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CLIMATE CHANGE RISKS
AND FOOD SECURITY
IN BANGLADESH

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Winston H. Yu, Mozaharul Alam, Ahmadul Hassan, Abu Saleh Khan, Alex C. Ruane,
Cynthia Rosenzweig, David C. Major and James Thurlow

earthscan
publishing for a sustainable future
London • Washington, DC

First published in 2010 by Earthscan

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Earthscan Ltd, Dunstan House, 14a St Cross Street, London EC1N 8XA, UK
Earthscan LLC,1616 P Street, NW, Washington, DC 20036, USA
Earthscan publishes in association with the International Institute for Environment and Development

For more information on Earthscan publications, see www.earthscan.co.uk or write to earthinfo@earthscan.co.uk

ISBN: 978-1-84971-130-2 hardback

Typeset by JS Typesetting Ltd, Porthcawl, Mid Glamorgan
Cover design by Susanne Harris

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

Climate change risks and food security in Bangladesh / Winston H.Yu … [et al].
p. cm.
Includes bibliographical references and index.
ISBN 978-1-84971-130-2 (hbk.)
1. Crops and climate–Bangladesh. 2. Climatic change–Bangladesh. 3. Food security–Environmental aspects–Bangladesh. 4. Agricultural productivity–Environmental aspects–Bangladesh. 5. Agriculture–Economic aspects–Bangladesh. I. Yu, Winston H.
S600.64.B3C65 2010
363.8'2095492–dc22
2009053662

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Printed and bound in the UK by the Cromwell Press Group.
The paper used is FSC certified.

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Acknowledgements

This report was prepared by a team led by Winston H. Yu (Task Team Leader, World Bank). Specific team contributions included: Mozaharul Alam, Rabi Uzzaman, Aminur Rahman (Bangladesh Center for Advanced Studies) and Sk. Ghulam Hussain (Bangladesh Agricultural Research Council), who identified and evaluated the adaptation options present in this study and provided agricultural information for crop models; Ahmadul Hassan, Bhuiya Md. Tamim Al Hossain, Mohammad Ragib Ahsan, Ehsan Hafiz Chowdhury and Giasuddin Ahmed Choudhury (Center for Environmental and Geographic Information Systems), who provided an analysis of the historical hydrology of the country; Abu Saleh Khan, Sardar M Shah-Newaz, Sohel Masud and Emaduddin Ahmad (Institute of Water Modelling), who developed the models used to project changes in future flooding; Alex C. Ruane, Cynthia Rosenzweig, David C. Major, Radley Horton and Richard Goldberg (Columbia University), with the advice of Md Sohel Pervez, who provided the future climate scenarios and developed the models used to project future crop production; and James Thurlow and Paul Dorosh (International Food Policy Research Institute), who developed the computable general equilibrium model.

The authors benefited enormously from the many technical discussions with colleagues and Government of Bangladesh officials. Specific reviewers included: Richard Damania, Julia Bucknall, Abel Lufafa, Ian Noble, Nagaraja Harshadeep, and Anna Bucher (from the World Bank), Abu Wali Raghib Hassan, Md Mahsin, Sanjib Saha, Md Abul Hossain, Mazharul Aziz, Mohammad Ataur Rahman, and Bilkish Begum (from the Department of Agriculture Extension), M. Akkas Ali (from the Bangladesh Agricultural Research Institute), Jiban Krishna Biswas (from the Bangladesh Rice Research Institute), Mahmuder Anwar, Zahangir Alam, and Razaul Hoque (from the Agricultural Information Service), and Ad Spijkers, Dr C.S. Karim, Tommaso Alacevich, Ciro Fiorillo, and Z Karim (from the Food and Agriculture Organization). Brooke Yamakoshi, Michael Westphal, and Siobhan Murray (World Bank) also provided valuable technical assistance during this study.

Finally, the authors are grateful for the support of the World Bank management team and several of the Bangladesh country office staff including: Zhu Xian (former Country Director), Robert Floyd, Adolfo Brizzi, Gajan Pathmanathan, John Henry Stein, Simeon Ehui, Karin Kemper, Masood Ahmad, Nihal Fernando, S.A.M. Rafiquzzaman, Shakil Ferdausi and Khawaja Minnatullah. Ryma Aguw, Tarak Chandra Sarker, Venkat Ramachandran and Talat Fayziev helped in the administration of this study. The photographs of various adaptation options were provided by the Department of Agricultural Extension, Ministry of Agriculture, Bangladesh and the Livelihood Adaptation to Climate Change (LACC-II) Project.

Generous support for this study was provided by the World Bank, the Global Facility for Disaster Reduction and Recovery (GFDRR), the Trust Fund for Environmentally and Socially Sustainable Development (TFESSD), the Economics of Adaptation to Climate Change (EACC) study team, and the Bank-Netherlands Water Partnership Program (BNWPP). We also acknowledge the Program for Climate Model

Diagnosis and Inter-comparison (PCMDI) and the WCRP Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, US Department of Energy.

This study is a product of the staff and consultants of the World Bank. The findings, interpretations, and conclusions expressed in this paper do not necessarily reflect the views of the Executive Directors of The World Bank or the governments they represent.

Foreword

This report is an important first step in better understanding how climate risks (both current and future) can undermine food security in Bangladesh. It identifies key areas that require concerted effort by the government and its many development partners.

The year 2007 was indicative of the development challenges that Bangladesh faces. Severe flooding from July to September 2007 along the Ganges and Brahmaputra rivers affected over 13 million people in 46 districts and caused extensive damage to agricultural production and physical assets. With hardly any time to recover, on 15 November 2007 the deadly Cyclone Sidr, a category IV storm, made landfall across the southern coast of the country, causing over 3000 deaths. The economic damages amounted to over US$1 billion, with over a million tons of rice destroyed. Then, the increase in international prices of oil and food, which Bangladesh imports, put further strains on both government budgets and household livelihoods.

The long-term economic consequences of these three simultaneous shocks remain to be seen, but they have shown the inherent vulnerability of Bangladesh to climate risks and the degree to which food security remains a major challenge for the country. With too much water during the heavy monsoon months and too little water during the spring and early summer months, communities have needed to adapt to changing conditions. They have done so by adopting new varieties of crops and new farming practices and by starting small businesses and trades to diversify incomes. Furthermore, over the last several decades the government has invested heavily and wisely to protect its citizenry to ensure growth and a prosperous nation. This includes investments in infrastructure, including embankments and cyclone shelters which have saved countless numbers of lives, in early warning systems to help the country prepare for imminent disasters, and polders to protect vital agricultural areas to maintain production to feed its population. The gains from these investments continue to support a growing nation.

Climate change, however, threatens to offset to some degree these important advances. The prospect of changing temperatures and precipitation patterns, the uncertainty of the timing and magnitude of extreme events, and rising sea levels will have important impacts on the agriculture sector. Action is needed today because Bangladesh will continue to depend on the agriculture sector for growth and poverty reduction. Investments from the public and private sectors will have to increase if Bangladesh is to ensure food security for its current and future populations.

The challenges that the agriculture sector will face as it adapts to climate change coincide well with the needs required to address the climate variability risks of today. Thus, the adaptation options identified are no-regret approaches and only a small example of what is possible. I hope that this report can serve as a useful and meaningful guide for Bangladesh (and other countries) in addressing a future uncertain world.

Isabel Guerrero

Isabel M. Guerrero
Vice President, South Asia Region, World Bank

Executive Summary

Background

Bangladesh is one of the countries most vulnerable to climate risks

From annual flooding to a lack of water during the dry season, from frequent coastal cyclones and storm surges to changing groundwater aquifer conditions, the importance of adapting to climate risks to maintain economic growth and reduce poverty is clear. Households have for a long time needed to adapt to these dynamic conditions to maintain their livelihoods. Moreover, substantial public investment in protective infrastructure (e.g. cyclone shelters, embankments) and early warning and preparedness systems has played and will continue to play a critical role in minimizing these impacts. In the long list of potential impacts from climate change, the risks to the agriculture sector stand out as among the most important.

Agriculture is a key economic sector in Bangladesh, accounting for nearly 20 per cent of the GDP (gross domestic product) and 65 per cent of the labour force

The performance of the sector has considerable influence on overall growth, the trade balance, the budgetary position of the government, and the level and structure of poverty and malnutrition in the country. Moreover, much of the rural population, especially the poor, is reliant on the agriculture sector as a critical source of livelihood and employment. Many also depend on the agriculture sector indirectly through employment in small-scale rural enterprises that provide goods and services to farms and agro-based industries and trades.

Climate is only one input factor in a sector that is already under pressure

The achievement of food self-sufficiency remains a key development agenda for the country. Significant progress has been made in the sector since the 1970s, in large part due to the rapid expansion of surface and groundwater irrigation and the introduction of new high-yielding crop varieties. The production of rice and wheat increased from about 10 million tonnes/metric tons (10Mt) in the early 1970s to almost 30Mt by 2001. The challenge now for Bangladesh is to enhance productivity, especially as demands for food increase with the growing population (1.3 per cent growth rate) and improved incomes. Moreover, overuse, degradation and changes in resource quality (e.g. salinity) will place additional pressures on already constrained available land and water resources.

Climate change is recognized as a key sustainable development issue for Bangladesh

Future climate change risks will be additional to the challenges the country and sector already face. Long-term changes in temperatures and precipitation have direct implications on evaporative demands and consequently on agriculture yields. Moreover, water-related disasters may increase in magnitude and frequency. Finally, sea level rise may have important implications for the sediment balance and may alter the profile of the area inundated and salinity in the coastal areas.

