be much more limited for the first half of the 21st century, during which climate scenarios for the different RCPs would be expected to overlap to a larger extent. For example, in Figure 11, the temperature changes for RCP8.5 are generally more extreme than those for RCP4.5 for the 2071-2100 period, but the temperature changes are much more similar between RCP4.5 and RCP8.5 for the 2021-2050 period.
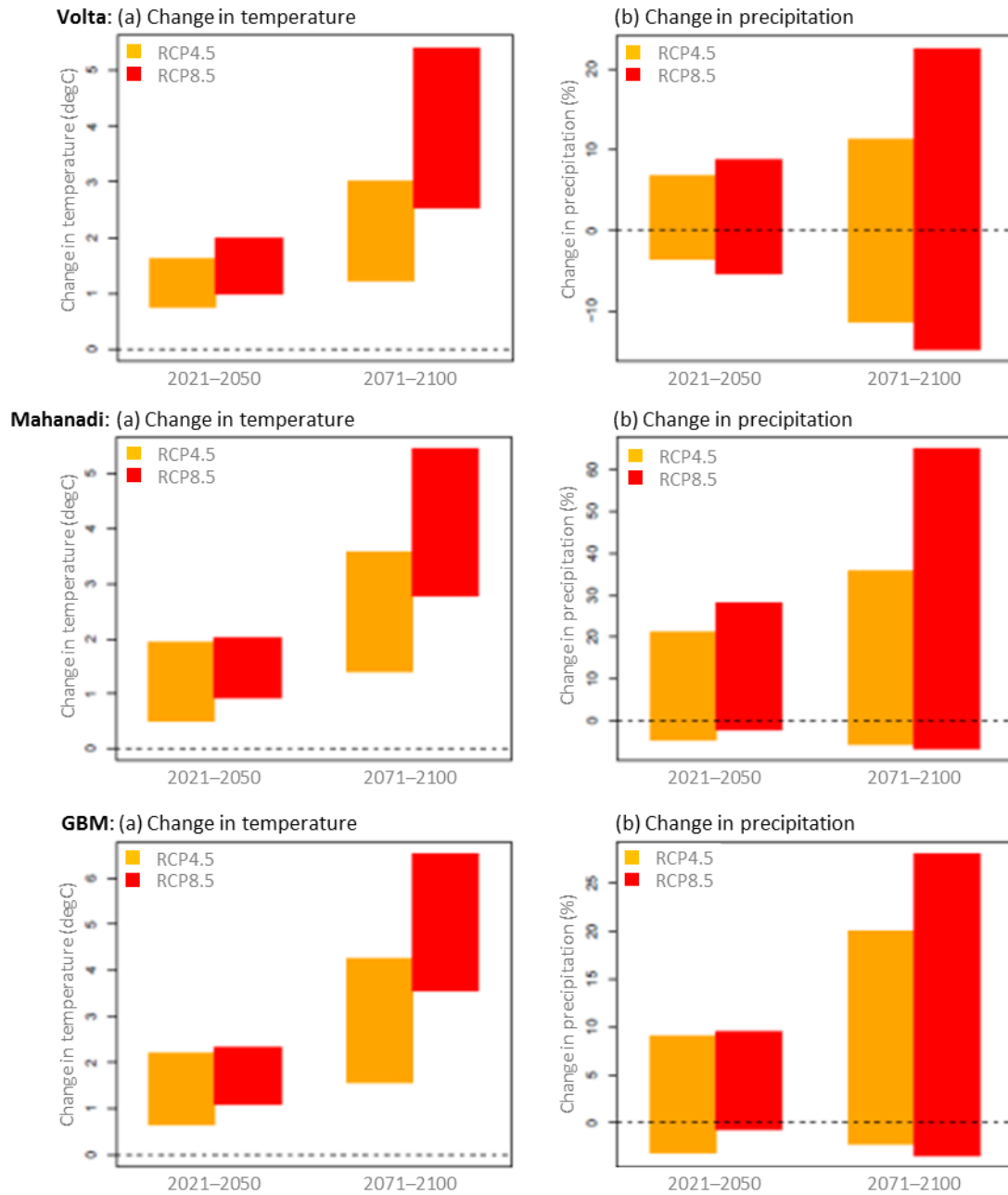
Figure 11: *Changes in annual mean temperature and precipitation between 1971-2000 and 2021-2050 and between 1971-2000 and 2071-2100 from RCP4.5 and RCP8.5 simulations of 38 CMIP5 GCMs. Changes shown are for regions around the Volta, Mahanadi and GBM catchments (Volta: -10 to 5°E, 0 to 15°N; Mahanadi: 75 to 90°E, 15 to 30°N; GBM: 70 to 100°E, 20 to 35°N). Note: the scales differ between catchments for display purposes.*

The RCPs and SSPs are not independent and, while in theory possible, only certain combinations of the RCPs and SSPs are plausible for detailed analysis. For example, only SSP5 (associated with the highest economic growth) could be compatible with RCP8.5 and lead to greenhouse gas emission levels that are consistent with RCP8.5, while RCP2.6 emission levels could not be attained under an SSP3 world (Riahi *et al.* 2016). Consequently, various plausible combinations of the RCP8.5 and SSPs were explored for consideration in DECCMA. However, the potential to explore other combinations of future states was also discussed across the project. With this in mind, 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; see Figure 8a). However, after 2050 only SSP3 and SSP5 can produce the

required emissions, although SSP2 is close. In DECCMA, three scenario narratives have been identified for up to 2050 that are closely consistent with the three SSP scenarios, i.e., SSP2, SSP3 and SSP5 respectively, while recognising their compatibility with our selected RCP8.5 scenario, as summarised below. These scenarios will inform the development of stakeholder-driven delta-scale scenarios and adaptation policy trajectories for up to 2050. In summary, in terms of the socio-economic scenarios, three narratives have been defined based on the SSP scenarios to be used together with the RCP8.5 climate scenario:

a) Up to 2050:

    i. Medium scenario (~SSP2)

    ii. Medium+ scenario of high economic growth, low population growth and high level of urbanisation (SSP5), and

    iii. Medium- scenario of low economic growth, high population growth and low level of urbanisation (~SSP3)

b) Beyond 2050:

    i. SSP5 will be considered. In combination with the Medium+ (SSP5) scenario, this scenario will provide continuity for pre- and post-2050 analysis. The post-2050 analysis based on the combination of RCP8.5 and SSP5 will form the focus of the long-term biophysical assessment in the project, which will be more exploratory in nature and will not include stakeholder-driven scenarios (see Figure 12).
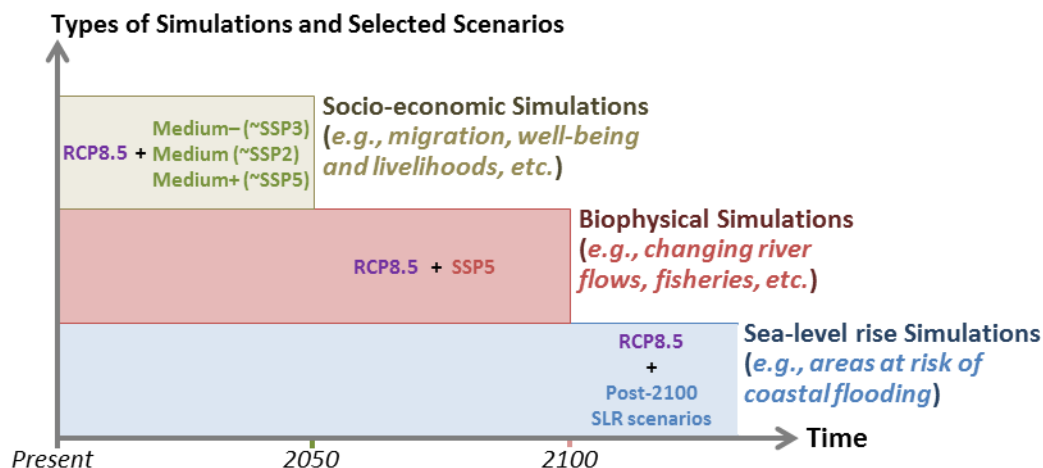
Figure 12: *Summary of the selected RCP and SSP scenarios for the three components and associated time horizons considered in DECCMA.*

2.3.4 Shared Policy Assumptions (SPAs)

The SPAs represent the last component (third/additional dimension) of the global scenario framework developed for the IPCC AR5 (see Figure 7), which plays a key role in linking the RCPs and SSPs discussed in Sections 2.3.1–2.3.3. The SPAs "capture key policy attributes such as the goals, instruments and obstacles of mitigation and adaptation measures" (Kriegler *et al.* 2014). They provide a platform for devising common assumptions across a range of studies to assess the consequences of specified adaptation and mitigation policy approaches. Together, the overall RCP–SSP–SPA framework improves interdisciplinary analysis and assessment of climate change, its impacts, and the policy options society have for adaptation and mitigation. As defined in Kriegler *et al*. (2014), the SPAs should include three key characteristics of climate mitigation and adaptation policies at the global and century scale, which are: (i) "climate policy goals" such as targets for emissions reduction and/or limiting residual climate damages, (ii) "policy regimes and measures" that need to be taken to achieve the policy goals, and (iii) "implementation limits

and obstacles" that could hinder achieving the policy goals. However, it has been recognised that there are clear overlaps between the climate policies that could be defined as part of the SPAs and that of the RCPs (in terms of the *mitigation policy goals*) and SSPs (in terms of the *adaptation policy goals*) (Kriegler *et al.* 2014). Consequently, two types of SPAs are proposed: (i) full SPAs that include all mitigation (including aspects of the RCPs) and adaptation (including aspects of the SSPs) policy targets, and (ii) reduced SPAs that exclude aspects of the mitigation policy goals of the RCPs (related to *emission reductions and global concertation and forcing outcomes*) and adaptation policy goals of the SSPs (related to *development goals*). Furthermore, application of the SPAs will require development of detailed characterisation of the key attributes, which can include qualitative (narratives) and quantitative information on plausible alternative visions of future worlds with different climate policies and their temporal and spatial evolution. However, the global SPA narratives are still less developed than the RCPs and SSPs, and are yet to be explicitly defined in terms of what they should include and what not. In addition, those proposed SPA specifications that have emerged so far are more focused on mitigation aspects of the climate policies (e.g., Figure 13).
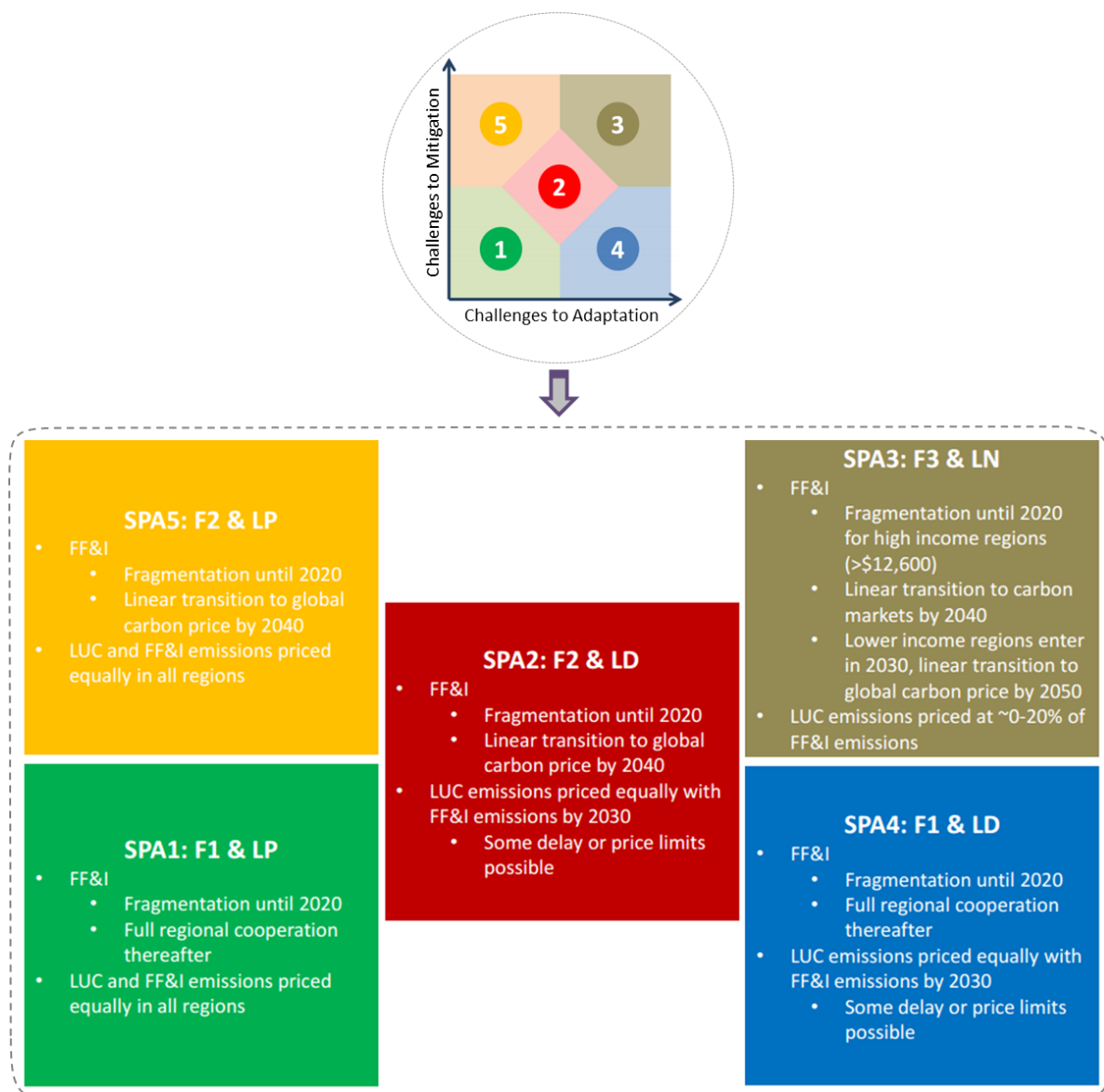
Figure 13: *Example SPA specifications based on two primary policy attributes that are consistent with the SSP narratives and mitigation challenges: (i) fossil fuel and industry (FF&I) emissions phases, i.e., F1/F2/F3: low/intermediate/high levels of cooperation, and hence challenges to mitigation, and (ii) land-use change (LUC) emissions pricing, i.e., LP/LD/LN: full (equal to FF&I)/partial or delay/limited to none. (Source: Riahi et al. 2015; Waldhoff 2014).*

Table 4 shows five example SPAs defined based on a set of policy attributes and describing the key components of associated narratives, which describe a range of climate mitigation and adaptation policies (Kriegler *et al*. 2014).

