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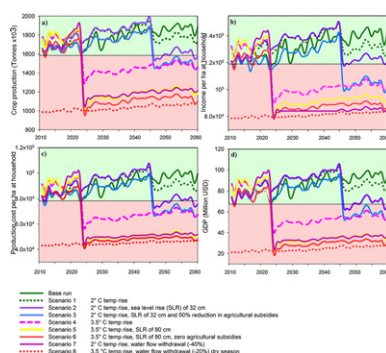
Operationalizing safe operating space for regional social-ecological systems

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HIGHLIGHTS

- First attempt to operationalize the safe operating space concept at a regional scale by considering the complex dynamics of social-ecological systems.
- The social-ecological system in the Bangladesh delta would push towards dangerous zone once 3.5 °C temperature increase was reached.
- The system also may move beyond a safe operating space when a withdrawal of subsidy for agriculture is combined with the effects of a 2 °C temperature increase and sea level rise.
- This study demonstrates how the concepts of tipping points and limit to adaptation can be operationalized in real world social-ecological systems.

GRAPHICAL ABSTRACT



Safe operating space simulated for the social-ecological system in Bangladesh delta.

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ABSTRACT

This study makes a first attempt to operationalize the safe operating space concept at a regional scale by considering the complex dynamics (e.g. non-linearity, feedbacks, and interactions) within a systems dynamic model (SD). 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 in 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 °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 °C temperature increase was reached. The social-ecological system 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) revising global policies (e.g. withdrawal of subsidy) that negatively impact at regional scales. 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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1. Introduction

The safe operating space for humanity concept provided through the planetary boundary framework (Steffen et al., 2015; Rockström et al., 2009a; Rockström et al., 2009b) has gained much attention. In brief, Rockström et al., 2009a used the theory of critical transitions (Scheffer et al., 2001) to define the modern boundaries for Earth system biophysical state variables, using the Holocene (the last 11,000 years) as a baseline period. Exceeding the boundaries takes the Earth beyond the 'safe operating space' where the risk of unpredictable and damaging change to social-ecological systems becomes very high.

Raworth (2012) introduced the 'doughnut' concept in order to locate social concerns within the original safe operating concept, where human wellbeing is deprived if fit falls below defined social foundations for basic needs (e.g. food, gender equality, health).

However, cross-scale issues remain because many of the planetary boundaries are aggregated from regional scale problems, such as land use and freshwater use (Nordhaus et al., 2012; Lewis, 2012), critical transitions can occur within biophysical and social systems singly or combined and at any scale (Scheffer et al., 2001), and setting a boundary at a global scale does not necessarily help to inform policy at a regional scale. Therefore, Dearing et al. (2014) proposed a methodology to downscale the safe operating space and 'doughnut' concepts to the regional scale. In brief, they defined the safe operating space as the gap between an environmental ceiling defined using empirical dynamical properties (e.g. envelope of variability, early warning signals) of ecological variables and a social foundation defined from minimum norms of human outcomes (e.g. health). But while this and other recent approaches (e.g. Hoornweg et al., 2016; Cole et al., 2014) provide useful snapshots of a regional social-ecological system, they do not generate insight about the complex interactions between social and ecological systems. The lack of dynamicity in current frameworks could lead to erroneous conclusions being drawn and might limit the utility of these concepts at a policy level and within the wider-decision making community.

The basis of the current research lies in a conceptualization of the potential modification of the safe operating space approach in four steps (Fig. 1) from the original Earth system concept to a full appraisal of interactions and feedback in social-ecological systems at regional and the global scale. In this paper, we make a first attempt to operationalize the safe operating space by focusing on the third step, which quantifies the interactions between social and ecological systems at the regional scale for a social-ecological system (south-west coastal Bangladesh). Our specific goal is identifying the optimum pathways for achieving

Sustainable Development Goals (SDGs) 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 are the boundaries of the safe operating spaces of social-ecological system?
4. What is the proximity of the social-ecological system to a major tipping point?

We accomplish this by using time series data to understand the co-evolution of the social-ecological system and analysed the linkages of the social-ecological system by focusing agriculture. Subsequently, we used system dynamic modelling to consider the interactions of social-ecological systems and to demonstrate the safe operating space in the Bangladesh delta.

2. Case study area - the Bangladesh delta

2.1. Selection of the study area

The south-west coastal area has been selected as the case study area (Fig. 2), which represents 16% of the land area of Bangladesh. This area represents the Ganges tidal flood plain (FAO-UNDP, 1998) and generates a Gross Domestic Product (GDP) of 1.3 billion USD but where ~38% of people already live below the national poverty line (Sarwar, 2005; BBS, 2010). Recorded statistics confirm that this area is one of the most vulnerable to climate change (Maplecroft, 2010; Ahmed et al., 1999) and is also under stress because of land use change, water scarcity, floods, salinity rise and urbanization (Hossain et al., 2015; ADB, 2005). Projections show that the detrimental effects of climate change in the area are likely to continue, as rice and wheat yields decrease due to temperature increases (MoEF, 2005). Approximately 40% of people are heavily dependent on agriculture for their livelihood (Hossain et al., 2016b). Given the significant influence of agriculture on the social-ecological system in this area, we concentrated on this sector in our first attempt to demonstrate the safe operating space at the regional scale. However, this can be extended to the other livelihood sources (e.g. fishery, shrimp farming, and forest goods) in future studies.