The objective of this study is to examine the implications of climate change on food security in Bangladesh and to identify adaptation measures in the agriculture sector

This objective is achieved in the following ways. First, the most recent science available is used to characterize current climate and hydrology and its potential changes. Second, country-specific survey and biophysical data is used to derive more realistic and accurate agricultural impact functions and simulations. A range of climate risks (i.e. warmer temperatures, higher carbon dioxide concentrations, changing characteristics of floods, droughts and potential sea level rise) is considered to gain a more complete picture of potential agriculture impacts. Third, while estimating changes in production is important, economic responses may to some degree buffer against the physical losses predicted, and an assessment is made of these. Food security is dependent not only on production stocks, but also future food requirements, income levels and commodity prices. Fourth, adaptation possibilities are identified for the sector. The framework established here can be used effectively to test such adaptation strategies. Multiple models are used in this integrated study, and as with all models, parameters may not be known with precision and functional forms may not be fully accurate; thus, careful sensitivity analysis and a full understanding of limitations (identified throughout the study) are required.

Vulnerability to Climate Risks (Chapter 2)

The performance of the agriculture sector is heavily dependent on the characteristics of the annual flood

Regular flooding of various types (e.g. flash, riverine) has traditionally been beneficial. However, low frequency but high magnitude floods can have adverse impacts on rural livelihoods and production (e.g. the 1998 flood resulted in a loss of over 2Mt of production). The timing of the peaks of the three major river systems (Ganges, Brahmaputra and Meghna) is an important determinant of the overall magnitude of flooding. The economy-wide impact of these extreme events can be substantial. Impacts on the 'aman' (monsoon season rice) and 'aus' (inter-season rice) are the primary drivers of declining overall production during major flood events (driven mainly by area changes); these losses, however, are increasingly being compensated for by 'boro' (dry season rice). As a result, compared to the pre-1990s, agricultural GDP is becoming less sensitive to this climate variability. Finally, droughts and coastal inundation from sea level rise can have consequences for agriculture production as large as those from floods.

Future Climate (Chapter 3)

Using global climate models (GCMs), a trend toward a warmer and wetter future climate is projected to impact the agriculture sector, particularly if the climate state goes beyond the variations found in the historical record

Median warming of 1.1°C, 1.6°C and 2.6°C by the 2030s, 2050s and 2080s respectively is projected from a range of plausible scenarios. Median annual precipitation increases of 1 per cent, 4 per cent and 7.4 per cent by the 2030s, 2050s and 2080s respectively is projected with greater contrasts between the wet and dry seasons. Greater model uncertainty (in terms of magnitude and direction) exists with future precipitation than future temperature. Simulated future temperature changes significantly separate from the background temperature variations. Precipitation is subject to large existing inter-annual and intra-annual variations. Projections of precipitation changes vary widely amongst models, with small median changes compared to historic variability. Using three scenarios of future sea level rise (15 cm, 27 cm, and 62 cm) the total area that perennially floods is projected to increase by 6%, 10%, and 20% respectively.

Future Floods (Chapter 4)

Primarily driven by increased monsoon precipitation in the Ganges-Brahmaputra-Meghna (GBM) basin, models on average demonstrate increased future flows in the three major rivers into Bangladesh (as much as 20 per cent)

Larger changes are anticipated by the 2050s compared to the 2030s. Larger changes are observed on average for the Ganges. The exact magnitude is dependent on the month. Given that most

GCMs project both an increasing trend of monsoon rainfall and greater inflows into Bangladesh, it follows that the flooding intensity would worsen. On average, models simulate increases in flooded area in the future (over 10 per cent by 2050). This is primarily located in the central part of the country at the confluence of the Ganges and Brahmaputra rivers and in the south.

Moreover, increases in yearly peak water levels are projected for the northern sub-regions and decreases are projected for the southern sub-regions. Not all estimated changes are statistically significant. Model experiments demonstrate more changes that are significant by the 2050s. Changes are in general less than 0.5m from the baseline. Furthermore, across the sub-regions, most GCMs show earlier onset of the monsoon and a delay in the recession of flood waters.

Future Crop Performance (Chapter 5)

The median of all rice crop projections shows declining national production, with boro showing the largest median losses

Potential future crop production is projected using well-developed crop models considering multiple climate impacts (temperature and precipitation changes, CO_2 fertilization, flood changes, sea level rise). For aus (-1.5 per cent) and aman (-0.6 per cent) the range of model experiments for the 2050s covers both potential gains and losses and does not statistically separate from zero. However, most GCM projections estimate a potential decline in boro production with a median loss of 3 per cent by the 2030s and 5 per cent by the 2050s. Wheat production is projected to increase out to the 2050s (+3 per cent). Boro and wheat changes are conservative as it is assumed that farmers have unconstrained access to irrigation. In each sub-region, production losses are estimated for at least one crop. The production in the southern sub-regions is most vulnerable to climate change. For instance, average losses in the Khulna region are -10 per cent for aus, aman and wheat, and -18 per cent for boro by the 2050s due in large part to rising sea levels. These production impacts ignore economic responses to these shocks (e.g. land and labour reallocation, price effects). These economic effects will to some degree buffer against the physical losses predicted.

Economy-wide Impacts of Climate Risks (Chapter 6)

Existing climate variability can have a pronounced detrimental economy-wide impact

This is explored using a dynamic computable general equilibrium (CGE) model. Compared to an 'optimal' climate simulation in which highest simulated yields are used and sector productivity and factor supplies increase smoothly at average long-term growth rates with no inter-annual variations, climate variability is estimated to reduce long-term rice production by an average 7.4 per cent each year over the 2005–50 simulation period. This primarily lowers the production of the aman and aus crop. Average annual rice production growth is lowered in all sub-regions. This simulated variability is projected to cost the agriculture sector (in discounted terms) US$26 billion in lost agricultural GDP during the 2005–50 period. This climate variability has economy-wide implications beyond simply the size-effect of the lost agricultural GDP. Existing climate variability is estimated to cost Bangladesh US$121 billion in lost national GDP during this period (US$3 billion per year). This is 5 per cent below what could be achieved if the climate were 'optimal'.

Climate change exacerbates the negative impacts of existing climate variability by further reducing rice production by a projected cumulative total of 80Mt over 2005–50 (about 3.9 per cent each year), driven primarily by reduced boro crop production

This is equivalent to almost 2 years worth of rice production lost over the next 45 years as a result of climate change. Uncertainty about future climate change means that annual rice production losses range between 3.6 per cent and 4.3 per cent. Climate change has particularly adverse implications for boro rice production and will limit its ability to compensate for lost aus and aman rice production during extreme climate events. This will further jeopardize food security in Bangladesh, necessitating greater reliance on other crops and imported food grains. Rice production in the southern regions of Patuakhali and Khulna is particularly vulnerable.

Overall, agricultural GDP is projected to be 3.1 per cent lower each year as a result of climate change (US$7.7 billion in lost value-added)

Climate change also has broader economy-wide implications. This is estimated to cost Bangladesh US$26 billion in total GDP over the 45-year period 2005–50, equivalent to US$570 million overall lost each year due to climate change, or alternatively an average annual 1.15 per cent reduction in total GDP. Average loss in agricultural GDP due to climate change is projected to be a third of the agricultural GDP losses associated with existing climate variability. Uncertainty surrounding GCMs and emission scenarios means that costs may be as high as US$1 billion per year in 2005–50 under less optimistic scenarios. Moreover, these economic losses are projected to rise in later years, thus underlining the need to address climate change related losses in the near-term.

These climate risks will also have severe implications for household welfare

For both the climate variability and climate change simulations, around 80 per cent of total losses fall directly on household consumption (cumulative total consumption losses of US$441.7 billion and US$104.7 billion for climate variability and climate change simulations respectively). Also, about 80 per cent of the economic losses occur outside of agriculture, particularly in the upstream and downstream agriculture value-added processing sectors. This means that both rural and urban households are adversely affected. Per capita consumption is projected to fall for both farm and non-farm households.

The southern and northwest regions are the most vulnerable

The south sits at the confluence of multiple climate risks, as shown throughout this study. These areas are expected to experience the largest decline in rice production due to climate change. This is for three reasons. First, these regions already experience significant declines in aus and aman rice production due to climate variability, which is expected to worsen under climate change. Second, boro yields are severely affected by changes in mean rainfall, temperature and mean shifts in the flood hydrographs. Thus, reductions in boro production limit the ability for these regions to compensate for lost aus and aman rice production during extreme events. The south is also affected the most by rising sea levels, which permanently reduce cultivable land. The largest percentage declines in per capita consumption are projected in these regions. Finally, the northwest is also vulnerable as the lost consumption is a large fraction of the existing household consumption. Adaptation measures should focus on these areas.

Adaptation Options in the Agriculture Sector (Chapter 7)

Adaptation options can address several different climate risks

Bangladesh will continue to depend on the agriculture sector for economic growth. Rural households will continue to depend on the agriculture sector for income and livelihoods. Though the government has made substantial investments to increase the resilience of the poor (e.g. new high-yielding crop varieties, protective infrastructure, disaster management), existing constraints in the sector may be exacerbated by long-term effects of climate change. The scale of current efforts remains limited and is not commensurate with the probable impacts. A no-regrets strategy is to promote activities and policies that help households build resilience to existing climate risks today.