Table 4: *Examples of reduced SPAs, policy attributes and associated narratives (Source: Kriegler et al. 2014).*

Policy Attribute	Four Illustrative Examples of Reduced SPAs[+]			
	Reference Policy	*Cooperation and Moderate Adaptation*	*Middle Road and Aggressive Adaptation*	*Fragmentation and Moderate Adaptation*
Mitigation: Level of global cooperation[1]	*Low*	*High*	*Medium*	*Low*
Mitigation: Start time of global cooperation[2]	*Never*	*Early*	*Mid Term*	*Late*
Mitigation: Sectoral coverage	*Focus on electricity and industry sectors. No significant inclusion of land use based mitigation options.*	*Carbon pricing on land. Full coverage of energy supply and end use sectors.*	*Forest protection and bioenergy constraints. Energy supply, transport and industry covered.*	*Limited forest protection, no limitation on bioenergy use. Electricity and industry covered.*
Adaptation: Capacity building[3]	*Small*	*Moderate*	*Large*	*Moderate*
Adaptation: International insurance[4]	*Only via international markets, with limited access for some countries*	*Insurance available for least developed countries*	*Global insurance provided*	*Only via international markets, with limited access for many countries*

[+] *Additional SPA is "no new policy", which contains existing climate policies until their time of expiration, and assuming no new climate policies thereafter.*
[1] *e.g., measured in terms of average share of emissions under a global climate target over some period.*
[2] *e.g., the time the first group of countries adopt a global target or an international carbon tax.*
[3] *e.g., measured in terms of the size of a global adaptation fund.*
[4] *e.g., measured in terms of the amount of climate impact insurance available between countries.*

In the absence of fully developed and detailed specifications of a global level narratives of the SPAs, in DECCMA, the concept of reduced SPAs is explored at national level as SPA extensions, with a particular focus on development of national level adaptation policy trajectories that are explored within the context of the selected RCP and SSP scenario combinations (discussed in Sections 2.31–2.3.3). The concept used for linking of the RCPs, SSPs and SPAs and defining the overall scenario matrix architecture is discussed in Section 2.9 as part of development of the delta scale scenarios and policy trajectories and the associated participatory (stakeholder engagement) process.

2.4 Regional Scenarios: Climate

In addition to projections of future changes in global average quantities (e.g. see Figure 7(b)), the CMIP5 GCM simulations can be used to generate projections of future changes in climate for regions somewhat smaller than a continent (e.g., see IPCC 2013). These projections are suitable as a basis for an overall narrative for future regional climate changes. However, due to the coarse spatial resolution of the CMIP5 GCM simulations (a typical CMIP5 GCM has grid cells more than 100km across), on their own, they cannot provide a basis for the detailed assessments of the impacts of climate change using impact models (e.g., hydrological and agricultural models) required in the DECCMA project. The GCM output must first be downscaled to finer resolutions to provide input to impact models. The DECCMA project has chosen to downscale the CMIP5 GCM output dynamically using Regional Climate Model (RCM) simulations. These are capable of representing fine-scale atmospheric processes that are important for regional climate but which are not well-represented in GCMs. They provide internally consistent datasets of numerous impact-relevant climate variables at a finer resolution than GCMs. In the case of DECCMA, RCMs have been used to provide climate data on grid cells tens rather than hundreds of kilometres across.

The IPCC AR5 climate projections for RCP8.5 were based on simulations of approximately 40 CMIP5 GCMs. As for projections of global mean temperature change (see Figure 7(b)), these simulations each give different changes in regional climate conditions for a given RCP (see Figure 10). However, since running RCM simulations is a computationally expensive activity, it is not possible for the DECCMA project to downscale all of the CMIP5 RCP8.5. Even if it was, it would not be possible for the impact modelling component of the DECCMA project to use data from so many simulations. Therefore, for each of the DECCMA study regions (West Africa, including the Volta catchment, and south Asia, including the GBM and Mahanadi catchments), RCP8.5 simulations of three different CMIP5 GCMs have been considered. These GCMs have been selected to sample as much of the uncertainty in changes in key climate variables over the 21st century spanned by the full set of CMIP5 GCMs as possible (for more information, see Macadam *et al*, in prep.). Table 5 lists the GCMs selected and, for each, describes the changes in annual mean temperature and precipitation simulated for RCP8.5. The magnitudes of the changes are described relative to the magnitudes of the changes simulated by the full set of CMIP5 RCP8.5 simulations.

Table 5: *Changes in annual mean temperature and precipitation simulated over the 21st century for RCP8.5 are described. The magnitudes of the changes are described relative to the magnitudes of the changes simulated by the full set of CMIP5 RCP8.5 simulations.*

Region	GCM	Precipitation Change	Temperature Change
West Africa	**CNRM-CM5**	*Moderate increase*	*Small increase*
	HadGEM2-ES	*Small increase*	*Large increase*
	CanESM2	*Large decrease*	*Large increase*
South Asia	**CNRM-CM5**	*Moderate increase*	*Small increase*
	GFDL-CM3	*Moderate increase*	*Large increase*
	HadGEM2-ES	*Large increase*	*Large increase*

Dynamically downscaled data for the selected GCMs were then sought. Although different RCMs will simulate different climate conditions for the same GCM forcing data, it was anticipated that greater uncertainty in future climate conditions would be contributed by differences between the selected GCMs. Hence, to aid interpretation of the regional climate scenarios, for each study region, downscaling simulations for the selected GCMs performed with the same RCM were sought. For West Africa, data from the ongoing CORDEX-Africa project, which collates RCM simulations over Africa from climate modelling centres around the world, were used. The CORDEX-Africa simulations include simulations of the SMHI RCA4 RCM that have downscaled RCP8.5 simulations of numerous GCMs to a resolution of 50km. The DECCMA project uses data from these simulations for West Africa. A large ensemble of pre-existing RCM simulations downscaling CMIP5 GCMs over South Asia was not available to the DECCMA project. It was therefore necessary for the project to run its own RCM simulations for this region. The Met Office has downscaled the GCM simulations selected for South Asia to a resolution of 25km using the HadRM3P RCM (for more information, see Macadam *et al*, in prep.).

2.5 Regional Scenarios: Catchments

The DECCMA project includes catchment flow and nutrient modelling for the River Volta system in Ghana plus catchment water quality modelling of the Ganga, Brahmaputra, Meghna (GBM) and Mahanadi Catchments in India and Bangladesh. The Integrated Catchment Model INCA (Whitehead *et al*. 2015a,b) will be run for each of the three catchments. The INCA modelling requires basin-averaged daily precipitation and temperature data for the 1970–2100 period as inputs. This data is derived from the RCM simulations described in Section 2.4. However, the unprocessed RCM outputs contained biases relative to the observed climate and so were combined with climate observations in a bias correction procedure to ensure that INCA simulated realistic outputs.

The simulations from the catchment models will be provided for the downstream coastal models. SSP scenarios will affect water quality in that changes to industry, agriculture and population levels will affect nutrients (N and P) and these change 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 on integrating social aspects of future change. The catchment socio-economic scenarios are defined based on the IPCC five broad SSP socio-economic development pathways that are compatible with the RCP8.5 scenario, focussing on the three narratives identified (see Section 2.3.3). 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 and public water use;

- Effluent discharge;

- Water demand for irrigation and public supply;

- Land use change;

- Atmospheric deposition driven by industrial development or GDP;

- Water transfer plans.

Each of these aspects of socio-economic change need to be considered for both the Volta catchment in Ghana, the GBM catchment in Bangladesh, and the Hooghly and Mahanadi catchments in India. A full and comprehensive analysis of all these river catchments is given in Appendix A. The following sub-sections present brief description and summary details of the catchment-specific scenarios and data considered in DECCMA for each river catchments.

2.5.1 West Africa: The Volta River Catchment (Ghana)

In Ghana, the medium growth scenario has a relatively high population increase, as the population is expected to grow more than 20% in the decade up to 2020 with 10% every decade up to 2050, as shown in Table 6. In the case of the Volta delta, the phenomena of high out migration and urbanization makes the coastal area likely to lose population, not having a clear big city attraction of immigration within the delta. The population peak is not reached until the year 2100, but from 2050 onwards the population growth is projected to be much slower. The medium minus population is expected to grow more than 20% each decade up to 2040, whereas the medium plus population is expected to increase by 20% up to 2020, and then increase by 6% per decade up to 2050 (see Table 4 for the population levels expected under each scenario).

Coupled to these changes in population growth, there are predicted to be increased GDP with the Ghana GDP rising from US$40 billion currently to US$162 billion in the year 2050 (Appendix A). These pressures will generate significant demands for enhanced water supply for people, industry and agriculture. Quantitative data provided for Western Africa for land use change and agriculture has been obtained using an integrated assessment model using projections for population, GDP, GDP per capita, urbanization and with the RCP projections (Appendix A). In Ghana, presently out of 20 million hectares of land, about 30% is cropland, another 30% forest and 40% permanent pastures and grazing land. In the medium scenario, the permanent pasture and grazing land will decline and agricultural production is expected to grow significantly (Table 6). Water intense crops such as rice are expected to increase and the water returns to the Volta from industrial and domestic effluents will increase as population levels rise. The Volta Lake created by the Akosombo Dam is the major man-made feature of the Volta River system and this dominates the water distribution system, controlling 90% of the downstream water. Thus, any water transfers are likely to be limited compared to this dam. However, there are other dams planned for upstream reaches and these will enhance water supply for irrigation.

Table 6: *Future water and agricultural change in the Volta catchment.*

Scenarios	1990s	2050s	2090s
	Population (million)		
Medium	24	46	57
Medium+	24	55	85
Medium-	24	39	40
	Intensive Agriculture (% change)		
Medium		78	85
Medium+		130	175
Medium-		94	68
	Irrigated Area (Ha)		
Medium	30500	54290	56425
Medium+	30500	70150	53375
Medium-	30500	59170	51240
	Reach Irrigation Water Demand (m^3/sec)		
Medium	0.53	0.94	0.98
Medium+	0.53	1.22	0.93
Medium-	0.53	1.03	0.89
	Reach Effluent Discharge (m^3/sec)		
Medium	0.37	0.72	0.89
Medium+	0.37	0.86	1.32
Medium-	0.37	0.61	0.62
	Reach Total Water Demand (m^3/sec)		
Medium	0.90	1.66	1.87
Medium+	0.90	2.07	2.25
Medium-	0.90	1.63	1.51

2.5.2 South Asia: The GBM (Bangladesh) and the Hooghly and Mahanadi (India) Catchments

For the India–Bangladesh catchments, Appendix A has all the details and only a summary is given here. Population increases vary from state to state and varies depending on assumptions about fertility. In the case of India, the general population is expected to increase for the three scenarios by 41%, 26%, and 61% respectively by the 2050s and by 37%, 3.5%, and 104% by the 2090s (Appendix A). These are very large population changes and will translate into changes in agriculture, water demand and effluent discharges. Future scenarios from changes in STW (Sewage Treatment Works) discharge rates need to reflect the population changes as well as the implementation of the Ganga Management Plan, which will enhance the capacity of all the STWs on the Ganga river system and treat effluents from a larger population. The Ganga Management Plan also aims to considerably upgrade the treatment processes. Assuming the secondary treatment processes are introduced, average ammonia discharge concentrations should fall from 19mg/L to 5mg/L. Nitrate is likely to stay much the same unless tertiary treatment is implemented. The demand for public water supply will also increase with population growth, although much of the supply in rural areas is from groundwater. Changes in irrigation water demand reflect changes in agriculture and land use. However, agricultural changes in India are difficult to predict as any changes will depend on factors such as world food prices, which are driven by increasing population, potential food scarcity and how farmers react to changing crop prices. Other key influential factors include technological developments such as the introduction of new crop varieties adapted to changing local environmental conditions. The Food and Agriculture Organization of the United Nations (FAO) estimates a 22.7% rise in Kcal/person/day in food production in India by 2050 with much of this from increased production of dairy and meat, as well as additional crops producing vegetable oils and sugar. Agricultural expansion and

intensification will be required to feed a growing population: improved crop yields and more efficient farming. As a result, irrigation abstraction from the rivers and groundwater will increase. For the purposes of this study we have assumed that the abstraction from the Ganga River will increase by 22.7% for the medium scenario in accordance with the predicted increase in food production. Under the medium plus scenario we assume that the abstractions will increase by only 11.3% reflecting changed crop varieties and improved irrigation.

Atmospheric nitrogen pollution has become an increasing problem around the world, as industrial development, power generation and ammonia release from intensive agriculture has expanded. For example, across Europe, a set of Nitrogen Protocols have been established by the UN/ECE Commission of Transboundary Pollution and these protocol have been agreed and implemented by all EU countries. Deposition can be high with 15kg N per hectare per year being deposited in certain parts of Europe such as the UK. The effect of high atmospheric N is to alter the terrestrial ecology of plants and natural vegetation, and provide a baseline source of N to groundwaters and streams, which can then affect aquatic ecology. Research in the Himalayas, in which INCA N was applied to a range of basins, suggests generally low concentrations of atmospheric N, but across northern India, levels are likely to be much higher, with greater urban and industrial sources of atmospheric N. In the future, increased industrial development and more intensive farming methods will cause atmospheric N concentrations to increase. INCA-N can incorporate these effects as deposition loads to the sub-basins, and thus N levels have been altered to reflect the different socio-economic scenarios into the future. It has been assumed that N deposition rates are 8, 10, and 6 kg/ha/year for the three scenarios.

Another key aspect of scenario analysis for the Ganga, Hooghly and Brahmaputra rivers is the likelihood of significant water transfers as part of the Indian Water Linking plans. This might see the diversion of waters from the Brahmaputra and the Ganga down to the south via canals or the Hooghly and this aspect needs to be considered as flows will be significantly affected as will water quality.

2.6 Regional Scenarios: Coastal Seas

In addition to the regional catchment modelling, the DECCMA project also includes regional coastal sea modelling for the Gulf of Guinea and the Bay of Bengal. Whereas the INCA model requires only atmospheric data from the climate modelling, the coastal seas model also requires data describing the physical and biogeochemical state of the ocean. In addition, data on sea-level rise are required. The atmospheric data required is sourced from the RCM simulations described in Section 2.4. The sea modelling required an internally-consistent gridded dataset incorporating data for multiple atmospheric variables. It was not feasible to apply bias correction in a way that would preserve the location-to-location and variable-to-variable relationships within the dataset. Therefore, the data were not bias corrected, which means that the potential impact of climate model biases on results derived from the coastal seas modelling must be considered.

Since the RCMs are atmosphere-only models, the physical and biogeochemical data at the ocean boundary of the sea model had to be sourced from the coarser resolution coupled atmosphere-ocean GCM simulations that were used to force the RCM simulations.

Regional mean sea-level rise data were derived using the method of Palmer *et al.* (in prep.), which is very similar to the work of Cannaby *et al.* (2016). This combines information on global mean sea-level rise from IPCC AR5 (IPCC 2013) with: spatial information on ocean circulation and density from the CMIP5 GCMs; the gravitational, rotational and lithosphere response associated with glaciers, ice sheets and ground water storage changes; and ongoing vertical land movement due to changes in the distribution of land-based ice in the distant past (Glacial Isostatic Adjustment). The resulting projections provide a more appropriate mean sea level baseline for the coastal sea modelling than projections of global mean sea level rise.

River flow and nutrient data provide an additional input to the regional sea models and for the Volta, GBM and Mahanadi regions these were taken from the INCA catchment model, with the central SSP

scenario used for the nutrients. All other river data was taken from global databases and assumed to be constant over the modelled period, with the exception of the Congo and Niger nutrients, which provide quite a large input to the model. In the absence of other information it was assumed these river basins would follow similar development routes to the Volta over the 21st century, so the nutrient concentrations would change in the same way. Other rivers have much smaller input to the model so any change will have negligible effects.

