Projecting marine fish production and catch potential in Bangladesh in the 21st century under long-term environmental change and management scenarios

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Abstract

The fisheries sector is crucial to the Bangladeshi economy and wellbeing, accounting for 4.4% of national Gross Domestic Product (GDP) and 22.8% of agriculture sector production, and supplying *ca.*60% of the national animal protein intake. Fish is vital to the 16 million Bangladeshis living near the coast, a number that has doubled since the 1980s. Here we develop and apply tools to project the long term productive capacity of Bangladesh marine fisheries under climate and fisheries management scenarios, based on downscaling a global climate model, using associated river flow and nutrient loading estimates, projecting high resolution changes in physical and biochemical ocean properties, and eventually projecting fish production and catch potential under different fishing mortality targets. We place particular interest on Hilsa shad (*Tenualosa ilisha*), which accounts for *ca.*11% of total catches, and Bombay duck (*Harpadon nehereus*), a low price fish that is the second highest catch in Bangladesh and is highly consumed by low income communities. It is concluded that the impacts of climate change, under greenhouse emissions scenario A1B, are likely to reduce the potential fish production in the Bangladesh Exclusive Economic Zone (EEZ) by less than 10%. However, these impacts are larger for the two target species. Under sustainable management practices we expect Hilsa shad catches to show a minor decline in potential catch by 2030 but a significant (25%) decline by 2060. However, if overexploitation is allowed catches are projected to fall much further, by almost 95% by 2060, compared to the Business as Usual scenario for the start of the 21st century. For Bombay duck, potential catches by 2060 under sustainable scenarios will produce a decline of less than 20% compared to current catches. The results demonstrate that management can mitigate or exacerbate the effects of climate change on ecosystem productivity.

Introduction

Bangladesh is recognized as being highly vulnerable to the potential impacts of global and regional climate change due to its geographic location and low-lying topography, putting it at risk of extreme flooding and weather events. The Bangladesh delta region is home to over 500 million of some of the poorest people worldwide (FAO, 2007), who rely on the rich ecosystem services available (Newton et al., 2007; Shamsuddoha and Chowdhury, 2007). The coastal population of Bangladesh has doubled since the 1980s, now reaching in excess of 16 million (~ 10 % of the total population), most of them experiencing both poverty and environmental vulnerability. It is known that in economic systems close to or below the poverty line, both subsistence and cash elements of the economy rely disproportionately on ecosystem services (Newton et al., 2007; Allison, 2009). Understanding the effects of climate change on ecosystem services is thus particularly relevant in poor regions (Nicholls et al., 2015).

Fisheries play an important provisioning service in Bangladesh, supplying 60% of the protein intake (DoF, 2013). Fisheries catches can be divided into marine (*ca.* 17%), inland open water or captured (*ca.* 28%) and closed water or cultured (*ca.* 55%). Inland open water includes river and estuaries, the Sundarbans mangrove area, shallow marshy lakes known as Beels, Kaptai Lake and seasonally flooded plains. Inland closed water corresponds to ponds, semi-enclosed water bodies, lakes and shrimp/prawn farms. Although cultured fisheries dominate the catch data, these depend strongly on river and marine ecosystems for the provision of larvae and juveniles. Marine catches come from the Bangladesh Exclusive Economic Zone (EEZ), which covers an area of 86,392 km^2, and represent an important economic activity, with 0.55 Mt of fish production in 2011. About 225 trawlers and 52,514 mechanized and non-mechanized boats are engaged in fishing (DoF, 2013). Climate change has been predicted to decrease the productive potential of fisheries in South and Southeast Asia **(**Barange et al., 2014). Understanding how this impact translates into the future provision of fish products in Bangladesh is crucial for the sustainability of fisheries dependent communities in coming decades.

In this paper we assess the impacts of climate change on Bangladesh's fish resources by quantifying the cumulative physical, biological and ecological impacts in the EEZ of Bangladesh over the 21st century, and how these affect the fish production potential in the coastal zone. We include a set of contrasting management and exploitation scenarios for the EEZ of Bangladesh to project plausible scenarios of fish production by 2060 that combine sustainable management and environmental impacts. These scenarios are specifically focused on the two species that provide the largest marine and inland catches, Hilsa shad, *Tenualosa ilisha,* and Bombay duck, *Harpadon nehereus.* The management scenarios are intended to inform fisheries managers in Bangladesh in the pursuit of sustainable management strategies under a future dominated by climate change.

Hilsa shad is a euryhaline anadromous shad found in marine, coastal and freshwater environments, often schooling in coastal waters. Hilsa is the single most important fish species in Bangladesh, accounting for more than 10% of the total national fish production, and responsible for about 1% of Bangladesh's GDP. About 460,000 fishers of 148 Upazilas (sub-districts) are directly employed in Hilsa fishing with an indirect employment of about 2.5 million people in the wider Hilsa sector (trading, processing etc.). Bombay duck is the second highest catch in Bangladesh and a much cheaper fish than Hilsa Shad (*approx.* 65 BDT.kg^{-1} vs 430 BDT.kg^{-1}, unpublished data). As it is cheap and still caught in abundance, Bombay duck, currently, is one of the most preferred fish for poor and middle class consumers all over the coast (on average, 14% of all daily sales is Bombay duck). Dried Bombay duck is also regarded as the number one dried fish and is very popular, particularly in the eastern part of the coast. It is a very soft and highly perishable table fish and also valuable in laminated or dried from.

Growth of human populations and changes in global consumption patterns will continue to place heavy demands on fish populations (Delgado et al., 2003), particularly in fish-dependent regions like Bangladesh (Toufique and Belton 2014). Here we used quantitative scenarios of climate and socio-economic changes in the Bangladeshi marine ecosystem and its major fish species to assist in the development of adaptation measures.

Material and Methods

In order to provide estimates of fish production potential under climate change we used a combination of atmospheric, hydrological, ocean circulation and ocean biogeochemical models, driving changes in ocean productivity and fisheries potential (Fig. 1). These models produce yearly time steps and spatially resolved results. The Bay of Bengal (BoB) physico-biogeochemical model simulates the cycling of the main nutrients through the benthic and planktonic pelagic ecosystems. Outputs from this model drive two fisheries models: a size-spectrum model to provide time-series of total marine fish production by size, and a species-based model to compute total marine production of the main species by size. The effects of human activities and fisheries management policies were explored through fishing mortality scenarios. Details of each model are provided below.

Climate and hydrological models

Previous climate modelling studies in this region have tended to focus on the wider Indian subcontinent rather than Bangladesh. Most studies project a generic increase in atmospheric temperature, annual rainfall and heavy precipitation events. Climate data for this study was taken from the UK Met Office regional climate model (RCM) HadRM3P, which is dynamically downscaled from the global circulation model HadCM3 (Caesar et al., 2015). The greenhouse gas emission scenario used here is the Special Report on Emissions Scenarios (SRES) A1B (IPCC 2007), a medium-high emissions scenario developed for Intergovernmental Panel on Climate Change (IPCC) 3rd and 4th Assessment Reports, which still underpins research into climate impacts. In order to capture some of the model uncertainties we considered three different climate projections from a 17-member ensemble of HadCM3 runs (Caesar et al 2015). The three climate model runs selected correspond to a range of possible future outcomes for the Bay of Bengal, between the standard (Q0), drier and warmer (Q16) and intermediate rainfall and temperature (Q8) projections (Caesar et al., 2015). Q0, Q8 and Q16 have successively higher sensitivity to greenhouse gas forcing because of the different parameter values used in the general circulation model for these ensemble members. As delta regions are particularly sensitive to precipitation and river run-off, outputs from an Integrated Catchment Model (INCA,Whitehead et al., 2015a,b) were used to determine run-off and associated nutrient loadings from the delta rivers into the BoB for each projection. The model simulates factors controlling flow and water quality dynamics in both land and stream components of river catchments. The INCA model application took account of both climatic scenarios (Q0, Q8, Q16) and patterns of upstream water use according to three socioeconomic scenarios (Less Sustainable, LS, Business as Usual, BaU, More Sustainable, MS) scenarios (Whitehead et al., 2015a,b). We used the results of the Q0-BAU, Q8-LS and Q16-MS INCA simulation runs to capture the variation of the simulated river flows and nutrient loads (Table I). The rivers in the Ganges-Brahmaputra-Meghna delta region (Fig. 2) account for 40% of flow into the model domain. For all other rivers, for which INCA data was not available, data was extracted from global databases (Global *NEWS*, http://marine.rutgers.edu/globalnews/datasets.htm and Dai and Trenberth Global River Flow and Continental Discharge Dataset, http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/index.html).

