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The socioeconomic future of deltas in a changing environment

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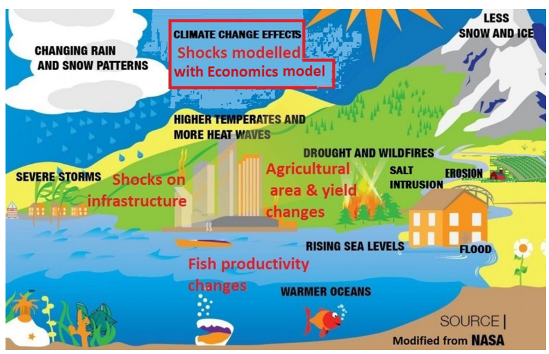
HIGHLIGHTS

- Biophysical (several models)-socioeconomics (CGE) link established through models.
- Key parameters are the rates (interest, depreciation) and trade assumptions.
- Cumulative GDP pc ↓ ~2.1% with Climate change shock (CChS) on crops for Mahanadi.
- Cumulative GDP pc ↓ ~10% (↓ 0.27% India) with CChS on crop+ fishery + infrastructure.
- Effective adaptation options of seeds & fertilizers, cyclone shelters and embankments.

GRAPHICAL ABSTRACT



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ABSTRACT

Deltas are especially vulnerable to climate change given their low-lying location and exposure to storm surges, coastal and fluvial flooding, sea level rise and subsidence. Increases in such events and other circumstances are contributing to the change in the environmental conditions in the deltas, which translates into changes in the productivity of ecosystems and, ultimately, into impacts on livelihoods and human well-being. Accordingly, climate change will affect not only the biophysical conditions of deltaic environments but also their economic circumstances. Furthermore, these economic implications will spill over to other regions through goods and services supply chains and via migration. In this paper we take a wider view about some of the specific studies within this Special Issue. We analyse the extent to which the biophysical context of the deltas contributes to the sustainability of the different economic activities, in the deltas and in other regions. We construct a set of environmental-extended multiregional input-output databases and Social Accounting Matrices that are used to trace the flow of provisioning ecosystem services across the supply chains, providing a view of the links between the biophysical environment and the economic activities. We also integrate this information into a Computable General Equilibrium model to assess how the changes in the provision of natural resources due to climate change can potentially affect the economies of the deltas and linked regions, and how this in turn affects economic vulnerability and sustainability in these regions.

1. Introduction

Mid- and low-latitude deltas are home for over 500 million people globally and have been identified for several decades as one of the

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most vulnerable coastal environments in the 21st century (Milliman et al., 1989)(De Souza et al., 2015; Ericson et al., 2006; Myers, 2002; Syvitski et al., 2009). They are vulnerable to multiple climatic and environmental drivers such as sea-level rise, storm surges, subsidence, changes in temperature and rainfall. These drivers of change operate at multiple geographical and temporal scales (Nicholls et al., 2016). Furthermore, their evolution is also affected by socioeconomic factors including, among others, economic activity, lifestyles, urbanisation trends and land use change and demographics. These complex challenges and potential impacts for populations and their livelihoods (Day et al., 2016; Szabo et al., 2016; Tessler et al., 2015) require a holistic understanding for planning appropriate adaptation policies (Chapman and Tompkins, n.d.; Haasnoot et al., 2012; Kwakkel et al., 2015).

In this context, DECCMA (DEltas, vulnerability, and Climate Change: Migration and Adaptation), as already introduced in this Special Issue by (Hill et al., 2018) and (Kebede et al., 2018), is a large multi-disciplinary research project which addresses these challenges within three case-study deltas in Asia and Africa: the world's largest delta – the Ganges-Brahmaputra-Meghna (GBM) in Bangladesh and India; the Volta in Ghana and the Mahanadi in India. The maps of these study sites are shown in Fig. A1 in the Appendix A (SM).

One of the main goals of DECCMA is the integration of biophysical, socioeconomic and vulnerability hotspot modelling of future migration and adaptation within and across the case study deltas (Lazar et al., 2015), under different future climatic, socioeconomic and adaptation scenarios[1] (Kebede et al., 2018).

The integrated modelling framework of DECCMA is summarized in the editorial of this Special Issue (Hill et al., 2018) (see also Fig. S1 of the Supplementary Material, SM). It consists of a set of models operating in different spheres that are used to analyse the impacts of climate change in deltas and to evaluate different adaptations options, with special emphasis on migration. For example, in the climatic sphere the CORDEX and PRECISE models are used to downscale the RCP scenarios (Jin et al., 2018) and produce climatic parameters that are used by other models of the integrated framework. The INCA model (see (Whitehead et al., 2015a, 2015b), and (Whitehead et al., 2017) in this Special Issue) is used for estimating the future evolution of key horological parameters. This information is further used by the FAO/AEZ (Agro-Ecological Zoning) model (Fischer et al., 2012) -which evaluates future crop potential production- and the POLCOMS-ERSEM biogeochemical mode- which focuses on the potential for fish production (Blanchard et al., 2012).

In the economic sphere, within DECCMA we have developed for each delta a dynamic Computable General Equilibrium (CGE) model (Delta-CGE) that interacts at several stages with the biophysical models of the integrated framework. The Delta-CGE model acts as an interface between the climate and biophysical models and the integrated model of migration, in the sense that it translates the biophysical impacts of climate change (e.g. reduction of crop productivity) into key socioeconomic drivers of migration (e.g. changes in wages). It is important to highlight that the Delta-CGE model does not seek to directly translate changes in climatic conditions into migration flows. Rather, it aims to take advantage of the biophysical models to capture the impacts of climatic changes on some critical variables affecting specific economic processes, and translates them into economic impacts. This information is further passed to the Integrated System Dynamics model and Bayesian Network model (Lazar et al., 2015)(Lazar and Al, 2017) where, in combination with the outputs of other models, it is used to assess the impact of climate change on human wellbeing and to evaluate different coping strategies. At the same time, partial assessments of these integrated models provide the Delta-CGE with an ex-ante exogenous default set of migration figures.

In this context, the main goal of this paper is to introduce the framework used in DECCMA to assess how different scenarios affect the economic outcomes in the delta and how these in turn affect vulnerability and sustainability in the region. This framework is innovative in several ways: 1) for the first time Social Accounting Matrices (SAMs) for deltaic areas have been constructed and used within a CGE model; 2) this CGE model has been linked to different biophysical models in order to assess the expected economic impacts of climate change under different scenarios, including information on the costs of extreme events, and costs/benefits of adaptation options. We apply the framework to the Mahanadi delta (MD)[2] in order to how it can be used to assess the socioeconomic future of deltas in a changing environment.

The remainder of the article is organized as follows. In Section 2 a literature review on linking biophysical and economic models is provided, with special focus on CGEs, and introduces the new Delta-CGE model that has been developed to analyse the economic impacts of climate change in deltas. Section 3 introduces the scenario framework. Section 4 presents the results of using the Delta-CGE to analyse the economic future the MD under different climatic and socioeconomic scenarios. Section 4 presents the results of using the Delta-CGE to analyse the economic future the MD under different climatic and socioeconomic scenarios. Finally, Section 5 discusses the results and concludes.

