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UNIVERSITY OF SOUTHAMPTON

FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES

Academic Unit of Geography and Environment

Safe Operating Space for Development and Ecosystem Services in Bangladesh

by

Md Sarwar Hossain Sohel

Thesis for the degree of Doctor of Philosophy (PhD)

Supervisor:

Prof John A Dearing   Dr Felix Eigenbrod   Dr Fiifi Amoako Johnson

November 2016

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES
Geography and Environment
Doctor of Philosophy (PhD)

Safe Operating Space for Development and Ecosystem Services in Bangladesh

By Md Sarwar Hossain Sohel

This thesis makes a first attempt to operationalize the safe operating space concept at regional scale by considering the dynamic relationships between social and ecological systems. Time series data for a range of ecosystem services (ES) and human wellbeing (HWB) are analysed to understand the co-evolution (trends, change points, slow and fast variables and drivers) of the Bangladesh delta social-ecological system (SES). The linkages between ES and HWB are analysed using regression models (GAM, linear and logistic) to develop a system model, which is used in a system dynamic (SD) model to demonstrate the safe operating space for the SES in the Bangladesh delta. I employ the model to explore eight 'what if' scenarios based on well-known challenges (e.g. climate change) and current policy debates (e.g. subsidy withdrawals).

Since the 1980s, HWB has improved in the Bangladesh delta mirroring rising levels of food and inland fish production. In contrast, ES have deteriorated since the 1960s in terms of water availability, water quality and land stability in the Bangladesh delta. The overall results suggest that material well-being (basic materials for a good life) have a strong relationship with provisioning services, which in turn, show a weak relationship with the quality of life (security and health). The SD model suggests that the Bangladesh delta may move beyond a safe operating space when a withdrawal of a 50% subsidy for agriculture is combined with the effects of a 2 ^{o}C temperature increase and sea level rise. Further reductions in upstream river discharge in the Ganges would push the system towards a dangerous zone once a 3.5 ^{o}C temperature increase was reached. The social-ecological system in the Bangladesh delta may be operated within a safe space by: 1) managing feedback (e.g. by reducing production costs) and the slow biophysical variables (e.g. temperature, rainfall) to increase long-term resilience, 2) negotiating for transboundary water resources and 3) also possibly by revising the global policy (e.g. withdrawal of subsidy) to implement at regional scale. This study demonstrates how the concepts of tipping points, limits to adaptations and boundaries for sustainable development may be defined in real world social-ecological systems.

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DECLARATION OF AUTHORSHIP

I, Md Sarwar Hossain Sohel
declare that this thesis

Safe operating space for development and ecosystem services in Bangladesh

and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

3. Where I have consulted the published work of others, this is always clearly attributed;

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

5. I have acknowledged all main sources of help;

6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. Parts of this work have been published as and the declaration for the author's contributions for each papers are as follows:

Paper 1: Hossain MS, Dearing JA, Rahman MM, Salehin M (2015) Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone. Regional Environmental Change. DOI:10.1007/s10113-014-0748-z

Hossain MS: Designed the research, collected data, performed analyses and wrote the paper
Dearing JA: Supervised the research design and analysis, suggested alternatives, corrected and commented on the manuscript.
Rahman MM and Salehin M: Commented on the manuscript.

Paper 2: Hossain MS, Johnson FA, Dearing JA, Eigenbrod F (2016) Recent trends of human wellbeing in Bangladesh delta. Journal on Environmental Development. doi:10.1016/j.envdev.2015.09.008

Hossain MS: Designed the research, collected data, performed analyses and wrote the paper
Johnson FA, Dearing JA and Eigenbrod F: Supervised the research design and analysis, commented on the manuscript and proof read on the final manuscript.

Paper 3: Hossain MS, Eigenbrod F, Johnson FA, Dearing JA (2016) Unravelling the interrelationships between ecosystem services and human wellbeing in the Bangladesh delta. International journal on sustainable development and world ecology. http://dx.doi.org/10.1080/13504509.2016.1182087

Hossain MS: designed the research, collected data, performed analyses and wrote the paper
Eigenbrod F, Johnson FA and Dearing JA: Supervised the research design and analysis, suggested alternatives, commented on the manuscript and proof read on the final manuscript.

Paper 4: Hossain MS, Dearing JA, Eigenbrod F, Johnson FA (In review) Operationalizing safe operating space for regional social-ecological systems. Science of the Total Environment
Hossain MS: Designed the research, collected data, performed analyses, carried out modelling and wrote the paper

Dearing JA , Eigenbrod F and Johnson FA: Supervised the research design and analysis, suggested alternatives, commented on the manuscript and proof read on the final manuscript.

Supplementary material: Chapter 5: Hossain MS, Dearing JA, Jhonson FA, Eigenbrod F (2016) Participatory modelling as the basis for a conceptual system dynamic model of the social-ecological system in the Bangladesh delta. The South Asian Network for Development and Environmental Economics (SANDEE), working paper (In press)

Hossain MS: Designed the research, undertook the fieldwork, performed analyses and wrote the paper
Dearing JA, Jhonson FA, Eigenbrod F: Supervised the research design, commented on the manuscript.

Hossain MS and Dearing JA (2013) Recent trends of ecosystem services and human wellbeing in the Bangladesh delta. Working paper #3, ESPA Deltas.

Hossain MS: Designed the research, undertook the fieldwork, performed analyses and wrote the paper. Dearing JA: Supervised the research design, commented on the manuscript and proof read on the final manuscript.

Conference presentation

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Hossain MS, Dearing JA, Eigenbrod F, Johnson FA (2016) Participatory modelling as the basis for a conceptual system dynamic model of the social-ecological system in the Bangladesh delta. International Conference on Sustainable Development, Dhaka, Bangladesh.

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Signed: ....
Date: ....

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Definitions and Abbreviations

ES- Ecosystem services

HWB- Human wellbeing

MDGs- Millennium Development Goals

SDGs - Sustainable Development Goals

SD- System dynamic

SES- Social-ecological system

SOS- Safe operating space

Chapter 1 Introduction

1.1. Background

The safe operating space for humanity concept provided through the planetary boundary framework (Rockström et al. 2009a; Rockström et al. 2009b) has attained significant policy and academic attention in sustainability science. Although this concept is rapidly becoming more prevalent in policy, it is not a completely new concept, but is built upon ideas such as 'limits to growth' (Meadows et al. 1972), 'ecological footprint', and 'carrying capacity' (Bass 2009). Rockström et al. (2009a) defined the boundaries of the 'SOS' beyond which the risk of unpredictable and damaging change to SESs becomes very high. The 'SOS' is defined based on biophysical data from the Holocene (the last 11,000 years) as baseline markers and applied to nine biophysical processes, namely, climate change, ocean acidification, stratospheric ozone, biogeochemical flows (nitrogen and phosphorus cycle), fresh water, land use and biodiversity. Amongst these, humanity has already exceeded the safe zone for climate change, biodiversity and the nitrogen cycle. Despite attaining significant policy attention (e.g. Rio +20, Planetary boundaries for Sweden by Swedish Environmental Protection Agencies, Switzerland Government and Oxfam), the operationalization of this concept has been criticized in terms of normative settings of the boundaries, exclusion of the social system, scale and interaction among the biophysical processes (Dearing et al. 2014; Lewis 2012; Raworth 2012). Defining the boundaries for each biophysical process is one of the main points of debate and has been improved further by using a more specific approach (e.g. net primary plant production (Erb et al 2012 and Running 2012) and phosphorus (Carpenter and Bennett 2011)). The planetary boundary concept did not include the social system that drives us towards many of the boundaries. That is why, considering the inequality of global resource distribution and use, Raworth (2012) introduced the doughnut framework, which integrates social foundations (food, water, gender equality, energy, income, education, social equity, jobs, voice, resilience, health) into the planetary boundaries concept. These dimensions captured the priorities of government sub-missions to the UN

Rio+20 Conference in 2012 and measured the deprivation indicators focusing the MDGs. Because of the integration of development goals in to planetary boundaries, this framework gained interest in UN General Assembly and other policy debates (IIED 2012). However, the doughnut framework does not identify the boundaries for social foundations, which could be set as per the national, regional or global scale norms, but highlights the possibility of increasing poverty if planetary boundaries are exceeded. For example, Bangladesh, which has high levels of poverty (~40% people are below the upper poverty line) and is one of the countries most vulnerable to climate change, is at a high risk of poverty increase for transgressing the boundary of climate change (Ahmed et al. 2009).

Lewis (2012) and Nordhaus et al. (2012) argued that with the exception of global climate change, stratospheric ozone and ocean acidification, the remainder of the planetary boundaries are aggregated from regional scale problems such as land use. Therefore, setting the boundary at a global scale may mislead regional scale policy choices. Hence, Dearing et al. (2014) proposed a new framework to operationalize the doughnut concept at the regional scale. This new framework has been applied to Chinese case studies to the SOS as the space between sustainable and unsustainable use of ecological process using the system behaviour of ecological variables for the environmental ceiling and using minimum standards of human outcomes (e.g. health, energy, food) for social foundations. When using system behaviour to define SOS, Dearing et al. 2014 proposed 4 types of dynamic properties, which include linear trends (e.g. environmental limit), non-linear trends (e.g. envelope of variability), thresholds (e.g. hysteretic changes) and early warning signals. Cole et al. (2014) also demonstrated the operationalization of the doughnut concept at a national scale by engaging stakeholders to define safe and just operating spaces for the environmental and social dimensions according to the national priorities.

The planetary boundary concept excludes the interactions among the biophysical boundaries and the complex interactions between social and ecological systems. For example, changes in climatic conditions (e.g. higher temperature) in Tibet directly affect water resources in Asia through higher evaporation rates (Rockström et al. 2009a). Deterioration in the status of water resources interacts with the climate system, leading to a higher sensitivity to climate (e.g. higher temperature) (Hossain et al. 2015; Adel 1999). Therefore, defining the boundaries for climate and water resources without considering the interactions between them could lead to erroneous conclusions being drawn.

The planetary boundary concept also excludes the complex interactions between the social and ecological sub-systems, e.g., as a result of the deterioration of water resources due to a warming climate, the social system may respond to changes in climatic conditions by extracting more groundwater and using more fertilizer for agricultural purposes. If these changes become self-perpetuating, then groundwater and water quality (increased fertilizer use leads to deterioration of water quality) will transgress the boundary due to the social response towards changes in climatic conditions. Therefore, the lack of dynamicity in both frameworks (planetary boundary and doughnut) could limit the utility of these concepts at a policy level and within the wider decision making community. Even recent developments (e.g. Hoornweeg et al. 2016; Dearing et al. 2014; Cole et al. 2014) on planetary boundaries do not consider the interactions among the biophysical boundaries and the complex interactions between social and ecological systems.

Here, we make a first attempt to fill these gaps, by applying these integrative concepts at the regional scale, by focusing on regional problems and most importantly by considering the interactions between the social and ecological systems. Therefore, we aim to operationalize the SOS concept at the regional scale for the SES by answering the following four research questions (RQ):

1. How has the SES evolved over the past five decades?
2. How is the SES interlinked?
3. What is the proximity of the SES to a major tipping point?
4. What are the boundaries of the safe operating spaces of the SES?

The overall approach to operationalize the SOS concept at the regional scale comprises three steps: (1) analysing (RQ1 & RQ2) available multi-decadal time-series of social, economic and biophysical variables to understand the evolution (trends, drivers and trade-offs) of the SES over time; (2) developing a conceptual understanding (RQ3) of the SES through the analysis of the relationships (e.g. strength, feedbacks, nonlinearity) between the trends of ecosystem services (ES) and human wellbeing (HWB) between 1960 and 2010; and (3) using system dynamics modelling to consider the interactions (e.g. feedbacks, thresholds) of the SES and to demonstrate the SOS in the Bangladesh delta (RQ3 & RQ4).

1.2 Case study area- The Bangladesh delta

The south west coastal area of Bangladesh has been selected as the case study area (Figure 1.1). This area represents 16% of the total land area (~25,000 km2) of Bangladesh with a population of 14 million people (BBS 2010). The humid climate of this region gives an annual rainfall of 1400–2100 mm and an average temperature of 30–34°C in the dry summer period and 15–20°C in winter (Hossain et al. 2014). This study area is selected for the following reasons:

1) Social-ecological system: This coastal ecosystem produces more than 1300 million USD of gross domestic product (GDP) (BBS 2010) which contributes to 277 USD GDP per person (Sarwar 2005). However, around 38% of the people of this region live below the poverty line (BBS 2010). The livelihoods in this region are dependent on agriculture (~40%), fishery (~20%) and forestry (~25%) with the remainder including labourers and professionals (e.g. teachers, government officials and businessman). The Sundarbans, the world's largest mangrove ecosystem, provides livelihoods for about 1.5 million people and protects about 10 million coastal people from storm surges (Islam & Haque 2004). This biodiversity-rich ecosystem (453 animal species and 22 families of trees representing 30 genera) provides a livelihood for ~3 million people (Iftekhar and Saenger 2008; Iftekhar and Islam 2004).

2) Threats of environmental degradation: Recorded statistics of death and destruction alone confirm that Bangladesh is one of the most climate vulnerable countries in the world (Maplecroft 2010; Ahmed et al. 1999). The region has been affected by 174 natural disasters within the 1965–2010 time period (Rahman et al. 2010). Floods in 1992 damaged 50% of total food grain, and drought in 1997 caused 1 million tons of food grain loss (Islam et al. 2011). Besides these natural disasters, the region is also experiencing challenges due to human intervention, including water shortages due to dam construction upstream of the Ganges delta (Hossain et al. 2015) and polder construction in coastal areas (Islam 2006). Moreover, expansion of the shrimp industry has degraded the water quality as well as the density of the mangrove forest (Hossain et al. 2015). The social-ecological system of this region is rapidly changing in comparison to previous decades, because of sea level rise, land-use changes, water scarcity, migration and urbanization (ADB 2005) with climate change (Hossain et al. 2013) adding an extra layer of complexity for environmental managers. The high

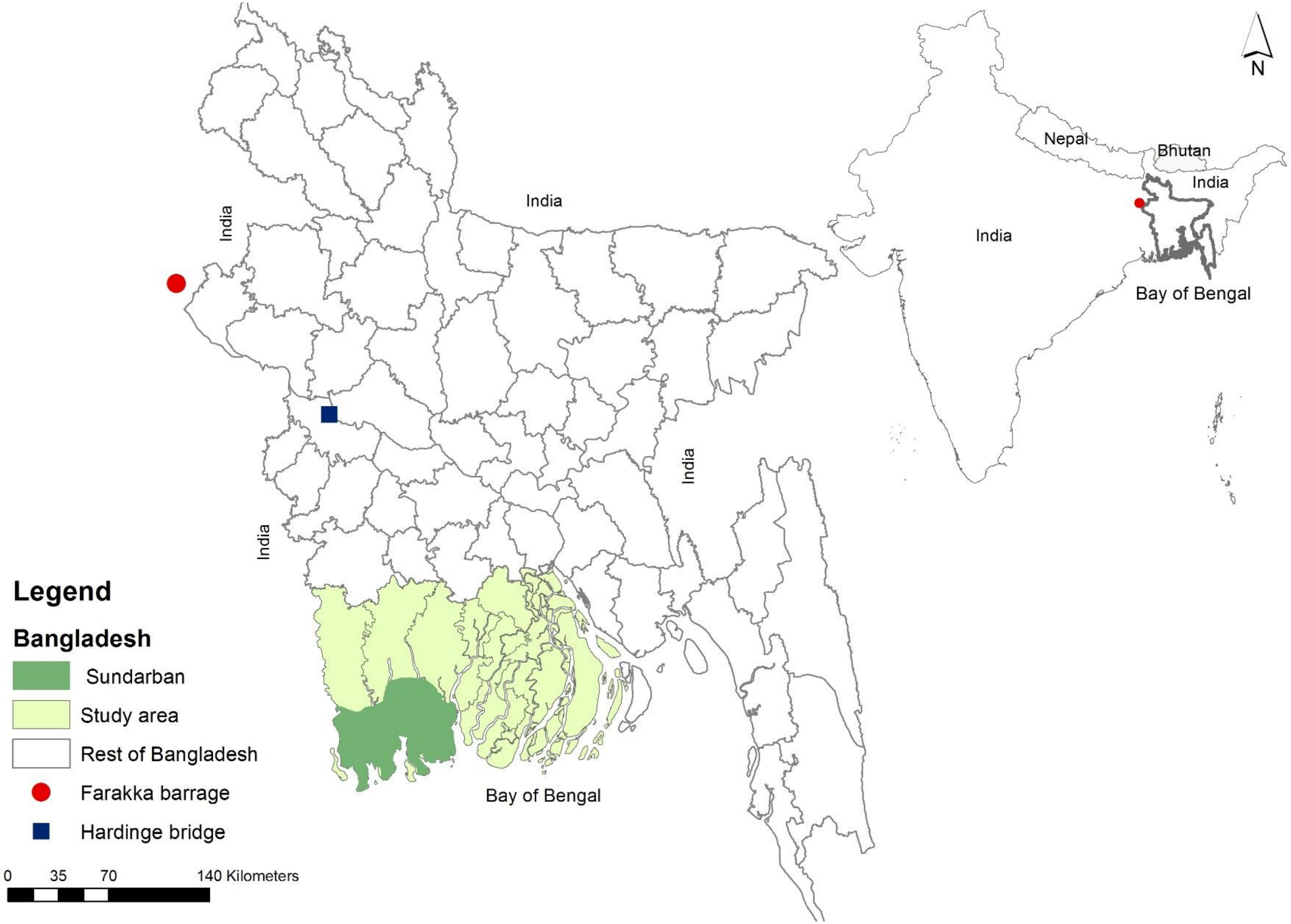

Figure 1.1 The Bangladesh map showing (left): the study area, the sundarbans and the location of Farakka barrage (red circle) and the river discharge data at Hardinge birdge (blue square). The South Asian map (right) showing: the location of Bangladesh and the location of Farakka barrage.

dependency of the residents' livelihoods on ES and their ability to adapt to growing environmental threats underpins the importance of treating the area as a highly complex social–ecological system.

3) System boundaries and the ESPA delta project: This area comprises 60% of the Khulna Division and the whole Barisal Division, an agro-ecological landscape representative of the Ganges tidal floodplain (FAO-UNDP 1998). The more severe salinity problem experienced by this region compared to the rest (40%) of the Khulna division (Sarker 2005) and mapping onto the linked ESPA delta project area (www.espadelta.net) are reasons for the selection of this 60% of the Khulna Division. Furthermore, it facilitates the comparison of the different methods used in the ESPA deltas project within the study area.

4) Familiarity with the area due to my citizenship, educational and professional experience in this specific region was another reason for selecting this area. This provided me with an advantage in collecting data for a wide range of indicators at the regional scale. Although the national scale data is available through the websites of national and international organizations, regional scale data is scarce, complicated to collect and requires familiarity with the databases, which are often not digitalized. Therefore, familiarity with this region and my greater access to data was one of the prime reasons to select the southwest coastal area as the study area.

1.3 Thesis structure

Following the three paper PhD format of University of Southampton, this thesis consists of 4 core papers which explored the answers of the above four research questions. In addition, one working paper which links the 3rd and 4th papers, has been included as appendix. Each of the research papers has a unique set of aims, its own literature review and conclusions relating to specific research questions. All these four papers are linked by the overarching theme of operationalizing the SOS concept at regional scale. Chapter 1 provides an overall background for the thesis and Chapter 6 provides the conclusion of the whole thesis. A more detailed description of each of the papers according to the research questions is given below.

Chapter 2: Paper 1. Recent trends in ES and HWB

In this first paper, time series data for a range of ES and drivers are analysed to define the range of trends, the presence of change points, slow and fast variables and the significant drivers of change. Time series of indicators for the ES and human well-being are collected from official statistics, published reports and articles. As well as visual inspection, statistical analyses (e.g. Mann–Kendall, Lepage test) are used to discriminate between improving, deteriorating and stable trends and to understand the evolution (trends, drivers and trade-offs) of the SES. Slow and fast variables of ecosystem services are also identified, where the slow variables are the controlling and shaping variables for system resilience (Biggs et al. 2012; Walker et al. 2012). It then presents the results of analysis and discussion on ES, economic growth and well-being. Environmental Kuznets curves have been used to show the relationship between wealth and environmental degradation over time. In addition, a comprehensive literature review is combined with statistical analysis through bivariate plots and correlation analysis to recognize the drivers of changes in relation to the observed trends and to identify tipping points. A tipping point occurs if the system shows at least one of the following characteristics identified by the CBD (2010): 1) changes become self-perpetuating through so-called positive feedbacks; 2) thresholds; 3) long lasting changes that are difficult to reverse; 4) time lag between drivers and impacts.

Chapter 3: Paper 2. Recent trends in HWB

In the first paper, we mostly focused on the ES, and only selected a few human well-being indictors to show the aggregated trends at the three regions in the study area. We extend our focus on HWB trends in the second paper, by analysing Household and Income Survey (HIES) and Demographic Health Survey (DHS) data from 1995 to 2010. Trends and drivers of trends provide insights to the human well-being trends at household level in respect to the Millennium Development Goals (MDGs) and provides policy implications for SDGs by 2030.

Chapter 4: Paper 3. The interrelationships between ES and HWB

This paper uses the summarized information from the previous two papers, and extends the analysis of the relationships (e.g. strength, feedbacks, nonlinearity) between the trends of ES and HWB between 1960 and 2010. Analysis of the relationship comprises two steps: 1) analyzing the relationships between regulating services (e.g. local climate, water availability) and provisioning services indicators (e.g. food, forest products); 2) analyzing the relationships between provisioning services and HWB indicators (e.g. income, education). The relationship analysis also includes external drivers such as sea level rise and damage of crops due to natural disasters. System connectedness was also analysed to measure the resilience in the SES. Results from these analyses and literature are used to develop a system dynamic (SD) framework in order to investigate how ES and HWB are interlinked. This system model provides the context for SD modelling to demonstrate SOS at regional scale.

Chapter 5: Paper 4. Operationalizing safe operating space for regional social-ecological system.

In this final paper, synthesized information has been used from the previous papers for familiarization and problem definition as part of the SD modelling. The structure of the system model developed in paper 3 has been validated using stakeholder engagement. The detailed methodology of this stakeholder engagement for system model validation has also been provided in Appendix D. The fourth paper includes the testing and validation of the model and explores the dynamic behavior of SES using eight 'What if' scenarios to define SOS at regional scale.

The overall structure of the thesis according to the papers, research questions and linkages among the papers is conceptualized in Figure 1.2 While challenges, study limitations and implications for future research are discussed in each paper, the concluding chapter of this thesis also revisits and summarizes findings from the study, presents overall challenges, and further developments

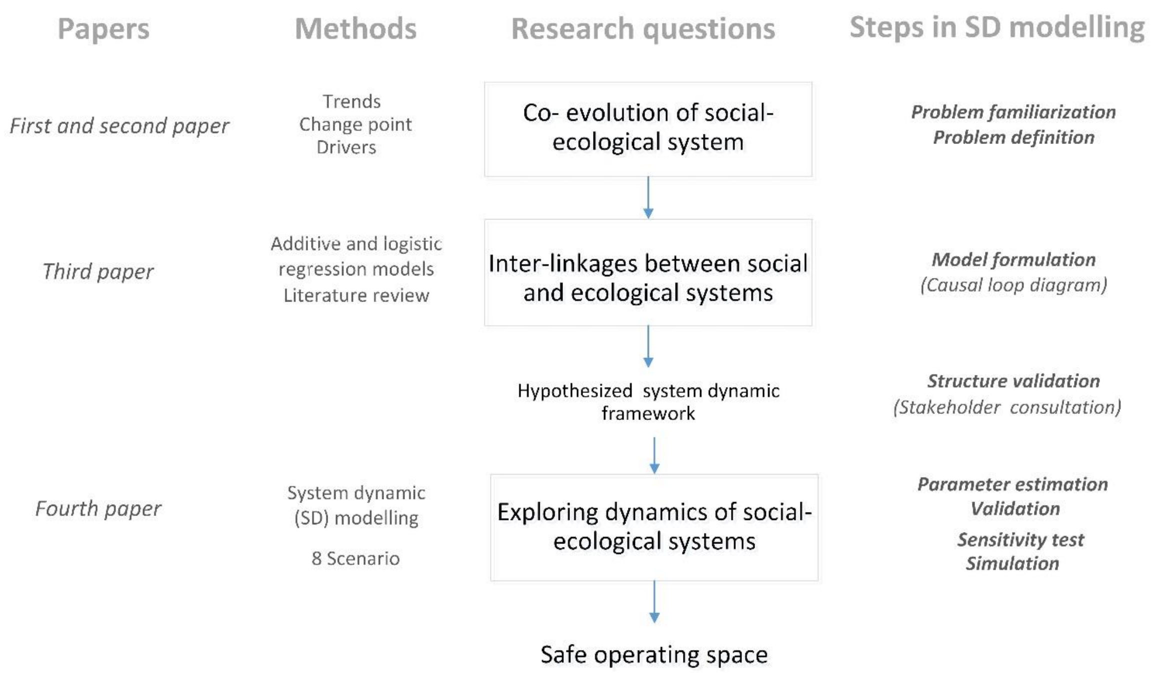

Figure 1.2 This figure depicts the methodological flow diagram of the thesis, and shows links among papers, research questions, methods and steps for SD modelling required for fourth paper.

Chapter 2: Paper 1

Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone

2.1 Abstract

This study takes a historical approach in order to establish how the form and function of the SES that represents the Bangladesh south-western coastal zone has changed over recent decades. Time series data for a range of ES and drivers are analysed to define the range of trends, the presence of change points, slow and fast variables and the significant drivers of change. Since the 1980s, increasing gross domestic product and per capita income mirror rising levels of food and inland fish production. As a result, the size of population below the poverty line has reduced by ~17 %. In contrast, non-food ES such as water availability, water quality and land stability have deteriorated. Conversion of rice fields to shrimp farms is almost certainly a factor in increasing soil and surface water salinity. Most of the services experienced statistically significant change points between 1975 and 1980, and among the services, water availability, shrimp farming and maintenance of biodiversity appear to have passed tipping points. An environmental Kuznets curve analysis suggests that the point at which growing economic wealth feeds back into effective environmental protection has not yet been reached for water resources. Trends in indicators of ES and HWB point to widespread non-stationary dynamics governed by slowly

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changing variables with an increased likelihood of systemic threshold changes/tipping points in the near future. The results will feed into simulation models and strategies that can define alternative and sustainable paths for land management.

Keywords: Bangladesh, Delta, Ecosystem services, Well-being, Trend analysis, Tipping points.

2.2. Introduction

The idea that adaptive management of ecosystems needs to capture the complex dynamics of SES (Liu et al. 2007) has rapidly gained ground over the past decade. It is recognised that society requires a more complete understanding of the interactions between social conditions, ecosystems and external drivers than hitherto so that it can respond to environmental feedback and change (e.g. Folke et al. 2005). Ostrom (2007) suggested that such an understanding implies the ability to diagnose the problems and potentialities of SES and established a nested, multi-tier framework for this purpose. Biggs et al. (2012) made the case that fostering an understanding of SES as complex adaptive systems should represent one of the key principles for managing ES. But although it is generally agreed that livelihoods, security from disasters and access to key resources may be increasingly dependent upon ES (MA 2005), it is far from clear how the complex dynamics of ES can be studied. Indeed, Norgaard (2010) argues that the ecosystem service metaphor actually blinds us to the complexity of natural systems. Thus, the implementation of analytical frameworks in the real world to the extent that the complex dynamics of human–environment interactions or ES are captured sufficiently well to inform management remains challenging (de Groot et al. 2010; Dearing et al. 2012a). One analytical approach that captures and prioritises complex SD is the co-evolutionary study of coupled systems (Kallis and Norgaard 2010), describing how system properties, such as land use or ecological condition, emerge as a result of multi-scale and bidirectional relationships between human activities and ecological change. In empirical co-evolutionary studies, the emphasis is on mapping the trends and rates of change in key variables in order to show the prevalence of slow adaptation or crisis and the extent to which driver–process–response interactions are time-lagged. Beddoe et al. (2009) argued that we also need evolutionary frameworks that acknowledge the physical limits to natural resource use (cf. Dearing et al. 2014) if we are to remove barriers to sustainability. Where a long-term, co-evolutionary approach has been tried using a combination of social and biophysical records (e.g. Dearing 2012b), the clarification of the nature of trade-offs between ES, benefits and economic growth, and the discrimination of 'slow' as opposed to 'fast' processes that underpin resilience (Carpenter and Turner 2001), is greatly improved. In other extended timescale or 'long now' (cf. Carpenter 2002) studies, the approach has revealed the mechanisms by which biophysical tipping points are reached as a result of human actions (Wang et al. 2012) and promises to reveal signs of growing instability across regional SES (Zhang et al. 2015).

In this study, we develop further the co-evolutionary approach through description and analysis of multi-decadal changes in social, economic and biophysical variables for a region where the need for enhanced management tools is pressing: the coastal zone of south-west Bangladesh. Our main aim is to use that information to infer the rates and direction of change, the possible existence of transgressed thresholds, the changes in system resilience and the long-term relationship between poverty alleviation and environmental degradation as a foundation for further studies on the social-ecological links and modelling of appropriate management practices.

The Bangladesh delta region

Recorded statistics of death and destruction alone confirm that Bangladesh is vulnerable to environmental change (Maplecroft 2010; Ahmed et al. 1999). The coastal zone has been affected by 174 natural disasters during the period 1974–2007 (Rahman et al. 2010). An estimated 100,000 people died as a consequence of cyclones in the period 1960–1990 (Ericken et al. 1997). Floods in 1998 caused losses of buildings and infrastructure worth two billion USD (Chowdhury 2001). The area of land lost through riverbank erosion through the period 1996–2000 led to financial losses totalling 540 million USD (Salim et al. 2007). Food security has been severely compromised. Around 1 million tons of food grain were lost to drought in 1997, and 50 % of all grain in 1982 was damaged by flood (Islam 2011). Projections of the likely impacts of climate change highlight substantial decreases in rice and wheat yields within 20–30 years as a result of current increases in annual maximum and minimum temperatures of 0.05 and 0.03 °C (MoEF 2005). It has been estimated that a sea level rise of 144 cm by 2050 would cause a 10 % drop in national gross domestic product (GDP) as a result of lost croplands (WB 2000).

The study area contains the world's largest mangrove forest, the Sundarbans. Growing on sediment deposited by the Ganges, it straddles the national boundary between Bangladesh (60 %) and India (40 %). This biodiversity-rich ecosystem (453 animal species and 22 families of trees representing 30 genera) provides a livelihood for ~3 million people (Iftekhar and Saenger 2008; Iftekhar and Islam 2004). The Sundarbans protect >10 million people from cyclonic storms, but are vulnerable to cyclonic damage, as in 2007 when ~36 % of the mangrove area was severely damaged, leading to losses of livelihood (CEGIS 2007). Construction of dams (Mirza 1998) in upstream channels of the Ganges river system and dykes and polders in the south-west coastal area (Islam 2006) has modified river flows to the mangroves and the balance of freshwater and seawater. These hydrological effects on water quality have been exacerbated by the shrimp farm industry (Swapan and Gavin 2011) over the last two decades.

Thus, there is significant evidence that the Bangladesh coastal SES is changing more rapidly than before as a result of many different interacting factors including sea level rise, greater storminess, new land uses, modified river flows, population growth, internal migration, urbanisation and stronger conservation measures (ADB 2005). In particular, total population numbers continue to grow despite adoption of family planning measures that have significantly reduced the rate of population growth (WB 2000). This growing complexity of interactions makes assessment of vulnerability to both general and specific pressures at any location even more challenging than before.

Previous studies of temporal and spatial changes in the ecosystems of the Bangladesh coastal zone (BCZ) have mainly focused on specific causative links or indicators of change. For example, Adel (2002) was concerned about the temperature change due to water diversion of the Ganges, and Mirza (1998) analysed the water discharges of Ganges over the time period. Few studies have attempted to link changes in biophysical processes to human well-being. Here, we use the ES concept to focus on the management of natural assets for their values to well-being and the complex interlinkages of ecosystem processes for designing adaptive management strategies (Hossain et al. 2013; Binning et al. 2001).

Objectives

The study aims to provide the basis for a dynamical analysis of the south-west coastal zone of Bangladesh (Fig 2.1). This is an area of ~2,550 km2 divided into the nine administrative districts Bagerhat, Barisal, Bhola, Borguna, Jhalokati, Khulna, Patuakhali, Pirojpur and Shatkhira with a total population of ~14 million, and population densities ranging from ~400 to 800 people/km2 (Bangladesh Bureau of Statistics 2011). The Sundarbans mangrove forest (a UNESCO World Heritage Site) extends across ~6,000 km2 of the southern parts of Bagerhat, Khulna, Shatkhira and Patuakhali districts. We draw upon a number of analytical techniques for time series analysis in order to establish how the SES in the Bangladesh delta zone, as defined by these nine districts, has evolved over past decades.

The dynamic baseline is used to diagnose the form and function of the system:
Which ES are deteriorating, improving or stable?
What are the apparent drivers of these trends?
What has been the importance of shocks and extreme events on ES?
Is there any evidence for tipping points or abrupt change points in the trends?
Which are the 'slow' and 'fast' variables?
How coupled are the ES to economic growth and well-being?
What are the implications for land use and management strategies?

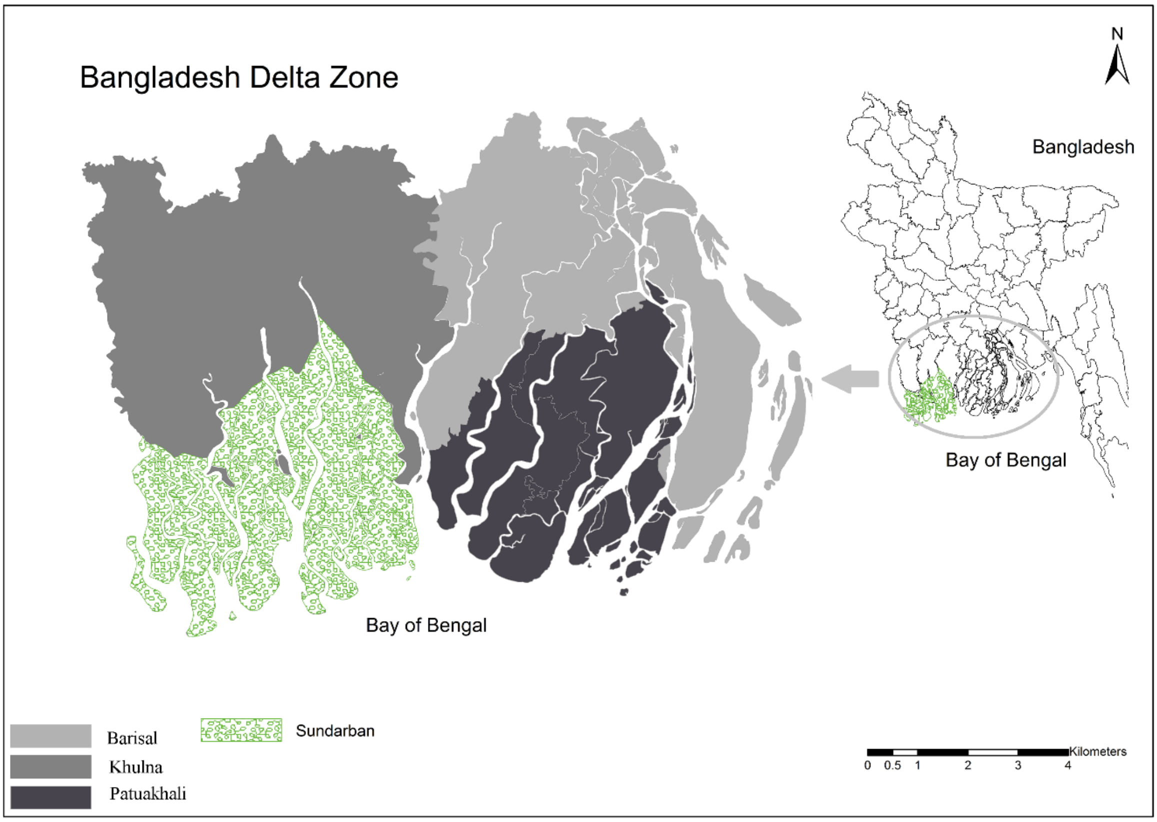

Figure 2.1 Bangladesh delta zone study area showing location in Bangladesh (inset), the three greater districts and the Sundarbans

2.3. Methods

We adopt a study framework (Fig. 2.2) based on the ideas that ES (e.g. water availability) are derived from ecosystem processes (e.g. nutrient cycling, primary production, soil erosion) (Fisher and Turner 2008) and that these services have impacts on human well-being (MA 2005). Ecosystem processes are the basis of ES (de Groot et al. 2010) but are currently omitted here due to lack of data (e.g. primary production). However, ecosystem processes are increasingly discriminated from ES in order to avoid double counting (Petz et al. 2012; de Groot et al. 2010). ES indicators (Table 1.1) have been selected based on the study framework, data availability, measurability and current environmental concerns (e.g. increasing soil salinity). Human well-being is the subset of economic and social conditions (OECD 2001), such as security, health, social freedom and choice, which are essential elements for life (MA 2005). The list of indicators including the data sources is given in Table 2.1, Table 2.2 and Appendix A. Our framework neither avoids making a priori definitions of drivers of environmental change nor assumes that strong causative links between variables are present.

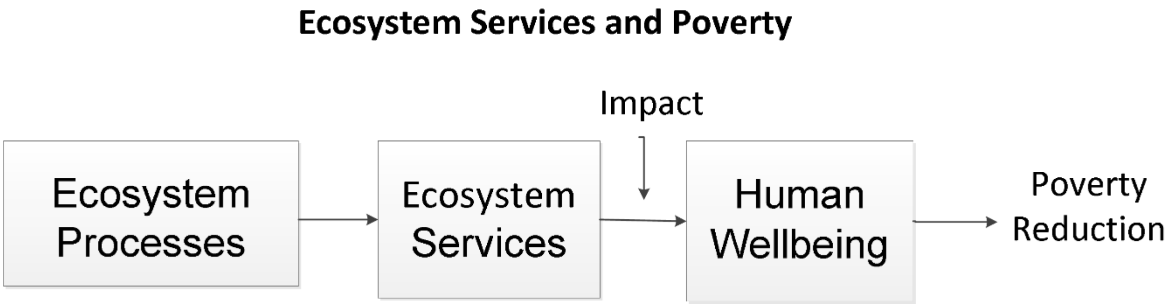

Figure 2.2 Linkage between ES and human well-being (adapted from Fisher et al. 2008 and MA 2005)

Table 2.1 Indicators for ES

ES	Indicators	Data sources
Provisioning services		
Food production	Rice (T- and HYV-Aus, T- and HYV-Aman, T- and HYV-Boro) Vegetables Potato Sugarcane, Jute, Onion, Spices (Garlic, Ginger, Turmeric and Coriander) Fish Shrimp Honey	Bangladesh Bureau of Statistics (BBS)
Forest products	Timber types (Glopata, Goran, Gewa), BeesWax	Department of Forest, Khulna, Bangladesh; Zmarlicki1994; Chaffey et al. 1985
Regulating services		
Water quality	Surface water salinity Soil salinity	Uddin and Haque (2010) Islam (2008)
Local climate	Temperature and precipitation	Bangladesh Meteorological Department
Water availability	River discharge Groundwater level	Bangladesh Water Development Board
Natural hazard protection	Crop damage (due to cyclones, flooding, water logging and excessive rainfall)	Bangladesh Bureau of Statistics (BBS)
Erosion protection	Fluvial erosion and accretion	Mapped data Rahman et al. 2011
Habitat services		
Maintenance of biodiversity	Mangrove density; Mangrove volume; Mangrove area; Mangrove floristic composition, tiger and deer	MoEF (2010); Dey (2007); Khan (2005) FAO (2007); FAO 1999, MoEF (2002): Chowdhury 2001; Helalsiddiqui 1998; Gittings 1980; Hendrick 1975
Cultural services		
Recreational services	Number of tourist visitors	IUCN, 1997; Department of Forest, Khulna

Table 2.2 Indicators for HWB. Details are given in appendix A

Indicators	Objective	Data source
Poverty (% of population below poverty line)	Measures the deprivation of well-being in the society	Bangladesh Bureau of Statistics (BBS)
Per capita income	Measures individual personal wealth	Deb (2008)
Gross domestic product	Measures the aggregated indices of well-being, encompasses of human and natural production	Bangladesh Bureau of Statistics (BBS)

Time series of indicators for the ES (Table 2.1) and human well-being are partly based on annual official data available for the nine districts, partly on data available for the Sundarbans National Park, and partly on ad hoc time series of monitored point data or sequences of mapped data from hydrological, climatological and agricultural organisations, and other scientific studies. Where possible, we aggregate district-level data collected since 1985 from the nine districts into three sets that are equivalent to the three larger 'greater districts' or 'regions' of Barisal, Khulna and Patuakhali, which existed before 1985 (Fig. 2.1). Together with pre-1985 data from each of the regions, we construct time series from the present (2010) back to the 1970s where possible (Table 2.1). We refer specifically to the study area comprising these three regions as the BCZ. Throughout the paper, data records are labelled by the names of the three regions (Barisal, Khulna and Patuakhali). Data for the Sundarbans National Park are referred to as mangrove forest that stretches across the three regions, and other time series are labelled according to the region of origin.

Food, shrimp, fish and raw materials, including timber, are selected to show the trajectories of provisioning services. People of the delta depend on a variety of crops, such as different varieties of rice, jute and sugarcane. Temperature and precipitation are used as the performance indicators of local climate (WRI 2013; De Groot et al. 2006). Fluvial erosion and floodplain accretion rates are the performance indicators for erosion prevention. We choose the time series statistics of crops naturally damaged by different disasters (flood, cyclone, water logging etc.) to analyse the trends of natural hazard mitigation. For indicators of biodiversity (Costanza et al. 1997 and De Groot et al. 2002), we use trees per hectare (ha), growing stock and the number of Royal Bengal tigers and deer in the mangrove forest.

The mangrove forest covers ~28 % of the study area with ~10 million people directly and indirectly dependent on the ES it provides. Moreover, the total coastal ecosystem produces around US$277 GDP per capita (Sarwar 2005). Collections of raw materials (mainly forest products) from the mangrove are secondary occupations.

However, biodiversity data for other parts of the study area are not available. Missing values amount to <5 % for most indicators (e.g. rainfall and water discharge), and these were analysed using statistical test (e.g. Mann–Kendall test) that assumes continuous series. Where time series data (e.g. raw materials, mangrove area and per capita income) were limited to specific years, these are shown only as simple plots.

Continuous series are expressed in raw and normalised z score forms (Wünscher et al. 2008). The data were analysed using linear regression and nonparametric Mann–Kendall statistics (MK stat) and the Lepage test in order to discriminate between improving, deteriorating and stable trends and to identify statistically significant change points. We have applied the nonparametric Mann–Kendall trend test to detect trends in the time series data of water discharges, ground water level, rainfall and temperature. High variability and nonlinear system characteristics are the reasons for applying this nonparametric test. The Mann–Kendall test has already been applied in detecting temperature (Vitale et al. 2010), precipitation (Hossain et al. 2014; Serrano et al. 1999) and river flow data (Danneberg 2012). The nonparametric Lepage test was also applied to detect change points in the trajectories of ES. The Lepage test has been used to detect change point or stepwise change for rainfall (Hossain et al. 2014), climate change (Inoue and Matsumoto 2007) and water resources (Zhang et al. 2009).

Aggregated and smoothed indices are produced from mean z scores in order to compare trends in different sets of indicators. The main rice crop is used as the index for food provisioning services. The trajectory of salinity has been reversed to represent a water quality index. Lowess smoothing has been applied to these entire indices before plotting. Lowess is the process of time series smoothing similar to running mean of about 15 years that removes the high and low frequencies from the time series data (Wilkinson 1997). This smoothing method is already applied to climate-related (Brazel et al. 2000) and water-quality-related (Hirsch et al. 1991) studies.

We have analysed the controls on the value-added production from agriculture and revenue from the mangrove forest products using bivariate plots, Spearman's Rank correlation coefficient and the literature review. Trend observations and bivariate plots are used to discriminate between slow and fast variables. We have attempted to identify slow and fast variables of ES, where the slow variables are the controlling and shaping variables for system resilience (Biggs et al. 2012; Walker et al. 2012). The literature review, bivariate plots and correlation analysis are used to identify the drivers of changes in relation to the observed trends and identifying the tipping points. Environmental Kuznets curves are used to show the relationship between wealth and environmental degradation over the time. This curve hypothesises that at an early stage of development, environmental degradation increases, but beyond some level of economic growth, environmental degradation declines (Grossman and Krueger 1995). Further details on the study area and methodology are given in Appendix A.

2.4. Results

2.4.1. Provisioning services

Food production in the BCZ is mainly derived from agricultural and aquacultural goods with a very small amount directly from ES (e.g. wild fish and honey). Since 1970, the net cultivated crop area of the BCZ (Figure A.1) has fluctuated between ~1,093 and 1,295 km2 with a current figure (2009) of ~1,200 km2 (300,000 acres), which represents ~47 % of the total land area. Despite the fairly constant figures for crop area (Figure A.1), regional rice production across the BCZ rose two- to fivefold between 1969 and 2010 (Figure A.2 and Figure A.3 for combined values since 1948). Rice production in Khulna, Barisal and Patuakhali steadily rose from 1969 to 2010 reaching highest values after 1998, although notable minima are recorded for Khulna in 1980–1981, 1998 and 2007–2008 and for Barisal in 1982 and 1995–1998. Rice varieties fall into two groups: the traditional (T), local varieties (T-Aman, Aus, and Boro) types and the introduced high-yielding (HYV) varieties (HYV-Aman, Aus and Boro). Since 1969, the T-Aman has been the dominant variety across the BCZ, showing peak production figures in the mid-late 1980s (Figure A.3). Since the 1980s, production figures for HYVs across the three regions have more than tripled, especially for HYV-Boro and HYV-Aman, with HYV production only exceeding that for T-Aman after the mid-2000s. The major rice varieties, except HYV-Aman, experienced a dramatic decline in 2007–2008. Records for sugarcane and jute production across the BCZ since 1969 show a declining trend since the 1970s, but production figures for both summer and winter vegetables and spices have risen since the 1990s. Potato production rose sharply in the 1990s, but since 2001, it shows a rapidly falling trend (Figure A.4).

About 100,000 t of shrimp and fish are produced each year with ~30 % from rivers and estuaries and <5 % from the natural wetlands (Sundarbans, beels and baors). The large majority comes from artificial ponds and fish farms. Data for fish production since 1986 (Figure A.5) show major changes in the use of different aquatic ecosystems and artificial systems. Production from rivers and estuaries declined dramatically in the 1980s and 1990s mirroring the increasing production from artificial ponds and shrimp farms that continues to the present. Aquacultural production figures for shrimp and fish across the BCZ since 1984 show step change increases in the 1990s when total production rose at least fourfold within a decade (Figures A.5 and A.6). Since then, annual shrimp production has risen from ~5,000 to >25,000 t and fish production from ponds has risen from ~22,000 to ~60,000 t. Shrimp and fish production figures are significantly higher in Khulna (>20,000 t) than Barisal (<50 t) and Patuakhali (<900 t). Trends in timber and related natural materials from the Sundarbans mangrove forest appear to have reached a maximum in the 1980s–1990s (data are missing 1987–1991) before declining steeply after 1997. Honey collection shows less of a trend with relatively low values in the 1970s and 1980s, and high values during the period 1996–2000 and 2007–2008. Overall honey collection increased by 1.7 t per year in the period 1974–2010 (Figure A.7).

2.4.2. Regulating services

Salinity concentrations in the Poshur river at Mongla Khulna increased steadily (Figure A.8) from <5,000 S (<5 dS/m) in the early 1970s to >50,000 S (>50 dS/m) in 2005. Similar salinity levels were found in rivers in the Rampal and Paikgacha areas until 1995, but these were followed by a steep decline in the late 1990s. The three salinity curves suggest that values for river salinity in 2005 stood at ~35,000–50,000 S, representing a two- to tenfold increase since the 1970s.

Soil salinity measured in dry and wet seasons for three sites in Khulna and four sites in Patuakhalia since the 1990s shows contrasting records, with generally higher and increasing values in Khulna. In Khulna, salinity values increased from <5 dS/m to reach peak values >10 dS/m in the 2000s, with maximum annual figures exceeding 20 dS/m. Recent years (since 2006) show contrasting trends between the seasons with wet season salinity decreasing and dry season salinity increasing. Soil salinity in the Patuakhali region shows lower absolute values (always <5 dS/m), even though it is closer to the sea than Khulna and has only slight rising trends towards the present (Figure A.9). Modelled nutrient loading (total fertiliser and manure input) for three locations in the study area (Global NEWS model) suggests more than a doubling in the application of fertiliser and manure between 1970 and 2000: 18 t/km2/year in 1970 to 39 t/km2/year in 2000.

Daily rainfall data (Figure A.10) from three stations are shown for the pre-monsoon, monsoon, post-monsoon and winter periods from 1948 (Barisal and Khulna) or 1973 (Patuakhali) to present. Mean daily rainfall figures are generally in the range 15–30 mm/day with extreme lows (<5 mm/day) in Khulna in 1971 and extreme highs (>45 mm/day) in Barisal in 1955 and 1960, and in Patuakhali in 1983. Monsoon and post-monsoon rainfall trends show increasing trends (MK stat 0.67 and 2.53, respectively) over the period 1948–2012. However, both of seasons are following negative trends since 1990. Monsoon is following a significant (95 %) sharp decreasing trend (48 mm/season/day, MK stat −1.77), whereas post-monsoon follows a non-significant declining trend (11 mm/season/day, MK stat −0.70) from 1948 to 2012. Rainfall trends in BCZ also reflect in regional scale except in Barisal, where post-monsoon rainfall shows a non-significant increasing trend. Though the rainfall trends show decreasing trends since 1990, rainfall mostly declined (from <15 to >15 mm/season/day) after 2007. Moreover, Mann–Kendall test statistics are also found to be significantly positive for the time period 1991–2007; in contrast, test statistics are found to be negative for the period 1991–2012. Pre-monsoon rainfall figures show a wide range of values between the three stations with Khulna generally showing the lowest (typically <5 mm/day) and Barisal the highest (typically >10 mm/day). There is a non-significant decreasing trend at all three sites over the time period 1948–2012 with a more sharply decreasing trend (overall −34 mm/season/year, MK stat −3.35, confidence interval 99 %) since the 1990s. Winter rainfall figures show generally low values (typically <2 mm/day) with a period of relatively high values in the 1990s. In all three regions, At Khulna and Barisal there are significant trends for increasing rainfall (5–8 mm/season/year; MK stat 0.7–2.85) for the period 1947–1990, and decreasing trends (3–6 mm/season/year; MK stat: −1.5–2.79, confidence interval ~85–99 %) after the 1990s. Overall, the BCZ shows a trend since the 1990s towards weakening monsoons and pre-monsoon with the timing of non-monsoon rainfall shifting from the monsoon to the post-monsoon period except after 2007. Temperature data (Figure A.11) are shown for pre-monsoon, monsoon, post-monsoon and winter seasons for Barisal, Khulna and Patuakhali from 1947. Absolute differences between the stations are small, but there are significantly increasing trajectories in all four seasons over the period. Pre-monsoon, monsoon and post-monsoon temperatures showed increasing trends (~0.02 °C/year; MK stat ~2) after the 1990s (confidence levels 95–99 %).

River discharge data from Hardinge Bridge on the river Padma (Ganges) are shown for the period 1931–2010, split into pre-monsoon, monsoon, post-monsoon and winter seasons (Figure A.12). Significant control of water flow occurred after 1975 when the Farakka barrage (in India to the north) came into operation. Winter dry season river discharge declined significantly from ~2,000 to 4,000 m3/s before 1975 to below 1,000–2,000 m3/s after 1975. Exceptions to this trend were observed only in 2000–2001 and 2007 as a result of extreme flood events. The overall trend in the dry season has declined at a rate of 10 m3/s/year in the period 1965–2010 (MK stat −1.67; confidence level 90 %). River discharge in the wet season (monsoon and post-monsoon) shows figures of ~1,500–2,500 m3/s with small declines (28 and 47 m3/s/year) in the post-Farakka period. Relative changes (Figure A.13) show similar long-term patterns in all seasons, but emphasise the relatively lower dry season discharge from 1975 to the late 1990s.

Ground water levels (Figure A.14) for four sites across Khulna and Barisal are shown as mean depths of ground water for pre-monsoon, monsoon, post-monsoon and winter periods since the 1970s. Data for Dacope (Khulna) show that groundwater has been rising over the period (0.04 m/year; MK stat >3.68; confidence level 95 %) in all four seasons. In contrast, the data for Rupsha (Khulna) show no overall trends except for a weak trend in the monsoon season towards deeper levels. At Gouronodi (Barisal), there is a trend of rising groundwater (0.02 m/year; MK stat 2.9; confidence level 95 %) in the drier seasons. At Bakergonj (Barisal), there are significant trends (confidence level 95 %) towards lower groundwater in monsoon and post-monsoon seasons. Overall, dry season (pre-monsoon and winter) groundwater levels were lowest in the 1980s and since then have risen at three sites. Groundwater levels in the wetter seasons (monsoon and post-monsoon) are generally higher and show weaker trends. For Barisal, there has been an inter-seasonal convergence of groundwater levels.

Crop damage figures for the BCZ from natural disasters, including flooding, cyclones and water logging, extend back to 1963 (Figure A.15). The figures show recorded damage in 35 % of years (16 years in the complete series to 2009) with three clusters (at least three consecutive years) of years 1963–1969, 1981–1991 and 2006–2009. Highest levels of damage are recorded for 1965, 1988 and 2007 with total agricultural losses (tonnes grain) estimated at ~290,000, 500,000 and 600,000 t. The last two of these disasters are linked to the impacts of the extreme floods in 1987–1988 and super-cyclone SIDR in 2007. The frequency of severe cyclonic storms with hurricane intensity doubled over the period 1991–2007 compared with 1960–1990 (Figure A.17).

Data for accretion and erosion rates (Figure A.17) along the major rivers of the Sundarban side of the BCZ since the 1970s show that erosion has been greater than accretion in all decades except the 1980s. Mean erosion rates have decreased from 23 km2/year in the 1970s to <10 km2/year in the 2000s, but mean accretion rates have also declined from 9 to 3 km2/year in the same period. The most recent estimate of net land loss is ~6 km2/year. However, there is also evidence that accretion rates around the Meghna estuary (alongside the region Barisal and Patuakhlia) are increasing. Though the net land loss and gain fluctuated over the time from 1973 to 2010, the most recent estimate of land gain is ~3 km2/year since 2001.

2.4.3. Habitat and cultural services

The total area of mangroves has increased over the period 1959–2000 (Figure A.18), while tree density and growing stock have declined substantially. The growing stock of mangrove forest is estimated to have halved (from 20 to 10 × 106 m3) between 1956 and 1996 (Figure A.19), a pattern mirrored in the reduction of tree density, including the main types Sundari (Heritierafomes) and Gewa (Excoecariaagallocha), from 300 to 150 trees per ha in the same period (Figure A.20). Numbers of deer (Figure A.21) in the mangrove forest show fluctuating numbers (50,000–95,000) since 1975, but numbers of tigers (Figure A.22) seem to have peaked at ~450 in 1982 and 2004 with a decline to 200 in 2007. Data are available for the total number of tourists visiting the Sundarbans between 1996 and 2004 (Figure A.23). Figures show ~5,000 visitors/year from 1996 to 2004 rising to 25,000 in the period 2010–2011.

2.4.4. Population and human well-being

Total population in the BCZ decreased from ~9 million in 1974 to ~8.5 million in 1991, with an increase since then to ~14 million in 2011 (Figure A.29). In 2011, the rural population made up ~80 % of the total population. The urban population rose from 1974 to reach a peak at ~2 million in 2001 before falling back to slightly lower levels in 2011. The rural population declined from ~8 million in 1974 to ~4 million in 1991 and rose to ~12 million in 2011. Over a 40-year period, the population in Barisal and Khulna rose from ~3.5 to 6 million and rose from ~1.5 to 2 million people in Patuakhali.

Total GDP across the BCZ increased from 74 million USD to around 1,025 million USD in the period 1978–2005 (Figure A.24). Sharply increasing trends date to the late 1980s (GDP 200–600 million USD) and late 1990s (GDP 600–1,000 million USD). Barisal, Khulna and Patuakhali all show similar trends, but Patuakhali currently has a significantly lower GDP (<400 million USD) than the others (>1,000 million USD). Per capita income (Figure A.27) is currently highest in Khulna (559 USD) followed by Patuakhali (393 USD) and Barisal (358 USD). Comparison with past decades suggests that the rate of increase in per capita income has been greatest in Khulna and least in Patuakhali. Rising levels of per capita income and GDP have resulted in a reduction since 1995 in the numbers of people classified as living below the poverty line (Figure A.25). Current (2010) levels of poverty (Figure A.26) for Khulna and Barisal are 33.4 % and 39.6 %, respectively, of the total population, down from 59.5 to 47.2 %, respectively, in 1983. Population numbers lying below the poverty level have declined by ~17 % across the BCZ since 1995.

Figures for total value-added income (Figure A.27) (at current prices) derived from agriculture and fishery across the BCZ are only available for the period 1977–1995. There was a major step increase around 1983 (to be validated), followed by a decline in 1992 and a rise to 1995. Figures for total revenue (Figure A.28) derived from the Sundarbans are available from 1974 to 2011 and show peak values in the 1980s and 1990s with a steep decline to the present day (Figure A.30). Current income from the Sundarbans is estimated at 2–3 million BDT. In 1995, the last year when the two sets of data can be compared, the income from the Sundarbans (225 million BDT) was equivalent to 0.06 % of the total value-added income from agriculture and aquaculture (35 billion BDT).