Ocean dynamics and biogeochemistry

A regional POLCOMS-ERSEM coupled model (Holt and James, 2001; Blackford et al. 2004; Holt et al., 2009) was used to project both the physical state of the ocean (temperature, salinity, currents, light level), and the biogeochemistry and lower trophic levels of the marine food-web in the BoB. The model simulates four phytoplankton functional types, three zooplankton functional types and bacteria, as well as three size classes of particulate organic matter and dissolved and semi-labile organic matter. Four nutrients (C, P, N and Si) are explicitly tracked within the model. The model domain covers the coastal area of the whole BoB (77° to 104° W, 1.3° S to 23° N), and its width is from the coast to 200 km beyond the edge of the continental shelf (Fig. 2). The model uses a rectangular grid with a horizontal resolution of 0.1° and 42 vertical levels distributed according to bottom depth. At the atmospheric boundary it was forced using 3-hourly and daily outputs from the HadRM3P regional climate model described above, and physical conditions at the open ocean boundary were set using monthly outputs from the HadCM3 GCM.

Nutrient values at the ocean boundary were fixed to values from the World Ocean Atlas (Garcia et al., 2010); since future projections are not available for these variables the values were kept constant during the run. The boundary is advective, so although nutrient values are kept constant nutrient losses and gains at the boundaries are allowed. Keeping nutrient levels at the boundary fixed could have some effect on primary production, but since production here is very low (Martin and Shaji, 2015) the effect is likely to be small compared to changes in more productive zones nearer the coast.

For each climate dataset, the model was run continuously for 1971-2099. Model outputs including temperature, salinity, current speeds, primary production, dissolved oxygen, pH and plankton biomass were recorded at daily intervals and used to run the fish production models.

The BoB POLCOMS-EREM model was validated by comparing model outputs to in situ measurements of temperature and salinity and to satellite values of surface chlorophyll.

Temperature and salinity data were taken from the World Ocean Database (Boyer et al. 2013), using all available data for the model domain for the period 1993 to 2009. Monthly-aggregated satellite chlorophyll data for 1997-2009 were taken from the database of the Ocean Colour Climate Change Initiative (Hollmann et al., 2013; http://www.esa-oceancolour-cci.org). For validation purposes the model was run with forcing from reanalysis data (ERAinterim, Dee et al., 2011, and GLORYS, Ferry et al., 2012).

Fish production models

Outputs from the POLCOMS-ERSEM model were 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 in to account temperature effects on the feeding and intrinsic mortality rates of organisms (Blanchard et al. 2012), and hence 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).

To make projections for key species, we used a Dynamic Bioclimate Envelope Model (DBEM), a combined mechanistic-statistical approach that has been applied to a large number of marine species globally (Cheung et al., 2009). The DBEM projects changes in species distribution and abundance while explicitly considering known mechanisms of population dynamics and dispersal (both larval and adult), as well as ecophysiological changes caused by changing ocean conditions (Cheung et al. 2011). Specifically, we employed the SS-DBEM version of the DBEM that incorporates species interactions based on size-spectrum theory and habitat suitability (Fernandes et al., 2013). In SS-DBEM, current distributions of the studied species (Hilsa shad and Bombay duck) are first estimated using the Sea Around Us database method (Close et al. 2006). Then the suitability of each species to different environmental conditions was defined, using its model inferred environmental preference profile (Cheung et al., 2008). Combining ocean dynamics with mortality, growth and dispersal processes the model projects future patterns in distribution, biomass and potential catch (see Cheung et al 2008, 2009 for more details). We applied the size-spectrum model to explore potential changes in the total productivity of the Bangladesh Exclusive Economic Zone under both climate change and fishing scenarios and the SS-DBEM for the two target species (Hilsa shad and Bombay duck).

<u>Fisheries Management scenarios</u>

The fisheries scenarios considered are based on the ecosystem carrying capacity of the Bangladesh Exclusive Economic Zone (EEZ) and aim to provide trends of fish potential for particular species by size class according to specific levels of fishing pressure in relation to the species' 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, MSY can be defined as:

$$MSY = B\infty * intR /4$$

where intR is the intrinsic rate of population increase and $B\infty$ is the biomass at carrying capacity (Schaefer 1954, Sparre and Venema 1992). In our application, the intR values are calculated based on natural mortality (Pauly 1980; Cheung et al., 2008). This is an approximation and not as reliable as estimates of biomass using survey-based methods (McAllister et al. 2001; 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., 2013).

Fishing mortality (F_m) scenarios were defined by comparing F_m estimates for Hilsa shad from the literature with the modelled fishing mortality associated with MSY. Our modelled averaged F_{MSY} is *ca.* 0.6, which contrasts with much higher levels of fishing mortality in the literature (Haldar and Amin 2005, Amin et al. 2008, Ahmed et al., 2008, Rahman et al., 2012), which would be consistent with expectations of significant overfishing in the region (Khan, 2007; Hussain and Hoq, 2010; Dutta et al., 2012). Thus, we considered three fishing mortality scenarios to provide fish catch and biomass projections as follows:

a) Sustainability scenario (MSY): Fishing effort consistent with average F_{MSY} (0.6). This is the theoretical 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}). The average fishing mortality for Hilsa shad, the largest fishery in the country, is 1.86, or 3*F_{MSY}. We will consider that Hilsa shad and many of the brackish species in the BoB are being exploited at that rate.

c) Overfishing scenario (F_{OF}): Corresponds to a scenario where management is not a constraint to the fishery. Initial runs indicate collapse of catches and biomass at 4 * MSY (F_m of 2.4). This is the highest exploitation scenario that we can consider.

Results

Correlation between modelled and observed values is high for temperature and salinity (0.97 and 0.87 respectively). Chlorophyll was observed to be consistently over-estimated compared to satellite values in the region (validation not shown), but the spatial and seasonal patterns of variation reproduced well. The model estimated net primary production is highest in deep waters near the coast, with production falling to low values at the model boundary (Fig. 3), consistent with the oligotrophic conditions expected for the central Bay (Martin and Shaji, 2015). The exception is some areas to the north and west of the domain, where production at the boundary is about half that of the maximum level; the model may miss some production in this part of the domain.

Projections of change for the 21st century show a steady rise in sea surface temperature, but a more mixed picture for net primary production (Fig. 3 and Table 1). For the Q0 (standard) climate run, there is a fall in net primary production across most of the northern Bay of Bengal, except for a small area in the main Meghna river mouth. The overall effect for the Bangladesh EEZ is to leave net primary production largely unchanged (<5% change). Primary production in the EEZ rises in both of the warmer runs, Q8 and Q16, and is greatest for Q8 in spite of decreasing river nitrate and phosphate inputs. In the wider bay the general tendency in the longer term is for decreasing production on the Indian coast, but rising production in the Andaman Sea to the east; however, the Indian coast shows rising production at the start of the century for Q8 and Q16. The temperature rise is greatest for the Q16 climate run, which has the highest climate sensitivity: a sea surface temperature rise of nearly 3°C for the Bangladesh area, compared to 2.3°C for Q0.