Our previous studies (Hossain et al., 2016b; Hossain et al., 2015) revealed that the ecosystem has clearly been degraded since the 1980s, because of the increasing temperatures and salinity levels (soil and water), rising sea levels and rising ground water levels (SI Fig. 1). Decreasing trends of rainfall in the dry season and the significant water

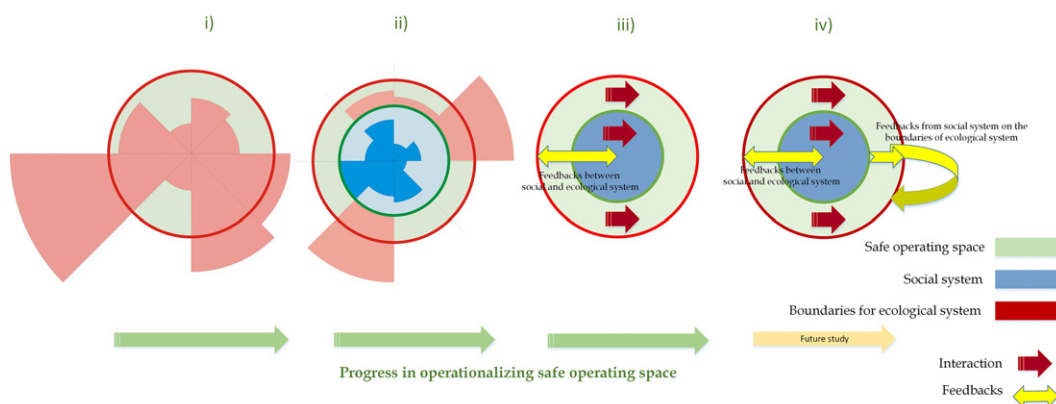


Fig. 1. A conceptualized sequence of the safe operating space concept for regional social-ecological systems. (i) the original approach (e.g. Rockström et al., 2009a, 2009b) defines the biophysical boundaries of the Earth system, with later mapping of some boundaries to regional scales (Steffen et al. 2015). This approach can also be used as the basis for calculating the regional burden of environmental pollution (e.g. CO₂ emissions) or regional share of resources in terms of equity. (ii) the doughnut framework (Raworth, 2012) that defines minimum boundaries for the Earth social system (Raworth, 2012) or the sustainable management of regional social-ecological system (Dearing et al., 2014). (iii) the third stage could focus on the dynamic (interaction, feedbacks, and non-linearity) relationships between social-ecological systems, focusing on the drivers that can move the social system beyond the safe operating space. (iv) a fourth stage could extend the approach further by investigating how the feedbacks from the social-ecological systems influence the safe operating space for the Earth system.