Overall, the RCPs are the primary drivers of the regional sea modelling; SSPs have only a minor effect through river nutrient levels. Total fish productivity is derived from the regional sea models and uses the same scenarios. The species-based fisheries model allows a further anthropogenic pressure via fishing effort: this is implemented in the model through three scenarios: business as usual, over exploitation, and sustainable management, as described below.

A set of contrasting management and exploitation scenarios are used to project plausible scenarios of fish production by mid-century, which combine sustainable management and environmental impacts. These scenarios are developed separately for each of the three deltas and their wider marine areas and are specifically focused on the key species that provide the largest marine catches. The management scenarios are intended to inform fisheries managers in each country in the pursuit of sustainable management strategies under a future dominated by climate change.

Fishing scenarios are considered in relation to the concept of maximum sustainable yield (MSY). MSY is defined as the highest average theoretical equilibrium catch that can be continuously taken from a stock under average environmental conditions (Hilborn & Walters 1992). In DECCMA, a simple logistic population growth function under equilibrium conditions is used to define fishing at MSY level (see Appendix B for more details).

Fishing mortality scenarios are defined by comparing mortality estimates for the considered species from the literature with the calculated fishing at MSY level. Here, three fishing mortality scenarios are considered to provide fish catch and biomass projections as follows:

a) Sustainability scenario (F_{MSY}): Fishing 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.

b) Business as Usual scenario (F_{BaU}): Fishing mortality consistent with the average of recent estimates of fishing mortality.

c) Overfishing scenario (F_{OF}): Corresponds to a scenario where management is not a constraint to the fishery.

The following sub-sections present brief summary of the area specific description of the regional scenarios and data used in DECCMA for the two coastal seas.

2.6.1 West Africa: Gulf of Guinea

Table 7 shows the projected change in some key environmental variables for the 21st century, as given by the GCMs listed above. The first two columns give data for the Volta delta area (0.1°E to 1.0°E), the second two for the wider Gulf of Guinea (19°W to 13°E); in both cases the area included is from the coast to about 150 km offshore.

Table 7: *Future climate projections for the Volta delta and the wider region for the 21st century.*

Climate Factor	Delta Area: mid-century	Delta Area: end-century	Wider Area: mid-century	Wider Area: end-century
Surface temperature (°C)	+1.0 to +1.7	+2.5 to +3.6	+1.0 to +1.8	+2.5 to +3.6
Precipitation (%)	-30 to +2	-25 to +40	-1 to +2	-4 to +13

Maximum wind speed (ms⁻¹)[1]	+0.1 to +0.2	+0.3 to +0.6	-0.6 to +0.1	-0.7 to +0.4
Frequency of high wind events (days per decade)[2]	+4 to +9	+27 to +34	-10 to +2	-11 to +5

[1] Maximum wind speed is defined as the 98th percentile of the daily mean wind speed.
[2] High wind events are defined as daily mean wind speed exceeding 8 ms⁻¹.

Sea level rise in the Gulf of Guinea is projected to be 0.21–0.36 m at mid-century and 0.55–1.1 m at end-century under RCP8.5, compared to a 2000 baseline (0.17–0.33 m and 0.36–0.80 under RCP4.5) (Cannaby *et al.* (2016); Palmer *et al.* in prep.).

Fisheries Status and fishing scenarios (based on Lauria *et al*. 2016):

Pelagic fish are the main exploited species in the Ghanaian marine coastal fisheries accounting for about 65% of total marine landings (Nunoo *et al.* 2014). For example round sardinella (*Sardinella aurita*), Madeiran sardinella (*Sardinella maderensis*) and Atlantic chub mackerel (*Scomber colias*) are very important in the entire Gulf of Guinea (Ansa-Emmim 1973; Anon 2003) followed by Scombridae, Carangidae and Thunninae (i.e. yellowfin tuna *Thunnus albacares*, skipjack *Katsuwonus pelamis* and big-eye Thunnus obesus; Nuuno *et al.* 2014). Between 2001 and 2010, the skipjack tuna dominated in terms of total catches followed by the yellowfin and the bigeye (Adinortey 2014). Demersal fishes are also caught by trawlers and artisanal gears and the most notably species are Sparidae or porgies mainly red pandora (*Pagellus bellottii*), Canary dentex (*Dentex canariensis*) and bluespotted seabream (*Pagrus caeruleostictus*). Among the farmed fish there are several species of tilapia such as Nile tilapia (*Oreochromis niloticus*), Tilapia zillii (*Sarotherodon galilaeus*), banded jewelfish (*Hemichromis fasciatus*), and the catfishes (African sharptooth *Clarias gariepinus* and African catfish *Heterobranchus bidorsalis*).

The fishing sector is relatively well organized; also there is an increasing desire among Ghanaian fishers to play a role in managing their local fisheries. Still, historic fisheries management settings have led to a situation where local fishers and communities have no real stake in the fishery. This is because Ghana's fisheries are regulated and managed primarily by the Fisheries Commission, established under the Fisheries Act (2002). The Ghana Fisheries and Aquaculture Sector Development Plan (FASDP) adopted by the Government of Ghana in 2011, provides guidelines for the reform process by setting operational targets and outlining the sequence of activities necessary to achieve the targets over the next five years. The FASDP provides fishers with a genuine stake in their local fisheries through the issuance of long-term and transferable licensing and effort control. In addition, the FASDP controls the fisheries sectors through the application of long-term and transferable licensing across all commercial fishing sectors. This action will develop a "Catch and Effort Database" to inform fisheries management decisions and prepare a "Compliance Strategy" to protect the integrity of the management regime for reducing unlicensed and illegal fishing. Currently the Government of Ghana is in the process of reforming the country's fisheries and aquaculture activities. The new fishery program is supported by the World Bank and the Global Environment Facility as part of the Bank's six-year investment in the West Africa Regional Fisheries Program (WARFP). This program will support the country to sustainably increase the net economic benefits from its fisheries and aquaculture investments through various initiatives as well as strengthening the managing of its fisheries resources.

Despite the current attempts to reform of the fishery policy in Ghana the country is facing major problems due to overfishing. In particular, Ghana's small pelagic fishery is currently on the edge of collapse with an exponential reduction of canoe fishery's annual catches of small pelagics (anchovies, sardinellas, mackerels and horse mackerel) have decreased from 277,000 metric tonnes in 1996 to about 92,000 to metric tonnes in 2011 (USAID/Ghana SFMP 2015). The crisis has been attributed to weak governance, overcapacity and open-access fishery that allows overfishing from an increasing number of boats and fishers. In addition, there is high rate of plastic pollution in the coastal waters which reduce catches with the potential of increasing health risk among consumers (Ofori-Danson et al., 2015). Desk research into Gulf of Guinea fisheries (Lauria *et al*. 2016) allows us to quantify the level of overfishing

based on the species biology (Table 8). Therefore, the considered scenarios should range between MSY and 3 or 4 times MSY.

Table 8: *Fishing mortality and the level of exploitation for two species in the Gulf of Guinea.*

Species	Source	Fishing Mortality (y^{-1})	MSY Fishing Mortality	Exploitation
Brachydeuterus auritus	Bannerman (2002)	1.43	0.39	3.0 times MSY
Ilisha Africana	Francis & Samuel (2010)	1.34	1.09	3.0 times MSY

2.6.2 South Asia: Bay of Bengal

Table 9 shows the projected change in some key environmental variables for the 21st century, as given by the GCMs listed above. The first two columns give data for the GBM delta area, the second two for the Mahanadi delta and the last two for the wider Bay of Bengal; in all cases the area included is from the coast to about 150 km offshore.

Table 9: *Future climate projections for the GBM and Mahanadi deltas and the wider coastal Bay of Bengal for the 21st century.*

Change in	GBM Delta Area: mid-century	GBM Delta Area: end-century	Mahanadi Delta Area: mid-century	Mahanadi Delta Area: end-century	Wider Area: mid-century	Wider Area: end-century
Surface temperature (°C)	+0.9 to +4.2	+2.6 to +6.6	+0.8 to +4.2	+2.6 to +6.3	+0.9 to +4.4	+2.6 to +6.5
Precipitation (%)	-3 to +4	-45 to +2	-8 to +25	-25 to +4	-2 to +20	-10 to -2
Maximum wind speed (ms^{-1})[1]	-0.3 to +0.5	-0.2 to +1.3	-0.5 to +0.4	0 to +1.3	-0.2 to +0.3	-0.3 to +0.1
Frequency of high wind events (days per decade)[2]	-5 to +10	-50 to +30	-37 to +13	-65 to +55	-1 to +4	-6 to +5

[1] Maximum wind speed is defined as the 98th percentile of the daily mean wind speed.
[2] High wind events are defined as daily mean wind speed exceeding 13 ms^{-1}.

Sea level rise in the Bay of Bengal is projected to be 0.18–0.33 m at mid-century and 0.49–1.0 m at end-century under RCP 8.5, compared to a 2000 baseline (0.16–0.31 m and 0.32–0.76 m under RCP 4.5) (Cannaby *et al.* (2016); Palmer *et al.* in prep.).

Fisheries status and fishing scenarios (based on Lauria *et al*. 2016):

East India

On the eastern coast of India the fish species that contribute to the majority of productivity are Hilsa shad and India oil sardine as well as the farmed Catla and Roho labeo. However some differences occur at state level, for example Scombridae are a quite important part of the marine landings in the Odisha state, though not in West Bengal. Inland fisheries catch the same species in both states, however the production of major carps, minor carps and catfishes is much higher in West Bengal. In general an increase in landings has been recorded in both states during the period 1976-2005 (data from the Central Marine Fisheries Research Institute).

Fisheries management in India can be divided into management of fisheries in the EEZ and in the territorial waters. According to the constitution of India, the Central (Federal) government has jurisdiction over the fisheries in the EEZ, while the State (Provincial) governments have jurisdiction over fisheries in territorial waters. Fisheries development and management planning is undertaken through the Five-Year Plans formulated by the government since 1951. This mainly focused on the development of the sector and increase of fish production, while the need for conservation was introduced later on. The main goal of the fishery policy is to ensure the sustainable development of marine fisheries for the protection of biodiversity. To ensure this a series of strategies have been proposed such as the

registration of fishing vessels, observation of closed fishing seasons, prohibition of destructive fishing methods, implementation of mesh size regulations and discards reduction (Fisheries and Fishing communities in India 2015). However the management of fisheries activity remains limited in India partly owing to lack of clear legislation. Several conservation measures have been initiated by the Ministry of Environment and Forests (MoEF) especially towards safeguarding against trade in endangered species (such as seaturtle, sea cucumbers, sea horse, and several species of molluscs), protection of certain habitats such as coral reefs, mangroves and breeding grounds of turtles, by designating protected areas (such as national parks and sanctuaries) but this is still an ongoing process.

Under the Marine Fishing Regulation Act (MFRA) a series of management plans at State level have been undertaken through licensing, prohibitions on certain fishing gear, regulations on mesh size and establishment of closed seasons and areas. Zones are demarcated by each State based on distance from the shoreline (from 5 km to 10 km) or on depth, and in these selected areas trawling and other forms of mechanized fishing are not permitted. A fishery closure period or 'monsoon fishing ban' is also implemented on both the east and west coasts of India for a period of 47 days and 65 days respectively (from April to May). For example, Tamil Nadu and Andhra Pradesh on the east coast observe a set period of 45 days, during April-May, and this only since 1999 and 2001, respectively (Vivekanandan2002). This measure aims to protect stocks during their most sensitive phase of the annual reproductive cycle (Vijayan and Edwin 2001). West Bengal fisheries department have notified (dated 4th April 2013) 5 restricted fishing zones (Hilsa Sanctuaries) to facilitate hilsa breeding and spawning. They are: (i) Lalbagh, Farakka, (ii) Katwa to Hooghly Ghat part, (iii) Diamond Harbour to Nischintapur, Godakhali, (iv) Five square kilometer area around the "Sand Bar" located in the river Matla, Roymongal and Thakuran in Sundarbans area, and (v) Farakka barrage. All types of fishing are banned in the hilsa sanctuaries during June to August and October to December every year to facilitate hilsa breeding and spawning. Fishing of hilsa is prohibited within 5 square kilometres around the Farakka barrage round the year to protect hilsa brooders. The mesh size is also restricted to conserve jatka/khoka ilish (Hossain *et al.*, submitted).

Bangladesh

Hilsa shad is the national fish of Bangladesh, locally known as ilish or ilisha, and is found in marine, coastal and freshwater environments. A significant part of the catch is exported to India, where it is especially consumed at religious holidays, and for consumption by non-resident Bangladeshis living in a number of countries. In 2012-13, it contributed 10% of the total fish production of Bangladesh (0.35 million tonnes with a market value of $2250 million), about 1% of Bangladesh's GDP. During the last two decades hilsa production from inland waters declined by about 20%, whereas marine water yield increased by about 3 times (Kathun 2004). Bombay duck provides the second largest fish catches in the Bangladesh coastal region. It is consumed fresh or dried. It represents a lucrative fishery in the Bay of Bengal: although its price is circa six times lower than Hilsa, still this species is more affordable for the poorest (Fernandes *et al.* 2016) and is widely eaten.

Bangladesh has a centralized system under the Department of Fisheries of the Ministry of Livestock and Fisheries. Although the Government of Bangladesh could take measures to address both the sustainability of marine resources and food security, the management trends in Bangladesh have not experienced any rapid change, because of the lack of funding and resources committed to sustainable fisheries management (FAO 2003).

A number of research projects on community-based fisheries management (CBFM) were initiated to promote sustainable use of inland capture fisheries and inform the Government of Bangladesh (GoB). Research was implemented in collaboration with national partners, including the Department of Fisheries (DoF) and a number of NGOs, through the course of several projects between 1987 and 2007. The present Fisheries Policy in Bangladesh was adopted in 1998. The objectives include enhancement of resources and production; poverty alleviation through self-employment in the sector; meeting the demand for animal protein; achieving economic growth and earning foreign exchange; and maintaining ecological balance, biodiversity and public health. In 2006 the Ministry of Fisheries and Livestock adopted

a Fisheries Strategy with eight sub-strategies for inland and marine capture fisheries, aquaculture and shrimp farming and aquaculture extension, quality control, human resources development and monitoring and evaluation. The strategy takes the policy further towards poverty reduction, co-management and conservation of resources, while creating an enabling environment for management and development. For the conservation of the hilsa fishery some activities and management measures have been taken on the basis of fishery regulations, such as the reduction the regulation of mesh size (less than 100 mm mesh size is legally prohibited) and the reduction of fishing time. In fact about 60-70% of hilsa are caught during the peak breeding season and almost 70% of them are sexually mature. For uninterrupted spawning, catch of brood hilsa has been banned in all major spawning grounds during the peak spawning season (15 to 24 October every year). Another action is the closure of some specific fishing areas or "hilsa sanctuaries" where fishing is banned during the breeding season. During the fishing ban the government provides food and alternative income-generating activities to compensate fisher communities for lost earnings (Mome 2007).