2.4.5. Social-ecological dynamics

We use normalised records (averaged where there are more than two indicator records) for each category of ecosystem service and human well-being since 1949 to summarise the major trends and SD (Fig. 2.3; Table 2.3). The majority of ES are declining, in the sense of deteriorating (Fig. 2.3). Only food production and cultural services, and water availability, are improving. For some ecosystems, the question of deterioration depends upon the precise nature of the indicator. For example, the area of mangrove forest may be relatively stable but mangrove density has declined since the 1950s. Although some non-food ES are declining, there are several positive changes in human well-being. The total GDP of the BCZ increased from 74 million USD to around 1,025 million USD in the period 1978–2005, resulting in a strongly increasing trend of per capita income. The size of population existing below the poverty line declined dramatically in the 1990s. The number of tourists visiting the Sundarbans has increased significantly after 2000. In dynamical terms, the most striking feature of the data (Fig.

2.4) is the dominance of trending lines and the lack of stationary curves. GDP, food production and water quality show the largest relative changes with both covering >2.5 standard deviation units. The rise in GDP is the most dramatic as it occurs in less than half the timescale of the others. Changes in water availability and groundwater levels are relatively smaller owing to reversal and slowing of the trends after the late 1980s and mid-1990s, respectively. Local climate shows a rising trend after 1980 reflecting increases in both monsoon and post-monsoon rainfall, and higher temperatures.

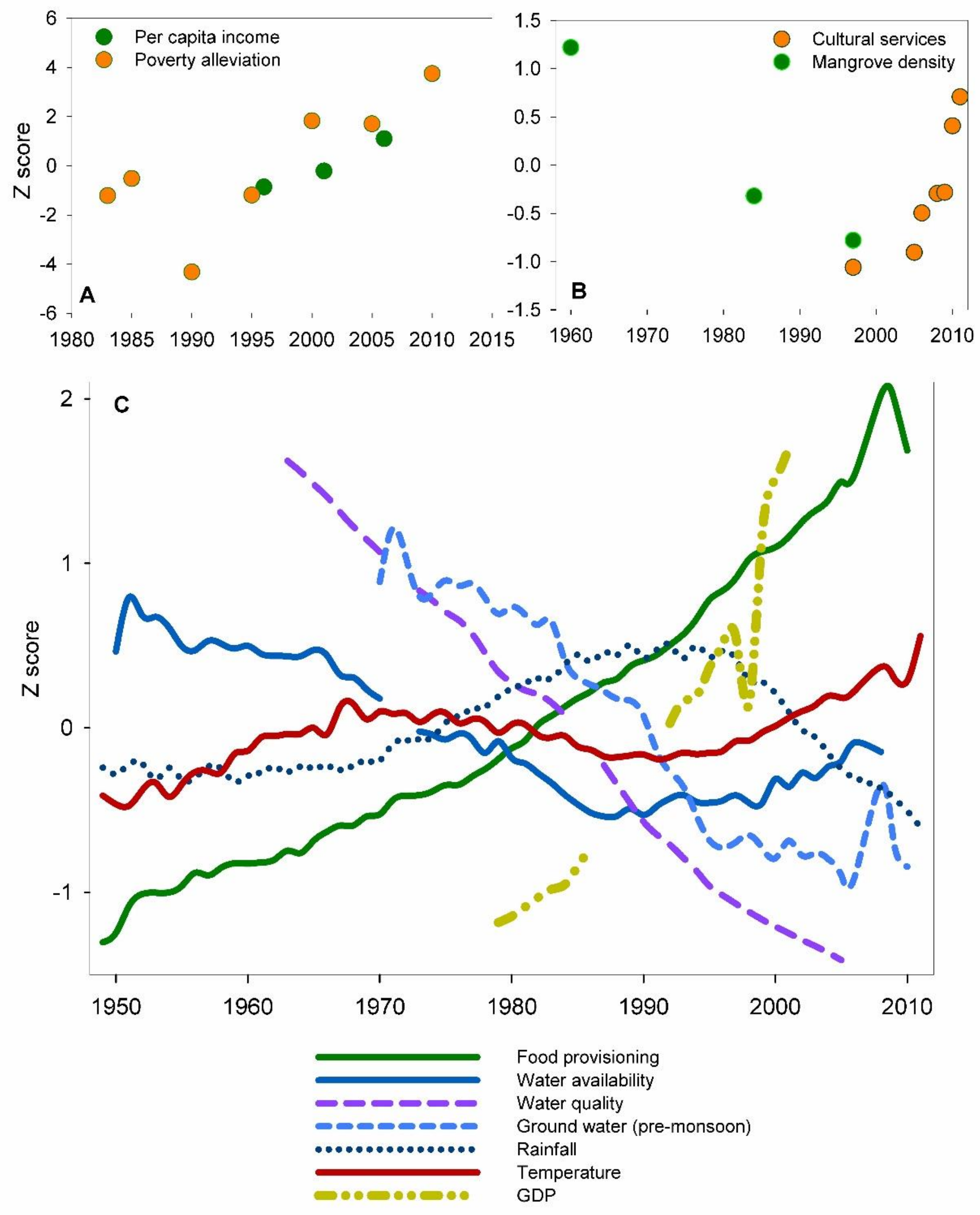

Figure 2.3 Trends for the different indicators index of human well-being (a), cultural and habitat services (b) and regulating and provisioning services (c)

Table 2.3 Dynamical state of final ES including slow and fast variables and major shifts, with potential drivers of change over past decades

Ecosystem service	Dynamic state	Fast or slow variable	Date of major shift in trend	Potential drivers
Food production	Improving	Slow	1985	Population and technology
Forest products	Deteriorating	Slow	1996	Water availability and water quality degradation
Water quality	Deteriorating /improving	Fast/slow	1980–1985	Water availability reduction, polders and shrimp industry
Local climate	Deteriorating	Fast/slow	1990	Global climate change
Water availability	Deteriorating	Fast/slow	1975	Farakka Barrage in the upstream
Natural hazard protection	Deteriorating	Slow	1990	Increased intensity of cyclones
Erosion protection	Deteriorating	Slow	1990	Water availability fluctuation
Maintenance of biodiversity	Deteriorating /stable	Slow		Shrimp farming, water availability reduction
Cultural services	Improving	Slow	2005	Policy

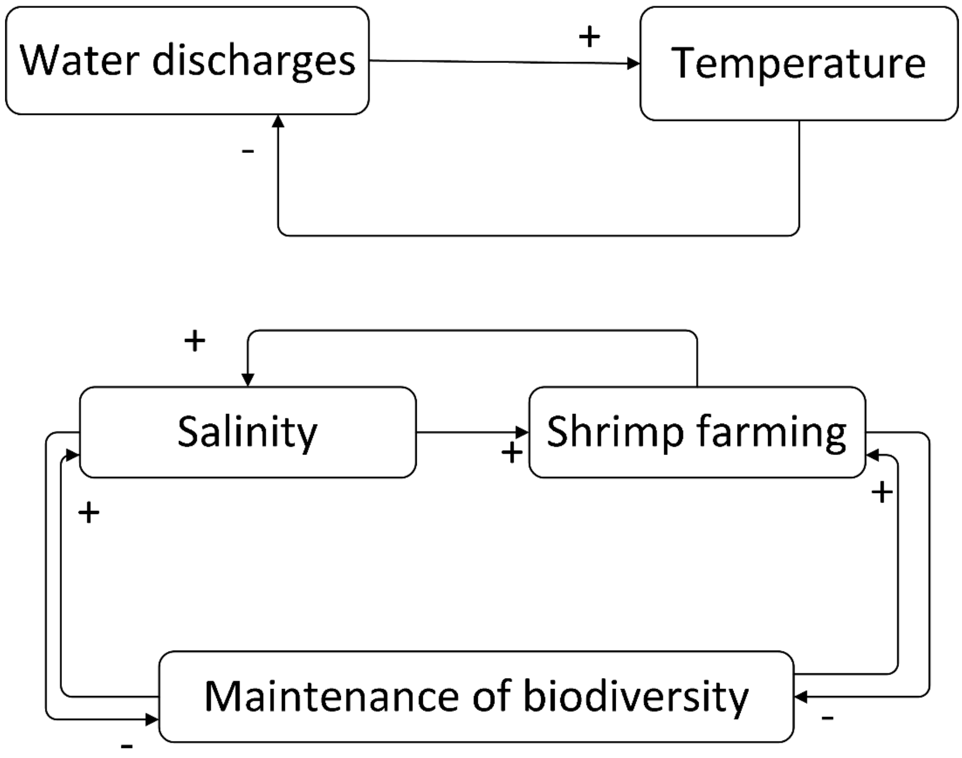

Figure 2.4 Changes in water resources, temperature and maintenance of biodiversity become self-perpetuating through positive feedback loops, which is one of the characteristics (CBD 2010) of tipping points. Shrimp farming increases salinity, which reduces mangrove diversity, and leads to increased salinity in the system. Moreover, shrimp farming also reduced mangrove diversity, which also favoured shrimp farming because of the high suitability of mangrove area for shrimp farming. Besides this positive feedback for shrimp farming, changes in water discharges and temperature become self-perpetual through the feedback loops, in which reduction in water availability because of Farakka dam increases temperature, which leads to decrease in water availability

2.5. Discussion

2.5.1. Ecosystem service trends

In the past three decades, there have been a number of changes in crop production, fishery output and raw materials availability. Production of HYV rice and some local rice varieties has increased, and although the production of some of the other local crops (T-Aman rice, sugarcane, jute) has declined, the overall production of regional food has accelerated since the 1980s. Changes in three sub-regions are consistent with the whole regional trend. Similarly, both shrimp and fishery production have increased over the same period, although shrimp production (>5,000 t) remains higher than fish production (<3,000 t). Around 80 % of shrimp production is obtained from the Khulna region. Meanwhile, in the mangrove, honey collection increased between 1980 and 2000, but declined around 2007–2008. Also, the collection of raw materials (mainly forest products) has declined since 1996.

Water quality and hydrological regimes are the substantial ES that are deteriorating after the 1980s. River water salinity stood at levels between 20,000 and 45,000 mS between the periods 1980–2008. Not only the river salinity is increasing, but also the nutrient load to watersheds shows an increasing trend within a very short period of time. Similarly, soil salinity also increases in the delta region, where soil salinity is higher in greater Khulna regions than Potuakhali region. Although the rainfall is declining in pre-monsoon, monsoon and post-monsoon seasons, the monsoon and post-monsoon seasons exhibit increasing trends up to 2007, followed by declining trends. However, temperature is rising across the whole BCZ in each season except winter, where it is been declining since the 1990s.

Human well-being shows an improving trend in the BCZ. The GDP trend is rising at a rate of 50 million USD/year over 15–20 years with per capita income increasing ~100 USD over the same period. Increasing trends of average human well-being have led to a reduction in poverty by ~17 % over the same 15 years. But while the urban population shows no trend, the rural population has increased similar to the total population trend. The trend of the total population is increasing, but has not experienced any major shift compared to ES and human well-being.

2.5.2. Social and biophysical drivers

Preliminary analysis based on correlation, published data and trend observation (Table 2.3) suggests that there are multiple drivers of ecosystem service change that range from global climate change and new agricultural methods to specific infrastructural developments (e.g. the Farakka barrage and polders), and local-policy-driven actions (e.g. commercial shrimp farming).

It is observed from the correlation analysis that HYV rice varieties (Table A.2 and Figure A.30) exhibited a significant negative ($r = -0.45$) relationship with pre-monsoon rainfall and a significant positive ($r = 0.2–0.8$) relationship with temperature. In addition, some of the rice varieties (e.g. HYV-Aus and HYV-Boro) are showing stronger relationships with temperature after the 1990s. However, a crop variety like T-Aman shows a negative ($r = -0.3$) relationship with post-monsoon temperature after the 1990s, whereas the relationship was positive ($r = \sim0.45$) before the 1990s. Similarly, though the HYV rice varieties exhibited negative relationships with pre-monsoon rainfall, they were positive relationships before the 1990s, indicating that the decreasing trend of pre-monsoon rainfall favoured the HYV rice production. Moreover, a negative association ($r = \sim-0.5$) between temperature and local crops (e.g. jute, sugarcane etc.) indicates that the increasing trends of HYV crops were favoured by the increasing trends of temperature (pre-monsoon to post-monsoon) and the declining rainfall trend in the pre-monsoon season. Though the climate variability favoured the HYV crop cultivation, technological innovation (Husain et al. 2001; Ali 1999) aimed at meeting the food demand for an increasing population was an important reason for adopting these crops.

Conversion of rice fields into shrimp farming appears to have been favoured by the rising trend of salinity which reduced the accessibility of forest products. Our correlation coefficient results ($r = 0.99$) confirm that the salinity increase (Swapan and Gavin 2011) promoted by polderisation and flood control projects in 1960s produced an environment that was favourable for shrimp cultivation (Islam 2006; Mirza and Ericksen 1996). In turn, this led to the destruction of around 9,500 ha of mangrove forest (Azad et al. 2009) followed by reduced accessibility of forest products ($r = \sim0.59$) due to imposed regulations (Iftekhar and Islam 2004). Though the explosion in the shrimp industry influenced the rising trend of salinity, the negative ($r = -0.60$) relationship between pre-monsoon water discharges and salinity indicates that the reduction in water availability was another factor for the salinity rise. The salinity rise is one of the reason for halving the mangrove stock despite the increase in total mangrove area due to afforestation program of government. Our trend statistics and change point analysis of water discharges are all consistent with the timing of the Farakka dam between 1965 and 1975 (Mirza 1998 and Mirza 1997). Moreover, the declining trend of pre-monsoon water discharge is negatively associated ($r = \sim -0.5$) with pre-monsoon temperature and ground water level. At the coast, river discharge maintains the pressure to counter sea water intrusion. Thus, the rising levels of ground water level possibly reflect the reduction in water availability from upstream discharge and the increasing risk of sea water contamination (Rahman et al. 2011; Bahar and Reza 2010).

2.5.3. Resilience, shocks and tipping points

A preliminary assessment of the indicator variables as 'slow' or 'fast' suggests that all the variables have a slow component, as defined by the presence of trends over decadal timescales. But some indicator variables also show fast- or high-frequency components over annual and shorter timescales, particularly water quality, rainfall and water availability (Table 2.3). System resilience depends upon the interactions between fast and slow variables. The observation that many of the deteriorating non-food ES that regulate and support key ecosystem processes are exhibiting slow components may indicate weakening resilience within the dependent agriculture and aquaculture sectors.

This is especially important because the BCZ is historically vulnerable to high-magnitude low-frequency events in external drivers. Flooding and severe cyclones, particularly in 1987–1988, 1991 and 2007, are the major shocks which have impacted on food production. The statistics suggest that the flooding between 1984 and 1990 together with the cyclone in 1991 may have affected negatively the percentage of population lying below the poverty level which rose to 63 % in 1991 from a level of 50 % in 1985. There is evidence for an increasing frequency of stronger cyclones since 1990 as a result of climate change (Khan et al. 2000 and Ali 1999). This combination of declining resilience and increased incidence of extreme events raises the prospect of a 'perfect storm' scenario (Dearing et al. 2012a) with a greater likelihood of tipping points. It is difficult to define precise dates for when the services shifted towards deterioration or improvement, but the evidence suggests a range of decades (Table 2.3 and Table A. 2–13). Lepage test and nonlinear test results (Table A.2–13) show that the shift towards deteriorating trends occurred in the mid-1970s (water availability and temperature), mid-1980s (water quality), early 1980s and 2007 (rainfall), and early 1990s (ground water level). Shifts towards improving trends occurred in the 1980s (food production) and in the 2000s (cultural services). In addition, change point analysis reveals that food production shifted towards improving trends in 1959, 1977 and 1999. Though the change point analysis does not necessarily imply a tipping point or regime shift to an alternative state, some of the ES such as water availability, water quality and maintenance of biodiversity may have passed tipping points because there are easily observed positive feedback loops within the system (cf. Wang et al. 2012). For example, the rise in salinity and deterioration in water quality encourage shrimp farming which in turn accelerates the process of localised salinisation (Fig. 4).

2.5.4. ES, economic growth and well-being

Bivariate plots (Figs. 2.5, 2.6) show the association between rising food provisioning services, rising GDP and poverty alleviation. Figure 5 shows that rising agricultural production is coupled with poverty alleviation that is also evident in other countries (e.g. Niger, Afghanistan and Mexico) (WB 2013). But it is also possible to explore the links between rising GDP, a measure of economic growth, and environmental quality. Environmental Kuznets curves are simple bivariate plots showing the relationship between economic wealth and environmental quality through time (e.g. Beckerman 1992). A bivariate plot (Fig. 7) of relative GDP against an index for water quality degradation (surface water salinity) in the BCZ shows that water resources have deteriorated as the Bangladesh economy has grown. In many middle- and high-income countries, the level of environmental degradation slows and reduces as GDP allows for investment in environmental remediation and protection measures. But in the BCZ, there is no indication that this turning point has been reached.

But is a turning point possible? Direct actions to reduce degradation could include greater control on water quality through stronger regulation on the extent and practice of shrimp farming and on the exploitation of the mangroves. But external controls on river discharge and regional climate may mean that these can only be partially successful. Proactive adaptive strategies for managing agriculture, such as through the introduction of new crop hybrids, might also be introduced although the dependence of T-Aman rice on irrigated water, obtained from declining resources, highlights the challenge of overcoming one problem without creating new ones or relying on environmental elements already stressed. The combined evidence from this study for declining resilience, possible tipping points and observable positive feedback mechanisms suggests growing unsustainability across the whole SES (cf. Zhang et al. 2015). Therefore, it is not unreasonable to suggest that a continuation of environmental degradation and losses of regulating services could eventually drive declines in rice, shrimp and fish production. This would impact first on rural poor farmers dependent on

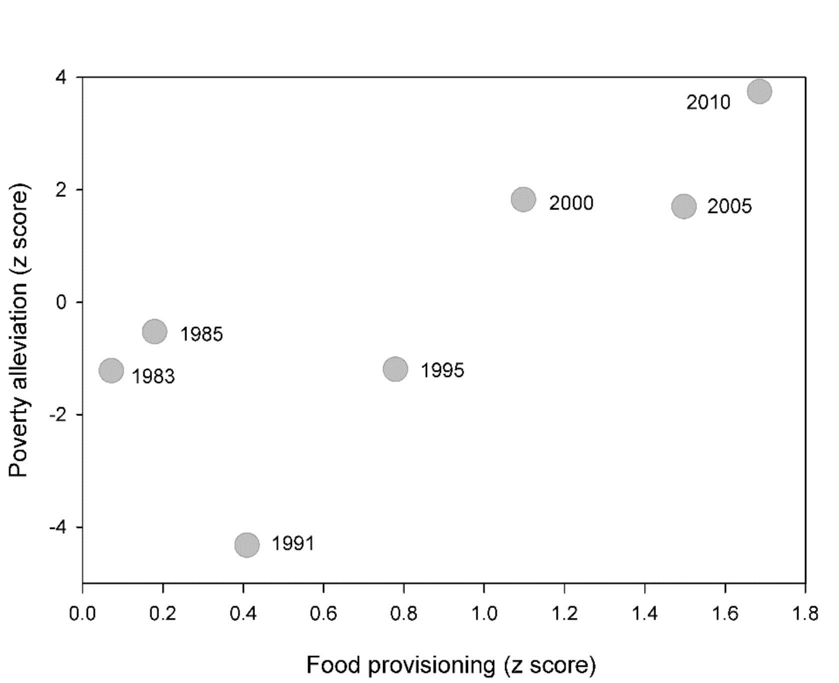

Figure 2.5 Poverty alleviation versus food provisioning services (rice production), showing a strengthening relationship after 1991

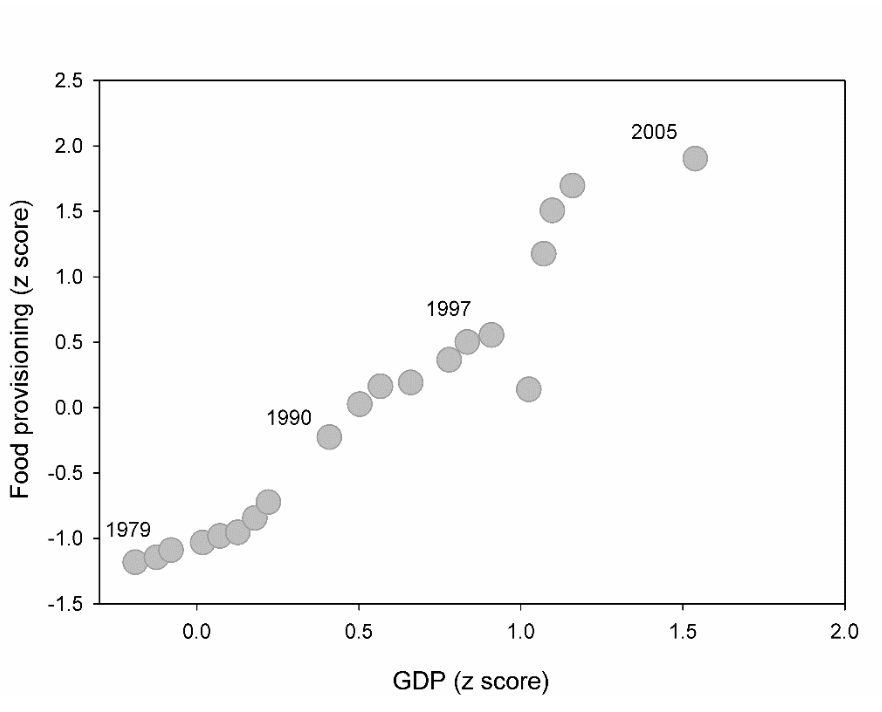

Figure 2.6 Relative food provisioning services (rice production) versus GDP, showing overall a strong relationship

wage income or subsistence products, and gradually the larger landowners and associated processing industries. In time, a partial environmental improvement might occur as land became less intensively used. But in this scenario, it is unlikely that regional economic growth based on agriculture would continue. Rather than economic growth constraining environmental degradation, there would be a reversal or upturn of the Kuznets curve towards an earlier stage of development (cf. Liu 2012). Such a bleak prospect calls for the rapid involvement of scientists, stakeholders and politicians to negotiate a management plan for the BCZ.

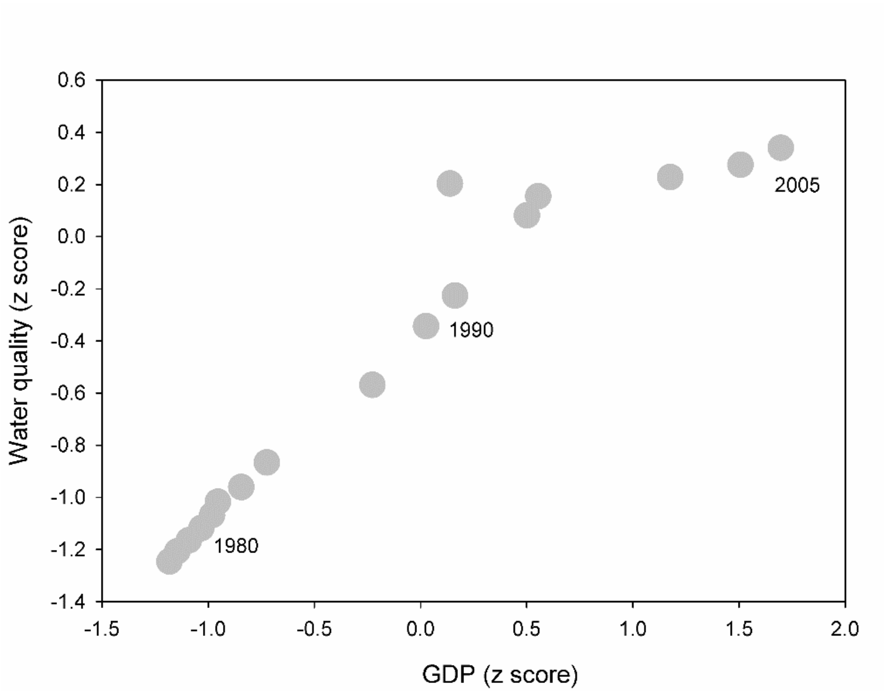

Figure 2.7 Relative water quality (surface water salinity) versus GDP, where higher water quality z scores are interpreted as deteriorating water quality (similar to an Environmental Kuznets curve). The strong association since the 1970s indicates that deteriorating water quality has been strongly coupled to economic growth, though the lower gradient after 2000 suggests a recent weakening

2.6. Conclusion

Since the 1980s, increasing GDP and per capita income mirror rising levels of food and inland fish production. As a result, the size of population below the poverty line has reduced by ~17 % over the past 15 years. In contrast, non-food ES such as water availability, water quality and land stability have deteriorated—at least by comparison with conditions in the 1960s. There is clear evidence for climate change from the early 1980s in terms of later monsoons and higher temperatures.

The extent to which the growing levels of food production and ecological deterioration are directly linked is difficult to judge, though conversion of rice fields to shrimp farms is almost certainly a factor in increasing soil and surface water salinity. An environmental Kuznets curve analysis suggests that the point at which growing wealth feeds back into effective environmental protection has not yet been reached for water resources.

The state of the Sundarbans mangrove forest is difficult to assess from the present data. The area of mangrove forest and production of timber forest products seem relatively stable, but declining tree density and volume suggest growing exploitation or fragmentation.

There are multiple drivers of these changes in ES that range from global climate change and new agricultural methods to specific infrastructural developments (e.g. the Farakka barrage and polders), and local-policy-driven actions (e.g. commercial shrimp farming). Most of the ES and well-being have experienced change points around 1980s, where water availability, shrimp farming and maintenance of biodiversity have passed tipping points.

Widespread trends in indicators of ES and human well-being point to non-stationary dynamics and slowly changing variables. As a result, theoretical arguments may be made for gradually declining resilience in agriculture and aquaculture with increased probability of positive feedbacks driving threshold changes/tipping points. There is evidence that high-magnitude events, such as large cyclones, that can potentially trigger threshold events are becoming more frequent. In the past, sequences of flooding and cyclones have reversed the long-term trend in poverty alleviation.

The historical database of ES and human well-being presented here is under construction and requires further data validation and analysis, but already provides a basis for hypothesis generation, model scenario development and model testing. This study serves as the basis for understanding the social-ecological complexities associated with regional scale sustainable development.

Chapter 3: Paper 2

Recent trends of human wellbeing in the Bangladesh delta

3.1 Abstract

Although recent studies show that HWB on global and national scales is improving, it is important to monitor the regional progress of HWB and MDGs. Here we provide an assessment of HWB in the south-west coastal part of Bangladesh by analysing Household Expenditure Survey (HIES) and Demographic Health Survey (DHS) data from 1995 to 2010. Indicators have been selected based on the five dimensions of HWB, including health, material condition, personal security and freedom of choice and actions. This study shows that the south-west coastal region has made commendable progress in meeting the target MGDs goal for 'child and maternal health'. However, the areas of 'personal security' and 'freedom of choice and action' have not achieved the target MDGs despite showing substantial progress for 'poverty alleviation' (17%), 'sanitation coverage' (40%) and 'education' (23%). Incomes from fishery and 'non-ecosystem' based livelihood have increased 76% and 8% respectively, whereas income from shrimp and agriculture show declining trends. Production costs have increased substantially since 1995 in response to a rise in GDP. At a household level, proxy indicators of provisioning services, such as crop production, are positively correlated with poverty alleviation. Overall, greater attention on education and sustainable land use is required if SDGs are to be achieved by 2030.

Keywords: Trends; Human wellbeing; Regional; MDGs; SDGs

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3.2. Introduction

Human wellbeing is the subset of economic (e.g. GDP, income) and social wellbeing (e.g. education, health) factors (OECD 2013) and has been classified into five dimensions: health (e.g. child mortality), material (e.g. income), security (e.g. sanitation), freedom and social relations (MA 2005). HWB has been used to measure the progress of humanity such as the "health for all" goal set in 1990 and to design development strategies (McGillivray and Clarke 2006). However, monitoring of the MDGs is still very challenging mainly because of the spatial heterogeneity of human well-being with respect to social norms and access to ES (MA 2005) and also data unavailability in low and middle income countries (UN 2014). This difficulty in monitoring the MDGs is a major issue, as more than one billion people across the world are still living below the extreme poverty line set at $1.00 per day (McGillivray 2006). Despite many studies that show increasing trends of environmental degradation (e.g. Zhang et al. 2015; Dearing et al. 2014), the global average of HWB is improving (Raudsepp-Hearne et al. 2010). Although ES make significant contributions (both direct and indirect) to security, basic materials and health for HWB (Santos-Martın et al. 2013 and MA 2005), the relationships between ES and HWB are complex (Vidal-Abarca et al. 2014; Raudsepp-Hearne et al. 2010). In particular, while the more efficient use of provisioning services (e.g. crops, fish) has supported poverty alleviation and human development (Scherr 2000, Irz et al. 2001, CRA 2006 and Santos-Martın et al. 2013), the effects of declining regulating and supporting services on wellbeing may be nonlinear and long term (Balmford and Bond 2005 and Raudsepp-Hearne et al. 2010). Besides the contribution of provisioning services to HWB, government initiatives for education and health, technological progress, development and investments are some of the prime factors explaining the positive global trends of HWB (Cervellati and Sunde 2005).

Risks of negative impact on HWB due to environmental change are increasing at both the global (Rockström et al. 2009) and regional scale (Dearing et al. 2014). These studies show that humankind has already transgressed the SOS (point beyond which is dangerous to humanity) for some of the planetary boundaries such as climate change, biodiversity and water quality. However, there are no systematic analyses that consider the impact on social systems (i.e. HWB) in terms of the capacity and resilience of societies in the face of changing environments (Raworth 2012). For this purpose, it is essential to develop an understanding of the dynamics of regional social and ecological systems, and their inter-relationship.

Bangladesh is one of the most densely populated countries of the world. It faces many challenges to meet the MGDs, specifically in alleviating poverty and providing education for all and access to health care. However, it has shown quite remarkable progress in achieving MGDs goals including a reduction of around 60% child and maternal mortality (Chowdhury et al. 2011) together with 2.5% poverty reduction per year (BBS 2011 and UNDP 2014). Beside these development issues, Bangladesh possesses a highly complex and challenging environment, encountering yearly natural disasters including floods, droughts and cyclone surges. Urbanisation, increased salinity and risks associated with climate change are all likely to increase in future (ADB 2005). Due to this, quantification of the impacts on HWB is important for regional sustainability in Bangladesh. Previous studies in Bangladesh have focused on analysing trends of environmental degradation (e.g. Hossain et al. 2015) and national progress of HWB (e.g. Chowdhury et al. 2011). Despite research showing that provisioning services are most influential for improving HWB (Raudsepp-Hearne et al. 2010), no studies have investigated the regional progress of MGDs and the income of people engaged in different occupations that are directly dependent on provisioning services as their income sources (e.g. farmers, fisherman, and shrimp farmers).

In this new study, we extend our previous work (Hossain et al. 2015) on trends in ES in south-west Bangladesh by reconstructing decadal changes in human development based on 13 HWB indicators in households engaged in agriculture, fishery, forest resource collection and shrimp farming. Moreover, we have analysed new datasets such as Household Income and Expenditure Survey (HIES) and Demographic Health Survey (DHS) for observing and understanding the causes of recent trends of HWB and policy implications for SDGs 2030 at regional scale. By quantifying the parallel changes in ES and human development, the study can serve as the basis for monitoring the process of rising wellbeing. Such analyses are a prerequisite for drawing together sufficient information and understanding of the socio-ecological SD to enable the definition of a SOS for the region in the progress towards meeting the SDGs by 2030.

3.3. Methods

3.3.1. Study area

We have selected the south-west coastal part of Bangladesh as our study area (Fig. 3.1). This area represents 16% of the total land (~25,000 km2) of Bangladesh, with a population of 14 million (BBS 2010). This south-west coastal ecosystem produces more than 1300 million USD of Gross Domestic Product (GDP) (BBS 2010), contributing 277 USD GDP per person (Sarwar 2005). However, around 38% people of this region live below the poverty line (BBS 2010). HIES data indicate that livelihoods in this region are heavily dependent on agriculture (~40%), fisheries (~20%) and forestry (~25%). The world's largest mangrove ecosystem 'Sundarban' located in this region supports the livelihoods of around 1.5 million people directly, and 10 million people indirectly. In addition, the mangrove forest also protects around 10 million coastal people from storm surges (Islam and Haque 2004).

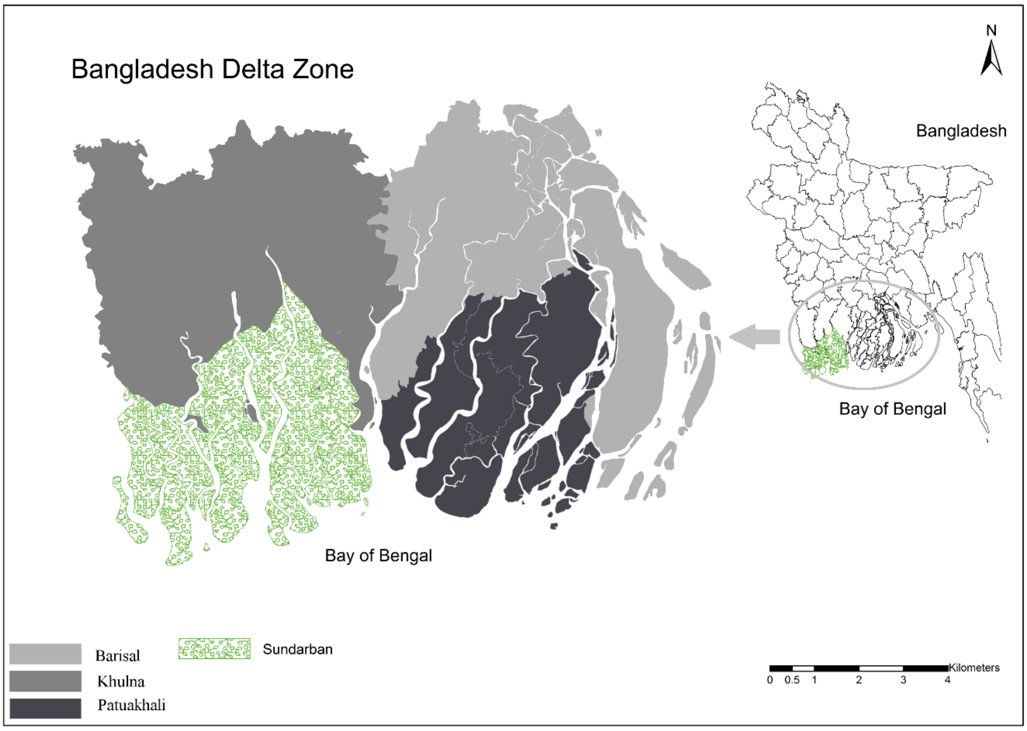

Figure 3.1 Bangladesh delta zone study area showing location in Bangladesh (inset), the three greater districts (three different grey colour) and the Sundarbans (in green).

3. 3.2. Selection of indicators

HWB is a subset of economic and social wellbeing factors (OECD 2013) and has been classified into five dimensions: health, material, security, freedom and social relations (MA 2005). The list of HWB indicators (Table 3.1) are selected according to the MDG goals (2015) for Bangladesh based on data availability, measurability and length of time series. We have used Household Income and Expenditure Survey (HIES) datasets collected by the Bangladesh Bureau of Statistics (BBS) and World Bank in 1995/96, 2000, 2005 and 2010 to compile data for the indicators such as income, sanitation, electricity, safe drinking water, crop production and production cost at household level.

We have used Demographic and Health Surveys (DHS) to compile data for child and infant mortality, maternal health, education and access to media, as the HIES datasets do not cover data for these indicators. Although, the DHS data is at divisional level, we have used two divisions (Khulna and Barisal) data for analysing the indicators as, our study area covers all districts of Barisal division and ~65% total area of Khulna division. This study has mainly used the results from the published reports on DHS dataset collected in 1993, 1996, 2000, 2004, 2007 and 2010.

3.3. 2.1. Material condition

Income

Household income level enables families to meet the norms for a decent level of living standard and consumption. We have analysed HIES datasets for 1995, 2000, 2005 and 2010 to calculate the mean income of the households who are engaged in agriculture, fisheries and non-ecosystem based activities such as labour, services holder, teacher, and construction workers. The HIES dataset does not capture income data for households engaged in shrimp farming and collecting non-timber forest products, so we have used other sources to show the trends of income from shrimp firms We have adjusted all sector incomes to a current price using the consumer price index (CPI). In addition, we also have normalised income (income per hectare) in order to compare the income over the time period after controlling for farm size.

Gross Domestic Product (GDP)

GDP measures welfare through the aggregated indices of human and natural production (Boyd 2004, Boyd and Banzhaf 2007 and Daw et al. 2011). We have analysed the trends of GDP (at a current price) for the each of the four provisioning services (rice, fish, forestry and shrimp). Total GDP data is available from 1978 to 2005, whereas sector-wise GDP is available only for the period 1993–2000. We have used the average share of each sector's GDP to calculate the sector-wise GDP between the period 1978 to 1992 and 2005.

Poverty (% of population below poverty line)

ES directly contribute to the poverty alleviation by enabling people to meet basic needs (food, cloth, and education) and security (safe drinking water, sanitation etc.) of individuals (UNEP/IISD, 2004 and MA, 2005). In addition, 'poverty' describes the deprivation of well-being and is a good indicator for measuring the material condition, as the income and GDP often ignore the deprivation of well-being level in the society (OECD 2013). We have used both upper and lower poverty thresholds which consider the cost of food items and the costs of both food and non-food items respectively in the cost of basic needs (CBN) method used by BBS (2010) and Wood (2007).

Security and freedom of choice

We have used the percentage of households with access to sanitation and safe drinking water to analyse the trends in 'personal security'. Data for the three indicators are derived from the HIES. We have classified both sanitation facilities and drinking water sources into improved and unimproved types as per the DHS (2007). Sanitary latrines and pacca latrines (water seal and pit) are categorized within the improved sanitation category, whereas kacha, open and other types of sanitation facilities are labelled as unimproved sanitation. Similar approaches have been followed to classify improved (supply, tubewell) and unimproved (pond/river, well and others) sources of drinking water.

Moreover, we have selected the percentage of people who completed primary school and the ratio of men and women achieving this level of education as the indicator for 'freedom of choice', together with the indicator 'access to mass media'. In this case, we have focused on women due to the data availability and an attempt to prioritise the women as per the MDGs. We did not select any indicators for 'good social relations' due to data unavailability.

We have also analysed mean crop output (all types) and production (per unit) cost for agriculture and shrimp farming at the household level. We have also calculated crop yield (kg/ha) by dividing total produced by cultivated area at the household level.

These indicators are not only part of the sustainable agriculture under the dimension of 'material condition', but also can be used as the proxy of provisioning services (e.g. food, fish) production at a household level. These data allow us to analyse the relationship between human well-being and provisioning services. It is also worth investigating whether the rising trend of food provisioning services is also increasing the cost of production. Hence, we have calculated normalised production cost per hectare to compare the production cost over the time period and also to compare with the mean income per hectare and crop yield.

3.3.3. Data analyses

The HIES uses a two stage randomly selected sampling, through the integrated multipurpose sampling (IMS) scheme in which, firstly, primary sampling units (PSU) were selected across the country and secondly, households were selected randomly per PSU. The number of PSU and household samples selected for the surveys in the HIES was 371 in the year 1995, 1000 in the year 2000, 7400 in the year 2005 and 12,240 in the year 2010.

Moreover, surveys were conducted across the year to account for the seasonality (BBS 1997 and BBS 2011). The survey datasets are representative at the national and divisional level for urban and rural sampling (Azam and Imai 2009). However, this study considers samples of all households located in all nine districts using the similar approach of Mottaleb et al. (2013) and (Szabo et al. 2015). In this approach, samples from the same nine districts are used to investigate the impacts of the natural disaster on household income and expenditure. Moreover, all these nine districts cover the whole Barisal division and 65% of the total Khulna division area. Because the HIES and DHS datasets are only representative at national and divisional levels, we are only able to investigate the trends aggregated over the all nine districts in our study region from 1995 to 2010, not at individual district level.

In the case of the HIES, data are combined into one dataset by merging (e.g. one to one) using the unique household identification. The householders' information (e.g. sex, area) also linked with the newly created datasets and the merged datasets for the nine districts are used for analyses. Household level crop production and the production cost were calculated from the individual level data. Descriptive statistics (e.g. mean, median, standard deviation) for the variables were then calculated using the statistical package STATA 13 (Stata Crop 2013).

Table 3.1 Human welling indicators based on MA (2005) and OECD (2013) classification

Dimension		Indicators	Temporal Scale	Data source
MA	OECD			
Health	Quality of life	Child mortality (probability of dying before the first birth day)	1993-2011	DHS
		Infant mortality (probability of dying between the first and fifth birth day)		
		Proportion of births attended by skilled health personnel (%)		
Material	Material condition	Sector wise Household income Production cost	1995-2010	authors own calculation (AOC) from HIES Income from shrimp farms and production cost (Islam, 2007)
		Gross Domestic Product (GDP)	1974-2005	BBS
		Poverty–Percentage of people living below the upper and lower poverty thresholds	1983-2010	BBS and Wood 2007
Security	Quality of life (Personal security)	Access to electricity, sanitation, drinking water source	1995-2010	AOC HIES data
Freedom of choice and action	Quality of life	Education (% of people completed primary education)- Man and women Access to mass media (television and newspaper)	1993-2011	DHS

3.4. Results

3.4.1. Health

In 1993, the infant mortality (Fig. 3.2a) rate was 95.5 per 1000 live births which declined to 42.5 per 1000 live births in 2011. Child mortality (Fig. 3.2a) shows a decline from 1993 to 2011, although the decreases were small between 1996 and 2004. Child mortality declined from 38 per 1000 live births in 1993 to 24.45 per 1000 live births in 1996 but rose to 25.7 per 1000 live births in 2000. Since 2000, it has declined by 16.7 per 1000 live births within 10 years.

Similarly, maternal health (Fig. 3.2b) has improved, as the proportion of births attended by skilled personnel has increased from ~10% in 1993 to ~38% in 2011 with a step change increase since 2011, when the proportion of births attended by skilled personnel has risen from 20% to 38% within the last four years (2007–2011).

3.4.2. Material condition

The total GDP (Fig. 3.3a) has increased from 74 million USD to 1025 million USD in the period 1978–2005 (at current prices), showing a sharply increasing trend (36 million USD/ yr) since the 1980s. Sector-wise curves of GDP linked to crops, fisheries, shrimp and forestry show (Fig. 3.3b) show that GDP from crops has seen the highest growth (>100 million USD), exceeding forestry and fisheries (~40–60 million USD) and shrimp production (~20–40 million USD).

Table 3.2 shows the changes in household income for all three sectors (agriculture, fishing and non-ecosystem). Household mean yearly income from agriculture has decreased from ~64,000 BDT in 1995 to ~54,000 BDT in 2010. The median income also declined from 45,000 BDT in 1995 to ~29,000 BDT in 2010. The median income per hectare (Table 3.3) declined 53,700 BDT in 2000 to 41,400 BDT in 2005, before rising to 52,400 BDT in 2010. However, mean income per hectare shows increasing trend since 2000. It has shown a stepwise increase from ~31,000 BDT in 2005 to 142,000 BDT in 2010. Household mean income from non-ecosystem sources (Table 3.2) is higher (>6000 BDT) for the period 2000 to 2010, compared to the mean income from agriculture and fishery. In addition, the median income and standard deviation of non-ecosystem based income are observed as quite stable (median 5000–6000 BDT; Stdv ~6400 BDT) since 2000. Mean yearly income from fisheries shows a sharp increasing trend (425 BDT/yr) with a stepwise increase in median (~5600 BDT in 2000 and ~18,000 in 2010) income in 2010.

Although, the mean income of households engaged in shrimp farming shows (Fig. 3.3d) a declining trend (2, 500 BDT ha^{-1}/yr) since 1985, the income is higher compared to the income from agriculture, fishery and non-ecosystem sectors. Household mean yearly income from shrimp was ~270,000 BDT/ha in 1975 and 1985, then falls back to ~230,000 BDT/ha and ~180,000 BDT/ha respectively in 1995 and 2007.

Table 3.3 shows the changes in income per hectare for crop production, crop yield and production costs from 1995 to 2010 at the household level. Mean crop yield (kg/ha) has increased 3 fold from ~3600 (kg/ha) in 2000 and 2005 to 10,600 (kg/ha) in 2010. Similarly, the mean crop production at household level has also increased from 3200 kg in 1995 to 3800 kg in 2010. However, the mean cultivated area has decreased from 1.3 ha in 2000 to 0.92 ha in 2010. Production costs and production costs ha^{-1} have increased, mirroring the rising level of crop yield and mean crop production. Both production costs and production costs ha−1 have increased respectively from 6000 BDT and ~20,000 BDT ha−1 in 2000 to 48,000 BDT and

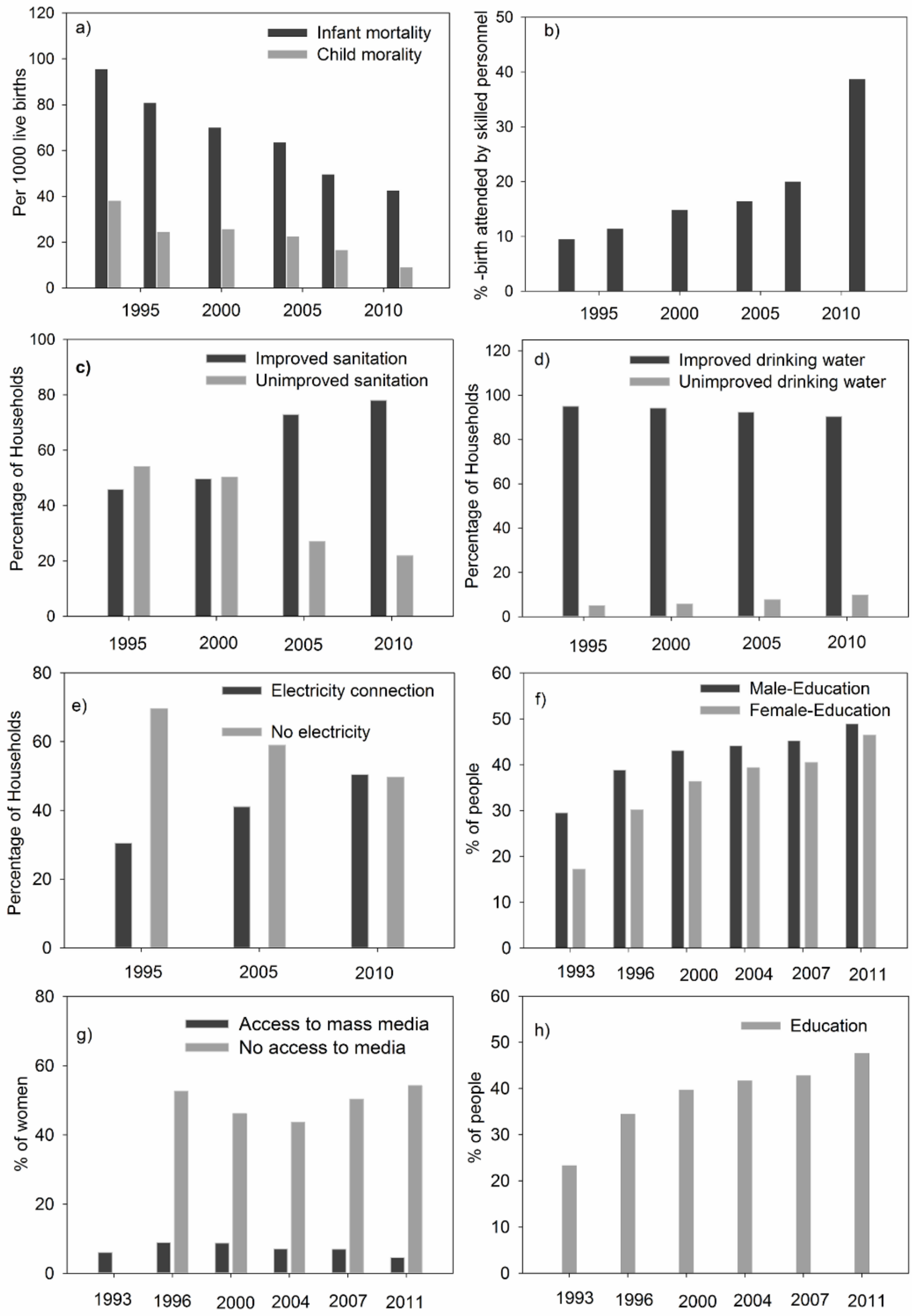

Figure 3.2 Trends of quality of life indicators in the study area from 1993 to 2011.

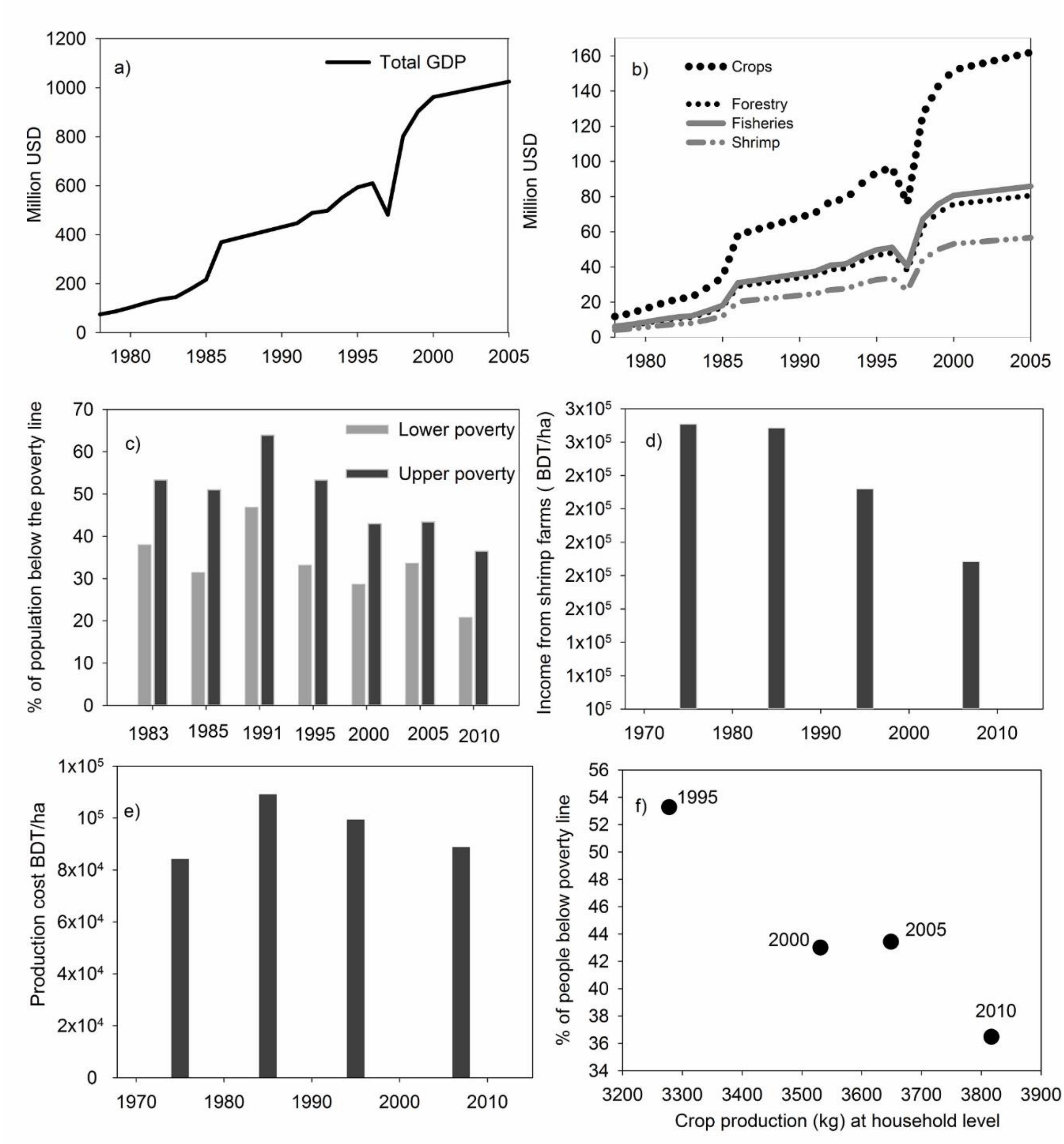

Figure 3.3 Trends of material wellbeing indicators: (a–b) Total and sector-wise gross domestic product (GDP), trends of poverty (c) income (d) and production cost from shrimp farms (e) and linkage between poverty and crop production at household level (f).

23,000 BDT ha−1 in 2010. The mean fish catch of households shows a steep increase from~186 kg in 2000 to ~465 kg in 2010, a 2.5-fold increase within only 10 years (Figure 10).

3.4.3. Poverty

Current (2010) levels of lower and upper poverty in the south-west coastal region are 36% and 20% of the total population down from 53% and 37% respectively in 1983 (Fig. 3.3c). Even though both lower and upper poverty have declined from 1983 to 2010, poverty trends show fluctuating figures in which, upper-level poverty rose from 51% to a peak at ~61% in 1991 before falling back to 43% in 2000 and 2005. Improvement of upper-level poverty becomes stagnant between the period 2000 and 2005, and even the lower level poverty rose from ~28% in 2000 to ~33% in 2005. Moreover, lower level poverty rose at ~46% in 1985 before falling back to ~28% in 2005.

Table 3.2 Income (Adjusted) (Bangladeshi Taka BDT) and sample size for agriculture, fishing and Non ES. Household samples (household size) selected from the HIE surveys (1995, 2000, 2005 and 2010) ranged from 211 to 437 for 'agriculture', from 280 to 347 for 'fishery', from 686 to 1,063 for 'Non-ES' based households.

Agriculture	Mean	Median	Standard deviation	Household size
1995	64,262	45,549	68,267	211
2000	71,231	40,665	91,785	333
2005	56,656	21,967	77,477	428
2010	54,661	37,117	47,528	437
Fishery				
2000	54,592	5,630	216,458	280
2005	60,614	24,140	37,292	504
2010	96,297	18,211	253,558	347
Non ES				
2000	80,761	67,559	77,946	681
2005	76,019	65,836	52,208	927
2010	87,654	72,843	77,198	1063

Table 3.3 Agriculture investment and production (crops and fish) at the household level.

Indicators	Mean	Median	Standard deviation
Income per hectare (BDT)			
2000	73,677	53,783	90,398
2005	58,170	41,424	81,784
2010	179,812	52,421	1,214,920
Crop production (Kg)			
1995	3278	2251	3505
2000	3531	2100	4246
2005	3649	2059	4807
2010	3817	2700	3683
Crop yield (Kg/ha)			
2000	3636	2520	2964
2005	3631	2471	2957
2010	10,648	3867	5,4548
Production cost (BDT)			
1995	5212	3568	5483
2000	15,065	6,709	21,286
2005	31,695	8,787	83,620
2010	48,786	26,633	76,467
Production cost per hectare (BDT)			
2000	19,951	10,441	47,951
2005	44,950	15,879	154,115
2010	123,738	69,760	550,557
Fish catch (kg)			
2000	186	45	914
2005	233	90	646
2010	465	160	1,252

3.4.4. Quality of life

The quality of life appears to have improved because of the improvement of access to electricity and sanitation, and high levels of access to improve drinking water (Figs. 3.2c–3h). Access to improved sanitation shows a rising trend since 2000, when improved sanitation shows stepwise change from 49% in 2000 to 72% in 2005. Currently (2010), ~78% have access to improved sanitation across the study area and ~75% households are using pacca and sanitary latrines, whereas in 1995 ~43% of households were using the inferior kacha latrines and ~10% no latrines at all (open space). Access to improved drinking water is high (>90% households), but the data show slightly worsening trends since 1995, while reliance on unimproved drinking water source rose from 1995 to 2010. The percentage of the households having access to electricity has increased from 30% in 1995 to 50% in 2010. However, currently (2010) half (49.7%) of households have no electricity in their house.

3.4.5. Freedom of choice and action

Overall access to primary education has improved from 23% to 47% in the period 1993–2010 (Figs. 3.2f and 3h). Moreover, significant progress has been made in increasing equitable education by reducing the difference between the percentages of people with access to education for male and female. In 2010, the gap between the percentage of male and female access to education is ~2.5%, whereas in 1993 the gap was ~12%. Even though the gap between male and female education has decreased substantially, the proportion of females having access to media (% of females reading newspaper weekly) has declined in the period 1993–2011 (Fig. 3.3g).

3.5. Discussion

Data unavailability was a major limitation of this study. For example, we could not construct yearly time series data for all the indicators as the datasets are collected every five years (e.g. HIES). HIES and DHS datasets are only representative at national and divisional level, thus, we are only able to investigate the trends aggregated over the all nine districts in our study region from 1995 to 2010, and not carry out analyses at the district level. In addition, HIES datasets do not cover the income of forest-dependent people and shrimp farmers. Thus, we had to depend on the GDP from the forest sector and literature sources for shrimp farm incomes. Despite these limitations, the findings serve as the basis for measuring the progress in achieving HWB goals (e.g. MDGs, SDGs) and drawing out policy implications for the region.

3.5.1. HWB trends

The study provides evidence that HWB could be improving in the south west coastal region of Bangladesh. However, this may not reflect the subjective wellbeing (e.g. happiness, life satisfaction) because we could not analyse the subjective wellbeing indicators due to data unavailability. The quality of life in terms of access to improved sanitation facilities and electricity connection has improved, although access to improved drinking water sources has remained not changed significantly since 1995. About 75% of tube wells were tested for the presence of arsenic, in which 5% of tube wells are contaminated by arsenic. However, this restricted analysis of drinking water quality in terms of metal toxicity needs to be extended to other properties of water relevant to health (e.g. salinity) which may be worsening (Hossain et al. 2015) but are not covered in the HIES datasets. Nevertheless, general health has improved since the 1990s, in particularly, with respect to infant and child mortality that have declined 50% and 75% respectively in less than two decades. Freedom of choice and action have improved mainly because of the improvement (23%) in both male and female education, whereas access to media (percentage of women who read newspapers weekly) has declined 2% over the period 1993 to 2010.