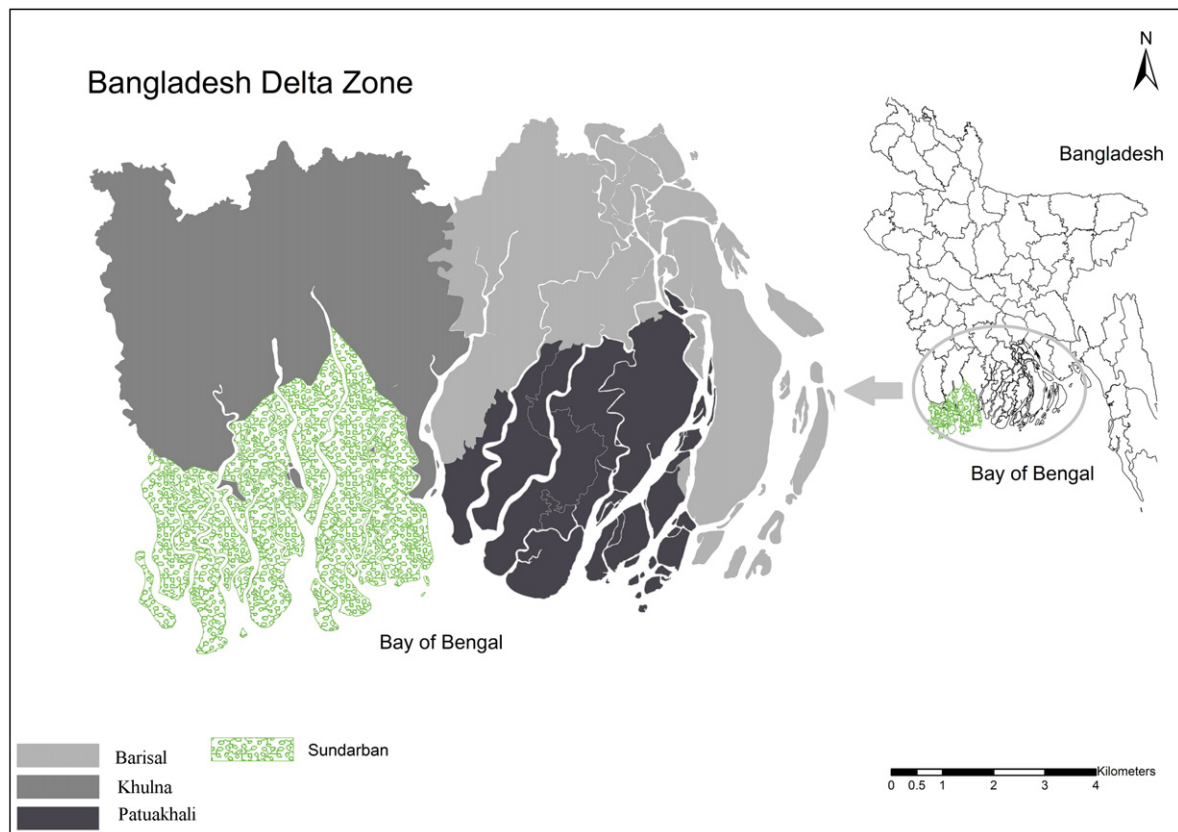


Fig. 2. South west coastal region of Bangladesh.

flow reduction in the rivers attributable to the Farakka dam on the upstream Ganges (built between 1965 and 1975) are also impacting the ecosystem. In contrast, the social system (SI Fig. 1) has improved since 1980s because of the increasing agricultural (rice) production has driven a rising share of GDP growth in the agricultural sector (8 million USD/yr). The increasing trends of agricultural production and regional GDP have helped to lessen poverty, which has declined 17% over 17 years.

3. Methods

The overall methodology (SI Fig. 3) of this study comprises six research steps: 1) Synthesis of information and creation of a conceptual system model from our previous studies serving the purpose of problem familiarization and the basis for the system dynamic modelling; 2) System model creation in STELLA (Ford, 2010), 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 to validate the structure of the system dynamic model developed in Step 2, and then to modify the system model developed at the Step 1; 4) Simulated changes based on the final system model using a graphical function approach validated against historical crop production data; 5) Sensitivity analysis of the model and exploration of the dynamics of the social-ecological system through generating eight 'what if' scenarios based on the well-known challenges; 6) Definition of the safe operating space in relation to the envelope of variability, environmental limit and impacts on society. The above methodology relies heavily on our previous empirical work (Hossain et al., 2016a, 2016b; Hossain et al., 2015), however, the system dynamic modelling and scenario development we present here has not been previously published. The detailed descriptions of each of the steps are given in the following sections.

3.1. Methodological steps

3.1.1. Conceptual and system dynamic models

System dynamic modelling is increasingly used to synthesize complex interactions (e.g. dynamic changes, feedbacks, and non-linearity) in social-ecological systems (Chang et al., 2008). This modelling technique was first 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 shifts (e.g. Ladea et al., 2015).

A conceptual system model (Hossain et al., 2016a) of the south-west Bangladesh coastal area, used as the basis for developing a system dynamics simulation model, was informed by facts and figures from our previous studies and other literature. The conceptual system model (SI Fig. 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 the case of the social system, social indicators such as the share of agricultural GDP, income and production costs are positively influenced by crop production in this delta. However, crop production exhibits 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.

3.1.2. Model development, validation and sensitivity analysis

Trends, drivers and change points were analysed (Hossain et al., 2015; Hossain et al., 2016b) to understand the co-evolution of the

system. We used regression (additive, linear, logistics) models and a literature review in Hossain et al. (2016a) to capture complex and dynamic relationships (non-linearity, interactions and feedbacks). With a main focus on agriculture, we focused mainly on the synthesized information of agriculture-related social (e.g. GDP, income, production cost) and ecological (e.g. climate, water) systems.

The hypothesized system dynamic model (SI Fig. 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. (2016a) has been used to define the relationships between variables in the system dynamic model. The empirical information such as coefficients used for this run are given in SI Table 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 (SI Fig. 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 are compared (Fig. 3a) 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., 2016); and 3) analysing the difference among three time series using Student *t*-test. The visual inspection of the three time series (Fig. 3a) 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 ($N = 50$) results (SI 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.

3.1.3. Participatory approach

The structure of the system dynamic model developed using empirical analysis is then validated through engaging with stakeholders in the study area. Structural validation procedures have been 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 et al., 2000; Barlas, 1996). A participatory approach is becoming increasingly common in system dynamics 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., 2010) and has already been used for conceptualizing system dynamics model of wetlands ecosystem (Ritzema et al., 2010), wildlife management (Beall and Zeoli, 2008), water resources management (Beall et al., 2011) and river basin management (Videira et al., 2009).

Structural validation of the previously designed model in SI Fig. 2 was undertaken through three focus group discussions (FGD) with farmers ($n \sim 25$ 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 ($N \sim 25$ 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 (SI Fig. 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 system dynamic model, which shows the conflicts with shrimp farming through reducing the cultivatable area, which in turn increases the crop intensity. The final system dynamic model (Fig. 4) has been used as the base (e.g. causal loop diagram) for the system dynamic modelling. Non-linear relationships observed through the empirical analysis coincide with the threshold temperature of $\sim 28^\circ\text{C}$ for crop production while consulting with stakeholders. In addition, stakeholders also reported a soil salinity threshold of $4\text{ dS}\cdot\text{m}^{-1}$ for crop production. The detailed methodology of this structural validation of the social-ecological system can be found in Hossain et al. (2016c).