2. Materials and methods

2.1. Linking biophysical and economic models to assess impacts of climate change

From an economic perspective, the analysis of the impacts of climate changes is challenging. First, it requires a deep understanding of the functioning and interactions of complex socioeconomic and natural systems.[3] Second, the analysis of the economic impacts is plagued with uncertainties arising from the knowledge gap in natural and social systems. Finally, in most cases, these analyses focus on the impacts of future climatic and socioeconomic trajectories and, therefore, have the uncertainty inherent to these trajectories. Different approaches have been traditionally used to assess the socioeconomic impacts of climate change and to link biophysical and economic spheres, such as Integrated Assessment Models, CGEs, partial equilibrium models or social cost/damage functions (Burke et al., 2015; Ciscar et al., 2010; Islam et al., 2016). A review of and information from previous studies on the biophysical and economics link is provided in Appendix A. In DECCMA, the integrated analysis is performed following a transdisciplinary, multi-method and multi-model approach.

The suite of models plays a key role in the process of understanding the environmental and socioeconomic implications of climate changes, informing adaptation options and interacting with stakeholders. In this sense, the link between the biophysical and economic models is critical to provide a consistent vision of the futures in the deltas. Fig. 1 shows main relations between the biophysical models (and modelled impacts of climate change) and the Delta-CGE model.

Starting from the top in Fig. 1, we see the large-scale general circulation models (GCMs) which have been used to simulate climate across the region and to assess the impacts of increasing greenhouse gas concentrations on the global climate system.[4] These provide a starting

[1] Scenario analysis has long been identified as a strategic management tool to explore future changes and associated impacts for supporting adaptation decision-making under uncertainty. Scenarios represent coherent, internally consistent, and plausible descriptions of possible trajectories of changing conditions based on 'if, then' assertion to develop self-consistent storylines or images of the future (Moss et al., 2010; O'Neill et al., 2014).

[2] The DECCMA definition of the Mahanaid Delta includes the districts falling within the 5 m high contour: Puri, Kendrapara, Bhadrak, Jagatsingpur and Khurda.

[3] Climate change affects directly or indirectly many different economic activities. For example, in the case of agricultural sector, the main impacts of include increasing demand and competition for natural resources as well as biotic and abiotic stresses, together with geographic and temporal variability also add complexity (Islam et al., 2016).

[4] GCMs typically have coarse spatial resolutions with horizontal grid boxes of a few hundred kilometres, and cannot provide the high-resolution climate information that is required for climate impact and adaptation studies.

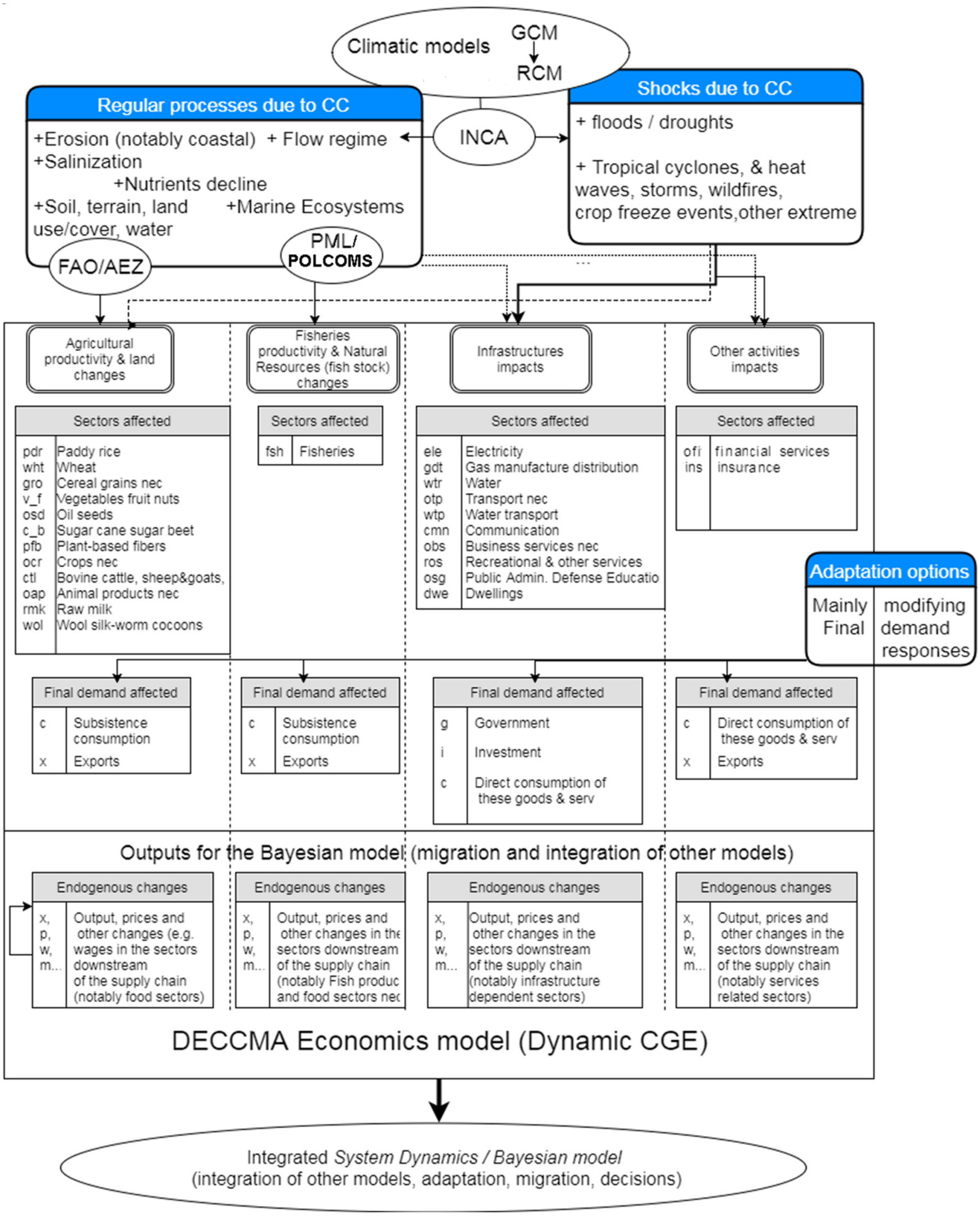

Fig. 1. Main relations of the biophysical effects of Climate Change and Socioeconomics (Delta-CGE) model.
Source: Own elaboration.

point for the regional climate models (RCMs), which dynamically downscale the results of the simulations with the GCMs.[5] CORDEX and PRECISE have been used by the UK Met Office to downscale the results for Africa and South Asia respectively (see Macadam et al., 2017 in this Special *i*ssue).

The set biophysical models take as inputs different outputs from the climate models provide. The INCA hydrological model serves to generate information on biophysical processes and ecosystems taking information form the climatic models. The model also makes use of some hypothesis on future evolution of human-driven drivers with influence in hydrological processes such as population, public water use, effluent discharge, water demand for irrigation and public supply, land use change, atmospheric deposition or water transfer (Whitehead et al., 2017). The results of the INCA model are further used by the crop and fisheries models described below.

The FAO/AEZ (Agro-Ecological Zoning) modelling (Fischer et al., 2012; IIASA, 2018) is a comprehensive framework accounting for climate, soil, terrain and management conditions matched with specific crop requirements under different input levels and water supply. It provides a georeferenced database at 1 km resolution of crop suitability and

[5] Using boundary conditions from GCMs, and providing resolution grids of around 50 km or smaller, typically representing better features such as local topography and coast lines and their effects on the regional climate, such as rainfall.

Table 1
Variables from other model components mapped to the variables of the CGE model.