Based on fisheries data collected (Lauria *et al*. 2016) and species biology, the level of overfishing for key species is estimated as shown in Table 10. Therefore, the considered scenarios should range between MSY and 3-4 times MSY.

Table 10: *Fishing mortality and the level of exploitation for two species in the Bay of Bengal.*

Species	Source	Fishing Mortality (y^{-1})	MSY Fishing Mortality	Exploitation
Tenualosa ilisha	Fernandes *et al*. (2016)	1.86	0.61	3.0 times MSY
Harpadon nehereus	Khan *et al*. (1992)	3.78	0.66	3.0 times MSY
Rastrelliger kanagurta	Mansor & Abhdulla (1992)	0.73	1.02	3.0 times MSY

2.7 Regional Scenarios: Land-Use / Land-Cover Change

The regional scenarios also need to reflect past observations, present change, as well as future trajectories of additional environmental factors such as land use and land cover changes. The global and regional land use / land cover change also plays an important role in shaping the land system at national and delta levels. Popp *et al*. (2016) provides quantitative projections of SSP-based future global and regional land use pathways based on a systematic interpretation of the SSP scenario narratives. These include SSP-specific dynamics of agricultural intensification, GHG emissions and food prices, in terms of changes over time (relative to 2005 levels). These projections are available on the interactive open SSP web-database hosted by IIASA[4]. For example, Figure 14 presents land use dynamics over time for two regions, which also include DECCMA's study regions, under the five SSP scenarios.
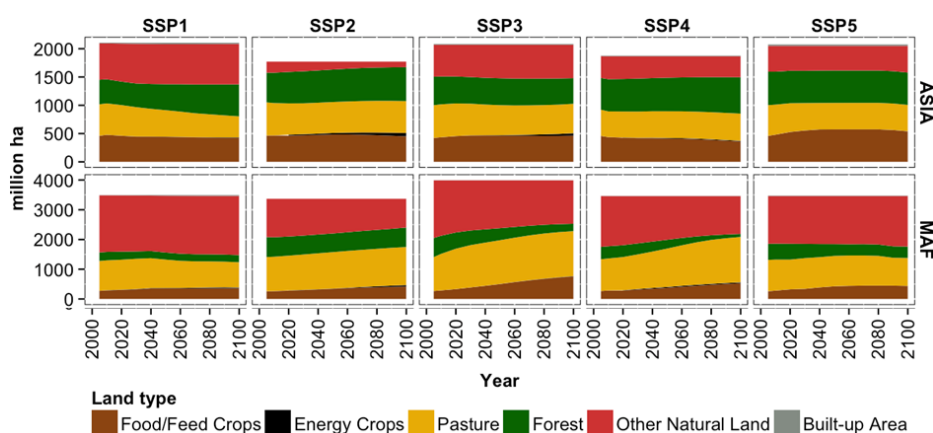
Figure 14: *SSP-based simulations of the regional land use dynamics over the 21st century for two aggregate regions: (i) ASIA (Asian countries with the exception of the Middle East, Japan and Former Soviet Union states) and (ii) MAF (countries of the Middle East and Africa) for the baseline case (Source: Popp et al. 2016).*

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[4] *See: https://secure.iiasa.ac.at/web-apps/ene/SspDb*

These SSP-based regional level land use change projections provide appropriate boundary conditions for the delta-scale land cover change scenario modelling in DECCMA under the various climate, socio-economic and policy scenarios. To this end, the widely used freely available CLUE-S (Conversion of Land Use and its Effects at Small regional extent) model (see Verburg *et al*. 2002) is used at the delta scale, which provides spatially and temporally explicit future land cover change scenario projections across the three deltas. It builds on existing land use and baseline land cover data, NAEZ (National Agro-Ecological Zoning, see Payo *et al*. 2015 for model description) model outputs (such as crop production gaps and yield potential), as well as global data (such as soil type) to provide output visualisations of changes in future landscape dynamics.

2.8 National Scenarios

The national socio-economic scenarios for Ghana, India and Bangladesh presented here are based on the *SSP Public Database Version 1.1*; IIASA 2016. This data provides future projections of the changes in population, GDP and urbanisation through the 21st century for each country under the five SSP scenarios. These are presented and discussed in detail in the following sub-sections (Sections 2.8.1–2.8.3). In addition, Jones and O'Neill (2016) provide spatially explicit projections of global population that are quantitatively consistent with the national population and urbanisation projections under the five SSP scenarios. Together, these data can be used as one of the boundary conditions to inform the delta-specific scenario development process, by providing the relevant stakeholders with a summary of these national level projections to provide a context for the deltas under the selected SSP scenarios (see Section 2.3.3).

2.8.1 Ghana

Historically, the national level population of Ghana has increased dramatically by 123% over the last three decades (i.e., from 10.9 million in 1980 to 24.4 million in 2010) (Figure 15). This is projected to increase by 61–123% (by 2050) and 56–275% (by 2100) relative to the 2010 level across the five SSP scenarios. The lowest and highest increases are projected under the SSP5 and SSP3 scenarios, respectively. When looking at urban share of the total population, almost 52% of the national population represents urban dwellers (in 2010), which is projected to increase to 80% (in 2050) and more than 93% by the end of the century under the SSP5 scenario.

Figure 15: *National level historic trends and future projections of population (total (top) and urban share (bottom)) in Ghana under the five SSP scenarios.*[5]

Similarly, Figure 16 shows the evolution of the Gross Domestic Product in purchasing power parity (GDPppp) in Ghana, both historic (between 1980 and 2010) trends and future projections under the five SSP scenarios). The historic trend shows that the national GDPppp (in 2005 prices) has increased from US$10.8 billion/year (in 1980) to US$36 billion/year (in 2010), representing a 232% increase over the last

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[5] *Source: ©SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb* (IIASA 2016)

three decades (Figure 15). Relative to the 2010 level, the GDPppp is also projected to increase by 552% (under the SSP4 scenario) to 1950% (under the SSP5 scenario) by 2050. By 2100, it is projected to increase up to US$742 billion/year and US$4,394 billion/year across the five SSP scenarios.

Figure 16: *National level historic trends and future projections of GDPppp in Ghana under the five SSP scenarios (US$2005).[6]*

2.8.2 Bangladesh

In Bangladesh, the total population has increased by 84% over the last three decades, i.e., from 81 million people in 1980 to 149 million people in 2010 (Figure 17). Under the SSP scenarios, the national total population of Bangladesh is projected to increase ranging between 15% (under the SSP5 scenario) and 49% (under the SSP3 scenario) by 2050 relative to the 2010 level. Except under the SSP3 scenario, the total population is projected to peak by 2050s. By 2100, the national total population is projected to fall significantly below the 2010 level (by up to 16% and 22% under the SSP1 and SSP4/SSP5 scenarios, respectively), while it is projected to increase by 13% (under the SSP2 scenario) and 76% (under the SSP3 scenario). When looking at the urban share of the national population, the historic data shows approximately a linear growth over the last three decades – with 28% of the total national population representing urban dwellers in 2010. While an almost continuation of the historic trend is projected under the SSP3 scenario, the urban share of the national population is projected to increase significantly over the coming decades under most of the SSP scenarios. For example, under the SSP5 scenario the percentage of national total population residing in urban areas is projected to increase to 67% (in 2050) and 90% by the end of the century.
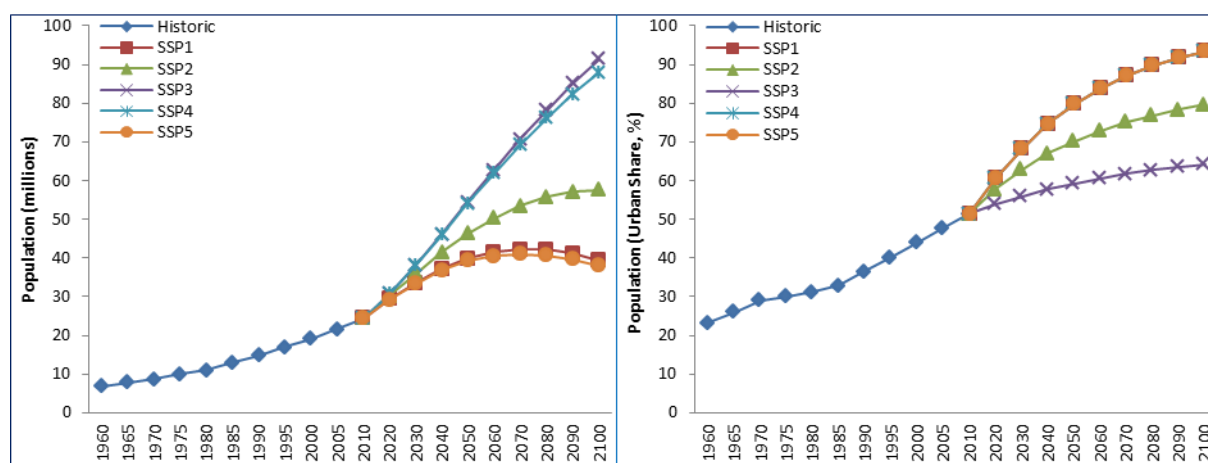

Figure 17: *National level historic trends and future projections of population (total (top) and urban share (bottom)) in Bangladesh under the five SSP scenarios.[7]*

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[6] *Source: ©SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb (IIASA 2016)*

Similarly, the historic GDPppp (in 2005 prices) has increased from approximately US$55 billion/year (in 1980) to over US$221 billion/year (in 2010), representing a 167% increase during the last three decades (Figure 18). The SSP scenario projections of the national level annual GDPppp (2005 prices) shows a significant increase (relative to the 2010 level) in the coming decades. In 2050, the projected GDPppp ranges between US$914 billion/year (under the SSP4 scenario) to US$3.4 trillion/year (under the SSP5 scenario). By 2100, these projections reaches up to US$930 billion/year and US$12.2 trillion/year (2005 prices) across the SSP scenarios.
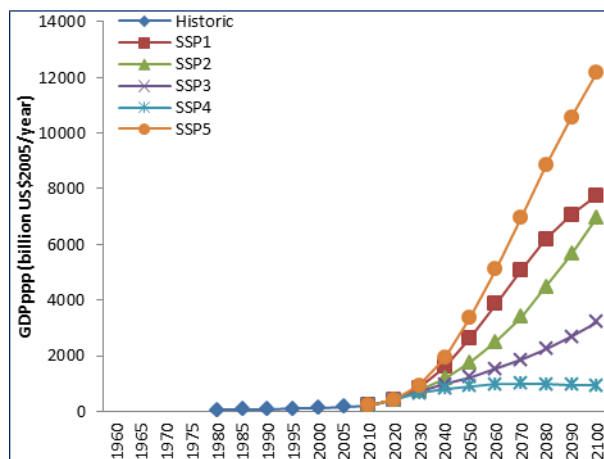
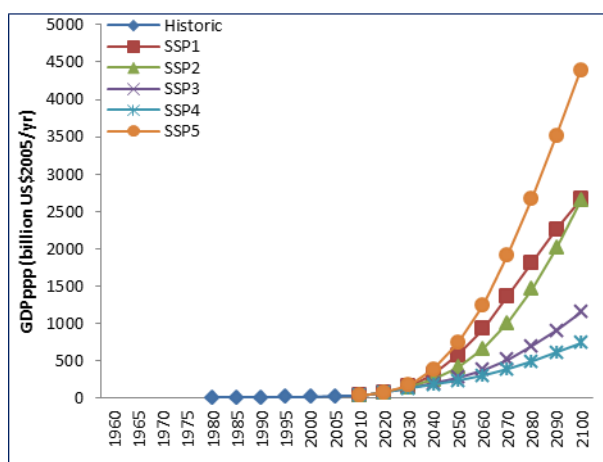**Figure 18:** *National level historic trends and future projections of GDPppp in Bangladesh under the five SSP scenarios (US$2005).*[8]

In light of the recent scenario framework developed as part of the Bangladesh Delta Plan 2100 (BDP 2100), the DECCMA socio-economic scenarios for Bangladesh need to take into account the BDP 2100 scenarios to provide consistent policy relevant scenarios. The BDP 2100 scenario framework provides six different scenario narratives based on the IPCC's scenario approach considering two key drivers (i.e., "Future water conditions based on trans-boundary development and climate change" and "Economic development and related land use changes"; resulting in four scenarios). These are then supplemented with two additional scenarios that fall within the "extreme edges" of the four scenarios, resulting in a total of six scenarios. These include:

(i) **Productive** (Market Driven Delta): *moderate water conditions (moderate climate change) and diversified economy (high per capita growth)*

(ii) **Resilient** (Dynamic Delta): *extreme water conditions (high climate change) and diversified economy*

(iii) **Active** (Basic Needs First): *extreme water conditions and traditional economy (low per capita growth)*

(iv) **Moderate** (Delta Under Pressure): *moderate water conditions and traditional economy*

(v) **Fast Urban Growth**: *high population growth and growing economy leading to significant growth of largest cities together with high climate change and upstream development*

(vi) **Business as Usual** (BaU): *continuation of current trends and policies with an average climate change*

Table 11 shows a comparison of the national level projections of selected socio-economic parameters, highlighting how the DECCMA scenarios could be mapped with some of the BDP2100 scenarios, for example, based on the population projections.