The final conceptual model developed (Fig. 4) 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 social-ecological system that caused the social system to step out the safe operating space.

3.1.4. Simulations

After the structural validation using stakeholders engagement (see above), the simulated changes (base run) for the crop production are 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 (Fig. 3d) and *t*-test results suggest that the modelled data compare and that they occur within the observational uncertainty (95% confidence intervals) of historical crop production time series.

As our models are informed and built using historical datasets, we tested the ability of our model to predict changes in our study system re-running our model using two subsets of our data - (1951–1980 and 1981–2010). The first training dataset (1951–1980) has been used to define the relationships between the variables in STELLA, and then used to predict changes between 1981 and 2010. Similarly, the 1981–2010 data was used to define relationships between variables and then predict changes between 1951 and 1980. Both of the predicted outputs from the STELLA simulations are compared with historical crop production data. The visual inspection (SI Fig. 6) suggests that the overall modelled data using the two training datasets matches well with the historical crop production data. Though the model cannot simulate the changes in case where the crop production declined

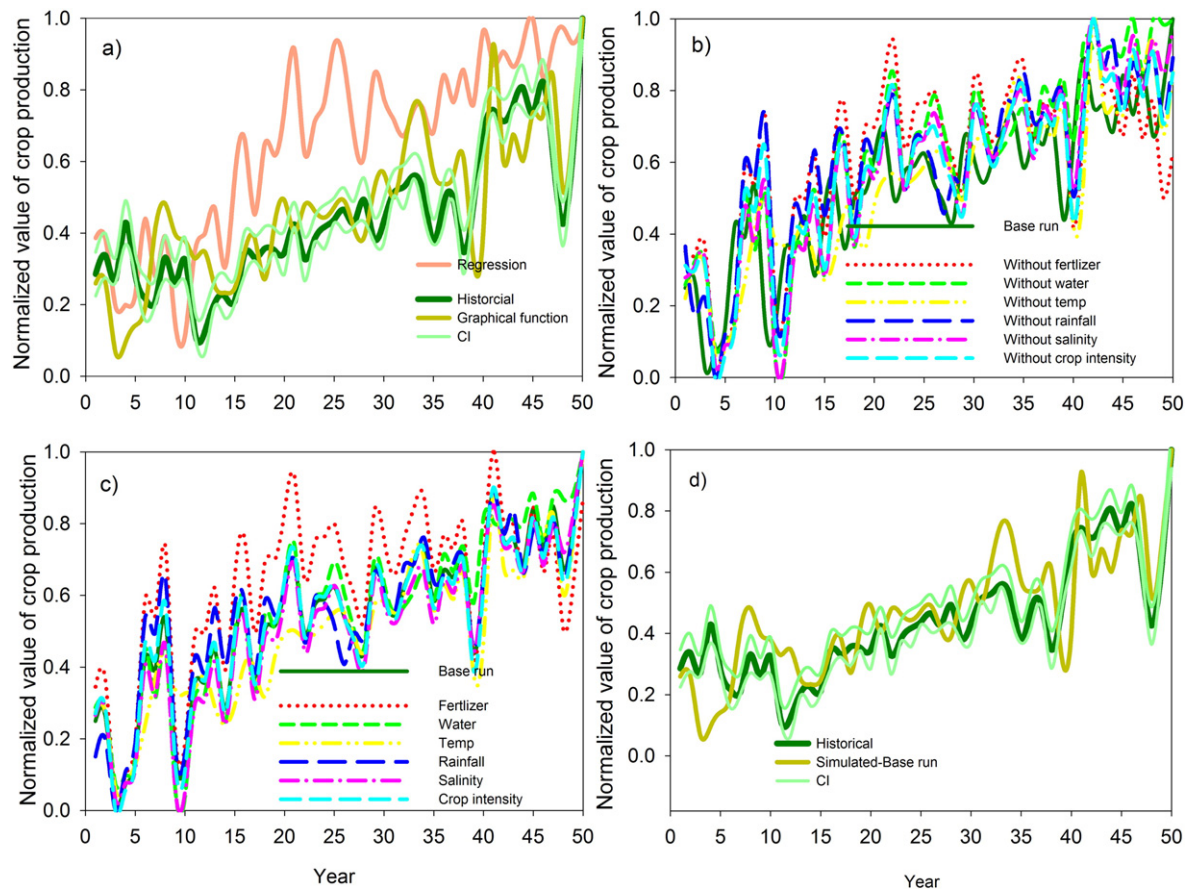


Fig. 3. Results from the validation and sensitivity tests of system dynamic model. Panel a shows the comparison of behaviour pattern derived from empirical (regression) analysis, graphical function and historical time series of crop production. Panels b and c illustrate that model is not highly sensitive to any parameters. Panel d 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 Panels a and d denote the 95% confidence interval (CI) bands of historical crop production data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

substantially due the shocks (e.g. cyclone, floods) in the system, it does explain broad overall system behaviour, which is the main goal of this study.