Both processes of adapting to climate change and stimulating the agriculture sector to achieve rural growth and support livelihoods align well.

This requires, among other things, efforts to: diversify household income sources; improve crop productivity; support greater agricultural research and development; promote education and skills development; increase access to financial services; enhance irrigation efficiency and overall water and land productivity; strengthen climate risk management; and develop protective infrastructure. Moreover, the current large gap between actual and potential yields suggests substantial on-farm opportunities for growth and poverty reduction. Expanded availability of modern rice varieties, irrigation facilities, fertilizer use and labour could increase average yields at rates that could more than offset the climate change impacts. Significant additional planning and investments in promoting these types of adaptations are still needed.

The Way Forward (Chapter 8)

The precise impact of climate change on countries in the developing world remains to be seen. This much is known, however: climate change poses additional risks to many developing countries in their efforts to reduce poverty, promote livelihoods and develop sustainably. As populations grow, the ability for many countries to meet basic food requirements and effectively manage future disasters will be critical for sustaining long-term economic growth. These are challenges above and beyond those that many countries are already currently facing.

The integrated framework used in this analysis provides a broad and unique approach to estimating the hydrologic and biophysical impacts of climate change, the macro-economic and household-level impacts and an effective method for assessing a variety of adaptation practices and policies. The framework presented here can serve as a useful guide to other countries and regions faced with similar development challenges and objectives of achieving food security. Continued refinements to the assessment approach developed in this volume will further help to sharpen critical policies and interventions by the Bangladesh government.

Glossary of Terms

B. aman: broadcast aman; a rice crop usually planted in March/April under dry land conditions, but in areas liable to deep flooding. Also known as deep water rice. This crop is harvested from October to December. All varieties are highly sensitive to day length.

T. aman: transplanted aman; a rice crop usually planted in July/August, during the monsoon, in areas liable to a maximum flood depth of about 0.5m. This crop is harvested from November/December. Local varieties are sensitive to day length whereas modern varieties are insensitive or only slightly sensitive.

B. aus: broadcast aus; a rice crop planted in March/April under dry land conditions. Matures on pre-monsoon showers, harvested in June/July, and is insensitive to day length.

T. aus: transplanted aus; a rice crop, transplanted in March/April, usually under irrigated conditions, and harvested June/July. The distinction between late planted boro and early transplanted aus is academic since the same varieties may be used. Varieties are insensitive to day length.

Boro: a rice crop planted under irrigation during the dry season from December to March and harvested in April to June. Local boro varieties are more tolerant of cool temperatures and are usually planted early in areas which are subject to early flooding due to rise in river levels. Improved varieties, less tolerant of cool conditions, are usually transplanted from February onwards. All varieties are insensitive to day length.

Kharif: the wet season (typically March to October) characterized by monsoon rain and high temperatures.

Kharif 1: the first part of the kharif season (March to June). Rainfall is variable and temperatures are high. The main crops grown are Aus, summer vegetables and pulses. Broadcast aman and jute are planted.

Kharif 2: the second part of the kharif season (July to October) characterized by heavy rain and floods. T. aman is the major crop grown during the season. Harvesting of jute takes place. Fruits and summer vegetables may be grown on high land.

Rabi: The dry season (typically November to February) with low or minimal rainfall, high evapo-transpiration rates, low temperatures and clear skies with bright sunshine. Crops grown are boro, wheat, potato, pulses and oilseeds.

High yielding variety: introduced varieties developed through formal breeding programmes, they have a higher yield potential than local varieties but require correspondingly high inputs of fertilizer and irrigation water to reach full yield potential.

Local varieties developed and used by farmers: Sometimes referred to as inbred varieties or local improved varieties (LIVs).

Net cultivable area: total area which is undertaken for cultivation.

Acronyms

AIS Agricultural Information Service
AR4 Fourth Assessment Report
BARC Bangladesh Agricultural Research Council
BARI Bangladesh Agricultural Research Institute
BBS Bangladesh Bureau of Statistics
BCAS Bangladesh Centre for Advanced Studies
BINA Bangladesh Institute of Nuclear Agriculture
BMD Bangladesh Meteorological Department
BRRI Bangladesh Rice Research Institute
BWDB Bangladesh Water Development Board
CEGIS Center for Environmental and Geographic Information Services
CERES Crop Environment Resource Synthesis
CGE computable general equilibrium
CO_2 carbon dioxide
DAE Department of Agriculture Extension
DEM digital elevation model
DSSAT Decision Support System for Agrotechnology Transfer
ENSO El Niño-Southern Oscillation
FAO Food and Agriculture Organization
FCDI Flood control and drainage infrastructure
FFWC Flood Forecast and Warning Center
GBM Ganges-Brahmaputra-Meghna
GCM global climate model
GDP gross domestic product
GOB Government of Bangladesh
GTOPO Global Topography
HIES Household Income and Expenditure Survey
HYV high yielding variety
IFPRI International Food Policy Research Institute
IMF International Monetary Fund
IPCC Intergovernmental Panel on Climate Change
IWM Institute of Water Modelling
LACC Livelihood Adaptation to Climate Change
MJO Madden-Julian Oscillation
Mt million tonnes (million metric tons)
MPO Master Plan Organization
MSL mean sea level
NASA National Aeronautics and Space Agency
NCA net cultivable area
NGO non-governmental organization
PCMDI Program for Climate Model Diagnosis and Inter-comparison
RCM regional climate model

SAM social accounting matrix
SRES Special Report on Emissions Scenario
SRTM Shuttle Radar Topography Mission
TAR Third Assessment Report
TRMM Tropical Rainfall Measuring Mission
USGS United States Geologic Survey

1

Introduction

Bangladesh is one of the most vulnerable countries to climate risks, both from existing variability and future climate change. From annual flooding of all types to a lack of water resources during the dry season, from frequent coastal cyclones and storm surges to changing groundwater aquifer conditions, the importance of adapting to these risks to maintain economic growth and reduce poverty is clear. Households have for a long time needed to adapt to these dynamic conditions to maintain their livelihoods. The nature of these adaptations and the determinants of success depend on the availability of assets, labour, skills, education, and social capital. The relative severity of disasters has decreased substantially since the 1970s, however, as a result of improved macro-economic management, increased resilience of the poor and significant progress in disaster management. Substantial public investment in protective infrastructure (e.g. cyclone shelters, embankments) and early warning and preparedness systems have played a critical role in minimizing these impacts. More investments are still required. In the long list of potential impacts from climate change, the risks to the agriculture sector stand out as among the most important.

Agriculture is a key economic sector in Bangladesh, accounting for nearly 20 per cent of the GDP and 65 per cent of the labour force. The performance of the sector, here to include crops (70 per cent of agricultural GDP), livestock (10 per cent) and fisheries (10 per cent), has considerable influence on overall growth, the trade balance, the budgetary position of the government, and the level and structure of poverty and malnutrition in the country. Moreover, much of the rural population, especially the poor, is reliant on the agriculture sector as a critical source of livelihoods and employment. Many may also do so indirectly through employment in small-scale rural enterprises that provide goods and services to farms and agro-based industries and trades.

Climate is only one input factor in an agriculture sector that is already under pressure. The achievement of food self-sufficiency remains a key development goal for the country. Significant progress has been made in the sector since the 1970s, in large part due to the rapid expansion of surface and groundwater irrigation and the introduction of new high-yielding crop varieties. The production of rice and wheat increased from about 10 million tonnes/metric tons (10Mt) in the early 1970s to almost 30Mt by 2001. The challenge now for Bangladesh is to enhance productivity, especially as demands for food increase with the growing population (1.3 per cent growth rate) and improved incomes. Moreover, overuse, degradation and changes in resource quality (e.g. salinity) will place additional pressures on already constrained available land and water resources.

Future climate change risks will be additional to the challenges the country and sector already face. Long-term changes in temperatures and precipitation have direct implications on evaporative demands and consequently on agriculture yields. Increased carbon dioxide concentrations may also impact the rates of photosynthesis and respiration. Moreover, water-related disasters may increase in magnitude and frequency. In fact, between 1991 and 2000, 93 major disasters were recorded, resulting in billions of US$ in losses, most of which were in the agriculture sector. Sea level rise may have important implications on the sediment balance and may alter the profile of available land for production in the coastal areas. It is clear that climate change is a key sustainable development issue for Bangladesh (World Bank, 2000).

1.1 Objective of Study

The objective of this study is to examine the implications of climate change on food security in Bangladesh and to identify adaptation measures in the agriculture sector. This objective is achieved in the following ways. First, the most recent science available is used to characterize current climate and its potential changes. Second, country-specific survey and biophysical data is used to derive more realistic and accurate agricultural impact functions and simulations. A range of climate risks (i.e. warmer temperatures, higher carbon dioxide concentrations, changing characteristics of floods, droughts and potential sea level rise) is considered, to gain a more complete picture of potential agriculture impacts. Third, while estimating changes in production is important, this is only one dimension of food security considered here. Food security is dependent on several socio-economic variables including estimated future food requirements, income levels and commodity prices. Fourth, adaptation possibilities are identified for the sector. The framework established here can be used effectively to test such adaptation strategies.