Incomes (median) from fishery and non-ecosystem based livelihoods have increased 76% and 8% respectively. The mean income from fisheries is higher than national and other regional average incomes (Kabir et al. 2012). Non-ecosystem-based average income is similar to the national average income for sectors (BBS 2011). However, both income (median) and income (median) per hectare from agriculture have decreased −18% and −2% respectively. The rising trends of income and GDP seem to support the progress in eradicating poverty and improving HWB because, overall, poverty has declined by 17% over 17 years. The rising trend of material wellbeing (income and GDP) in the agriculture and fisheries sector are mainly because of the adoption of technology (e.g. high yielding rice varieties, irrigation and fertilizer inputs) and fish cultivation in ponds (Ali 1995 and Husain et al. 2001). Our previous findings (Hossain et al. 2013 and Hossain et al. 2015) showed how wild fish catches in rivers have declined substantially in contrast to the rising trend of fish cultivation in ponds (FAO 2014).

All these improvements in HWB are primarily the result of the poverty alleviation efforts of government and NGOs that have provided access to sanitation, safe drinking water, better health facilities, raised educational attainment and free primary education. The Bangladesh government received more than 8500 million USD from 1981 to 2012 as foreign aid to develop health, education and family planning sectors and now allocates ~20% of the annual national budget each year to these sectors. Other government investment in commercial sectors such as agriculture, industry, energy and rural development have also supported the eradication of poverty (UNDP 2014 and MoF 2014).

3.5.2 Provisioning services and material wellbeing

The proxy indicators of food provision services at a household level such as the mean crop have increased 16% between 1995 and 2010. Moreover, the evidence of increase (200%) in crop yield, despite a decrease (−29%) in mean cultivated area at household level suggests that people have intensified cultivation to cope with the growing need for food security. Farmers have adopted high yield varieties of crops (rice) which demand more fertilizer, pesticides and others input compared to the traditional local rice varieties (Hossain et al. 2015, Hossain et al. 2013 and Ali 1995). That is why, in response to the intensive cultivation, the production cost has also increased ~7 fold as crop yields have risen. Increase in production cost and the lack of fair pricing (Hossain et al. 2013 and IFPRI 2014) may be the reason for decreasing income of households engaged in agriculture. Moreover, the stable level of crop yield and income per hectare both in 2000 and 2005, coincides with a rising lower poverty level and a stable trend in upper poverty level in 2005. Moreover, the bivariate plots (Fig. 3.3f) suggest that crop production at household level is positively related to poverty alleviation, which is also linked with total rice production in the region (Hossain et al. 2015). The contribution of provisioning services in improving HWB at region scale is also evident from national (Hossain et al. 2007) and global studies (Raudsepp-Hearne et al. 2010). Despite showing the links between crop production and poverty alleviation there are several reasons to be cautious.

First, the recent HIES survey reports (2010) estimated that ~22% of the total poor households are engaged in agriculture, forestry and fisheries. Indeed, the data for average income from agriculture and for the poverty lower threshold line (monthly ~5600 BDT per household) suggests that farmers are more likely to belong to the poor income level of the society, whereas fishermen and non-ecosystem-based people are more likely to be above the lower poverty line. Therefore, it would be useful to document the changing percentage of households living below the poverty line within different occupations, especially in the south west coastal part of the study area which is the second poorest region (just above the Rangpur division).

Second, the apparent link between poverty and crop production suggests that poverty could increase because of the increasing trends of environmental threats, like salinity and flooding (Ali 1995, ADB 2005 and Hossain et al. 2015) that are more likely to affect disproportionately the crop production in south west coastal Bangladesh. In addition, increased fertilizer usage is also raising the nutrient loads to rivers through runoff (Hossain et al. 2015) that may affect the sustainability of fish production in future. This will not only increase the poverty in agricultural sectors but will also raise the threat of food security problems across the whole densely populated delta area. As Raudsepp-Hearne et al. (2010) have argued, despite the generally observed rise in provisioning services and poverty alleviation, the growing losses of regulating and supporting may be eventually be expected to feedback negatively on essential provisioning services, and in turn HWB.

Third, besides the environmental threats, there is a risk of an increase in income poverty because of the increase in production costs, which are rising faster than crop production. Rising trends of fertilizer input to improve production in agriculture was evident in previous studies (Ali 1995, Husain et al. 2001 and Hossain et al. 2015) but costs may make fertilizer applications prohibitively expensive.

Fourth, in the case of shrimp farming, despite an increasing trend of total GDP from shrimp production the sector can produce other consequences, such as an increase in poverty and environmental pollution. The salinity increase due to shrimp farming reduces crop production and creates unemployment for farmers because of the low labour demand in shrimp farming compared to crop production (Swapan and Gavin 2007). All these indicate the potential of human capital investment to improve the wellbeing of the population in response to environmental changes in the study area.

3.5.3. Achievements of MDG goals

Table 4 provides an assessment of the progress in achieving MDG goals at national and regional scales. The south-west coastal area has shown (Table 3.4) progress (similar to national achievements of MGD targets 4 and 5) by reducing child and infant mortality and improving maternal health. Although the maternal mortality was not covered in this study due to the lack of data, national trends on maternal mortality have also achieved the target of MDG 2015 (Chowdhury et al. 2011). However, the poverty eradication target (to halve figures between 1990 and 2015) has not been achieved for MDG 2015, despite showing significant poverty eradication (17%) within 15 years. Similarly, personal security and freedom of choice indicators have not achieved the MDG target in regional and national scale and it seems unreachable by 2015, with the exception of the provision of sanitation facilities which has progressed well (78%) compared to the national (51%) scale. In contrast, half of the households are still without coverage of electricity and achievable education attainment (primary education).

3.5.4. Moving beyond MDGs

This study suggests that achieving some of the SDG goals by 2030 is achievable while others will remain challenging. Our results suggest that reaching the goals for a healthy life for all (Goal 3: child and infant mortality) and sustainable use of water and sanitation for all (Goal 6: sanitation and safe drinking water source) appear to be achievable in this region by 2030. Great emphasis has been placed on reducing discrepancies within countries (Goal 10).

In this study, with respect to reducing child and infant mortality generally and, specifically, to ensuring improved sanitation and births attended by skilled personnel, south west coastal Bangladesh is developing well compared to the nation as a whole.

Table 3.4 Target and progress of MDGs in regional and national scale of Bangladesh.

Indicators	Regional Target by 2015	2010	2005	2000	1995	National Target by 2015	National - 2010
Child mortality	16	9	22	25	24	48	53
Infant mortality	53	42	63	70	80	31	43
Proportion of births attended by skilled health personnel (%)	50	20	16	14	11	50	31
Poverty	26	36	43	43	53	27	31
Improved sanitation	100	78	72	49	45	100	51
Improved drinking water source	100	90	92	94	95	100	95
Electricity	100	50	41		30	100	55
Education	100	42	41	39	34	100	48

On the more challenging side, quality education (Goal 4) needs to receive higher attention as half of the households are still without primary education attainment. The proposed SDGs also recommends the promotion of sustainable agriculture (Goal 2) by increasing productivity and farm incomes (Goal 2.3). These goals will be quite challenging to achieve by 2030 as the analysis shows that despite an increasing trend of mean crop production (16%) and crop yield (kg/ha) (192%) at household level, median income per hectare from agriculture production has already decreased −2% between 2000 and 2010. Evidence of production cost increases from this study (also from Ali 1995; Husain et al. 2001), as well as claims that farmers suffer from the lack of fair pricing (Hossain et al. 2013 and IFPRI 2014) suggest that poor regulation of commodity markets and weak agricultural investment needs to be reversed. Without these reforms, farmers may become demotivated with serious consequences for production, such as a reduction in jute production (Hossain et al. 2015) and for personal health (e.g. rising suicides among Indian farmers) (BBC 2013 and BBC 2015).

Although there has been significant poverty alleviation in this region, it is unlikely that it will achieve the SDG Goal 1 of poverty elimination in MDGs by 2015. Moreover, going beyond MDGs, towards achieving SDGs by 2030, may be even more challenging. Declining or stationary crop production coupled with ongoing environmental degradation (e.g. salinity rise, water scarcity) and projected climate change may impact negatively on incomes. This underlines the need to establish sustainable agriculture as the basis for poverty alleviation.

3.6. Conclusions

Since the 1990s, child mortality and infant mortality have declined 50% and 75% respectively in the south-west coastal area of Bangladesh. Moreover, the number of births attended by trained personnel also increased (28%) from 1993 to 2011.

Data for the material condition, such as incomes from agriculture, fishing and Non-ES based livelihoods, have increased from 1995 to 2010. Income from fishing has shown a sharply increasing trend since 2000. Even though GDP from shrimp farms is sharply increasing, as in other sectors such as agriculture, fishery and forestry, income from shrimp firms declined after 1995.

Over this period, poverty has been reduced by an impressive 17%, a figure that is closely linked with crop production at the household level and total rice production over the region. However, associated production costs have increased 7-fold in response to the changing nature of farming aimed at raising crop yields to meet the growing demand for regional food security.

Despite showing improving trends in all these HWB indicators, including education for men and women, the region has only achieved the MDGs target for 2015 for child and maternal health. It has failed to meet several important targets (e.g. poverty alleviation, education, and sanitation) by 2015.

Achieving the SDGs by 2030 will be highly challenging because of a) the increasing likelihood of environment threats and ecological feedbacks affecting agricultural and fishing incomes, and water availability; and b) the need to raise production levels through financial investment in poor households already constrained by high production costs.

The study demonstrates the importance of detailed monitoring of HWB trends at regional scales to support policy-making. Achieving the SDG targets by 2030 will require new policies and their implementation with continued monitoring of livelihoods as an essential element in monitoring progress. The study also provides the basis for ongoing attempts to define and model SOSs (Dearing et al. 2014) as the basis of determining sustainable land use within the region.

Chapter 4: Paper 3

Unravelling the interrelationships between ecosystem services and human wellbeing in the Bangladesh delta

4.1 Abstract

Coupled social and ecological systems need to be understood from a dynamic perspective in order to operationalise complexity concepts, such as tipping points, for sustainable ecosystem management. In this study, we strive to achieve this type of conceptual understanding through the analysis of the relationships (e.g. strength, nonlinearity) between the trends of ecosystem services (ES) and human wellbeing (HWB) between 1960 and 2010 in the south-west Bangladesh delta using generalized additive and logistic regression models. We use sequential principal components analysis to investigate the connectedness within the social–ecological system as a measure of resilience. We also use published literature to help develop a SD framework in order to investigate how ES and HWB are interlinked. Overall, our results support previous work, which depicts that material wellbeing (basic materials for a good life) having a strong relationship with provisioning services, which in turn, show a weak relationship with the quality of life (security and health). Moreover, our analysis confirms the 'Environmentalist's Paradox' that HWB has increased despite the deterioration in ES. However, our results suggest that provisioning services are not the only important reason for the increases in observed HWB,

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as these have also been substantially influenced by technology and capital investment (aid and subsidy). In addition, worsening trends in regulation services and in 'slow' variables such as climate suggest that the resilience of the overall SES is decreasing. Such changes may have severe consequences if they continue, for example, if temperatures exceed the upper physiological limits of key provisioning services (e.g. rice, fish) in the Bangladesh delta. These indicators all suggest that although in terms of HWB the deltaic social–ecological system may be successfully adapting to environmental change, it may also be close to transgressing critical ecological boundaries in the near future.

Keywords: Dynamic framework, ecosystem services, human wellbeing, nonlinear, threshold, social–ecological system

4.2. Introduction

The Millennium Ecosystem Assessment (MA) developed a conceptual framework to explore the complex relationships between ecosystem services (ES) and human wellbeing (HWB). Due to the importance of this relationship for policy decisions and human actions, several studies have adopted this framework empirically at national and subnational scales (Butler & Oluoch-Kosura 2006; CRA 2006; Hossain et al. 2013; Santos-Martın et al. 2013). It is evident from regional (e.g. Scherr 2000; Irz et al. 2001; CRA 2006; Hossain et al. 2013; Santos-Martın et al. 2013) and global scale (Raudsepp-Hearne et al. 2010) studies that provisioning services are supporting improvements in HWB. Of particular note is the study by Santos-Martın et al. (2013) who analysed the relationship between ES and HWB in Spain using comprehensive lists of indicators and a structural equation model within the Driver-Pressure-State-Impact-Response framework. They demonstrated that, in contrast to regulating services, provisioning services have a direct and highly significant relationship with HWB. However, HWB indicators, such as life expectancy at birth, are not only affected by provisioning services, but are also directly driven by human capital formation (e.g. GDP, education) and technological progress (Cervellati & Sunde 2005). In addition, rising living standards and wellbeing could eventually be affected by the negative consequences of low levels of regulating services, as in the argument put forward to explain the 'Environmentalist's Paradox' (Raudsepp-Hearne et al. 2010) of rising HWB in the face of environmental deterioration, which then may need to be offset by investments in human capital (e.g. government initiatives for education and health) and technology (e.g. water quality purification, alternative livelihood sources) (Hossain, Johnson, et al. 2015). An understanding of the full relationship between ES and HWB demands a dynamical perspective based on time series data (Carpenter et al. 2009) that can give insight into the complex and uncertain nature of a social–ecological system, for example, the potential time lag effects between regulating services and HWB.

Previous social–ecological studies in Bangladesh delta have mainly used conceptual models for specific sectors, such as shrimp farming, (Datta et al. 2010) and climate change adaptation (Shamsuddoha et al. 2013, FAO 2006) and analysed the likely impacts of single drivers of change, such as climate (e.g. Husain et al. 2001; Swapan & Gavin 2011; Hossain et al. 2013). An improved approach would use a conceptual model that describes a fuller range of complex and dynamic relationships (e.g. nonlinearity, feedbacks) between social and ecological systems that would provide the means of structuring real world situations and aid the understanding of sustainable ecosystem management (Hodge 1997; Rounsevell et al. 2010). In this study, we strive to achieve this type of conceptual understanding through the analysis of the relationships (e.g. strength, nonlinearity) between the trends of ES and HWB between 1960 and 2010 using generalized additive and logistic regression models. We use sequential principal components analysis (PCA) to investigate the connectedness within the social–ecological system as a measure of resilience. We also use published literature to help develop a SD framework in order to investigate how ES and HWB are interlinked. It is intended that the findings from the present study will be useful in operationalising concepts such as 'thresholds and tipping points' and 'safe and just operating spaces', beyond which the risk of unpredictable and damaging change to social–ecological systems becomes very high, for regional-scale sustainability and for ecosystem management (Dearing et al. 2014).

Our approach comprises six research steps: (1) collecting and collating time series data for ES and HWB indicators as well as for other social, economic and climate change; (2) analysing the past trends of provisioning and regulating services, and the current status of HWB; (3) analysing the relationship between regulating services and provisioning services indicators; (4) analysing the relationship between provisioning services and HWB indicators; (5) developing a conceptual SD model for each of those indicators and (6) exploring the relationships between each of those indicators.

4.3. Methods

4.3.1. Study area

The south-west coastal part of Bangladesh (Figure 4.1) represents 16% of the total land area (~25,000 km^2) of Bangladesh with a population of 14 million people (BBS 2010). Our study area comprises 60% of the Khulna Division and the whole Barisal Division, an agro-ecological landscape representative of the Ganges tidal floodplain (FAO-UNDP 1998) and mapping onto the linked ESPA delta project area (www.espadelta.net). This coastal ecosystem produces more than 1300 million USD of gross domestic product (GDP) (BBS 2010) which contributes to 277 USD GDP per person (Sarwar 2005). However, around 38% of the people of this region live below the poverty line (BBS 2010). The livelihoods in this region are dependent on agriculture (~40%), fishery (~20%) and forestry (~25%) with the remainder including labourers and professionals (e.g. teachers, government officials and businessman).

The Sundarbans, the world's largest mangrove ecosystem, provides livelihoods for about 1.5 million people and protects about 10 million coastal people from storm surges (Islam & Haque 2004).

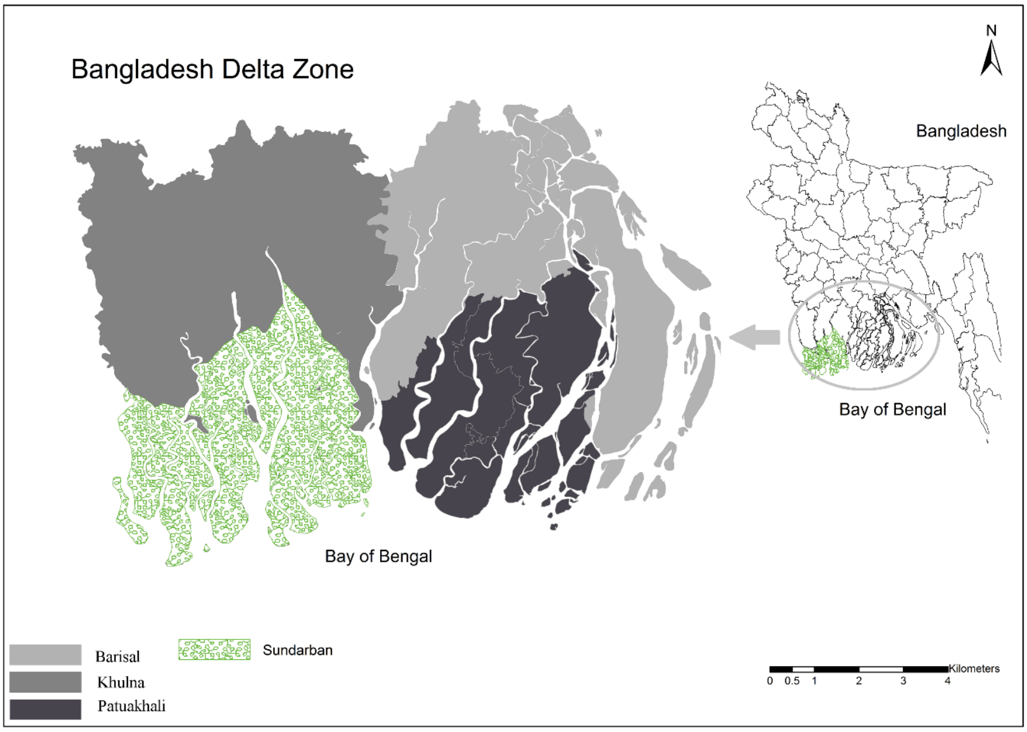


Figure 4.1 South-west coastal region of Bangladesh.

The humid climate gives an annual rainfall of 1400–2100 mm and an average temperature of 30–34°C in the dry summer period and 15–20°C in winter (Hossain et al. 2014). The region has been affected by 174 natural disasters within the 1965–2010 time period (Rahman et al. 2010). Floods in 1992 damaged 50% of total food grain, and drought in 1997 caused 1 million tons of food grain loss (Islam et al. 2011). Besides these natural disasters, the region is also experiencing challenges due to human intervention, including water shortages due to dam construction upstream of the Ganges delta (Hossain, Dearing et al. 2015) and polder construction in coastal areas (Islam 2006). Moreover, expansion of the shrimp industry has degraded the water quality as well as the density of the mangrove forest (Hossain, Dearing et al. 2015). The SES of this region is rapidly changing in comparison to previous decades, because of sea level rise, land-use changes, water scarcity, migration and urbanization (ADB 2005; Hossain, Dearing et al. 2015) with climate change (Hossain et al. 2013) adding an extra layer of complexity for environmental managers. The high dependency of the residents' livelihoods on ES and their ability to adapt to growing environmental threats underpins the importance of treating the area as a highly complex social–ecological system.

4. 3.2. Ecosystem services

Ecosystem service indicators (Table B.1) from different locations across the region were selected based on data availability 1960–2010, the degree to which they reflect well-known environmental challenges, and their measurability. Total rice, shrimp and fish production, plus the mass of raw materials obtained from the mangrove forest are the main indicators for provisioning services, whereas temperature and precipitation are the key indicators of local climate (de Groot et al. 2006; WRI 2013; Hossain et al. 2014; Hossain et al. 2015). Climate data from three weather stations (Khulna, Barisal and Patuakhali) have been used to calculate trends in average annual climate for the study area. Water flow data from Hardinge Bridge (1931–2010) have been used to investigate the trend in water availability. This stream point of the Padma River (Ganges) is the major passage of water flow into the Bay of Bengal and also the major water source of the Sundarbans. We also chose surface water salinity and soil salinity to show the trends of water quality and soil quality, respectively, key indicators of regulating services. Crops damaged by different natural disasters have been selected to analyse the trends of natural hazards protection. Mangrove density was selected as the best indicator (Costanza et al. 1997; de Groot et al. 2002) of maintenance of biodiversity, which is the main source of raw materials in this area.

An earlier paper (Hossain et al. 2015) provides details about the selection of ES indicators and also the detailed analysis of ES at different spatial and temporal scales using a number of time series analyses (e.g. Mann–Kendal and Lepage tests). Supporting ecosystem services (e.g. nutrient cycling, primary production) are excluded due to the lack of data and avoidance of double counting (de Groot et al. 2010; Petz et al. 2012).

4. 3.3. Human wellbeing

HWB is a subset of economic and social wellbeing factors (OECD 2013) and has been classified into five dimensions: health, material, security, freedom and social relations (MA 2005). Except for material wellbeing, all these indicators fall within the quality of life dimension (OECD 2013). Our main data source for HWB is the most recent (2010) household income and expenditure survey (HIES) undertaken by the Bangladesh Bureau of Statistics (BBS) with the help of the World Bank using a two-stage randomly selected sampling strategy. The number of primary sample units (PSU) and household samples selected for the surveys are 1000 and 12,240, respectively. Moreover, surveys were conducted across the year to account for seasonality (BBS 1997, 2011). The HIES is representative at national and divisional level (Azam & Imai 2009; Szabo et al. 2015). The list of selected HWB indicators (Table B.2) is based on data availability, measurability and the SDG 2030 and MDG 2015 for Bangladesh, for example, the percentage of 'births attended by skilled health staff' and 'primary education' attainment. In addition, we have also used the percentage of households with access to 'sanitation' and 'safe drinking water' in each year to analyse the trends in personal security over the study area. We have classified both sanitation facilities and drinking water sources into improved and unimproved types as per the Demographic and Health Survey (DHS 2007). Sanitary latrines and pacca latrines (water seal and pit) are categorized within the 'improved sanitation' category, whereas kacha, open and other types of sanitation facilities are labelled as 'unimproved sanitation'. Similar approaches have been followed to classify improved (supply, tube well) and unimproved (pond/river, well and others) sources of drinking water. In case of 'education', we have defined the categories as 'primary education completed' and 'primary education not completed'.

Gross domestic production (GDP) and income have been used for analysing material wellbeing (both converted to current values using the Consumer Price Index). Trends of GDP have been analysed with respect to each of the four provisioning services (crops, fish, forestry and shrimp) from 1978 to 2005. A lack of data means that we have calculated the GDP share from each sector (except forestry) only for the period 1978–1992, and 2005. Besides GDP, we also analysed the average annual production and average cultivated area for crop production for all household level data in our study region. Similar to crop production, we have also analysed the average fish production (fish catch from rivers and cultivated in ponds) at household level and the average annual production of fish. These indicators are not only part of the sustainable agriculture under the dimension of material wellbeing, but also can be used as the proxy of provisioning service (e.g. food, fish) production at the household level to analyse the possible relationships between HWB and provisioning services.

4. 3.4. Interlinkages between ES and HWB

In general, it may be assumed (Raudsepp-Hearne et al. 2010; OECD 2013) that there are two major sets of linkages that define the relationship between ES and HWB: (1) the underpinning role of regulating services with respect to provisioning services, and (2) the strong dependence of HWB on provisioning services (Figure B.1). In the Bangladesh delta, previous work (Mirza 1998; Azad et al. 2009; Swapan and Gavin 2011; Hossain et al. 2013; Hossain et al. 2015a; Hossain et al. 2016b) provide ample evidence to enable us to explicitly link relevant regulating services to provisioning services, and thereby to identify dependent and independent variables within a relationship. Examples of this include the declining trends of water flow and higher rates of sea water intrusion that are leading to increasingly high ground water levels, and water flow reduction, higher temperatures and rainfall change that strongly influence food production. We use these empirical observations to develop hypothesized SD models for agriculture, fisheries, shrimp farming and forestry, where dependent and independent variables are defined as a basis for statistical (both generalized additive models and logistics regression) analysis. Because of the nonlinear (characterized by thresholds and limiting functions) relationships between ecosystem functions and ES (Koch et al. 2009), we have used generalized additive models to analyse the types of relationships between the time series data of regulating services and provisioning services based on these hypothesized links. This non-parametric regression technique allows us to determine the underlying relationships between the variables (Hastie & Tibshirani 1990) using the following equation:

$$g(\mu) = \propto + \sum_{j=1}^{m} fj(xj) \qquad (1)$$

Here, response variable μ is related to link function g (.) and is a smooth non-parametric function (spline) (Green & Silverman 1994). Because of the power of this regression and capacity to analyse the complex relationship (e.g. nonlinear and non-monotonic relationships) between ecological variables, it has already been used for analysing ecological (Thomas & Mitchell 1991; Guisan et al. 2002) climate (Khan et al. 2007; Kim et al. 2011) and social-economic (Gouveia et al. 2003) systems. We have tested for heteroscedasticity in the time series data in order to avoid bias in the least squares estimates of the variance of the coefficients. We have also used sequential PCA in 10- and 20-year moving windows to measure changes in connectedness (Billio et al. 2010) between provisioning and regulating services (Zhang et al. 2015) as an indicator of system resilience (Ash & Newth 2007; Scheffer et al. 2012). For this, we have used trends for different varieties of crops since 1967 and trends for water discharge, temperature, rainfall and water salinity since 1967.

For the linkage between provisioning services and HWB, we use linear regression to analyse the relationship between the GDP time series (as an indicator of material wellbeing) and provisioning services. However, the lack of long time series data for HWB means that we can only link the provisioning services to quality of life indicators through the household level information in the HIES data. In this case, we generate linear relationships from linear and logistic regression because: (1) linear relationships (e.g. GDP and production) are exhibited in the linearity diagnostics (e.g. scatterplot, normality of residuals); (2) dependent variables (e.g. education, sanitation) are categorical and (3) unlike the ecosystem, the relationships in the social system often show linearity (e.g. income and health, wealth and primary school attainment) between independent and dependent variables (Ecob & Smith 1999; Gylfason 2001). We also analyse the 2010 HIES data with logistic regression to give the relationships between binary outcomes (e.g. having improved sanitation versus unimproved sanitation, connected to electricity versus not connected to electricity) and continuous covariates (e.g. crop produce, fish production). The categorization of improved and unimproved HWB indicators has already been given in the HWB indicator section. Here, we use code 0 as an unimproved and code 1 as an improved category of HWB (e.g. 0 = not completed, 1 = primary completed) for logistic regression. The relationship between the dependent variable and independent variables is established by the following equation:

$$\text{logit}(p) = \log(p/(1\text{-}p)) = x_i b + b_o \qquad (2)$$

Here, p is the probability of an improved HWB outcome, and p/(1-p) is the odds of improved HWB outcome (Menard 1995).

In our case, quality of life (e.g. primary education, improved sanitation) is the dependent variable and production of crops and fish at household level is the independent variable. This analysis is limited to crop and fish production because data for households engaged in shrimp and forest production from the mangrove are not collected in the household surveys. Moreover, the sample size of HIES also varies for the households engaged in agriculture (N = 437) and fisheries (N = 347). Some of the HWB indicators such as 'child mortality', 'infant mortality' and 'access to media' are only available in the DHS dataset, which does not cover any production or income data and cannot be linked to the HIES dataset, meaning that analysis of the relationship between provisioning services and those HWB indicators is not possible.

4.4. Results

4.4.1. Trends of ES

Figure 4.2 shows the trends of ES in the Bangladesh delta. For provisioning services, total rice production in Bangladesh delta has increased two-fold (1.5–3.0 Mt) from 1972 to 2010, whereas total crop (all) production declined since 1975 in the same region. Inland fish production has increased since 1986 mirroring the increasing production from shrimp (from ~22,000 t to >30,000 t) and ponds (from ~50,000 t to >70,000 t) since 1999 (Figure 4.3(c)). In contrast, collection of raw material (e.g. timber) from the Sundarbans rose to peak in the 1980s and 1990s (data are missing 1987–1991) before declining rapidly (from 150,000 t to 20,000 t) after 1996 (Figure 4.2(f)).

Records of regulating services show significant change. Salinity concentrations (Figure 4.2(g)) in the river rose 2–10 fold and stood between 20,000 and 45,000 dS m−1 in the period 1980–2008. Similarly, soil salinity has also increased from ~1.5 dS m−1 in 1990 to ~3.5 dS m−1 in 2008. Overall, water availability declined from 1968 to 2000 because of the Farakka Barrage in the upstream Ganges (built in 1975). The mean flow rate has declined by ~50 m3/s/year in the period 1948–2010 with mean annual flows ~2000 m3/s lower in the post-Farakka period (1975–2010) compared to the pre-Farakka period. In addition, mean flow rates in the dry season have declined by ~−35 m3/s/year in the period 1965–2010, whereas wet season figures show small declines ~−6 m3/s/year in the post-Farakka period. Similarly, levels of ground water (Figure 3(k)) have risen from ~2.5 m to ~1.75 m all over the delta region. In the recent four decades

(1971–2012), the annual average temperature (Figure 4.2(i)) has increased by 0.74°C over the previous two decades (1948–1970). This change in annual temperature is also consistent with seasonal temperature trends which show an accelerating upward trend (~0.03°C/year) for pre-monsoon and monsoon seasons since 1990. Meanwhile, mean values for dry season (pre-monsoon and winter) and monsoon rainfall show declining trends (−60 mm/year and −35 mm/year, respectively) whereas post-monsoon rainfall shows an increasing trend (+4.5 mm/year) trend up until 2007. Annual rainfall (Figure 4.2(j)) has increased by ~400 mm in the period 1991–2007 compared to 1971–1990. Damage to crops due to natural disaster (flood, rainfall and drought) was highest between 1987 and 1991 but the data show no long-term trend. Sea level may exert an influence on salinity, river flows and ground water level. It has risen (Figure 4.2(o)) by ~200 mm in the period 1978–2003 at a rate of ~8.5 mm/year.

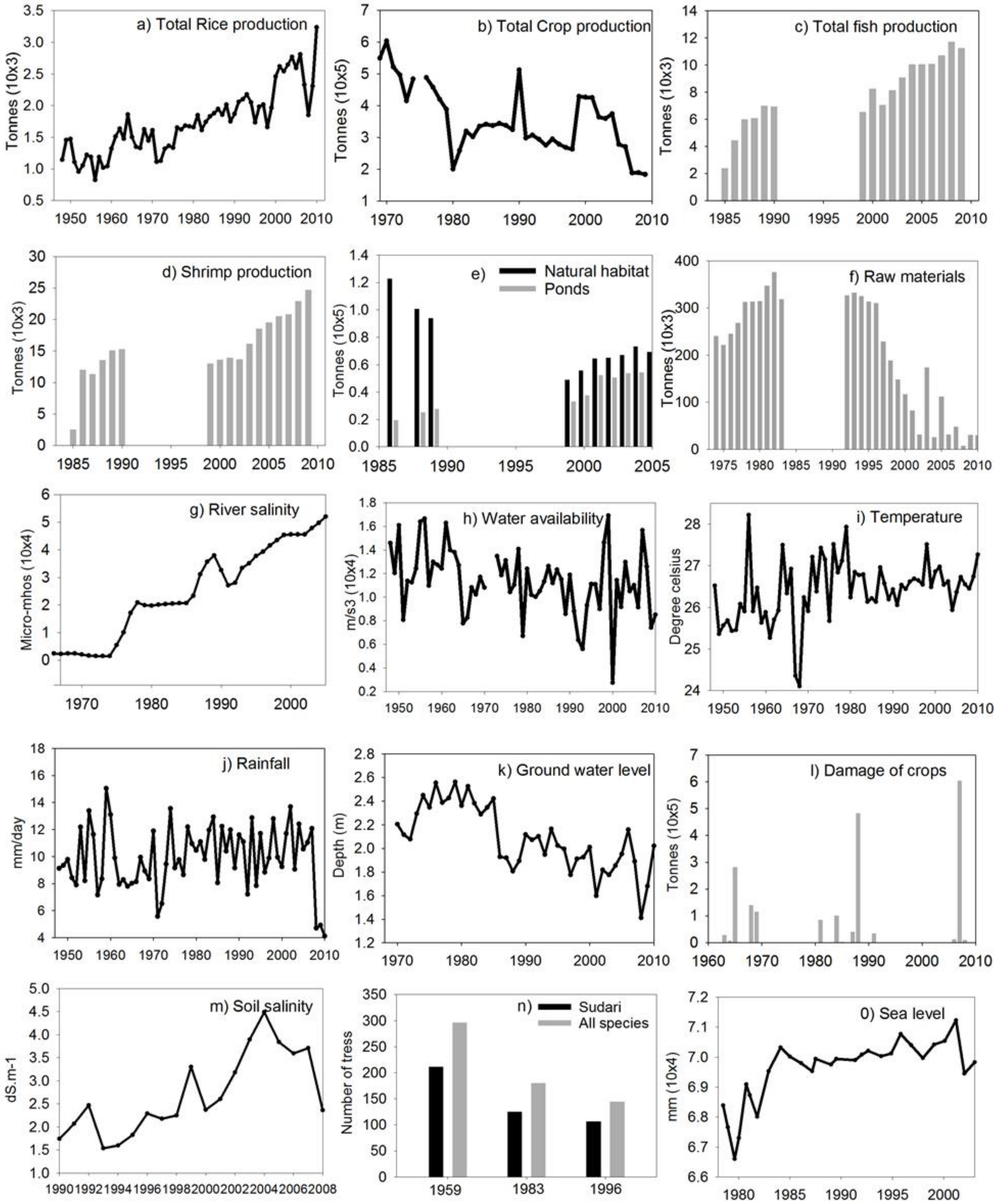


Figure 4.2 Trends of ES and of ecosystem service indicators in Bangladesh delta.

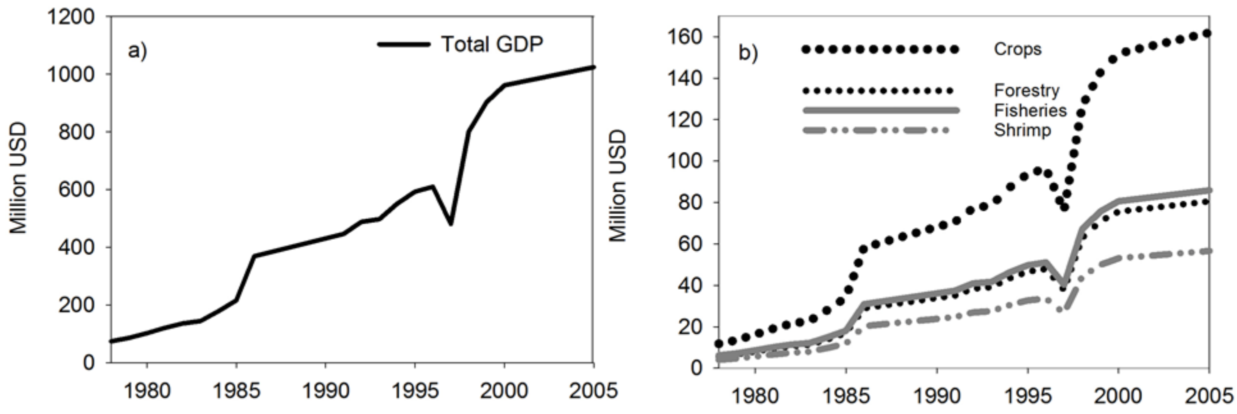


Figure 4.3 Trends of GDP (a) and GDP shared by different sectors (b) in Bangladesh delta.

Tree density (Figure 4.2(n)), used as the indicator of biodiversity, has halved for all types of species including the main species of sundari (Heritierafomes) from 1959 to 1996. Despite the loss of tree density, the number of tourists visiting the mangrove forest has increased six-fold (5000~35,000) between 1996 and 2010.

4.4.2. Human wellbeing

Total GDP (Figure 4.3(a)) has increased from 74 million USD to 1025 million USD in the period 1978–2005 with an annualized increase of 36 million USD/year since the 1980s. GDP from crops, fisheries, shrimp and forestry show (Figure 4.3(b)) similar trends to total GDP, but GDP from crops is higher (>100 million USD) than forestry and fisheries (~40–60 million USD) and shrimp (~20–40 million USD). About 40% of households are engaged in agriculture, whereas 20% and 25% households are engaged in fishery and forestry, respectively (Table B.3). The mean cultivated area is ~0.92 ha in which on average ~3800 kg crop is produced at the household level giving estimated mean and median household yields of ~10,600 kg/ha and 3800 kg/ha, respectively. The mean annual household incomes and costs of production are about 34,000 Bangladeshi Taka (BDT) (median 23,000 BDT) and 30,000 BDT (median 16,000 BDT), respectively (1 BDT = ~0.13 USD). The annual mean fish production per household at 465 kg gives a higher annual mean income (96,000 BDT) than from crop production.

Table 1 shows that in 2010, ~74% households had access to improved 'sanitation' both for households engaged in fishery and in agriculture. In the case of access to improved 'drinking water sources', ~90% of households engaged in fishery had access to improved 'drinking water sources'. Approximately, 34% and 41% of households engaged in agriculture and fishery, respectively, have an ‘electricity connection’ at home. For ‘births attended by skilled health staff’, a similar difference exists for households engaged in agriculture (46%) and fishery (30%). Besides these figures, currently ~45% of household individuals engaged in agriculture and fishery have completed primary education.

Table 4.1 Target and current status of MDGs in regional (South-west Bangladesh delta) and national scale of Bangladesh

Indicators	Regional - 2010	National -2010	MDGs Target by 2015
Proportion of births attended by skilled health personnel (%)			
Average (all occupations)	35	31.7	50
Agriculture	46		
Fishery	30		
Improved Sanitation (%)			
Average (all occupations)	78	51	100
Agriculture	74		
Fishery	74		
Access to safe drinking water (%)			
Average (all occupations)	90	95	100
Agriculture	88		
Fishery	90		
Electricity connection (%)			
Average (all occupations)	50	55	100
Agriculture	34		
Fishery	41		
Primary education attainment (%)			
Average (all occupations)	42	48	100
Agriculture	45		
Fishery	45		

4.4.3. Regression analyses of ES

The generalized additive regression analysis shows (Table B.4 and Figure B.4) that rice exhibits significant and positive relationships (Figure 4.4(a, b)) with temperature ($\beta = 0.22$, $p = 0.03$) and soil salinity ($\beta = 0.71$, $p = 0.01$), a non-significant relationship (Figure 4(c)) with rainfall ($\beta = 0.19$, $p = 0.12$, and a significant ($p = 0.04$) negative ($\beta = -0.21$) relationship (Figure 4.4(a)) with water discharge (water availability). Within these relationships, a linear relationship is observed for water discharge and soil salinity, whereas nonlinear relationships are found for both rainfall (cubic) and temperature (quadratic). It is evident (Figure 4.4(b)) that rice productivity increases with temperature, although at temperatures beyond 27°C rice productivity begins to fall. Rice production declines when rainfall drops to within the range 4.0–6.7 mm/day or rises to more than ~12 mm/day.

Total fish production is negatively (Figure 4.5(a)) related to water salinity ($\beta = -0.13$, $p = 0.00$) but positively (Figure 4.5(c)) related to water discharge ($\beta = 0.84$, $p = 0.23$). Although fish production from ponds (Figure 4.5(d)) shows a significant positive relationship ($\beta = 1.47$, $p < 0.01$) with water salinity, fish production from natural habitats (Figure 4.5(b,e)) exhibits a negative relationship for both water discharge ($\beta = -0.13$, $p = 0.90$) and water salinity ($\beta = -2.32$, $p < 0.01$). Nonlinear effects on fish production from ponds and natural habitats are found for water discharge respectively at ~9800 m3/s and ~13,370 m3/s. Similar nonlinear (quadratic) relationships are observed at ~39,000 dS m−1 water salinity for forest products (Figure 4.5(f)). Moreover, the relationship between forest production and water salinity is negative ($\beta = -0.63$) with a higher confidence level ($p < 0.01$). Forest production also exhibits a weak negative but non-significant ($\beta = -0.08$, $p = 0.66$) relationship with water discharge (Figure 4.5(h)).

For selected covariate relationships with regulating services, Figure 6 shows that water discharge is positively (non-significant) associated ($\beta = 20$, $p = 0.13$) with rainfall (Figure 4.6(a)), and also show non-significant and negative association ($\beta = -0.92$, $p = 0.18$) with water salinity (Figure 4.6(g)). Water discharge exhibits a linear relationship with rainfall and water salinity. The rise in sea level shows a significant ($p < 0.01$) negative ($\beta = -0.63$) relationship with ground water levels (Figure 4.6(d)), which also exhibits a significant ($p < 0.01$) negative ($\beta = -0.70$) relationship with water salinity (Figure 4.6(e)). Soil salinity is also positively ($\beta = 0.73$) associated with water salinity (Figure 4.6(f)), whereas it is non-significantly ($p = 0.27$) and negatively ($\beta = -0.26$) associated with ground water levels (Figure 6(h)). Both of these relationships are nonlinear in that soil salinity remains at the same level as the ground water level rises between 1.41 and 1.79 m, but drops if the ground water level rises beyond 1.79 m. Soil salinity increases when water salinity exceeds 39,500 dS m−1.

Curves for combined PCA axis 1 and 2 (Figure 4.7) since 1967 for two rolling windows (10 years and 20 years) suggest high levels of connectivity existed between regulating and provisioning services in the early 1980s were followed by a sharp decline until the 1990s with a rising trend after 1995. The changes in the connectivity curve from high to low values coincides with the shift in economic regimes from nationalization in the late 1970s to greater privatization from the early 1990s onwards. At this time, widespread rice-based farming gave way to an increasing diversity of land use, especially shrimp and fish cultivation, and a large variety of crop types. The recent rise in the curves tracks the trade globalization that started in the early 2000s, which may have had the effect of synchronizing the regional production of local products, such as jute, shrimps and fish, for export according to prevailing commodity prices.

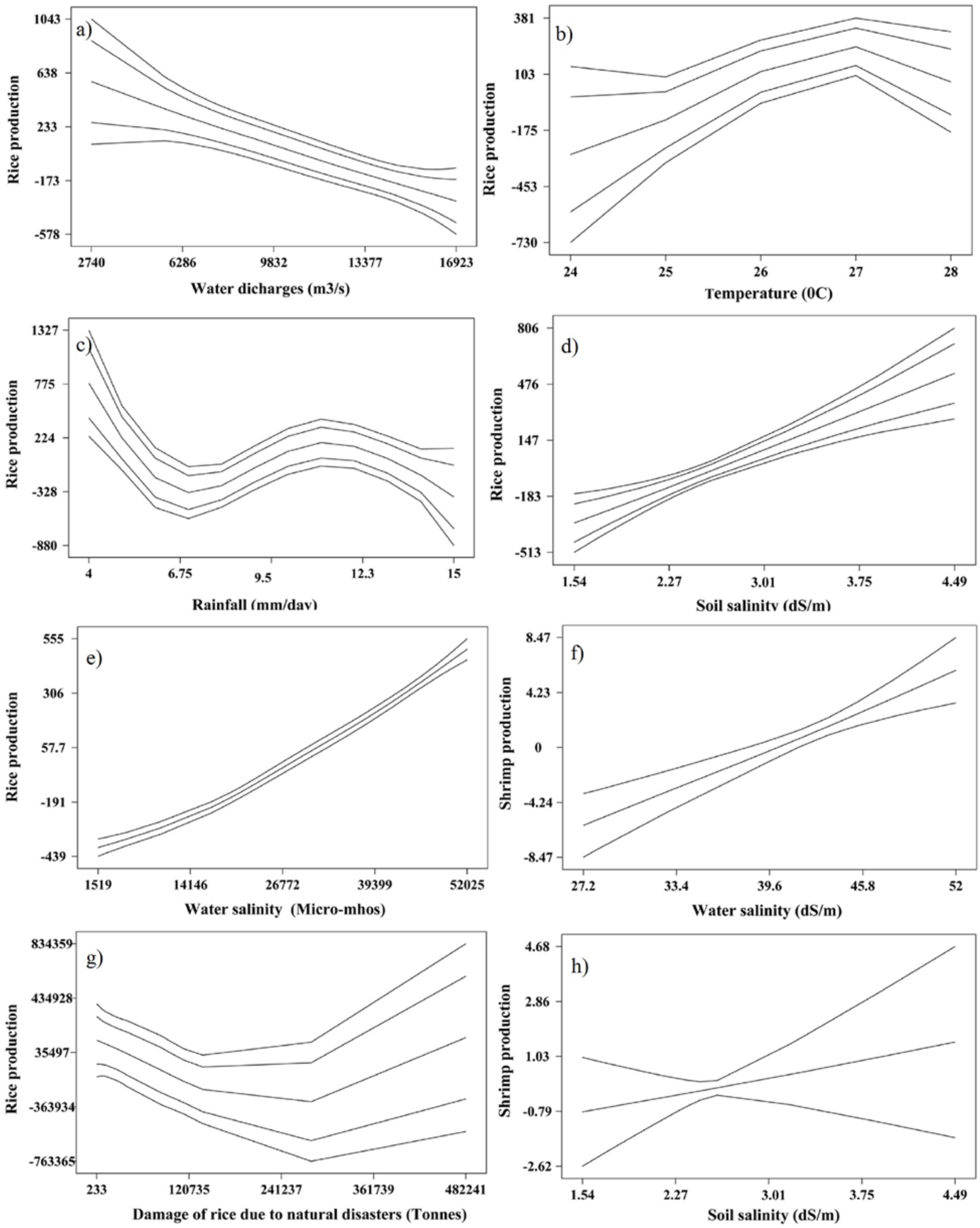


Figure 4.4 Linear and nonlinear relationships between provisioning (rice and shrimp production) and regulating services. The central line represents estimated mean (spline), whereas the other two lines represent 95% (top lower and top higher) and 80% (middle two lines) credible interval, respectively.

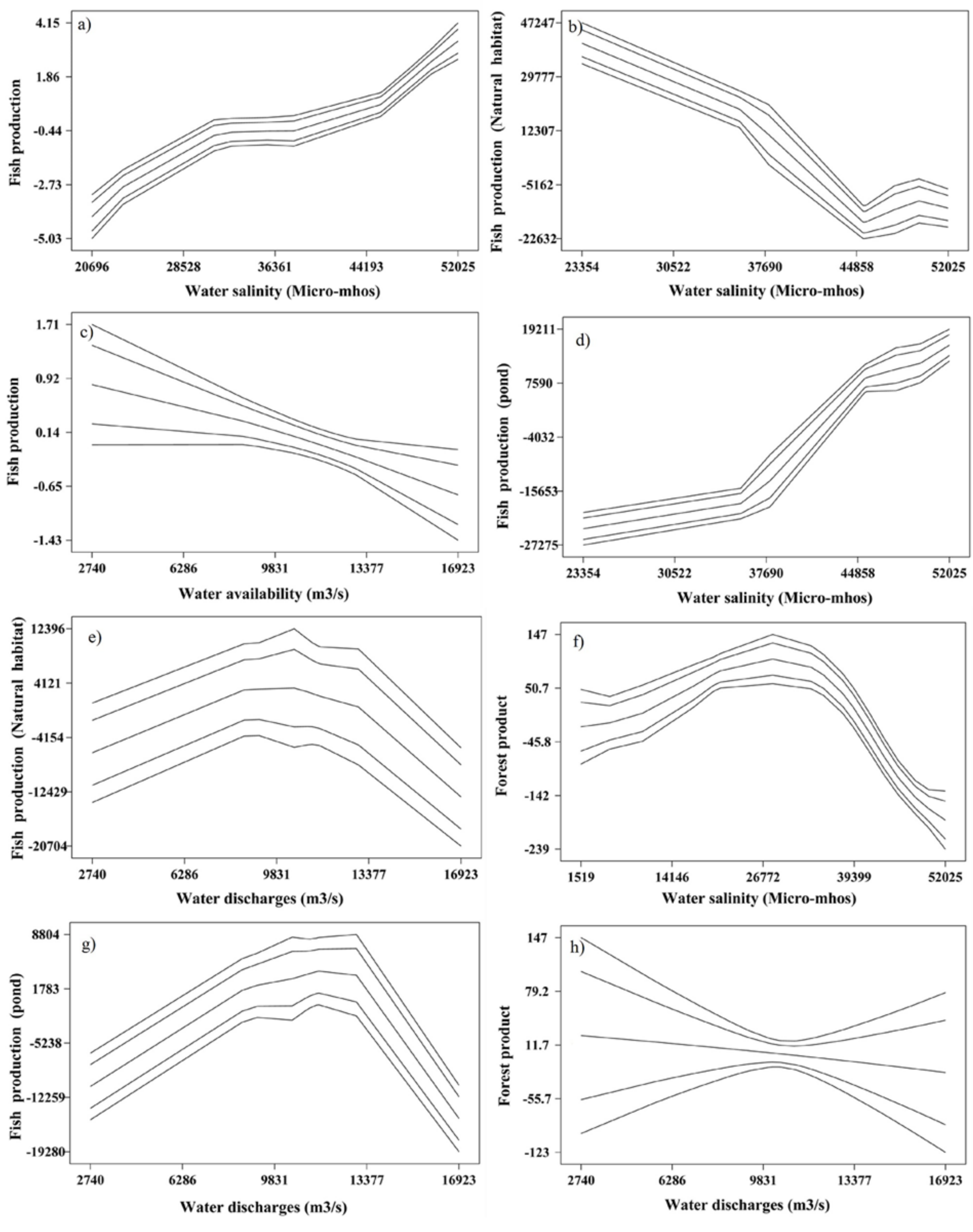


Figure 4.5 Linear and nonlinear relationships between provisioning (fish and forestry production) and regulating services. The central line represents estimated mean (spline), whereas the other two lines represent 95% (top lower and top higher) and 80% (middle two lines) credible interval, respectively.

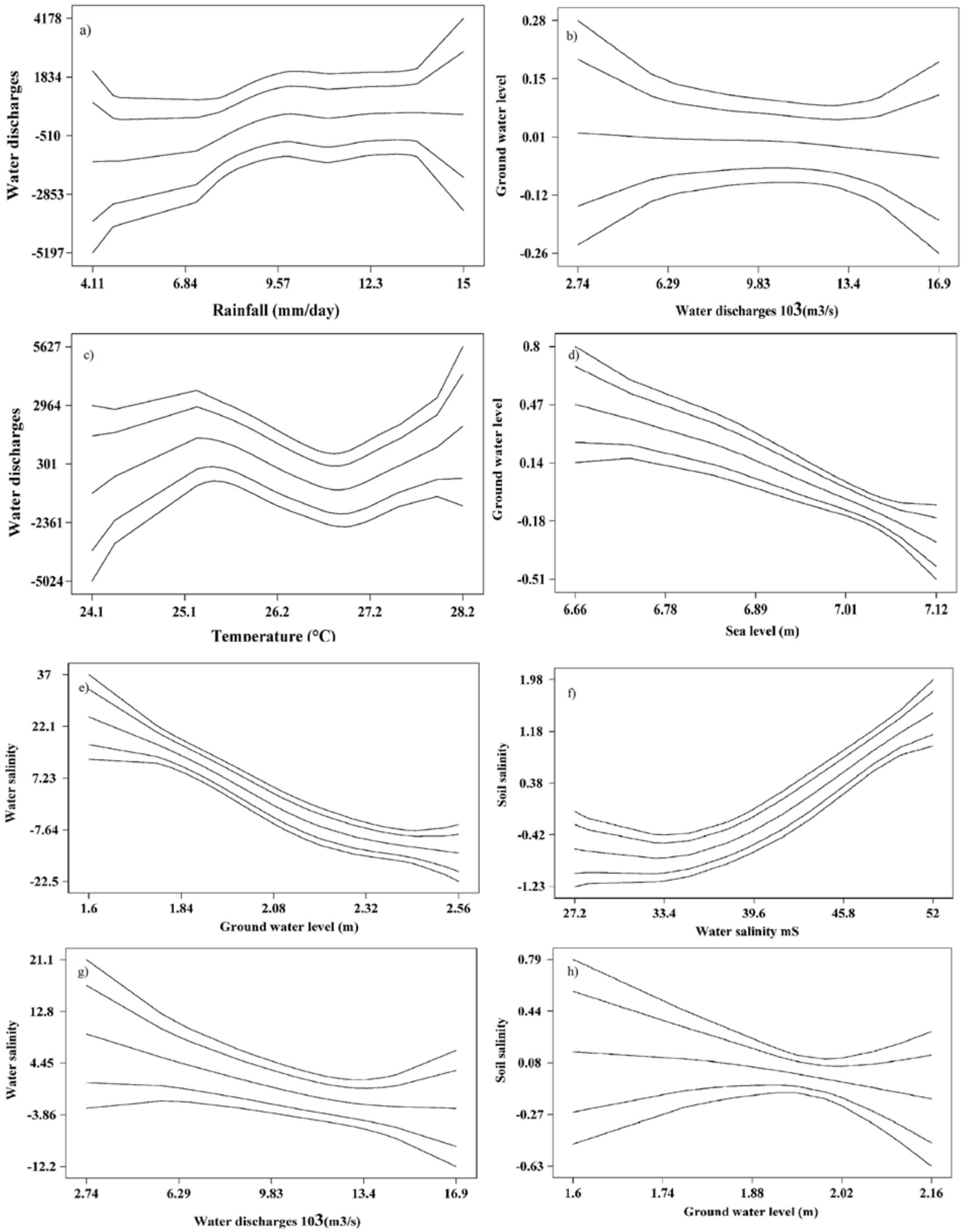


Figure 4.6 Linear and nonlinear relationships among the variables of regulating services. The central line represents estimated mean (spline), whereas the other two lines represent 95% (top lower and top higher) and 80% (middle two lines) credible interval, respectively.

4.4.4. Regression analyses of provisioning services and HWB

At the household level, provisioning services (independent variable) are strongly associated with GDP ($\beta = 0.70$, $p < 0.01$) and income from crop production ($\beta = 0.75$, $p < 0.01$). Moreover, production cost is also positively ($\beta = 0.50$, $p < 0.01$) associated with production. Similar to crop production, GDP is also positively associated with forest products ($\beta = 0.90$, $p < 0.01$), shrimp production ($\beta = 0.83$, $p < 0.01$) and fish production ($\beta = 0.94$, $p < 0.01$) (Table B.5). Tables 2 and 3 show the results of the logistic regression between independent variables (continuous variable, e.g. crop production, fish catch at household level) and dependent variables (categorical variable, e.g. sanitation, education).

Table 4.2 Logistics regression results of cross sectional data (HIES 2010) for analysing the relationship between quality of life (e.g. 'electricity', 'safe drinking water') and production at household level. In case of production at household level, production of crops (N=437) at household level has used as the proxy of provisioning service. Here, the quality of life indicators are binary variables.

HWB	Occupation	OR (Odd ratio)	P value (level of significance)	95% CI (Confidence interval)
Birth attended by skilled health staff	Agriculture	1.22	0.04	1.00-1.47
Electricity connection	Agriculture	1.39	0.04	1.11-1.74
Improved sanitation	Agriculture	1	0.64	0.74-1.20
Access to safe drinking water	Agriculture	1	0.09	0.4-1.06
Primary education attainment	Agriculture	1.17	0	1.07-1.27

Results from logistic regression show that households with higher crop production levels have a higher odds (39%) of 'electricity connection' (odd ratio (OR) = 1.39, $p = 0.05$) compared to the 10% higher odds of 'electricity connection' (OR = 1.10, $p = 0.20$) for the households engaged in fisheries (Table 3). Although the households with higher crop production have higher odds (22%) of 'births attended by skilled health staff' (OR = 1.22, $p = 0.04$) and higher odds (17%) of 'primary education' (OR = 1.17, $p < 0.01$), but the higher fish production at household level does not have higher odds of 'primary education' (OR = 1, $p = 0.24$) nor 'birth attendance by skilled health staff' (OR = 1.03, $p = 0.60$). In addition, 'improved sanitation' and 'access to safe drinking water' is not associated with crop production and fish production at households.

Table 4.3 Logistics regression results of cross sectional data (HIES 2010) for analysing the relationship between quality of life (e.g. 'electricity', 'safe drinking water') and fish catch at household level. In case of fish catch at household level, fish catch (N = 347) at household level has used as the proxy of provisioning service. Here, the quality of life indicators are binary variables.

HWB	Occupation	OR (Odd ratio)	P value (level of significance)	95% CI (Confidence interval)
Birth attended by skilled health staff	Fishery	1	0.57	0.75-1.17
Electricity connection	Fishery	1.1	0.21	0.94-1.29
Improved sanitation	Fishery	1.12	0.19	0.94-1.33
Access to safe drinking water	Fishery	1.08	0.21	0.94-1.29
Primary education attainment	Fishery	1	0.16	0.74-1.10

4.5. Discussion

4.5.1. ES and wellbeing

Since the 1980s regulating services have deteriorated while provisioning services and HWB have improved. The coastal zone has shown remarkable progress on improving 'maternal health' (births attended by skilled health staff) and 'sanitation' facilities compared to the national scale (Table 4.1). For both these indicators, the progress of the households engaged in fishery and agriculture at the regional scale is higher than at the national scale. Even the proportion of 'births attended by skilled health staff' is closer to the MDG target (50% by 2015) for the group of households engaged in agriculture (46%) in 2010. Although 'access to safe drinking water' for all occupation is closer to the MDG target, half of the households are still without an 'electricity' connection at national and regional scale. Moreover, the average electricity coverage for the households engaged in fishery (41%) and agriculture (34%) are below the national (55%) and regional (50%) average.