Model	Variable in model	Variable in CGE
POLCOMS-ERSEM (PML)	Fisheries catch and output (physical, i.e. tons, and monetary, $, for the baseline) and endowment (physical units)	Fisheries output (monetary terms) and natural resources (fisheries cell) endowment (natural resources availability, in physical units)
	Productivity change of fisheries (%, yearly up to 2050)	Fisheries output change of (yearly up to 2050)
FAO/AEZ	Cropland used and available area (ha, Baseline data)	Cropland coefficient (use) and land endowment (Baseline data)
	Cropland area potentials (ha, yearly up to 2050)	Cropland endowment change (yearly up to 2050)
	Crop output potentials (tons, yearly up to 2050)	Crop output change (yearly up to 2050)

Source: Own elaboration.

potential productivity for current (baseline conditions averaged over 30 years of observations) and future scenarios for major crops. From the economic perspective, the key output from the model is the evaluation of current and future land suitability and the estimation of crop yields, potential production and ecosystem services.

The POLCOMS-ERSEM biogeochemical model is used to drive a dynamic marine ecosystem model that explicitly accounts for food web interactions by linking primary production to fish production through predation. The model estimates potential for fish production by size class, taking into account temperature effects on the feeding and intrinsic mortality rates of organisms (Blanchard et al., 2012). Hence it can make climate-driven projections of changes in potential fish production. Size-based methods like this capture the properties of food webs that describe energy flux and production at a particular size, independent of species' ecology (Barange et al., 2014). It also incorporates species interactions based on size-spectrum theory and habitat suitability (Barange et al., 2013; Fernandes et al., 2017, 2016). Productivity changes then are also derived for three GCMs in each delta.

As it can be seen in Fig. 1, biophysical models produce information on the effects of changes in the environmental conditions on some parameters such as crop yield, land availability or fisheries productivity that affect the economic system. In this regard, the biophysical models serve as the between climatic models and the economic model.

Data from the biophysical models, together with information on climate-related shocks directly affecting the economic systems (e.g. damages in infrastructures due to floods) and adaption options are used by the Delta-CGE model to analyse the economic implications of climate change in the deltas. Specifically, Table 1 shows the links between the variables of the biophysical models and the Delta-CGE model. Next, we describe in detail the Delta-CGE model.

2.2. The Delta-CGE model

The economic approach in DECCMA develops and makes use of a comprehensive dataset, assembled in the Social Accounting Matrix (SAM), and a flexible model in the form of a dynamic Computable General Equilibrium adapted to the delta level (Delta-CGE).[6]

The SAM represents the economic transactions between all institutional agents (Households, Government, Firms and "Rest of the World") that take place within an economy. SAMs were created to identify all monetary flows from sources to recipients, within a disaggregated national accounting system. The economic information of the SAM is integrated into the Delta-CGE model which is further used to analyse how the economy might react to changes in external factors.

CGE models are descended from the input-output (IO) models, but with more flexible structures, especially in the production and consumption blocks. Thus, where a classical Leontief demand-driven IO model (Leontief, 1937, 1936) assumes for example, that a fixed amount of production factors, such as labour or capital, is required to produce 1 unit worth of a product, a CGE model allows for some substitution across factors which is influenced by their costs (e.g. wages and interest rates). The equations then tend to be inspired by neoclassical economics, often assuming cost-minimizing behaviour by producers, average-cost pricing, and household demands based on optimizing behaviour. However, most CGE models conform only loosely to the theoretical general equilibrium paradigm. In particular, they allow for non-market clearing, especially for labour (unemployment) or for commodities (inventories), imperfect competition (e.g., monopoly pricing) and for demands not influenced by price (e.g., government demands) (see (Mitra-Kahn, 2008) for a review of their historical development, and debunking some of the misunderstandings or myths around them).

Appendix B presents the Delta-CGE model in more detail, and Figs. B1–B3 provide a graphical exposition of the production structure. Production is represented by three-level Constant Elasticity of Substitution functions (see Rutherford, 2002) including the inputs of capital (K), labour (L), energy (E) and other intermediates (M). Substitution elasticities between factors are obtained from (Koesler and Schymura, 2015). In Fig. B "Scheme of the elasticities" in Appendix B the scheme is illustrated, and a more in depth review, and discussion on the functional forms, elasticities and key parameters of CGEs for sensitivity testing is provided in the Appendix C.

As suggested by many growth models (Domar, 1946; Harrod, 1939; Romer, 1986; Solow, 1956; Swan, 1956) savings and, subsequently, investments are the major determinants of long-term economic growth. Our dynamics of capital accumulation equation follows (Dellink et al., 2004). The rate of return on investments is determined on the domestic market, the capital stock and investment levels are fully endogenised, and households decide the share of their income that is saved. These savings in turn are used by the producers for capital investments and the rate of return on investments equals the exogenous interest rate. The forward-looking behaviour of the agents and the endogenous savings rate make this a model of the (Ramsey, 1928)-(Cass, 1965)-(Koopmans, 1965)- type (see (Barro and Sala-i-Martin, 1995; Carroll, 2017; Heijdra, 2016)). Total factor productivity growth is introduced, and adjusted to differentiate among agriculture, industry and services, to reflect structural changes, as projected from the expert information obtained from the questionnaires (see more in Appendix B and Fig. B1).

Within the dynamic Delta-CGE model, the sets of labour types are divided as formal (related to the urban employed) and informal (more related to the pool of labour from rural areas that does not have a "regular" job, either temporally or permanently). The model assumes different wages for the different types of labour and two additional constraints are added to the Delta-CGE model. The first is the "unemployment" constraint determining the relative price of the formal labour. The second is the "mobility rate" constraint, which also determines the relative wage of the informal labour to the formal labour, and which hence establishes to what extent people will move due to an expected higher wage in the urban area (i.e. the non-delta area). Finally, migration equations also take into account that, due to several costs, migration does not occur when the difference between the "expected wages" are not large enough, and that mobility does not occur if the initial wealth is not enough to cover migration costs (Lazar and Al, 2017; Safra de Campos and Al, 2017a, 2017b).[7]

[6] Numerically, the model is implemented in GAMS software (Brooke et al., 1996) and solved using PATH (Dirkse and Ferris, 1995).

[7] The main reason for migration claimed (by the majority of respondents) is "search for employment". In the Mahanadi also the reason of join spouse/marriage is very important (around 20% of respondents), slightly above the reason of education. There is also a positively correlation in the migrant sending households with high in vulnerability (35%), being female headed household (13% of all), who furthermore takes further responsibility with the typical male migration.

Apart from the search of data for all these components, and especially for the calibration of the model, within the economic modelling literature, and in particular in that of CGEs, sensitivity analyses tests are partially conducted. Very rarely though are these done in a comprehensive way (typically rather in a discrete way with a few variations) through Monte-Carlo simulations, with multiple combinations of values of parameters, as has been done here. In this study we have explored wide ranges of possible values for the parameters according to recent literature. A more in-depth discussion on the functional forms, elasticities and key parameters of CGEs for sensitivity testing is provided in the Appendix C.

The database for the Delta-CGE model has been compiled from many sources and combines official statistics with own estimations. As mentioned before, the IO tables of the deltas and associated SAM constitute the core data of a Delta-CGE model (see (Arto and Cazcarro, 2017) and (Arto et al., 2018). Appendix E ("IO and SAM elaboration") describes the process of obtaining the SAM tables in DECCMA. The main sources of information were different Regional/District datasets and analytical reports, such as the census, specific information from industrial, agriculture and fisheries statistics in terms of production, value added, employment, factor uses, intermediate consumption and final demand. In the case of MD, these sources were the Primary Census and the Odisha Economic Surveys and agricultural statistics (GoO, 2016, 2015; PCA, 2011). Employment by district and gender (male/female) for the main 12 activities/sectors[8] were compiled and further split into 57 sectors. At the national level, some small corrections were applied to the employment data in order to obtain consistent wages. Other key data for the construction of the database, in particular for the agricultural sector, are the agricultural land use, crop and animal production, prices, data of livestock and fisheries stock and catches.