1.2 Literature Review

Global changes in climate will have important implications for the economic productivity of the agriculture sector. The sector will be impacted by three primary water-related climate drivers. First, gradual changes in the distribution of precipitation and temperature will impact agriculture yield through possible changes in water availability and evaporative demands, tolerance of crops and incidence of pest attacks. Second, changes in the frequency and magnitude of extreme events (i.e. above-average floods, prolonged droughts) may result in additional shocks to the agriculture sector. The ability to recover from these short-term production losses and the impacts on long-term prospects is dependent on many macro and micro factors. Third, the prospects of sea level rise in the coastal areas will change the profile of available land for agriculture production and potentially the quality of groundwater used for irrigation. This is especially critical in land-constrained countries such as Bangladesh. Increases in carbon dioxide concentrations will also impact the rates of photosynthesis and respiration.

Much of the existing analysis on climate change impacts on the agriculture sector has primarily been focused on the first driver: changes in temperature and precipitation. Several global studies look at these impacts. For instance, Cline (2007) demonstrates using a range of methodologies and several global circulation models (GCMs) that agriculture production may decline in Bangladesh by as much as between 15 and 25 per cent. This study is dependent on global statistical production functions. Fischer et al (2002) derive similar estimates using an agro-ecological approach and the results from four global circulation models.

Several regional level studies also exist which show mixed responses to climate change. Lal et al (1998a,b,c) demonstrate that rice yields in neighboring India could decline by 5 per cent under a 2°C warming and CO_2 doubling. Karim et al (1994) indicated a decrease in potential yields for aman and boro rice in Bangladesh when only a 2°C or 4°C temperature change is considered, but this decrease was nearly offset when the physiological effect of 555 parts per million (ppm) CO_2 fertilization was taken into account. More recent results (Karim et al, 1998; Faisal and Parveen, 2003) show overall enhancement of potential rice yields but declines in potential wheat yields when 4°C temperature changes and 660ppm CO_2 fertilization are simulated. The offset potential by carbon fertilization effects remains an area of active research (Long et al, 2005;IPCC, 2007b; Tubiello et al, 2007a,b; Hatfield et al, 2008; Ainsworth et al, 2008).

Although it is clear that floods can affect agriculture production significantly, little is known about the incremental future damages from more frequent extreme events or increased discharges. Economic damages have been calculated after several recent extraordinary flood events (e.g. almost US$700 million in agriculture losses were reported after floods in 2004). Hussain (1995) developed a methodology to incorporate yield losses from annual flooding into a crop simulation model. Sea level rise and salinity intrusion implications on the agriculture sector are even less understood. Habibullah et al (1998) calculated that the loss of food-grain due to soil salinity intrusion in the coastal districts is about 200,000 to 650,000 tons.

1.3 Integrated Modelling Methodology

The methodology employed in this study includes several stages. Climate and hydrologic models are used to produce future scenarios of climate and land inundation (from floods and sea level rise) for various GCMs and emissions scenarios. Then, these are linked to crop models to produce physical estimates of climate- and flood-affected potential crop yield changes for the three main rice varieties and wheat. These yield estimates are based on climate and biophysical data for 16 agro-climatic sub-regions in Bangladesh and provide a picture of the geographic distribution of climate change impacts on the agriculture sector. Then, the economic implications of these projected crop yield changes are assessed using a dynamic computable general equilibrium (CGE) model. The CGE model estimates their economy-wide implications, including changes in production and household consumption for different sectors, household groups and agro-climatic sub-regions in the country. Additional impacts from extreme events are also considered here.

As noted, multiple models are used in the study. These are among the best mathematical representations available of the physical and economic responses to a variety of exogenous changes (here, climate). However, like all modelling approaches, uncertainty exists as parameters may not be known with precision and functional forms may not be fully accurate. Thus, careful sensitivity analysis and an understanding and appreciation of the limitations of these models (identified throughout the study) are required. Further collection and analysis of critical input and output observations (e.g. climate data, farm-level practices and irrigation constraints) will enhance this integrated framework methodology and future climate impact assessments.

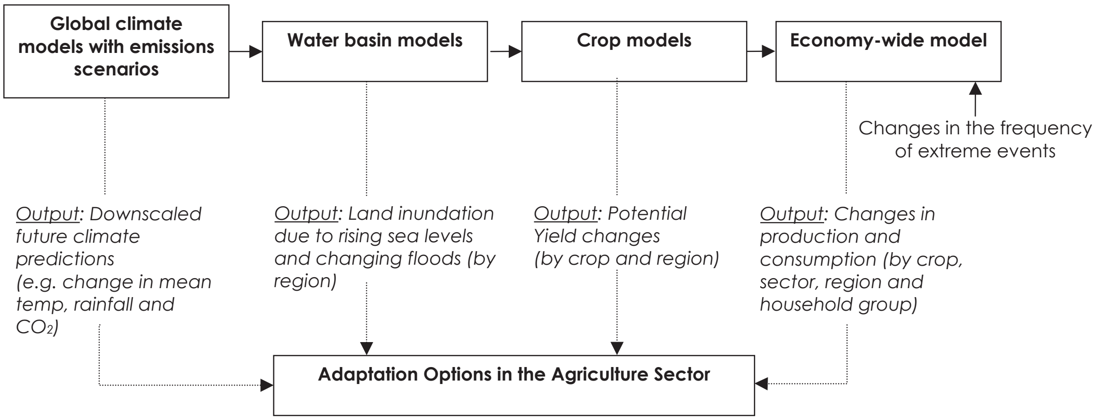


Figure 1.1 Integrated modelling framework

1.4 Organization of Study

This study is organized into seven further chapters. Chapter 2 sets the historical context of climate risks in Bangladesh. Past experience with floods, droughts, sea level rise and observed trends is reviewed. Broader regional issues are also briefly discussed. Chapter 3 reviews the predicted future changes in precipitation and temperature (both at the country level and at the Ganges-Brahmaputra-Meghna [GBM] river basin level). Chapter 4 presents an analysis on modelling the hydrology of future floods. This consists of both descriptions of a regional and national hydrologic models used and an analysis of the characteristics of the future floods both temporally and spatially. Among other aspects, the extent of the flood and the changes in the peak floods are analysed. A procedure for selecting a sub-set of global climate models is also presented as all available climate models could not be used. Chapter 5 describes the dynamic biophysical crop production models used. Here, various impacts of different climate risks (floods, droughts and sea level rise) on agriculture yields, focusing on rice and wheat, are incorporated. Chapter 6 describes a dynamic computable general equilibrium model used to evaluate the macro-economic and household welfare impacts of both climate variability and change-induced yield losses and gains. Chapter 7 presents potential adaptation options for the agricultural sector including unit costs that are currently being piloted in the field. Finally, in Chapter 8, the study concludes with general recommendations. Annexes provide additional information about using the crop models to test adaptation options and technical details of the CGE.

2

Vulnerability to Climate Risks

Box 2.1 Key messages

- Despite the challenging physiography and extreme climate variability, Bangladesh has made significant progress towards achieving food security. Investments in surface and groundwater irrigation and the introduction of high yielding crop varieties have played and will continue to play a key role in this.
- The performance of the agriculture sector is heavily dependent on the characteristics of the annual flood. Regular flooding of various types has traditionally been beneficial. However, low frequency but high magnitude floods can have adverse impacts on rural livelihoods and production.
- The timing of the peaks on the three major river systems (Ganges, Brahmaputra and Meghna) is an important determinant of the overall magnitude of flooding.
- The economic toll of these extreme events can be significant, the order of billions of US dollars.
- Aman and aus rice are the primary drivers of declining overall production during major flood events, which is increasingly being compensated for by boro rice. Agriculture share of total GDP is declining and is likely to continue to do so, thus increasingly insulating the country from these shocks.
- Lean-season water availability, particularly in the northwest, can have consequences on agriculture production comparable to floods.
- In coastal areas, agriculture productivity is affected by the surface and groundwater salinity distribution.
- Future regional changes in the Ganges-Brahmaputra-Meghna basin will play an important role in the overall timing and magnitude of water availability in Bangladesh.

Bangladesh is indeed a hydraulic civilization situated at the confluence of three great rivers – the Ganges, the Brahmaputra and the Meghna. Over 90 per cent of the Ganges-Brahmaputra-Meghna (GBM) basin lies outside the boundaries of the country. The extensive floodplains at the confluence are the main physiographic feature of the country. The country is intersected by more than 200 rivers; there are 54 rivers that enter Bangladesh from India alone. Moreover, more than 80 per cent of the annual precipitation of the country occurs during the monsoon period between June and September. These hydro-meteorological characteristics of the three river basins are unique and make the country vulnerable to a range of climate risks, including severe flooding and periodic droughts.

Most of Bangladesh consists of extremely low land. The capital city of Dhaka (population of over 12 million) is about 225km from the coast but within 8m above mean sea level (MSL). Land elevation increases towards the northwest and reaches a height of about 90m above MSL (Plate 2.1). The highest areas are the hill tracts in the eastern and Chittagong regions. The lowest parts of the country are in the coastal areas. These areas are particularly vulnerable to sea level rise and tidal storm surges.

Bangladesh has a humid sub-tropical climate. The year can be divided into four seasons: the relatively dry and cool winter from December to February, the hot and humid summer from March to May, the southwest summer monsoon from June to September and the retreating monsoon from October to November. The southwest summer monsoon is the dominating hydrologic driver in the GBM basin. The Tibetan Plateau, the Great Indian Desert and adjoining areas of northern and central India heat up considerably during the summers. This causes a low pressure area over the Indian subcontinent and western China which quickly fills with moisture-laden winds from the Indian Ocean. The Himalayas act like a wall, forcing moist air masses to rise in order to pass into the Tibetan Plateau. With the gain in altitude of the clouds, the temperature drops and moisture condenses into heavy precipitation. Some areas of the South Asia subcontinent can receive up to 10,000mm of rain.