4.5.2. Interlinkages and connectivity within social–ecological system

All four types of provisioning services show negative linear relationships with water availability, which exhibit nonlinear relationships with fish production in ponds and natural habitats. Linear relationships are exhibited between sea level and ground water level, water salinity and ground water level and between water discharge and water salinity. However, nonlinear relationships exist between the indicators, such as water discharge and temperature, soil salinity and water salinity and soil salinity and rainfall. The negative relationship between sea level rise and ground water level, indicating the possibility of decreasing (actually increasing) ground water level for the sea level rise. Furthermore, a positive strong relationship is shown between water salinity and soil salinity. All these indicate the possibility of salinity increasing in both soil and water because of the sea level rise due to global warming. This salinity rise is likely to worsen because of the water flow reduction (e.g. Farakka dam), which exhibited negative relationship with salinity and ground water level.

Provisioning services are positively (strongly) linked with material wellbeing (GDP and income). In addition, positive links between production costs and production at the household level indicate the fact that higher crop production through intensive cultivation, shifts in technology and changes in crop varieties are associated with the higher production costs (Ali 1995; Husain et al. 2001; Hossain et al. 2015a; Hossain et al. 2016b). Although the material wellbeing exhibits a positive relationship with provisioning services, some of the quality of life indicators such as access to 'safe drinking water' and improved 'sanitation' are not related to production at the household level. This could be because of the contribution of government (20% of annual budget), private and foreign aid (8500 million USD from 1981 to 2012) to improve HWB (e.g. safe drinking water, sanitation, etc.) (MoF 2014; UNDP 2014). This development programme could be also another reason that households with higher production levels have only a 22% higher chance of attending 'births by skilled health staff'. In the fishery groups, there is no relationship observed between fish production and births by skilled health staff. Similarly, there is only a 17% higher chance of completing 'primary education' for those with higher crop production at households, even though 'primary education' is free in Bangladesh. This impact of free 'education' is evident for households engaged in fishery as these do not show any association between fish production and 'primary education' attainment. This difference between the households engaged in fishery and agriculture could be because of the fact that farmers often leave primary level 'education' early as they need to help in cultivation and the primary school system does not offer technical knowledge on agriculture (Alam 2008; The Daily Prothom alo 2014).

Our analyses support the overall MA (2005) framework, which depicts that material wellbeing (basic materials for a good life) show a strong relationship with provisioning services, which in turn, show a weak relationship with the quality of life (security and health). But our analysis also confirms the 'Environmentalist's Paradox' that HWB has increased despite the deterioration in ES (Raudsepp-Hearne et al. 2010). However, provisioning services are not the only important factor for HWB, which have also been substantially influenced by technology and capital investment (aid and subsidy).

4.5.3. System stability

In terms of the stability of the delta zone system, there are two major findings. The generally weak relationships between provisioning services and the slowly changing (and worsening) driving variables (e.g. temperature, rainfall, water discharges) may reflect the effect of 'slow variables' on system resilience that are not observable until a threshold is reached (Hossain et al. 2015). For example, the warming climate may have no negative effect on provisioning services until a threshold temperature is exceeded. In addition, the rising systemic connectivity between regulating and provisioning services since 1996 seems to reflect the homogenization of cultivation practices and their environmental impacts caused by trade globalization. Thus, deteriorating slow variables coupled to rising connectivity could be interpreted, as in other regions (e.g. Zhang et al. 2015) as indicating declining resilience and growing systemic instability. This means that the region could become more vulnerable to external shocks (e.g. floods, cyclones, crop disease) with the increased likelihood of volatility, failure or even the collapse in key components, such as rice production. In order to understand how these changes might be mitigated by alternative management strategies, it is useful to consider the structure of the system in terms of key interactions and feedback loops (Biggs et al. 2012).

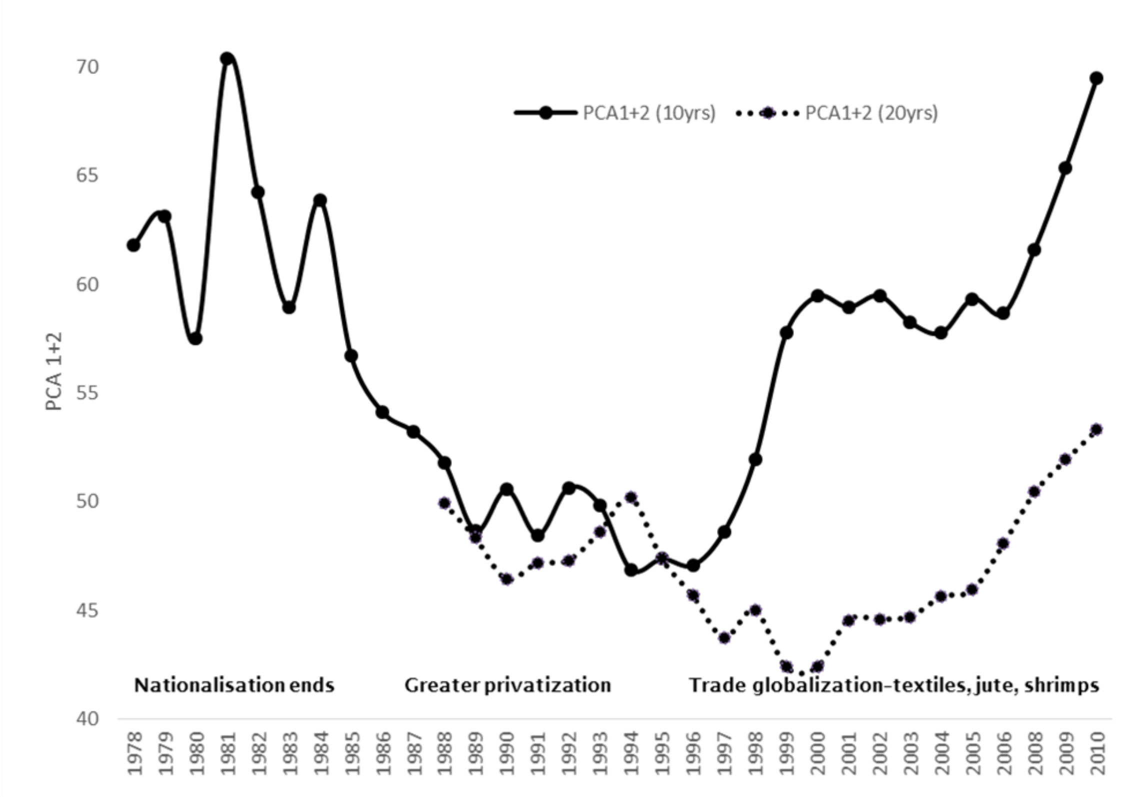


Figure 4.7 Connectivity between regulating and provisioning services since 1978. Curve of PCA axis 1 and 2 combined data both for the provisioning services (different varieties of crops) and seasonal regulating services, such as water discharges, temperature, and rainfall and water salinity since 1967. Moreover, black line represents the connectivity between regulating and provisioning services using 10-year moving window and line in dot shows the connectivity between regulating and provisioning services using 20-year moving window.

4.5.4. Systems model of the social–ecological system

Based on our analysis and evidence from previous work, we have developed a hypothesized systems diagram (Figure 4.8). Although food production is not directly linked with quality of life, we include in the system diagram the role of GDP in contributing to the national and regional budgets that in turn improve HWB. Positive feedback loops are especially important to assess because they have the potential to grow and destabilize the SES (CBD 2010). In the case of our studied region, a major positive feedback loop exists between shrimp farming, mangrove forest and water salinity (Hossain 2015a). Higher profits from shrimp industry increase the possibility of conversion of rice farms into shrimp farms (Swapan

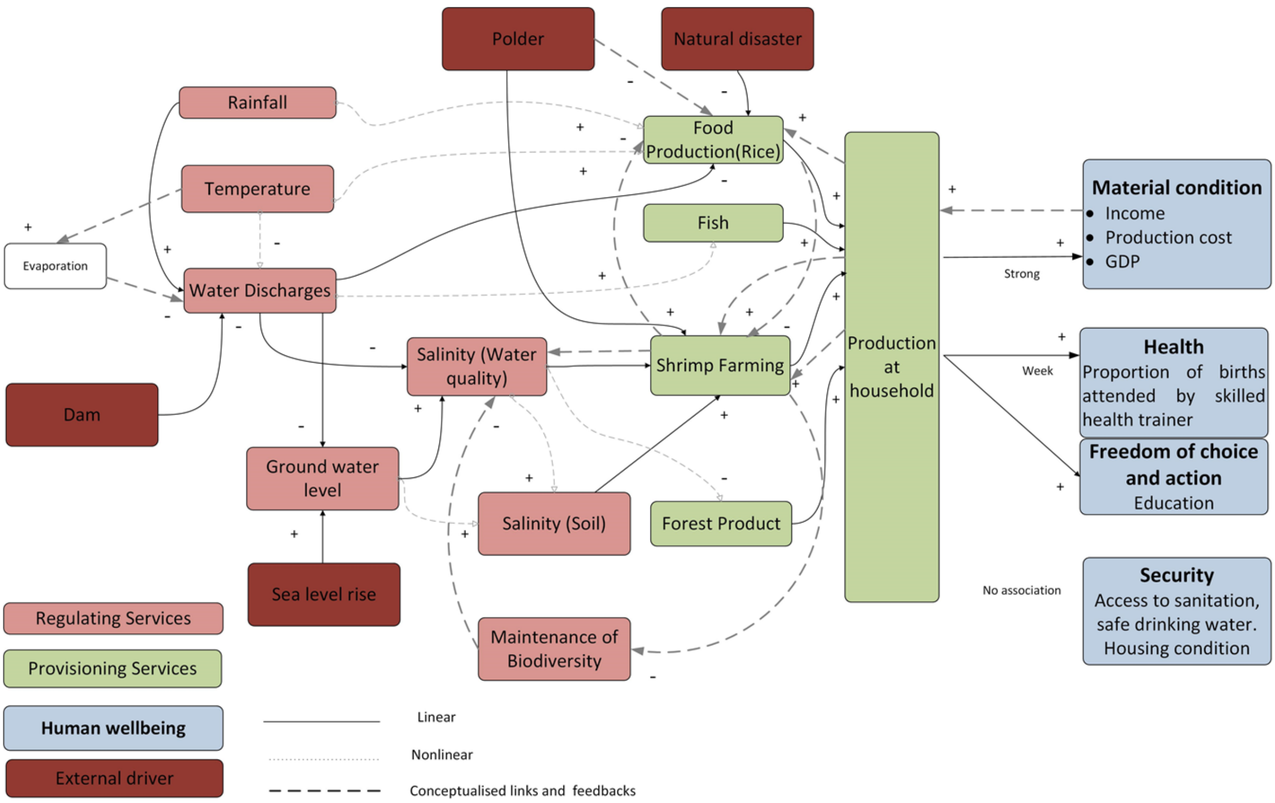


Figure 4.8 Hypothesized SD framework for the SES in south-west coastal Bangladesh.

& Gavin 2011) with further destruction of the mangrove forest (Azad et al. 2009), but the higher water salinity that conversion and destruction causes makes the shift from rice to shrimp farms even more likely. Also, important is the long-term decrease in water discharge that is believed to increase the regional temperature (Adel 2002), potentially bringing forward the time when the critical temperature for crop production is exceeded.

The combination of strengthening positive feedback loops, declining resilience and the evidence for increasing production costs all suggest that the SES is in a vulnerable transition state as it adapts to rapidly changing conditions (Renaud et al. 2013). Management strategies certainly need to consider alternative land use and agriculture in high salinity and high temperature conditions. Future improvement of HWB may need to rely less on local ES and more on technological advances and capital investment if a ‘perfect storm’ of social-ecological failings (Dearing et al. 2012; Zhang et al. 2015) is to be avoided.

The system analysis is relevant to the ~60% of households that are engaged in agriculture and fishery. The study could be extended through surveys of shrimp and forest people that are not included within the HIES and more fully. The findings could be also be used to develop SD modelling for identifying the impacts of alternative management strategies in adaptation planning for regional sustainability.

4.6. Conclusions

This study represents the first regional scale analysis of a complex social–ecological system in a coastal area of Bangladesh using the concept of ES and HWB. Analysis of this study has increased our understanding of the linear and nonlinear relationships, as well as the threshold points in the social–ecological system. Time series analysis of ES reveals that, in the past four decades, food provisioning services such as rice and fish production have sharply increased while, in contrast, regulating services are deteriorating. HWB is also improving in this region, in particular, since the 1980s. Households engaged in agriculture have progressed well in achieving the MDGs target in the case of 'births attended by skilled health staff'; however, all households did not meet some other MDGs targets such as 'education', 'sanitation' and 'electricity'. Linear and nonlinear relationships (e.g. water discharge and temperature), as well as threshold points (water availability and temperature, soil salinity and ground water level) are identified through a generalized additive model. Provisioning services are positively linked with material wellbeing (e.g. GDP and income). The development programme by the Government of Bangladesh and NGOs are the likely reasons why households with higher production have only 22% and 17% of higher chance of attending 'births by skilled health staff' and completing primary 'education', respectively, whereas there is no similar effect for fishery groups. Moreover, evidence such as rising connectedness and growing positive feedback loops, suggest that the social–ecological system is losing resilience with a higher probability of instability in the near future, particularly through the effects of higher salinity and temperatures. Our hypothesized systems dynamic framework based on the linear and nonlinear relationships helps to summarize the main interactions and to draw out key feedbacks within the system. We limited our analysis within the households engaged in agriculture and fishery, mainly because the HIES data do not cover the information for households engaged in shrimp and forestry. The findings of this study can serve as the basis for SD modelling to identify how the social system will respond to changes in the ecological system. The methodology of this study can also be used for analysing and modelling social–ecological system in other data-poor areas for sustainable ecosystem management.

Chapter 5: Paper 4

Operationalizing safe operating space for regional social-ecological systems

5.1 Abstract

This study makes a first attempt to operationalize the safe operating space (SOS) concept at a regional scale by considering the complex dynamics (e.g. non-linearity, feedbacks, and interactions) within a systems dynamic (SD) model. We employ the model to explore eight 'what if' scenarios based on well-known challenges (e.g. climate change) and current policy debates (e.g. subsidy withdrawal). The findings show that the social-ecological system (SES) in the Bangladesh delta may move beyond a SOS when a withdrawal of a 50% subsidy for agriculture is combined with the effects of a 2 ^{o}C temperature increase and sea level rise. Further reductions in upstream river discharge in the Ganges would push the system towards a dangerous zone once a 3.5 ^{o}C temperature increase was reached. The SES in Bangladesh delta may be operated within a safe space by: 1) managing feedback (e.g. by reducing production costs) and the slow biophysical variables (e.g. temperature, rainfall) to increase the long-term resilience, 2) negotiating for transboundary water resources and 3) also possibly by revising the global policy (e.g. withdrawal of subsidy) to implement at regional scale. This study demonstrates how the concepts of tipping points, limit to adaptations and boundaries for sustainable development may be defined in real world SES.

Key words: Safe operating space, system dynamic, social-ecological system and sustainable development

This paper is in review as: Hossain MS, Dearing JA, Eigenbrod F, Johnson FA (In review) operationalizing safe operating space for regional social-ecological systems. Science of the Total Environment

5.2. Introduction

The safe operating space for humanity concept provided through the planetary boundary framework (Rockström et al. 2009a; Rockström et al. 2009b) has attained significant policy and academic attention in global sustainability. In brief, Rockström et al. 2009a has used Holocene (the last 11,000 years) as baseline markers to define the boundaries of the 'safe operating space' beyond which the risk of unpredictable and damaging change to SESbecomes very high. Despite attaining significant policy attention (e.g. Rio +20, Planetary boundaries for Sweden by Swedish Environmental Protection Agencies, Switzerland Government and Oxfam), the operationalization of this concept has been criticized in terms of normative settings of the boundaries, exclusion of the social system, scale and interaction among the biophysical processes (Dearing et al. 2014; Lewis 2012; Raworth 2012).

Defining the boundaries for each biophysical process is one of the main points of debate and has been improved further by using more specific approaches (e.g. biodiversity: (Mace et al., 2014); net primary plant production: (Erb et al. 2012 and Running 2012); phosphorus: Carpenter and Bennett (2011). The planetary boundary concept did not include the social system that drives humanity towards many of the boundaries hence Raworth (2012) introduced the doughnut framework, which incorporates social foundations (e.g. food, gender equality, health) into the planetary boundaries concept. This visual framework identifies the minimum boundaries below which human wellbeing is deprived of basic needs but does not provide the basis to study the complex interactions between social and ecological systems.

Because many of the planetary boundaries are aggregated from regional scale problems, such as land use and freshwater (Nordhaus et al. 2012 and Lewis 2012), and critical transitions can occur at any scale (Scheffer et al. 2001), setting the boundary at a global scale does not necessarily help to inform policy at a regional scale. Hence, Dearing et al. 2014 proposed a new framework to operationalize the doughnut concept (Raworth 2012) at the regional scale. This pragmatic framework has been applied to Chinese case studies to define safe and just operating spaces considering both biophysical processes and social foundations. In brief, these studies defined the SOS as the space between sustainable and unsustainable use of ecological process using the dynamical properties (e.g. envelope of variability, early warning signals) of ecological variables for environmental celling and using minimum standards of human outcomes (e.g. health, energy, food) for social foundations. Cole et al. (2014) also demonstrated the operationalization of the doughnut concept (safe and just operating space) at a national scale by engaging stakeholders to define the boundaries for environmental and social dimensions.

The planetary boundary concept excludes the interactions among the biophysical boundaries and the complex interactions of social-ecological system. For example, the deterioration in the status of water resources due to a warming climate (Rockström et al. 2009a), interacts with the climate system, leading to a higher sensitivity to climate (e.g. higher temperature) (Hossain et a. 2015; Adel 1999). The social system may possibly respond to changes in climatic conditions and degradation of water resources by extracting more groundwater and using more fertilizer for agricultural purposes. If these changes become self-perpetuating, then groundwater and water quality (increased fertilizer use leads to deterioration of water quality) will transgress the boundary due to the social response towards changes in climatic conditions. Therefore, the lack of dynamicity in the both frameworks (planetary boundary and doughnut) could lead to erroneous conclusions being drawn and could limit the utility of these concepts at a policy level and within the wider decision making community. Even recent developments (e.g. Hoornweeg et al. 2016; Dearing et al. 2014; Cole et al. 2014) on planetary boundaries do not consider the interactions among the biophysical boundaries and the complex interactions between social and ecological systems.

Here, we make a first attempt to fill these gaps, by applying these integrative concepts at the regional scale, by focusing on regional problems and most importantly by considering the interactions between the social and ecological systems. Therefore, we aimed at operationalizing SOS concept at the regional scale for a SES (south west coastal Bangladesh) by answering the following four research questions:

1. How has the social-ecological system evolved over the past five decades?
2. How is the social-ecological system interlinked?
3. What is the proximity of the social-ecological system to a major tipping point?
4. What are the boundaries of the safe operating spaces of social-ecological system?

Our main motivation is to demonstrate how we can operationalize the SOS at the regional scale by considering the interactions between the social and ecological systems. In this paper, we have provided a case study from the Bangladesh delta for which we have used time series data to understand the co-evolution of the social-ecological system and analysed the linkages of the

SES by focusing agriculture. Subsequently, we used system dynamic modelling to consider the interactions of social-ecological systems and to demonstrate the SOS in the Bangladesh delta.

5.3. Case study area- The Bangladesh delta

5.3.1. Selection of the study area

The south west coastal area has been selected as the case study area (Fig 5.1), which represents 16% of the land area of Bangladesh. This area represents the Ganges tidal flood plain (FAO-UNDP 1998) and generates 1.3 billion USD Gross Domestic Product (GDP) (Sarwar 2005). Recorded statistics confirm that this area is one of the most vulnerable to climate change (Maplecroft 2010; Ahmed 1999) and is also under stress because of land use change, water scarcity, salinity rise and urbanization (Hossain et al. 2015; ADB 2005). In addition, this coastal area is highly vulnerable to natural disasters, responsible for an estimated 100,000 deaths between 1974 and 2007 (Rahman et al. 2010). River erosion and floods have damaged food grains in this area (Islam 2011). Projections show that the detrimental effects of climate change are likely to continue, as rice and wheat yields decrease due to temperature increases (MoEF 2005) in south-west coastal Bangladesh, where ~38% of people already live below the national poverty line (BBS 2010). Approximately 40% of people are heavily dependent on agriculture for their livelihood in this region (Hossain et al. 2015). The remainder of the population (~60%) are also directly dependent on agriculture for food security and other essential necessities. Given the significant influence of agriculture on the SES in this area, we concentrated on this sector in our first attempt to demonstrate the SOS at the regional scale. However, this can be extended to the other livelihood sources (e.g. fishery, shrimp farming, and forest) in future studies.

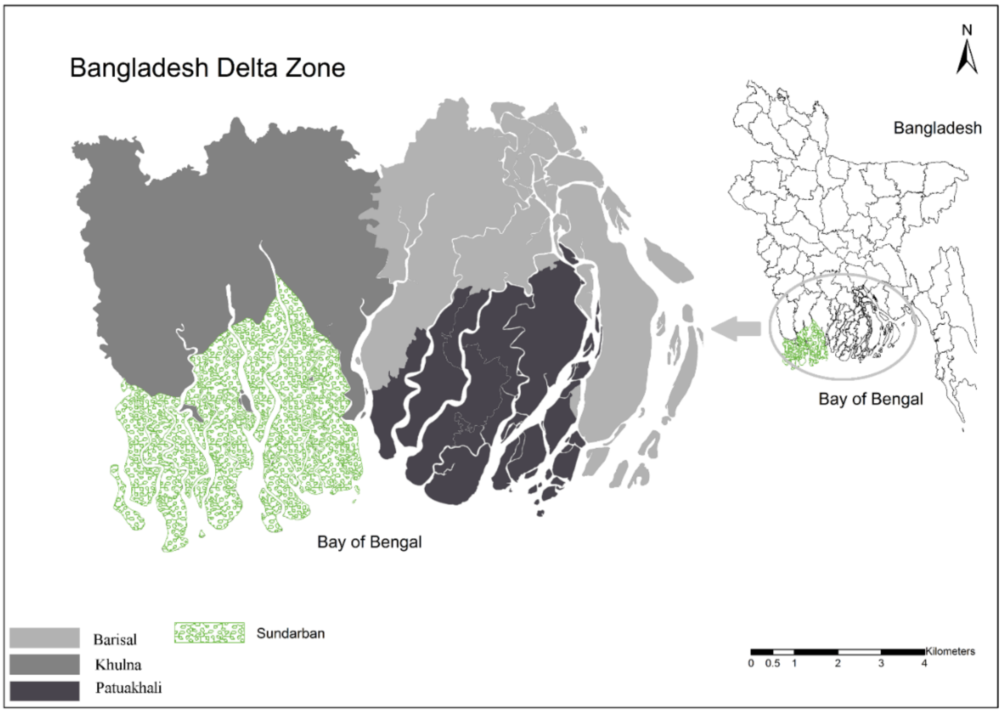


Figure 5.1 South west coastal region of Bangladesh

5.3.2. Social-ecological dynamics and system model in Bangladesh delta

Our previous studies (Hossain et al. 2015; Hossain et al. 2016b) revealed that the ecosystem has clearly been degraded since the 1980s, because of the rising temperature, salinity (soil and water), sea level and ground water level in the south-west coastal delta (Figure C.1). Decreasing rainfalls trends in the dry season and the significant water flow reduction in the rivers attributable to the Farakka dam in the upstream of Ganges built between 1965 and 1975, are also degrading the ecosystem in this delta. In contrast, the social system (Figure C.1) has improved since 1980s because of the increasing trends of agriculture (rice) production, which triggered the growth (8 million USD/yr) of GDP shared by agriculture. The increasing trend of GDP and progress in agriculture seem to support the mitigation effect on poverty, which has declined 17% over 17 years. Production costs ha^{-1} at the household level rose seven fold between 1995 and 2010, whereas, income ha^{-1} has decreased 2% between 2000s and 2010.

A conceptual system model developed in Hossain et al. (2016a) has been used as the base for the SD modelling to demonstrate safe operating space. This conceptual system model (Figure C.2) depicts a positive link between rainfall and water flow, and a negative link with water salinity. Water salinity also exhibits a negative relationship with ground water level in this conceptual model. The negative relationships of ground water level with sea level rise and soil salinity indicate that, soil salinity will increase through the rising of ground water level due to sea level rise in this delta.

Crop (rice) production is positively influenced by temperature, rainfall and soil salinity. In case of the social system, social indicators such as GDP shared by agriculture, income and production costs are positively influenced by crop production in this delta. However, crop production exhibited a weak influence on quality of life indicators such as health, education and sanitation. These quality of life indicators are significantly influenced by technology and aid.

5.4. Methods

The overall methodology (Figure C.3) of this study comprises six research steps: 1) synthesis of information and a conceptual system model from our previous studies serving the purpose of problem familiarization and the conceptual base for the system dynamic modelling; 2) The system model was then run using two approaches (regression and graphical function; full definition below) for comparison with the historical crop production data. This step justifies the use of graphical function to estimate the parameters of the model; 3) A participatory approach has been used to validate the structure of the system dynamic model developed in Step 2, and then to modify the system model developed at the first step; 4) The simulated changes based on the final system model using a graphical function approach has been compared against historical crop production; 5) After sensitivity analysis of the model, the dynamics of the SES were explored through generating eight 'what if' scenarios based on the well-known challenges; 6) The SOS was defined in relation to the envelope of variability, environmental limit and impacts on society. The detailed description of each of the steps are given in the following sections.

5. 4.1. Model development, validation and sensitivity analysis

First, the information gained from our previous empirical studies (Hossain et al. 2016a; Hossain et al. 2016b; Hossain et al. 2015b) has been used to understand the SES and to develop a conceptual system model. In brief, trends, drivers and change points were analysed (Hossain et al. 2015a; Hossain et al. 2016b) to understand the co-evolution of social-ecological systems. We have used regression (additive, linear, logistics) models and literature review in Hossain et al. (2016a) to develop hypothesized system model to capture complex and dynamic relationships (non-linearity, interactions and feedbacks) of social-ecological system. With a main focus on agriculture as a case study to make a first attempt to operationalize SOS at regional scale, we have mainly focused on the synthesized information of agriculture related social (e.g. GDP, income, production cost) and ecological (e.g. climate, water) systems to develop a system model. This section (5.3.1 and 5.3.2) serves the purpose of problem familiarization and developing conceptual system model, as the base (Ford 2010) for the SD modelling to demonstrate SOS at regional scale focusing on agriculture as a case study in the south-west coastal Bangladesh delta.

SD modelling is increasingly used to synthesize complex interactions (e.g. dynamic changes, feedbacks, and non-linearity) in social-ecological system (Chang et al., 2008). This modelling technique developed in early 1960s by Jay Forrester, has been widely used in managing eco-agriculture systems (e.g. Li et al. 2012), water resources (e.g. Beall et al. 2011), wild life systems (e.g. Beall and Zeoli 2008), lake ecosystems (e.g. Xuan and Chang 2014) and the social dynamics of ecological regime shift (e.g. Lade et al. 2015).

Second, the hypothesized SD model (Figure C.2) developed at the first step (the conceptual system model) has been used to run in the simulation software STELLA. In absence of mathematical relationships, regression (multivariate and linear) analysis conducted in Hossain et al. (2016b) is used to define the relationships between variables in the SD model. The empirical information such as coefficients used for this run are given in Table C.1.

In parallel to the regression approach, the graphical function approach has been used for parameter estimation of the variables. Graphical function is a built feature in STELLA designed to enable relationships between variables to be quantified even where there is little data. This can be done in three ways : 1) assuming the different types relationships (e.g. linear, non-linear, s-shaped growth, oscillation) or probability in absence of data and information about the system; 2) drawing or assuming the relationships through stakeholder views and perceptions, in the absence of time-series data to help develop tools for policy; 3) defining the relationships between variables to be derived from imperfect data, such as where the length of time-series data is short (< 30 data points) and where different time series datasets differ in length. For example, in our case, the time series of soil salinity data is shorter in length compared to other variables such as temperature and water – we therefore used the graphical function to interpolate this relationship.

In this study, the time series data collected from official statistics, published reports and articles have been used to define the relationships in the graphical function. These functions are defined by input values (e.g. temperature) representing the x-axis and output values (e.g. crop production) representing the y-axis (Figure C.4). In graphical function, each data input is used to create a curve, which is linked to a specific equation by definition in STELLA.

Results from both empirical and graphical function approaches were compared (Figure 5.2a) against the historical time series data of crop production through; 1) matching with trends; 2) comparing within the observational uncertainty of 95% confidence intervals (Olsen et al. 2015;) and 3) analysing the difference among three time series using Student t-test. The visual inspection of the three time series (Figure 5.2a) reveals that though both simulation results correspond well with historical data, simulation results using graphical function occurring within the observational uncertainty (95% confidence intervals) of historical time series of crop production. Student t-test results (Table 2) also suggest that, simulation output using the graphical function ($t = 0.83$, $p > 0.40$) corresponds well with the historical time series compared to the simulation result obtained using empirical analysis ($t = 4.7$, $p = 0.00$). Therefore, we have used the graphical function approach in the remainder of the modelling.

Third, the structure of the SD model developed using empirical analysis was then validated through engaging with stakeholders in the study area. Structural validation procedures were used to assess reliability and accuracy of the model structure, the components and the interrelationships between components. Structural validation has been emphasized over behaviour validation (Khan et al. 2009). The real behaviour is impossible to validate, whereas, the reliability of the structure is important, so that the model can demonstrate behavioural changes while testing the effects of policies (Barlas 2000; Barlas 1996). A participatory approach is becoming increasingly common in SDs research, allowing local stakeholders to become involved in model development through sharing their perceptions and knowledge (Jakeman et al. 2006; Cain et al. 2001). This qualitative approach can often solve the issues related to data limitation for ecosystem management (Ritzema et al. 2009) and has already been used for conceptualizing SD model of wetlands ecosystem (Ritzema et al. 2009), wildlife management (Beall and Zeoli 2008), water resources management (Beall et al. 2011) and river basin management (Videira et al. 2009).

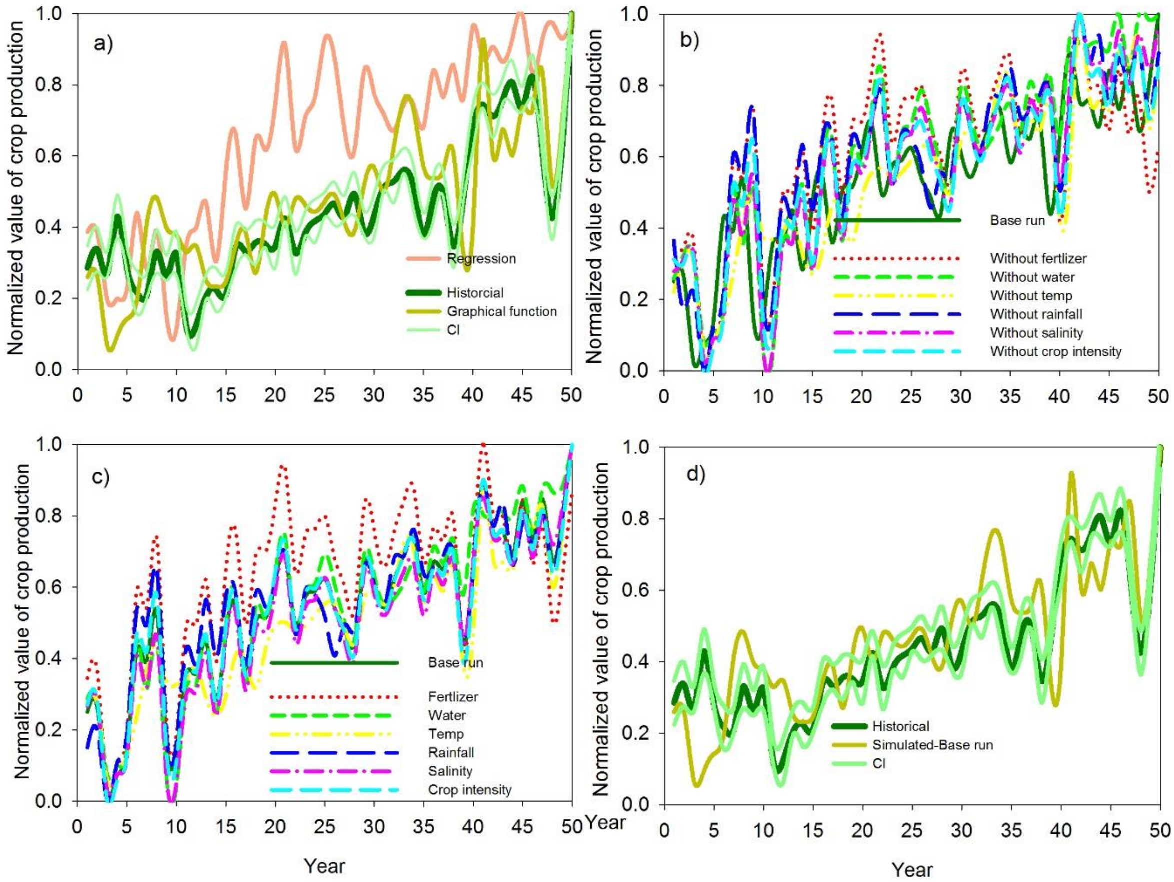


Figure 5.2 Results from the validation and sensitivity tests of SD model. Figure 5.2a shows the comparison of behaviour pattern derived from empirical (regression) analysis, graphical function and historical time series of crop production. Figure 5.2b and 5.2c illustrates that model is not highly sensitive to any parameters. Figure 5.2d illustrates the comparison of behaviour pattern derived from the model base run after the structure validation of the system model and historical time series of crop production. Light green lines (CI) in figure 5.2a and 5.2d denote the 95% confidence interval (CI) bands of historical crop production data.

Structural validation of the previously designed model in Figure C.2 was undertaken through three focus group discussions (FGD) with farmers (n~25 in each FGD) and two stakeholder workshops each in Barisal, Khulna and Patuakhali regions. Each group was engaged in developing one final system model through the discussion in each FGD and workshop. The main topics of discussion during the FGDs included the factors affecting farmers' livelihoods and the relationships among those factors. In addition, we enquired about feedbacks and thresholds during the workshops with stakeholders. We invited experts (N~25 in each) from academia, Non-Governmental Organizations and journalists engaged in agriculture, food security, water resource management and soil salinity. We also interviewed experts to collect information on threshold for agriculture. In our previous study (Hossain et al. 2016c), system models developed independently by stakeholders in the previous study are compared with the system model (Figure C.2) developed using empirical analysis and literature review. Based on the stakeholder's discussion, we have included the role of subsidy on crop production in the updated final SD model, which shows the conflicts with shrimp farming through reducing the cultivatable area, which in turn increases the crop intensity. The final SD model (Figure 5.3) has been used as the base (e.g. causal loop diagram) for the SD modelling. Non-linear relationships observed through the empirical analysis coincide with the threshold temperature of ~28 ºC for crop production while consulting with stakeholders. In addition, stakeholders also reported a soil salinity threshold of 4 dS.m-1 for crop production. The detailed methodology of this structural validation of SES can be found in Hossain et al. 2016c.

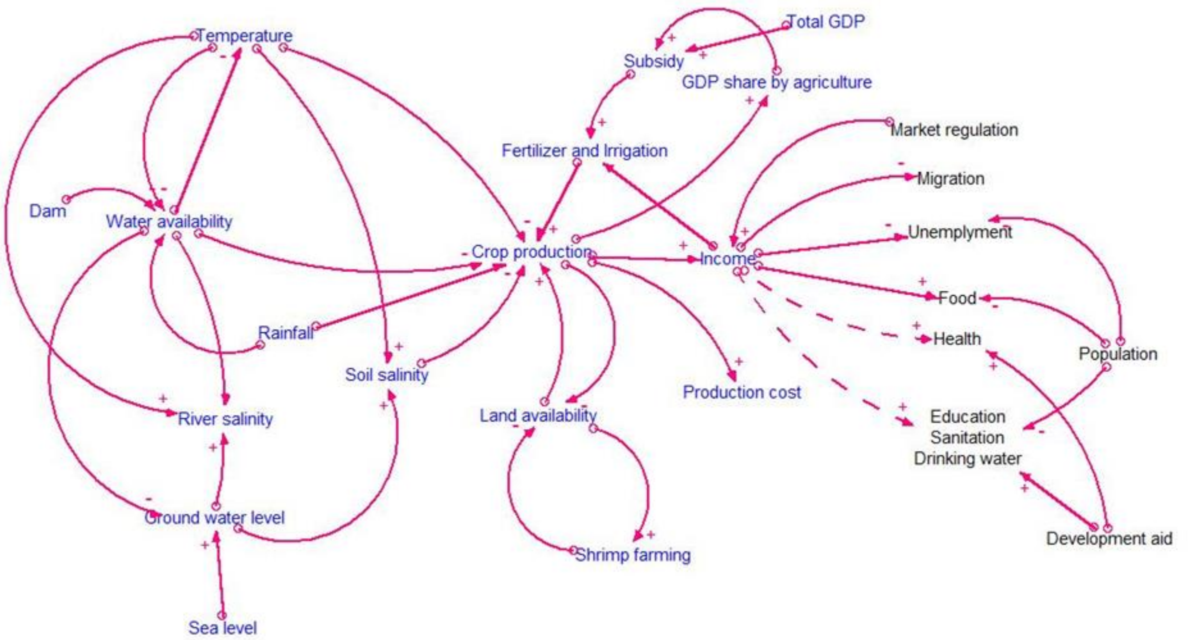


Figure 5.3 Conceptual SD model of SES in Bangladesh delta. This system model developed using the empirical analysis, followed by stakeholder engagement to validate the structure of the social-ecological system. The positive (+) and negative (-) signs denote respectively the positive and negative relationships between the variables. In addition, the solid lines depicts the strong relationships, whereas, the dotted line depicts the week relationship between the variables.

In our first approach of defining SOS at the regional scale, we did not model the black marked variables because of the complexities and lack of information in defining the relationships such as for migration, and also the fact that some of the human wellbeing indicators (e.g. education, sanitation) are strongly dependent on development aid and exhibited week relation with crop production at household level via income.

The final conceptual model developed (Figure A.3) through engagement with stakeholders has been adopted as the basis for using the graphical function to define the relationships among the variables and for running the simulation. We have used equal weighting (0.16) (Hahn et al. 2009; Böhringer and Jochem 2007) for the each six independent variables (e.g. temperature, water) by equally dividing the total weighting of 1 that is assigned to estimate the crop production. We have validated the model and tested the sensitivity of the model before simulating the changes in the SES that caused the social system to step out the safe operating space.

Fourth, after the structural validation using stakeholders engagement (see above), the simulated changes (Base run) for the crop production were compared with a time series (50 years) of normalized crop production data in order to demonstrate similar general trends in observed and modelled data. Similar to the second step, the visual inspection (Figure 5.2d) and t-test results suggest that the modelled data coincides well and occurring within the observational uncertainty (95% confidence intervals) of historical crop production time series.

We run behaviour sensitivity tests to investigate whether or not the model was highly sensitive to any parameter and if this sensitivity makes sense in the real system. Through varying each parameter weighting (0.16) from a minimum of 0 to a maximum of 0.32, we tested if the model is highly sensitive to any parameters. In Figure 5.2b and 5.2c, behaviour sensitivity test results are illustrated which indicates that, the model is not highly sensitive to any parameters, alternatively, all relationships defined in the model may be considered valid and logically meaningful.

5.4.2. Exploring dynamic behaviour and testing policies

After validation and sensitivity analysis, eight 'what if' scenarios (Table 5.1) were generated in order to evaluate how the social system will respond to changes in the social-ecological system. The formulation of these 'what if' scenarios is based on well-known challenges, current policy debates and stakeholder consultations on the Bangladesh delta in relation to issues such as climate change (debate of 2^{0}C and 3.5 ^{0}C temperature rise in Paris agreement), sea level rise, withdrawal of subsidy according to World Trade Organization (WTO) by 2023 and withdrawal of water in the upstream of Ganges delta. The model was run for a period of

50 years. We limited our analysis to these 'what if' scenario as our main motivation is to make a first approach to demonstrate the operationalisation of the SOS concept at regional scale through a case study. Moreover, we aimed at understanding the behaviour of the system, thus the simulation results should not be read quantitatively in precise way.

5.4.3. Assumptions of the model

1. The model assumes that, the net cropped area and population are constant
2. The area of shrimp farms and production also remain constant
3. The model does not consider the impact of abrupt rainfall change on crop production.
4. Although water salinity affects crop production through irrigation in the dry season, the impact is usually compensated for by rainfall and by irrigation through pumping which is dependent on the on agriculture subsidies. Moreover, crop production is mainly affected by soil salinity.
5. This model does not consider the impacts of disaster events such as flood and cyclone.
6. The model assumes that the nature of the relationships between the parameters will be the same in the future as in the past

5.4.4. Defining the safe operating space

The scientific discourse on the cascading effects of ecological degradation (Peters et al. 2011) at the regional scale as a global concern recognizes the necessity of defining SOS at regional scale concerning the non-linear systematic change (e.g. thresholds) (Rockström et al. 2009) and dynamic relationships (e.g. feedbacks and interaction) between SES (Dearing et al. 2015; Lade et al. 2015). In addition to the approach of using regional share of global resource use and links between SES (Dearing et al. 2014), the dynamic relationships between social-ecological systems can provide evidence of system behaviour to define the SOS or to demonstrate the tipping points in SES (Biggs et al. 2012). In addition, the argument of operationalizing the sustainability science concepts such as critical transitions and tipping points in relation to society (Jax 2014; Scheffer 2009) also our motivation to extend our previous pragmatic approach (Dearing et al. 2014) by using system behaviour and considering the consequences in society to define the SOS for regional social-ecological system. In case of using system behaviour to define safe operating space, Dearing et al. 2014 proposed 4 types of dynamic properties, which include linear trends (e.g. environmental limit), non-linear trends (e.g. envelope of variability), thresholds (e.g. hysteretic changes) and early warning signals. Linear trends involve in defining the environmental limits using expert or public opinion such as the

Table 5.1. Description of scenarios and assumptions for SD model

Scenarios	Scenario description	Model assumptions	Source of model assumptions
Scenario 1	This run simulates the effects of a 2° C temperature rise	Crop production declines 10% once a temperature crossing 28 °C temperature and for 2 ^{o}C temperature increase	Stakeholder consultation & Hossain et al. 2016c; Basak et al. 2012; Basak 2010; Mondal et al. 2001; Mahmud 1998; Karim et al. 1996
Scenario 2	This run simulates the effects of 2° C temperature rise and sea level rise of 32 cm	Crop production declines 20% once a temperature of 28 ^{o}C is exceeded and when salinity rises beyond 4 dS/m	
Scenario 3	This run simulates the combined effects of a 2 ^{o}C temperature rise, sea level rise of 32 cm and 50% reduction in agricultural subsidies	Same as scenario 2	
Scenario 4	This run simulates the effects of a 3.5 ^{o}C temperature rise	Crop production declines 25% once a temperature of 28 ^{o}C is exceeded and for 3.5 ^{o}C temperature increase	
Scenario 5	This run simulates the effects of a 3.5 ^{o}C temperature rise and sea level rise of 80 cm	Crop production declines 40% due to 3.5 ^{o}C temperature rise and also salinity increase beyond 4 dS/m due to an 80cm sea level rise	
Scenario 6	This run simulates the combined effects of a 3.5 ^{o}C temperature rise, sea level rise of 80 cm and zero subsidy on agriculture	Same as scenario 4	
Scenario 7	This run simulates the effects of a 2 ^{o}C temperature rise and water withdrawal (-40%) in the dry season	Crop production declines 40% due to 2 ^{o}C temperature rise and also salinity increase beyond 4 dS/m due to water withdrawal (-40%)	
Scenario 8	This run simulates the effects of a 3.5 ^{o}C temperature rise and water withdrawal (-20%) in the dry season	Most of the rice sowing and growing periods are in the dry season when the plant requires irrigation through cannels which connect the field to the rivers. A substantial decrease in water flow during the dry season also influences soil salinity through rising groundwater levels. Increases in soil salinity substantially affect rice production, although modern rice varieties can withstand soil salinity levels of up to 4 dS/m with current technology	Hossain et al. 2016c; Hossain et al. 2015; FAO 2008; Mondal et al., 2001

limit for air quality, whereas, early warning signal measures the loss of resilience prior to threshold using statistical properties (e.g. variance, skewness). Thresholds describe the transition or rapid changes due to the changes in the internal system, leading towards new state of system. This type of boundary is rare in real world examples, and can be detected when the system has experienced catastrophic shifts (Wang et al. 2012; Groffman et al. 2006). The nonlinear trends describe the system properties, when the system moves outside the normal envelope of variability (Figure 4) in the long run (Dearing et al. 2014), such as the idea of global climate change in which, temperature is rising beyond the normal envelope of variability.

However, the fundamental premise of this approach is limited to the upper and lower limit of the range within the envelope of variability (Kaene et al. 2009). Therefore, we have extended our previous pragmatic approach (Dearing et al. 2015) of an envelope of variability by combining with an environmental limit approach in relation to the impacts on society. According to the environment limit (e.g. expert and public opinion), there is no doubt that higher production or income beyond the upper limit (Figure 5.4) of the envelope of variability for crop production or income is good for humanity in response to the population increase, whereas the production or income below the lower limit of the envelope is dangerous to humanity. In addition, the environmental limit (lower) can be defined in relation to the historic events such as disasters or stress (e.g. famine), when the system moved out (i.e. below the lower limit) of envelope and negatively affected society by increasing a substantial percentage of poverty or by inducing mortality.

In summary, the dangerous zone is defined when both; 1) the system moves outside the envelope of variability, and 2) this, in turn, causes a negative impact on society.

In this study, we use the base run (similar to historic data) simulation as the reference trend to identify the normal envelope variability and compared the other scenarios in relation to the base run and the implications for society if negative trends of social indicators (e.g. GDP and income) are not safe for humanity. The rationale for selecting crop production, income and GDP to define the SOS are:

1) Research evidence shows that production loss leads to income loss (Hartel 2016; Mottaleb et al. 2013) and also increases social conflicts such as in Syria (Kelley et al. 2015) and India (Behere et al. 2015). In addition, based on our previous studies (Hossain et al. 2016a; Hossain et al. 2016b; Hossain et al. 2016c), the strong dependency of food security and poverty on crop production and the weak

dependency of other human wellbeing indicators (e.g. sanitation, health, education) on income from crop production, are also the main motivation to select crop production, income and GDP to define SOS at regional scale.

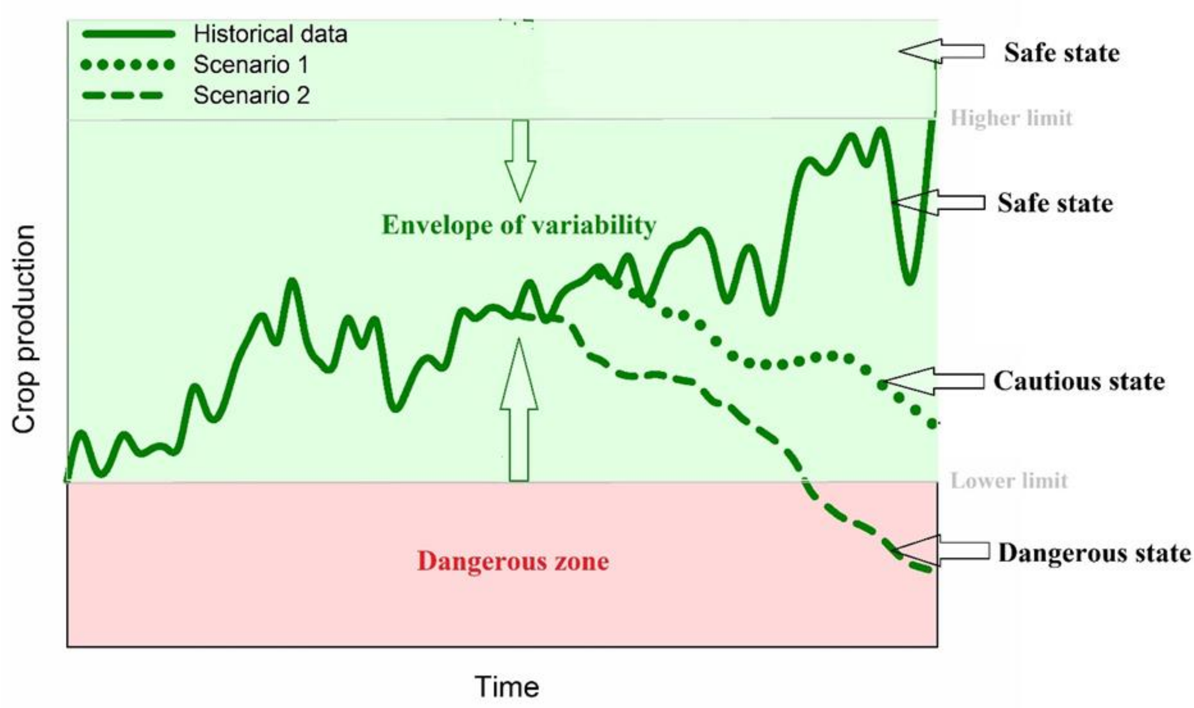


Figure 5.4 Conceptual framework attributing 'safe', 'cautious' and 'dangerous' status of social-ecological system. We have combined envelope of variability and environmental limit approach in relation to the social system to define safe operating space. Status defined as 'safe' (green) if the system is within the normal envelope of variability (Dearing et al. 2015) according to the time series data and defined as 'dangerous' (red) state when the trend is out of the normal envelope of variability and if this outside the envelope trend is negatively effecting society (Jax 2014; Scheffer 2009). The status also defined as 'cautious' if the trend of social indicator is within the normal envelope of variability but following a negative trend compared to the reference trend (historical data).

2. Despite the rising trend of crop production, evidences such as declining food (rice) per capita (Ghose et al. 2014) and loss of revenue from crop production due to the increase of production cost (Hossain et al. 2016a; Hossain et al. 2015; Iqbal and Roy 2014) suggesting that, the declining trend of crop production will negatively affect society.

3. Recorded statistics show that 40% of households are directly dependent on crop production as a main source of livelihood and food security, and rest of the households (60%) are dependent on crop production for food security in the south-west coastal Bangladesh. In addition, the evidence (Hossain et al. 2015) of sudden reduction in crop production substantially below the average production due to the natural disasters shows

the severe negative impacts on food security in-terms of food availability and food price (Ninno et al. 2001; Hossain 1990). For example, several hundred thousand people died in famine 1974 due to food shortage (substantially below average production) after the natural disasters in Bangladesh (Crow 1984; Sen 1981).

Hence, it will not be erroneous if we argue that, outside the envelope of variability (Figure 5.4) for crop production, income and GDP, the society will move out from SOS beyond which is dangerous to humanity.

As the main motivation is to make a first approach to demonstrate the SOS at the regional scale, we limited our analysis on material wellbeing such as income and GDP. This study can be extended in future by including social variables (e.g. migration, food security) to define safe operating space. We have used the same colour coding of our previous study (Dearing et al. 2014) to identify safe (green) and dangerous (red) status in social-ecological system. In addition, we also define the cautious state if the trends of social indicators are within the normal envelope variability but following negative trends or below the reference trend, but we have not used any colour coding for this cautious state.

We have analysed the system instability and early warning signals prior to moving beyond the SOS based on critical slowing down or flickering theories. In these theories, increases in variance are recognized as one of the most robust signals for the system instability (Dakos et al. 2012; Wang et al. 2012; Carpenter and Brok 2006). Residuals and standard deviations are calculated from detrended time series using Gaussian kernel smoothing to remove the low and high frequencies of long-term trend (Zhang et al. 2015; Dakos et al. 2012). We have analysed 34 years of time series of modelled data (crop production and income at household level) prior to moving towards the cautious and dangerous state for the scenarios 1, 2 and 3. The base run (similar to historical time series) also has analysed using same length (34 years) of time series, though it has not crossed the safe operating space. The rest of the scenarios are excluded due to the shorter length (~13) of time series prior to moving beyond the safe operating space. All time series are standardized (z score) before analysing the residuals and standard deviation. In the case of standard deviation, the variance is computed for a sliding window representing half the length of time series. All these analyses are conducted using the 'earlywarnings' package of R downloaded from http://www.r-project.org/.

5.5. Results

Figure 5.5 illustrates the simulation results for the different scenarios using SD modelling. It is worth noting that, the results should not read quantitatively in precise way as, we aimed at understanding the dynamic behaviour of social-ecological system. However, the 50 year simulation indicates the period between the 1960s and 2010. The first scenario 1 evaluated 'what if' temperature increased by 2 °C throughout the simulation. This simulation indicates that, the rising trend of crop production would continue ~25 years, followed by a sudden decrease, and subsequently could return to the production level of the 1960s. Scenario 2 and Scenario 3 both show that the crop production will decrease even below the production of 1960s. The reduction will be higher in scenario 3 because of sea level rise (32 cm) and the withdrawal of a 50% subsidy in the era of 2 °C temperature rise. Even the production loss (scenario 3) will be similar to scenario 4 which evaluates the impact of 3.5 °C temperature rise. In contrast to the scenario 3, production would experience sudden decrease after 10 years in scenario 4. Furthermore, we evaluated 'what if' sea level increases 80 cm in the era of 3.5 °C temperature rise in scenario 5 throughout the simulation. As for this scenario, production will decrease ~40% for rising salinity due to sea level rise and also for rising temperature. This loss of production could be higher if there is a withdrawal of all subsidy in combination with sea level rise of 80 cm and 3.5 °C temperature rise.

We also evaluated how the system will respond if there is a withdrawal of water from the upstream Ganges in scenario 7 and scenario 8. Scenario 7 demonstrated the impact of a 3.5 °C temperature increase and 20% withdrawal of water through the Farakka dam. This scenario depicts that production will decline similarly to scenario 5 which shows the impact of a 3.5 °C temperature increase and sea level rise (80 cm). We also evaluated (Scenario 8) the impact of water withdrawal (-20%) during dry season (Dec to May) as most rice varieties have their sowing and growing seasons in this period. Thus, we hypothesized that a substantial reduction of water in the dry season could lead to a rise in groundwater level due to sea level rise, which will in turn increase soil salinity in this region. Similar impact shows while simulating this scenario 8, which depicts that crop production, will be the lowest compared to any other scenarios and will be stable over the time period of 50 years. The massive decline in crop production mainly because of the salinity increase (beyond threshold of 4 $dS.m^{-1}$) because of the water withdrawal and temperature increase.

As a consequence of the dynamic relationships in the social-ecological systems, the social system (income, production cost and GDP) also responds (Figure 5.5) to the changes in temperature and sea level rise and to the withdrawal of water and agricultural subsidies. Because of the direct linkages between crop production and social indicators, the social indicators such as income, production and GDP will increase up to 25 years, followed by a sudden decline in scenario 1, 2 and 3. In scenarios 4, 5 and 6, income, production cost and GDP will also experience a rapid decrease after 10 years in the era of a 3.5°C temperature rise and also because of sea level rise, and withdrawal of subsidy respectively. All these scenarios indicate that the social system will respond negatively and will be more severely impacted by a 3.5°C temperature rise compared to 2°C temperature increase.

We also analyse the instability of SES prior to moving beyond the safe operating space. Figure C.6 shows the instability analysis of modelled crop production and income at household time series data prior to exceeding the safe operating space. Both the crop production and income records show decreasing variance (residuals and standard deviation) for scenario 1, 2 and 3. However, the variance is increasing for the base run (similar to historical trend), which does not move beyond the safe operating space.