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[7] *Source: ©SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb* (IIASA 2016)
[8] *Source: ©SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb* (IIASA 2016)

Table 11: *Comparison of scenario projections for Bangladesh across the three frameworks.*

		IIASA SSP Public Database					DECCMA		
		SSP1	SSP2	SSP3	SSP4	SSP5	Medium (~SSP2)	Medium- (~SSP3)	Medium+ (SSP5)
Population (mill)	2050	178	196	222	177	171	196	222	171
	2100	125	167	261	116	116	167	261	116
Urban share (%)	2050	67	52	38	67	67	52	38	67
	2100	90	71	49	90	90	71	49	90
GDPppp (billion US$2005/yr)	2050	2637	1754	1236	914	3367	749	470	1329
	2100	7747	6976	3208	932	12184	2614	740	5025

		BDP 2100					
		Productive	Resilient	Moderate	Active	Fast Urban Growth	BaU
Population (mill)	2050	200	170	210	230	225	200
	2100	165	125	190	260		
Urban share (%)	2050	70	60	52	48	70	55
	2100	85	75	70	60		

2.8.3 India

India the historic national level population has increased by 75% over the last three decades, i.e., from 700 million people in 1980 to 1.14 billion people in 2010 (Figure 19). By 2050, the national total population of India is projected to increase ranging between 26% (under the SSP5 scenario) and 61% (under the SSP3 scenario) relative to the 2010 level. Except under the SSP3 scenario, the total population is projected to peak by 2050s. By 2100, while the total population is projected to fall below the 2010 levels (by up to 5–7% under SSP4 and SSP1/SSP5 scenarios, respectively), it is projected to increase between 31% (under the SSP2 scenario) and 113% (under the SSP3 scenario). When looking at the urban share, the historic data shows a linear growth over the last three decades – with 30% of the total population representing urban dwellers in 2010. While a continuation of the historic trend is projected under the SSP3 scenario, the urban share is projected to accelerate and increase significantly under most of the SSP scenarios. For example, under the SSP5 scenario the percentage of total population residing in urban areas is projected to increase to 67% (in 2050) and approximately 91% by the end of the century.
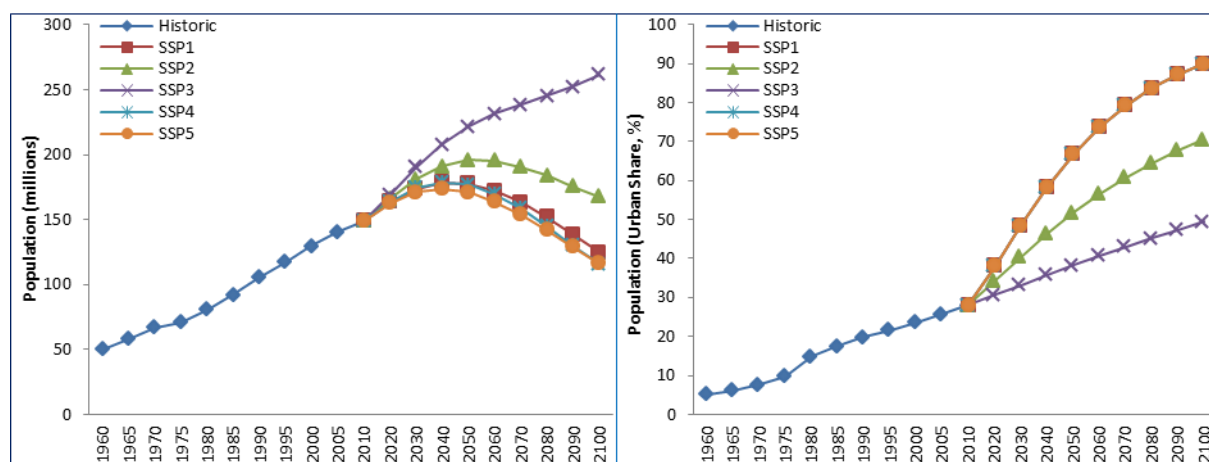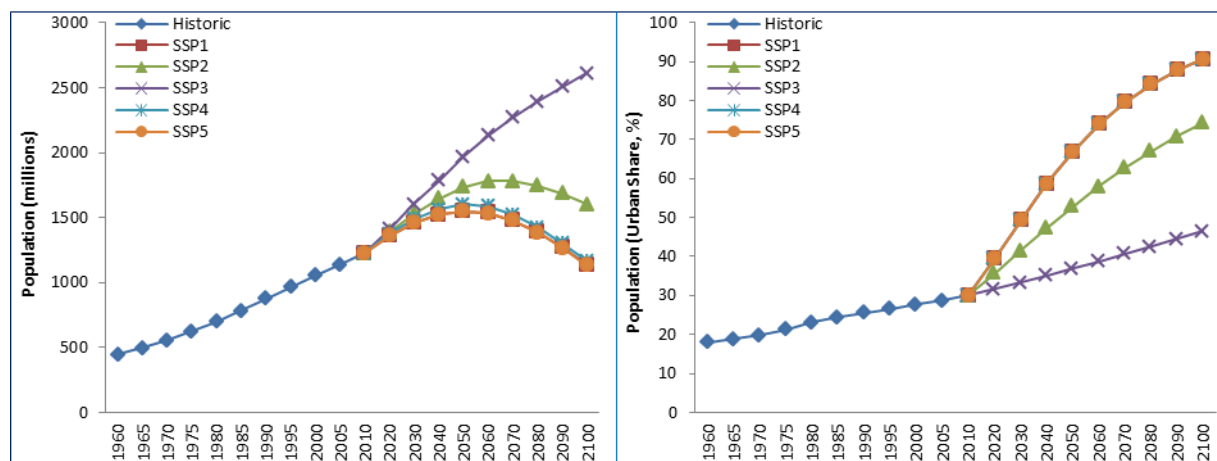

Figure 19: *National level historic trends and future projections of population (total (top) and urban share (bottom)) in India under the five SSP scenarios.*[9]

Similarly, India's historic GDPppp (in 2005 prices) has increased from US$615 billion/year (in 1980) to US$3.8 trillion/year (in 2010), representing a 3147% increase just during the last three decades. The

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[9] *Source: ©SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb* (IIASA 2016)

GDPppp (2005 prices) is also projected to increase (relative to the 2010 level) dramatically in the coming decades, ranging between US$18.9 trillion/year (under the SSP2 scenario) to US$46.5 trillion/year (under the SSP5 scenario) by 2050. By 2100, the projected GDPppp reaches between US$37 and US$145 trillion/year (2005 prices) across the five SSP scenarios (see Figure 20).
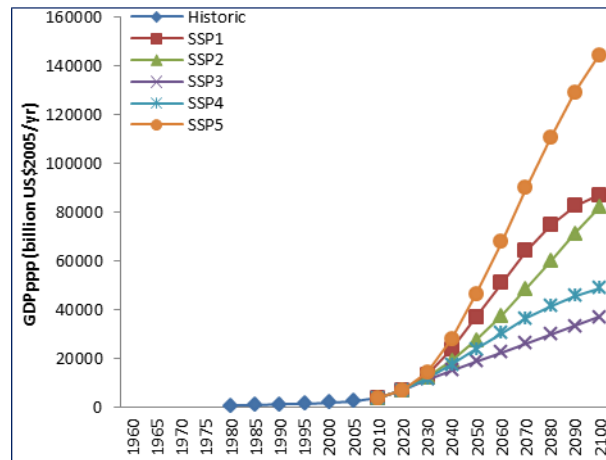
Figure 20: *National level historic trends and future projections of GDPppp in India under the five SSP scenarios (US$2005).[10]*

Regionally, the population is projected to change (relative to 2010) between -11% and +36% (in Odisha) and -8% and +40% (West Bengal) across the three scenarios by 2050 (Figure 21). By 2100, the population change is projected between -64% and +60% (Odisha) and -63% and +67% (West Bengal). On the other hand, the GDPppp is projected to grow (relative to 2010) by 750–1350% in Odisha and 540–980% in West Bengal by 2050.
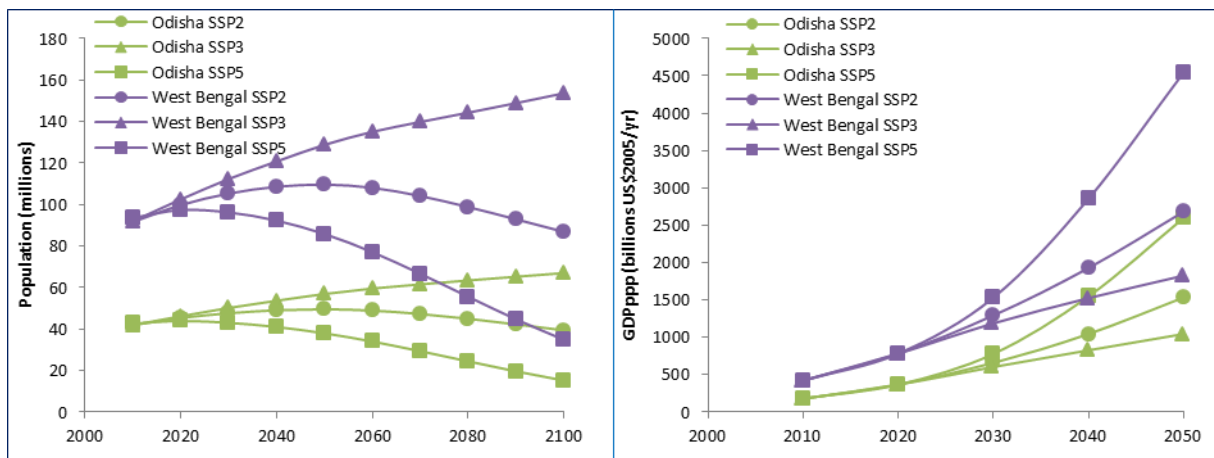
Figure 21: *India's regional level (for Odisha and West Bengal) future projections of population (left) and GDPppp (right) under the three selected SSP scenarios.*

In summary, the national level projections of the changes in population, urbanisation and GDP (presented in Sections 2.8.1–2.8.3) provide one of the various boundary conditions for the delta scenario process. However, in addition to these drivers, other socio-economic parameters also play an important role influencing the potential climate change impacts, adaptation and migration assessment. Hence, these also need to be considered in order to explore appropriate delta scenarios and adaptation policy trajectories. Examples of some of these key parameters include: demographics (e.g., age and gender distribution of the population), average household size, seasonal population variation, type and distribution of infrastructure, level of education and people's awareness (e.g., to environmental hazards), and attitudes towards the environment, rural-urban migration, etc.

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[10] *Source: ©SSP Public Database (Version 1.1) https://tntcat.iiasa.ac.at/SspDb (IIASA 2016)*

2.9 Delta Scenarios: Adaptation Policies and the Participatory Process

At the delta scale, the environmental or socio-economic change driving pressures could come from inside of the human-environment delta system (endogenous) and/or from outside the delta system (exogenous). As discussed in previous sections, the environmental or socio-economic drivers that operate at higher/coarser spatial scales (e.g., national, regional, global) represent part of the exogenous drivers, which will define the boundary conditions for the delta scale scenario and adaptation policy narratives and trajectories (see Figure 5). Global climate change and sea-level rise are two examples of mainly exogenous pressures, while local human-induced subsidence (e.g., due to groundwater extraction) is an example of an endogenous driver. In DECCMA, each case study delta is considered as socio-environment systems for which there are endogenous and exogenous pressures that are identified and defined as scenarios accordingly. The following sub-sections present delta scenarios (e.g., population and GDP projections) and the participatory scenario process employed for development of alternative adaptation policy trajectories.

2.9.1 Population and GDP Changes in Deltas

SSP-based projections of population and GDP changes for the three deltas are available from spatially explicit (gridded) global datasets (e.g., Jones and O'Neill 2016; Murakami and Yamagata 2016). The grid-based global level projections across the various SSP scenarios can be aggregated for each delta area as presented in Figure 22. Both studies are based on the national level projections from IIASA's SSP Database (see Section 2.8). However, there are some significant differences (in magnitude and/or trend) in the baseline as well as future population projections between the two studies. This is partly due to differences in the spatial resolution and methods used for downscaling (from national to grid level distribution at the global scale) used in the two studies. For example, in 2010 the delta populations are estimated at 0.93 million (Volta), 7.63 million (Mahanadi) and 64.41 million (GBM) people based on the J&O2016 data (i.e., Jones and O'Neill 2016), while estimated at 0.55 million (Volta), 4.25 million (Mahanadi) and 62.05 million (GBM) people based on the M&Y2016 data (i.e., Murakami and Yamagata 2016). Looking at the extreme ranges in future projections by 2050, the total delta populations are projected to increase by 55–158% (Volta delta), 24–178% (Mahanadi delta), and 7–51% (GBM delta) (relative to 2010 levels) across both studies and all the scenarios. By 2100, the changes relative to 2010 levels are projected between 43 to 284%, -12 to 207%, and -32 to 75% for the Volta, Mahanadi and GBM deltas, respectively. Similarly, the delta-scale GDPppp are also projected to increase from US$0.84 billion (Volta), US$13 billion (Mahanadi) and US$96 billion (GBM) in 2010 to US$6–18 billion (Volta), US$82–281 billion (Mahanadi) and US$543–1053 billion (GBM) in 2050 across the three SSP scenarios. By 2100, these are expected to reach up to US$24–105 billion (Volta), US$183–868 billion (Mahanadi) and US$1304–2738 billion (GBM) across the scenarios. While it's important to recognise the differences between the two data sources, the use of these projections can allow exploring uncertainties of potential future socio-economic changes as well as the effect of different downscaling methods across the various scenarios and studies.
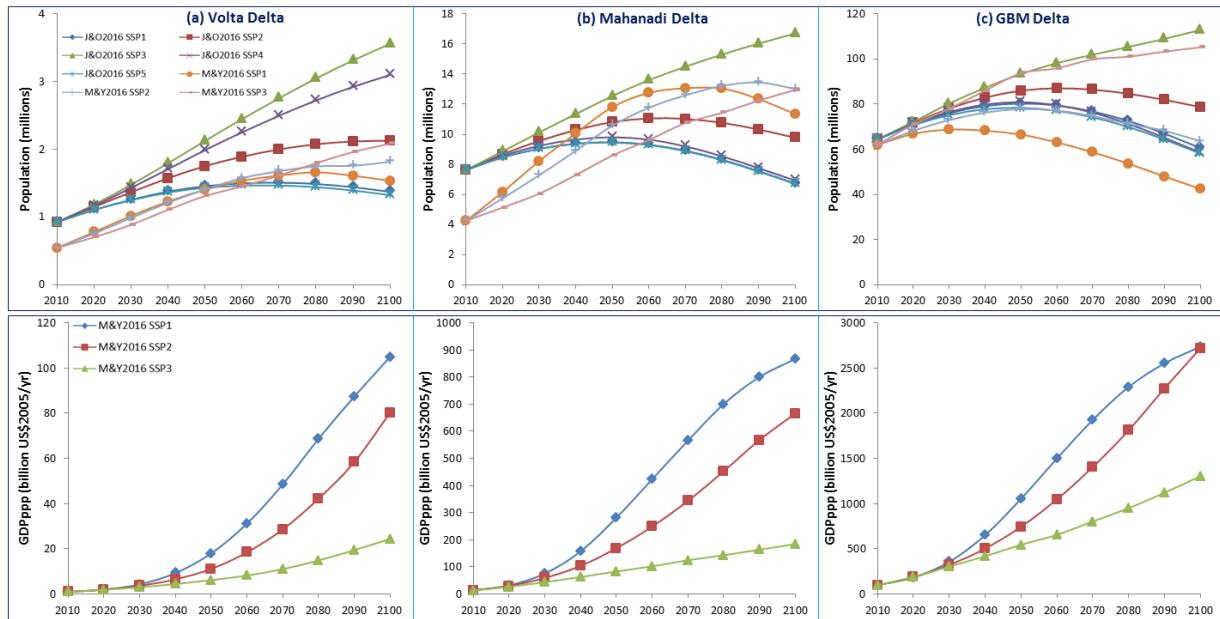
Figure 22: *SSP-based population and GDP projections in the deltas based on gridded data obtained from Jones and O'Neill (2016) and Murakami and Yamagata (2016). Note differences in y-axes.*

Within DECCMA, population projections for each delta have been developed using the Spectrum 5 software package (which uses the Cohort-Component Method). The projections take into account population change factors such as composition, fertility, mortality, and migration (based on census data and assumptions on future changes of these factors). Figure 23 shows summary of the population projections for the four deltas.
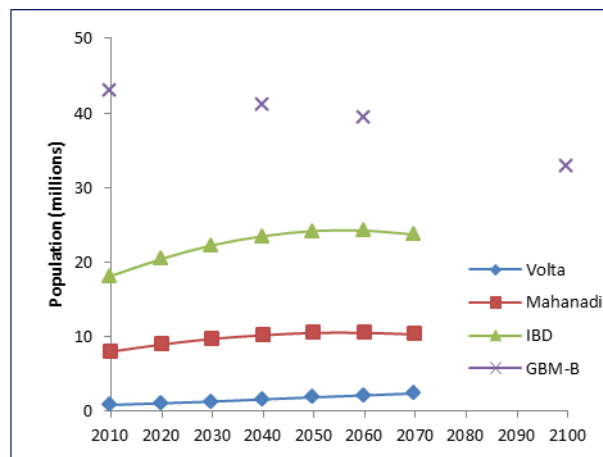
Figure 23: *Delta population projections in DECCMA based on the Cohort-Component Method.*