3. Scenario framework

3.1. General overview

(Kebede et al., 2018), in this Special Issue, describe in detail the scenarios framework of DECCMA, which is based on the new global scenario framework developed for the Fifth Assessment Report (AR5) of the IPCC. The framework provides a foundation for an improved integrated assessment of climate change impacts and adaptation and mitigation needs under a range of climate pathways, socioeconomic scenarios, and adaptation and mitigation policy assumptions. For each of these three spheres the scientific community has developed a set of quantitative and qualitative narratives, namely Representative Concentrations Pathways, RCP (van Vuuren et al., 2011), Shared Socioeconomic Pathways, SSP (O'Neill et al., 2014) and Shared Policy Assumptions, SPA (Kriegler et al., 2014).

From the climatic perspective, DECCMA focuses on the RCP8.5 scenario in order to consider the strongest climate (a 'high-end') signal, which shows the highest concentration of greenhouse gas concentrations in the late 21st century. RCP 8.5 simulations (with three GCMs for each delta[9]) represent a worst-case end of the 21st century projected temperature increases and atmospheric CO_2 concentrations. In the case of the FAO/AEZ the outputs are provided under climate scenario ensembles (ENS, that is to say, synthesized results from combinations or averaging results from the different GCMs considered for each delta).

Up to 2050 the RCP8.5 was judged to be capable of being combined with practically any SSP (see (Riahi et al., 2017)), as high divergence of forcings from the different RCPs occur mainly beyond 2050s. However, after 2050 only SSP3 and SSP5 can produce the required emissions, although SSP2 is close. Fig. 5 in (Kebede et al., 2018) presents a summary of the selected RCP and SSP scenario combinations and associated time horizons considered for assessing different socioeconomic and biophysical components of the delta systems investigated within DECCMA.

SSP3 presents a world of Fragmentation/Regional Rivalry (*High mitigation and adaptation challenges*), SSP5 presents a Conventional/Fossil-fuelled Development (*High mitigation and low adaptation challenges*), and SSP2 is known as the Middle of the Road (*Intermediate mitigation and adaptation challenges*). Based on this three SSP, in DECCMA three SSP-based scenario narratives have been identified up to 2050: Business as Usual or Medium (~SSP2), Medium− (~SSP3) and Medium+ (~SSP5). These narratives are then used to downscale the global projections to regional and national levels, and to inform the development of the participatory-based delta-scale scenarios and adaptation policy trajectories up to 2050.

It is important to highlight, that in the simulations, all these scenarios are considered as "baseline" scenarios, in the sense that they assume that there is no climate change. In other words, climate change shocks are simulated "on-top" of these three scenarios and the resulting economic effects are analysed in terms of differences with respect the baseline scenario.

At the national scale, the socioeconomic scenarios for the three countries (Ghana, India, and Bangladesh) are based on the *SSP Public Database Version 1.1*.[10] This database provides historic trends and future projections of the changes in population, share of population in urban areas, and GDP in power purchasing parities (PPP) through the 21st century for each country under the five SSP scenarios (Fig. 7 in Kebede et al. (2018)). Together, these data are used as one of the boundary conditions to inform the development of the delta-scale scenarios, that were developed with the support of experts through questionnaires.

GDP is one of the few economic measures which are numerically estimated and projected for the different SSPs different futures.

Fig. 2 shows the ranges of paths of growth of the GDP per capita for the India and the MD for the different SSPs. We may observe how the gap between the regions increases over time, something which contributes to increase out migration from the delta.

Apart from the RCPs and SSPs, a number of adaptation policy trajectories (ATPs), inspired in the SPA, are also taken into account in order to provide a complete view of the possible futures in the deltas. Indeed, these futures may be radically different depending on the adaption pathways selected. This leads us to an approach in DECCMA, as schematized in Fig. A3 in the Appendix A (reproduced from (Kebede et al., 2018)), linking the RCPs, SSPs and APTs.

3.2. From general scenarios to biophysical impacts

Once the RCP8.5 is implemented in the GCM and the results downscaled with the support of the RCM, the resulting climatic parameters for the case study areas are passed to biophysical models which report the impacts of climatic change in a number of variables related to crop production and fisheries.

In the case of the FAO/AEZ, Fig. 3 reports cropland production potentials for the two climate scenario ensembles (ENS) as well as cropland area, which includes the very suitable (>85%), suitable (55–70%) and moderately suitable (40–55%) (IIASA, 2018). The main simulated shocks ("CC_Agr" shock) to 2050 follow these potential reductions in yield, which in the case of the delta of focus here, the MD,[11] is 5% at the end of the period with CO_2 fertilization and 16% without it, and

[8] Cultivators; Agricultural labourers; Plantation, Livestock, Forestry, Fishing, Hunting & allied activities; Mining & Quarrying; Manufacturing; Electricity, Gas & Water Supply; Construction; Wholesale & Retail Trade; Hotels & Restaurants; Transport, Storage & Communications; Financial Intermediation, Real Estate, Renting & Business; Public Administration, Other Community, Social & Personal Services, Private Households Employing Persons.

[9] Using the French GCM, CNRM-CM5, and the UK GCM, HadGEM2-ES, both for Africa and South Asia. Then for South Asia (see (IIASA, 2018)) it is also used the German GCM, GFDL-CM3, and for Africa the CanESM2.

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

[11] The MD, like the GBM Delta, is fed by three rivers, the Mahanadi, Brahmani, and Baiterani, which drain into the Bay of Bengal on the east coast of India.

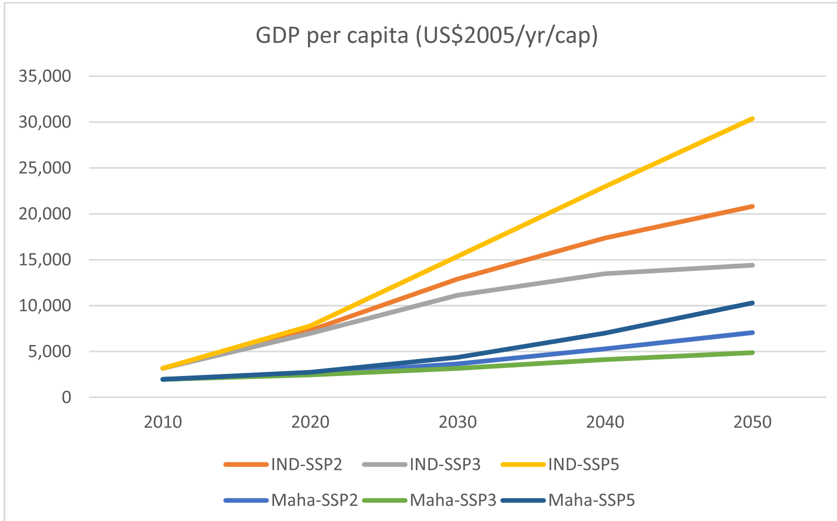

Fig. 2. GDP per capita of the MD and India
Source: Own elaboration.

suitable area, which implies a much larger reduction, of about 40% the existent in the baseline, mainly driven by the reduction in the area for oil seeds.