5.6. Discussion

5.6.1. Safe operating space for Bangladesh delta

This study attempts to define the SOS for the south-west coastal Bangladesh delta using SD modelling. This modelling suggests that the SES in the Bangladesh delta will move to a cautious state after 35 years due to 2 °C temperature increase and sea level rise. The system will go slightly beyond the cautious status

and will transgress the safe operating space for withdrawing 50% subsidy for the agriculture sector in combination with the effects of a 2 °C temperature increase and sea level rise. Similarly, the analysis shows that the delta may head towards the dangerous zone for a 3.5 °C temperature increase but could be sooner in comparison to the combined effects of subsidy withdrawal (50%), 2 °C temperature increase and sea level rise. The SD model also indicates that, impacts on society could be extreme in the era of a 3.5 °C rise, if the other challenges (e.g. withdrawal of subsidy, sea level rise) combine with the effects of a 3.5 °C

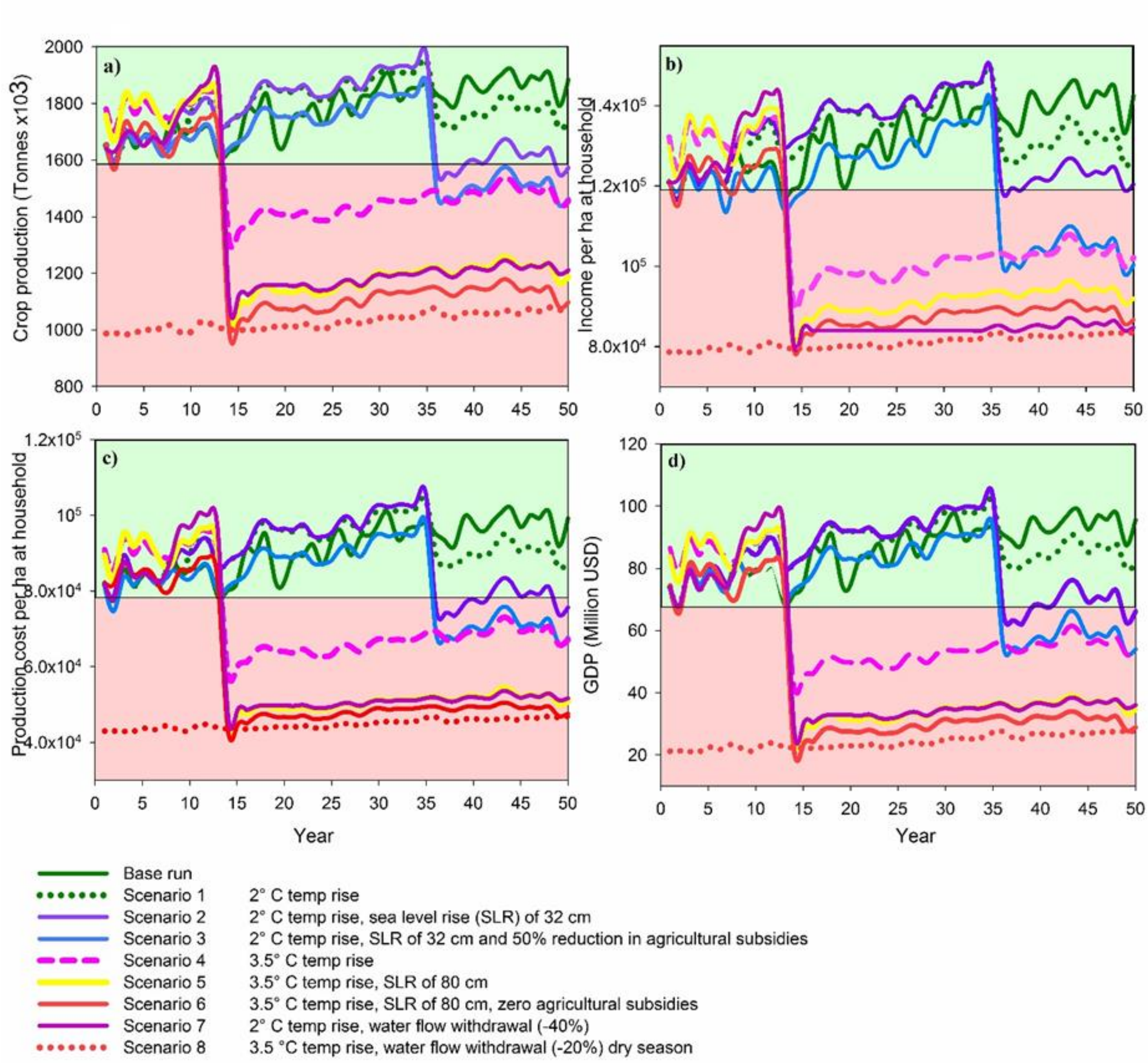


Figure 5.5 SOS simulated for the SES in Bangladesh delta. Colour coded segments show the safe (green) and dangerous (red) status for crop production (a), income ha-1 at household (b), production cost ha-1 at household (c) and GDP shared by agriculture (d) in Bangladesh delta.

temperature increase. The SES could be stepped out from the SOS after 15 years for both sea level rise and for the combined effects of sea level rise and withdrawal of all subsidy in the era of 3.5 °C temperature rise. Furthermore, the withdrawal of water discharges from the upstream of Ganges delta through the Farakka Barrage could push the system towards a sharp decrease in crop production, but the impact of this would be higher than the combined effects of sea level rise and withdrawal of all subsidy in the era of 3.5 °C rise temperature. However, if we consider the water discharges in dry season, which coincides with the sowing and harvesting period of the crops, the social-ecological system, could be in the dangerous zone due to the 20% withdrawal of water discharges and a 3.5 °C temperature rise. This is because of the capillary rise of seawater due to the withdrawal of water discharges, leading towards higher salinity, which is also triggered by the interaction between soil salinity and temperature.

5.6.2. Trade-offs: living within safe operating space

The instability analysis of this study implies that the system may move beyond the SOS without any early warning signal. Although, the rising variance postulated for critical transition or tipping point in previous studies (Zhang et al. 2015; Wang et al. 2012; Dakos et al. 2008), the system may collapse without prior warning (Boerlijst et al. 2013; Hasting and Whysham 2010) and rising variance may enlarge the SOS for the SES (Carpenter et al. 2015). All these indicate the difficulties and challenges of providing an early warning signal to avoid moving beyond SOS (Boettiger and Hasting 2013). Therefore, a critical challenge for the management is how to operate the SES within safe operating space. The SES in Bangladesh delta may be operated within a safe space by managing some of the feedbacks such as reducing production costs, which in turn can reduce dependency on subsidy and household income to invest in agriculture. In addition, disconnecting the feedback loops among crop production, GDP and subsidies, could reduce the investment on subsidy. This may help developing other sectors (e.g. education, research, technology) instead of investing GDP to support the farmers for subsidy. This investment in other sectors could include the innovation of crop varieties with low production cost, which may help in managing some of the feedback loops by reducing dependency on subsidies.

Managing the slow variables (e.g. temperature, rainfall) to increase the long term resilience (Biggs et al. 2012; Bennet et al. 2009; Gordon et al. 2008) could also support overcoming the challenges such as climate change. Although the SD model shows that 3.5 ^{o}C temperature increase could be more dangerous than 2 ^{o}C increase, but the social system could still experience negative impacts such as decrease in income and crop production for 2 ^{o}C temperature rise. Thus, the global agreement adopted in Paris 2015 on remaining below a 2 ^{o}C temperature increase and possibly pursuing the greater effort in limiting the temperature within 1.5 ^{o}C temperature increase, would require operating the SES within safe space at regional scale. Moreover, managing slow variables could also reduce the interactions with other variables such as the interactions between temperature and soil salinity. Protecting the coastal area of Bangladesh against the sea level rise could also be the part of managing slow variables by using advanced technology for embankment construction concerning the SES in this delta. Besides protecting the coastal area from sea level rise, ensuring water flow from the Ganges through the transboundary negotiation could also be part of reducing the interactions among the variables such as water, ground water level and salinity. Otherwise, the interactions among these variables and other proposed development (e.g. river linking project in Ganges (Gourdji et al. 2008)) may pose risk to Bangladesh delta which could step out from the safe operating space.

The rising connectivity in this delta (Hossain et al. 2016a) coupled to slow variables deterioration can be interpreted as declining resilience and systematic instability (Zhang et al. 2015), which can be managed by creating a heterogeneous naturally developed landscape for sustainable and resilient SES (Sceffer et al. 2012).

Hence, the model indicates the importance of new technological innovation such as temperature and salinity tolerant crops to avoid the crossing of thresholds, which in turn, could avoid a 'perfect storm' of social-ecological failings (Zhang et al. 2015; Dearing et al. 2012).

5.6.3. Scope, limitation and future development

This study also can be useful for operationalizing some of the international discourse such as tipping points (Dearing et al. 2015), limit to adaptation (Dow et al. 2013) and boundaries of agricultural intensification (Chares and Godfray 2015). Furthermore, it can serve the purpose in fostering the understanding of SES at regional scale by overcoming the data limitation challenges. This study can be extended in the future by: 1) testing of other hypothesis (e.g. increase in shrimp farms) with the existing model set up, 2) modifying the fundamental relationships of the model to quantify the changes precisely, and also 3) extending the model for seasonal changes and other main livelihood sources such as shrimp, forest and fishery in Bangladesh delta.

This study was limited to income and GDP for social system because of the long-term data unavailability of other indicators (e.g. migration, equity, food security) for the households engaged in agriculture. However, the indicators such as income are useful because of the capacity to provide crucial information on basic human capacities and measuring poverty (Anand and Sen 2000). Although this study did not focus on the spatial changes, the SD model of this study also serves the purpose in understanding the behaviour and making the trade-offs at different scales. For example, the scenario development considering only temperature and the combined impacts of salinity and temperature, indicates the fact that, the non-salinity affected area, Barisal, which is located far from the sea, can still be stepped out from the SOS because of the increasing temperature, whereas, the highly salinity effected area can be stepped out from the SOS sooner than the Barisal region. The settings of thresholds of rice can be varied with the development of technology, however, but the stakeholder driven approach used for collecting threshold information is completely based on the current state of knowledge. The exclusion of abrupt changes in rainfall from the model is mainly because of the lack of understanding and complexities in analysing the relationship between production and abrupt changes in rainfall. Inclusion of some of the impacts such as abrupt changes in rainfall, water quality and conflicts of shrimp farming with rice in the model will shrink rather than expand the boundaries of the SOS for the social-ecological system.

The traditional approach of scenario analysis is often criticized as a misleading approach because of the straight forwardness, ignorance of non-linearity and dynamic interaction (Postma and Liebl 2005). For example, hydrological models (e.g. GWAVA, GLOBWB) and agriculture models (e.g. CROPWAT) (Wahaj et al. 2007) do not consider the interaction and feedbacks among the biophysical and social components. Integrated models based on such models (e.g. Wada et al. 2015) can therefore sometimes mislead the policy for managing environment. Therefore, despite limiting our study to understanding the dynamic behaviour of social-ecological system, this study not only serves the purpose of demonstrating, for the first time the SOS at regional scale but also, recognises the global call for system integration of coupled social-ecological systems (Lui et al. 2015), including modelling the behaviour (Dearing et al. 2015; Anderies 2015; Lansing et al. 2014; Walker and Salt 2006) of SES for sustainability and some other international initiatives (e.g. SDGs 2030) to ensure food security and promoting agriculture by defining the boundaries of agriculture intensification (Chares and Godfray 2015).

Besides the SD modelling approach for analysing tipping points and SOS at regional scale, some of the econometric method (e.g. nonlinear Granger Causality test (Chen et al. 2013); feedback models (Granger 1969)) can also provide insights of causal relationships and systemic risk considering the interactions and feedbacks in the system. Social-ecological model such as AIRES (http://www.ariesonline.org) may also useful in analysing critical transition or tipping points in biophysical processes. System models such as agent based modelling are useful for macro level modelling of individual discrete behaviour such as migration and fisheries production and the decision making behaviour of individual agents. The SD model has a similar capacity for analysing the aggregated behaviour with a greater emphasis on understanding how the behaviour operates within a system (Rahmandad and Sterman 2008;

Borshchev and Flippov 2008). Therefore, combining the agent based model and SD model might be useful (Martin and Schlüter 2015; Borshchev and Flippov 2008) in understanding the SD of social-ecological system, and modelling human behaviour, such as how the changes will affect the social issues (e.g. migration) and at what point the SES will collapse, or experience a tipping point, or will step out from the safe operating space.

5.7. Conclusion

This study makes a first attempt to operationalize SOS concept at regional scale considering the complex dynamics in social-ecological system. We have used SD modelling, incorporating eight 'what if' scenarios based on well-known challenges (e.g. climate change) and current policy debates (e.g. SDGs) to demonstrate SOS in Bangladesh delta. This study reveals that a 3.5 ^{o}C temperature increase can be dangerous for the social-ecological system. The impacts could be severe if other challenges such as sea level rise, withdrawal of water and subsidy occur in combination with a 3.5 ^{o}C temperature increase. This study underlines the importance of pursuing the greater effort adopted in Paris agreement 2015 for limiting the temperature increase within 2 ^{o}C. In addition, the global policy such as WTOs recommendation to withdrawal of agricultural subsidy could pose risk to other global policies such as SDGs to reduce poverty and hunger worldwide. Strengthening transborder negotiations for water resources management is essential as the withdrawal of water through existing infrastructure and or any other proposed developments (e.g. river linking project), could lead to the dangerous zone in the era of 3.5 ^{o}C temperature increase. The methodology of this study can serve the purpose of defining the boundaries for sustainable development at regional scale, as well as, operationalizing the sustainability science concepts such as tipping point and limit to adaptation. In addition, this can also be used for analysing and modelling SES in other data poor areas for identifying policy options for sustainable development.

Chapter 6: Conclusions

Despite growing sustainability challenges in the face of environmental degradation, human well-being is improving both at global and local scale. In such a case, it is important to know the SOS beyond which the risk of unpredictable and damaging change to human well-being becomes very high. Although, the SOS has attained significant academic attention and is rapidly becoming more prevalent in policy, the operationalization of this concept has been criticized in terms of normative settings of the boundaries, exclusion of the social system, scale and interaction among the biophysical processes.

I make a first attempt to operationalize SOS concept at regional scale, by: 1) analysing time series data to detect drivers, change point, 2) analysing the linkages between SESs using regression models (e.g. non-linearity, feedbacks) to develop system model and 3) by using SD model to demonstrate SOS for the SES in Bangladesh delta.

Time series data analysis revealed that, human well-being is improving in contrast to the ecosystem degradation since 1980s. The interrelationships analysis supports that material well-being (basic materials for a good life) having a strong relationship with provisioning services, which in turn, show a weak relationship with the quality of life (security and health). The connectivity analysis provides the insight of decreasing resilience of the SES. The SD model developed using the analyses of trends and interrelationships, provides the base for SD modelling to demonstrate SOS at regional scale.

The SD model implies that, the SES of Bangladesh delta may step out of the SOS at a 3.5 ^{o}C temperature increase. The impacts on society could be severe if other challenges such as sea level rise, withdrawal of water and agricultural subsidies combine with a 3.5 ^{o}C temperature increase. Further water withdrawal through existing infrastructure (e.g. Farakka dam) or any other proposed development (e.g. river linking project) may lead the SES towards a dangerous zone. The system can also be in the dangerous state if 50% of the subsidy for the agriculture sector is withdrawn in the era of 2 ^{o}C temperature increase and sea level rise. Therefore, the model implies that the SES in the Bangladesh delta can be operated within the SOS by managing feedbacks (e.g. subsidy, production and production cost) and slow variables such as greater effort to limit temperature increase to below 1.5 ^{o}C according to the global agreement adopted in Paris 2015. In addition, there is a need to revise global policies, such as the WTO's policy to withdraw subsidies for agriculture , which may pose a risk to other global policies such as the SDG goals to reduce hunger and poverty. Transboundary issues, such as negotiating for water resources at South Asian scale, may help Bangladesh operating the SES within safe space.

This study neither avoids making a priori definitions of drivers of environmental change nor assumes the presence of strong causative links between variables. Though the indicators were selected based on data availability, measurability, current environmental concerns (e.g. climate, salinity) and development goals (e.g. MDGs, SDGs), data unavailability was a major limitation of this study. Time series data at the national and divisional levels are available both for ecological and social indicators. In the absence of a quality digital database, time series data for ecological indicators at the regional (e.g. sub-division, district) scale are difficult to obtain and, when available, the procedures for accessing these data are often extremely complicated. Though some of the indicators (e.g. temperature, rainfall) are available at the district level, many of the indicators (e.g. water, salinity) are drawn from the monitored point data or sequences of mapped data from hydrological and soil resource organizations and other scientific studies. Therefore, time series analysis was limited for aggregated trends at the regional scale and could not focus on the spatial changes. In the case of the social system, yearly time series data could not be constructed as the datasets are collected every five years (e.g. HIES). HIES and DHS datasets are only representative at national and divisional level, thus, only the aggregated trends over the study region were constructed from 1995 to 2010. In addition, HIES datasets do not cover the information for forest dependent people, shrimp farmers and other social indicators (e.g. happiness, life satisfaction and crime). Despite these limitations, the finding serves as a basis for understanding the evolution, relationships and measuring the progress of SES.

In order to operationalize the SOS concept at regional scale, this study was limited to income, production cost and GDP for the social system in the absence of long-term data, income measures for poverty and deprivation from basic human needs. In addition, this study also focused only on agriculture as a case study and did not attempt to quantify the system behavior precisely, but simulates general trends to serve the purpose of demonstrating SOS at regional scale. Although this study did not focus on mapping spatial changes in-terms of SOS at different scales, understanding the drivers and responses for social system, provide the implications for SOS at different scales. For example, model results suggest that the rising temperature can still drive the SES of Barisal (far from sea) out of the safe operating space, whereas, impacts could be severe in Khulna (close to sea) for the combined effects of temperature, salinity and sea level rise.

This study can be extended in the future by: 1) testing other hypotheses (e.g. increase in shrimp farms) with the existing model set up, 2) modifying the fundamental relationships of the model to quantify the changes precisely, 3) extending the model for seasonal changes, system shocks (e.g. cyclone, floods) and other main livelihood sources such as shrimp, forest and fishery in the Bangladesh delta, 4) capturing the conflicts (e.g. crops vs shrimp, food vs biofuels) between social and ecological systems, 5) testing the model for other SES such as other regions of Bangladesh or even other countries, 6) investigating how the feedbacks from the SES can influence the SOS for the biophysical system, and 7) combining agent model and system dynamic models to examine the changes in human behaviour (e.g. migration) due to the collapse of SES.

Besides contributing to the SOS operationalization, this thesis also represents the first regional scale analysis of a complex SES using real world data to increase our understanding of the linear and nonlinear relationships, as well as the threshold points in the SES. In addition, discrepancies between the national and regional scale HWB improvements, highlighting the importance of monitoring HWB at regional scale in relation to the SDG goals of ensuring equitable progress across the globe.

This first attempt of operationalizing the SOS concept at regional scale will also support the operationalization of other sustainability science concepts such as tipping points, limits to adaptation and defining the boundaries for sustainable development. Furthermore, it can foster the understanding of social ecological systems at the regional scale by overcoming the data limitation challenges and informing optimum development pathways for achieving local and global development goals (e.g. SDGs).

AppendixA

Supplementary material: Chapter 2

A.1 Study Area

The study is limited to the former (before 1990) three Greater District[1] areas of Khulna, Barishal and Patukhali. Since 1990, these three Greater District areas are represented by nine Districts: Khulna (present-day: Khulna, Satkhira, Bagerhat Districts), Barishal (present-day: Barishal, Bhola, Jalakathi, Perojpur Districts) and Patukhali (present-day: Barguna, Patuakhali Districts). Data have been collected from both the Greater District and District area administrative units. The area covered by these nine Districts is ~ 25 000 km2 with a population ~14 million representing 16% of the total national land area and 10% of the national population BBS (2010).

- Barisal District pop. 2291000 area 2785km^2 pop density 823/km^2
- Khulna District pop. 2294000 area 4394 km^2 pop density 522/km^2
- Patuakhali District pop. 1517000 area 3221 km^2 pop density 472/km^2

This flood plains delta acts as a passage to pass the river water flow (Ganges-Bhrahmputra-Meghna) into Bay of Bengal in the south. This area is very dynamic with high rates of erosion and accretion as a result of the high sediment discharges and strong river flow (Iftekhar and Islam, 2004).

The delta is naturally characterized by a humid climate receiving a mean annual rainfall of 1400-2100 mm. The average total dissolved solid (TDS) in ground water is about 1.7 ppt along the coast and 0.01 ppt in north and is about 1ppt in fresh water during dry season (Nobi and Gupta 1997). The northern part of this area is highly vulnerable to riverine flooding and the southern part is vulnerable to storm surges flooding (Tingsanchali and Karim, 2005). The mean sea level of this area is about 0.9-2.1 m and sea level rise is threatening the ES. Sundarban is the unique and world largest mangrove forest covering Khulna and part of Potuakhali region (Sarwar 2005).dominated by alluvium washed down from the Himalayas (Islam 2003).

[1] District is the administrative unit of Bangladesh Government. At present, Bangladesh is divided into 64 districts where, it was divided into 21 greater districts before 1985.

The average population density is about 743 per km^2 with fishing, shrimp farming, agriculture and tourism the major economic activities. The mangrove ecosystem is the major income source of around 1.5 million people directly and indirectly for 10 million people (Islam & Haque 2004). Moreover, the total coastal ecosystem produces around US$277 GDP per capita (Sarwar 2005). Collections of raw materials (mainly forest products) from the mangrove are secondary occupations. The percentage of the engagement in different occupation varies seasonally.

A.2 Selection of the indicators

Human well-being is the subset of economic factors and social wellbeing (OECD 2001) consistent with determinants such as security, health, social freedom and choice, and basic materials for life (MA 2005). The rationality of the indicators of human well-being is given below:

1. Poverty (% of population below poverty line): ES changes have direct impacts to reduce poverty by contributing to meet the demands for basic materials (food, cloth, education) and security (safe drinking water, sanitation etc.) of individuals (MA 2005; UNEP/ISSD 2004). Moreover, poverty measures the deprivation of well-being in the society (Daw et al. 2011 and OECD 2001). We have used the upper poverty line as the poverty measure defined by Bangladesh Bureau of Statistics (BBS). This definition considers the cost of basic needs (food and non-food items) and the adjusted prices of food items (BBS 2010). We have used this dataset for analysing the trends of poverty. Details of the methodology of the defining upper level poverty line are found elsewhere in (BBS 2010)

2. Per capita income: Individual personal wealth is measured by per capita income (Cutter et al. 2003) which enables to meet basic materials such as food, literacy, health etc. for life.

3. Gross domestic product: GDP is the welfare indicator (Boyd, 2004) which measures the aggregated indices of well-being encompasses of human and natural production (Daw et al. 2011; Boyd and Banzhaf 2007).

Though higher GDP and per capita income are associated with lower income inequality (Fedderke and Klitgaard 1998), these can hide the wealth variation in society (Ravallion 2001). The delta zone is highly productive for agriculture, fishery and mangrove so the main three indicators of human well-being are also supported by other indicators such as gross value added product from agriculture and total revenue from mangrove forest. Gross value added production is the difference between the production cost and selling price of the product. In addition, we also have analyzed the total, urban and rural population growth trends (1974-2011) in order to explore the complex interlinkages among population, ES and human well-being (MA 2005). The detailed data sources have been provided in the individual graphs.

Food, shrimp, fish and raw materials are selected to show the trajectories of food provisioning services. People of the delta mainly depend on crops such as different varieties of rice, jute and sugarcane. Spices, potato and different seasonal vegetables are also obtained from the ecosystem. Natural forest products in the mangrove forest are a major source of livelihood.

We choose surface water salinity and soil salinity as the main performance indicators of water quality, as the salinity increase is reducing the availability of the fresh water and in turn threatening the ecological and agricultural functioning (Rahman et al., 2010; Musa, 2008).

Water discharge data from Hardinge Bridge (1931-2010) has been used for the hydrological regime performance indicator. This point on the river Parma (Ganges) is the passage way for the Ganges water volume to reach the Bay of Bengal (Islam 2008) and the major source of dissolved nutrients to the south west delta including the largest mangrove ecosystem of the world (Figure 1).

Temperature and precipitation are used as the performance indicators of local climate (WRI 2013; de Groot et al. 2006). Water discharge, rainfall and temperature data were arranged as per the seasonal variation: pre-monsoon (March-May), monsoon (June-August) and post-Monsoon (September-November) and winter (December-January-February) (Islam and Uyeda (2007). In addition, the rainfall and temperature dataset were arranged into three time segments (1949-1970; 1971-1990 and 1991-2012) to observe the variability in different time segments. Rainfall and temperature dataset have been averaged from monthly data of two weather stations located in Khulna and Barisal to observe the overall BCZ climate. In addition, the spatial variability of three regional climates (Khulna, Barisal and Patuakhai) has also been analyzed.

Fluvial erosion and accretion rate are the performance indicators for erosion prevention. Because, if the accretion rate is lower than the erosion rate, then the erosion prevention capacity is reduced. Moreover, we choose the time series statistics of crops naturally damaged by different disasters (flood, cyclone, water logging etc.) to analyze the trends of natural hazard mitigation.

For indicators of biodiversity (Costanza et al. 1997 and De Groot et al. 2002) we use trees per hectare (ha), growing stock, and number of tigers and deer in the mangrove forest. We have focused on mangrove in analyzing the data of water discharges, raw materials and forest area as this mangrove accounts around 28% of the total land area and around 10 million people directly and indirectly dependent on mangrove. Most of the rivers networks in this area are receiving water discharge through the Hardinge Bridge point which also supplies water flow to the mangrove forest. Therefore, the scale of the mangrove, the dependency and the non-availability of data in other areas motivated a mangrove focus. Though we discuss the spatial variation in this delta, we have concentrated mostly on the aggregated trends that represent the overall trends in ES and HWB of the coastal zone.

We have attempted to identify slow and fast variables of ES, where the slow variables change slowly and are the controlling and shaping variables for system resilience (Biggs et al. 2012; Walker et al. 2012). Literature review, bivariate plots and correlation analysis are used to identify the drivers of changes in relation to the observed trends. Environmental Kuznets curves are used to show the relationship between wealth and environmental degradation over the time. This curve hypothesizes that at the early stage of development, environmental degradation increases, but beyond some level of economic growth, environmental degradation declines (Torras et al. 1998; Grossman and Krueger 1995).

A.2 Data Analysis

Time series plots have been used to analyze the trajectories of different ES. Aggregated indexes of the total dataset have been developed by using the z-score method (Crawford and Howell 1998; Dibley et al. 1987). This method follows the normal distribution of the population with a mean zero and variance 1. Z-score values are obtained using the following formula:

$$Zi = (Xi\text{-mean } (x))/\ S.D.$$

Here, Xi is the observed value, mean (x) is the mean value of the population and S.D is the standard deviation (Wunscher et al. 2008; Hogg and Craig 1978). Minitab has been used for descriptive statistics which are required for z-scores.

A linear regression method has been also applied for detecting and analyzing the trends in the time series. The main statistical parameter, the slope, resulting from the regression analysis indicates the mean temporal change. We have applied the non-parametric Mann–Kendall trend test to detect trends in the time series data of water discharges, ground water level, rainfall and temperature. High variability and non-linear system characteristics are the reasons for applying this non-parametric test. The Mann-Kendall test was formulated by Mann (1945) as a non-parametric test for trend detection and the test statistic distribution was explained by Kendall (1975). Mann-Kendal test has already applied in detecting temperature (Vitale et al. 2010), precipitation (Serrano et al., 1999) and river flow data (Danneberg 2012). The details about this test could be found elsewhere in (Burn and Elnur 2002). In this study, p value of less than 0.05 and 0.10 signify the confidence level of 95% and 90% respectively. The nonparametric Lepage test was also applied to detect change points in the trajectories of ES. This two sample test for location and dispersion (Lepage, 1971) assumes that the studied series size is equal to or greater than ten and this test follows the Chi-squares ($\chi 2$) distribution with two degrees of freedom. The Lepage test has been used to detect change point or step wise change for rainfall (Benjamin and Roger 2005), climate change (Inoue and Matsumoto 2007) and water resources (Chen et al. 2009; Zhang et al. 2009).

The z-scores has been averaged to develop a climate index from the temperature, rainfall, water discharges seasonal trends and pre-monsoon ground water level. The main crop rice has been used as the index for food production. Trajectory of water salinity has been reversed for water quality index. Aggregated trajectories of indicators such as food production, water availability index, climate index, GDP, poverty and per capita income have been used to investigate aggregated coevolution of ES and well-being. Lowess smoothing has been applied to these entire indexes before plotting. Lowess is the process of time series smoothing similar to running mean of about 15 years that removes the high and low frequencies from the time series data (Wilkinson 1997). This smoothing method is already applied to climate (Brazel et al. 2000; Mayo and March 1990) and water quality (Hirsch et al. 1991) related studies.

We have analyzed the association among the variables using Spearman rank correlation coefficients (more than 95% confidence interval). While running the correlation analysis among the variables, we applied two techniques:

1. We correlated the regulation services and provisioning services using a lag-1 dataset. This is because the changes in any regulating services possibly will have impact on the next year food production. This is also mostly due to the official timing of data collection of different national agencies. As an example: if there is a drought event in a year (e.g 1990) due to high temperature, the impact on food will be mostly followed in next year (e.g.1991) as the official period of data collection is from June (1990) to June (1991) of the year.

2. We have also analysed the correlation coefficients for local climate and temperature in two time segment, before the 1990s (1969-1990) and after the 1990s (1991-2010), where we found different climate variability regimes.

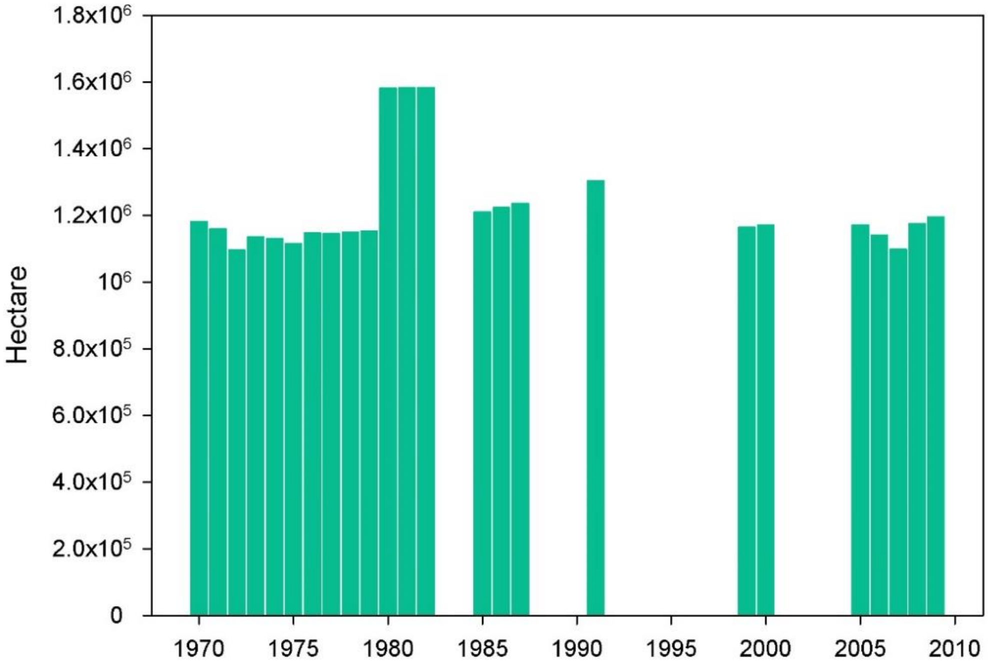


Figure A.1: Net cropped land area (Bangladesh Bureau of Statistics)

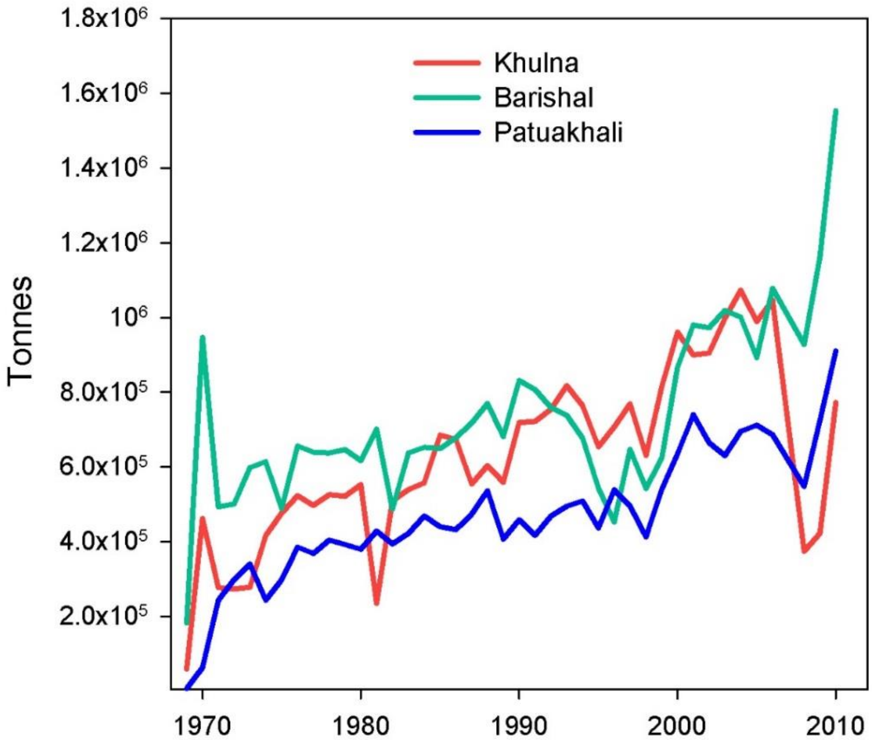


Figure A.2: Rice production in the three regions of Bangladesh delta (Bangladesh Bureau of Statistics; Chowdhuri and Zulfikar 2001).

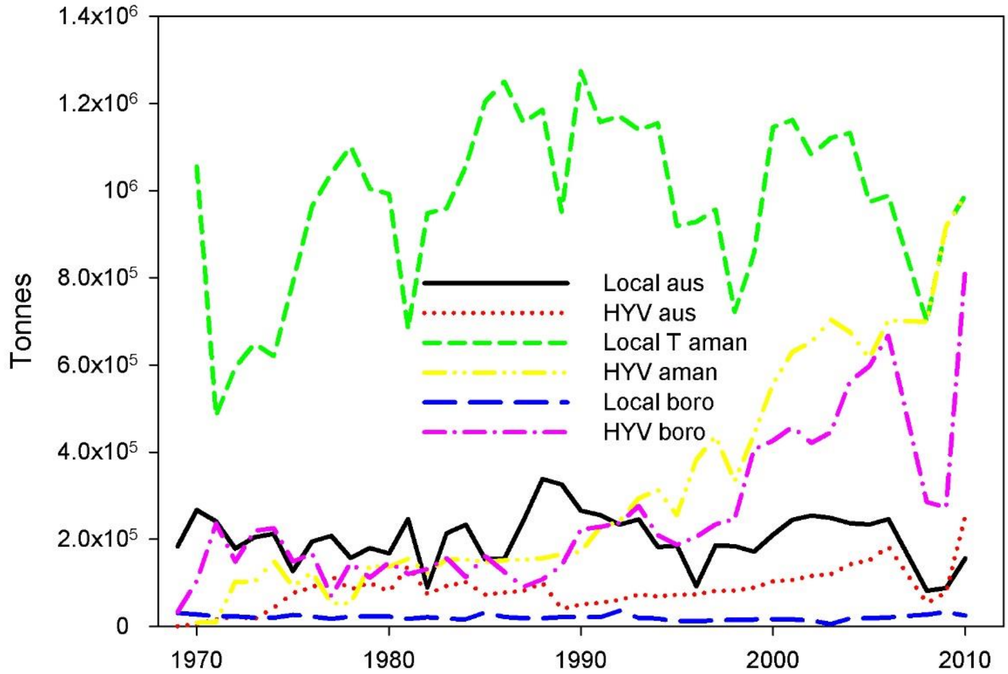


Figure A.3: Use of different rice varieties (Bangladesh Bureau of Statistics; Chowdhuri and Zulfikar 2001).

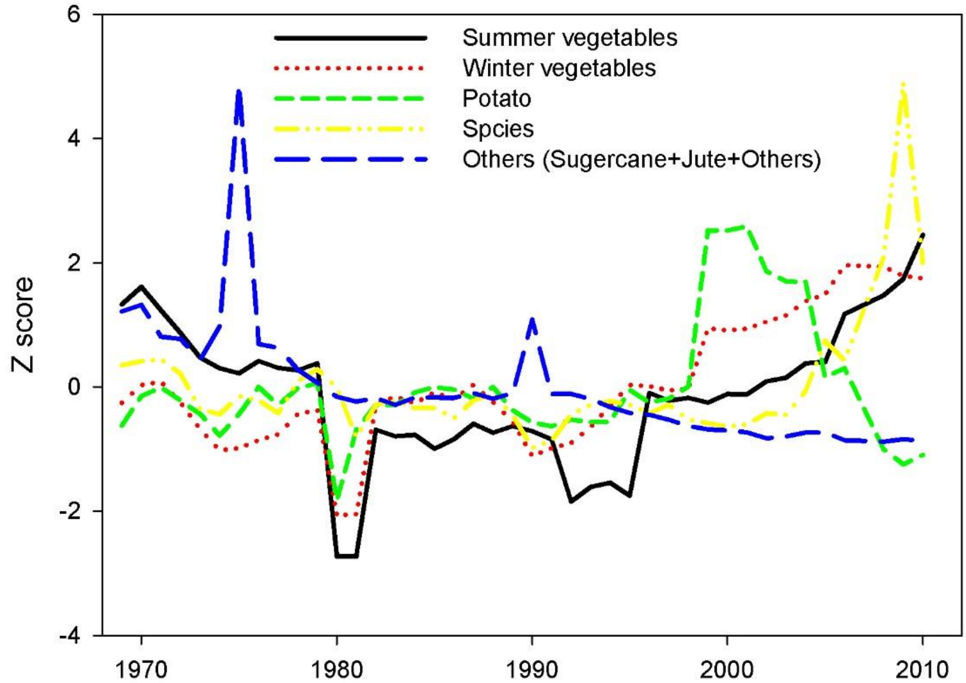


Figure A.4: Production of non-rice crops (Bangladesh Bureau of Statistics).

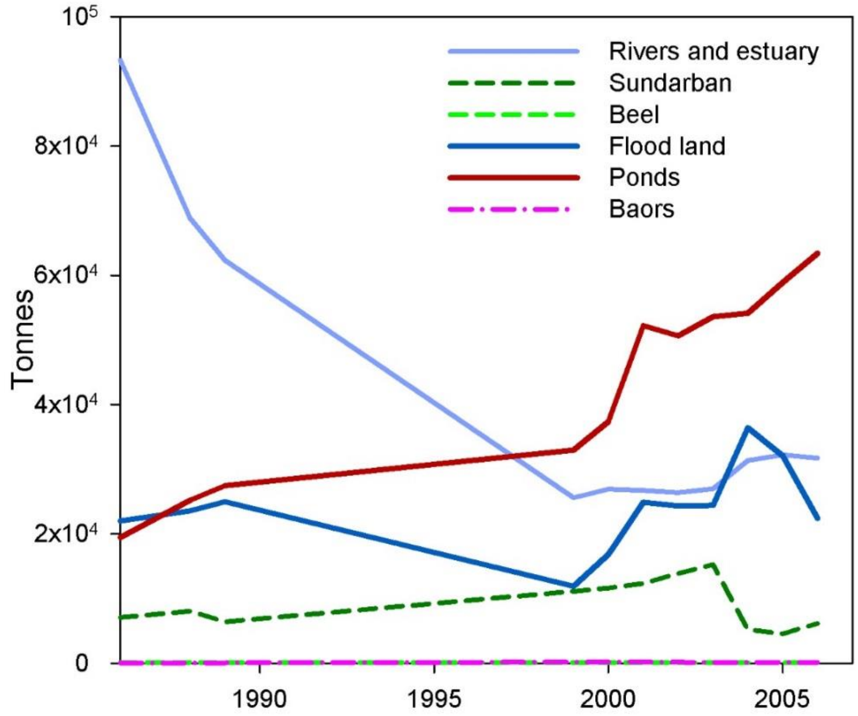


Figure A.5 Fish and shrimp production in different ecosystems (Bangladesh Bureau of Statistics).

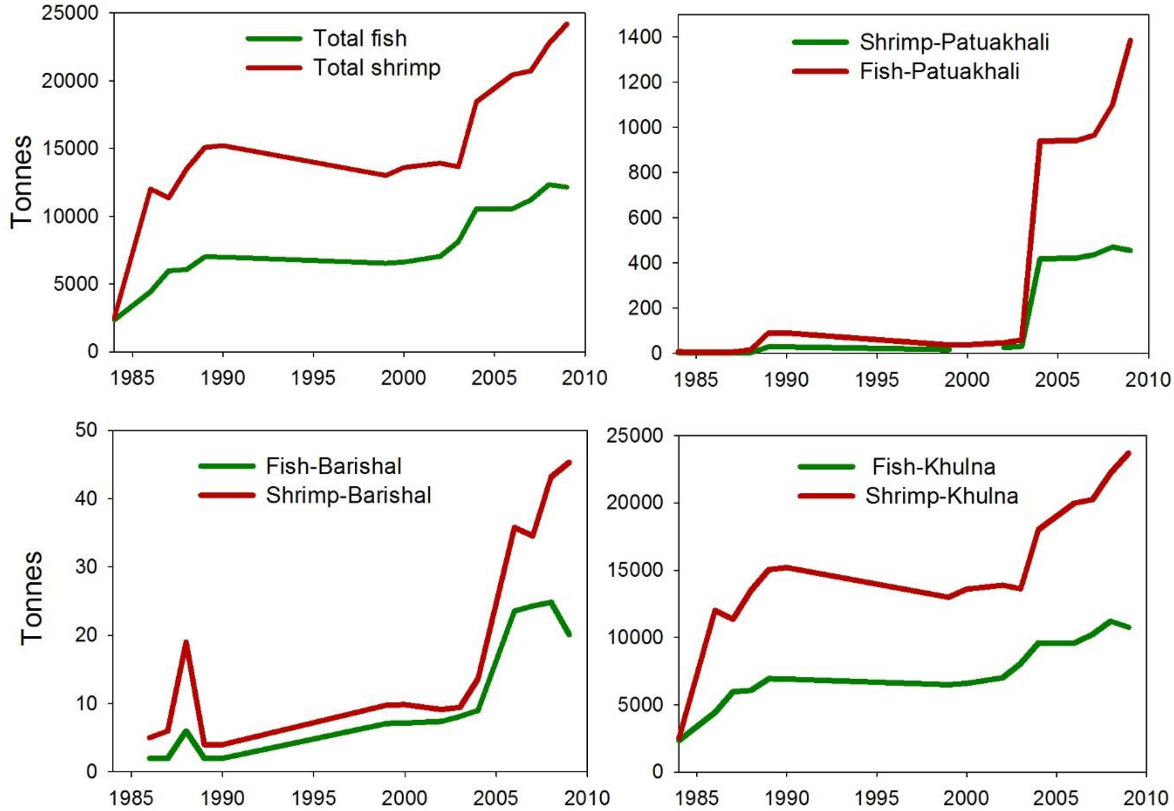


Figure A.6 Fish production inland fish production in BCZ (Bangladesh Bureau of Statistics)

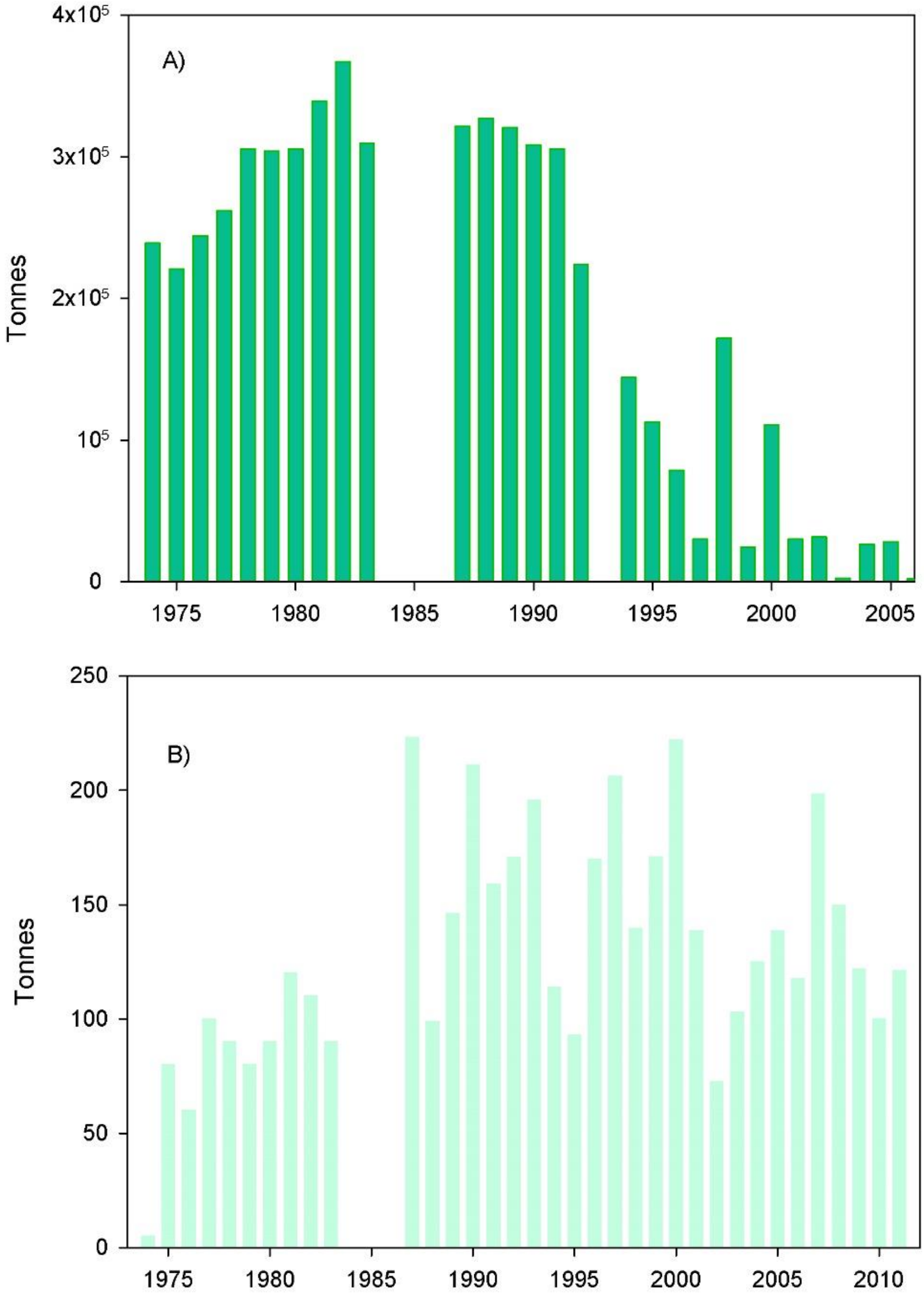


Figure A.7: Forest products from the Sundarbans mangrove forest: (A) timber and related products; (B) honey (Department of Forestry, Zmarlicki 1994; Chaffey et al. 1985)

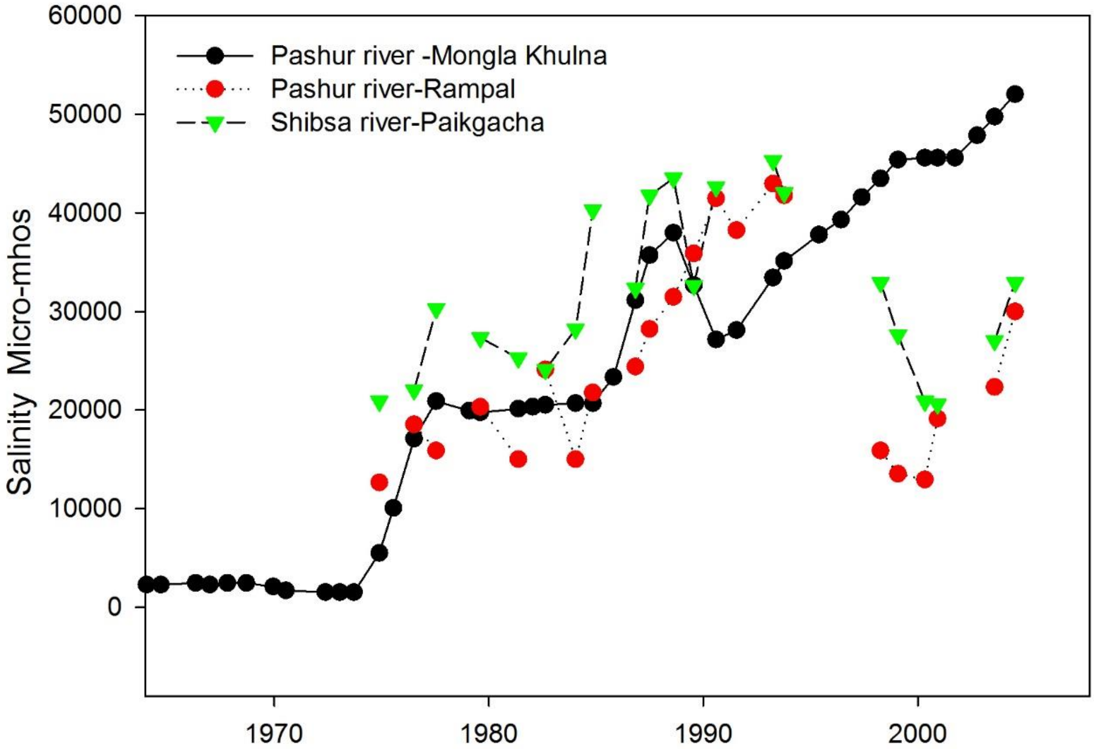


Figure A.8: Surface water salinity (Uddin and Haque , 2010; Islam, 2008).

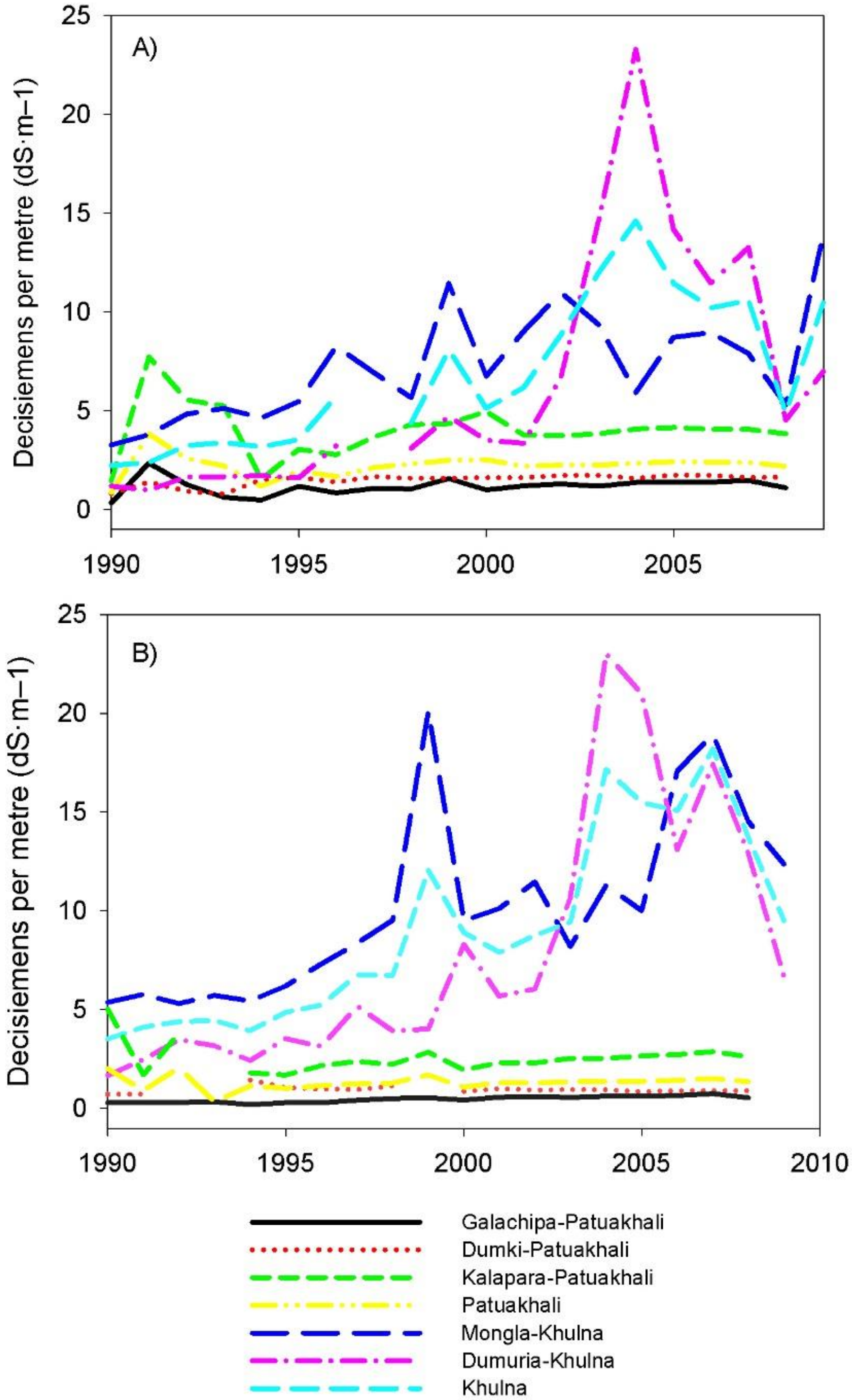


Figure A.9: Dry season (December to June) (A) and wet season (July to November) (B) soil salinity (Soil Research Development Institute Bangladesh).

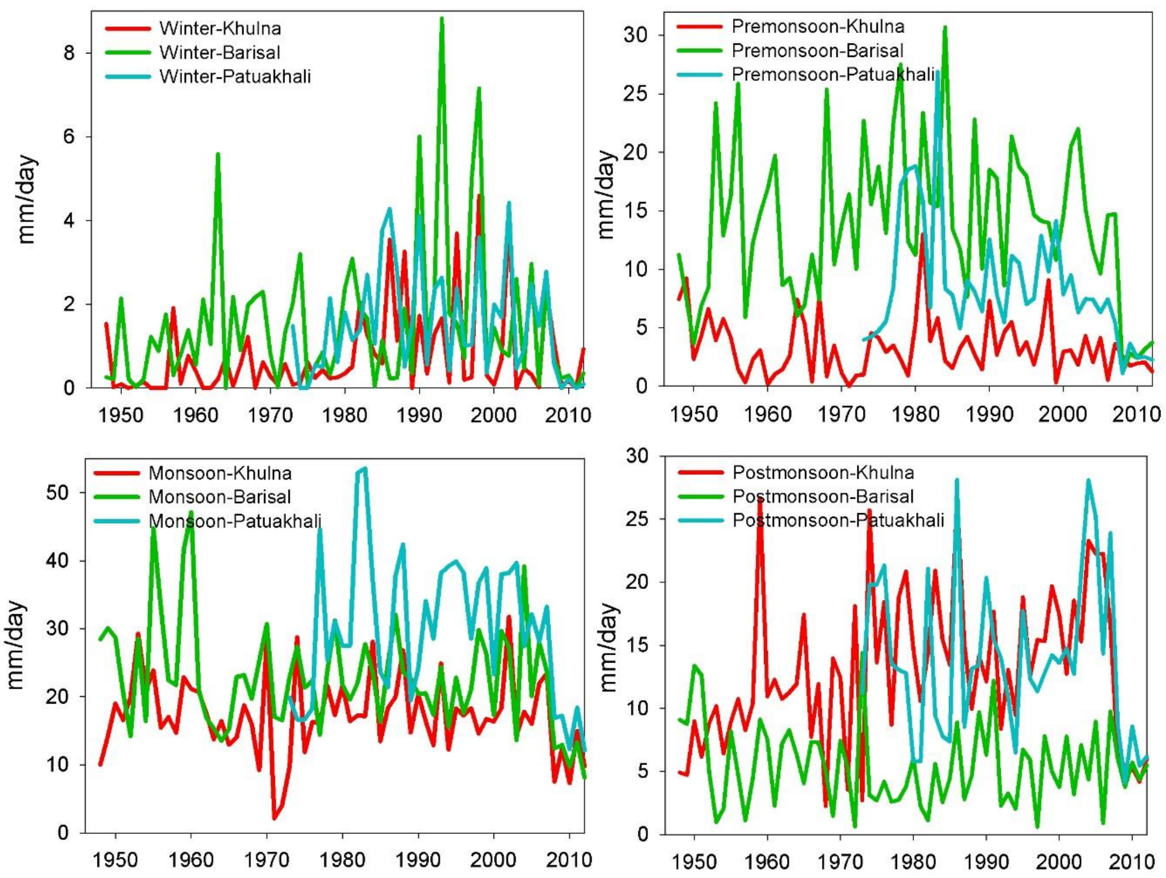


Figure A.10: Seasonal rainfall (Bangladesh Meteorological Department).