In order to investigate the impacts of changes on fish and fisheries potential we ran a size-based model to compute the total potential fish production capacity from 2000 to 2100, in the absence of fishing (Fig. 4). This model projects the transfer of energy from primary to secondary and tertiary producers based on metabolic theory (Blanchard et al. 2012). It has the advantage of having relatively limited parameter demands while providing good estimates of potential catch from the EEZ, which emphasizes the dominant role of body size in accounting for patterns of predatory interaction and production (Blanchard et al. 2012). The results (Fig. 4 and Table II) indicate that all three climate runs (all associated with an A1B greenhouse gas emission scenario) project declines in fish productivity. As would be expected, a significant inter-annual and inter-scenario variability is observed. Averaging the results per decade shows that the total fish productivity would decline between 2.6% (Q8 – intermediate temperature rise) and 8.3% (Q0 – standard run) by 2100, depending on the climatic ensemble run considered (Table II). However, the trajectory of this decrease is different for each scenario: steady, significant decrease over time under the Q0 scenario, moderate variations (increase followed by a decrease) until the mid-century under the Q8 scenario, and moderate decrease after the mid-century under the Q16 scenario (Fig. 3). The results for the Bangladesh EEZ domain are consistent with results for the entire BoB shelf region (Table II).

The weakness of the size-based model is that it does not provide predictions of production and thus potential catches from individual species, and thus does not account for their specific responses to environmental change and fishing. In order to explore the impact of management scenarios we conducted runs using the species-based SS-DBEM model for the two major marine captured species, Hilsa shad and Bombay duck. Given the small difference in overall fish production between the climate ensemble runs (Table II), and to facilitate analysis, we averaged outputs of the three climate ensembles in subsequent species-specific runs and focused on the relative impacts of fisheries management decisions. The results indicate that both Hilsa shad and Bombay duck catches are expected to decline over time regardless of the fisheries management regime, but to different degrees (Fig. 5). For Hilsa the decline stabilises under MSY considerations at 175,000t by 2035, while it virtually collapses around the same period under overfishing (OF) scenarios. A significant inter-annual variability is observed (Fig. 5a). By the 2050s the decline in catches is between 39% (under MSY) and 87% (under OF, Table III). For Bombay duck inter-annual variability is reduced but climate ensemble variability increases the size of the error bars (Fig. 5b). Catch potential declines continuously under all management scenarios but without biological collapse. By the 2050s this decline is around 35% for all management scenarios (Table III). It must be noted that the projected catches of both species at the start of the presented time series (2010) differ between management scenarios. This is because fishing mortality rates were applied in the model starting in 1980, to allow populations to stabilise in response to these rates. Thus, by 2010 each management scenario is already delivering significant differences in catch potential. Potential catches are on average higher in the more sustainable scenarios (MSY) than in the Business and Usual (BaU) scenarios for both species (91% in Hilsa Shad and 37% in Bombay Duck by the 2050s) (Table III). The less sustainable scenario (Overfishing, OF) projects a decrease of catches of Hilsa shad to <20% of the BaU potential by 2050s (Table III).

If we compare the outcomes of the current “Business as Usual” (BaU) scenario in the 2000s (2000-2009) period with a more sustainable scenario in coming decades, we expect the management change to result in a very minor decline in potential catches by the 2020s but a still significant (25%) decline by the 2050s (Table IV). Conversely, a future that follows BaU with an overexploitation scenario will bring catches by 2050s almost 95% lower than in the

BaU scenario for the start of the 21st century (Table IV). For Bombay duck, potential catches by 2020s under an MSY scenario will produce over 20% more fish than under BaU at the start of the century, with a decline of less than 20% by the end of the projection period. (Table IV). Conversely, maintaining BaU fishing to the end of century would result in 40% decline in catch potential. This demonstrates that management can mitigate or exacerbate the effects of climate change on ecosystem productivity.

Discussion

The results presented constitute the first effort to project fish and fisheries catch potential in the Bangladesh EEZ over the 21st century, combining state of the art regional climate models, associated river run-off and nutrient loading volumes, a shelf-specific biochemical model and two conceptually distinct high trophic level model frameworks. The results also assess the subsequent impacts of a number of plausible management scenarios in order to investigate the consequences of global environmental change and management options on the sustainability and food provision of Hilsa shad and Bombay duck.

Climate change showed a clear impact in the model projections, with sea surface temperatures rising by 2-3° C over the 21st century and the biggest increases generally in the north of the BoB. The change in net primary production for the whole domain is 3% or less (Table I), in line with the near-static values found by Bopp et al. (2013) in a global study and Blanchard et al (2012) for the Bay of Bengal. This overall small change hides sub-regional differences, with the east and west of the BoB showing different, and scenario-dependent patterns (Fig. 3); further modelling studies, with more up to date climate scenarios and a model domain that includes more of the Bay, would be needed to fully characterize this variation. Net primary production is positively correlated to temperature in the north-western part of the model domain, negatively correlated in the south. Production is weakly correlated to nitrate and phosphate values in the coastal and delta areas but strongly correlated for the deepest areas, suggesting that production is nutrient limited in the central Bay. Production in much of the Andaman Sea is correlated to nutrient values but not to temperature, suggesting that this shallow area is also nutrient-limited, but temperature seems to be a stronger factor for the GBM delta.

Projected change in net primary production for the Bangladesh EEZ is in the range 0-5% and, as for the wider bay, there are scenario-dependent areas of positive and negative change. Two of the three climate runs tested showed a rising trend in primary production, with the standard climate run the exception. The highest primary production was associated with reduced river flows and nutrient loadings, suggesting that the increase is more affected by changing temperature and sea dynamics than by river inputs. This is supported by analysis of correlations between the modelled nutrient levels and net primary production, which show a relatively weak link in the area of the EEZ.

In spite of the slight increase in primary production, the projections show a decrease in the potential fish production in the Bangladesh EEZ, of 0-10%. This is because at a higher temperature the steepness of the primary production and fish abundance relationship will increase. This means that there would be higher proportion of fish biomass of smaller size, but lower total fish biomass. As an example using a simple size-spectrum approach that uses only temperature and primary production (Jennings et al., 2008), at the same primary production level, an increase of 2 degrees in temperature can mean a 20% decrease in total biomass. Our model is more complex as it uses different phytoplankton and zooplankton functional groups and additional prey-predator relationships (Blanchard et al., 2012). Blanchard et al. (2012) project declines of 30-60% in tropical shelf and upwelling areas and an increase of pelagic predators by ca. 30-90% in high latitude shelf areas. This temperature driven effect has been also suggested for the Mediterranean Sea (Lejeusne et al., 2010) where temperatures have steadily increased. Hilsa migration is synchronous with the increase of the average water flow and increase in average temperature of river water (Haroon, 1998; Bhaumic et al., 2011). The preferred (optimum) temperature for Hilsa in the breeding ground is 29.3-30.2°C and in the nursing ground is 29.8-30.8°C. The surface temperature is the principal factor governing the distribution of Bombay duck in Bay of Bengal (Bapat 1970).