For GDP, an expert-based questionnaire (see Appendix C) was used in order to obtain information, expert judgment and visions about future economic conditions in the case study deltas and the countries they are located in. The information and projections obtained are used to develop and refine the regional and national economic scenarios developed in DECCMA. This introduction of the goal, together with presentation of the DECCMA project and the economics Wok Package is the introduction made in the calls and in approaching the (socio)economic experts. With most of the experts, it was possible to set-up in-person interviews in order to be able to clarify/complete the answers and any possible doubt about the questions. In few exceptional cases (when not possible to meet in person, etc.), the responses were received by email. In most deltas, the questionnaires completion (with more than 10 responses in each) allowed to obtain projections for 4 points in time (2020, 2030, 2040, and 2050). The information about past and present data on the variables questioned, notably for 2010-2011 (the baseline years for the Delta input-output tables, Social Accounting Matrices, and Computable General Equilibrium models we

run) as well as for 2005-2006 and 2015-2016, were provided in order to serve as reference points. All the questions on the variables were asked both at the delta scale as well as at the country level. The topics comprised the Urban share, population, GDP growth (in nominal terms, and in PPP terms), the GDP composition (agriculture, industrial and services shares), wages, income share (labour vs. capital), enrolment of education (by levels and by gender), inequality, and land use. The analysis of the answers, after verifying and refining the consistency (e.g., the question on agriculture, industrial and services shares should add up to 100% for each time period; also the growth indices need to properly reflect the starting and end year considered), have been used to obtain average medium paths for each delta and country. Figure 24 presents the delta scale projections of GDP growth and its compositions for each delta. The country data (see Appendix C) shows that the visions at the country level match quite well with IIASA's GDP and population projections under the SSP2 scenario (see Section 2.8), highlighting the role of these condensed visions as medium paths for the future.
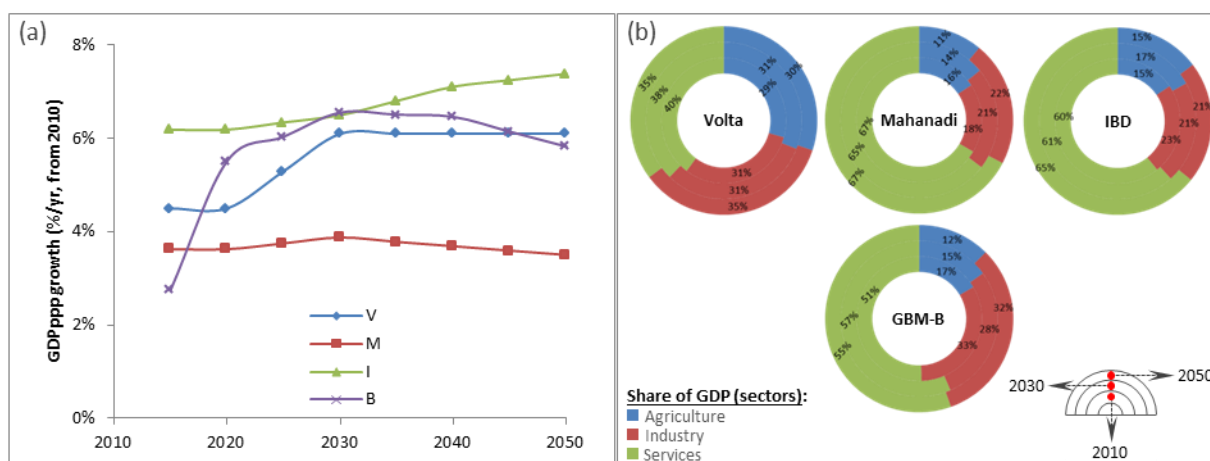
Figure 24: *Projections of annual change in GDPppp (left) and its sectoral compositions (right) in the deltas based on a participatory process using expert-based questionnaire (see Arto et al. in prep. and Cazcarro et al. 2018; Appendix C for further details; and maybe subject to revision). Note: the 'V', 'M', 'I', and 'B' stand for the Volta, Mahanadi, IBD, and GBM (Bangladesh) deltas, respectively.*

The following sub-sections present the participatory process and the concept and methods used for developing adaptation policy trajectories in DECCMA by combining inputs from experts and stakeholders.

2.9.2 The Participatory Process

As part of the participatory scenario process, a set of procedures are considered through which stakeholders and DECCMA experts collaborate to develop, test, and validate the delta scenarios and adaptation policy trajectories. 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 a number of different complex project strands and to develop these in a way that incorporates inputs and views of different interested groups as appropriate during the remainder of the DECCMA project. The main strands to be integrated are as follows (in no particular order of importance):

1. The adaptation policy trajectories developed as part of WP6 (Chapman *et al.* 2016);

2. Broad categories of adaptation interventions, developed as part of WP6 in collaboration with WPs 1, 2, 5, that are considered to be broadly applicable to a greater or lesser extent across all case study deltas;

3. A finite number of possible socio-economic futures, based on the IPCC SSP approach;

4. Modelling of the combination of these SSPs with RCP8.5 (in WP5);

5. Bearing in mind the need for these modelled results to be consistent with WP4 economic scenario needs based on the OECD/IIASA projections; and

6. The need for stakeholder views to be taken into account in order to maximize the credibility and relevance of the final results.

The four key stages of the participatory process considered in achieving the aims outlined above are discussed below:

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

▪ Identifying selected number of broad categories of adaptation based on the theoretical and practice-based literature

▪ Developing narratives of four adaptation policy trajectories (APTs)

▪ Identifying specific national adaptation interventions under the various broad categories that are relevant for each case study delta under each APT

▪ Validating the broad categories, APT narratives, and list of specific interventions with project country experts. In this context, local expert advice is sought on how the baseline (i.e., the present day) situation would be characterised in terms of the broad adaptation categories and specific interventions in order to understand and capture what strategies are currently in use. Then, they are asked to examine the narratives of the four APTs and estimated how the baseline categories might change between now and 2050. This provides a full picture of what each of the four APTs would look like in each of the case study deltas.

▪ Preparing for the first-round stakeholder workshop:

   o *The selected climate (RCP) and socio-economic (SSP) scenarios are used to define the physical and macro-economic boundary conditions at the higher scales (see Sections 2.3– 2.7), which help frame stakeholder discussions. These boundary conditions include historic trends and future projections in terms of, e.g., temperature, precipitation, sea-level rise, population, urbanisation, GDP, freshwater flow, etc.*

   o *The effects/benefits of the four APTs and associated adaptation interventions are modelled using the DECCMA integrated assessment model under the various climate (RCP) and socio-economic (SSP) scenario combinations focusing on up to the 2050s to present to stakeholders.*

Stage 2: *Evaluate and validate – Engaging stakeholders*

▪ Stakeholders are presented with the boundary conditions (established pre-workshop) for the medium scenario along with narratives of the four adaptation policy trajectories (APTs) and associated specific interventions and modelled outputs of selected impact indicators assessed with and without adaptation under the selected scenario (for baseline and 2050).

   o *Consistency of approach is maintained across all case study deltas by running the first national level workshop in Dhaka (where there is already experience and expertise) and inviting country team members from all deltas to attend in order to have the formats replicated by the country teams for their respective case study deltas.*

▪ Stakeholders are asked to:

- o *Evaluate and validate the modelled outputs based on the APTs and associated specific bundles of adaptation interventions under the medium scenario (RCP8.5/SSP2) boundary conditions.*

- o *Comment on and determine which of the APTs most resemble how they anticipate the existing policy trajectory will proceed, based in part on their knowledge of how policy implementation has gone in the past. This resulted in the stakeholders identifying which of the APTs best matches what their current policy vision for the future is (i.e., the BAU equivalent). They are then asked to comment on what changes would need to be made to the most relevant trajectory in order to match their expectations more closely, and these comments are taken on board by the modelling team. These changes are expressed through changes to the trajectory in terms of the list of relevant specific interventions.*

- ▪ Stakeholders are also asked to:

  - o *Characterise basin management governance on their respective rivers – how do they characterise it now, and how do they expect it to look like in 2050 based on their existing policy intervention, and*

  - o *Comment on implementation of policy, identifying the factors that influence/could be expected to influence this. This incorporates findings from the barriers survey work already conducted within the project, but also findings from the governance analysis. Both of these elements are used to help frame assessment of effectiveness of the APTs.*

Stage 3: *Revise and remodel – Expert*

- ▪ The modelling team took stakeholders' comments and feedbacks and re-model using the amended/modified APTs and list of relevant specific interventions.

- ▪ The modelling is done both for the medium scenario (that was presented in the first-round workshop) as well as the more extreme scenario combinations (with respect to medium+/SSP5 and medium-/SSP3) in order to provide appropriate uncertainty ranges. This provides a total of twelve projections for each delta, i.e.,:

  - o *4 APTs; multiplied by*

  - o *3 RCP/SSP scenario combinations*

- ▪ As these will be too unwieldy to take back to stakeholders directly, in order to reflect the breadth of uncertainty, stakeholders are presented with:

  - o *The four projections they saw at the beginning of the year; with their BAU modified taking into account their comments at that point; plus*

  - o *Three additional representative projections from the medium+ and medium– scenarios (i.e., with SSPs 5 and 3) showing the highest and lowest across these. It will not be feasible to present them with all 8 of the projections for these scenarios, so a selection (e.g., 3 as low, medium, high?) showing the spectrum of possibility will be presented instead.*

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 – covering the medium and the two (low/high) extreme RCP/SSP scenario combinations as identified above.

- They are asked to identify what changes (in terms of their list of intervention strategies) they would make to what they have identified (at the first-round workshop) as their BAU equivalent trajectory in order to address the additional level of uncertainty that they have seen in the more extreme scenario combinations.

- Expected physical changes between 2050 and 2100 under the medium scenario are also explored by asking stakeholders to consider how well they believe the system they expected to exist in 2050 is likely to respond to the increased impacts of climate change anticipated in the next 50 years (post-2050). This maximises the opportunity for stakeholders to track progress and development that takes account of improved understanding and changes in circumstances over longer-time periods.

The following section presents the overall conceptual framework for linking the global climate (RCPs), socio-economic (SSPs) scenario narratives and policy assumptions (SPAs) considered in DECCMA as part of the participatory process discussed above and outlines the selected broad categories of adaptations, narratives of the four adaptation policy trajectories (APTs) and examples of the associated specific interventions that are considered relevant to one or more of the case study deltas.

2.9.3 Adaptation Policy Trajectories and Interventions in Deltas

In order to explore robustness of different national policy interventions under the various climate and socio-economic scenarios, four distinct adaptation policy trajectories (APTs) are defined in DECCMA, which are considered as both 'visionary and realistic' to address potential impacts of future changing conditions. Drawing on Hall *et al.* (2016), the APTs are developed by combining expert-based and participatory methods as appropriate. Each APT is tested by taking into account baseline conditions (e.g., based on household survey, adaptation inventory and policy reports conducted within the DECCMA project) and historic trends of various drivers. The participatory scenario process is facilitated by a systematic conceptualisation of the links between the global climate change (RCPs) (see Section 2.3.1) and socio-economic change (SSPs) (see Section 2.3.2) scenario narratives and policy assumptions (see Section 2.3.4) considered in order to develop appropriate adaptation policy trajectories and specific national interventions as illustrated in Figure 23. The four APTs are defined below (see Chapman *et al.* 2016 and Suckall *et al.* 2017 for further details):

(i) **Minimum Intervention**: *which aims to keep costs down at the lowest possible level while protecting citizens from climate change impacts*,

(ii) **Economic Capacity Expansion**: *which focusses primarily on encouraging economic growth and utilizing the increased financial capacity it brings to protect the economic system from climate-induced harm*,

(iii) **System Efficiency Enhancement**: *which focuses on promoting most efficient management and exploitation of the current system, looking at ways of distributing labour, balancing livelihood choices, and best utilising ecosystem services to enhance livelihoods and wellbeing under climate change*, and

(iv) **System Restructuring**: *which links closely to ideas of 'transformational adaptation' (Kates et al. 2012) embracing 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*.
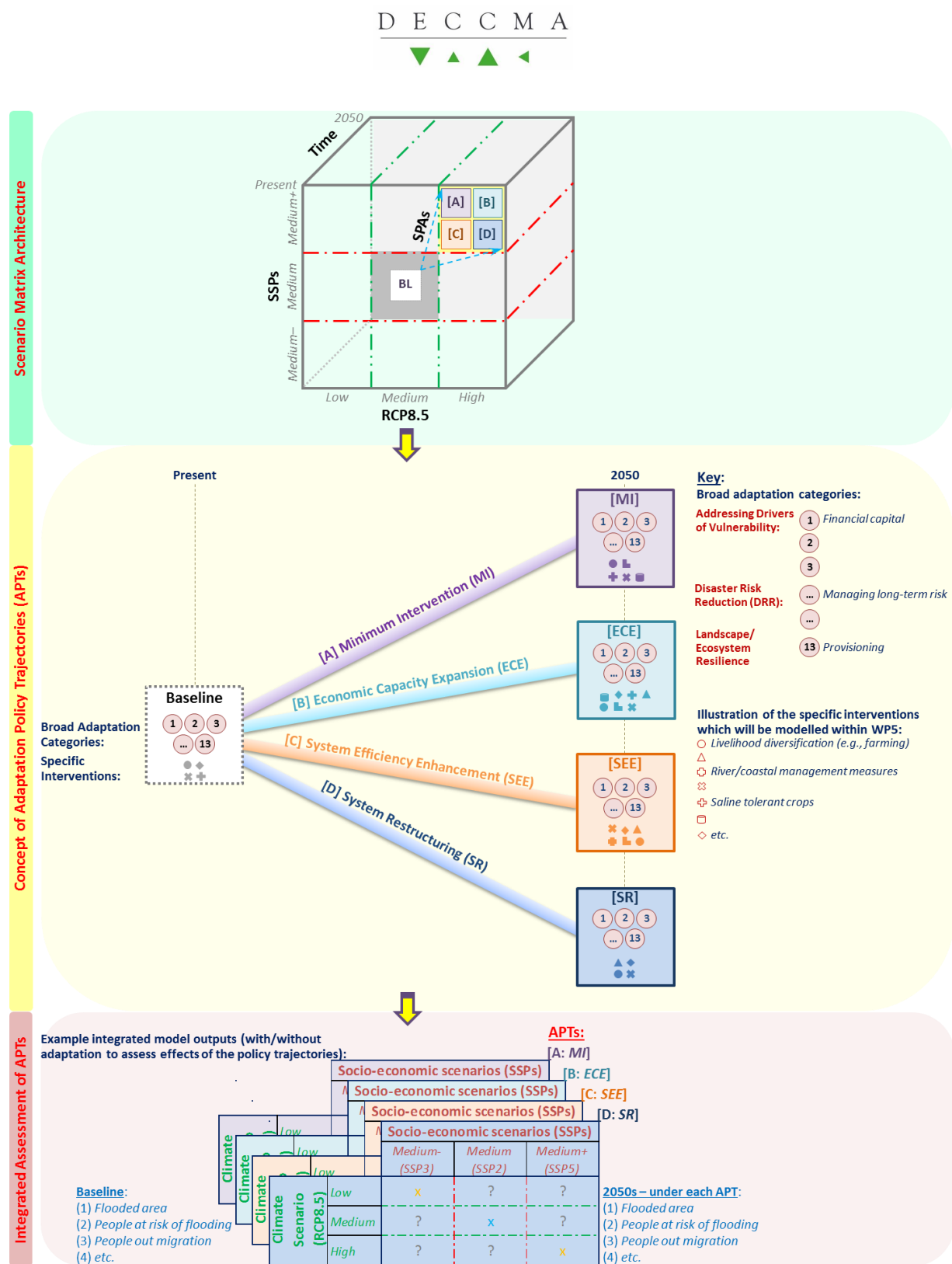
Figure 25: *Schematic illustration of the overall scenario matrix architecture linking the global climate (RCPs) and socio-economic (SSPs) scenarios and policy assumptions (SPAs) and the conceptual framework for developing the national adaptation policy trajectories (APTs) in DECCMA.*