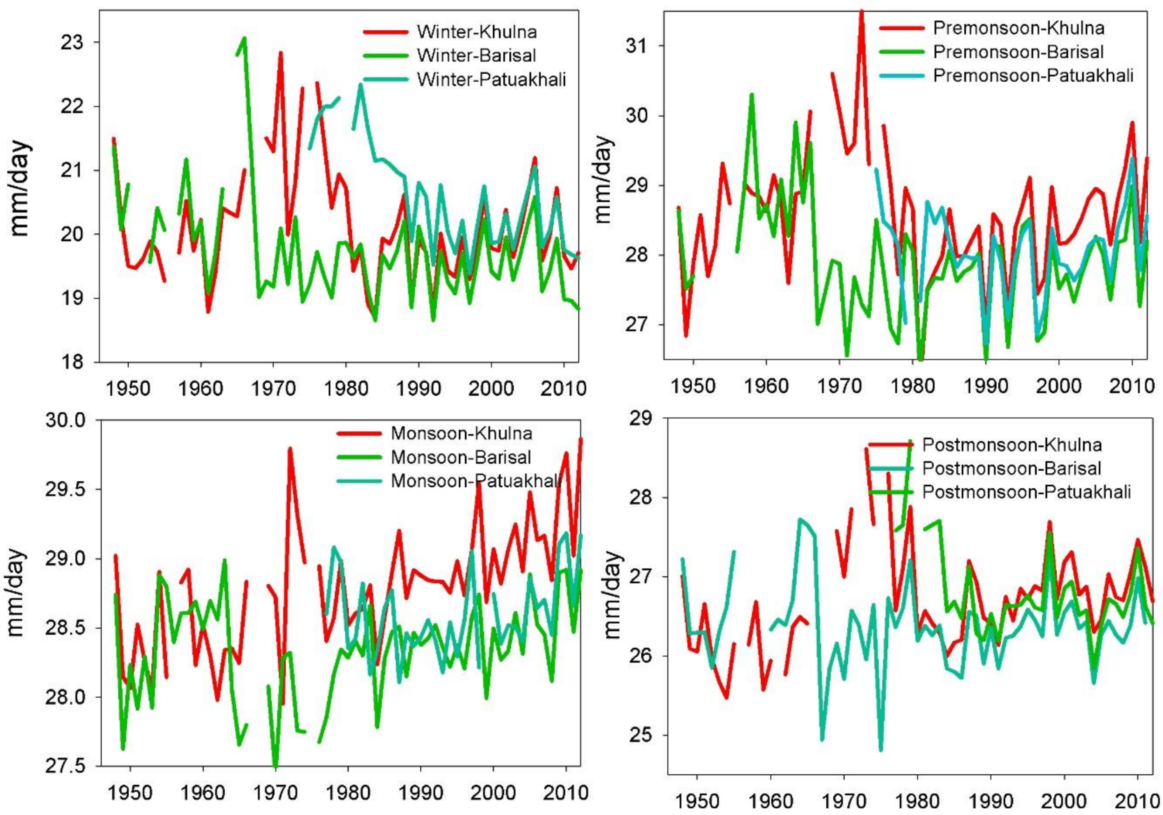
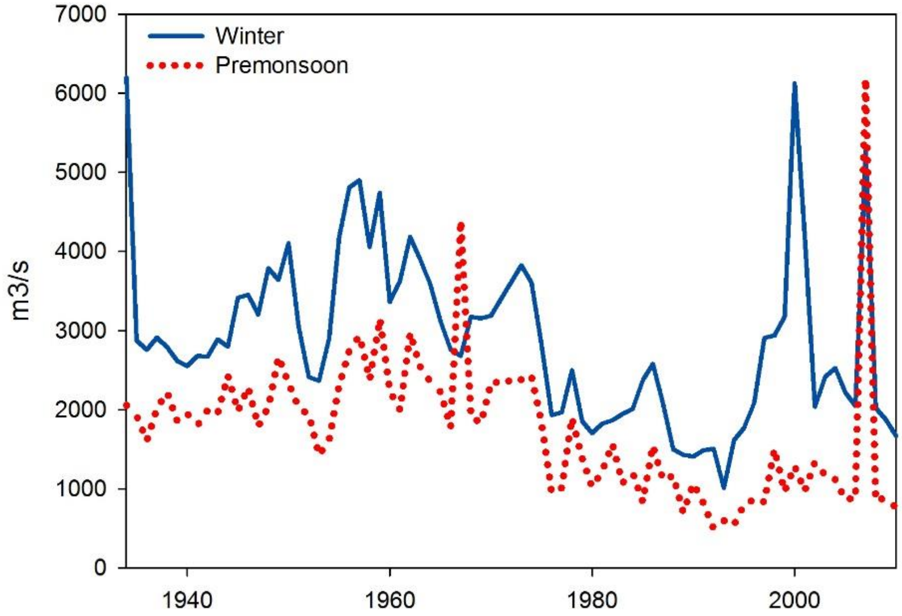


Figure A.11: Seasonal temperatures (Bangladesh Meteorological Department).



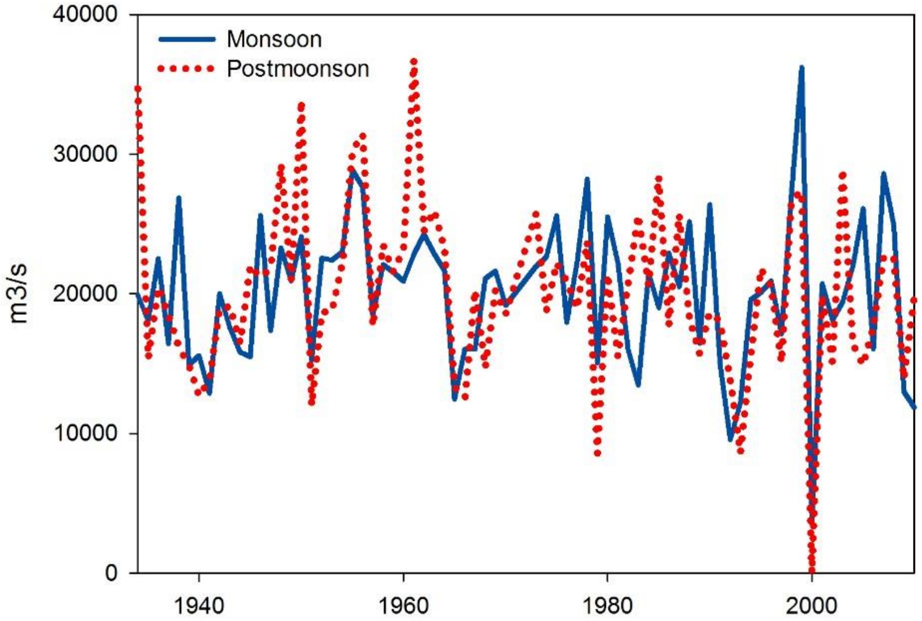


Figure A.12: River discharge raw data for four seasons (Bangladesh Water Development Board).

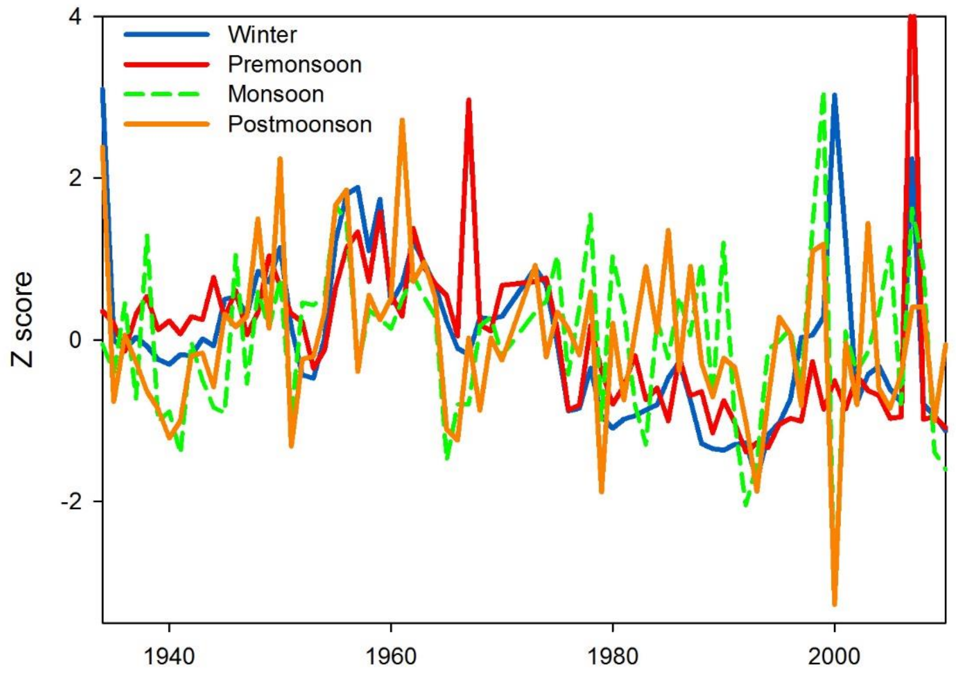


Figure A.13: River discharge relative data for four seasons (Bangladesh Water Development Board).

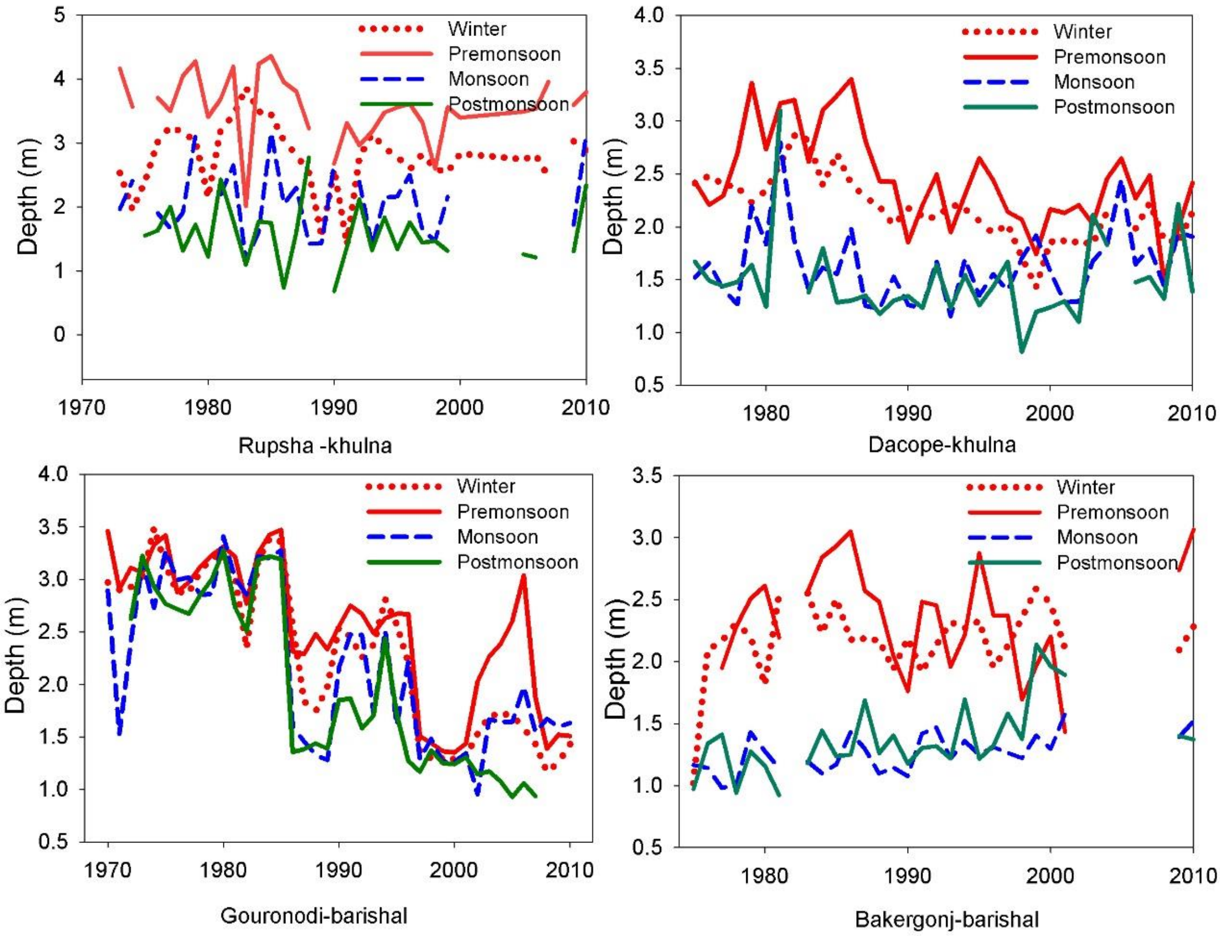


Figure A.14: Ground water levels (Bangladesh Water Development Board).

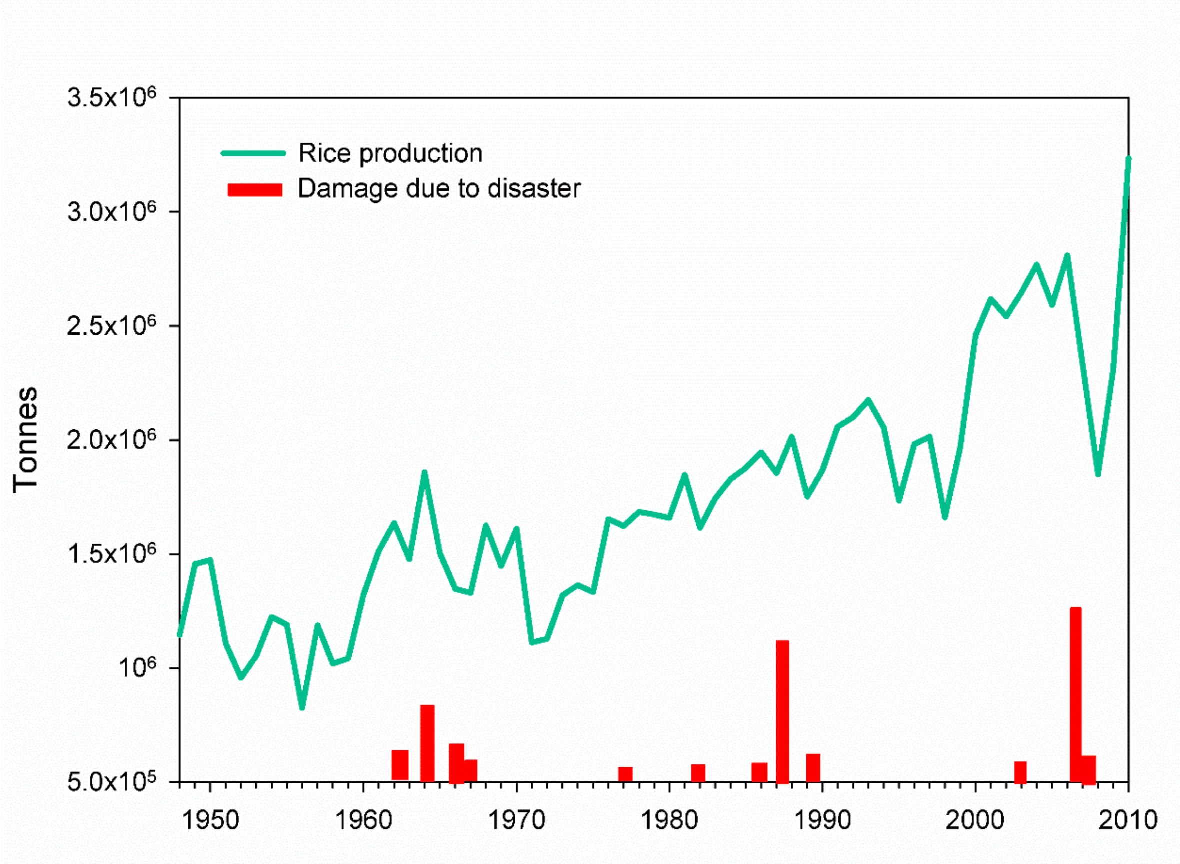


Figure A.15: Crop damage due to natural disasters and rice production (Bangladesh Bureau of Statistics).

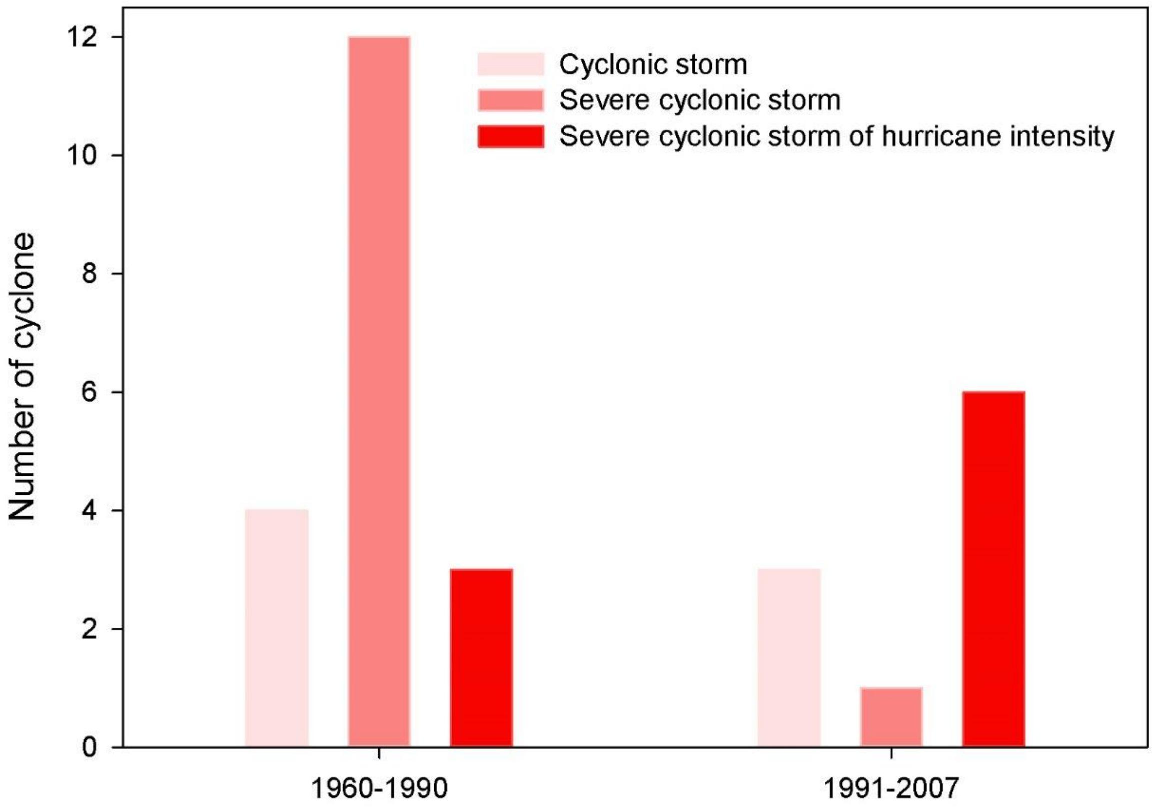


Figure A.16: Cyclone frequency (Bangladesh Meteorological Department).

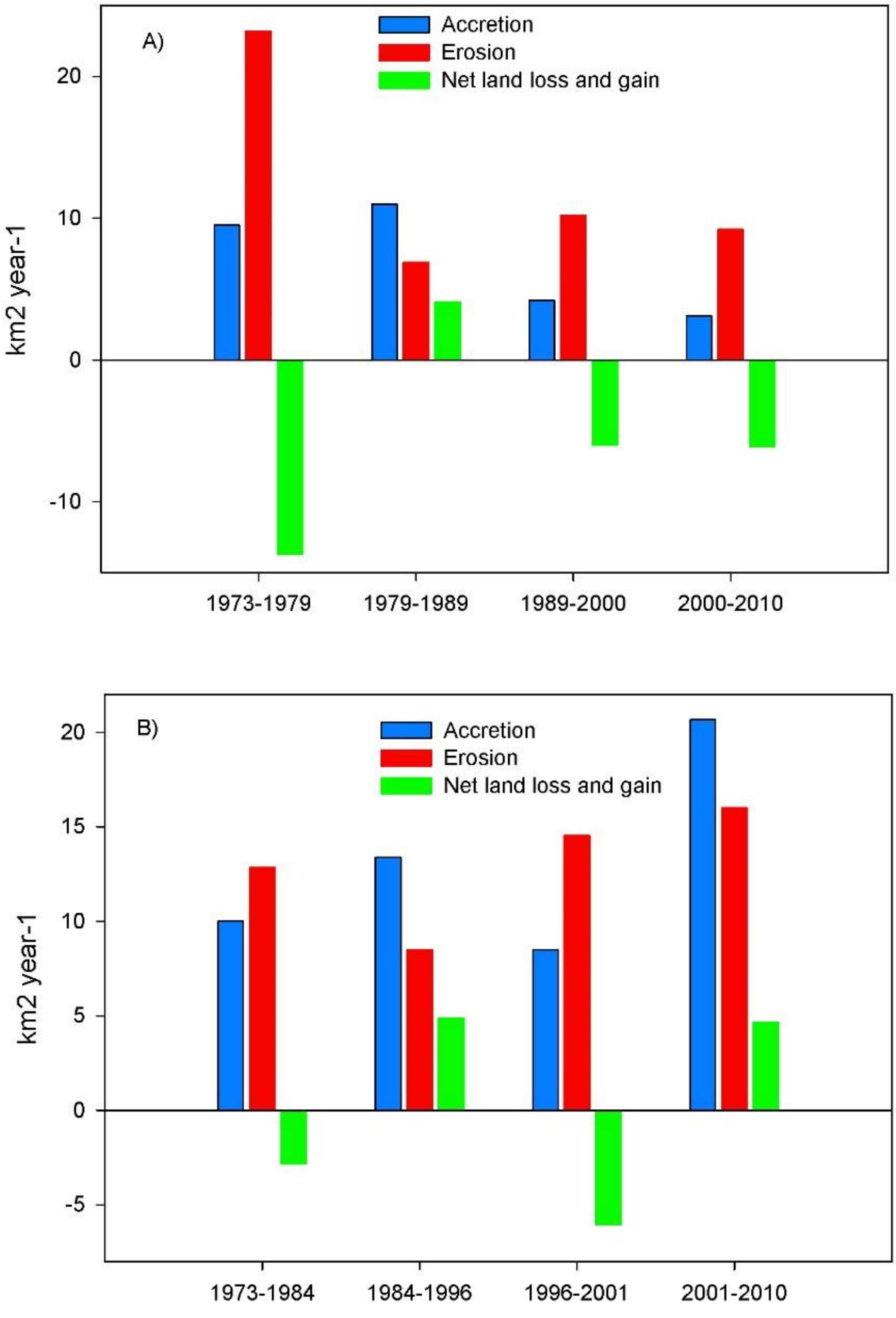


Figure A.17 Accretion and erosion rates in Khulna region (Sundarban coast) (A) and in Patuakhali and Barishal region (B) (Bangladesh Water Development Board and Rahman et al. 2011).

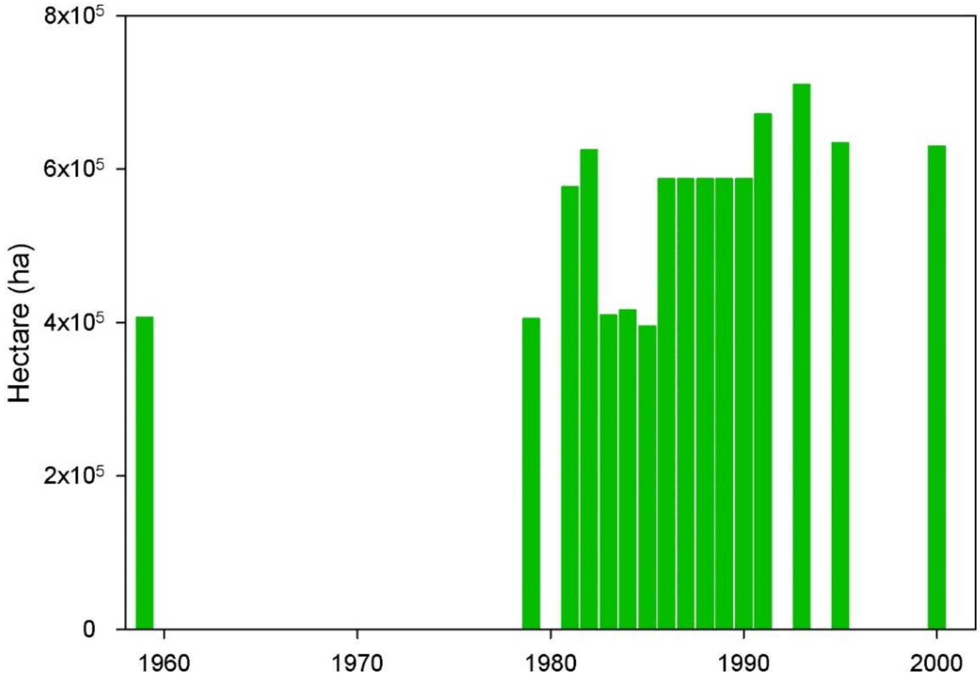


Figure A.18: Mangrove forest area (Food and Agricultural Organization 2007).

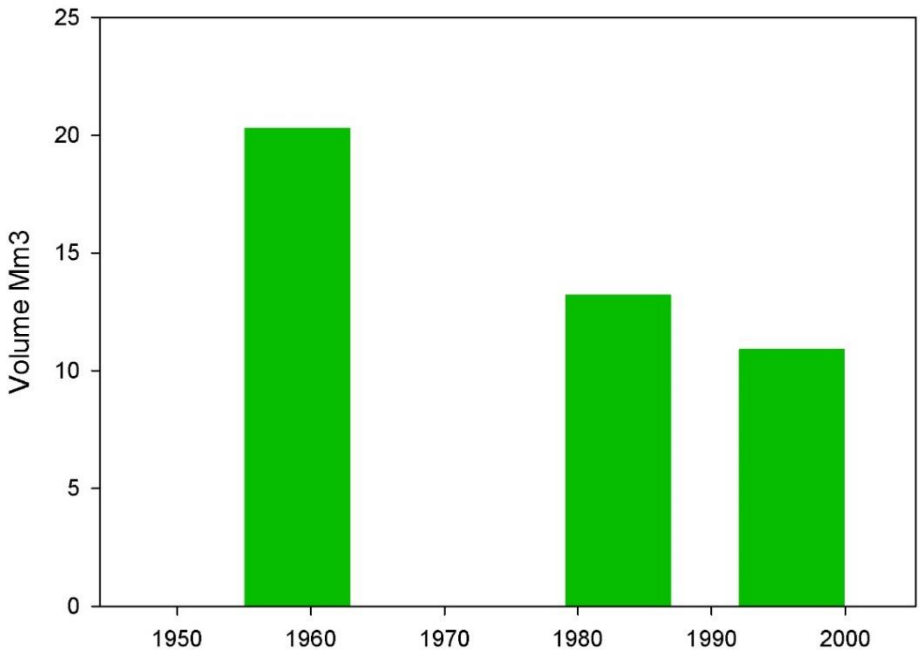


Figure A.19: Growing stock (volume) of trees in the Sundarbans (Food and Agricultural Organization 1999).

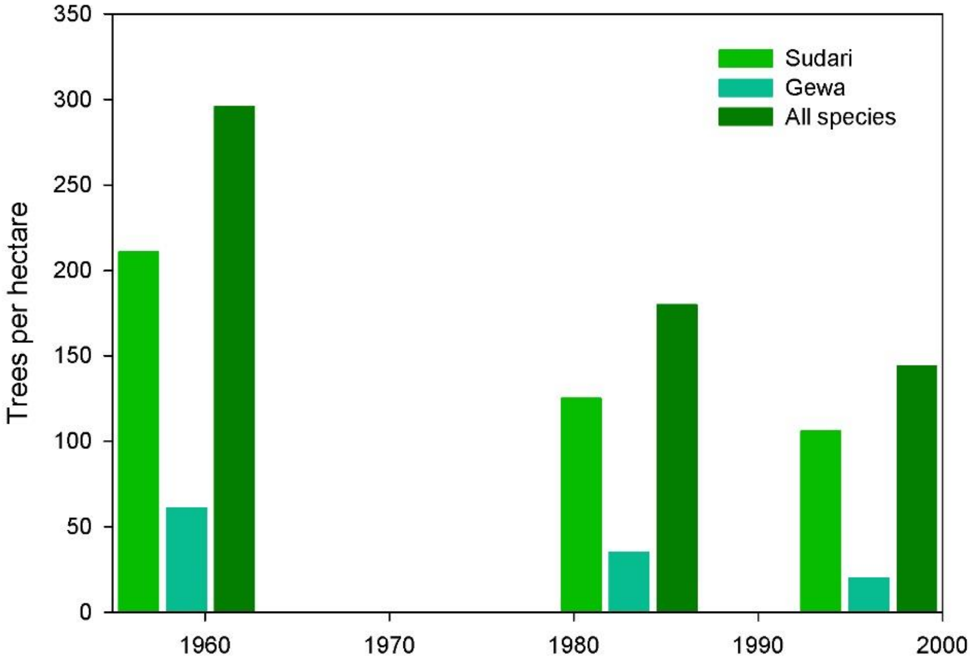


Figure A.20: Tree density in the Sundarbans (MoEF, 2010)

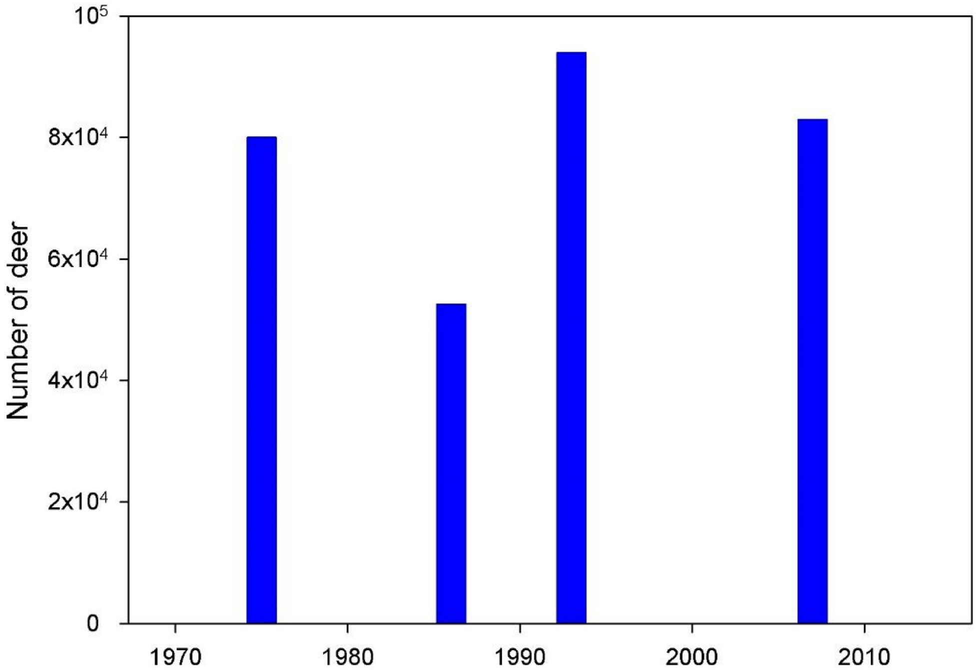


Figure A.21: Deer numbers in the Sundarbans (Dey 2007 cited in MoEF 2002)

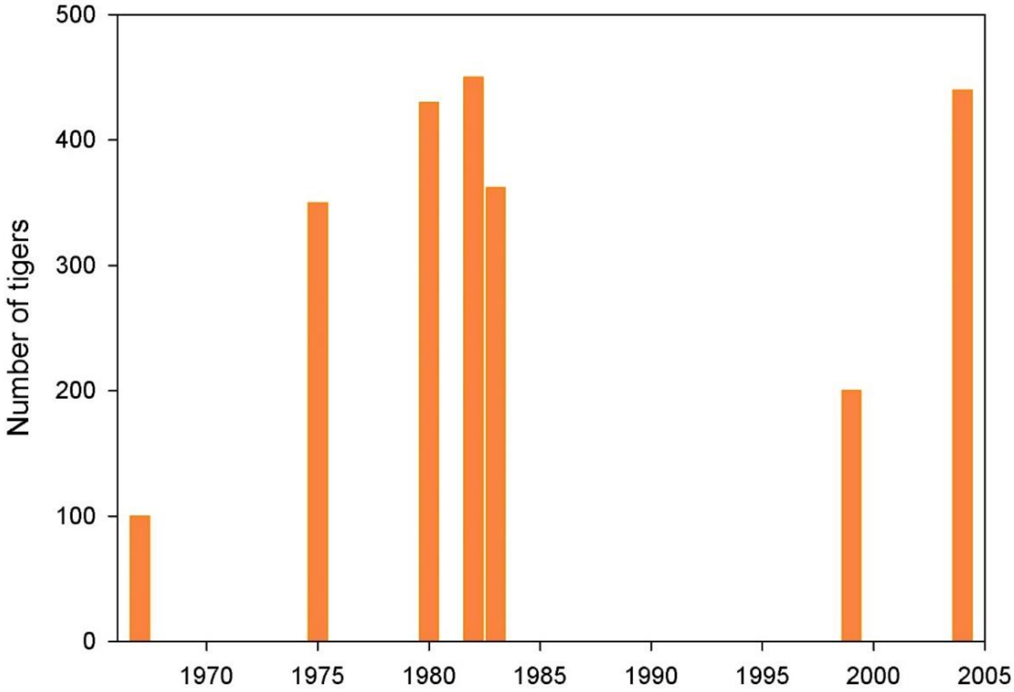


Figure A.22: Tiger numbers in the Sundarbans (Khan 2007; Chowdhury 2001; Helal Siddiqui 1998; Gittings 1980; Hendrick 1975)

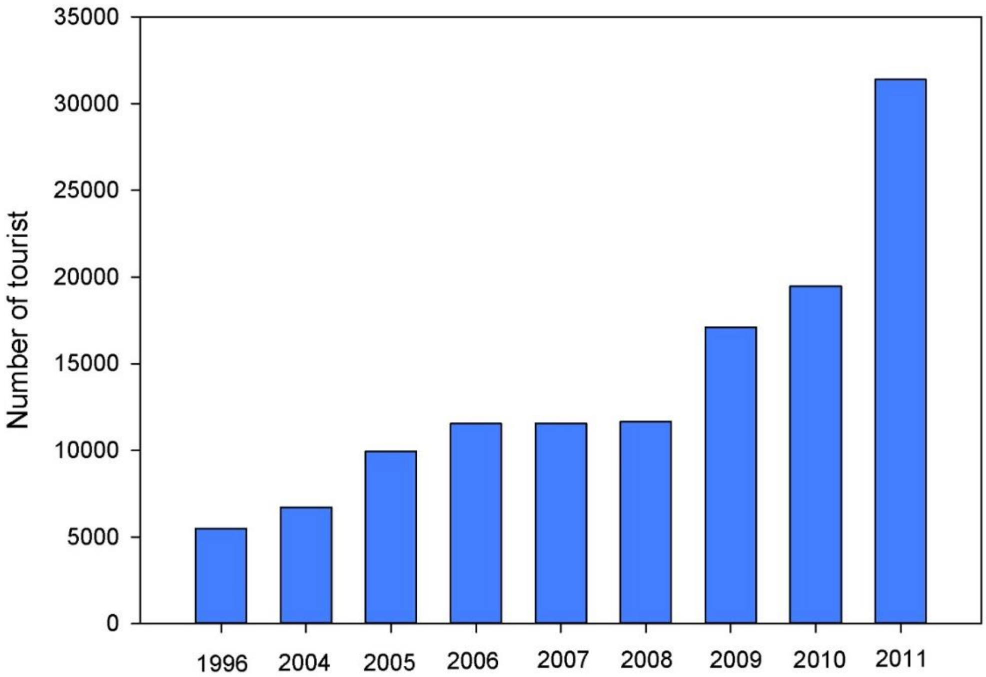


Figure A.23: Tourist figures (Bangladesh Bureau of Statistics).

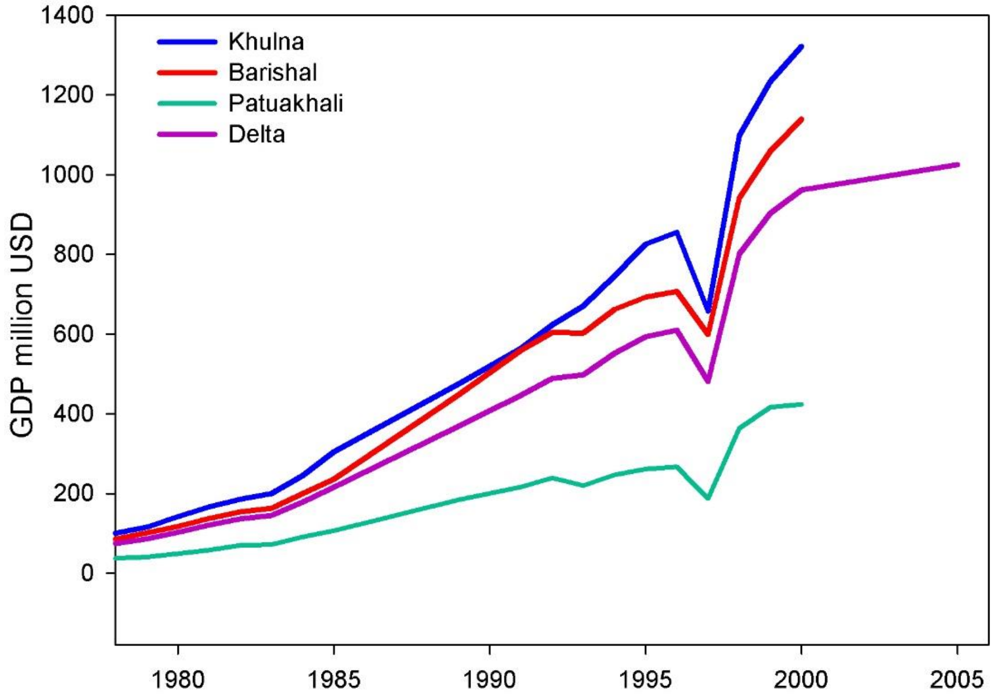


Figure A.24: Gross domestic product (Bangladesh Bureau of Statistics).

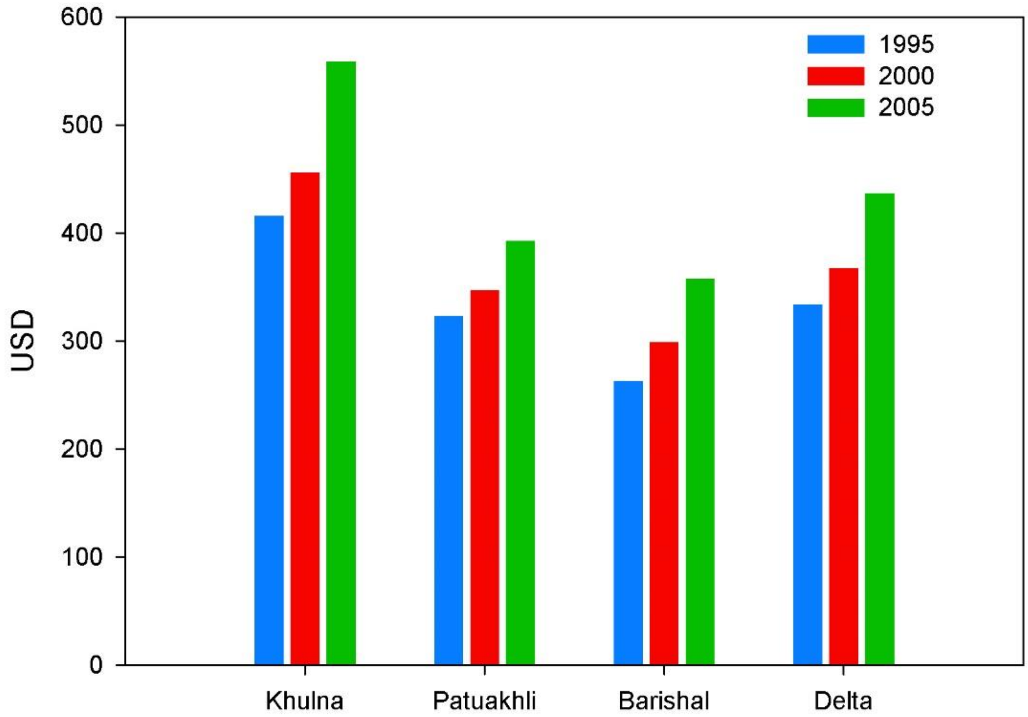


Figure A.25: Per capita income (USD) (Deb 2008).

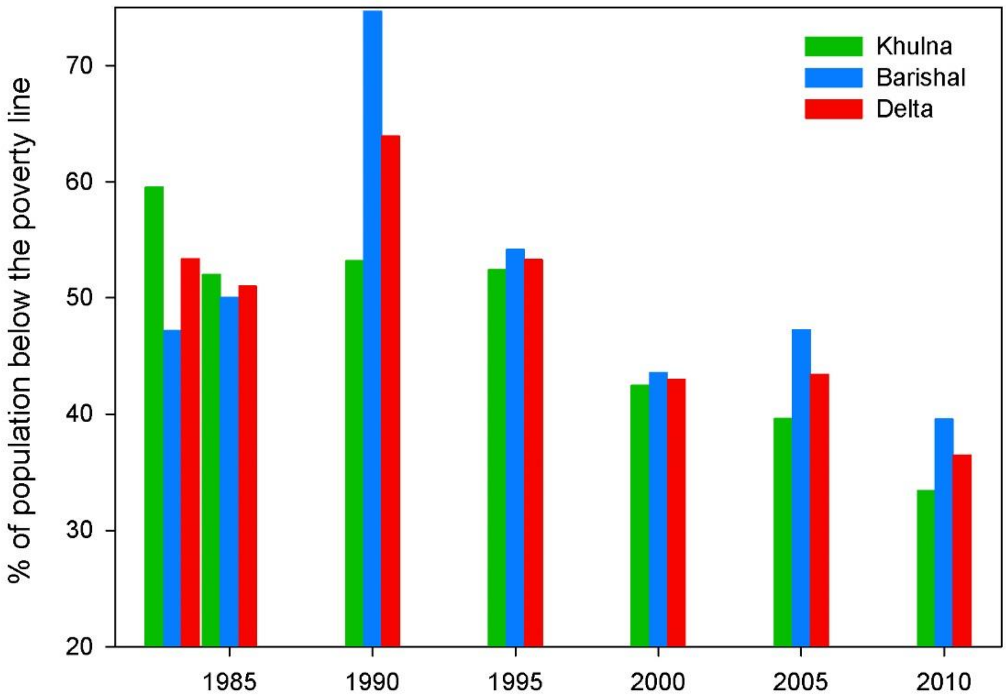


Figure A.26: Trends of regional poverty using the cost of basic need (CBN) method (Bangladesh Bureau of Statistics 2011 and Wodon 1997)

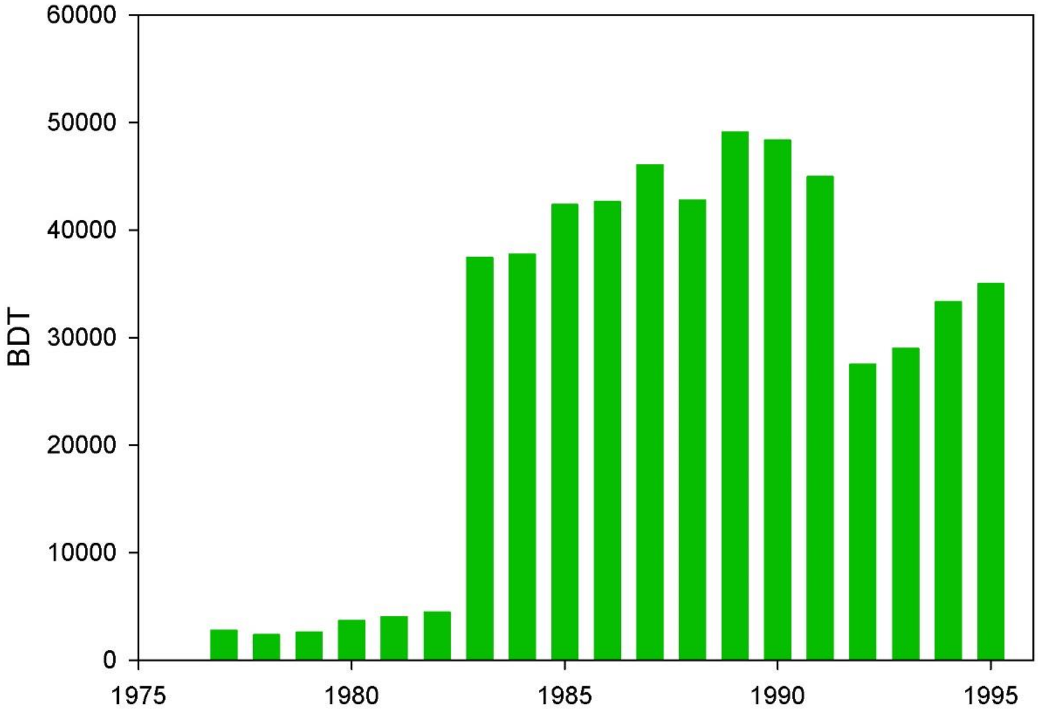


Figure A.27: Total value added from agriculture (Bangladesh Bureau of Statistics).

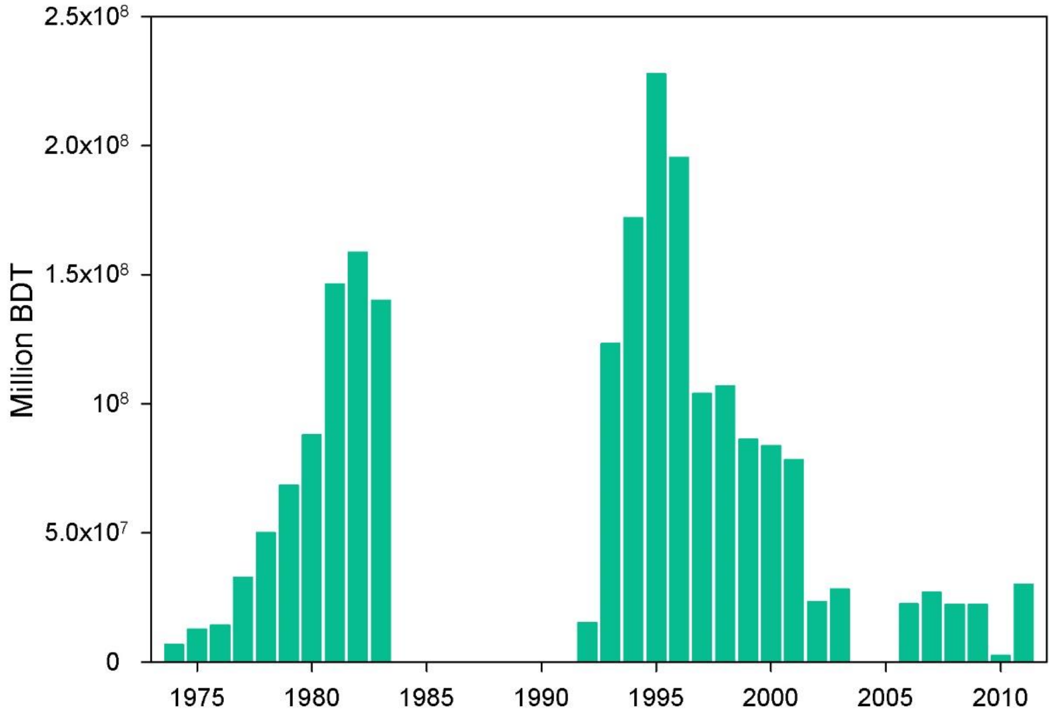


Figure A.28: Total revenue from the Sundarbans (Department of Forest, Khulna; Chaffey et al. 1985).

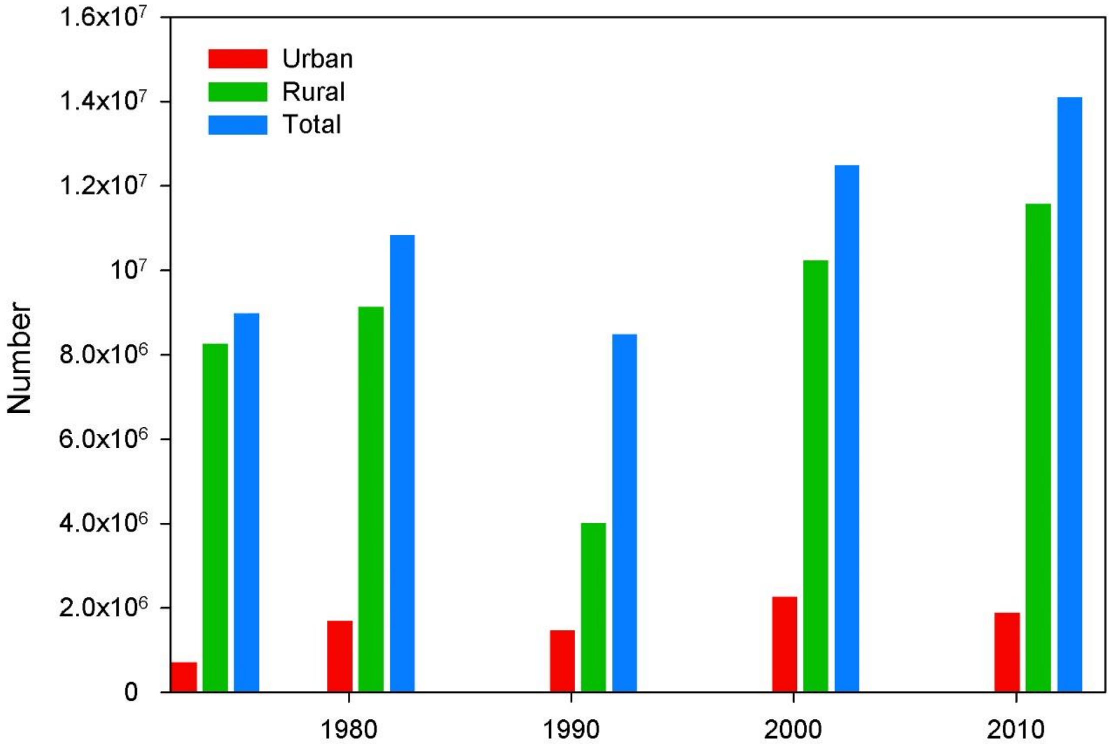


Figure A.29: Population growth (Bangladesh Bureau of Statistics). The sudden drop in population ~1990s in contrast to the population increase over the periods 1980s to 2010, mainly because of the administrative re-arrangement in 1987.

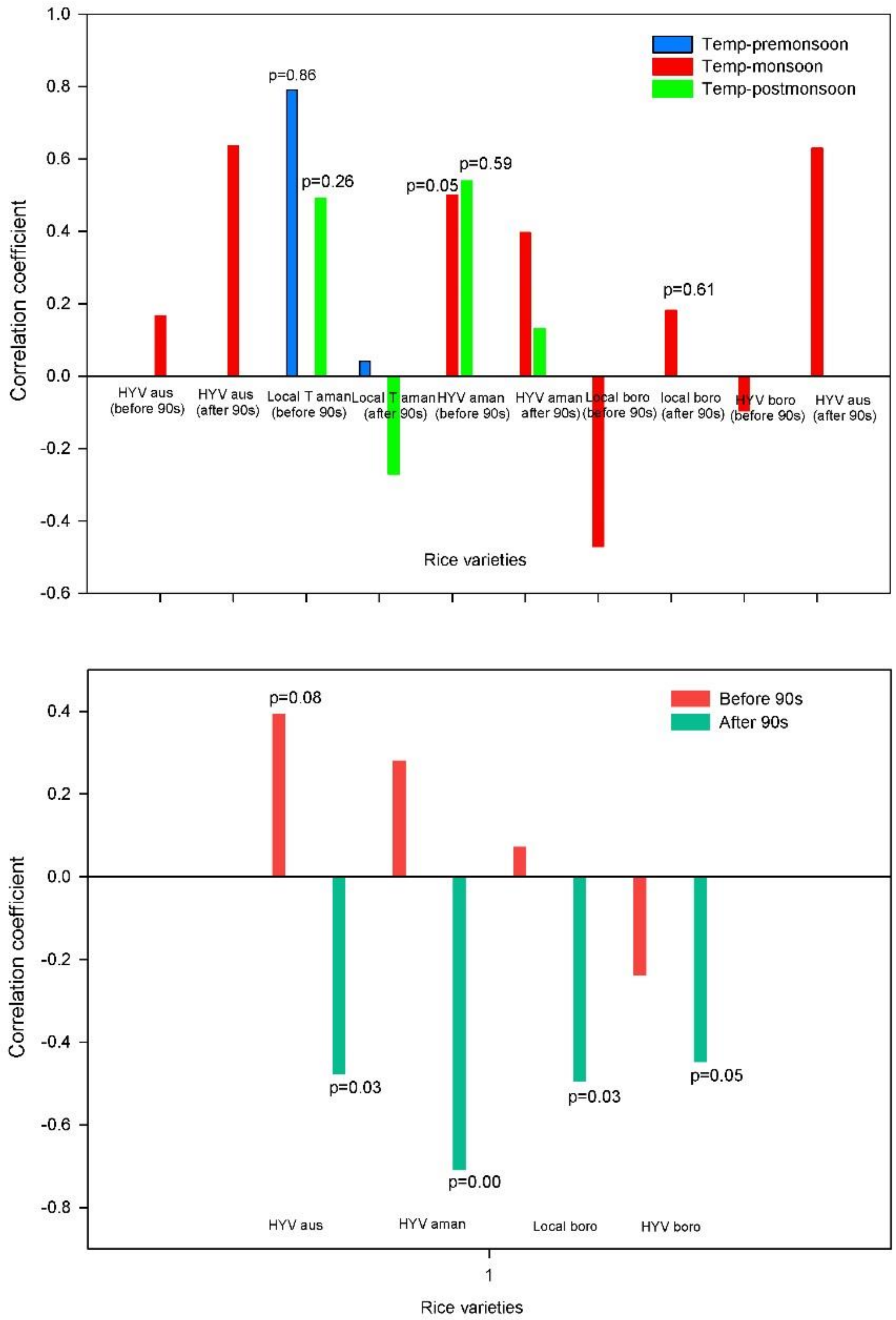


Figure A.30: Correlation analysis between crop varieties and climate (temperature and rainfall) in BCZ from 1969-2010. This figure shows the changes in correlation in two time segments: 1969-1990 (before 90s)and 1991-2010 (After 90s). Though we have considered those results only which are significant (more than 95% confidence interval), some of the significant level (p value) shown in the figure to show the changes in correlation in two time segments of BCZ.