Official statistics reveal that marine and inland fish catches in Bangladesh have doubled since 1995 reaching 1.6 million tonnes per year, of which Hilsa has contributed *ca.* 350,000 tonnes (Fig. 6). Over the same period, the number of marine fishing boats and gears has increased about 4 times resulting in tremendous pressure on Hilsa populations. In addition, the intensity of marine catches has increased due to the introduction of nylon twine and mechanized boats (Rahman et al., 2012). Given that our results indicate no evidence of increased productivity, we conclude that such increase in catches is due to the increase in demand for fish on the Bangladeshi and global markets. Although, the population in the South-West coastal zone has not increased significantly between 2001 and 2011 (from 13.9 million to 14.1 million, Szabo 2015), because of rural to urban migration, the total population of Bangladesh has steadily increased from 135 to 153 million in the same period (2001-2011) and from 120 million to 158 million people during the 1995-2014 period (World Bank 2015). Fish takes up the majority of the animal protein intake in Bangladesh and its consumption has increased from 42.1 (2005) to 49.5 (2010) grams per capita per day (BBS 2011). This increase in fish intake was greater in urban areas (49.6 to 59.9 g per capita per day). Thus, the increasing domestic population coupled with changes in consumption levels and urbanisation might be responsible for the increasing commercial and subsistence fishing pressure.

The difference in trends between fish landings in the recent past (2000-2015, Fig. 6) and model projections over the same period (Fig. 5) deserves clarification. As mentioned above, historical landings reflect more than ecosystem and fish productivity, especially when management is not sophisticated enough to respond to interannual productivity cycles. There is no detailed spatial and temporal information available in Bangladesh to estimate the annual level of fishing pressure that resulted in the reported recent fish landings. In our simulations, however, we fix fishing mortality over the time of the simulation according to our defined management scenarios (Fig. 5). Thus, the trend and magnitude of the simulated catches within a single simulation reflects ecosystem productivity changes, while differences between simulations show the impact of a fixed fishing pressure on top of the effects of environmental variability. These trends are therefore not expected to match past landings, although their average is consistent with the yield obtained in the Business as Usual scenario.

Larger decreases are projected for the two main species compared to the total fisheries productivity change from the size-spectrum model, even under sustainable management practices. This apparent discrepancy can be caused by the potential replacement of species such as Hilsa shad and Bombay duck by alternative species, thus resulting in more stable total potential catches at ecosystem level. In the case of Hilsa Shad there are two fish species that have the potential to replace Hilsa Shad: Chacunda Gizzard Shad (*Anodontostoma chacunda*) and Toli Shad (*Tenualosa ilisha*). Due to their morphological similarity they are often confused with Hilsa on the markets, particularly if they are young, and are often sold as Hilsa, even though the real value of an adult is three times lower. It is known that the complexity of ecological interactions in the marine food web makes it difficult to extrapolate studies on individual species to community or ecosystem level (Walther et al. 2002). Thus, it is quite possible to observe differential impacts at the community level compared to species patterns. The second cause for this discrepancy is structural: overall fisheries potential is computed using a size-based model, while individual species responses rely on a species-based model. However, both models are forced with the same environmental data, and previous comparisons suggest that both model frameworks tend to have comparable outputs at the right scale (Barange et al. 2014).

Model runs that combine environmental change and management considerations demonstrate that the management options to be followed in coming decades are crucial for the sustainability of fisheries and their role as a nutritional and economic resource for the country. Hilsa shad is the largest fishery by volume, and a species with significant economic and cultural value. We showed that the implementation of sustainable management practices would stabilise the marine catch to *approx.*170,000 tonnes by the 2050s, at 70% of current catches, is likely to reduce Hilsa catches by up to 90% by 2050. A decrease in Hilsa shad catch of this order would have important consequences. While some fish sellers will be able to weather the storm by focusing on other alternative species, it is expected that the impact will be more severe for fishers that have adapted their practices to the dynamics of this species and its consumers' demand. As many of these fishers depend heavily on Hilsa any decline in Hilsa population will result in poorer living conditions for the people engaged in fishing. The cultural value (Urquhart et al., 2011) and unique taste of Hilsa, which drive its higher value and demand, make it unlikely that the loss of catches for this species will be compensated by fishing other species. This might cause a shift in the workforce from fishing to other livelihood options (Hossain et al., 2013; Nicholls et al., 2013). The loss of fishing livelihood may thus lead to migration to already over-crowded large cities in search of alternative livelihoods.

Bombay duck productivity is around half that of Hilsa shad, but the catches and biomass are more stable. Our projections indicate that catches of Bombay duck may not collapse as a result of unsustainable fishing practices and climate effects by 2060, contrary to projections for Hilsa. Sustainable practices would maintain current catches to a large extent. The reason for the different response compared to Hilsa relies on the fact that Hilsa shad has slightly higher estimated intrinsic population growth rates and adult movement rate (FishBase database; http://www.fishbase.org/) compared to Bombay duck, which makes it more abundant and widely distributed, allowing it to track environmental changes more closely but this also means that it is more sensitive to environmental and climate conditions. In addition, Bombay duck has a higher range of feeding options, from zooplankton, fish larvae and shrimp to other fish species of smaller size (Zhang and Jin, 2014); whereas Hilsa shad is mostly herbivorous though it does eat crustaceans (Dutta et al., 2014). Thus Bombay duck seems to be more resilient to changes in the marine food chain.

Despite the complexity of the modelling framework, there are still processes that may be under-represented, such as top-down effects (Kearney et al., 2012). Top-down pressures in terms of predator mortality is represented in the models as part of the natural mortality. There is some data about natural mortality of Hilsa, which had a mean value of 1.24 ± 0.08 in the period between 1992 and 2006 (Ahmed et al., 2008; BOBLME, 2010), however this is insufficient to say something quantifiable about top-down effects. Moreover, Hilsa is a highly fecund fish enabling it to compensate for any great loss of progeny which may occur due to predation and unfavorable hydrological conditions (Raja, 1985; de Graaf, 2003; Rahman and Cowx, 2006). There are several piscivorous species that have the potential to predate Hilsa and Bombay Duck (Bahadur, 2010; Murugan et al., 2012) such as sharks, Indian mottled eel (*Anguilla bengalensis*), narrow-barred Spanish mackerel (*Scomberomorus commerson*) tunas (*Kasuwonus pelamis*, *Thunnus albacares*,*Thunnus obesus*), dolphins (*Platanista gangetica gangetica*), seabirds and tooth whales (Nelson, 1998). However, top-predator studies (e.g. stomach content) in this area are rare (Sumontha et al., 2008; Thangavelu et al., 2012; Mazumder et al., 2014). In Sumontha et al. (2008), fish represented 38.9% of the stomach content of several tuna species, the rest were cephalopod. Thangavelu et al. (2012) shows predation of Greater lizardfish (*Saurida tumbil*) on Bombay Duck, but the study is too limited to determine if it is just an opportunistic predation. These fish species are all also fishing targets (Bahadur, 2010; DoF, 2013) and therefore susceptible to human pressures similar to their prey.

We have not considered in the model the impact that changes in the extension and composition of mangroves would have on fish production. Although the importance of mangroves as fish habitats and nursery grounds are recognized (Hoq, 2003; Chowdhury et al., 2010; Hutchison *et al.*, 2014), the exact impacts of changes are still uncertain and unquantified. Current research efforts aimed at the kind of quantification that would be needed for modelling relate only to indirect factors. For example, Hutchison *et al.* (2014) review work related to the impacts on primary production (Alonsegi, 2009; Harrison et al., 1997; O'Donohue and Dennison, 1997). Specific experimental and monitoring work would be needed before we can understand the role of mangroves in their ecosystems further than what-if scenarios.