2.1 The Success of Agriculture

Despite the challenging physiography and extreme climate variability, enormous success has been achieved in the last several decades, with the country largely food self-sufficient. Agriculture is the most important sector in the Bangladesh economy, contributing 19.6 per cent to the national GDP and providing employment for 63 per cent of the population. Rice is the dominant crop in Bangladesh. There are three major rice varieties: aman (flood season rice), boro (dry season rice) and aus (inter-period rice). The overall production of rice has increased from about 12Mt in 1981 to over 25Mt in 2001. Note that the population increased from 90 to 129 million over this same time period. The rice production growth rate from 1981 to 1991 was about 3 per cent per annum and increased to 4 per cent per annum. The introduction of high yielding varieties of aman and boro and groundwater irrigation (surface and groundwater) have significantly contributed to these gains. The aus crop has steadily decreased in response. Moreover, public investment in flood protection and drainage works have contributed to an overall increase in cropped area. Cropping intensity is at present about 180. Table 2.1 shows the production of the different crop varieties of rice.

Table 2.1 Production of different crop varieties (tonnes)

Crop Variety	1981	1991	2001
Local aus	2,176,670	1,630,006	980,650
HYV aus	1,044,810	690,590	934,950
B. aman	1,499,430	1,006,230	962,520
HYV aman	1,083,890	3,596,210	6,938,360
Local t. aman	4,309,705	3,923,520	3,348,050
Local boro	630,290	406,670	367,380
HYV boro	1,756,945	5,816,200	11,573,560
Total	12,501,740	17,069,426	25,105,470

Plates 2.2 and 2.3 show the spatial distribution of the aman (specifically transplanted aman, or t. aman) and boro cropped areas respectively in the country. The total aman rice area cultivated was 5,225,058ha in the year 2002. The aman crop is grown mostly in the northern and southern regions. The total cropped area dedicated to aman rice is also slowing. The total aus rice cropped area has declined significantly over the years. In 1981, it was 3.11 million hectares (Mha) and only 1.33Mha in 2001. The total boro rice area cultivated in Bangladesh was 3,973,414ha (31 per cent of the total country area) in the year 2002, with production concentrated mostly in the northern regions. Winter season boro cropping is reduced in the southwest due to the presence of saline water. The cropped area under boro has increased significantly over the years. In 1980, it was 1.15Mha and increased to 3.76Mha in 2000. This is in large part due to the expansion of groundwater irrigation (Plate 2.4). This has raised some concerns in terms of overall sustainability as water tables have fallen dramatically over the decades.

Besides rice, Bangladesh also produces a number of other crops of which wheat, maize, different types of pulses, oil seeds, jute, sugar cane, tea and tobacco are significant. It is found that production of wheat has increased from 0.97Mt in 1981 to 1.67Mt in 2001 (Plate 2.5). Maize production has also increased from 1.35 thousand tonnes in 1981 to 3.04 and 10.46 thousand tonnes in 1991 and 2001 respectively. Maize (mainly used for poultry feed) is particularly popular in the northwestern part of Bangladesh where droughts and high temperatures are common. Total production of pulses increased from 1981 to 1991 but declined from 1991 to 2001. Total production of different pulses was 0.20, 0.52 and 0.37Mt for the years 1981, 1991 and 2001 respectively. Production of sugar cane is typically between 6.5 and 7.5Mt and has showed a decline in recent years. Sugar cane is the primary input material for sugar mills operated by the public sector.

Historical climate variability and agricultural production

Figure 2.1 below shows historical agricultural GDP growth and total GDP growth. Despite the continued growth that Bangladesh has seen over the last three decades (i.e. Bangladesh has not seen a single year of negative growth since 1975), agricultural GDP growth remains highly erratic. Moreover, total GDP and agricultural GDP growth track fairly closely until the early 1990s, reflecting the steadily falling share of agriculture to total GDP as the economy becomes more diversified. Major floods are indicated by black dots in Figure 2.1. Until the 1990s, major floods resulted in sharp declines in agricultural GDP growth, with similar effects for total GDP. However, after 1990 the relative effects of major floods have diminished. Growth in fact remained positive even during the extraordinary flood of 1998.

The composition of rice production has clearly shifted towards greater reliance on boro rice (Figure 2.2). Major flood years are characterized by sharp declines in aman and aus production. By contrast, boro production is increasingly playing a compensating role, rapidly expanding production during major flood years. This is most evident in the 1998 flood (and to a lesser extent in the 1988 flood). Moreover, in years following a major flood, aman and aus production rebound as boro continues to grow.

The variability in aman production is even more pronounced when looking at the rice area under cultivation (Figure 2.3). Aman land area

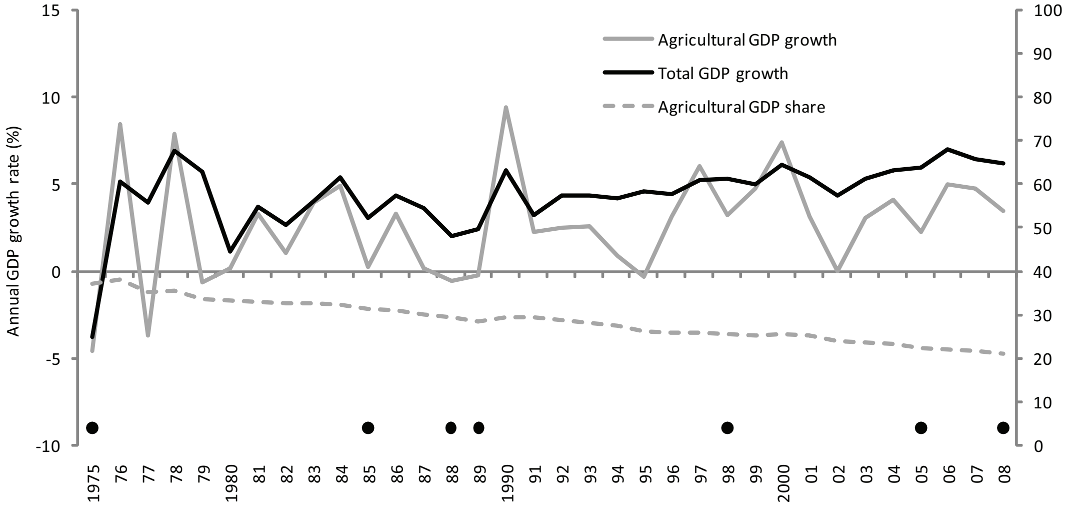


Figure 2.1 Agricultural and total GDP growth trends, 1975–2008

Note: Black dots represent years where the historical climate data indicate major flood occurrences; these are calendar years and represent the second part of a typical crop season (e.g. 1975 calendar year is the crop season 1974–5).

Source: Bangladesh Bureau of Statistics, 2009; World Bank, 2009.

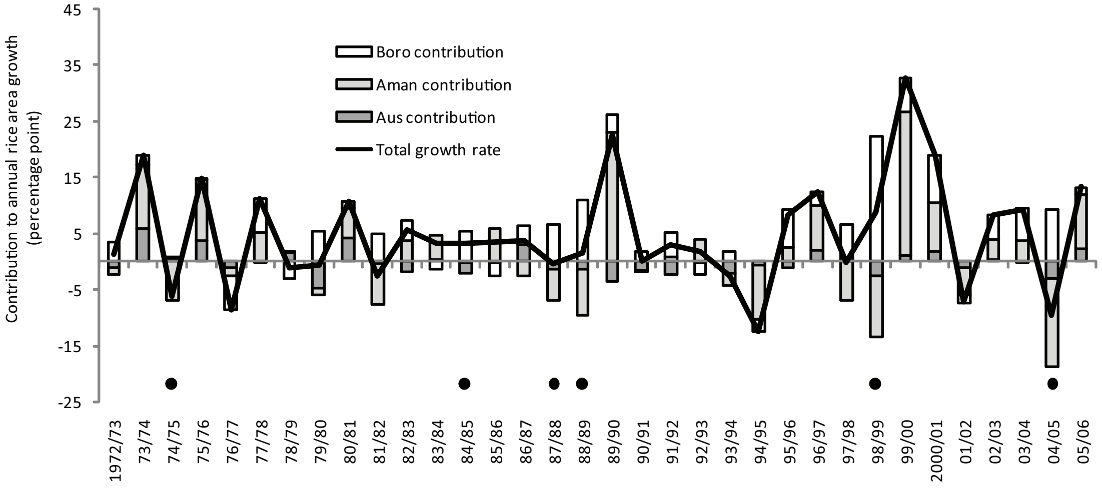


Figure 2.2 Historical trends in rice production quantities in Bangladesh, 1972–2006

Source: Bangladesh Bureau of Statistics, 2008c.