Table A.1: Temporal and spiral scale of ES indicators in BCZ

ES	**Indicators**	**Data Sources**	**Types of Data**	**Temporal scale**	**Spatial scale**
Provisioning services					
Food production	Rice (Aus-local and HYV, Aman- local and HYV, Boro- local and HYV), Vegetables Potato Sugarcane, Jute, Onion, Spices (Garlic, Ginger, Turmeric and Coriander) Fish Shrimp Honey	BBS	Official statistics	Total rice 1948-2010, Rice varieties : 1969-2010	1948-2010 before 1985 date from greater Khulna district which comprise Shatkhira, Khulna and Bagerhat districts after 1985.
Forest products	Timber types (Glopata, Goran, Gewa) BeesWax	DoF, Zmarlicki, 1994; Chaffey et al., 1985	Official statistics	1974-2010	Mangrove data
Regulating services					
Water Quality	Surface water salinity Soil salinity	Islam (2008)	Station measurement	1964-2006	Three major rivers data
Local climate	Temperature Precipitation	BMD	Station measurement	1949-2007	3 regions data
Water availability	River discharge	BWDB	Station measurement	1934-2010	One point
	Groundwater level		Borehole measurement	1970-2010	3 regions: 4 points data
Natural hazard protection	Crop damage (due to cyclones, flooding, water logging and excessive rainfall)	BBS	Official statistics	1963-2009	3 regions
Erosion protection	Fluvial erosion and accretion	Rahman et al., 2011, BWDB	Image analysis, Station measurement	1973-2010	Delta region
Habitat services					
Maintenance of biodiversity	Mangrove density Mangrove volume Mangrove area Mangrove floristic composition Tiger Deer	DoF	Official Statistics	1960-1997	Mangrove data
Cultural services					
Recreational services	Number of tourist visitors	IUCN, 1997; DoF	Official Statistics	2000-2009	Mangrove data

Table A.2: Correlation coefficient (r) results (more than 90% confidence interval) for regulating and provisioning services in BCZ

Variables	**Spearman correlation coefficient**
Shrimp-Salinity	0.994
Pre monsoon water discharges-Pre monsoon temperature	-0.581
Salinity - Pre monsoon water discharges	-0.601
Salinity-Raw materials	-0.594
Ground water (Pre monsoon)-Water discharges (Pre monsoon)	0.486
Pre monsoon temperature-Others (Sugercane+Jute+Others)	-0.598
Monsoon temperature-Others (Sugercane+Jute+Others)	-0.449
Post monsoon temperature-Others (Sugercane+Jute+Others)	-0.559
Pre monsoon water discharges water discharges-Rice	-0.488
Pre monsoon water discharges-Local T Aman	-0.579

Table A.3: Trend statistics and change points analysis for rainfall on the BCZ for the period 1948-2012

Rainfall-BCZ	**Non miss**	**Test Stat**	**Std. Dev.**	**MK-Stat**	**p-value**	**Covari-ance**	**Correla tion**	**Rate of Changes mm/day/ yr**	**r**	**Change point**
Monsoon										
1948-2012	65	120	176	0.67	0.49	31200	1	0.00	0.00	1993
1948-1970	23	-45	37	-1.18	0.23	1433	1	-0.14	0..02	
1971-1990	20	72	30	2.33	0.01	950	1	0.39	0.21	
1991-2012	22	-63	35	-1.77	0.07	1257	1	-0.54	0.29	
Post-monsoon										
1948-2012	65	447	176	2.53	0.01	31199	1	0.05	0.07	1973, 2010
1948-1970	23	45	37	1.18	0.23	1433	1	0.05	0.01	
1971-1990	20	20	30	0.64	0.51	950	1	0.11	0.04	
1991-2012	22	-25	35	-0.70	0.48	589	1	-0.13	0.04	
Pre-monsoon										
1948-2012	65	-96	176	-0.54	0.58	31200	1	0.02	0.01	1976,2007
1948-1970	23	-17	37	-0.44	0.65	1433	1	-0.02	0.00	
1971-1990	20	14	30	0.45	0.64	950	1	0.02	0.00	
1991-2012	22	-119	35	-3.35	0.00	1257	1	-0.38	0.57	
Winter										
1948-2012	65	382	176	2.16	0.03	31200	1	0.01	0.07	1979, 2007
1948-1970	23	85	37	2.24	0.02	1433	1	0.03	0.17	
1971-1990	20	98	30	3.17	0.00	950	1	0.07	0.22	
1991-2012	22	-87	35	-2.45	0.01	1257	1	-0.08	0.18	

Table A.4: Trend statistics and change points analysis for rainfall on the Barisal region for the period 1948-2012

Barisal-Rainfall	Non miss	Test Stat	Std. Dev.	MK-Stat	p-value	Covaria-nce	Correlation	Rate of Changes mm/day/yr	r	Change point
Monsoon										
1948-2012	65	-328	176	-1.85	0.06	31200	1	-0.12	0.08	2007
1948-1970	23	-25	37	-0.66	0.50	1433	1	-0.25	0.03	
1971-1990	20	32	30	1.03	0.29	950	1	0.20	0.07	
1991-2012	22	-57	35	-1.60	0.10	1257	1	-0.36	0.09	
Post-monsoon										
1948-2012	65	-148	176	-0.83	0.40	31200	1	-0.02	0.01	1952
1948-1970	23	-45	37	-1.18	0.23	1433	1	-0.13	0.07	
1971-1990	20	40	30	1.29	0.19	950	1	0.07	0.01	
1991-2012	22	11	35	0.31	0.75	1257	1	0.00	0.00	
Pre-monsoon										
1948-2012	65	-2	176	-0.01	0.99	24583	1	-0.02	0.00	2007
1948-1970	23	27	37	0.71	0.47	1433	1	0.09	0.00	
1971-1990	20	-18	30	-0.58	0.55	950	1	0.087	0.00	
1991-2012	22	-95	35	-2.67	0.00	1257	1	-0.67	0.46	
Winter										
1948-2012	65	125	176	0.70	0.47	31199	1	0.01	0.01	No
1948-1970	23	89	37	2.35	0.01	1433	1	0.72	0.15	
1971-1990	20	16	30	0.51	0.60	950	1	0.05	0.04	
1991-2012	22	-99	35	-2.79	0.00	1257	1	-0.16	0.21	

Table A.5: Trend statistics and change points analysis for rainfall on the Patuakhali region for the period 1948-2012

Patuakhali-Rainfall	Non miss	Test Stat	Std. Dev.	MK-Stat	p-value	Covari-ance	Correlation	Rate of Changes mm/day/yr	r	Change point
Monsoon										
1973-2007	40	-38	85	-0.44	0.65	4956	1	-0.11	0.01	1978, 2007
1971-1990	18	19	26	0.72	0.47	695	1	0.10	0.00	
1991-2007	22	-107	35	-3.01	0.00	589	1	-1.02	0.50	
Post-monsoon										
1973-2007	40	-32	85	-0.37	0.70	7363	1	-0.03	0.00	2009
1971-1990	18	-7	26	-0.26	0.79	695	1	-0.07	0.00	
1991-2007	22	-27	35	-0.76	0.44	589	1	-0.12	0.01	
Pre-monsoon										
1973-2007	39	-13	82	-0.15	0.87	6825	1	-0.17	0.14	1975, 2007
1971-1990	18	33	26	1.24	0.21	697	1	0.13	0.01	
1991-2007	22	-123	35	-3.46	0.00	1257	1	-0.35	0.46	
Winter										
1973-2007	40	-44	85	-0.51	0.60	7358	1	0.00	0.00	1983
1971-1990	18	70	26	2.65	0.00	696	1	0.15	0.16	
1991-2007	22	-62	35	-1.74	0.08	1256	1	-0.06	0.10	

Table A.6: Trend statistics and change points analysis for rainfall on the Khulna region for the period 1948-2012

Khulna-Rainfall	Non miss	Test Stat	Std. Dev.	MK-Stat	p-value	Covaria-nce	Correlation	Rate of Changes mm/day/ yr	r	Change point
Monsoon										
1948-2007	65	-150	176	-0.84	0.39	31200	1	-0.02	0.00	1968,1974, 2007
1948-1970	23	-25	37	-0.66	0.50	1431	1	-0.03	0.00	
1971-1990	20	70	30	2.27	0.02	950	1	0.58	0.24	
1991-2007	22	-45	35	-1.26	0.20	1257	1	-0.23	0.07	
Post-monsoon										
1948-2007	65	496	176	2.80	0.00	31198	1	0.07	0.06	1974, 2007
1948-1970	23	119	37	3.14	0.00	1431	1	0.23	0.11	
1971-1990	20	4	30	0.12	0.89	950	1	0.15	0.02	
1991-2007	22	-37	35.	-1.04	0.29	1257	1	-0.28	0.09	
Pre-monsoon										
1948-2007	65	-171	176	-0.96	0.33	31198	1	-0.01	0.01	No
1948-1970	23	-66	37.	-1.74	0.08	1432	1	-0.14	0.14	
1971-1990	20	38	30.	1.23	0.21	950	1	0.12	0.06	
1991-2007	22	-73	35	-2.05	0.03	1257	1	-0.11	0.15	
Winter										
1948-2007	65	428	176	2.42	0.01	31106	1	0.01	0.07	1981
1948-1970	23	34	37	0.91	0.36	1389	1	0.00	0.00	
1971-1990	20	88	30	2.85	0.00	1095	1	0.09	0.32	
1991-2007	22	-39	35	-1.09	0.27	1257	1	-0.04	0.03	

Table A.7: Trend statistics and change points analysis for temperature on the BCZ for the period 1948-2012

Temp-Delta	Non miss	Test Stat	Std. Dev.	MK-Stat	p-value	Covariance	Correlation	Rate of Changes o C/yr	r	Change point
Pre-monsoon										
1948-2012	62	-265	164	-1.60	0.10	27104	1	-0.008	0.04	1975
1948-1970	21	62	33	1.87	0.06	1069	1	0.02	0.04	
1971-1990	19	-57	28	-1.99	0.04	817	1	-0.05	0.26	
1991-2012	22	57	35	1.60	0.10	1257	1	0.03	0.13	
Monsoon										
1948-2012	62	707	164	4.29	0.00	27104	1	0.00	0.28	1992
1948-1970	21	-10	33	-0.30	0.76	1255	1	-0.00	0.00	
1971-1990	19	31	28	1.08	0.27	949	1	0.00	0.07	
1991-2012	22	79	35	2.22	0.02	1257	1	0.02	0.36	
Post-monsoon										
1948-2012	61	304	160	1.89	0.05	25823	1	0.00	0.05	1983
1948-1970	20	2	30	0.06	0.94	950	1	0.00	0.00	
1971-1990	19	-57	28	-1.99	0.046	817	1	-0.04	0.19	
1991-2012	22	39	35	1.09	0.27	1257	1	0.01	0.03	
Winter										
1948-2012	61	-356	160	-2.21	0.02	25823	1	-0.01	0.06	No
1948-1970	20	40	30	1.29	0.19	950	1	0.04	0.05	
1971-1990	19	-65	28	-2.27	0.02	817	1	-0.04	0.22	
1991-2012	22	-3	35	-0.08	0.93	1257	1	0.007	0.01	

Table A.8: Trend statistics and change points analysis for temperature on the Khulna region for the period 1948-2012

Temp-Khulna	**Non miss**	**Test Stat**	**Std. Dev.**	**MK-Stat**	**p-value**	**Covari -ance**	**Correlation**	**Rate of Changes o C/yr**	**r**	**Change point**
Monsoon										
1948-2012	62	311	164	1.88	0.05	27104	1	0.01	0.39	1971
1948-1970	21	-20	33	-0.60	0.54	1096	1	0.00	0.02	
1971-1990	19	59	28	2.06	0.03	817	1	0.00	0.00	
1991-2012	22	63	35	1.77	0.07	1257	1	0.03	0.38	
Post-monsoon										
1948-2012	59	495	152	3.23	0.00	23383	1	0.01	0.11	1964,1975, 1982
1948-1970	19	21	28	0.73	0.46	817	1	0.01	0.02	
1971-1990	19	-71	28	-2.48	0.01	817	1	-0.09	0.46	
1991-2012	22	37	35	1.04	0.29	1257	1	0.03	0.01	
Pre-monsoon										
1948-2012	61	-24	160	-0.14	0.88	25823	1	-0.00	0.03	1965, 1976
1948-1970	20	92	30	2.98	0.00	950	1	0.09	0.46	
1971-1990	19	-77	28	-2.69	0.00	817	1	-0.13	0.42	
1991-2012	22	73	35	2.05	0.03	1257	1	0.04	0.23	
Winter										
1948-2012	61	-118	160	-0.73	0.46	25823	1	-0.00	0.01	1965
1948-1970	20	54	30	1.75	0.07	950	1	0.04	0.14	
1971-1990	19	-77	28	-2.69	0.00	817	1	-0.12	0.43	
1991-2012	22	41	35	1.15	0.24	1257	1	0.02	0.11	

Table A.9: Trend statistics and change points analysis for temperature on the Barisal region for the period 1948-2012

Temp-Barisal	Non-miss	Test Stat	Std. Dev.	MK - Stat	p-value	Covari -ance	Correlation	Rate of Changes o C/yr	r	Change point
Monsoon										
1948-2012	62	311	164	1.88	0.05	27104	1	0.00	0.05	No
1948-1970	21	-20	33	-0.6	0.54	1069	1	-0.01	0.05	
1971-1990	19	59	28	2.06	0.03	817	1	0.02	0.23	
1991-2012	22	63	35	1.77	0.07	1257	1	0.01	0.18	
Post-monsoon										
1948-2012	58	-5	149	-0.03	0.97	22223	1	-0.00	0.00	No
1948-1970	18	7	26	0.26	0.79	697	1	0.00	0.00	
1971-1990	19	-31	28	-1.08	0.27	817	1	-0.00	0.00	
1991-2012	21	30	33	0.9	0.36	1069	1	0.00	0.17	
Pre-monsoon										
1948-2012	59	-241	152	-1.57	0.11	23383	1	-01	0.08	1966
1948-1970	18	-1	26	-0.03	0.96	697	1	-0.00	0.00	
1971-1990	19	25	28	0.87	0.38	817	1	0.01	0.01	
1991-2012	22	33	35	0.93	0.35	1257	1	0.01	0.04	
Winter										
1948-2012	59	-525	152	-3.43	0.00	23383	1	-0.02	0.10	1965
1948-1970	18	-17	26	-0.64	0.51	697	1	0.03	0.05	
1971-1990	19	-3	28	-0.1	0.91	817	1	0.00	0.05	
1991-2012	22	-15	35	-0.42	0.67	1257	1	0.00	0.23	

Table A.10: Trend statistics and change points analysis for temperature on the Patuakhali region for the period 1948-2012

Temp-Potuakhali	Non miss	Test Stat	Std. Dev.	MK-Stat	p-value	Covari-ance	Correlation	Rate of Changes o C/yr	r	Change point
Monsoon										
1973-2012	36	148	73	2.01	0.04	5390	1	-0.11	0.01	No
1971-1990	15	-11	20	-0.54	0.58	408	1	0.59	0.06	
1991-2012	21	84	33	2.53	0.01	1096	1	-0.92	0.43	
Post-monsoon										
1973-2012	37	-158	76	-2.06	0.03	5846	1	-0.03	0.00	1983
1971-1990	15	-49	20	-2.42	0.01	408	1	-0.07	0.00	
1991-2012	22	-3	35	-0.08	0.93	1257	1	-0.12	0.01	
Pre-monsoon										
1973-2012	37	-22	76	-0.28	0.77	5846	1	-0.17	0.14	No
1971-1990	13	-24	16	-1.46	0.14	268	1	0.13	0.01	
1991-2012	22	51	3	1.43	0.15	1257	1	-0.35	0.46	
Winter										
1973-2012	38	-401	79	-5.04	4.62E-07	6327	1	-0.05	0.56	1988
1971-1990	16	-56	22	-2.52	0.011	493	1	-0.07	0.35	
1991-2012	22	-23	35	-0.64	0.51	1257	1	-0.00	0.00	

Table A.11: Trend statistics and change points analysis for water availability in BCZ for the period 1934-2010

Water Discharges	Non -miss	Test Stat	Std. Dev.	MK-Stat	p-value	Covar -iance	Correlation	Rate of Change sm³/s	r	Change point
Pre-monsoon										
1934-1960	27	109	47.96	2.27	0.02	2301	1	24.09	0.22	
1961-1975 (Barrage Construction period)	13	-10	16.39	-0.61	0.54	268	1	-17.59	0.01	
1976-2010 (Post Barrage)	35	-85	70.41	(-1.67) -1.20	(0.09) 0.22	4958	1	-10.30 (10.45)	0.11 (0.01)	
1934-2010	75	-1215	218.61	-5.55	0.00	47791	1	-17.21	0.17	1955, 1975
Monsoon										
1934-1960	27	77	47.96	1.60	0.10	2301	1	204	0.14	
1961-1975 (Barrage Construction period)	13	6	16.39	0.36	0.71	268	1	116	0.01	
1976-2010 (Post Barrage regime)	35	-23	70.41	-0.32	0.74	4958	1	-28.92	0.00	
1934-2010	75	-19	218.61	-0.08	0.93	47791	1	-3.50	0.00	1990
Post-monsoon										
1934-1960	27	101	47.96	2.10	0.03	2301	1	205	0.07	
1961-1975 (Barrage Construction period)	13	-18	16.39	-1.09	0.27	268	1	-630	0.14	
1976-2010 (Post Barrage regime)	35	-51	70.41	-0.72	0.46	4958	1	-47.20	0.00	
1934-2010	75	-167	218.61	-0.76	0.44	47791	1	-43.41	0.02	no
Winter										
1934-1960	27	113	47.96	2.35	0.01	2301	1	33.58	0.08	
1961-1975 (Barrage Construction period)	13	-18	16.39	-1.09	0.27	268	1	-47.81	0.15	
1976-2010 (Post Barrage regime)	35	115	70.41	1.63	0.10	4958	1	27.93	0.08	
1934-2010	75	-803	218.61	-3.67	0.00	47751	1	-17.74	0.13	1975, 1987, 1993

Table A.12: Trend statistics and change points analysis for ground water level in BCZ for the period 1970-2010

Ground water	Non miss	Test Stat	Std. Dev.	MK-Stat	p-value	Cova-riance	Correlation	Rate of Changes m/yr	r	Change point
Rupsha-Khulna										
Pre-monsoon	31	-67	58.83	-1.13	0.25	3461	1	-0.01	0.05	1986
Monsoon	28	26	50.61	0.51	0.60	2562	1	0.00	0.00	1986
Post-monsoon	29	-28	53.31	-0.52	0.59	2842	1	0.00	0.00	1984, 2000
Winter	34	-25	67.45	-0.37	0.71	4550	1	0.00	0.00	1986,1996
Dacope-Khulna										
Pre-monsoon	41	-430	89.03	-4.82	0.00	7926	1	-0.04	0.58	No
Monsoon	41	-328	89.03	-3.68	0.00	7926	1	-0.04	0.47	
Post-monsoon	38	-433	79.54	-5.44	0.00	6327	1	-0.05	0.68	
Winter	42	-522	92.26	-5.65	0.00	8513	1	-0.05	0.78	
Gouronodi-Barisal										
Pre-monsoon	36	-214	73.41	-2.91	0.00	5390	1	-0.02	0.28	1987
Monsoon	36	66	73.41	0.89	0.36	5390	1	0.00	0.00	No
Post-monsoon	34	-37	67.45	-0.54	0.58	4550	1	0.00	0.00	No
Winter	35	-349	70.41	-4.95	0.00	4958	1	-0.02	0.48	1987
Bakergonj-Barisal										
Pre-monsoon	26	-38	45.35	-0.83	0.40	2056	1	0.00	0.01	No
Monsoon	28	151	50.60	2.98	0.00	2561	1	0.01	0.38	
Post-monsoon	28	150	50.61	2.96	0.00	2562	1	0.01	0.33	1997
Winter	28	60	50.61	1.18	0.23	2562	1	0.00	0.07	No

Appendix B

Supplementary material: Chapter 4

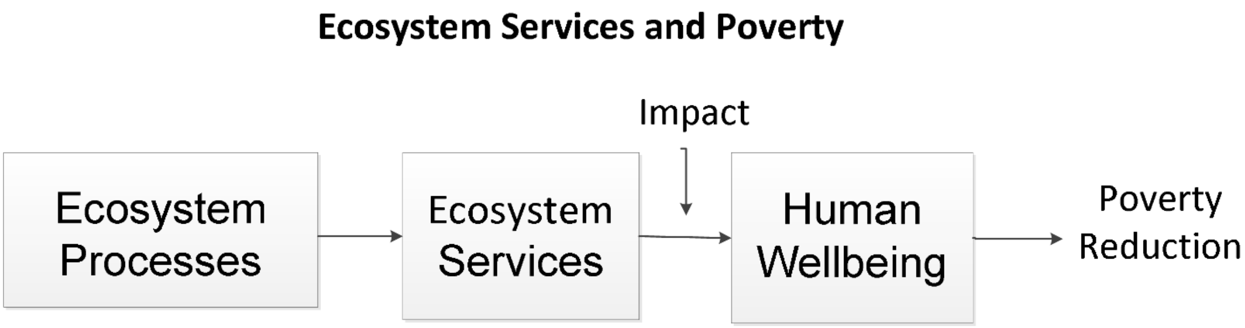


Figure B.1: linkage between ES and HWB (adapted from Fisher et al. 2008 and MA 2005)

Table B.1: ES indicators

ES	Indicators	Data Sources	Types of Data	Temporal scale
Provisioning services				
Food production	Rice Fish Shrimp	BBS	Official statistics	Total rice 1948-2010
Forest products	Timber types (Glopata, Goran, Gewa)	DoF, Zmarlicki, 1994; Chaffey et al., 1985	Official statistics	1974-2010
Regulating services				
Water Quality	Surface water salinity Soil salinity	Islam (2008)	Station measurement	1964-2006
Local climate	Temperature Precipitation	BMD	Station measurement	1949-2007
Water availability	River discharge	BWDB	Station measurement	1934-2010
	Groundwater level		Borehole measurement	1970-2010
Natural hazard protection	Crop damage (due to cyclones, flooding, water logging and excessive rainfall)	BBS	Official statistics	1963-2009
Habitat services				
Maintenance of biodiversity	Mangrove density	DoF	Official Statistics	1960-1997
Cultural services				
Recreational services	Number of tourist visitors	IUCN, 1997; DoF	Official Statistics	2000-2009

Table B.2 Human welling indicators based on MA (2005) and OECD (2013) classification

Dimension		Indicators	Data source
MA	OECD		
Health	Quality of life	Proportion of births attended by skilled health personnel (%)	HIES
Material	Material condition	Sector wise Household income Production cost	HIES
		Sector wise GDP	BBS
Security	Quality of life	Access to electricity, sanitation, drinking water source	HIES
Freedom of choice and action	Quality of life	Education (% of people completed primary education)- Man and women	HIES

Table B.3: Descriptive statistics for material condition at household level

Indicator	**Sample size**	**Mean**	**Median**	**Standard deviation**
Cultivated area (ha)	437	321	160	238
Production (kg)		3871	2700	3783
Income from total produce (BDT)		34,178	23,208	37,582
Yield (kg/ha)		10,648	3,867	54,548
Production cost (BDT)		30,504	16,652	47,812
Fish catch (Kg)	347	467	160	1,252
Income from fish catch		60,212	11,386	15,8541

Table B.4: Generalized additive models results for analysing the relationships between regulating and provisioning services and also among the indicators of regulating services. The significant coefficients are marked ***, ** and * respectively for the 1%, 5%, and 10% level of significance.

Dependent variables	Independent variables	Coefficients	P value	Confidence interval (CI)	Standardized coefficients	P value	Confidence interval (CI)
Rice	Water discharges	-0.06***	0.00	-0.11 -0.02	-0.21	0.04	-0.42 -0.00
	Temperature	134.82**	0.05	-3.21 272	0.22	0.03	0.01 0.44
	Rainfall	12.80	0.62	-38.01 63.62	0.19	0.12	-0.05 0.44
	Soil salinity	298***	0.00	163 432	0.71	0.00	0.39 1.04
	Natural hazards	-0.35	0.59	-1.67 0.31	0.07	0.55	-0.16 0.31
Fish	Water discharges	-8.66	0.29	-0.00 7.38	-0.13	0.23	-0.36 0.09
	Salinity	0.00***	0.00	0.00 0.00	0.84	0.00	0.55 1.13
Fish (natural habitat)	Water discharges	-0.02	0.90	-0.48 0.43	-0.13	0.90	-2.51 2.24
	Salinity	-0.98***	0.00	-1.41 -0.55	-2.32	0.00	-3.33 -1.30
Fish (Ponds)	Water discharges	0.03	0.91	-0.49 0.55	0.08	0.911	-1.38 1.55
	Salinity	1.16***	0.00	0.67 1.66	1.47	0.00	0.84 2.09
Forest product	Water discharges	-0.00	0.67	-0.01 0.01	-0.08	0.66	-0.45 0.28
	Salinity	-0.00***	0.00	-0.00 -0.00	-0.63	0.00	-0.94 -0.26
Water discharges	Temperature	-337	0.48	-1284 610	-0.08	0.48	-0.33 0.15
	Rainfall	238	0.13	-73 550	0.20	0.13	-0.06 0.46
Ground water	Water discharges	-0.00	0.86	-0.02 0.02	-0.02	0.86	-0.34 0.28
	Sea level	-1.67***	0.00	-2.4 -0.85	-0.63	0.00	-0.95 -0.32
Water salinity	Water discharges	-0.92	0.18	-2.29 0.43	-0.15	0.18	-0.38 0.07
	Ground water	-43.28***	0.00	-57.38 -29.18	-0.70	0.00	-0.94 -0.47
Soil salinity	Water salinity	0.09***	0.00	0.04 0.13	0.73	0.00	0.39 1.07
	Ground water	-0.71	0.55	3.06 1.63	-0.26	0.27	-0.74 0.21
	Rainfall	0.06	0.40	-0.20 0.08	0.23	0.33	-0.24 0.71
	Temperature	-1.13	0.22	-1.99 0.47	-0.28	0.22	-0.75 0.18

Table B.5: Regression (linear) results (N=20) for analysing the relationship between provisioning services (e.g. crops, shrimp, fish production) and GDP shared by crops, shrimp, fish and forestry sectors. The significant coefficients are marked ***, ** and * respectively for the 1%, 5%, and 10% level of significance

Dependent variable	Independent variable	Coef.	Std. Err.	P>|t|	Standardized Coef
GDP-agriculture	Production-agriculture	0.13***	0.03	0.00	0.70
GDP-shrimp	Production-shrimp	2.8**	1.06	0.07	0.83
GDP-fishery	Production-fishery	9.7***	1.92	0.01	0.94
GDP-forestry	Production-forestry	0.84***	0.10	0.00	0.90

Appendix C

Supplementary material: Chapter 5

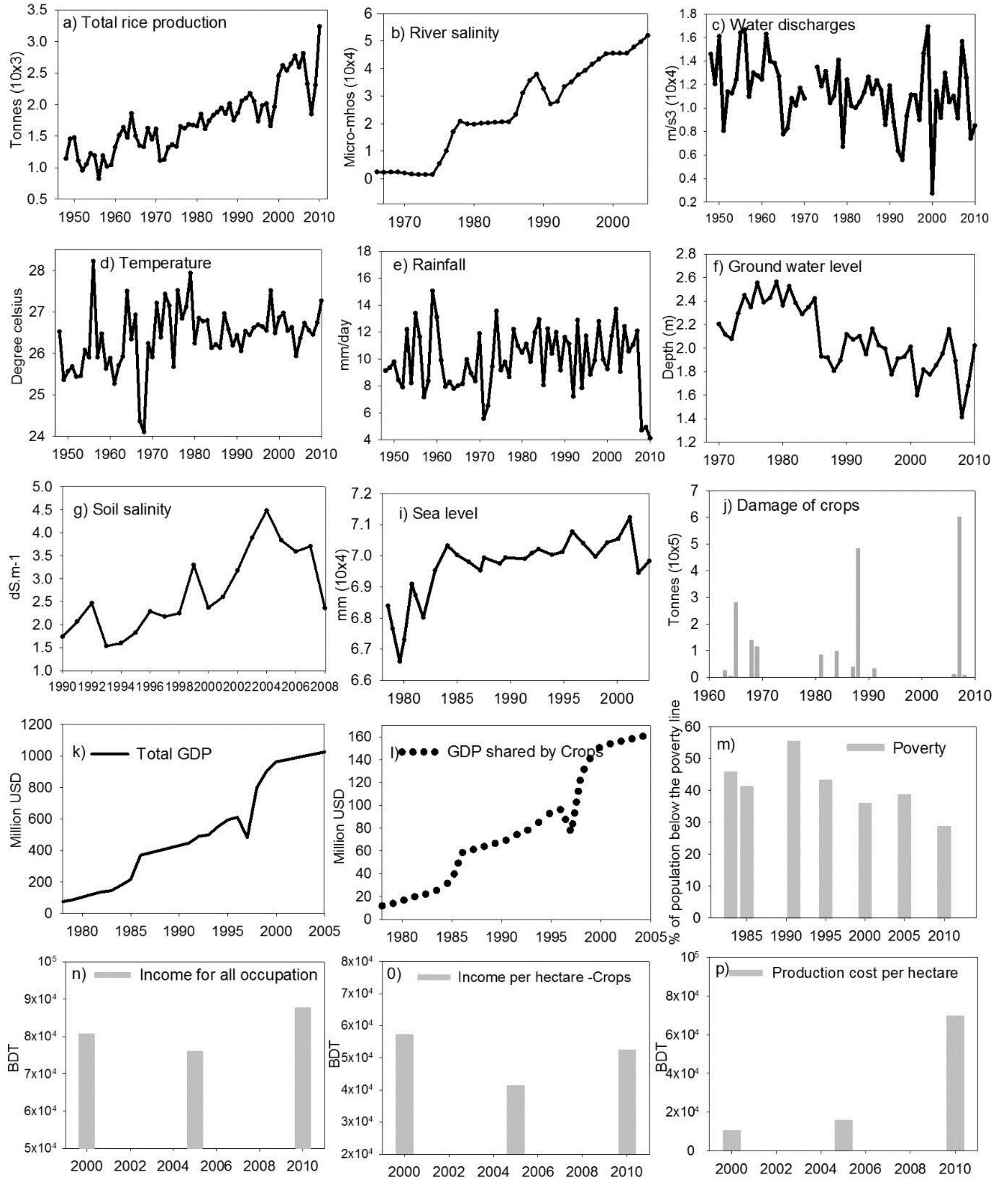


Figure C. 1 Trends of social-ecological indicators in Bangladesh delta

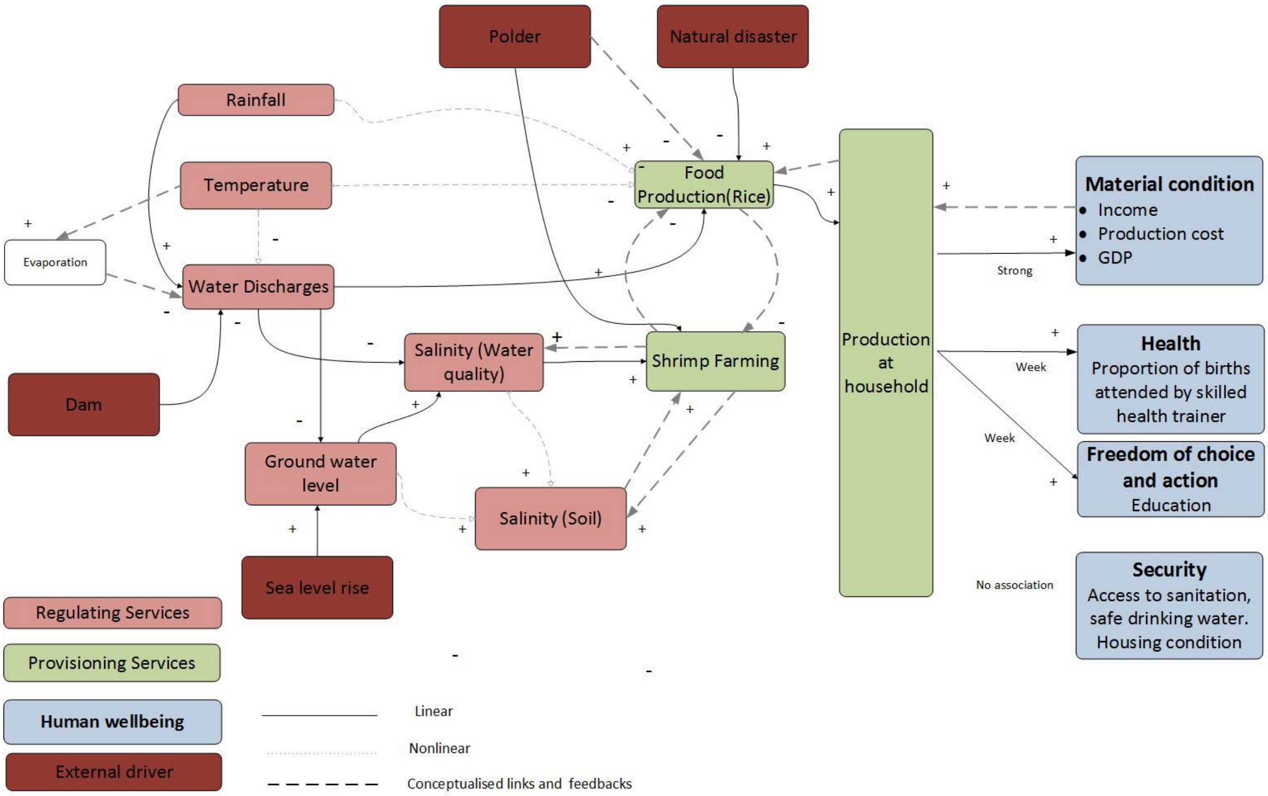


Figure C.2: Conceptual SD model developed using the regression analysis and literature review for the SES in south west coastal Bangladesh.

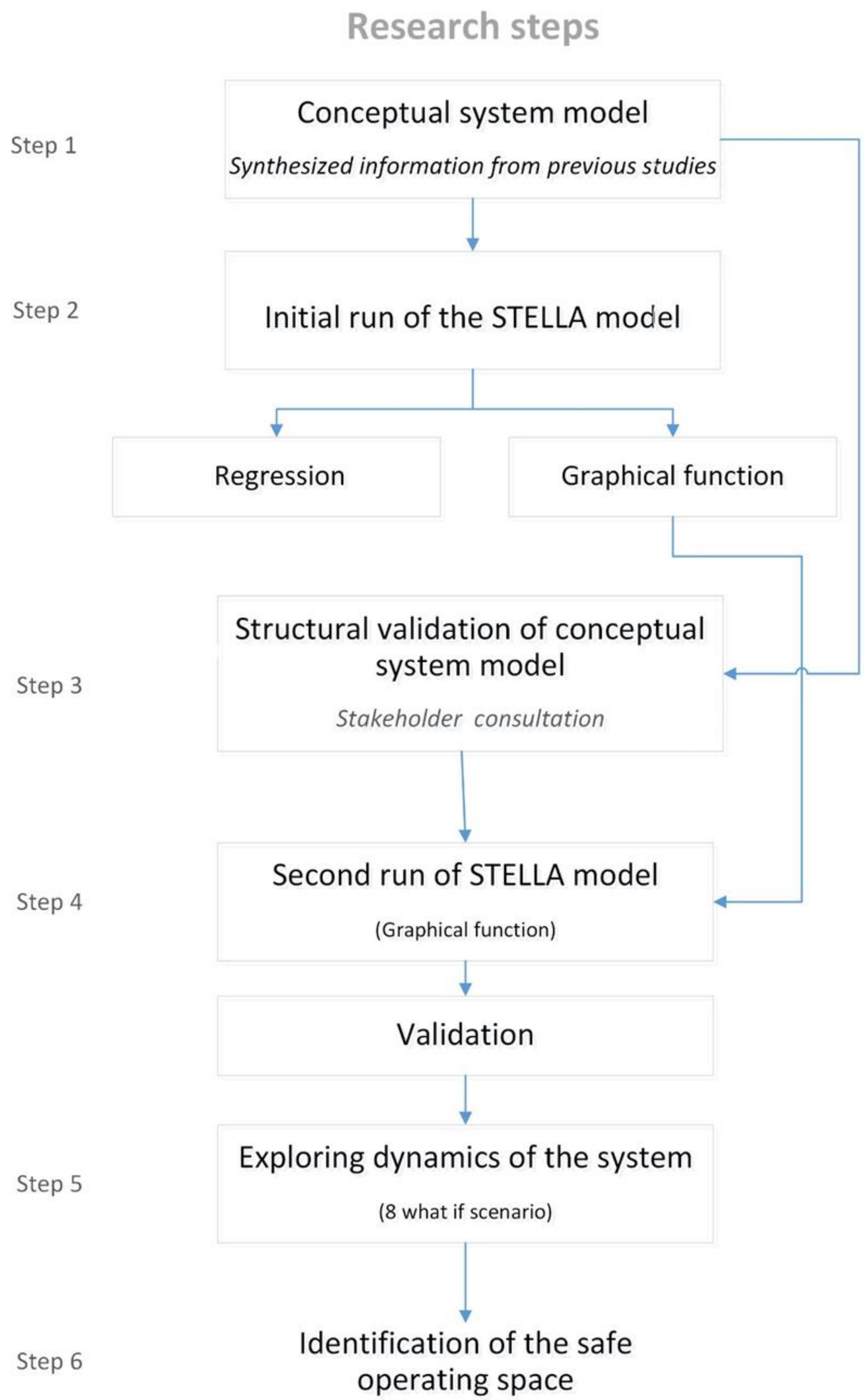


Figure C.3 Conceptual flow diagram of overall methodology of this study

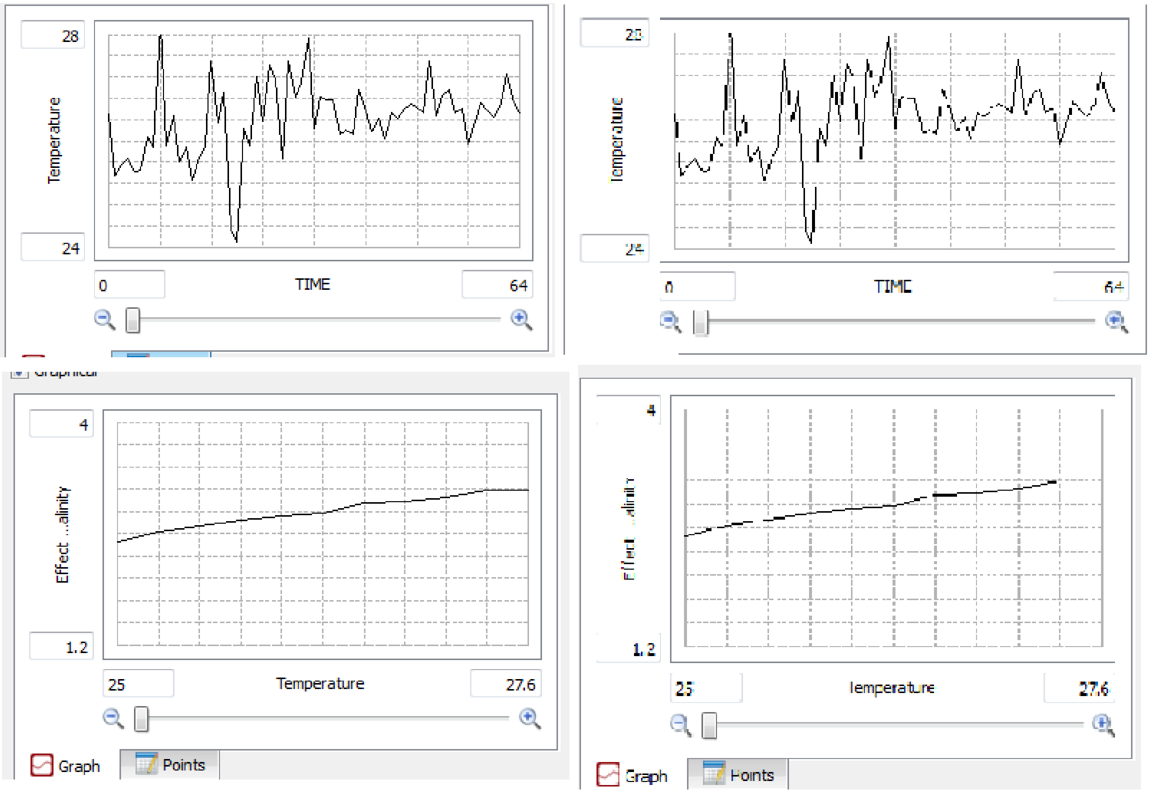


Figure C.4: Examples of graphical function to define the relationship between variables in STELLA. These functions are defined by input values (e.g. temperature) representing the x-axis and output values (e.g. crop production) representing the y-axis. All equations and graphical functions for defining the relationships are given SI equation 1.

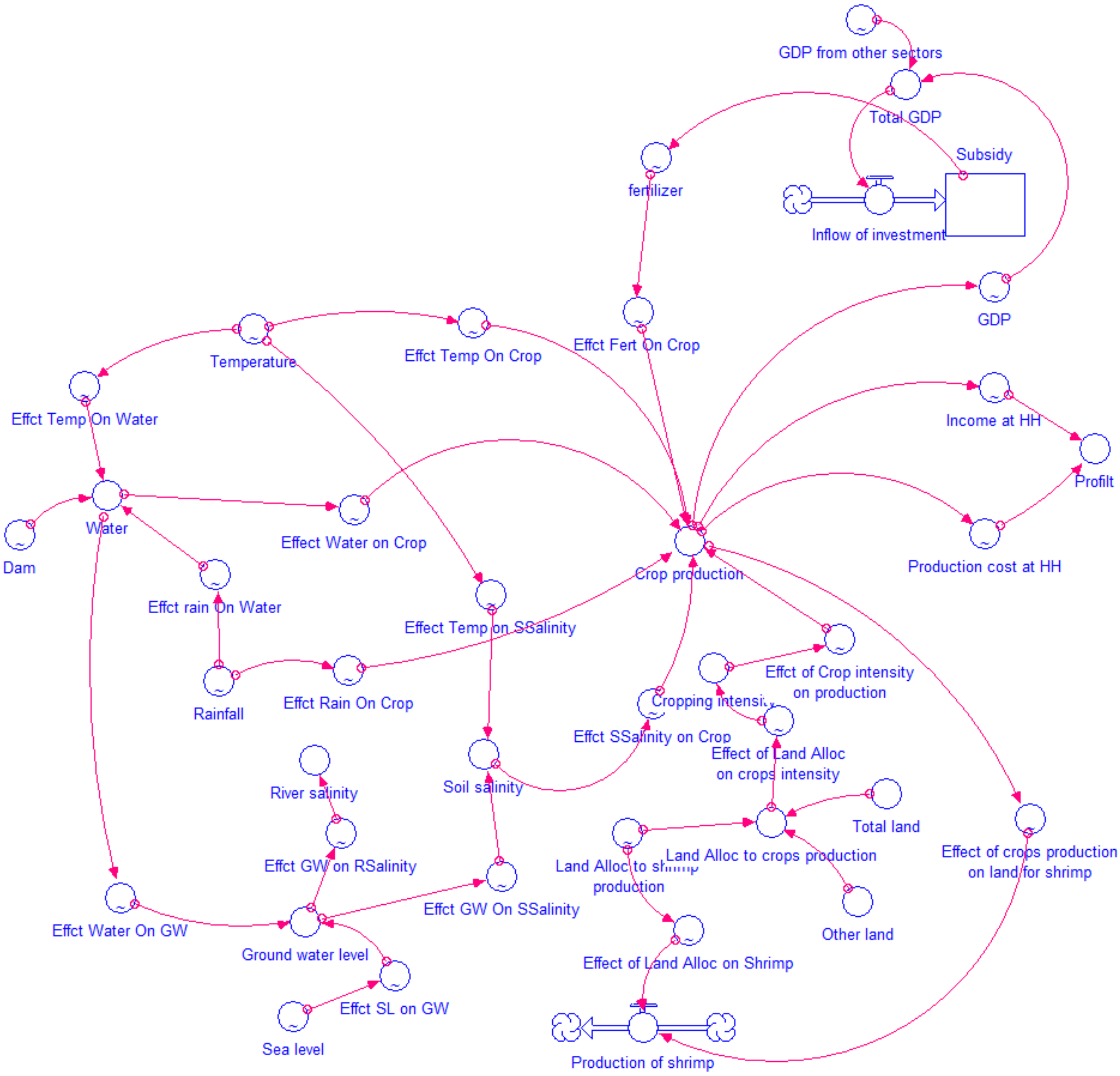


Figure C.5: Full SD model in STELLA depicting the converters, stock, flow and connections detailed in equation C.1

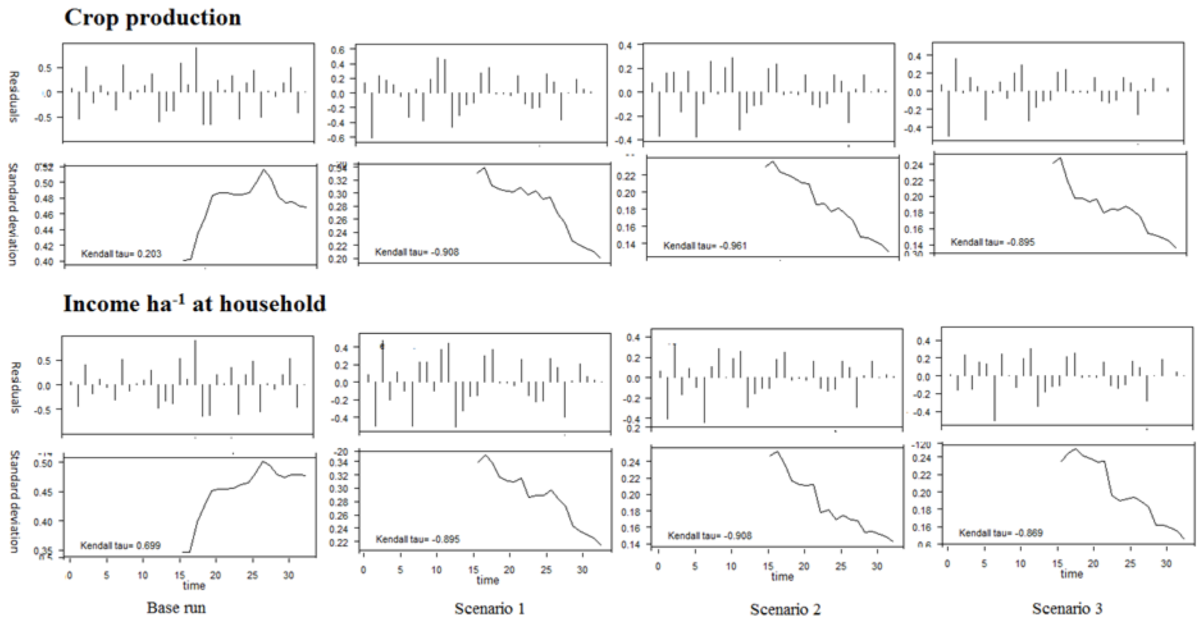


Figure C.6 Variance (residuals and standard deviation) of modelled time series of crop production and income ha-1 at household level. Standard deviation is calculated for a moving window (half time series) after detrending standardized data prior to moving beyond safe operating space

Table C.1 Regression analysis results for analysing the relationships between environmental and social variables (Hossain et al. 2016b)

Dependent variables	Independent variables	Standardized coefficients	P value (level of significance)	Confidence interval (CI)		Types of regression
Rice	Water discharges	-0.21	0.04	-0.42	-0.00	Generalized additive regression
	Temperature	0.22	0.03	0.01	0.44	
	Rainfall	0.19	0.12	-0.05	0.44	
	Soil salinity	0.71	0.00	0.39	1.04	
	Natural hazards	0.07	0.55	-0.16	0.31	
Water discharges	Temperature	-0.08	0.48	-0.33	0.15	
	Rainfall	0.20	0.13	-0.06	0.46	
Ground water	Water discharges	-0.02	0.86	-0.34	0.28	
	Sea level	-0.63	0.00	-0.95	-0.32	
Water salinity	Water discharges	-0.15	0.18	-0.38	0.07	
	Ground water	-0.70	0.00	-0.94	-0.47	
Soil salinity	Water salinity	0.73	0.00	0.39	1.07	
	Ground water	-0.26	0.27	-0.74	0.21	
	Rainfall	0.23	0.33	-0.24	0.71	
	Temperature	-0.28	0.22	-0.75	0.18	
GDP	Rice	0.70	0.00			Linear regression

Table C.2 Two sample t-test to compare three time series (N = 50) of historical data, simulation results using graphical function and regression approaches. After normalizing the data, we run t-test for group 1 (simulation results using graphical function and historical time series data), group 2 (simulation results using graphical function and historical time series data) and group 3 (summation results and historical data). The significance level smaller than 0.05 (e.g. 0.00) indicates that the null hypothesis is rejected and the mean for the two variables is different from the hypothesized value.

Variable	F	Sig.	Mean	Std. Err	Std. Dev	95% conf. interval	
Group 1							
Simulation (graphical function)	0.83	0.40	0.47	0.02	0.20	0.41	0.52
Historical			0.43	0.02	0.19	0.41	0.49
Group 2							
Simulation (regression)	4.7	0.00	0.65	0.03	0.25	0.58	0.72
Historical			0.43	0.02	0.19	0.38	0.49
Group 3							
Simulation (graphical function)	0.83	0.40	0.47	0.02	0.20	0.41	0.52
Historical			0.43	0.02	0.19	0.41	0.49

Equation C.1: Equations for defining the relationships among the variables of SD model in STELLA.

Subsidy(t) = Subsidy(t - dt) + (Inflow_of_investment) * dt

INIT Subsidy = 0

INFLOWS:

Inflow_of_investment = (Total_GDP*16)/100

UNATTACHED:

Production_of_shrimp = Effect_of_Land_Alloc_on_Shrimp-Effect_of_crops_production_on_land_for_shrimp

Cropping_intensity = Effect_of_Land_Alloc_on_crops_intensity

Crop_production = Effct_Fert_On_Crop*0.166+Effect_Water_on_Crop*0.166+Effct_Temp_On_Crop*0.166+Effct_Rain_On_Crop*0.166+Effct_SSalinity_on_Crop*0.166+Effct_of_Crop_intensity_on_production*0.166

Dam = GRAPH(TIME)

(0.00, 14597), (1.02, 12049), (2.03, 16090), (3.05, 8077), (4.07, 11386), (5.08, 11258), (6.10, 12429), (7.12, 16408), (8.13, 16665), (9.15, 10983), (10.2, 13004), (11.2, 12757), (12.2, 12431), (13.2, 16293), (14.2, 13985), (15.3, 13820), (16.3, 12705), (17.3, 7779), (18.3, 8264), (19.3, 10836), (20.3, 10227), (21.3, 11712), (22.4, 10814), (23.4, 13481), (24.4, 11871), (25.4, 13118), (26.4, 10441), (27.4, 11048), (28.5, 14087), (29.5, 6718), (30.5, 12406), (31.5, 10190), (32.5, 10026), (33.5, 10528), (34.6, 11332), (35.6, 12650), (36.6, 11199), (37.6, 12336), (38.6, 11531), (39.6, 8580), (40.7, 11897), (41.7, 8814), (42.7, 6357), (43.7, 5601), (44.7, 9319), (45.8, 11118), (46.8, 11101), (47.8, 8990), (48.8, 14645), (49.8, 16923), (50.8, 2740), (51.8, 11440), (52.9, 9164), (53.9, 12977), (54.9, 10508), (55.9, 11024), (56.9, 9139), (57.9, 15666), (59.0, 12601), (60.0, 7417), (61.0, 8510)

Effct_Fert_On_Crop = GRAPH(Fertilizer)

(0.00, 1280), (3390, 1280), (6780, 1280), (10169, 1280), (13559, 1280), (16949, 1280), (20339, 1280), (23729, 1280), (27119, 1300), (30508, 1300), (33898, 1300), (37288, 1310), (40678, 1330), (44068, 1340), (47458, 1340), (50847, 1360), (54237, 1380), (57627, 1390), (61017, 1400), (64407, 1420), (67797, 1440), (71186, 1450), (74576, 1480), (77966, 1500), (81356, 1520), (84746, 1540), (88136, 1560), (91525, 1600), (94915, 1620), (98305, 1640), (101695, 1650), (105085, 1680), (108475, 1690), (111864, 1720), (115254, 1750), (118644, 1770), (122034, 1780), (125424, 1810), (128814, 1850), (132203, 1880), (135593, 1910), (138983, 1930), (142373, 1950), (145763, 1980), (149153, 2020), (152542, 2040), (155932, 2070), (159322, 2090), (162712, 2120), (166102, 2140), (169492, 2160), (172881, 2190), (176271, 2210), (179661, 2230), (183051, 2270), (186441, 2290), (189831, 2310), (193220, 2350), (196610, 2370), (200000, 2430)

Effct_GW_on_RSalinity = GRAPH(Ground_water_level)

(1.50, 5560), (1.60, 5150), (1.70, 4560), (1.80, 3970), (1.90, 3410), (2.00, 3000), (2.10, 2560), (2.20, 2130), (2.30, 1690), (2.40, 1030), (2.50, 590)

Effct_GW_On_SSalinity = GRAPH(Ground_water_level)

(1.50, 4.76), (1.54, 4.51), (1.58, 4.34), (1.62, 4.12), (1.66, 3.89), (1.69, 3.76), (1.73, 3.57), (1.77, 3.33), (1.81, 3.18), (1.85, 2.95), (1.89, 2.91), (1.93, 2.48), (1.97, 2.33), (2.01, 2.12), (2.04, 1.97), (2.08, 1.86), (2.12, 1.60), (2.16, 1.41), (2.20, 1.28)

Effct_of_Crop_intensity_on_production = GRAPH(Cropping_intensity)

(0.00, 830), (100, 960), (200, 1040), (300, 1130), (400, 1290), (500, 1450), (600, 1570), (700, 1670), (800, 1780), (900, 1910), (1000, 2020)

Effct_Rain_On_Crop = GRAPH(Rainfall)

(4.00, 1680), (5.20, 1770), (6.40, 1840), (7.60, 1870), (8.80, 1990), (10.0, 1990), (11.2, 2130), (12.4, 2220), (13.6, 2250), (14.8, 2530), (16.0, 2600)

Effct_rain_On_Water = GRAPH(Rainfall)

(4.00, 8700), (5.20, 8800), (6.40, 9200), (7.60, 9600), (8.80, 10000), (10.0, 10600), (11.2, 10800), (12.4, 11200), (13.6, 11700), (14.8, 12100), (16.0, 12300)

Effct_SL_on_GW = GRAPH(Sea_level)

(6600, 2.53), (6650, 2.43), (6700, 2.33), (6750, 2.19), (6800, 2.10), (6850, 2.02), (6900, 1.93), (6950, 1.83), (7000, 1.73), (7050, 1.63), (7100, 1.55)

Effct_SSalinity_on_Crop = GRAPH(Soil_salinity)

(1.50, 1720), (1.85, 1870), (2.20, 1950), (2.55, 2080), (2.90, 2210), (3.25, 2300), (3.60, 2380), (3.95, 2530), (4.30, 2660), (4.65, 2810), (5.00, 2880)

Effct_Temp_On_Crop = GRAPH(Temperature)

(24.0, 1080), (24.4, 1130), (24.8, 1260), (25.2, 1400), (25.6, 1510), (26.0, 1580), (26.4, 1690), (26.8, 1830), (27.2, 2010), (27.6, 2100), (28.0, 2150)

Effct_Temp_On_Water = GRAPH(Temperature)

(25.0, 12600), (25.4, 12200), (25.9, 12200), (26.3, 12000), (26.7, 12000), (27.1, 11700), (27.6, 11500), (28.0, 11000), (28.4, 10800), (28.9, 10400), (29.3, 10400)

Effct_Water_On_GW = GRAPH(Water)

(8000, 1.59), (8207, 1.62), (8414, 1.65), (8621, 1.67), (8828, 1.69), (9034, 1.71), (9241, 1.74), (9448, 1.77), (9655, 1.79), (9862, 1.82), (10069, 1.85), (10276, 1.88), (10483, 1.91), (10690, 1.94), (10897, 1.97), (11103, 1.99), (11310, 2.02), (11517, 2.04), (11724, 2.08), (11931, 2.11), (12138, 2.14), (12345, 2.17), (12552, 2.20), (12759, 2.24), (12966, 2.27), (13172, 2.32), (13379, 2.38), (13586, 2.44), (13793, 2.50), (14000, 2.51)

Effect_of_crops_production_on_land_for_shrimp = GRAPH(Crop_production)

(0.00, 51.5), (250, 51.5), (500, 51.5), (750, 51.5), (1000, 51.5), (1250, 51.7), (1500, 51.7), (1750, 51.7), (2000, 52.1), (2250, 38.5), (2500, 25.6)

Effect_of_Land_Alloc_on_crops_intensity = GRAPH(Land_Alloc_to_crops_production)

(0.00, 900), (10.0, 830), (20.0, 760), (30.0, 680), (40.0, 650), (50.0, 580), (60.0, 520), (70.0, 440), (80.0, 400), (90.0, 320), (100, 280)

Effect_of_Land_Alloc_on_Shrimp = GRAPH(Land_Alloc_to_shrimp__production)

(0.00, 500), (1.67, 700), (3.33, 800), (5.00, 1100), (6.67, 1300), (8.33, 1400), (10.0, 1900), (11.7, 2200), (13.3, 2600), (15.0, 2750), (16.7, 3100), (18.3, 3400), (20.0, 3600), (21.7, 4400), (23.3, 4800), (25.0, 5200), (26.7, 5600), (28.3, 6000), (30.0, 6500), (31.7, 6500), (33.3, 6900), (35.0, 7200), (36.7, 7500), (38.3, 8100), (40.0, 8500), (41.7, 8800), (43.3, 9400), (45.0, 9600), (46.7, 9800), (48.3, 10400), (50.0, 10700), (51.7, 11300), (53.3, 11500), (55.0, 11900), (56.7, 12800), (58.3, 13400), (60.0, 13900), (61.7, 14500), (63.3, 14900), (65.0, 15800), (66.7, 16500), (68.3, 17200), (70.0, 17900), (71.7, 18500), (73.3, 18900), (75.0, 19600), (76.7, 20600), (78.3, 21900), (80.0, 22000), (81.7, 22400), (83.3, 22900), (85.0, 23600), (86.7, 24200), (88.3, 24900), (90.0, 25300), (91.7, 26500), (93.3, 27100), (95.0, 27200), (96.7, 27800), (98.3, 28800), (100, 29100)

Effect_Temp_on_SSalinity = GRAPH(Temperature)

(25.0, 2.50), (25.3, 2.63), (25.5, 2.69), (25.8, 2.78), (26.0, 2.82), (26.3, 2.86), (26.6, 2.98), (26.8, 3.01), (27.1, 3.06), (27.3, 3.16), (27.6, 3.16)

Effect_Water_on_Crop = GRAPH(Water)

(7000, 2460), (7700, 2330), (8400, 2280), (9100, 2190), (9800, 2120), (10500, 1970), (11200, 1970), (11900, 1870), (12600, 1700), (13300, 1600), (14000, 1560)

fertilizer = GRAPH(Subsidy)

(0.00, 13000), (76.3, 14000), (153, 17000), (229, 17000), (305, 18000), (381, 21000), (458, 24000), (534, 26000), (610, 28000), (686, 29000), (763, 31000), (839, 32000), (915, 35000), (992, 36000), (1068, 39000), (1144, 40000), (1220, 43000), (1297, 46000), (1373, 50000), (1449, 51500), (1525, 55000), (1602, 59000), (1678, 61000), (1754, 63000), (1831, 66000), (1907, 68000), (1983, 72000), (2059, 75000), (2136, 76000), (2212, 77000), (2288, 83000), (2364, 84000), (2441, 87000), (2517, 90000), (2593, 93000), (2669, 95000), (2746, 97000), (2822, 100000), (2898, 103000), (2975, 106000), (3051, 109000), (3127, 112000), (3203, 114000), (3280, 117000), (3356, 119000), (3432, 121000), (3508, 124000), (3585, 130000), (3661, 134000), (3737, 136000), (3814, 140000), (3890, 144000), (3966, 146000), (4042, 149000), (4119, 150000), (4195, 155000), (4271, 157000), (4347, 161000), (4424, 165000), (4500, 167000)

GDP = GRAPH(Crop_production)

(800, 12.0), (829, 12.5), (858, 14.1), (886, 15.2), (915, 16.9), (944, 18.5), (973, 20.1), (1002, 22.3), (1031, 23.9), (1059, 26.7), (1088, 28.3), (1117, 29.9), (1146, 32.1), (1175, 33.7), (1203, 35.4), (1232, 37.6), (1261, 39.2), (1290, 40.8), (1319, 42.4), (1347, 45.2), (1376, 46.8), (1405, 49.5), (1434, 52.2), (1463, 53.9), (1492, 56.1), (1520, 59.3), (1549, 62.6), (1578, 66.9), (1607, 68.6), (1636, 72.4), (1664, 75.1), (1693, 78.4), (1722, 80.5), (1751, 82.7), (1780, 86.5), (1808, 88.7), (1837, 91.4), (1866, 93.1), (1895, 96.9), (1924, 99.0), (1953, 102), (1981, 104), (2010, 106), (2039, 108), (2068, 111), (2097, 114), (2125, 115), (2154, 118), (2183, 121), (2212, 125), (2241, 127), (2269, 131), (2298, 134), (2327, 138), (2356, 140), (2385, 143), (2414, 147), (2442, 149), (2471, 150), (2500, 152)

GDP_from_other_sectors = GRAPH(TIME)

(0.00, 62.9), (3.16, 72.6), (6.32, 86.7), (9.47, 102), (12.6, 115), (15.8, 122), (18.9, 151), (22.1, 182), (25.3, 311), (28.4, 376), (31.6, 412), (34.7, 419), (37.9, 465), (41.1, 500), (44.2, 514), (47.4, 405), (50.5, 675), (53.7, 761), (56.8, 810), (60.0, 863)

Ground_water_level = Effct_Water_On_GW*0.5+Effct_SL_on_GW*0.5

Income_at_HH = GRAPH(Crop_production)

(1000, 81000), (1120, 88000), (1240, 95000), (1360, 104000), (1480, 110000), (1600, 117000), (1720, 126000), (1840, 138000), (1960, 150000), (2080, 164000), (2200, 172000)

Land_Alloc_to_crops_production = Total_land-Land_Alloc_to_shrimp__production-Other_land

Land_Alloc_to_shrimp__production = GRAPH(TIME)

(0.00, 7.60), (1.02, 8.10), (2.03, 8.10), (3.05, 8.60), (4.07, 9.10), (5.08, 10.2), (6.10, 10.7), (7.12, 11.2), (8.13, 11.7), (9.15, 12.2), (10.2, 12.2), (11.2, 13.2), (12.2, 13.7), (13.2, 13.7), (14.2, 14.7), (15.3, 14.7), (16.3, 15.2), (17.3, 17.3), (18.3, 18.8), (19.3, 19.8), (20.3, 20.3), (21.3, 21.3), (22.4, 21.8), (23.4, 22.8), (24.4, 23.4), (25.4, 23.9), (26.4, 24.9), (27.4, 26.4), (28.5, 26.4), (29.5, 26.9), (30.5, 27.9), (31.5, 28.9), (32.5, 28.9), (33.5, 30.5), (34.6, 31.0), (35.6, 31.5), (36.6, 32.0), (37.6, 33.5), (38.6, 34.0), (39.6, 35.0), (40.7, 35.5), (41.7, 36.0), (42.7, 37.1), (43.7, 37.6), (44.7, 38.1), (45.8, 40.1), (46.8, 40.6), (47.8, 40.6), (48.8, 42.6), (49.8, 42.6), (50.8, 43.7), (51.8, 44.2), (52.9, 44.2), (53.9, 45.2), (54.9, 45.7), (55.9, 46.2), (56.9, 47.2), (57.9, 48.2), (59.0, 48.7), (60.0, 49.7), (61.0, 49.7)

Other_land = 23

Production_cost_at_HH = GRAPH(Crop_production)

(800, 34000), (940, 41000), (1080, 47000), (1220, 52000), (1360, 61000), (1500, 70000), (1640, 81000), (1780, 91000), (1920, 102000), (2060, 112000), (2200, 120000)

Profilt = Income_at_HH-Production_cost_at_HH

Rainfall = GRAPH(TIME)

(0.00, 9.12), (1.02, 9.35), (2.03, 9.78), (3.05, 8.42), (4.06, 7.90), (5.08, 12.2), (6.10, 8.21), (7.11, 13.4), (8.13, 11.6), (9.14, 7.16), (10.2, 8.35), (11.2, 15.0), (12.2, 13.1), (13.2, 9.90), (14.2, 7.94), (15.2, 8.29), (16.3, 7.79), (17.3, 8.02), (18.3, 8.14), (19.3, 9.94), (20.3, 8.93), (21.3, 8.34), (22.3, 11.9), (23.4, 5.57), (24.4, 6.52), (25.4, 9.34), (26.4, 12.4), (27.4, 9.54), (28.4, 10.3), (29.5, 11.4), (30.5, 12.9), (31.5, 12.6), (32.5, 11.5), (33.5, 11.6), (34.5, 13.4), (35.6, 15.7), (36.6, 13.1), (37.6, 8.91), (38.6, 13.1), (39.6, 11.8), (40.6, 13.3), (41.7, 9.50), (42.7, 12.8), (43.7, 12.2), (44.7, 9.01), (45.7, 13.8), (46.7, 9.94), (47.7, 13.4), (48.8, 10.8), (49.8, 11.1), (50.8, 13.8), (51.8, 12.3), (52.8, 10.1), (53.8, 13.1), (54.9, 14.3), (55.9, 11.7), (56.9, 13.6), (57.9, 12.6), (58.9, 11.6), (59.9, 13.5), (61.0, 5.41), (62.0, 5.37), (63.0, 4.71), (64.0, 4.71)

River_salinity = Effct_GW_on_RSalinity

Sea_level = GRAPH(TIME)

(0.00, 6839), (2.26, 6766), (4.52, 6660), (6.78, 6730), (9.04, 6909), (11.3, 6873), (13.6, 6801), (15.8, 6953), (18.1, 7032), (20.3, 7002), (22.6, 6980), (24.9, 6953), (27.1, 6994), (29.4, 6975), (31.6, 6994), (33.9, 6990), (36.1, 7008), (38.4, 7021), (40.7, 7003), (42.9, 7012), (45.2, 7077), (47.4, 7040), (49.7, 6997), (52.0, 7042), (54.2, 7054), (56.5, 7123), (58.7, 6945), (61.0, 6983)

Soil_salinity = Effect_Temp_on_SSalinity*0.5+Effct_GW_On_SSalinity*0.5

Temperature = GRAPH(TIME)

(0.00, 26.5), (1.00, 25.4), (2.00, 25.6), (3.00, 25.7), (4.00, 25.4), (5.00, 25.5), (6.00, 26.1), (7.00, 25.9), (8.00, 28.2), (9.00, 25.9), (10.0, 26.5), (11.0, 25.6), (12.0, 25.9), (13.0, 25.3), (14.0, 25.7), (15.0, 25.9), (16.0, 27.5), (17.0, 26.3), (18.0, 26.9), (19.0, 24.4), (20.0, 24.1), (21.0, 26.2), (22.0, 25.9), (23.0, 27.2), (24.0, 26.4), (25.0, 27.4), (26.0, 27.2), (27.0, 25.7), (28.0, 27.5), (29.0, 26.8), (30.0, 27.1), (31.0, 27.9), (32.0, 26.2), (33.0, 26.8), (34.0, 26.8), (35.0, 26.8), (36.0, 26.1), (37.0, 26.2), (38.0, 26.1), (39.0, 27.0), (40.0, 26.6), (41.0, 26.2), (42.0, 26.4), (43.0, 26.1), (44.0, 26.5), (45.0, 26.4), (46.0, 26.6), (47.0, 26.7), (48.0, 26.6), (49.0, 26.5), (50.0, 27.5), (51.0, 26.5), (52.0, 26.9), (53.0, 27.0), (54.0, 26.5), (55.0, 26.6), (56.0, 25.9), (57.0, 26.4), (58.0, 26.7), (59.0, 26.6), (60.0, 26.5), (61.0, 26.7), (62.0, 27.3), (63.0, 26.7), (64.0, 26.6)

Total_GDP = GDP+GDP_from_other_sectors

Total_land = 100

Water = Effct_Temp_On_Water*0.25+Effct_rain_On_Water*0.25+Dam*0.5

Appendix D

Supplementary material: Chapter 5

(Participatory modelling as the basis for a conceptual system dynamic model of the social-ecological system in the Bangladesh delta)

This appendix is in press as working paper: Hossain MS, Dearing JA, Jhonson FA, Eigenbrod F (2016) Participatory modelling as the basis for a conceptual system dynamic model of the social-ecological system in the Bangladesh delta. The South Asian Network for Development and Environmental Economics (SANDEE), working paper (In press)

D.1 Abstract

Recently, the concept of complex SESs capturing system properties, such as regime shifts, interaction, and feedbacks, have attained both academic and policy level attention for sustainable ecosystem management. This study aims to improve the understanding of the SES by using a participatory modelling approach to help develop a conceptual system dynamic model for the SES in south-west coastal Bangladesh. The participatory approach centred mainly on focus group discussions (FGD) with farmers, fisherman, shrimp farmers and forest people and were conducted in order to understand the factors affecting the SES. We have also consulted experts, such as academicians, Government employees, and NGO professionals, consultation to help identify the interactions, feedbacks and thresholds for the SES. Interactions identified between climate and water, salinity and climate, shrimp farming and mangrove, provide the dynamicity in the SES. Feedback loops were identified for the ecological (e.g. climate and water, mangrove and salinity) and social (e.g. income and production, shrimp farming and mangrove, agriculture production and subsidy) systems in the Bangladesh delta. The biophysical thresholds that impact on social conditions, such as for water (1500 m^3/s to 2000 m^3/s), climate (28^oC) and soil salinity (~4 dS m^{-1} to ~10 dS m^{-1}), suggest that the SES may lose resilience in near future, making regime shifts more likely. This study contributes to the management of the ecosystem by 1) increasing the understanding of the SES in Bangladesh delta, 2) operationalizing the sustainability science concepts such as interaction, and feedbacks in the real world, 3) collecting threshold information for the SES and 5) modelling the SES in data poor areas using a participatory approach. Moreover, the participatory approach also serves the purpose of 6) providing structural validation of the SD model and 7) providing inputs to the SD model in order to simulate social changes in response to the changes in the ecological system.