The narratives and key characteristics of the four adaptation policy trajectories are defined mainly based on three main adaptation policy components and thirteen subsequent broad adaptation sub-categories and description of how they are projected to evolve over time (between now and 2050) under each policy trajectory. The thirteen broad adaptation sub-categories are conceptualized and grouped based on

the three main adaptation policy components as outlined below, with examples of specific national adaptation interventions under each broad category (see Suckall *et al*. 2017 for more details):

A. Addressing drivers of vulnerability – which is defined using the five capitals within the broader context of sustainability livelihood framework;

   1. Financial capital (e.g., livelihood diversification)

   2. Human capital (e.g., use of climate resilient farming techniques)

   3. Social capital (e.g., use of cooperatives)

   4. Physical capital (e.g., access to markets)

   5. Natural capital (e.g., land re-distribution to poor)

B. Disaster Risk Reduction, DRR (managing weather/climate risk) – which is defined in four parts:

   6. Managing long-term risk (e.g., river/coastal management infrastructure)

   7. Preparedness (e.g., community training in DRR management)

   8. Response (e.g., use of high land during flood time)

   9. Post-disaster recovery and rehabilitation (e.g., relocation of households)

C. Landscape/ecosystem resilience: defined using the four ecosystem services:

   10. Provisioning (e.g., use of saline tolerant crops)

   11. Regulating (e.g., mangrove forest planting)

   12. Habitat (e.g., promoting protecting green spaces)

   13. Cultural (e.g., wildlife conservation in natural heritage sites)

Bearing in mind the thirteen broad adaptation sub-categories used to define the narratives of the four APTs, a number of specific national level adaptation interventions are identified for each case study delta. These include 68 specific adaptation options in total across all the four deltas; representing *19 in category A; 27 in category B; and 22 in category C*, which will be incorporated within the integrated model. These lists of specific interventions within the integrated model will serve as a quantitative representation of the policy trajectories, which will allow exploring associated effects/benefits of the APTs in general in reducing potential future impacts under the various climate and socio-economic scenarios and adaptation options. The conceptual adaptation framework provides a useful platform for linking the global climate and socio-economic scenarios and policy choices and developing appropriate adaptation policy pathways in deltas, which can also be applied in other contexts.

3. THE SCENARIOS DEVELOPMENT PROCESS: CONCEPTS AND METHODS

The following sub-sections present an overview of the concepts and methods of the integrated scenario and adaptation policy frameworks developed for, and the overall lessons learned from, the scenario development process adopted in DECCMA.

3.1 Background Context

As discussed earlier, scenarios are plausible alternative images of how the future may develop; they represent coherent, internally consistent and possible trajectories, rather than projections. They

represent a challenging context and boundary conditions against which to test robustness of the human and natural systems and associated policy choices. Some example building blocks of a typical scenario include: (i) identifying the various driving forces, (ii) defining the spatial context, (iii) outlining the time horizon and time steps, and (iv) developing the narratives or storylines. In climate change research, scenario analysis plays an important role to better understand uncertainties for robust adaptation and mitigation policy decision making under a wide range of possible futures. Various studies consider a range of climate and socio-economic change scenarios to assess potential impacts, and vulnerability as well as adaptation needs under changing and uncertain future conditions. To this end, a variety of scenario methods and frameworks have been developed and applied in the literature, and there are different types and classes of scenarios. For example, Star *et al*. (2016) classifies scenario approaches into two categories based on who "owns" the scenario development process (experts or stakeholders) and the purpose of the scenarios (exploratory or normative) as: (i) research-driven process and (ii) participatory process. On the other hand, Börjeson *et al*. (2006) outlines three broader categories and six types of scenarios based on three user's needs as presented below:

- **Predictive (*Probable*) scenarios**: *that are based on user's need to know "What will happen?" They are usually considered for the short-term and there are two types under this category based on a condition: (i) forecasts – that "if the likely development unfolds", and (ii) what-if's – of "some specified events".*

- **Explorative (*Possible*) scenarios**: *that are based on user's need to know "What can happen?" They apply for long-time horizon, with two types of scenarios to explore what can happen: (i) external – focusing on the "development of external factors", and (ii) strategic – if we take actions in a certain way (i.e., taking into account policy measures).*

- **Normative (*Preferable*) scenarios**: *that are based on user's need to know "How can a specific target be reached?" These are based on how the "system structure is treated", which leads to two types of scenarios: (i) preserving – in terms of how can a target be reached "by adjusting to current situation", and (ii) transforming – "when the prevailing structure blocks necessary changes".*

The choice and focus of any specific type of these scenarios depends on the mail goal(s) and objective(s) of the scenarios to be investigated. In addition, it requires understanding the key scenario development challenges in terms of, for example: (i) integrating the latest RCP–SSP–SPA scenario framework and associated narratives, (ii) identifying the specific quantitative data needs across scales (spatial and temporal) and use of appropriate downscaling and/or upscaling approaches, and (iii) linking both qualitative (e.g., narratives) and quantitative (e.g., model outputs) scenarios across scales of interest. In DECCMA, while the higher scale climate change scenarios (e.g., at the global scale) and socio-economic change scenarios (e.g., at the regional or national levels) mainly have explorative nature to provide a boundary condition, at the delta scale a loose combination of the explorative and normative policy scenarios has been considered in order to: (i) explore the potential impacts of future changing conditions, as well as (ii) understand the benefits of alternative adaptation policies for each case study delta. In order to achieve this, the DECCMA scenario framework presented here integrates two key aspects of scenario development techniques: (i) multi-scale hybrid approach – in order to capture the multi-scale (both spatial and temporal) nature of the various climate and socio-economic change drivers at which they operate, and (ii) participatory approach – for engaging various stakeholders at multiple scales (e.g., national/state, regional/district, and local/community as well as capturing household level conditions and choices) in order to produce coherent and consistent scenarios that are relevant to policy makers at various scales. Implementation of the DECCMA multi-scale hybrid methods and participatory process presented in this working paper will provide a detailed worked example of application of such approaches and scenario development exercise. These two key aspects of the framework are further discussed in the following sub-sections.

3.2 Multi-Scale Hybrid Scenario Approach

The DECCMA project is investigating future impacts of and adaptation options, limits and potential in selected deltaic environments to current weather variability and extremes, as well as future climatic and societal changes. As discussed in previous sections, the project focuses on three contrasting deltaic systems of different size/scale: (i) the Volta (small) delta (Ghana), (ii) the Mahanadi (medium) delta (India), and (iii) the GBM (large) delta (Bangladesh/India). For example, the GBM river catchment is one of the largest transboundary river basins, with the total area covering more than 1.7 million sq. km. Its area is distributed over five neighbouring countries: (i) India (64%), (ii) China (18%), (iii) Nepal (9%), (iv) Bangladesh (7%), and (v) Bhutan (3%). This river system is the third world's largest freshwater outlet to oceans (after the Amazon and the Congo River systems) (Chowdhury and Ward 2004). Understanding the future dynamics and uncertainties of the potential impacts of future changes in climate and society on such complex coastal systems require an integrated and hybrid approach at multiple scales. Hence, assessment of the future of each of these deltas as well as a comparison across the three deltas requires envisaging a coherent future world within which each delta sit. In addition, it is important to recognise that the various climatic and socio-economic drivers of change that influence the deltas also originate and operate at multiple spatial and temporal scales, ranging from the global phenomenon (e.g., climate change and sea-level rise) to local scale (e.g., societal changes). In addition, the processes at the different scales may also depend on each other. For example, understanding which global or regional (sub-global) drivers of change are external factors to the national/sub-national or local systems is crucial in order to identify the key boundary conditions for developing appropriate responses and strategies. Furthermore, the various drivers at the different spatial scales have varying temporal scales, ranging from short-term (e.g., policy planning) to long-term (e.g., biophysical factors) changes. Recognising these multi-spatial and temporal scale scenario requirements, the DECCMA scenario framework integrated six discrete levels of scenarios at the various spatial scales of interest (i.e., global, regional (catchments, coastal seas, and political boundaries), national, and delta scales) and three broad temporal scales (i.e., socio-economic simulations up to 2050, biophysical simulations for 2050–2100, and sea-level simulations beyond 2100). A number of studies have highlighted the importance of such linking of scenarios across different scales (e.g., Biggs *et al.* 2007; Döll *et al.* 2002; Kok *et al.* 2007; Zurek and Henrichs *et al.* 2007). Furthermore, developing appropriate exogenous and indigenous scenarios at a particular scale requires use of such multi-scale hybrid scenario approaches, for example, for integrating the climate scenarios (RCPs), socio-economic scenarios (SSPs) and policy assumptions (SPAs) at the various scales. Hence, the multi-scale hybrid approach in DECCMA highlights the importance of maintaining the applicability, plausibility, and consistency of the various scenario combinations across the multiple scales of interest, ranging from global to local and short- to long-term, as appropriate.

3.3 Participatory Process and Multi-Stakeholder Engagement

The implementation of sustainable development goals under changing conditions requires appropriate engagement of various stakeholders at multiple levels. As outlined in Section 2.9, the DECCMA scenario approach also highlighted the concept of combining expert-based and participatory methods. It demonstrates the role of a systematic multi-stakeholder engagement process in the development of alternative adaptation policy trajectories for deltas that are both visionary and realistic to respond to future changes in climate and socio-economic drivers. The main purpose of the DECCMA scenario and participatory process was to integrate various complex strands of the project for developing appropriate multi-scale scenarios and policy trajectories. The concepts and methods used allowed to incorporating inputs of various experts (including technical country experts from each case study delta), views and priorities of (non-technical) stakeholders (e.g., policy/decision-makers) at multiple-scales, and integrated modelling approaches. Such approaches recognise the role of, and provide an important platform to capitalise on, local knowledge (e.g., on historic trends and existing policy directions) and bringing various (technical and non-technical) ideas together on how best to plan for and respond to the potential impacts of future climate and environmental as well as societal changes in deltas. Furthermore, the participatory approach takes into account the multi-scale scenario needs identified within the project. As such, it considers the latest RCP–SSP–SPA global scenario narratives and associated regional and national

scenario projections as boundary conditions in order to develop delta-specific policy trajectories and identifying associated list of specific adaptation interventions. This was achieved through the implementation of the integrated scenario framework that recognises the multi-dimensional nature of the scenario matrix architecture and the needs and challenges of stakeholders at multiple scales as outlined in Figures 5 and 23.

4. CONCLUSIONS

Globally, deltas are home for over half a billion people and they are one of the most vulnerable coastal environments during the 21st century. Coastal deltas are susceptible to multiple climatic factors (e.g., sea-level rise, storm surges) and socio-economic factors (e.g., human-induced subsidence, population changes, GDP growth). In addition, these drivers of change operate at multiple scales, ranging from local to global and short- to long-term. As a result, deltas face complex challenges in terms of both their long-term sustainability as well as the well-being of their residents and the health of ecosystems that support the livelihood of large (often very poor) population under uncertain future changing conditions. A holistic understanding of these challenges and the potential impacts of future climate and socio-economic changes is central for devising appropriate adaptation policies. Scenario analysis has long been identified as a strategic management tool to explore future climate change and its impacts for supporting robust decision-making under uncertainty.

This working paper presented the overall scenario framework and the concept and various methods and processes adopted for the development of the DECCMA scenarios. The scenario development process adopted here builds on and learns from the ESPA Deltas experience, recognising that DECCMA is a more complex scenario space. The scenarios will be used for analysing the future of three contrasting deltas in South Asia and West Africa: (i) the Ganges-Brahmaputra-Meghna (GBM) delta (Bangladesh/India), (ii) the Mahanadi delta (India), and (iii) the Volta delta (Ghana). This includes assessment and comparisons of the implications of future climate and socio-economic changes in terms of (i) the short- to medium-term socio-economic impacts (e.g., up to 2050), (ii) the long-term biophysical changes (e.g., up to 2100), and (iii) simulations of the implications of sea-level rise beyond 2100 across the three deltas. In order to achieve this, the scenario framework comprises a multi-scale hybrid approach, with six levels of scenario considerations: (i) global (climate change, e.g., sea-level rise, temperature change; and socio-economic assumptions, e.g., population and urbanisation changes, GDP growth); (ii) regional catchments (e.g., river flow modelling), (iii) regional seas (e.g., fisheries modelling), (iv) regional politics (e.g., transboundary disputes), (v) national (e.g., socio-economic factors), and (vi) delta-scale (e.g., future adaptation and migration policies) scenarios. Furthermore, the framework includes and combines expert-based and participatory approaches and provides improved specification of the role of scenarios to analyse the future state of adaptation and migration across the three deltas. It facilitates the development of appropriate and consistent endogenous and exogenous scenario futures: (i) at the delta-scale, (ii) across all deltas, and (iii) with wider climate change, environmental change, and adaptation and migration research. The scenario approach and framework presented in this paper could be transferred to other deltas and potentially to other coastal areas with multi-scale challenges.

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APPENDICES

Appendix A: *Catchment socio-economic scenarios based on economic assessment*

The socioeconomics introduced in the model are associated to the Shared Socioeconomic Pathways (SSPs) compatible, i.e., to be used alongside, with the 8.5 W/m2 Representative Concentration Pathways (RCP), which is being explored in DECCMA. We work with the 3 narratives (medium, medium+ of high economic growth, and medium- of low economic growth), which are inspired (respectively close to SSP2, SSP5 and SSP3, but with the closest features – such as agricultural productivity- to 8.5) and downscaled based on 3 of the set of 5 SSP storylines/narratives (O'Neill *et al*. 2011; 2014). Up to the year 2050, several SSPs may fall within the band of results compatible with the RCP8.5, and the 3 chosen narratives reach above 4W/m2 in 2050. For scenarios after 2050, even when all these narratives would lead to more than 6W/m2 in 2100, only one SSP (SSP5) seems clearly in line with this RCP (SSP5, associated to the highest growth, which also creates high emissions very soon, etc. (e.g., Edmonds *et al*. 2013; Riahi *et al*. 2016). In any case for the socioeconomics, it seems long-run enough to discuss about 2050, and hence the main projections on population, GDP, urban share, gender share, land use change, GHG emissions, energy costs, etc. are provided mainly up to 2050. Also, a few information is also detailed by the 2 Indian states (West Bengal and Odisha), e.g., for the population, GDP projections, etc., while for the projections which are not available at the deltas or state level (e.g., projections run for wider regions with a recursive dynamic partial equilibrium model (called Global Change Assessment Model, GCAM (Kim *et al*. 2006; Calvin *et al*. 2016; GCAM v4.3 2016, used for example by the IPCC), the general projections on the whole India had to be taken.