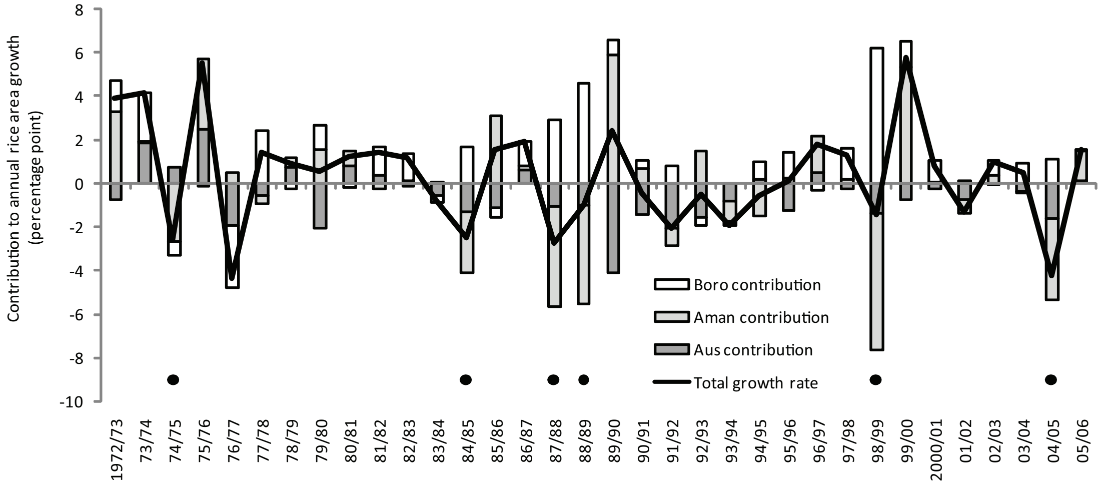


Figure 2.3 Historical trends in land area under rice cultivation in Bangladesh, 1972–2006

Source: Bangladesh Bureau of Statistics, 2008c.

drops dramatically during major flood years, driving almost the entire decline in overall production.

Decomposing the historical aman rice production into land area and yield contributions shows that both contribute to the decline of aman production during major flood years (Figure 2.4). However, in relative terms, the land area declines dominate the yield changes. In contrast, yield improvements dominate the recovery years after floods. Observed yields for rice and wheat in Bangladesh from 1985 to 2000 have improved marginally over time (Figure 2.5).

Actual yields are much lower than the potential yields (5–10kg/ha) observed at research plots under controlled field conditions (Sattar, 2000).

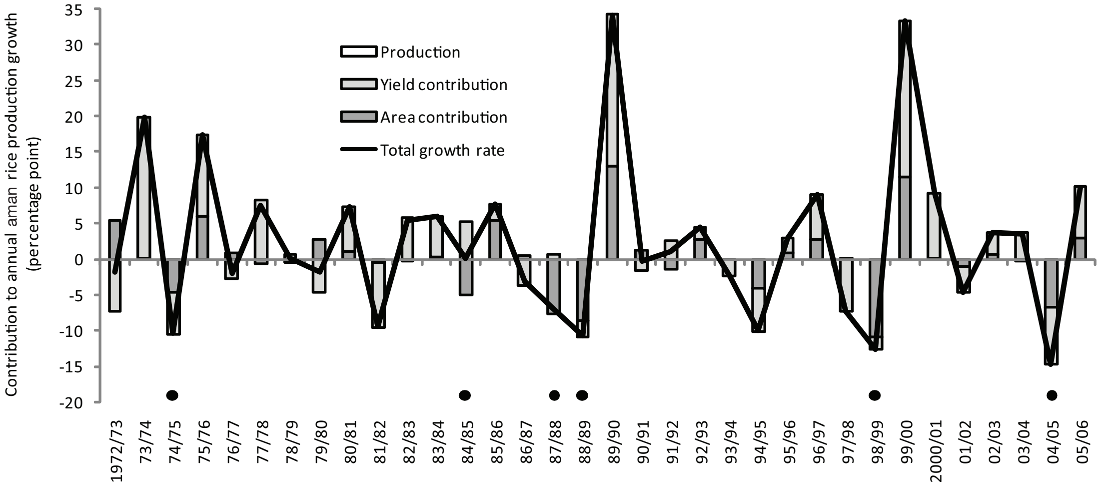


Figure 2.4 Decomposition of historical aman rice production trends into land area and yield contributions, 1972–2006

Source: Bangladesh Bureau of Statistics, 2008c.

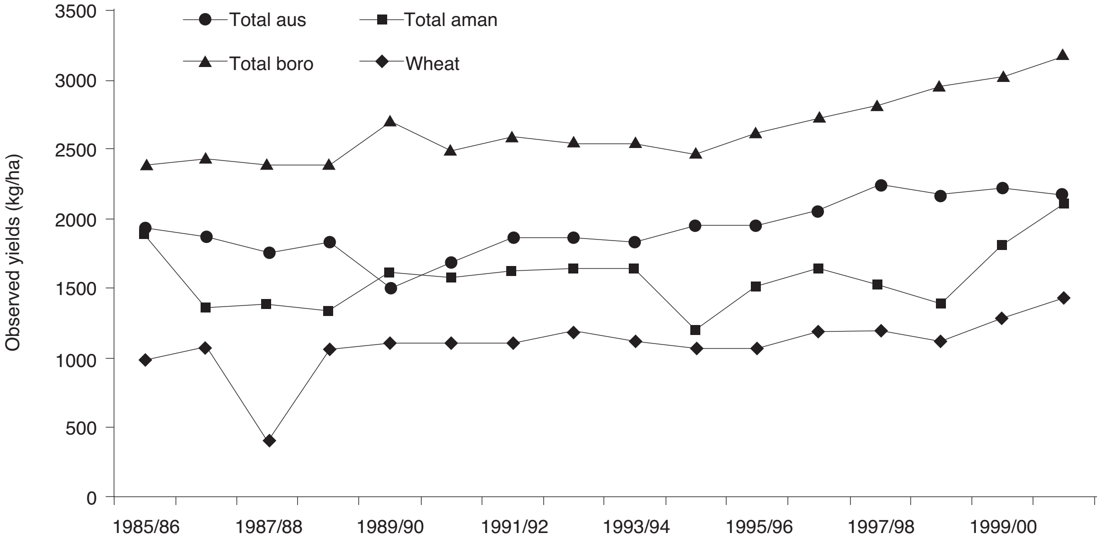


Figure 2.5 Observed yields for major staples (kg/ha)

Source: Bangladesh Bureau of Statistics, 2008c.

A major factor for this can be attributed to the ability of existing varieties of rice to withstand the annual variations in climate conditions (unfavourable temperatures, floods and droughts) as well as pests and disease pressures which vary from season to season. In addition, low levels of management play an important role including sub-optimal time of planting, use of poor quality seed, unbalanced use of fertilizers and other inputs, and failure to control weeds. In addition, many farmers have not yet adopted modern rice varieties. Soil-related factors include reduced organic matter content and the widespread occurrence of sulphur and zinc deficiencies. Mahmood et al (2003) noted a large yield gap in Bangladesh, with actual average yields approximately one-sixth of the potential yields produced under high-input conditions that were protected from floods. Closing this yield gap would lead to higher average production and enhanced climate resilience.

2.2 Living with Annual Floods[1]

Bangladesh is one of the most flood-prone countries in the world. The literature on floods in the country is extensive. Due to its location in the low-lying deltaic floodplains at the convergence of the Himalayan rivers, heavy monsoon rainfall concomitant with poor drainage often results in annual flooding. Exposure to storm surges in the coastal areas also exacerbates the severity of the floods. These river systems drain a catchment area of about 1.7 million km^2. The intensity of the floods is dependent on the magnitude and pattern of precipitation in the three river sub-basins. Among the peak discharge of the three rivers, the Brahmaputra contributes the greatest volume, 58 per cent, while the Ganges and Meghna contribute about 32 per cent and 10 per cent respectively. These floodplains are home to a large population (most of which is rural and poor) whose life is intricately linked to the flooding regime. Annual regular flooding has traditionally been beneficial, providing nutrient-laden sediments and recharging groundwater aquifers; while low frequency but high magnitude floods can have adverse impacts on rural livelihoods and production. Table 2.2 shows the classification of floods from Mirza (2002). About 26 per cent of the country is subject to annual flooding and an additional 42 per cent is at risk of floods with varied intensity (Ahmed and Mirza, 2000).

Table 2.2 Flood classifications

Types of Flood	Range of flooded area (km^2)	Range of percent inundation	Probability
Normal	31,000	21	0.50
Moderate	31,000–38,000	21–26	0.30
Severe	38,000–50,000	26–34	0.10
Catastrophic	50,000–57,000	34–38.5	0.05
Exceptional	>57,000	>38.5	0.05

Source: Mirza, 2002.

Historical records describe that five major floods occurred in the 19th century (1842, 1858, 1871, 1885 and 1892) and 16 such floods occurred in the 20th century (1900, 1902, 1907, 1918, 1922, 1954, 1955, 1956, 1962, 1968, 1970, 1974, 1984, 1987, 1988, 1998) (Rashid and Paul, 1987; Khalil, 1990; Haque, 1997; Chowdhury, 2000). Many of these serious floods can affect 35–75 per cent of the land area. The catastrophic flood of 1998 was the worst on record and lasted from the first week of July to the third week of September and was the most severe both in terms of depth and duration. It inundated more than 70 per cent of the total lands and caused severe damages to lives and properties. This flood alone caused 1100 deaths, flooded nearly 100,000km^2, affected 30 million people and impacted the property of about 1 million households. It also damaged 16,000km and 6000km of roads and embankments, respectively, and affected 6000km^2 of standing crop lands. A time-series of total area affected by floods is shown in Figure 2.6.

The relative severity of these disasters in Bangladesh has decreased substantially since the 1970s as a result of improved macro-economic management, increased resilience of the poor and progress in disaster management and flood protection infrastructure. Despite several major disasters, Bangladesh remains among the few countries that have avoided a single year of negative growth since the 1990s. Agricultural damage due to flooding has decreased with changes in cropping patterns, particularly the shift from deepwater aman rice (highly susceptible to floods) to boro rice, which is harvested before the monsoon season starts. Table 2.3 summarizes statistics from some recent large floods in the country.