Keywords: Social-ecological system, feedbacks, thresholds, regime shifts, participatory modelling

D.2 Introduction

The notion of social-ecological system (SES) has rapidly gained ground over the past decades (Hossain et al. 2016a; Liu et al. 2007; Folke et al. 2005) and become one of the major research priorities for sustainable ecosystem management (Dearing et al. 2015). This management approach requires understanding of the SES in an integrative way to capture the complex interaction between causal factors and responses, as well as the lags, feedbacks and thresholds in social and ecological systems (Dearing et al. 2015; Biggs et al. 2012). A systems perspective can be used to synthesize all these complex concepts (e.g. lags) (Chen et al., 2009). SD (SD) modelling is becoming more commonly used to capture complexities using a systems perspective (Chang et al., 2008). SD modelling was developed in the early 1960s by Jay Forrester of the Massachusetts Institute of Technology. This modelling technique provides insight into the behaviour of a system, including feedback, delay, nonlinearities (Videira et al. 2009; Beall and Zeoli 2008). It can be used to explore the changes of SES and the pathways for limits to growth (Meadows et al., 1974). SD modelling has already been used in managing eco-agriculture systems (Li et al. 2012), water resources (Beall et al. 2011), wild life systems (Beall and Zeoli, 2008), lake ecosystems (Xuan and Chang 2014) and social dynamics of ecological regime shift (Lade et al. 2015). Although it has been used as an effective decision making tool, testing and validation of SD models are well debated in SD research (Barlas 1996). Structural validity and model behaviour validity are some of the commonly used validation processes. Validating the model generated behaviour against the real behaviour (e.g. historical) of the system is known as validating model behaviour. Structural validity refers to the validation of the factors and their interrelationships with the system. Structure validation has been emphasized compared to the behaviour validation (Khan et al. 2009), as the researchers (e.g. Barlas 2000; Barlas 1996) argued that real behaviour is not important and impossible to validate, whereas, it is important to validate the reliability of the structure and the model can demonstrate the changes in the behaviour while testing the policies. While validating the structure of the system, the use of the participatory approach is increasing in SD research. Participatory modelling involves local stakeholders or directly affected people to play an active role and share their perceptions in reconstructing the knowledge and understanding the processes of a system (Jakeman et al. 2006; Cain et al. 2001). Participatory approach can often solve the data limitation for ecosystem management (Ritzema et al. 2009) and it has already been used for conceptualizing the SD model of wetlands ecosystem (Ritzema et al., 2009), wildlife management (Beall and Zeoli 2008), water resources management (Beall et al. 2011) and river basin management (Videira et al. 2009). Thus, we have aimed at using the participatory approach for conceptualizing the SD model of a SES in Bangladesh delta by answering the following research questions:

1. What are the key factors that affect their livelihood?
2. How do these factors affect their livelihood?
3. How do you understand the interlinkages and causality of those factors?
4. Is there any threshold point in the social–ecological system or in any individual biophysical process?
5. Is there any feedback within the SES of this region?

Findings from this study can be fed into the SD modelling as a structure validation approach to simulate the changes in SESs and tipping points for biophysical and social conditions. This study is part of the PhD project SOS for development and ES in Bangladesh. We have already analysed the evolution of the SES, and the interlinkages between social and ecological systems, and based on these analyses, we have hypothesized a SD model which is validated through this study using a participatory modelling approach before simulating the changes of the SES. The simulation of SES and conceptual SD model from this study will be included in another manuscript along with the results from the previous works (Hossain et al. 2016a; Hossain et al., 2016b; and Hossain et al. 2015a).

D.3 Methods and study area

D.3.1 Study area

We have selected the south-west coastal part of Bangladesh as our study area (Fig. D.1). This is an area of ~25,000 km^2 (16% of the total land area of Bangladesh), with a total population of 14 million (BBS 2010). The ecosystem of this area produces more than 1,300 million USD of Gross Domestic Product (GDP) (BBS 2010). People of this area are dependent on agriculture (~40%), fisheries (~20%) and forestry (~25%) for the source of their livelihood (Hossain et al. 2015). Moreover, around 1.5 million people are directly and 10 million people are indirectly dependent on the world's largest forest mangrove 'Sundarban' (Islam and Haque 2004). We are assuming that, for changing in ecological system, the livelihoods of agriculture, fisheries and forestry dependent people (~80%) will be affected directly and rest of the people who are dependent on these sources at least for food security will be affected indirectly. Thus, we focused on four main livelihood sources (agriculture, fishery, shrimp farming and forestry) for modelling the SES.

D.3.2 Methods

A qualitative research method has been used for modelling the SES in Bangladesh delta. We have used a participatory approach as the primary technique of data collection, which includes focus group discussion (FGD) with farmers, fisherman, forest dependent people and shrimp farmers. We have also organized workshops in which different stakeholders (e.g. academics, NGO professionals) participated in the discussion. In total, seven FGDs were conducted in Barisal, Khulna and Patuakhali (Barguna). On average, there were 20-24 participants in each FGD, the majority being participants between 30-60 years age or older who had engaged in their profession for at least 10 years. Before starting the discussion, we divided 20-24 participants into two groups to ensure the saturation of information from the same area. These were selected in order to maximize the understanding on the SES in this region.

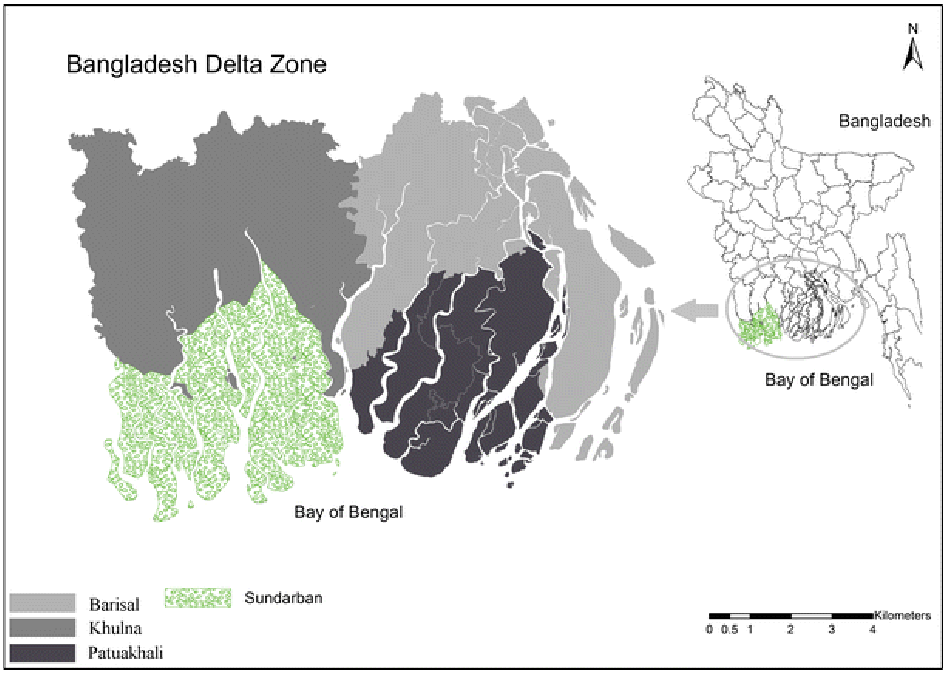


Figure D.1: Bangladesh delta zone study area showing location in Bangladesh (inset), the three greater districts and the Sundarbans

First, we asked the participants about the key factors affecting their livelihood and how these factors are affecting their livelihood. Then we also asked them about the interlinkages of those factors. We mainly collected information on feedback and thresholds from the workshops due to the expert knowledge of the participants in the workshops. The high level of FGD participant's illiteracy prevented questioning regarding feedback and thresholds.

In the case of the workshops, experts from academia working in environment, fishery, agriculture, forestry, water resource management and government employees from those sectors were invited for the workshop. We also invited journalists, NGO professional and students working on environmental and other relevant issues. In total, two workshops were organized in Khulna and Patuakhali to collect qualitative data. The total participants (n~25) during each workshop were divided in two groups for discussion in order to develop a conceptual SD model. Each group presented their findings and were engaged in a feedback session to develop a final one conceptual SD model in the workshop. The average time for the workshops and FGDs was two and half hours which allowed to participate in the discussion. The discussion both for workshop and FGD was facilitated by a session chair selected by the participants at the beginning of the discussion. All participants developed a causal loop diagram with the help of the session chair. We have also interviewed some experts to collect the information on threshold for the biophysical processes, such as the threshold of temperature for fish production. We have used SD model platform STELLA to visualize the conceptual SD models for the SES in Bangladesh delta.

D.3.3 Ethical aspects

This study was approved (Ethics ID: 14651) by the ethics and research governance committee of the University of Southampton. Participants were informed at the beginning of the FGDs and workshops that their identity would be kept anonymous. Anonymity has been assured by removing any participant information (e.g. name, list of participants, photo) that could lead to identification.

D.4 Results

D.4.1 Agriculture

Farmers identified factors (Figure D.2) such as quality of seeds, use of pesticides, irrigation and fertilizer which positively influence the production of crops. Whereas, drought, salinity and temperature negatively affect production of crops. Both flood and rainfall have positive and negative influence on crop production. Flood not only damages the production of crops but also improves the soil fertility which leads to the higher production of crops. Similarly, heavy rainfall not only damages crops in post monsoon during harvesting season, but also has been also identified as one of the prime factors which positively influences the production of rain-fed agriculture in this region. Experts stated that crop production is effected negatively by low water availability from the upstream of Ganges, which in turn, increases the irrigation demand in the field. Salinity is a more common problem in Khulna and Patuakhali regions, whereas the mark of salinity in Barisal has not been identified by the farmers in Barisal.

Production from agriculture is directly linked with their income which is directly and positively linked with daily food availability and consumption, access to health facilities and electricity. Although the government and NGOs have constructed community clinics and hospitals, where the farmers can access cheap medical facilities but they depend on their income for purchasing medicines and medical tests. In case of education, sanitation and access to safe drinking water, farmers depend on both aid from the Government and NGOs and also on their personal income. For example, although primary education is free for all, the cost of private tuition to complete their education is one of the barriers in attaining primary education.

Factors such as subsidy and market regulation affect their income substantially. When they can purchase fertilizer, pesticides and irrigation materials (e.g. fuel, pump) at low and reasonable prices due to the government subsidy, they can make profit from their production. Similarly, when the market price of selling rice is higher than their production cost, their profit becomes higher. However, they often experience financial loss because of poor market regulation which sets the price of the agricultural commodity at equal to, or slightly higher than, their production cost. Possibly for this reason, experts also recognized that national policy such as subsidies for fertilizer and electricity for irrigation substantially affect the production and income of the farmers. Experts also stated that production is positively linked with poverty alleviation which also has a positive influence on the level of unemployment and negatively effects the migration pattern in a region.

D.4.2 Fisheries

Figure D.3 depicts the causal loop diagram for fishery in Bangladesh delta. It has been discussed by experts during the workshops that rising temperature and salinity have a negative effect on fish production. An increase in water flow leads toward higher production of fish in rivers, however, a high water level during flooding reduces the possibility of fish catch. Similarly, water depth has a negative association with fish catch. Both water depth and flood support the increase in the production of fish in rivers and ponds. Fisherman also observed that fish catch increases during natural disaster and tidal flow. Moreover, Fisherman and experts have reported that reduced water flow from the northern part of the country is one of the reasons for decreasing fish production.

In case of socio-economic sector, the coast guard plays an important role in protecting the over exploitation of fish by restricting the catch of mother fish during the breeding period. This creates conflicts between coast guard and local fisherman, as the fisherman income reduces for limited fish catch during breeding season. Use of the current net has a negative impact on fish production in the long run. Income of the fisherman depends on the daily fish catch, market price of fish and debt. Debt is required to rent boats and other fishing materials to catch fish in the rivers. The local mahajon (powerful group who are financially and politically strong) often charge a higher rate of interest for the debt and they force the fisherman to sell their fish according to the desired price of local mahajon. This syndicate

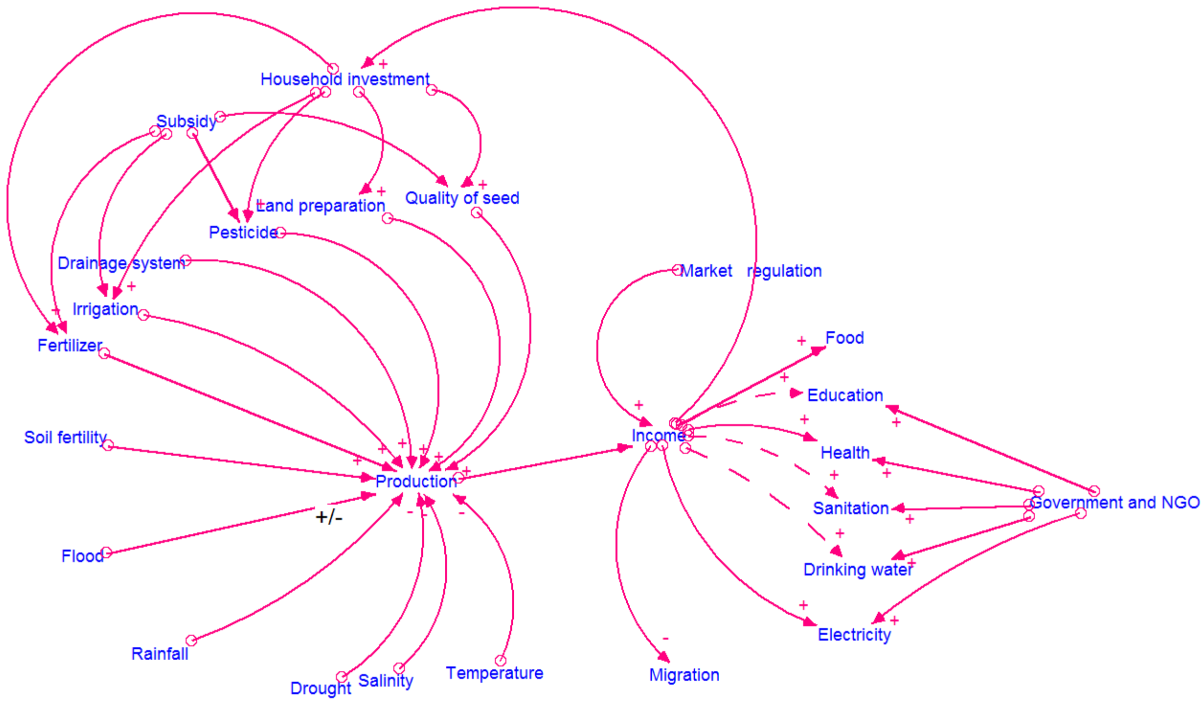


Figure D.2: Causal loop diagram for agriculture (FGD with farmers) in Bangladesh delta. The + and – signs depict the positive (+), negative (−) or both (+/−) relationship between the variables.

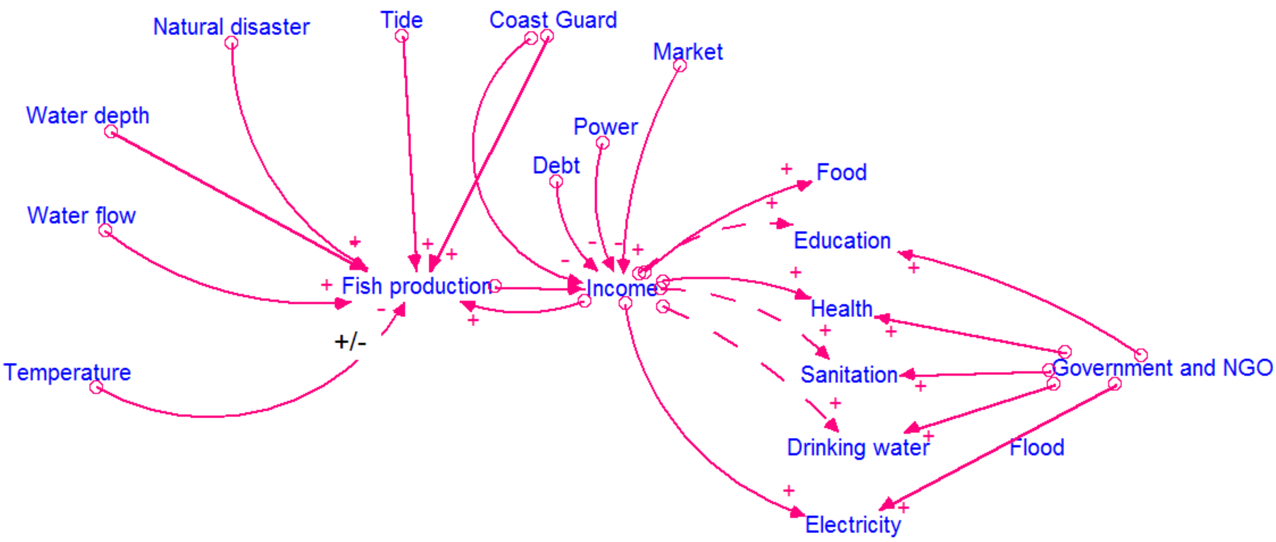


Figure D.3: Causal loop diagram for fish production (FGD with fisherman) in Bangladesh delta. The + and – signs depict the positive (+), negative (−) or both (+/−) relationship between the variables.

often control the local and national price of the fish. Fisherman also expressed that income from the fish catch positively linked with their food consumption, health service (purchasing medicines and medical tests) and electricity. However, primary education attainment, sanitation and drinking water access depend on the both government and NGOs support and contribution from some part of their income.

D.4.3 Shrimp farming

Figure D.4 shows the causal loop diagram for shrimp production in Bangladesh delta. Fertilizer plays a role in preparing the soil of shrimp ponds (gher) and increasing the fertility of the ponds. After that, good quality of fingerlings collected from rivers or from the hatchery is one of the pre-requisites for higher production of shrimp. Erratic patterns of rainfall, water flow during flood and water logging due to heavy rainfall, damage the shrimp production. Sudden rainfall leads to sudden drops of temperature and reduces the salinity level, which has negative consequences on shrimp production. Shrimp farmers also experience viral issues, the causes of which are unknown to the farmers. They are often experiencing loss from their shrimp ponds due to the virus and this has become regular in the last 5 years. Experts discussed that because of the temperature increase, sudden rainfall and higher level of salinity, shrimp farming is often threatened by the virus which reduces at least 50% of the total production. The low water depth of the shrimp pond is also another cause for this virus. Farmers reported that the income from the shrimp ponds is becoming lower in comparison to the time period between 1990s and 2000. Experts commented that this could be because of the loss of soil fertility, rising temperature and erratic pattern of rainfall in this region. In the case of linkage between income of shrimp farmers and other factors of HWB, similar linkages of farmers and fisherman reported by the shrimp farmers, where, income directly influence food consumption and health (purchasing medicines and tests) and sanitation, education and safe drinking water are dependent on aid from the Government and NGOs .

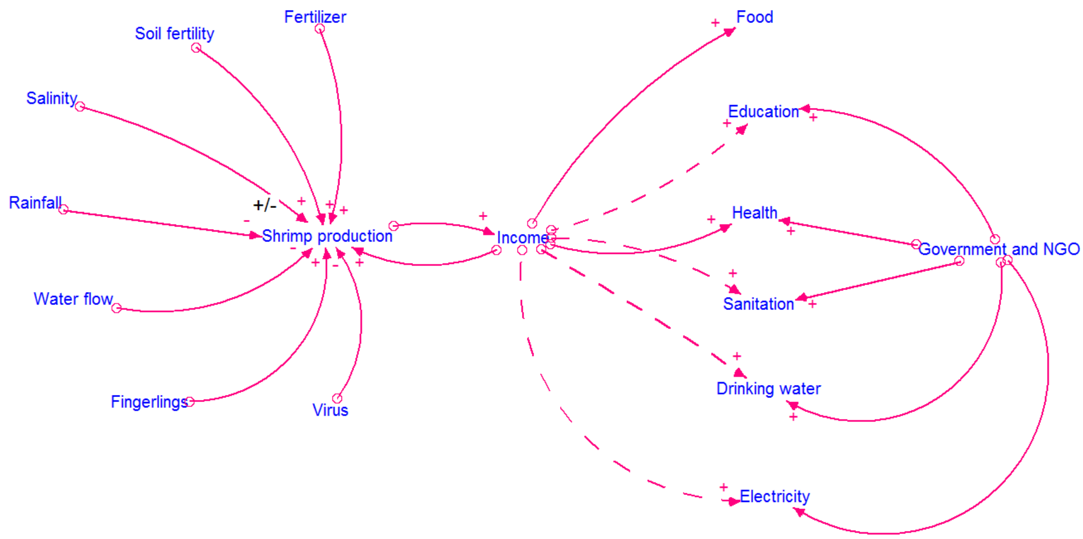


Figure D.4: Causal loop diagram for shrimp production (FGD with shrimp farmers) in Bangladesh delta. The + and – signs depict the positive (+), negative (−) or both (+/−) relationship between the variables.

Crab, honey and fish fry collection are three main products (Figure D.5) which forest people collect from the mangrove ecosystem. Wood collection from the mangrove used to be the main forest product, but the government banned collecting woods to protect mangrove degradation due to the top dying disease of mangrove. The government provides permits through the forest department to the forest dependent people to collect sundari leaves only 40 days per year. However, community people mentioned that, despite banning wood collection, illegal wood loggers who are powerful with political connections usually collect wood from the mangrove all year round. Forest dependent people discussed that temperature and rainfall are negatively linked with crab and honey collection. They mentioned that they get lower stocks of honey in the mangrove if the temperature of the season is high and rainfall is low. Moreover, fresh water flow is required for honey production as the bees collect fresh water as part of the physiological process. They perceived that the stock of honey has reduced since they are experiencing reduced water flow from the northern part of Bangladesh. The water scarcity problem becomes more severe due to the salinity rise, which also reduces fresh water availability for the bees. Experts discussed that water flow reduction and salinity rises are some of the main causes of the top dying disease for which government banned collection of wood from the mangrove. Salinity rise supports crab cultivation, but crab productivity reduces when the salinity becomes very high. Moreover, experts perceived that the stock of honey, wood and fish from around Sundarban, all depend on the stock of mangrove in terms of main species composition such as Sundari, Nipa etc. Even the shrimp production may decrease because of the depletion of mangrove by reducing the fertility and suitability of shrimp cultivation.

It has also been reported by shrimp farmers that they are experiencing reduced production compared to the periods between 1990 and 2000. Besides the regulating services, social factors such as an increase in forest product collection and cultivated honey around Sundarban are one of the reasons for decreasing honey and fish fry collection. Fish fry collection is mainly negatively affected by water flow and salinity rise. In case of linkages between the provisioning services and HWB, we found similar linkages of fisherman, agriculture and shrimp farmers.

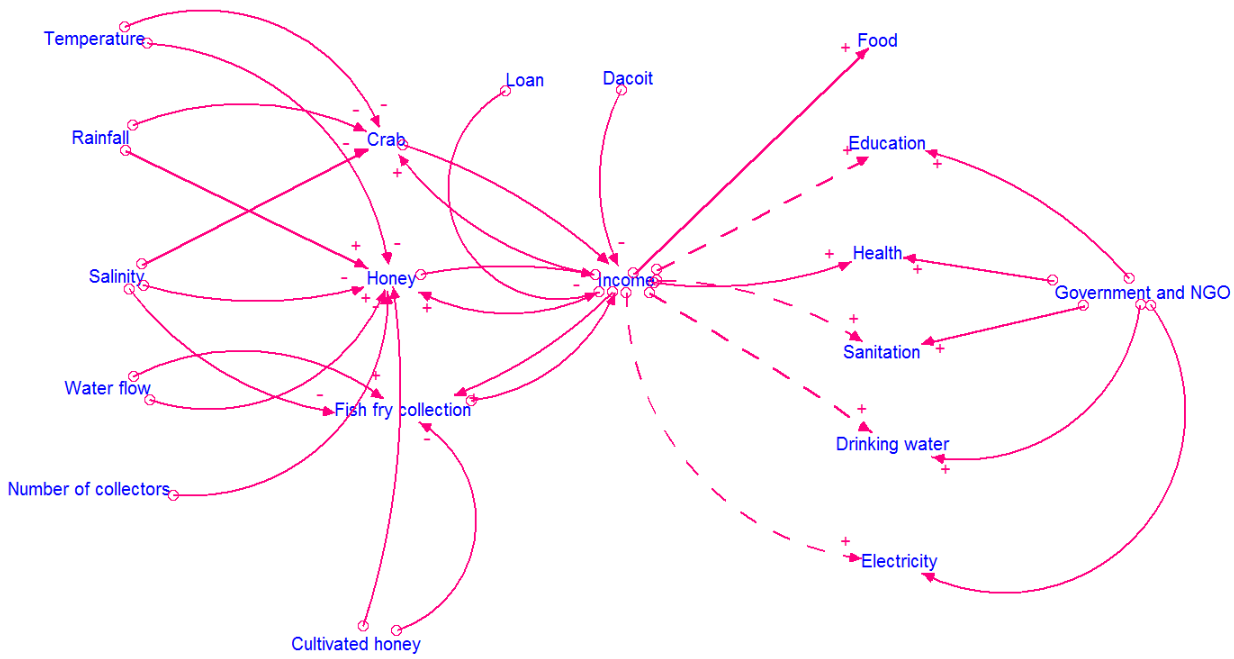


Figure D.5: Causal loop diagram for forest productions (FGD with forest people) in Bangladesh delta. The + and – signs depict the positive (+), negative (−) or both (+/−) relationship between the variables.

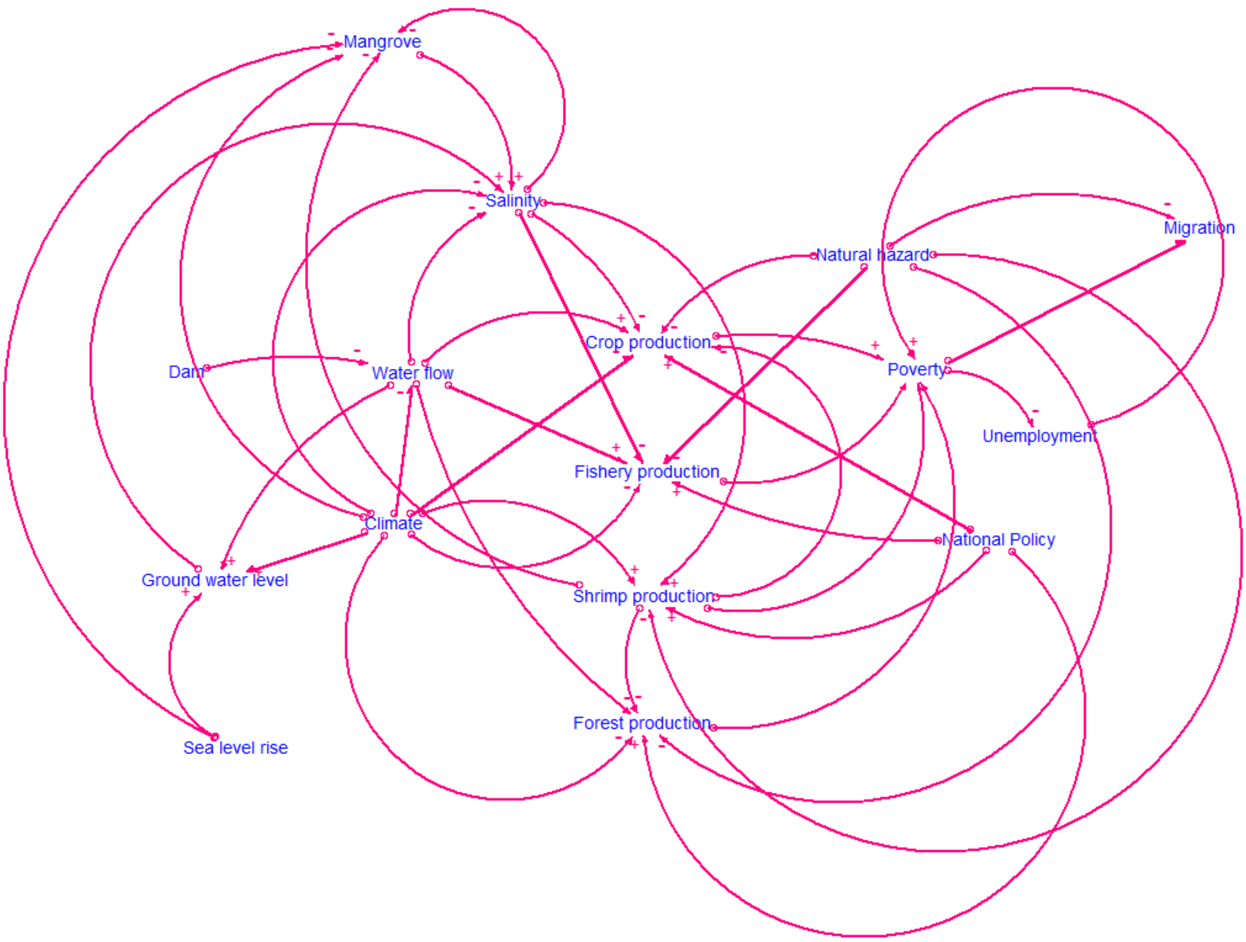


Figure D.6: Conceptual SD model for the SES based on the expert's consultation in Bangladesh delta. The + and – signs depict the positive (+), negative (−) or both (+/−) relationship between the variables

D.5 Discussion

D.5.1 Factors in social-ecological system

Water availability and rainfall are positively linked with production of crops, fish and forest production, whereas, these two environmental factors negatively affect shrimp production. Shrimp production is positively linked with temperature which negatively influences crops, fish and forest production. Similar negative links exist between salinity and production such as fish, crops and forest production. Production costs in terms of fertilizer, pesticides and land preparation are essential for the high production of crops and shrimp. Fish production from ponds is also associated with fertilizer and preparation costs, whereas, the community need credit support in the form of loan for engaging in fish catch from rivers and forest product collection from mangrove forest. Loan is also essential factors for crops and shrimp production, but this credit is needed for using fertilizer, pesticides and land preparation.

In the case of the social system, production is directly linked with income, which is, in turn, directly linked with the food, health and electricity provision of the households. However, HWB indicators such as sanitation, education attainment and access to drinking water are dependent on the development aid of government and NGOs, rather than relying on the income of the households. Market regulation is one of the important factors which influences the income of the households.

D.5.2. Interaction, feedbacks and thresholds

Interaction and feedback are the prime factors for the dynamics of SES and coproduce the services provided by ecosystem (Biggs et al. 2012). Therefore, in order to understand the complex dynamics of SESs in Bangladesh delta, we have used mainly experts' opinion from the workshops to identify interactions and feedback. Figures 6 and 7 show the interaction and feedback in the SES. Interaction between ground water level and salinity and also the interaction between water availability and salinity indicate the possibility of salinity rise which will impose negative impacts on the provision of ecosystem. Similarly, climate and ground water level, and climate and salinity are also identified as interaction in the SES.

We have identified positive feedback between crop production and investment in agriculture (e.g. income, GDP, fertilizer use). Positive feedbacks also exist between temperature and water discharge, and also between shrimp farming and soil salinity. The feedback between shrimp farming and crop production is necessary to include in consideration as the decrease in income from crop production increases the possibility of adopting shrimp farming, which in turn, decreases the land availability of crop cultivation due to the conversion of rice field into shrimp farms and cause a salinity rise both in river and soil. Moreover, an increase in shrimp farms leads to the further depletion of mangrove forest, which increases the shrimp farming and salinity in the coastal area. This positive feedback between shrimp farming and mangrove indicates the possibility of depletion of mangrove in future.

Table 1 depicts the thresholds for four livelihood sources in Bangladesh delta. Although the threshold for rice depends on the varieties of rice, the physical process (e.g. germination, flowering) of rice shows a detrimental effect on the average temperature below the 20^{o}C and above 30^{o}C (Hamjah 2014; BARC 2012; Talukdar et al. 2001). However, a modern high yield and salinity tolerant rice variety such as BRRI dhan28 responds negatively to temperatures above 28^{0}C (BRRI 2015). We have also identified 27^{o}C as the threshold temperature for rice production using generalized additive modes (GAM) in our previous analysis (Hossain et al. 2016a). In addition, the model predicts that the rice yield will decline ~18% and ~25% respectively for rising temperatures of 2^{o}C and 4^{o}C (Basak et al. 2012; Basak 2010; Mahmud 1998; Karim et a. 1996). Therefore, considering these thresholds of temperature for rice and the different growing seasons of different varieties of rice (Sarkar et al. 2014; BBS 2009), it will not be erroneous if we assume that there is threshold for rice production at ~28oC mean temperature and there will be at least 10% yield reduction of rice because of the changes in seasonal and annual temperature of 2^{o}C. Rainfall (annual 1000-1200 mm) and soil salinity (2 dS m-1) are also limiting factors for rice production. Although rice production decreases ~10% for above soil salinity 2 dS m-1, some of the modern rice varieties could resist soil salinity up to 4 dS m-1 (Mondal et al. 2001).

It has been revealed during consultation with stakeholders that forest products in the mangrove forest Sundarban are highly dependent on the water availability from upstream and river salinity in the south west coastal Bangladesh. Islam 2011 and Islam 2008 have identified ~40, 000 dS m-1 of river salinity level as a threshold value for Sundarban mangrove forest, which will also sustain for water availability of 2000 m3/s in dry season. These thresholds for forest production show resemblance with our previous studies (Hossain et al. 2016b).

Despite decreasing fish production from rivers (Hossain et al. 2015), Bangladesh became one of the major (Fifth) fish producing countries around the world in 2014, because of the revolution of fish production from ponds (FAO 2014). However, this progress in fish production from ponds may be limited by the rising temperature, reduced water availability and salinity rise. Experts from fisheries stated that the optimum temperature for some of the major produced and consumed fish such as Rohu (Labeo Rohita) and Catla (Catla Catla) is $27^{o}C$ to $29^{o}C$, beyond which, there is a detrimental effect on the physiology of the fish for hatching of eggs. Fish production reduces at least 50% over the temperature of $32^{o}C$ and shows at least a 15% reduction for exceeding $29^{o}C$. However, some of the fish species such as Tilapia can tolerate a temperature range of 22-$25^{o}C$. The salinity level of 12 dS m-1 to15 dS m-1 is the limiting range for the fish production in ponds. Moreover, at least ~1500 m3/s of water availability is required for fish production in rivers.

Stakeholders perceived that the rising temperature and other climatic changes will favour shrimp farming in the coastal Bangladesh. However, the field level data collected from Bangladesh Fisheries Research Institute (BFRI) shows that there is an optimum water temperature ($25^{o}C$ – $32^{o}C$) and soil salinity (7.80-39 dS m-1) for the production of shrimp.

Experts and shrimp farmers stated that above these threshold ranges, shrimp production declines at least 50% because of virus outbreak in shrimp farms. The findings (e.g. factors, interaction, feedbacks) of this study show resemblance with our previous studies (Hossain et al. 2016a; Hossain et al. 2016b; Hossain et al. 2015) and also with other studies (e.g. Swapan and Gavin 2011; Azad et al. 2009; Adel 2002). This study not only validates the finding of the previous study (Hossain et al. 2016b), but also adds value to the knowledge-base for ecosystem management. For example, the influence of salinity and temperature on shrimp production up to a certain point denies the possibility of the previous assumption of increase in shrimp production due to climate change. Moreover, the dependency of fish production on temperature and salinity was excluded in our hypothesized conceptual model (Hossain et al. 2016b) development based on statistical analysis and literatures.

Table D.1 Thresholds for SES in Bangladesh

Livelihood sources	Thresholds	Source
Agriculture	28^{0} C (Air temp) 4 dS m-1 (Soil salinity)	Stakeholders & Basak et al. 2012; Basak 2010; Mondal et al. 2001; Mahmud 1998; Karim et a. 1996
Forest (mangrove) product	~40,000 dS m-1 (Water salinity) 2,000 m3/s (Water flow) 25-28^{o} C , 35^{o} C (Air temp)	(Islam 2011 and Islam 2008) Nandy and Ghose (2001); Field (1995); Wong and Tam (1995)
Fisheries	27^{o}C to 29^{o}C (Water temp) 0-5 ppt (Soil salinity) ~1,500 m3/s (Water flow)	Stakeholders
Shrimp	25^{o}C – 32^{o}C (Water temp) 7.80-39 dS m-1 (Soil salinity)	Stakeholders

D.5.2. Conceptual SD model and policy implications

Based on the consultation with stakeholders, we have developed a conceptual SD model (Figure D.7) for the SES in Bangladesh delta. We combined all the information from the causal loop diagrams (Figure D.2 to Figure D.6) developed by different stakeholders during FGDs and workshops in the study area. The interaction between the slow variables (e.g. temperature, rainfall, water availability) that shape and control the system resilience may lead to gradual declining of resilience in social and ecological systems (Hossain et al. 2016a; Zhang et al. 2015). Besides the interactions in SES, feedbacks identified in the SES also cause a decline in the resilience and may lead the SES towards tipping points (CBD 2010).

Evidence of the high dependency of human development (e.g. sanitation, education) on development aid and the dependency of crop production on subsidy suggests that the SES in Bangladesh delta is in transition phase as it is adapting well against the changes in environment (Hossain et al. 2015; Renaud et al. 2013). This is why the proposed subsidy phase out of SDGs (Sustainable Development Goals) in 2030 may pose a risk to the SDGs goal of zero poverty by 2030. Moreover, the non-linearity (physical thresholds) identified for the slow variables (e.g. temperature, salinity, and water availability), interaction and feedback loops suggest that the SES may transgress the SOS where the risk of unpredictable and damaging change to the SES becomes very high for sustainable ecosystem management (Dearing et al. 2014; Rockström et al. 2009). Thus, it is essential to investigate how the social system will respond to changes in the ecological system. This study can serve the purpose of simulating the changes in social system in response to the changes in ecological system and for the sustainable ecosystem management in Bangladesh delta. Moreover, despite the complexity of extrapolating the sustainability science concepts (e.g. interaction, feedback) in the real world, we have operationalized these sustainability concepts in managing the SES. This study also demonstrates how we can model SESs in data poor areas, validation of structure for the SD model and the importance of incorporating stakeholder engagement in ecosystem management and adaptation planning.

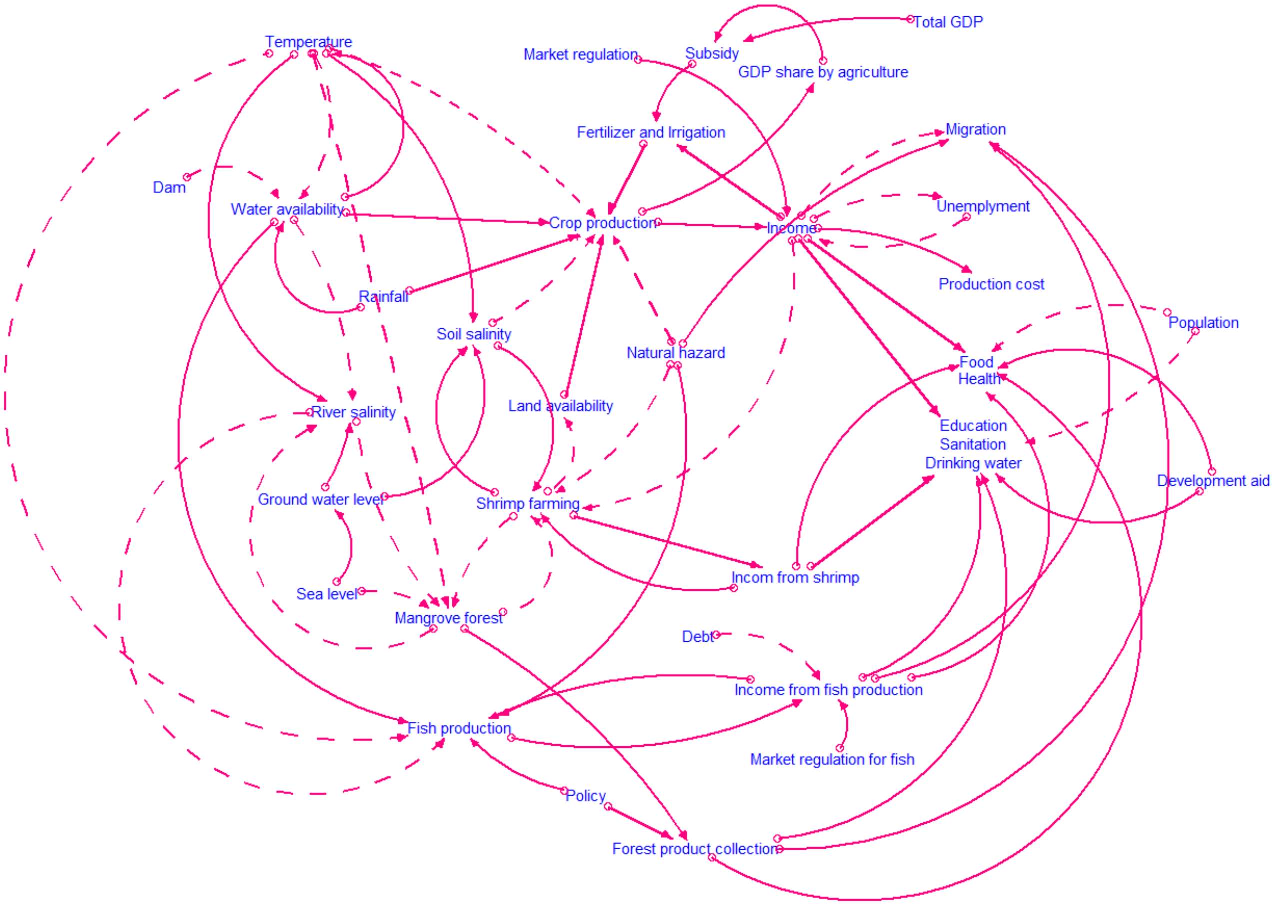


Figure D.7: Conceptual SD model for the SES based on stakeholder's consultation in Bangladesh delta. We combined the information from FGDs with farmers, fisherman, shrimp farmers and forest people, as well as the experts' consultation in workshops. The solid line and dots line depict the positive (+) and negative (−) relationships between the variables.

Figure D.8 Experts discussing in Patuakhali to develop conceptual SD model for the SES.

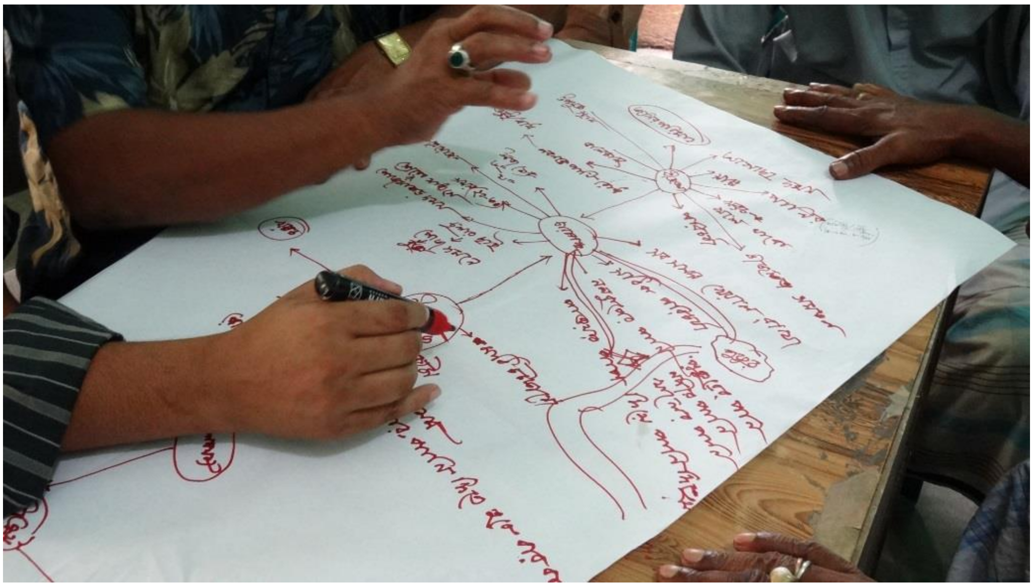


Figure D.9: Farmers identifying factors for causal loop diagram of agriculture in Barisal.

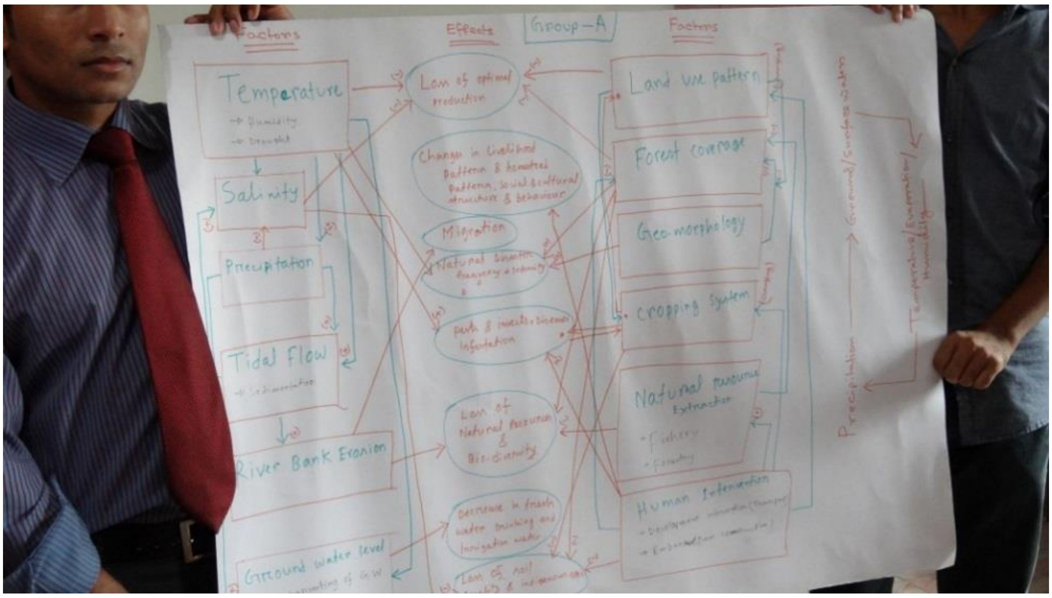


Figure D.10: Conceptual SD model for the social-ecological system. Research assistants holding the conceptual SD model during discussion and feedback session with stakeholders in Patuakhali.

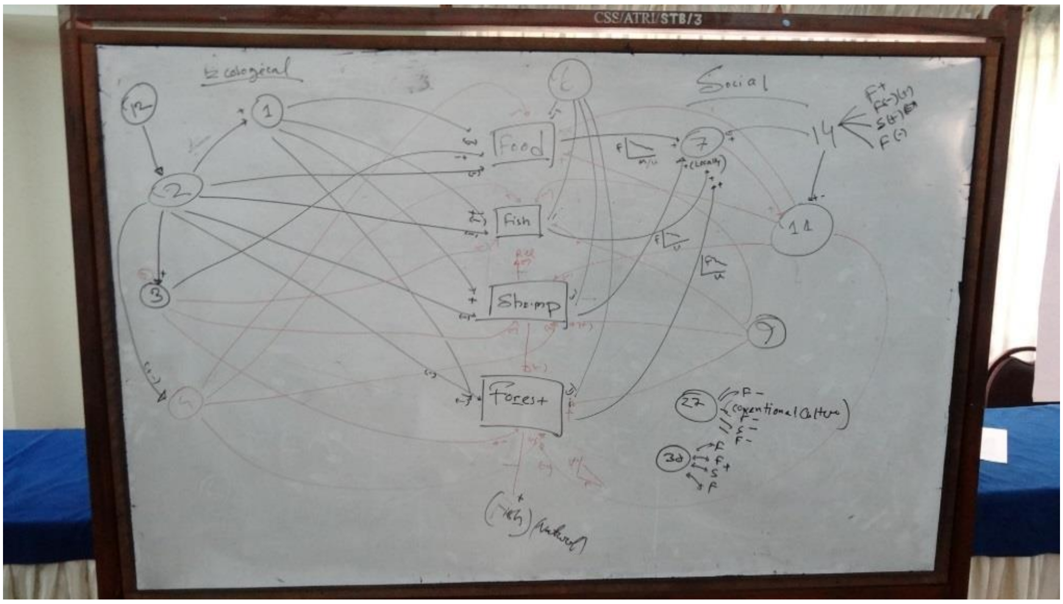


Figure D.11: Conceptual SD model for the social-ecological system based on stakeholder's consultation in Khulna region. Experts use coding for capturing the factors effecting the complex SES.

D.6 Conclusion

This study represents the first regional scale operationalization of complexity concepts (e.g. interaction, threshold) using stakeholder consultation for managing the SES. Analysis in this study has increased our understanding of complex relationships between social and ecological systems. In addition, we make a first attempt to collect the threshold data for SES in Bangladesh delta.

Water availability and rainfall are positively linked with production of crops, fish and forest production, whereas, these two environmental factors negatively affect shrimp production. Shrimp production is positively linked with temperature which negatively influences crops, fish and forest production. Similar negative links exist between salinity and production such as fish, crops and forest production. The identified interactions (e.g. water availability and climate, climate and salinity) as well as the feedbacks (e.g. crop production and policy, shrimp farming and mangrove forest) in SES provide the dynamicity in the system. The threshold for the SES has been collected based on the experts' consultation and literature review. Both the agriculture and fisheries (shrimp and fish) systems are sensitive to 28/29^{o}C temperature beyond which the production may decrease at least 10%. Thresholds of soil salinity level varies for crops (4 dS m-1), shrimp (12 dS m-1to15 dS m-1) and fisheries (7.80-39 dS m-1) production. Moreover, the range of 1500 m3/s to 2000 m3/s water availability in rivers is critical for fish production in rivers and also for sustainability the mangrove forest. We provide a conceptual SD model based on stakeholder consultation. This conceptual SD model implies that the interactions and feedback may reduce the resilience of SES and may lead the SES towards tipping points.

Findings from this study can be fed into the SD modelling as a structure validation approach to simulate the changes in SESs and the use of threshold data for the biophysical and social conditions can be supported for ecosystem management. The simulation of SES and conceptual SD model will be included in another manuscript along with the results from the previous works (Hossain et al. 2016a; Hossain et al. 2016b; and Hossain et al., 2015). This final manuscript will also acknowledge PhD dissertation support fund of SANDEE, besides the main sponsors of the PhD project.

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