In the case of the results on productivity changes of fisheries from the POLCOMS-ERSEM modelling, the inter-annual variation is quite notable. Also, contrary to the projections for the Volta delta where these changes reveal relatively linear decreasing trends with the 3 GCMs, for the deltas of the Bay of Bengal (Bangladesh and Indian ones) typically one of the 3 models shows some positive change at the end of the period analysed (year 2050). In the particular case of the MD studied here, the results from these models are particularly erratic and different across models, as shown in Fig. A3. While the full range of cases have been analysed in the sensitivity analyses, in the main results we will focus on the scenario with the CNRM-CM5, which is the one that may show some impacts and be of interest under precautionary principles, as well as being the least erratic one.

Climate change projections for Indian sub-continent indicate an increase in temperature by 3.3–4.8 °C by 2080s relative to pre-industrial times. There is already evidence of negative impacts on yields of wheat and paddy in some parts of India due to increased temperature, water stress and reduction in number of rainy days. In the medium-term (2020–2039), crop yield is projected to reduce by 4.5 to 9%, depending on the magnitude and distribution of warming (NICRA, 2013). More general projections from combinations of data points from crop model projections indicate decreases of between 10 and 25% in yield by 2050 in a RCP8.5 scenario (see Fig. 2.7 of the IPCC AR5, (IPCC, 2014)). This implies up to around 0.5% loss per year, and so we will also examine such paths in the Sensitivity analysis section.

Finally, as mentioned before, the economic analysis also takes into account the direct economic impacts of climate change in the economic. In particular, the model considers the progressive productivity or capital losses (e.g. coastal erosion which affects infrastructure) and shocks such as extreme events affecting infrastructures ("CC_Infr" shock). This information does not come from other models in DECCMA, but simply from literature review on the effects of past events. The most important shocks to be modelled have to do with those extreme events that have been documented for the MD, and more extensively for deltas such as the ISD (see the summary and complementary information in Table A2). These shocks typically affect sectors which need infrastructures or are located at the coast (see Fig. 1), and their projections are

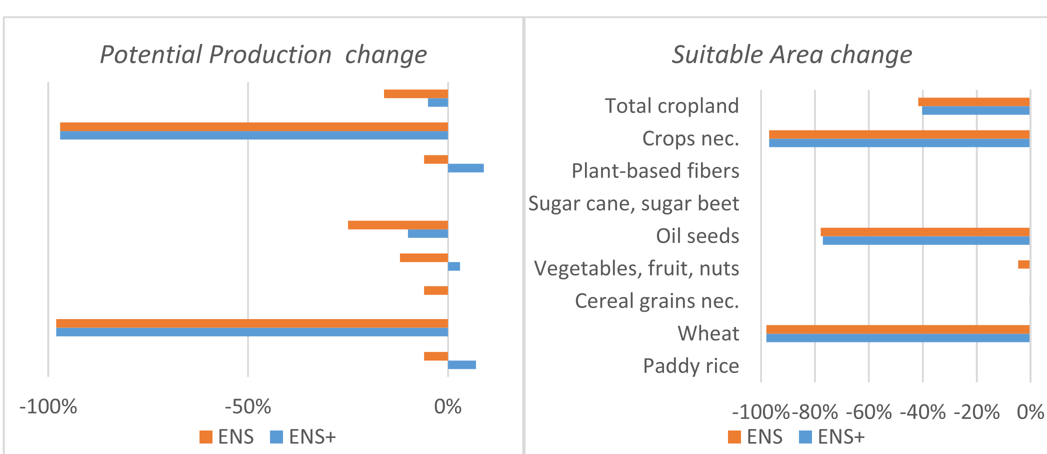

Fig. 3. Production potential and Suitable area change for climate scenario ensembles (ENS) for 2050s with (+) and without CO2 fertilization for the MD.
Source: Own elaboration from (IIASA, 2018).

Table 2
Documented extreme events impacts for the MD.

Event	Year	MD districts affected	Crop area affected (in hectare)	Houses damaged	Crop loss (in USD)	Private house damaged (in USD)	Damaged to different public utility (in USD)
Flood	2001	5	236,968	46,752	524,069	2,881,390	85,241,894
Flood	2004	1	13,340	42	32,023	3182	6,546,455
Cyclone	2005	3	78,770	209	362,161	15,107	5,814,227
Cyclone	2007	2	120,486	21,891	7,585,252	2,437,220	
Flood	2008	5	196,765	106,643	11,517,901	12,607,934	

Source: Own elaboration from several reports (SRC, 2017).

based on the documented frequency, intensity and damage (Bahinipati, 2014; GoO, 1999; SRC, 2017). Table 2 provides key examples of these.

Summarising, in terms of impacts, four different types of effects are considered: productivity losses in agriculture, productivity losses in fisheries, capital losses affecting infrastructure sectors and other related assets at the coast, and other associated sectors (insurance and financial services).

3.3. Delta scenarios: Adaptation policies and interventions

The narratives and key characteristics of the APTs are based on the expected evolution (between now and 2050) of broad adaptation categories (see Suckall et al., 2017 for details). Each of these broad categories covers a number of specific adaptation interventions. Table 3 shows the actual adaptation interventions modelled.

In general, most adaptations are directly or indirectly related to agriculture but also some to fisheries. The majority of these adaptation options are introduced in the Delta-CGE model as exogenous shocks, typically as if subsidies or aid from external sources were made available. Alternatively, some shocks can be modelled as covered by the national budget but in "fiscal neutral" way, i.e. the associated expenditure is compensated by an equivalent reduction in public expenditure elsewhere.

The nature of the adaptation is typically of small scale, and their effects tend to be reflected either in the output expansion, input structure change (technology improvements) or area expansion (in the case of cropland) (GO, 2017; OSDMA, 2014). Agricultural adaptation options and costs are shown in Table A4 and fisheries in Table A5.

Adaptation options related to Disaster Risk Reduction (DRR) tend to be more related to final demand categories of government and investment, spending more on sectors such as construction activities, when infrastructure needs to be put in place. Other adaptation options

Table 3
Selected adaptation interventions modelled with the CGE.