3.1.5. Sensitivity tests

Tests were run to investigate whether or not the behaviour of the model is highly sensitive to any parameter, and if this sensitivity makes sense in the real system, by varying each parameter weighting from a minimum of 0 to a maximum of 0.32. In Fig. 3b and c, sensitivity test results are illustrated which indicates that, the model is not highly sensitive to any parameters indicating that all the relationships defined in the model may be considered valid and logically meaningful. However, prior to exploring system behaviour it is important to emphasize the main assumptions in the model:

- The model assumes that the net cropped area and population are constant.
- The area of shrimp farms and production also remain constant.
- The model does not consider the impact of abrupt rainfall change on crop production.
- 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.
- This model does not consider the impacts of disaster events such as flood and cyclone.

- The model assumes that the nature of the relationships between the parameters will be the same in the future as in the past.

3.1.6. Exploring dynamic behaviour and testing policies

After validation and sensitivity analysis, eight ‘what if’ scenarios (Table 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 °C and 3.5 °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’ scenarios as our main motivation is to make a first approach to demonstrate the operationalization of the safe operating space 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.

3.2. Defining the safe operating space

Dearing et al. (2014) proposed 4 types of time-series properties that could define a safe operating space: exceeding environmental limits in linear trends, moving outside envelopes of variability, retrospective analysis showing that thresholds have already been crossed, and entering periods where early warning signals suggest threshold change is

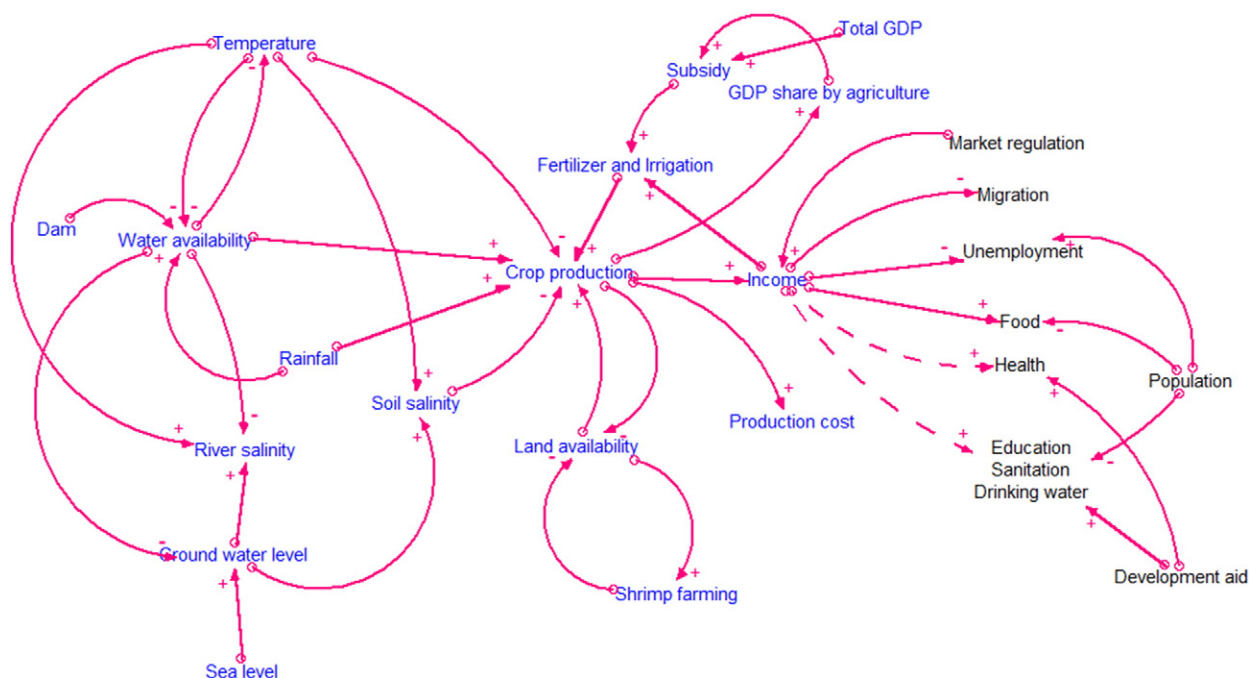


Fig. 4. Conceptual system dynamic model of social-ecological system in Bangladesh delta. This system model developed using the empirical analysis, followed by stakeholder engagement to validate the structure of the social-ecological system. The positive (+) and negative (−) signs denote respectively the positive and negative relationships between the variables. In addition, the solid lines depicts the strong relationships, whereas, the dotted line depicts the weak relationship between the variables. In our first approach of defining safe operating space 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 weak relation with crop production at household level via income.

imminent. The focus here is on analysing two of the dynamic properties: 1) envelopes of variability and 2) early warning signals.

3.2.1. Envelopes of variability

The extent to which the system moves beyond the recent envelope of variability. However, with agricultural production the envelope is asymmetric with regards the impact on society, with only exceedance of lower limits deemed to be unsafe. In the study area, examination of

the impact on society of the system moving outside the envelope can be partly gauged from historical events, such as disasters and famine.