Moreover, adequate reserves of food grains and increases in rice imports by both the public and private sectors have played a major role in managing any potential food insecurity following a flood event. This was evidenced following the 2004 and 2007 flood events which did not impact

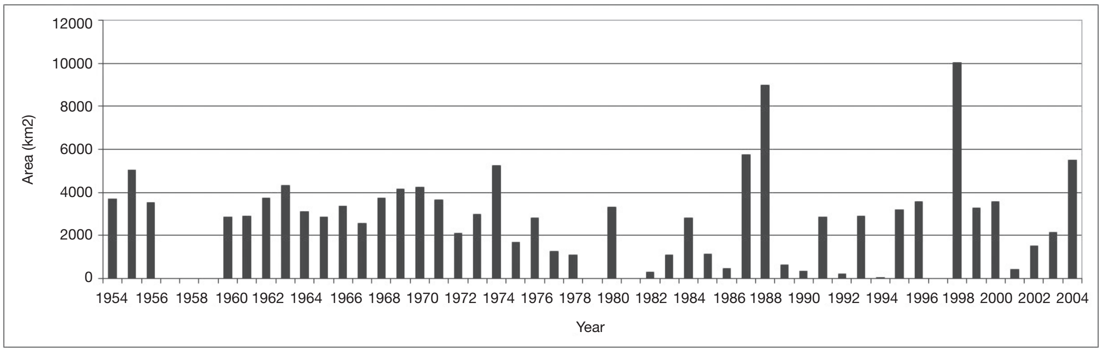


Figure 2.6 Time-series of flood-affected areas (km^2) in Bangladesh (1954–2004)

Table 2.3 Comparison of losses resulting from recent large floods

Item	1988	1998	2004	2007
Inundated area of Bangladesh (%)	60	68	38	42
People affected (million)	45	31	36	14
Total deaths (people)	2,300	1,100	750	1110
Livestock killed (nos)	172,000	26,564	8,318	40,700
Crops fully/partly damaged (million ha)	2.12	1.7	1.3	2.1
Rice production losses (million tons)	1.65	2.06	1.00	1.2
Roads damaged (km)	13,000	15,927	27,970	31,533
Number of homes fully/partly damaged (million)	7.2	0.98	4.00	1.1
Total losses:				
Tk (billion)	83	118	134	78
US$ (billion)	1.4	2.0	2.3	1.1

Source: World Bank (2007)

overall rice availability despite flood losses of over a million tons of rice. Some segments of the population (e.g. rural landless and small and marginal farmers), however, were adversely affected by changes in production and retail prices. Adequate access for these households depends on the level of income, purchasing power and available social safety nets.

Types of floods

Bangladesh can be divided into eight primary hydrological regions (see Plate 2.6). The northeast (NE) region is at the foot of the hill catchments in India. In this region flash floods are one of the major problems. The south-central (SC), southeast (SE), and river and estuarine (RE) regions in the coastal areas are mainly vulnerable to tidal flooding and salinity intrusion. The northwest (NW) is impacted most from lean-season water availability. Most regions are impacted by riverine flooding occurring during the monsoon period (May–September).

Observed historical trends with precipitation

Using data from 32 rainfall stations (both Bangladesh Meteorological Department [BMD] and Bangladesh Water Development Board [BWDB] stations) from 1960 to 2001, the national mean annual rainfall is 2447mm, with a maximum of 4050mm (in Sylhet, northeastern Bangladesh) and minimum of 1450 mm (in Rajshahi, northwestern Bangladesh). The maximum rainfall occurs during the June, July and August monsoon months (JJA). Neither the annual nor seasonal precipitation time-series show any statistically significant changes over this time period (Figure 2.7).

Observed historical trends with discharge

A summary of the extreme flood events on record and the observed peaks and corresponding dates are given in Table 2.4. In some cases, the discharges are almost twice the average, highlighting the extreme inter-annual variability characterizing these river systems. The 1987 flood was

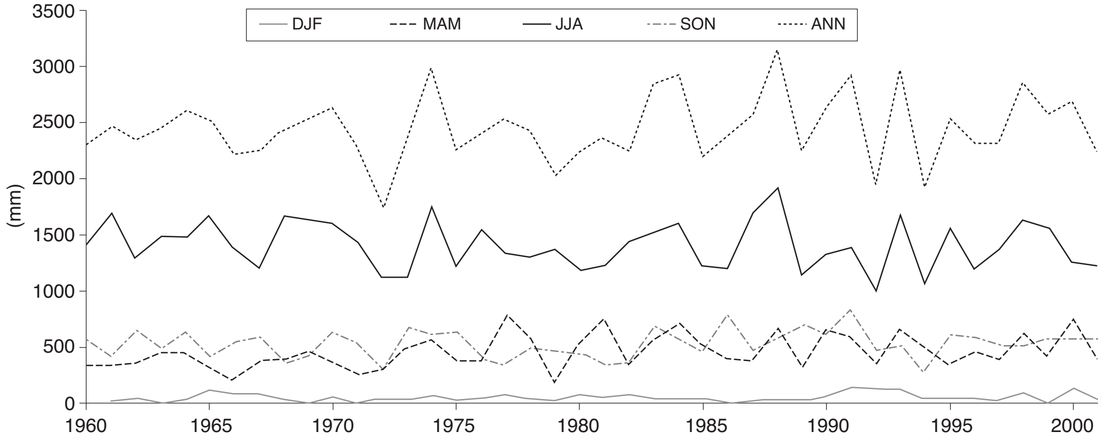


Figure 2.7 Annual and seasonal precipitation time-series (mm) averaged across Bangladesh Meteorological Department stations

Note: DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November.

Table 2.4 Peak discharge and timing during extreme flood years

Extreme Years	Brahmaputra		Ganges		Meghna		Return period	Return period
	Date	m^3/s	Date	m^3/s	Date	m^3/s	(area)	(vol)
1974	7 Aug	91,100	3 Sep	50,700	–	21,100	7.04	6.61
1980	20 Aug	61,200	22 Aug	57,800	7 Aug	12,400	2.31	2.12
1984	20 Sep	76,800	17 Sep	56,500	17 Sep	15,400	1.85	4.20
1987	16 Aug	73,000	20 Sep	75,800	4 Aug	15,600	9.44	9.77
1988	31 Aug	98,300	4 Sep	71,800	18 Sep	21,000	79.34	33.54
1998	9 Sep	103,100	11 Sep	74,280	–	18,600	100	51.60
2004	12 Jul	83,900	19 Jul	77,430	–	16,300	9.86	20.14
Average		67,490		51,130		13,370		
Min		40,900		31,500		7,940		
Max		103,130		77,440		21,070		

Source: BWDB.

primarily from the Ganges. In 1988, all three rivers had peaks within one week of each other. The 1998 flood discharge in the Ganges and Brahmaputra rivers was even higher. This particularly devastating flood was a result of a simultaneous peak in both the Brahmaputra and the Ganges rivers (Mirza, 2003). In 2004, the Ganges and Brahmaputra peaked early. Moreover, assuming a Gumbel Type I distribution, return periods (both in terms of total area affected and total volume discharge of the Ganges and Brahmaputra) can be estimated. The 1998 event is the 1 in 100-year event from the total area impacted perspective and the 1 in 50-year event from the discharge perspective.

Hydrographs for a normal year (2002) and an extreme year (1998) are also plotted for these locations in Figure 2.8. The historical water level data shows that the timing of the peak discharges on the Ganges, Brahmaputra and Meghna rivers on average do not coincide. The Brahmaputra starts rising in March due to snow melt in the