Sector type	Adaptation interventions	Type[a]	Main link to the DECCMA-economics model	Cost in Million $	Source
Agr	Agr 1. Salt tolerant Paddy seed supply store	I	Exogenous subsidy to agriculture to be spent on the own sector (seeds). Agricultural output loss buffered.	0.05	(GoO, 2017a, 2017b; NICRA, 2017; Seed_Freedom, 2012; Shiva et al., 2017; Singh et al., 2006)
Agr	Agr. 2. Input Subsidy in seeds, fertilizers, biofertilizers	I	Exogenous subsidy to agriculture to be spent on Chemical products. Agricultural output loss buffered.	10.3	(GoO, 2017a, 2017b)
Agr	Agr. 3. Subsidy under state agriculture policy (capital investment)	I	Exogenous subsidy to agriculture to be spent on capital. Agricultural output loss buffered.	4.2	(GoO, 2017a, 2017b)
Agr	Agr. 5. Promotion of System Rice Intensification	I	Exogenous subsidy to paddy rice to be spent on chemicals, water, electricity and capital. Paddy rice output loss buffered.	1.7	(GoO, 2017a, 2017b; Prasad et al., 2008)
Agr	Agr. 27. Corpus Fund for OSSC for seeds and quality planting materials	I	Exogenous subsidy to agriculture to be spent on the self-purchases within the agricultural subsectors	10.0	(GoO, 2017a, 2017b)
Agr	Agr. 38. Sub mission on agriculture extension	I	Exogenous increase in land use endowment	2.465	(GoO, 2015, 2017a, 2017b)
Fsh	Fsh. 15. Development of retail fish markets and allied infrastructure	I	Exogenous subsidy to fisheries to be spent on trade sectors, and to trade sectors to be spent on fisheries. Increased access to markets.	0.17	(GoO, 2017c, 2017d)
Fsh	Fsh. 24. Housing for fishers	I	Exogenous subsidy to fisheries to be spent on construction. Fisheries output loss buffered.	0.02	(GoO, 2017c, 2017d)
Fsh	Fsh. 26. Construction of community hall with sanitation, water supply	III	Exogenous subsidy to fisheries to be spent on the water sector. Fisheries output loss buffered, water sector output increased	0.007	(GoO, 2017c, 2017d)
Fsh	Fsh. 36. Solar power support system for aquaculture	I	Exogenous subsidy to fisheries to be spent on the Electricity sector. Fisheries output loss buffered.	0.025	(GoO, 2017c, 2017d)
Infr	Infr. 1. Several (10) embankments	II	Government expenditure increase on construction and infrastructure. Agricultural and capital loss buffered	4.3	(GoWB, 2017) (OSDMA, 2014)
Infr	Infr. 2. multipurpose cyclone shelters	II	Government expenditure increase on construction. Capital loss buffered.	2.73	(ODSMA, 2017)
Infr	Infr. 3. Post-disaster recovery and rehabilitation	II	Government transfers to households and expenditure on construction and infrastructure. Capital loss buffered.	2.73[b]	(SRC, 2017)

Source: Own elaboration.
[a] Note: Type of adaptation. Addressing drivers of vulnerability; II. DRR, III. Landscape/ecosystem resilience.
[b] No specific documentation on this exists, based on (SRC, 2017) we find reasonable to implement it with the same amount than the DRR action of multipurpose cyclone shelters focused on government expenditure.

affecting biodiversity and ecosystems in general are more difficult to be captured by the economic model. The main documented information about these DRR are the multipurpose cyclone shelters (OSDMA, 2014) that Indian government constructed in the most vulnerable 10 km band along 480 km of coastline in the Mahanadi[12] for 112.6 million $ (6756 million Rs), to which we apportion about 95 million $.

3.4. Summary of scenarios

In total we ran >100 scenarios resulting from combining the 3 socioeconomic scenarios considered in DECCMA (SSP2, SSP3 and SSP5), 3 different types (and combinations of them) of effects or shocks induced by climate change, and 12 specific adaption interventions. Furthermore, CGE model simulations are usually accompanied by sensitivity analyses in terms of specific model parameters which are considered difficult to measure (such as elasticities) and, therefore, it is highly convenient to evaluate their role in varying the results. For all these, we implemented a Monte Carlo analysis in order to run all these possible combinations of variables and parameters. Apart from testing the uncertainty on some key parameters of the economic model, we also requested the biophysical modellers to provide us with ranges (if possible distributions) for the main climatic impacts from the biophysical models, that were included in the Monte Carlo analysis. The parameters for which we perform the Monte Carlo analysis are shown in Table A6 in the SM.

4. Results and sensitivity

4.1. Future economic impacts of climate change in the MD

The following results illustrate the economic implications of a combination of climatic, socioeconomic and adaptation scenarios for the MD and for the whole India. We use as headline indicator the change in the GDP per capita due to climate change with respect the scenario without climatic impacts. For the sake of simplicity, in terms of socioeconomic scenarios, we just present the results of the SSP2 scenario, which is referred as Business As Usual (BAU). On top of this BAU, the different shocks described in the previous section are implemented and analysed. Finally, we provide a sensitivity analysis of simulated shocks.

In the following we examine the Cumulative Changes in macroeconomic variables from Climate Change shocks for the Mahanadi Delta with respect to BAU (up to 2050).

Climate Change (CC) shocks with respect to BAU scenario for the Mahanadi delta.

Based on the SSP2 scenario for the Mahanadi delta and India (grey line in Fig. 2 above) and also for the Mahanadi delta, which we call BAU, we examine the projected shocks described in previous section. We may see in Fig. 4 the “CC_Agr” shock, in which both consumption and investment fall percent wise more than GDP per capita, which reaches a cumulative loss of about 5% with respect to BAU.

As indicated above, in the case of the shock on fisheries (“CC_ Fisheries”), inter-annual variation is quite notable, particularly erratic and different across models for the case of the Mahanadi delta (this does not happen e.g. for the Volta delta), leading in 2050 to marginal (<0.1% decrease in GDP per capita with the shock) changes compared to shocks on agriculture and on infrastructures.

When we apply only the scenario of “CC_Infr” shock to the sectors considered in Fig. 1, we get the results of Fig. 5. What we may observe is that the shock is introduced yearly, and at some point in time (based on frequency of events) the loss is much higher in specific years of strong events, which furthermore trigger the effects across the economy. For the cumulative loss (around 8% in 2050) we see some increased steepness of the GDP per capita loss. We may observe how the percentage losses in GDP per capita are largely driven by the modelled -according to current evidence and frequency- shocks in infrastructure.

Finally, we examine the results of the adaptation interventions presented in Table 3.

In the scenario in which we assume equivalent buffering of shocks per monetary unit of cost[13] we observe that buffering the shock for all activities, as typically agriculture, have downstream effects which reduce the shock on GDP per capita by more than the share of the activity in GDP (in this case about 15%). For example, with the intervention “Agr 2. Input Subsidy in seeds, fertilizers, biofertilizers” buffering the shocks in agriculture by 10%, buffers the GDP per capita shock by 3%. The intervention “Fsh. 26. Construction of Community Hall with sanitation, water supply” has differential notable positive effects in the economy and in many social aspects related to development. In that regard, we consider that the evaluation of interventions such as the DRR intervention of multipurpose cyclone shelters (the adaptation option with the major investments in the delta) still depends too much on the value of preventing a fatality, the valuation of damage (well documented mostly for large infrastructure and housing) and of the statistical life. Even when considering purely the economic benefits, interventions such as “Infr. 1. Several (10) embankments” present great effects in terms of avoided losses, as shown in Fig. 6. In particular, despite the initial costs involved (red line) and maintenance costs involved, with the adaptation intervention of embankments construction, we find a great buffering of shocks on agricultural production (from a cumulative loss in 2050 above 2.2% to one around 1.5%), and especially on avoided infrastructural loss (schools, houses, etc., from a cumulative loss in 2050 above close to 8% to one below 3%). Further information is shown in Appendix D.

4.2. Sensitivity analysis of simulated shocks

The above shocks reveal a specific trajectory of changes under climate change shocks according to the climate and modelling ensembles of the biophysical models, and the BAU parametrization. Sensitivity and Monte Carlo analysis were performed for the parametrization, to examine wider ranges of trajectories. “Appendix D. Complementary results” of the SM summarizes these analyses. We found that in order to understand the growth of GDP (PPP) and GDP per capita, the most sensitive parameters were total factor productivity and population pathways, followed by the interest rates and the assumptions on the production functions and trade. The changes in interest and depreciation rates were also highly influential in the evolution of capital, investments, and in general in the performance of adaptation options focused on Disaster Risk Reduction.

For the sake of comparison of the size of the resulting changes, we also ran ranges of shocks from climate change for those same biophysical models. For example, the analogous figure to Fig. 4 of a yearly 0.5% shock with respect to BAU in agricultural land cover is shown in Fig. D1.