The present study is part of a much broader analysis of coastal Bangladesh. The fisheries model and its results will be used in the integrated analytical framework of the Ecosystem Services of Poverty Alleviation In Populous Deltas (ESPA Deltas, www.espadelta.net) project, which will allow the detailed analysis of not only the fishery resources, but also the fishing livelihoods and its interactions with other provisioning ecosystem services such as agriculture. Since fishing is the second most important source of livelihood in coastal Bangladesh, the integrated model will allow the exploration of the future trajectories of the fishery sector through testing plausible scenarios as a tool to aid sustainable resource management and regional development planning.

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Tables

Table I

	Area	Climate scenario	Present day	Mid-century	End-century
SST (°C)	Bangladesh	Q0	28.3	29.5	30.6
precipitation (mm day^{-1})	EEZ		8.6	9.1	9.3
net PP (g C m^{-2} day^{-1})			1.65	1.67	1.66
river flow (×10^{10} m^3)			98	103	104
river nitrate (tonne)			345	321	370
river phosphate (tonne)			50	50	56
SST (°C)	BoB	Q0	29.5	30.8	31.7
precipitation (mm day^{-1})			6.9	7.2	7.5
net PP (mg C m^{-2} day^{-1})			1.26	1.24	1.24
SST (°C)	Bangladesh	Q8	28.4	29.9	31.0
precipitation (mm day^{-1})	EEZ		7.2	6.8	7.1
net PP (g C m^{-2} day^{-1})			1.68	1.77	1.78
river flow ×10^{10} m^3)			108	97	109
river nitrate (tonne)			370	319	334
river phosphate (tonne)			56	49	53
SST (°C)	BoB	Q8	29.5	30.8	31.9
precipitation (mm day^{-1})			3.2	6.0	5.9
net PP (mg C m^{-2} day^{-1})			1.29	1.33	1.29
SST (°C)	Bangladesh	Q16	29.2	30.8	32.1
precipitation (mm day^{-1})	EEZ		5.8	5.4	5.8
net PP (mg C m^{-2} day^{-1})			1.79	1.84	1.83
river flow ×10^{10} m^3)			94	97	108
river nitrate (tonne)			322	268	267
river phosphate (tonne)			48	52	55
SST (°C)	BoB	Q16	30.3	31.7	32.9
precipitation (mm day^{-1})			5.0	4.9	5.1
net PP (mg C m^{-2} day^{-1})			1.35	1.33	1.37

Table I. Illustration of the differences between the three climatic and hydrological scenarios used to drive the oceanic physical-biogeochemical model of the Bay of Bengal. Sea surface temperature (SST), precipitation and net primary production (net PP) data are given for the Bangladesh EEZ region, north of 18^{o}N, and for the whole BoB (in shaded rows). Present-day, mid- and end-century values are means for 1991-2010, 2041-2060 and 2081-2099 respectively. River flow and nutrient loadings are for the Ganges-Brahmaputra-Meghna (GBM) system only. Note that the river flow depends on precipitation in the Ganges and Brahmaputra basins, to the north and west of the model domain, and on patterns of river water extraction, rather than precipitation in the Bay of Bengal.

Table II

Area	Climate Scenario	Fish Class	2020s-2000s Δ change (%)	2050s-2000s Δ change (%)	2090s-2000s Δ change(%)
Bangladesh	Q0	Total (<120 cm)	-0.6	-4.9	-8.3
EEZ		<30cm	-0.7	-5.5	-9.1
		30-90cm	-1.0	-5.3	-9.0
BoB	Q0	Total (<120 cm)	-3.0	-7.3	-7.7
		<30cm	-3.2	-8.0	-8.8
		30-90cm	-2.9	-7.2	-7.7
Bangladesh	Q8	Total (<120 cm)	-0.7	-2.6	-2.6
EEZ		<30cm	-0.8	-3.1	-3.4
		30-90cm	-1.1	-3.3	-3.4
BoB	Q8	Total (<120 cm)	-0.3	-1.8	-5.3
		<30cm	-0.8	-2.4	-7.2
		30-90cm	-0.8	-2.4	-5.6
Bangladesh	Q16	Total (<120 cm)	-1.8	-1.3	-5.6
EEZ		<30cm	-2.4	-1.4	-6.5
		30-90cm	-2.1	-1.6	-6.4
	Q16	Total (<120 cm)	-1.9	-4.3	-3.5
BoB		<30cm	-4.4	-5.0	-2.2
		30-90cm	-1.8	-4.2	-3.7

Table II. Change in production potential in the 2020s, 2050s and 2090s decades (10-year averages), compared to the 2000s decade, by climate ensemble run. Potential production refers to total fish, and fish of <30cm and between 30-90cm, using a size-spectrum model.

Table III

		2020s-2000s	2050s-2000s	2000s	2020s	2050s
		Δ catch (%)	Δ catch (%)	Average catch (‘000 tonnes/yr)	Average catch (‘000 tonnes/yr)	Average catch (‘000 tonnes)
Hilsa Shad	MSY	-20.6 ± 14.5	-39.0 ± 20.1	283.0 ± 30.0	221.7 ± 14.9	168.5 ± 35.3
	BaU	-30.7 ± 12.7	-42.1 ± 7.6	227.9 ± 14.0	156.7 ± 19.7	101.3 ± 11.9
	OF	-29.3 ± 8.8	-87.2 ± 11.1	165.6 ± 3.0	116.9 ± 13.0	15.7 ± 13.6
Bombay Duck	MSY	-7.4 ± 4	-37.2 ± 4.0	124.2 ± 15.6	114.7 ± 10.2	77.8 ± 11.4
	BaU	-13.9 ± 1.9	-32.4 ± 7.0	98.2 ± 23.7	84.4 ± 19.5	57.3 ± 15.4
	OF	-19.2 ± 1.7	-33.5 ± 7.3	80.3 ± 20.7	65.0 ± 17.3	43.5 ± 13.6

Table III. Change in catch potential for Hilsa shad and Bombay duck in the 2020s and 2050s, referenced to the 2000s decade (in %), and average catch in each of the three decades (t/yr), according to three fisheries management scenarios. The reported values are the mean and standard deviation across Q climate scenarios.

Table IV

		2020s Δ catch (%)	2050s Δ catch (%)
Hilsa Shad	Present BaU to MSY	-2.5 ± 7.6	-25.9 ± 14.0
	Present BaU to BaU	-31.1 ± 8.3	-61.1 ± 11.0
	Present BaU to OF	-48.6 ± 5.6	-93.1 ± 5.2
Bombay Duck	Present BaU to MSY	20.9 ± 24.1	-18.0 ± 18.4
	Present BaU to BaU	-11 ± 24.4	-39.6 ± 18.1
	Present BaU to OF	-31.5 ± 20.4	-54.7 ± 15.1

Table IV. Change in catch potential for Hilsa shad and Bombay duck in the 2020s and 2050s, according to three fisheries management scenarios, referenced to the period 2000-2010 under the Business as Usual (BaU) scenario (in %). The reported values are the mean and standard deviation across the three climate ensemble runs.

Figures

Figure 1. Flowchart and structure of the models used to estimate the impacts and consequences of climate change and socio-economic scenarios on Bangladesh fisheries. The shaded boxes represent the models directly used in this paper.

Figure 2. Map of the Bay of Bengal showing the POLCOMS-ERSEM model domain (shaded), the position of river mouths in the model and the Bangladesh Exclusive Economic Zone. Diamonds show the position of rivers whose flow and nutrient loadings were estimated from the INCA model; circles indicate river flows and nutrients estimated using global databases (see text for details). Depth contours are shown for 100 and 1000 metres.