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 used 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

Table 1
Description of scenarios and assumptions for system dynamic 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 °C temperature increase	Stakeholder consultation & Hossain et al., 2016c; Basak et al., 2012; Basak et al., 2010; Mondal et al., 2001; Mahmood, 1997; 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 °C is exceeded and when salinity rises beyond 4 dS/m	
Scenario 3	This run simulates the combined effects of a 2 °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 °C temperature rise	Crop production declines 25% once a temperature of 28 °C is exceeded and for 3.5 °C temperature increase	Hossain et al., 2016c; Hossain et al., 2015; Mondal et al., 2001
Scenario 5	This run simulates the effects of a 3.5 °C temperature rise and sea level rise of 80 cm	Crop production declines 40% due to 3.5 °C temperature rise and also salinity increase beyond 4 dS/m due to an 80 cm sea level rise	
Scenario 6	This run simulates the combined effects of a 3.5 °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 °C temperature rise and water withdrawal (−40%) in the dry season	Crop production declines 40% due to 2 °C temperature rise and also salinity increase beyond 4 dS/m due to water withdrawal (−40%)	Hossain et al., 2016c; Hossain et al., 2015; Mondal et al., 2001
Scenario 8	This run simulates the effects of a 3.5 °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 canals 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	

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 safe operating space are:

- 1) Research evidence shows that production loss leads to income loss (Hertel, 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 for selecting crop production, income and GDP to define safe operating space at the regional scale.
- 2) Despite the rising trend of crop production, the declining food (rice) per capita (Bishwajit et al., 2014) and loss of revenue from crop production due to the increase of production costs (Hossain et al., 2016a; Hossain et al., 2015; Iqbal and Roy, 2014) suggests that, any plausible declining trend of crop production due to socio-environmental drivers 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) for a sudden reduction in crop production to substantially below average production due to 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 the famine of 1974 due to food shortage (substantially below average production) after natural disasters in Bangladesh (Crow, 1984; Sen, 1981).

Hence, it will not be erroneous if we argue that, outside the envelope of variability (Fig. 5) for crop production, income and GDP, the society will move out from the safe operating space beyond which is dangerous to humanity.

As the main motivation is to make a first approach to demonstrate the safe operating space at the regional scale, we limited our analysis to 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 as our previous study (Dearing et al., 2014) to identify safe

(green) and dangerous (red) status in the social-ecological system. In addition, we also define cautious state, where if the trends of social indicators are within normal envelope variability but follow negative trends or are below the reference trend, but have not used any colour coding for this state.

3.2.2. Early warning signals

We have analysed early warning signals of increasing system instability based on critical slowing down and flickering theories. In these theories, increases in variance are recognized as one of the most robust signals of system instability (Dakos et al., 2012; Wang et al., 2012). Residuals and standard deviations are calculated from detrended time series using Gaussian kernel smoothing to remove the low and high frequencies in the long-term trend (Zhang et al., 2015; Dakos et al., 2012) using the 'earlywarnings' package of R (<http://www.r-project.org/>). We have analysed 34 year time series from the base run and from modelled data (crop production and income at household level) for scenarios 1, 2 and 3. Variance was computed for a sliding window representing half the length of the time series.

4. Results

Fig. 6 illustrates the simulation results for the different scenarios over 50 years (2010s–2060s). The first scenario 1 evaluated the effects of temperature increasing by 2 °C over the period. This shows a rising trend of crop production over the first ~25 years, followed by a sudden decrease, and subsequently a return to the production level of the 1960s. Scenarios 2 and 3 both show crop production decreasing below the production levels of the 1960s. The reduction in yields are higher in scenario 3 because of sea level rise (32 cm) coupled with a withdrawal of a 50% subsidy. These production losses are similar to that of scenario 4, which evaluates the impact of a 3.5 °C temperature rise over the period. In contrast to scenario 3, production in scenario 4 would experience a sudden decrease after 10 years. In scenario 5, where sea level increases by 80 cm and temperature rises by 3.5 °C, production decreases ~40% due partly to the higher temperatures but also higher salinity caused by sea level rise. This loss of production would be even higher if there is a withdrawal of all subsidies.

We also evaluated in scenarios 7 and 8 how the system will respond if there an increase in the withdrawal of water from the upstream Ganges. Scenario 7 shows the production losses from a 3.5 °C temperature increase and 20% withdrawal of water are similar to scenario 5 which