Following Fig. 1, we examine in Table 4 ranges of change for each of the 4 types of impacts explained, affecting the sectors considered in that figure, adding also a general “CC_All above” shock which includes all those impacts being studied all together. In order to put into context some of the changes, we may examine the 2.25% of loss for the Mahanadi delta in GDP per capita for the shock on agriculture, via land availability.

In the reference case, a yearly 0.5% loss in land availability implies a cumulative loss of about 17% of land after 20 years. Interestingly as well, in addition to the 2.25% of loss in GDP per capita in the delta, we may see a cumulative 0.23% loss in the GDP per capita of the non-delta (of the rest of India, representing agriculture also for the whole India around 16% of the value added). For the shocks on fisheries, we observe some smaller effects given the size of the sector, but we find now big

[12] The districts covered where Puri, Kendrapara, Jagatsinghpur, Khordha, Bhadrak (the 5 included in the DECCMA definition of the MD) and Balasore.

[13] Information on actual reach/benefits/accomplishments of the interventions is very useful and allows for a few fair comparisons, but it lacks for many of them and so it is taken from other interventions.

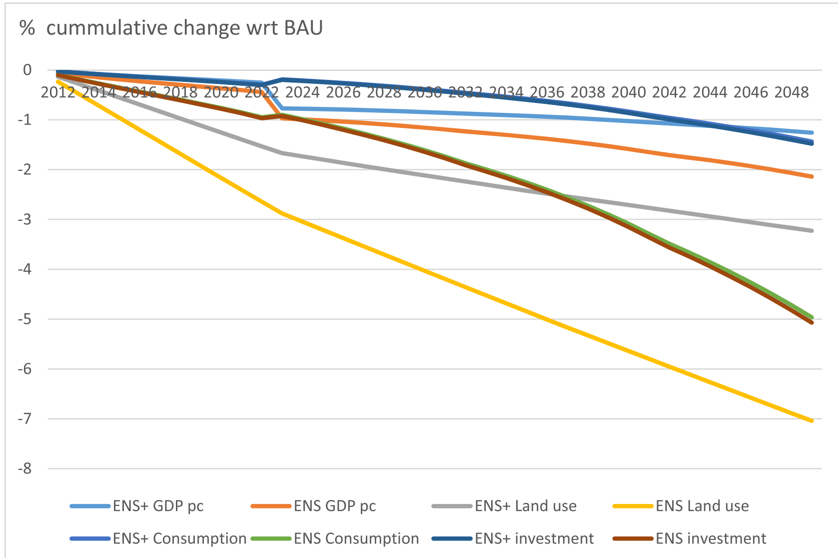

Fig. 4. Yearly changes with respect to BAU ("CC_Agr" shock) for the Mahanadi delta.
Source: Model results.

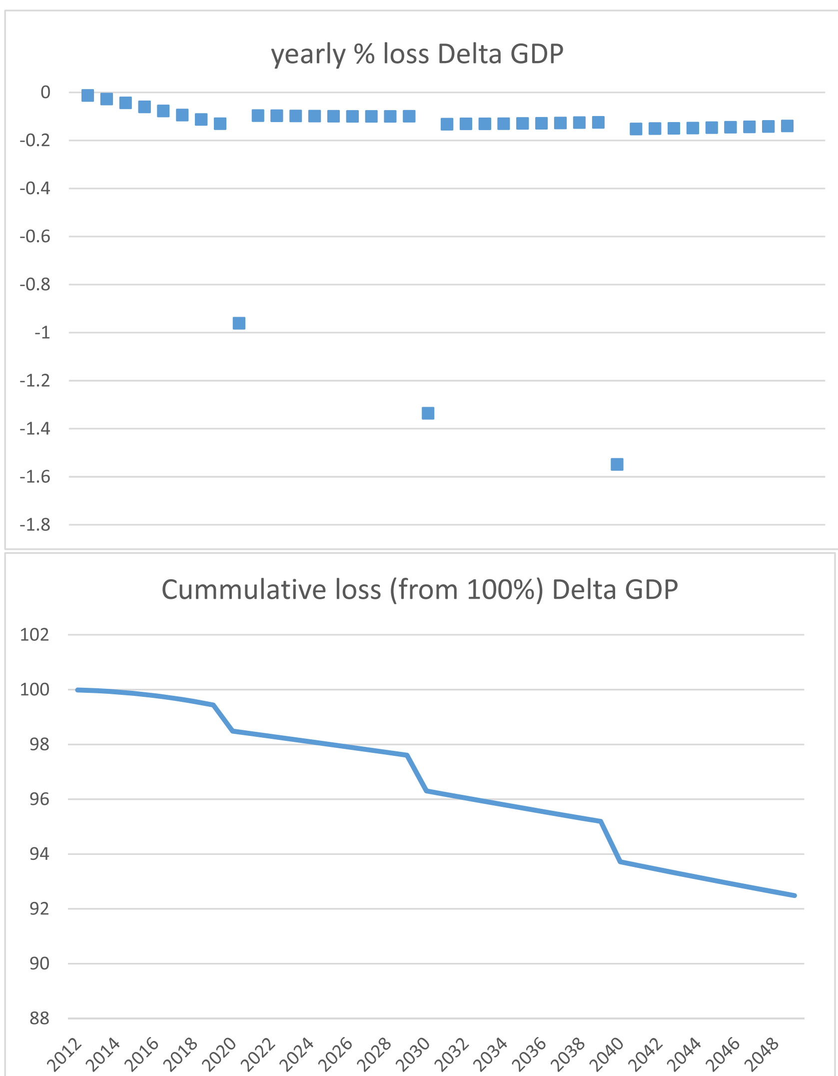

Fig. 5. Loss of GDP per capita under shock in infrastructures ("CC_Infr") with respect to BAU, yearly and cumulative
Source: Model results.

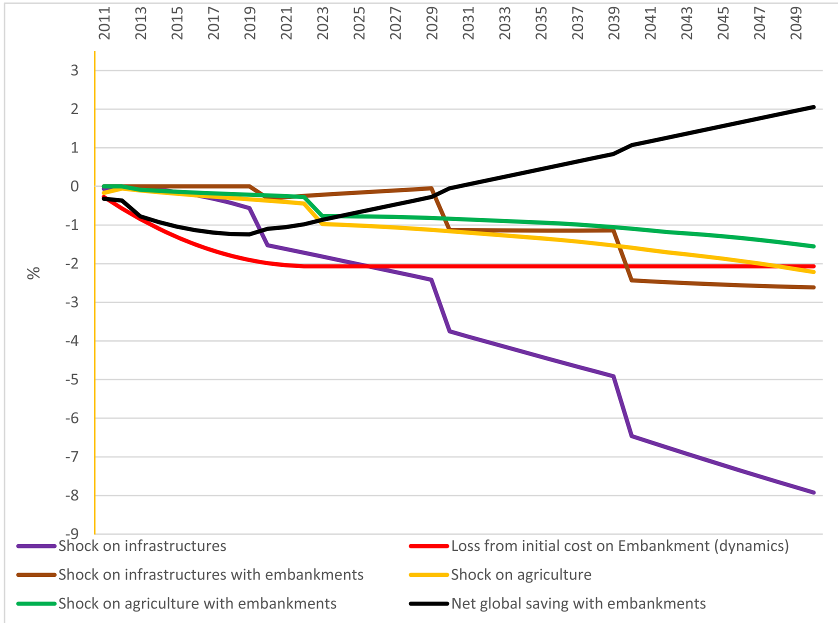

Fig. 6. % cumulative change with respect to BAU of shocks with and without embankments Notes: Construction of Embankments equivalent to 10 km along the shoreline and 6 m wide. The net global saving with embankment also considers the maintenance cost (estimated from previous literature at about 17% of the projects cost), not represented here for clarity.
Source: Model results.

differences in terms of how (in)substitutability of factors may affect more or less this activity than agriculture. Shocks on infrastructures.