In particular, the socioeconomics data is based on the main IIASA projections of population (by age, sex, and education); urbanization; and economic development (GDP) (information about the scenario process and the SSP framework can be found in Moss *et al*. 2010; Arnell and Kram 2011; Arnell and Lloyd-Hughes 2014; Kriegler *et al*. 2012; van Vuuren *et al*. 2012). The population projections by Indian State are obtained from the scaling of the national projections of the SSPs with the scenarios given by PFI-RB (2007). The projections of GDP - PPP (billions of $US) by Indian state for the different SSPs are projected, deviating from the national average, based on the relation of the past 10 year average annual growth compared to that of the whole India (see MSPI 2016). As general trends, we may highlight that the projected GDP (Purchasing Power Parity, PPP, adjusted) (of 2005) for the whole of India is of US$3,885 billion in 2010, reaching in the medium scenario US$30,535 billion in 2050. In particular, the analogous info for the states of West Bengal (Hooghli river) and Odisha (Mahanadi delta) are of US$422 billion and US$179 billion in 2010, and reach in the medium scenario respectively to US$2,690 and US$1,530 billion in 2050. For Bangladesh, it is US$215 billion in 2010, and in the medium scenario US$749 billion in 2050, while for Ghana, US$30 billion in 2010 and in the medium scenario US$162 billion in 2050. These figures may almost double in the high growth scenario (narrative) for Bangladesh and Ghana (slightly less for India and the particular states studied). If GDP PPP growth ranges across these regions between 3% and 5.5% yearly average growth up to 2050, in terms of population it goes from the low projection for West Bengal and Odisha states (yearly average around 0.4%) up to 2050 (point at which even slower growth rate is projected from then on) to around 1.6% yearly average growth up to 2050 for Ghana (being of 0.7% for Bangladesh and 0.9% for the whole India). The lowest population growth projected for Odisha and highest GDP PPP growth (the cited 5.5% yearly average growth up to 2050) projects clearly the highest GDP PPP per capita growth. Another startling fact is that in the baseline scenario the urban share of Ghana is 51% already (compared to the 28% and 30% of Bangladesh and India), being projected to reach around 70% in 2050 in the medium scenario, while the other two countries would reach this share only under the fast growth scenario (in the medium narrative they will reach in 2050 the current urbanization share of Ghana, with 51% and 53% respectively for Bangladesh and India).

Another important group of results obtained from our runs for the different SSPs for this hydrological model are the long-term global scenarios for changes on agricultural production changes, on land use allocation, industrial outputs, energy uses and on air pollutant emissions consistent with the above scenarios. An assessment and comparison of the results on air pollution emissions by 6 different integrated assessment models, which shows that GCAM provides results similar to the average of all the other models (e.g., can be found in Rao *et al*. 2016). The importance of these results on agricultural production, land use change, industrial output, energy uses and emissions that we obtain with our GCAM-DECCMA (the runs with SSPs

implemented in GCAM but twisted to account, e.g., for agricultural productivity changes as related to RCP8.5) is key for the hydrological model.

General patterns that emerge from the socioeconomic scenarios for these variables have to do with the fact that in the medium, and especially in the medium+ (high growth) scenario, the structural change in which the industrial production and especially services increase are more marked. This leads (somehow paradoxically) to more moderate pressures on water from the side of irrigation, which are on the contrary much higher in the medium- (low growth) scenario. In the medium+ scenario though, the improvements in the available technology (more "industrialized" production processes) and capability of advanced agricultural production does not reduce in most of these areas the agricultural land allocation and agricultural production. Furthermore, this high growth scenario leads to some relevant increases in water demands from energy and electricity plants and sources. On the other hand, this medium+ scenario, which shows the highest GDP PPP, and less population growth (especially in India the peaks of population, and high GDP levels are reached earlier on), derives less pressure on the household water demands and much further capabilities and desires for higher quality of life, including much more coastal protection (much necessary given the increasing greenhouse gas emissions and radiative forcing trends), water and sanitation systems, developing water treatment plants, and new sewage treatment plants. In the case of the medium- (low growth scenario), the major pressures come from irrigation (with a more traditional management) but also from the unstopped population increases, having also less possibilities for higher quality of life, in terms of coastal protection, water and sanitation systems, and treatment plants.

Looking at the results of the socioeconomic scenarios for these variables, in particular we find that in India out of 3 million km2 (or 300 million hectares) of land, slightly less than half is cropland area sown. In the medium scenario this type of land slightly decreases, a bit more than 2% in 2050 from current levels.

In Ghana out of 200 thousand km2 (or 20 million hectares) of land, about 30% is cropland area sown (about another 30% of forest area, and about 40% Permanent pastures & other grazing land). In the medium scenario this type of land slightly decreases in general in Western Africa, a bit more than 2% in 2050 from current (2010) levels. In Bangladesh out of 150 thousand km2 (or 15 million hectares) of land, close to 2/3 is cropland area sown (about another 30% of forest area, and about 5% Permanent pastures & other grazing land, i.e., like in India, much less than in Ghana). In the medium scenario this type of land slightly decreases in general in South Asia, almost 4% in 2050 from current levels. In the medium- (low economic growth) scenario, cropland use increases in the 3 countries, notably in South Asia (e.g., in India 6.7% increase in 2050 from 2010 levels). Implicitly in these results we are under the estimates that the transitions from important shares of agriculture in the economies to lower ones while higher ones in the industrial and services sectors do not take place as clearly as in the other 2 scenarios. The high growth scenario does not give a clear-cut answer for the 3, probably given that productivity, technical change and agricultural production increase, and it may be profitable to have more "industrialized or technified" agricultures for these economies, but cropland allocation may be also reduced due to the expected structural change for these economies. As hinted, pastureland in general is a relevant allocation of land for the 3 areas, and what emerges consistently in all the 3 scenarios is that the part that is grazed pastureland (a small share of total land in 2010 for these areas, between 0.5% and 2%) it is the allocation that increases the most in percentage terms, especially in the medium- (low economic growth) scenario. Taken together the changes of cropland allocation (reduction in the medium scenario) and grazed pastureland allocation (increase in all the scenarios) in India this joined land allocation is reduced in 2050 (-1.3%) from 2010 levels in the medium scenario, and increased in the low and high growth scenarios (respectively 8.2% and 3.7%). For the other 2 areas, this joined land allocation slightly increases in the medium scenario and again does it a bit more in the high growth scenario and even more in the low growth scenario. Aquaculture land allocation is projected to grow the most in the high economic growth scenario (with more industrialized production, fishmeal, etc.), following current trends such as the almost exponential increase in Bangladesh (so far opportunistic in terms of meal for the fish, using frequently larvae as inputs, etc.) or the very recent increases in nurseries in Ghana.

Still, despite the cited reduction in cropland allocation (e.g. in the medium scenario), agricultural production is expected to grow in the 3 countries, in particular in the medium scenario for India, Western Africa and South Asia, by 23%, 78% and 66% in 2050 from 2010 levels. In the highest growth scenario, these percentage changes are slightly higher, respectively, 25%, 94% and 78%. Interestingly again it is in the low economic

growth scenario when these increases in agricultural production are projected to be the highest for the 3 countries (less marked for India, being respectively, 33%, 130% and 102% changes in 2050 from 2010 levels), under the estimates that the structural change or agricultural transitions described do not take place as clearly as in the other 2 scenarios. Water demands are expected then to increase not only due to the higher industrial production, but also due to increased agricultural production. Water intense crops such as rice are expected to increase (except in general in the rest of South Asia) both in India and in Western Africa in the 3 scenarios more than in general the agricultural production (hence with an even more important share). In particular, in the medium scenario, for India, Western Africa and South Asia, it increases respectively by 57%, 82% and 59% in 2050 from 2010 levels. Comparing the changes of cropland allocation (reduction in the medium scenario) and grazed pastureland allocation (increase in all the scenarios) and these much notable increases in agricultural production, it can be clearly seen the implicit expected agricultural productivity increases.

N fertilizer use (including imports) increases for India in the medium scenario around 55% in 2050 (from 2010), slightly more (58%) in the medium+ (high growth) scenario and even more (64%) in the medium- (low economic growth) scenario.

Regarding the total Final energy consumption (measured in EJ), the three scenarios rank equal to the growth path, i.e., the medium- (low economic growth) scenario has the lowest increases, and the medium+ (high economic growth) scenario has the highest increases. The percentage increases in India are projected to be among the lowest (departing from a started increased energy consumption) but still around 400% increase in 2050 from 2010 levels in the medium scenario, reaching 456% increase in the medium+ (high economic growth) scenario.

Regarding (especially CO_2) greenhouse gas emissions, quite expectedly also the three scenarios rank equal to the growth path, i.e., the medium- (low economic growth) scenario has the lowest increases, and the medium+ (high economic growth) scenario has the highest increases. The percentage increases in India are projected to be among the lowest (departing from a started increased energy consumption) but still around 368% increase in 2050 from 2010 levels in the medium scenario, reaching 572% increase in the medium+ (high economic growth) scenario. This means that compared to the energy use, the CO_2 emissions notably increase but less than the energy consumption in the medium scenario (expected technological –less emissions intensities- improvements and transitions from coal and fossil fuel based to more renewables, such as now the current efforts in solar energy, etc., something which also occurs to some extent in the medium- scenario). But the increases in emissions are expected to be higher than the energy use in the high growth scenario, meaning that this scenario, which leads to 4.8W/m2 in 2050 and to 8.1W/m2 in 2100, implies notable uses of fossil fuels and industrial productions with high emissions which not only do not reduce the emissions per EJ of energy consumption, but increases it.

Regarding some key emissions related to Nitrogen, which also relates to the water quality aspects, in Western Africa, while N2O is expected to increase more from sheeps, goats and beef, the industrial increase of NOx is expected to come mostly from the continuation (even slight decrease) of that of Unmanaged Land (the current highest contribution) and the increase in process heat cement. In India, the N2O currently (year 2010) comes already more from Dairy (0.13Tg in 2010), followed by Sugarcrop production (0.11Tg in 2010), miscellaneous crops, rice and industrial processes (0.8Tg, 0.7Tg, 0.6Tg in 2010). The major increase up to N20 is expected to occur clearly from this last one, the industrial processes (0.35Tg in 2050), followed by Dairy (0.27Tg in 2050), while also somehow from some increase from rice and miscellaneous crops. The N2O from fodder_grass and from electricity is expected to markedly increase as well, while the N2O from Sugarcrop production and other like from residues are expected to decrease. The increase of NOx is expected to come mostly from the continuation of expansion of the major cause, the electricity (3.3Tg in 2010 and 6Tg in 2050), followed by some other smaller causes such as the industrial energy use (0.45Tg in 2010 and 0.90Tg in 2050), N fertilizer (stable 0.54Tg across the period) and process heat cement (0.16Tg in 2010 and 0.59Tg in 2050). The transport_freight by road, which is currently the 2nd cause of NOx is expected to notably decrease. In South Asia, the N2O currently comes mostly from rice production, and it is expected to slightly increase, while notably increase far more from industrial processes, followed by some other such as Dairy and beef production. The increase of NOx is expected to come mostly from the continuation of expansion of the major cause, the electricity, followed by some other smaller causes such as the transport_freight by road, the Unmanaged Land and the aviation.

Appendix B: *Fishing scenarios: The concept of Maximum Sustainable Yield (MSY)*

Fishing scenarios are considered in relation to the concept of maximum sustainable yield (MSY). MSY is defined as the highest average theoretical equilibrium catch that can be continuously taken from a stock under average environmental conditions (Hilborn & Walters 1992). Based on a simple logistic population growth function and under equilibrium conditions, fishing at MSY level can be defined as:

$$F_{MSY} = intR / 4$$

where intR is the intrinsic rate of population increase. In our application, the intR values are calculated based on natural mortality (Pauly 1980; Cheung *et al*. 2008) as:

$$intR = c * M$$

where c is a constant that commonly ranges between 1 and 3. Natural mortality rate (M) was estimated from an empirical equation (Pauly 1980):

$$M = -0.4851 - 0.0824 * log(W_{inf}) + 0.6757 * log(K) + 0.4687 * log(T)$$

where W_{inf} is asymptotic weight, K is the von Bertalanffy growth parameter and T is the average water temperature in the animal's range.

This is an approximation and not as reliable as estimates of biomass using survey-based methods (Pauly *et al*. 2013). However, these estimates have proven to be significantly correlated with those from aggregated stock assessments (Froese *et al*. 2012; Fernandes *et al*. 2013a).

Fishing mortality (F_m) scenarios are defined by comparing F_m estimates for the considered species from the literature with the calculated F_{MSY}. We consider three fishing mortality scenarios to provide fish catch and biomass projections as follows:

a) Sustainability scenario (MSY): Fishing effort consistent with average F_{MSY}. This is the value that results in maximum catches while maintaining the population at their productivity peak.

b) Business as Usual scenario (BaU): Fishing mortality consistent with the average of recent estimates of F_m (F_{BaU}).

c) Overfishing scenario (F_{OF}): Corresponds to a scenario where management is not a constraint to the fishery.

Appendix C: *Main questions and elements of the expert-based questionnaire used to obtain expert insight for development of the regional and national socio-economic scenarios in DECCMA.*

2005	2010	2015	Questions	2010	2020	2030	2040	2050
			Delta_urban share					
			Country_urban share					
			Delta_population levels					
			Country_population levels					
			Delta_yearly nominal GDP growth					
			Country_yearly nominal GDP growth					
			Delta_yearly "real" (Purchasing Power Parity, from 2010) GDP growth					
			Country_yearly "real" (PPP, from 2010) GDP growth					
			Delta_Agricultural share in GDP					
			Country_Agricultural share in GDP					
			Delta_Industrial share in GDP					
			Country_Industrial share in GDP					
			Delta_Services share in GDP					
			Country_Services share in GDP					
			Delta_level of Labour wages					
			Country_level of Labour wages					

			Delta_Capital income share (vs. the labour share)					
			Country_Capital income share (vs. the labour share)					
			Delta_% of enrolment in Secondary education					
			Country_% of enrolment in Secondary education					
			Delta_% of enrolment in Tertiary education					
			Country_% of enrolment in Tertiary education					
			Delta_levels of Female education enrolment					
			Country_levels of Female education enrolment					
			Delta_levels of inequality					
			Country_levels of inequality					
			Delta_agricultural land use quantities (1000 hectares)					
			Country_agricultural land use quantities (1000 hectares)					

Figure below shows the country level population and GDP projections (and composition) obtained from the expert-based questionnaire for Ghana, India, and Bangladesh. As stated in Section 2.9, these projections match quite well with IIASA's projections of the SSP2 scenario, highlighting the experts' vision as a medium scenario.