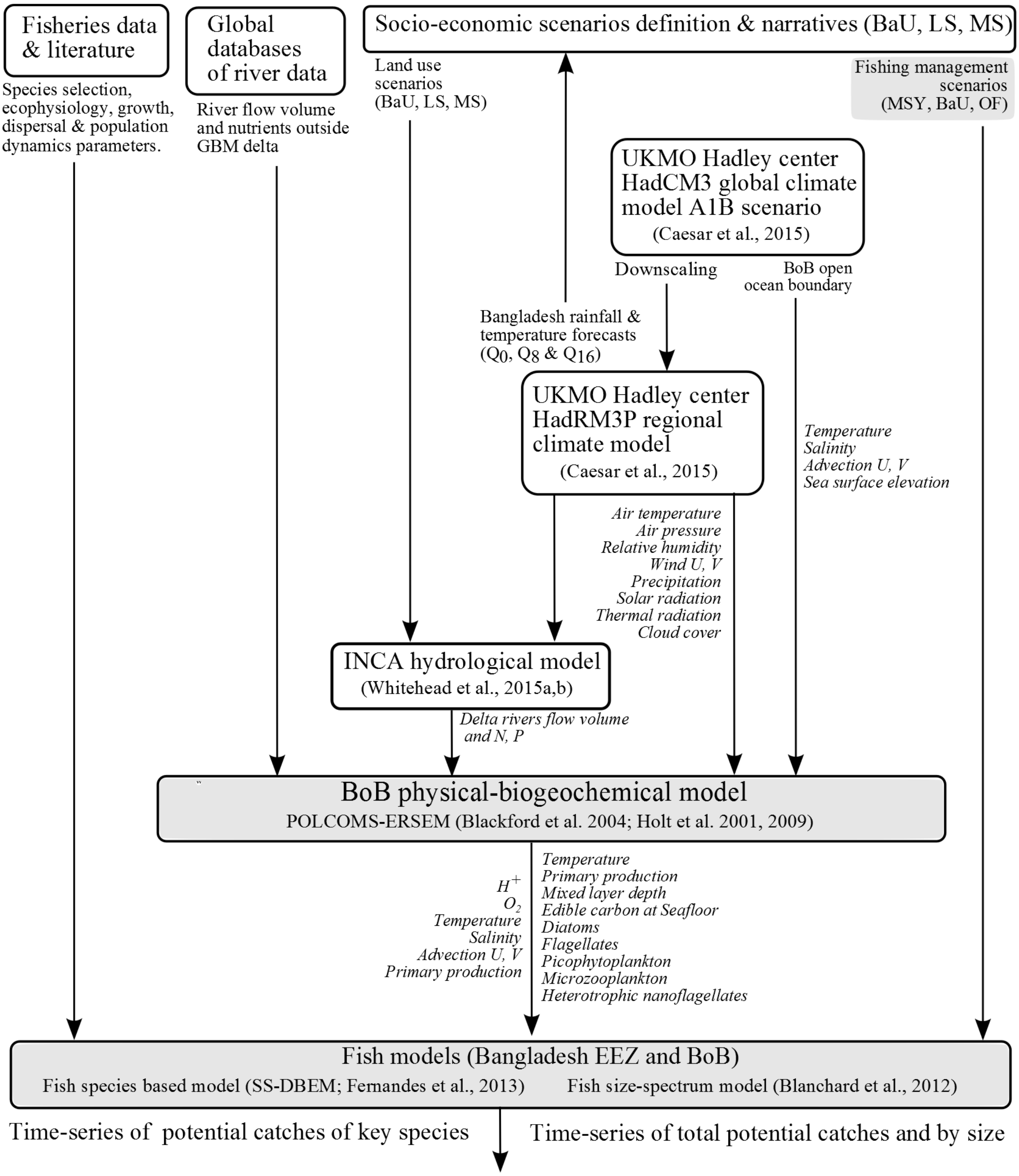
Figure 3. Changes in sea surface temperature (SST) and net primary production (net PP) projected by the Bay of Bengal model for the 2020s, 2050s and 2090s, compared to a baseline of values for the 2000s. The rows show results for the three climate ensemble runs Q0 (top row), Q8 (middle) and Q6 (bottom row). Changes in river flow volume, nitrate (N) and phosphate (P) loads of the GBM rivers are shown in the left hand panel of each pair, these values also hold for the right hand panel. Note that the SST legend changes for each time slice.

Figure 4. Time series of changes in projected total fisheries production potential in the Bangladesh EEZ according to the three climate ensemble runs (Q0, Q8 and Q16) and in the absence of fisheries extractions. Values are expressed as a percentage deviation from the 2000 production for each ensemble run.

Figure 5. Time series of catch potential projections (t) in the Bangladesh EEZ for Hilsa shad (A) and Bombay duck (B) under different fisheries management scenarios (MSY or Sustainable exploitation, BaU or Business as Usual and OF or Overfishing scenario). Error bars indicate variability between the three climate ensemble runs (Q0, Q8 and Q16) and associated river run-off and nutrient loadings.

Figure 6. Time series of marine and inland catch (Total and for Hilsa shad) and total aquaculture production in Bangladesh since 1950 (source: FAO Global database).

Figure 1



Fisheries data & literature
Species selection, ecophysiology, growth, dispersal & population dynamics parameters.
Global databases of river data
River flow volume and nutrients outside GBM delta
Socio-economic scenarios definition & narratives (BaU, LS, MS)
Land use scenarios (BaU, LS, MS)
Fishing management scenarios (MSY, BaU, OF)
UKMO Hadley center HadCM3 global climate model A1B scenario
(Caesar et al., 2015)
Downscaling
BoB open ocean boundary
Bangladesh rainfall & temperature forecasts (Q_0, Q_8 & Q_{16})
UKMO Hadley center HadRM3P regional climate model
(Caesar et al., 2015)
Temperature
Salinity
Advection U, V
Sea surface elevation
Air temperature
Air pressure
Relative humidity
Wind U, V
Precipitation
Solar radiation
Thermal radiation
Cloud cover
INCA hydrological model
(Whitehead et al., 2015a,b)
Delta rivers flow volume and N, P
BoB physical-biogeochemical model
POLCOMS-ERSEM (Blackford et al. 2004; Holt et al. 2001, 2009)
H^+
O_2
Temperature
Salinity
Advection U, V
Primary production
Temperature
Primary production
Mixed layer depth
Edible carbon at Seafloor
Diatoms
Flagellates
Picophytoplankton
Microzooplankton
Heterotrophic nanoflagellates
Fish models (Bangladesh EEZ and BoB)
Fish species based model (SS-DBEM; Fernandes et al., 2013)
Fish size-spectrum model (Blanchard et al., 2012)
Time-series of potential catches of key species
Time-series of total potential catches and by size