A relatively surprising insight from the modelling of these shocks is the relative linearity (and symmetry with respect to the reference shock) found, i.e., having a 50% higher (or lower) impact with respect to the reference, creates also 50% lower (or higher) impact on the GDP per capita, and a 50% higher (or lower) impact on prices.

In the case of infrastructures, the yearly shock modelled is smaller because the loss of capital is likely to be less pronounced, more of a slow process (except for the point in time shocks which could be associated to extreme events) than for agriculture or fisheries. Still given those shocks the effects on GDP per capita are relatively high given the simulated loss of capital in many key sectors, given the key role of capital in the dynamics of the model. Furthermore, it is worth indicating the different share that these factors of production represent. In terms of monetary equivalent, the stock of fish for the fisheries sector represents about 35% of the total of factors, while for agricultural sectors land represents about 44%. In both cases, possible substitutions (to a certain degree, based on the elasticities) exist with capital and labour. In the case of the sectors affected by the shock of infrastructures, capital can only be substituted (to a certain degree) with labour, when the initial share of capital in the total of factors is of the order of 77% (Communication), 86% (Dwellings), up to 96% (gas manufacture distribution). So in some cases even small percentage loss shocks are relating to important losses

Table 4
Cumulative (%) Changes in macroeconomic variables from Climate Change shocks with respect to BAU (up to 2050) for the Mahanadi Delta.

			Cumulative (up to 2050) % change in variable with respect to BAU (reference path without shocks)				
	Yearly shock on sectors affected	Point in time (frequency depending on event) shock	Land endowment	Natural resources endowment	GDP (PPP) per capita delta	GDP (PPP) per capita non-delta	Prices
CC_Agr	0.1%		−3.62	0.00	−0.42	−0.04	0.04
	0.25%		−9.07	0.00	−1.09	−0.12	0.11
	0.5%		−17.34	0.00	−2.26	−0.22	0.21
	0.75%		−24.88	0.00	−3.66	−0.34	0.32
CC_Fisheries	0.02%			−0.9	−0.05	0.00	−0.00
	0.25%			−4.48	−0.43	−0.01	0.01
	0.5%			−8.76	−0.85	−0.03	0.02
	0.75%			−12.86	−1.27	−0.04	0.03
	0.0025%[a]	0.1%[a]			−0.39	0.00	−0.00
CC_Infrastr	0.025%[a]	1%[a]			−5.22	0.03	−0.03
	0.05%[a]	1%[a]			−7.32	0.04	−0.04
	0.075%[a]	1%[a]			−8.50	0.05	−0.05
CC_All above	Very low	=Infrastr	−3.62	−0.9	−0.86	−0.04	0.04
	Low	=Infrastr	−9.07	−4.48	−6.74	−0.10	0.08
	Ref	=Infrastr	−17.34	−8.76	−10.44	−0.21	0.19
	High	=Infrastr	−24.88	−12.86	−13.52	−0.33	0.30

Source: Model results.
[a] Shocks are simulated also independently and altogether under the hypothesis that some process, as damage on infrastructure, may be a regular process, but also specific point in time shocks may occur with a certain frequency.

of infrastructure for these sectors and the whole economy. For example, the impacts of these sectors when shocked, as seen in Fig. 4, represent three times the GDP per capita loss of the agricultural sectors, and about 27 times more than the fisheries sectors, even though both of these activities are greatly important in the delta and for the livelihoods of much of population. We also see in Table 4 from the last 3 rows of shocks taken together that all the climate change related changes considered, result (for the delta only) in cumulative (up to 2050) percentage losses in GDP per capita with respect to BAU of about 11% for the delta, while barely of 0.25% nationally.

5. Conclusions

In this paper we have developed the conceptual and practical links between the climate, biophysical and socioeconomics model in DECCMA. In particular, we have focused on the background and the conceptualisation of the links between the global climate (RCPs) and socioeconomic (SSPs) scenario narratives and policy assumptions (SPAs) for developing appropriate adaptation policy trajectories and associated specific interventions in the deltas. The review of the literature shows how biophysical-economic models represent a diversity of approaches to describing human-nature interactions. Following the line of dynamic CGE models which connect with other Partial Equilibrium, biophysical, crop/hydro/(…) models in this framework we have translated the biophysical changes (coming from simulations with a specific RCP 8.5) into changes in our dynamic economic model (Delta-CGE). Furthermore, we have incorporated national and regional scenarios (3 SSPs) and adaptation policy alternatives which have reasonable translations to our parameters or variables.

Our model is set up to incorporate the outputs from various biophysical models, harmonizing results into common metrics to be used as inputs in the economic models. Similarly to the recognition explained in (Wiebe et al., 2015), obtaining these variables under a high emissions pathway allows us to study and highlight how production and food security may be affected by climate change from various perspectives. Furthermore, it can examine the impacts of climate change on yields, production, area, prices, and trade across multiple socioeconomic and policy pathways. For this reason, despite some possible feedbacks among variables which ideally could be captured with the integrated framework of the project, the DECCMA Economics model already represents the natural next step or way forward of analysing biophysical impacts further in the supply chains.

Indeed, the main design of the model and scenarios analysis has been done so that the robust Monte-Carlo type runs create an "emulator" which can be implemented in the integrated (Bayesian type) framework of the project. In this regard, we have performed a wide sensitivity analysis on how the endogenous variables in the model respond to the main parameters and exogenous information which enters it as inputs. In particular, we found that in order to understand the growth of GDP, the most sensitive parameters were total factor productivity and population pathways, followed by the interest rates and the assumptions on the production functions and trade. The modelling of the climate change impacts via loss of land dramatically affected more the agricultural outputs and GDP in general than the specification via productivity losses. The changes in interest and depreciation rates were also highly influential in the evolution of capital, investments, and in general in the performance of adaptation options focused on Disaster Risk Reduction. As also found in (Eboli et al., 2010), one may also observe how second-order, system-wide effects of climate change impacts typically have significant distributional effects at the regional and industrial level. The interaction between endogenous and exogenous dynamics generates non-linear deviations from the baseline, amplifying or counteracting exogenous shocks on the long run.

The main future steps with the DECCMA Economics modelling have to do with this further validation, and with the implementation with much more data on scenarios, coming from all the different (notably the biophysical, but also from the integrated Bayesian) models results, and implemented for all the deltas under study in DECCMA. Intercomparison of results should also serve us to further disentangle how the choice of parameters affects the results, and in general the uncertainty of the modelling. Probably even more importantly, we should then be able to fully address how the variables evolve, to be able to provide comprehensive measures on output, prices, welfare, income or wages, for each of the scenarios and adaptation options, hopefully provide guidance on the socioeconomic implications of the different choices, and on specific policy implications, such as the positive effects found here of specific adaptation interventions, namely the input subsidies in seeds and fertilizers, and the DRR interventions of building multipurpose cyclone shelters and constructing embankments. Also possible future distinction of socioeconomic groups (from the Social Accounting Matrices) may serve us to differentiate impacts on vulnerable groups, based on their different patterns on migration and vulnerability to climate change, leading to interesting results and discussion on distributional issues and policy measures.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.08.139.

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