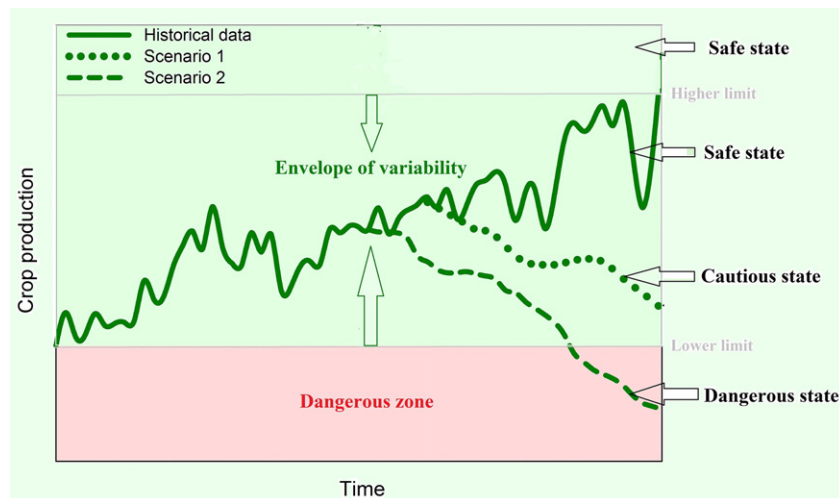


Fig. 5. Conceptual framework attributing 'safe', 'cautious' and 'dangerous' status of social-ecological system. We have combined envelope of variability and environmental limit approach in relation to the social system to define safe operating space. Status defined as 'safe' (green) if the system is 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 affecting 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

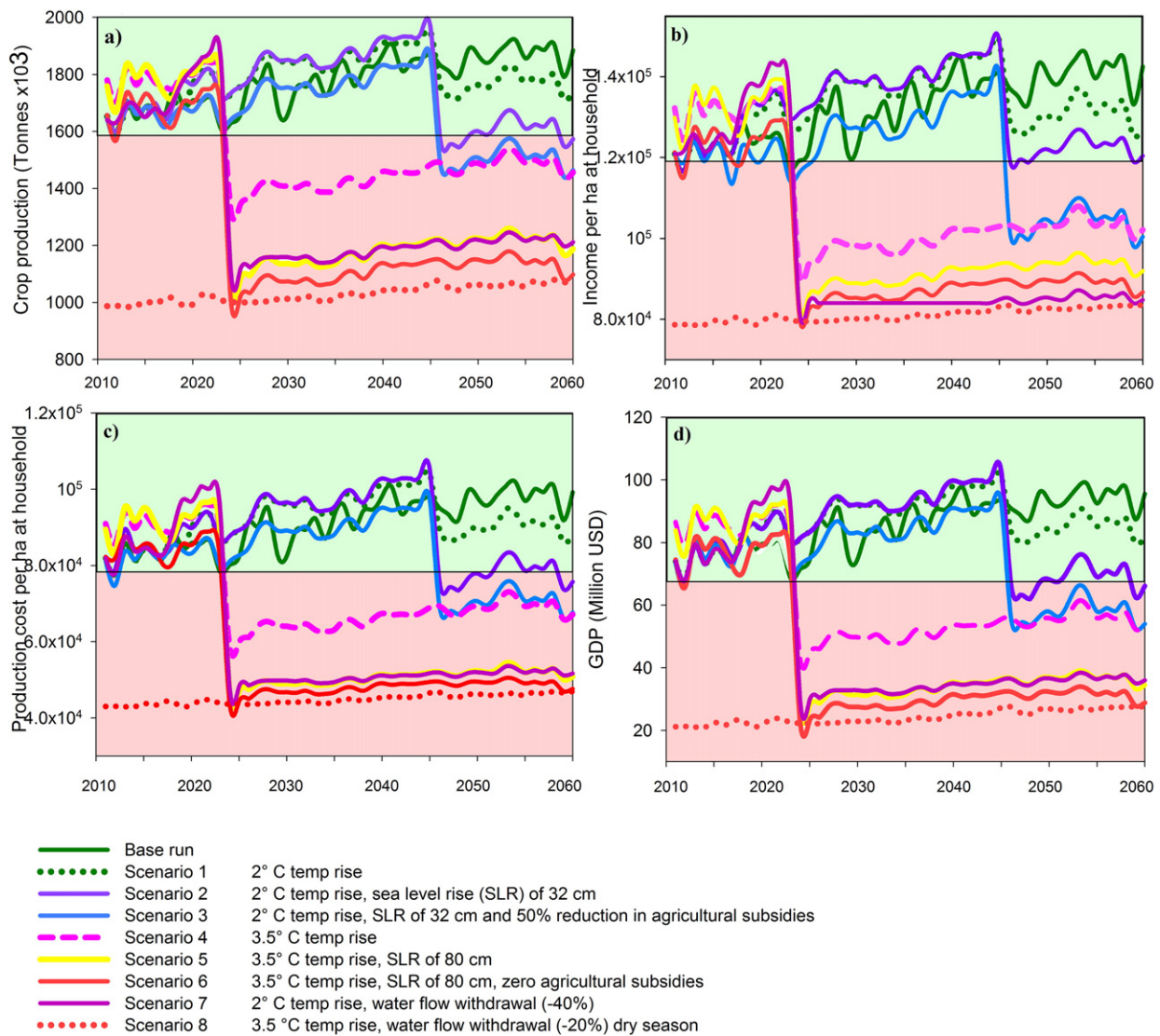


Fig. 6. Safe operating space simulated for the social-ecological system in Bangladesh delta. Colour coded segments show the safe (green) and dangerous (red) status for crop production (a), income ha-1 at household (b), production cost ha-1 at household (c) and GDP shared by agriculture (d) in Bangladesh delta. We aimed at understanding the behaviour of the system, thus the simulation results should not be read quantitatively in a precise way. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shows the impact of a 3.5 °C temperature increase and an 80 cm sea level rise. We also evaluated in scenario 8 the impact of water withdrawal (20%) during the 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. A 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 the threshold of $4 \text{ dS} \cdot \text{m}^{-1}$) 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 (Fig. 6) 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, social indicators such as income, production and GDP will increase up to 25 years, followed by a sudden decline in scenarios 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 the 3.5 °C temperature rise and

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 a 2 °C temperature increase.