Figure 2

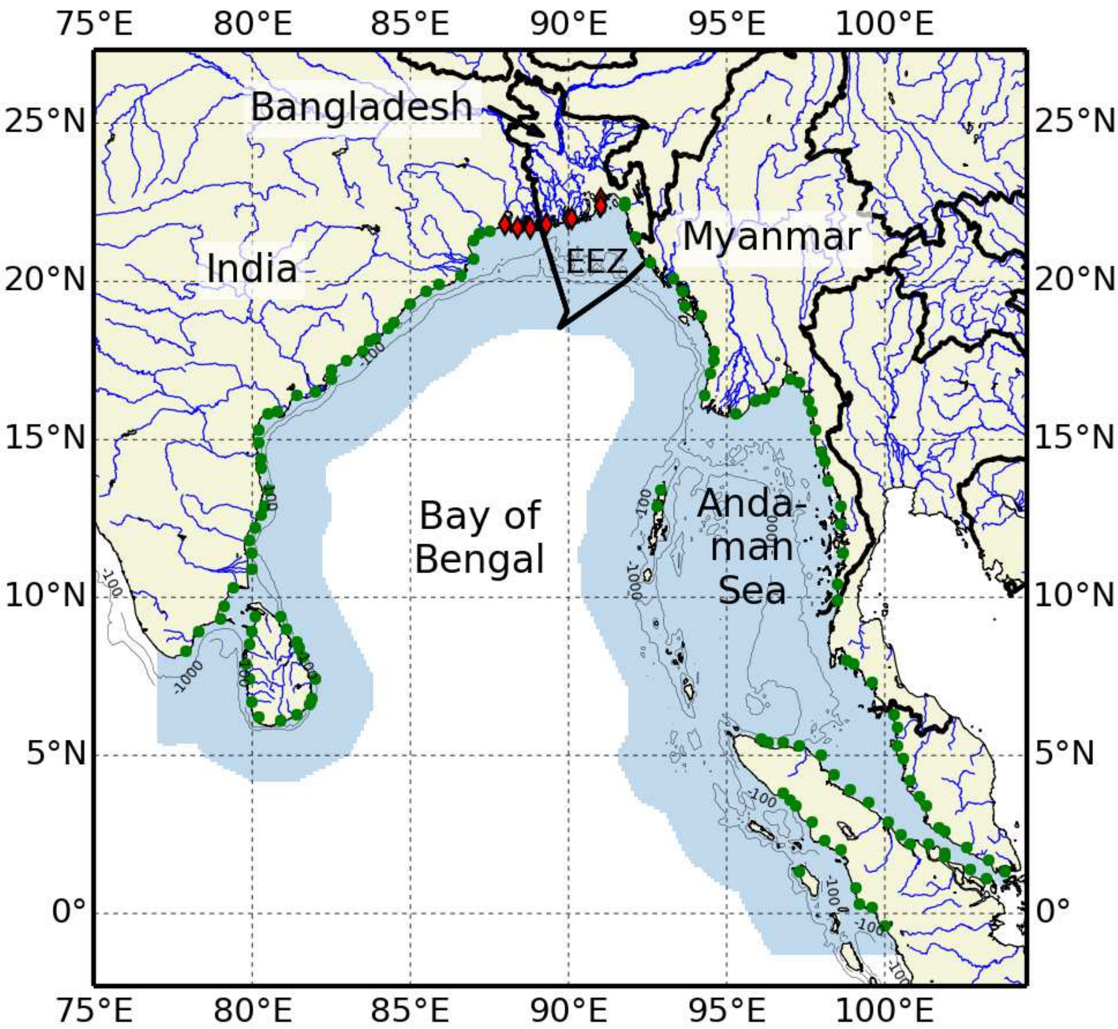

75°E
80°E
85°E
90°E
95°E
100°E
25°N
20°N
15°N
10°N
5°N
0°
Bangladesh
India
EEZ
Myanmar
Bay of Bengal
Andaman Sea
-100
-1000

Figure 3.

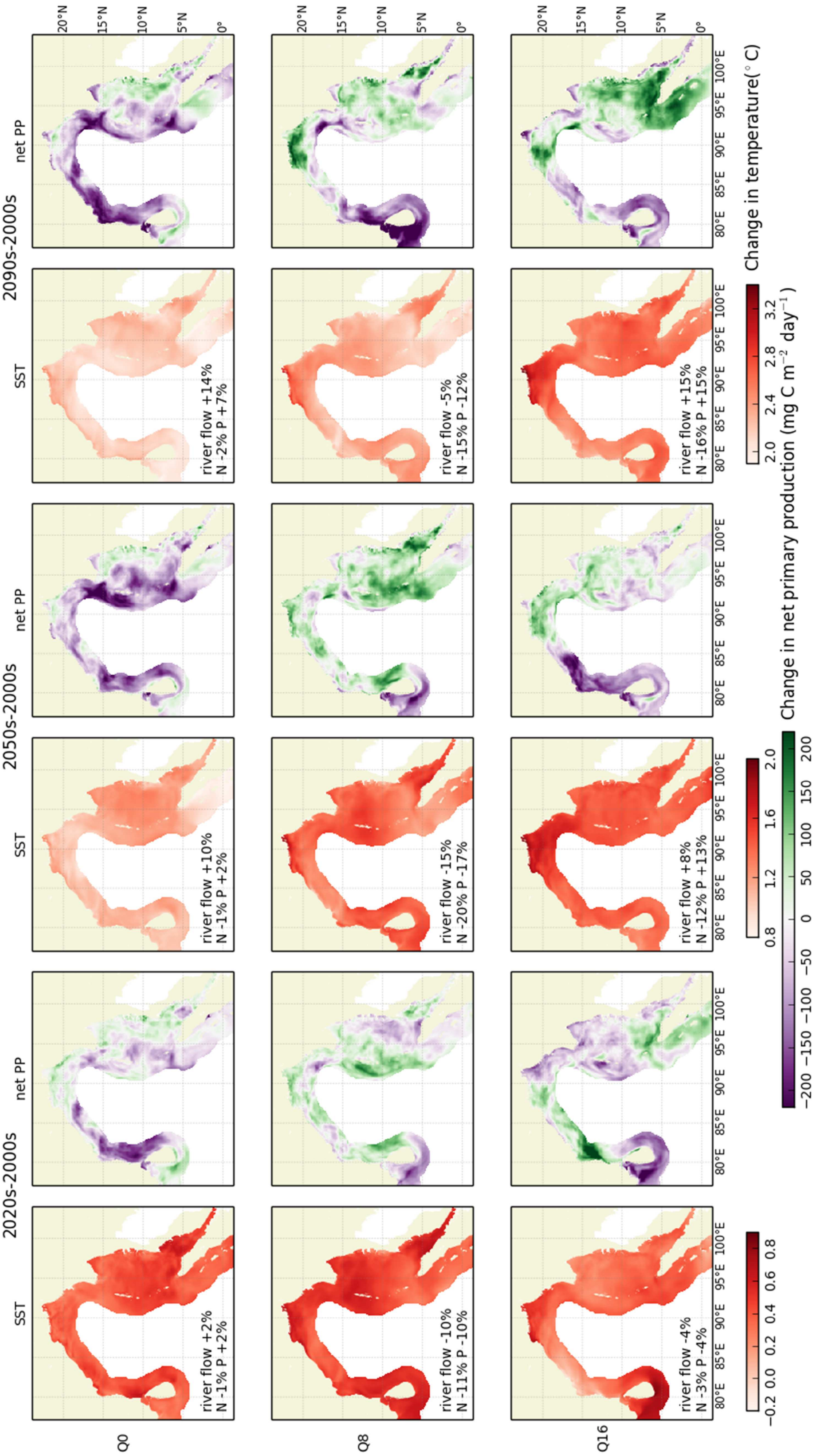

2020s-2000s
2050s-2000s
2090s-2000s
SST
net PP
Q0
Q8
Q16
river flow +2%
N -1% P +2%
river flow +10%
N -1% P +2%
river flow +14%
N -2% P +7%
river flow -10%
N -11% P -10%
river flow -15%
N -20% P -17%
river flow -5%
N -15% P -12%
river flow -4%
N -3% P -4%
river flow +8%
N -12% P +13%
river flow +15%
N -16% P +15%
Change in temperature(°C)
Change in net primary production (mg C m^{-2} day^{-1})

Figure 4.