SI Fig. 7 shows the early warning signal analysis of modelled crop production and income for household time series data prior to exceeding the safe operating space. Both the crop production and income records show decreasing variance for scenario 1, 2 and 3. However, the variance does increase for the base run.

5. Discussion

This study attempts to define the safe operating space for the south-west coastal Bangladesh delta using system dynamic modelling. The findings suggest that the social-ecological system in the Bangladesh delta could move out of a safe space after 35 years due to a 2 °C temperature increase and sea level rise, and this would be exacerbated by withdrawing the 50% subsidy for the agriculture sector. With a 3.5 °C temperature increase, the system could move out of the safe space much earlier especially in combination with subsidy withdrawal (50%) and sea level 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, and the impact of this would be higher than the combined effects of sea level rise and withdrawal of all subsidies in the era of the 3.5 °C rise in temperature. However, if we consider water discharges in the dry season, which coincides with the sowing and harvesting period for crops, the social-ecological system, could move into the dangerous zone due to the 20% withdrawal of water discharges and the 3.5 °C temperature rise. This is because of the capillary rise of seawater due to the withdrawal of water discharges, leading to higher salinity, which is also triggered by the interaction between soil salinity and temperature.

The instability analysis of this study implies that the system may move beyond the safe operating space without any early warning signal. Although, rising variance is postulated for critical transitions in previous studies (Zhang et al., 2015; Wang et al., 2012; Dakos et al., 2008), it is recognized that a system may collapse without prior warning (Boerlijst et al., 2013; Hastings and Wysham, 2010) and rising variance may actually enlarge the safe operating space for the social-ecological system (Carpenter et al., 2015). All these indicate the difficulties and challenges of providing an early warning signal to avoid moving beyond safe operating space (Boettiger and Hastings, 2013). Therefore, a critical challenge for the management is how to maintain the social-ecological system within safe operating space.

The social-ecological system in Bangladesh delta may be operated within a safe space by managing some of the feedbacks such as reduction of production costs, which in turn can reduce dependency on subsidy and household income when investing in agriculture. In addition, disconnecting the feedback loops among crop production, GDP and subsidies, could reduce the investment in subsidy. This may help develop 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 long term resilience (Biggs et al., 2012; Bennett et al., 2009; Gordon et al., 2008) could also support to overcome challenges such as climate change. Although the system dynamic model shows that a 3.5 °C temperature increase would probably be more dangerous than a 2 °C increase, the social system could still experience negative impacts such as decrease in income and crop production with a 2 °C temperature rise. Thus, the global agreement adopted in Paris in 2015 on remaining below a 2 °C temperature increase is crucial for maintaining the south-west Bangladesh coastal zone social-ecological system within safe space. Moreover, managing slow variables could also reduce 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 social-ecological system in this delta. Besides protecting the coastal area from sea level rise, ensuring water flow from the Ganges through transboundary negotiation could also be part of reducing interactions among the variables such as water, ground water level and salinity. Otherwise, the interactions among these variables and other proposed developments (e.g. the river linking project in the Ganges (Gourdji et al., 2008)) may pose a risk to the Bangladesh delta, causing it to step out from the safe operating space.

The sudden changes simulated by the model at ~15 and ~35 years are due to exceeding the threshold for crop production. This model indicates the importance of new technological innovation such as (e.g. temperature and salinity tolerant crops) to in avoiding the crossing of thresholds, which, in turn, could avoid a 'perfect storm' of social-ecological failings (Zhang et al., 2015; Dearing et al., 2012).

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 in order to

quantify the changes precisely; and 3) extending the model to account for seasonal changes and other main livelihood sources such as shrimp farming, forest goods and fisheries.

6. Conclusion

This study attempts to operationalize the safe operating space concept within the south-west Bangladesh coastal area by considering the complex dynamics of the social-ecological system through a system dynamics model.

Eight 'what if' scenarios for the period 2010s to 2060s reveals that a 3.5 °C temperature increase over the period could be dangerous for the social-ecological system especially when combined with sea level rise, withdrawal of water and loss of subsidies.

Maintaining the system within a safe operating space demands a temperature rise of <2 °C over the period as agreed by the 2015 Paris Agreement. Strengthening transborder negotiations for water resources management is also essential for maintaining adequate water supply.

The findings highlight the adverse effects of global policy. For example, the WTO recommendation to withdraw agricultural subsidies would pose a risk to the social-ecological system achieving reductions in poverty and maintaining sustainable agriculture as stated in SDGs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2017.01.095>.

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