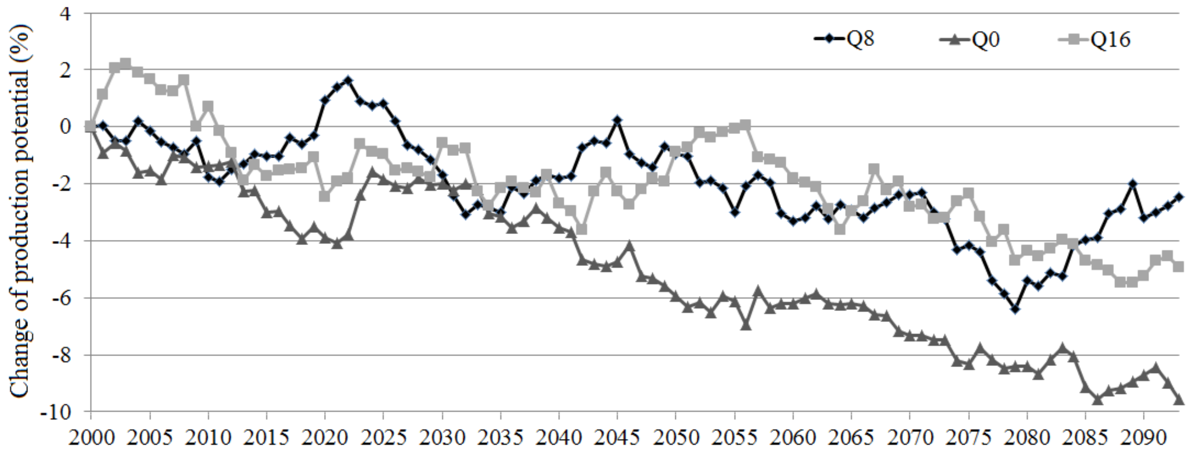

Q8
Q0
Q16
Change of production potential (%)
4
2
0
-2
-4
-6
-8
-10
2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090

Figure 5.

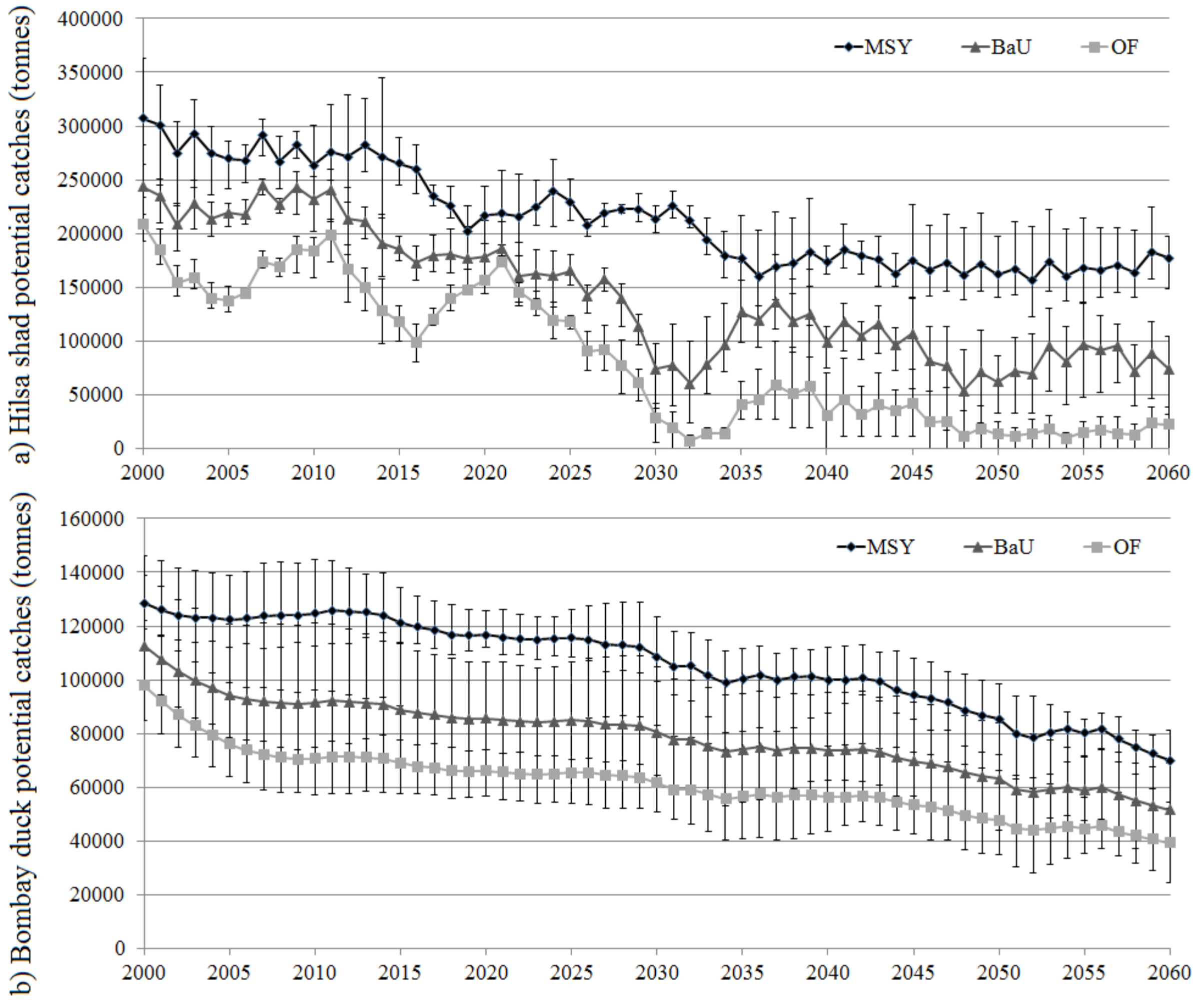
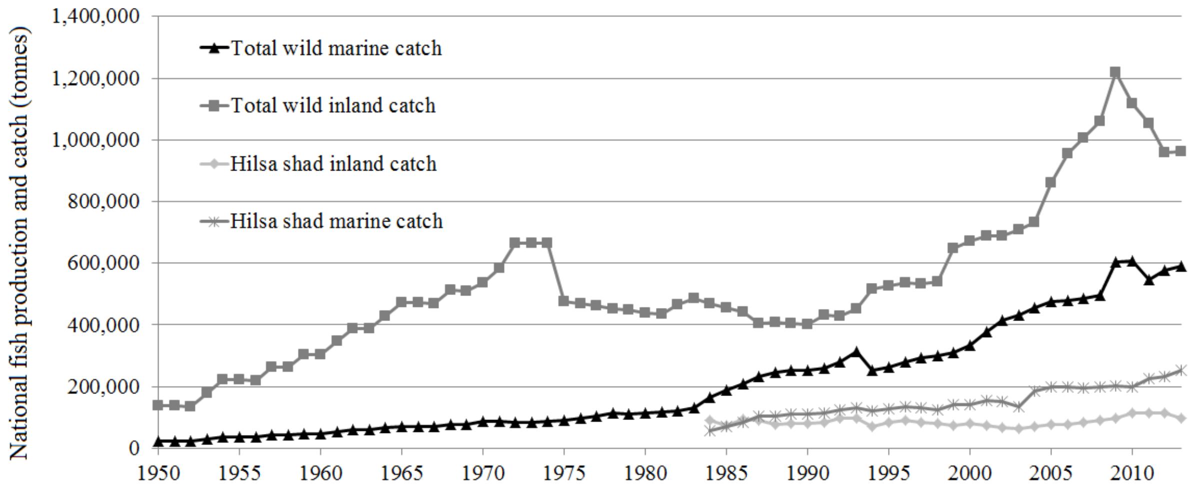

a) Hilsa shad potential catches (tonnes)
400000
350000
300000
250000
200000
150000
100000
50000
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
MSY
BaU
OF
b) Bombay duck potential catches (tonnes)
160000
140000
120000
100000
80000
60000
40000
20000
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060
MSY
BaU
OF

Figure 6


National fish production and catch (tonnes)
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Total wild marine catch
Total wild inland catch
Hilsa shad inland catch
Hilsa shad marine catch