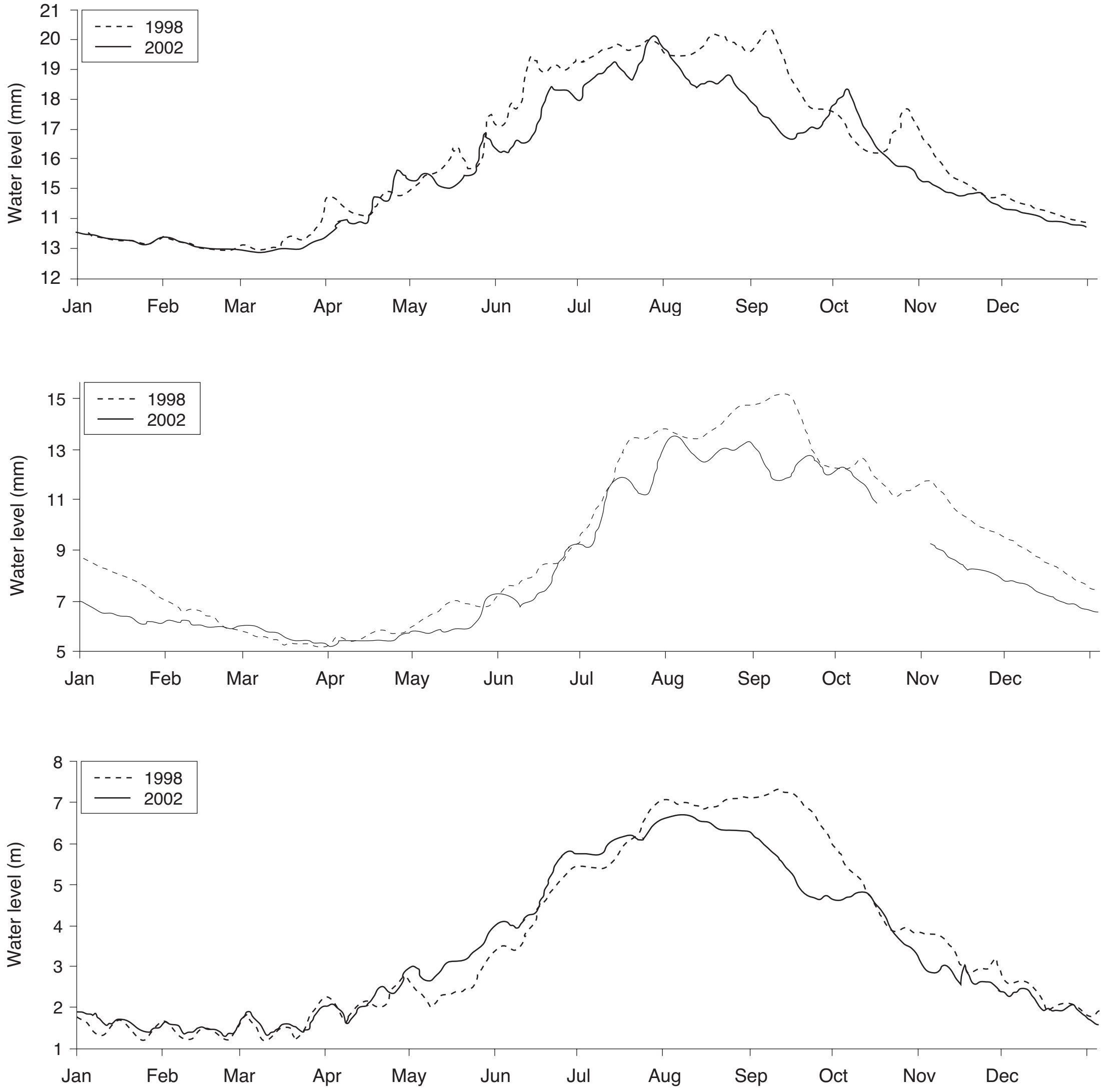


Figure 2.8 Average discharges in 1998 and 2002 for (a) Brahmaputra, (b) Ganges and (c) Meghna rivers

Source: BWDB.

Himalayas while the Ganges starts rising in early June with the onset of the monsoon. Monsoon rainfall occurs in the Brahmaputra and Meghna basins earlier than the Ganges basin due to the pattern of progression of the monsoon air mass. The flood peaks of the Brahmaputra occur in July and August, while peak flows occur in the Ganges in August and September.

Using available long-term records,[2] trends in peak discharges were statistically analysed. Though records show small increasing trends in peak discharges, these are not statistically significant except for the Ganges. Similarly, shifts in the timing of the peak are not statistically significant except for the Meghna (over the time period of record, the peak has shifted later by almost two months).

Flood determinants of agricultural performance

The performance of the agriculture sector is heavily dependent on the annual floods. If floods unexpectedly arrive early this will affect the harvesting of the boro crop while a late recession delays the transplanting of the aman crop. An indicator-based classification system for floods is used to characterize the primary flood determinants for agriculture performance (Hassan et al, 2007). These include onset and recession of flood waters, the observed peak discharge and the duration above a defined danger level. Table 2.5 represents a typical crop calendar for the major rice crops in Bangladesh. These planting practices are given graphically in Figure 2.9 for various flood land types.

The rice variety grown by farmers in large part depends on the normal flooding characteristics of the land. Flood land types were categorized more specifically by the Master Plan Organization (MPO, 1987) and are based on a three-day maximum flood depth with a return probability of

Table 2.5 Typical crop calendar for four different rice varieties

Crop	Seedling		Sowing/ transplanting date		Harvesting date	
	Start	End	Start	End	Start	End
Aus	20 Mar	20 Apr	20 Apr	20 May	20 Jul	20 Aug
T. aman	1 Mar	1 Apr	1 Apr	30 Apr	1 Jul	31 Jul
	1 Jun	15 Jul	1 Jul	31 Aug	1 Nov	15 Dec
B. aman	20 May	30 Jun	15Jul	15 Aug	15 Nov	31 Dec
	–	–	15 Mar	15 Apr	1 Nov	15 Dec
Boro	–	–	15 Mar	15 Apr	1 Nov	15 Dec
	20 Nov	20 Dec	1 Jan	31 Jan	1 May	31 May
	20 Nov	20 Dec	1 Jan	31 Jan	1 May	31 May
	–	–	1 Jan	31 Jan	1 May	31 May
	–	–	1 Jan	31 Jan	1 May	31 May
	–	–	15 Dec	15 Jan	15 Apr	15 May

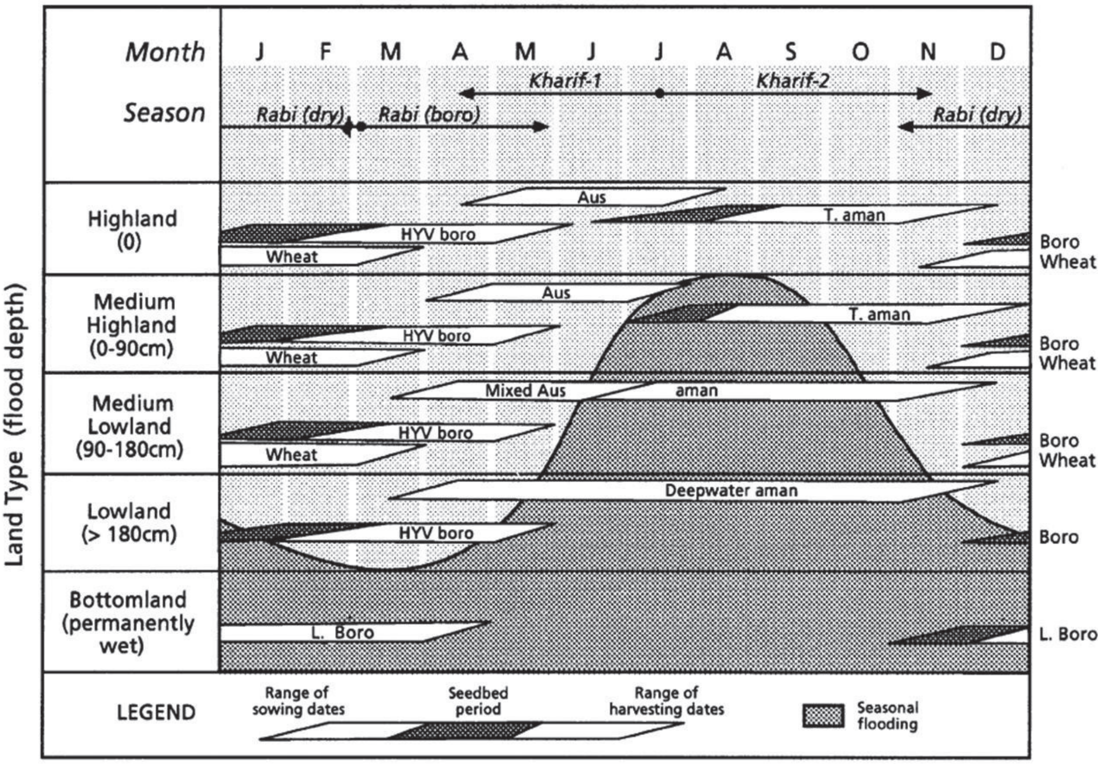


Figure 2.9 Cropping calendar corresponding to flood land type

Table 2.6 Hydrological regions and flood land types

Hydrological Region	Percentage (%) area				
	Highland F0 (0–30cm)	Medium Highland F1 (30–90cm)	Medium Lowland F2 (90–180cm)	Lowland F3 (180–300cm)	Very Lowland F4 (over 300cm)
Eastern Hill	85	14	1	0	0
North Central	24	59	13	4	0
Northeast	23	19	10	43	5
Northwest	33	57	6	4	0
River and Estuary	11	69	14	7	0
South Central	0	73	27	0	0
Southeast	18	54	17	8	2
Southwest	35	47	18	0	0
Bangladesh Total	29.98	48.39	12.65	8.10	0.88

one in two years. The five main flood land types include: F0 (0–30cm), F1 (30–90cm), F2 (90–180cm), F3 (180–300cm) and F4 (over 300cm). F0 is typically classified as *flood free*. These flood land types represent the average expected depth of inundation during a normal flood season. Table 2.6 describes the percentage distribution of areas for the eight hydrologic regions described earlier. On F0 lands the main crop is t. aman during the monsoon season and wheat and HYV boro in the rabi, or dry, season. Many of the same crops are also grown on F1 lands with the addition of some local varieties of aus. On F2 lands the main crop is b. aman during the monsoon season and similarly, wheat and HYV boro in the rabi. Many of the same crops are grown on F3 lands with the exception of wheat.

The aman crop is the main rice crop grown during the monsoon season. A major factor affecting the total production of aman during the kharif, or rainy, is the overall magnitude of the floods. Figure 2.10 shows the aman production losses (reported by the Bangladesh Bureau of Statistics [BBS]) as a function of the combined discharge in the Ganges and Brahmaputra. A statistically significant positive relationship is observed whereby an increase in flood discharges correlates with an exponential increase in production losses. The severe floods on record are also shown. The performance of the boro crop is more dependent on the availability of irrigation and lean-season water availability. Early flooding and flash floods areas may disrupt the harvesting of the boro.

2.3 Lean Season Water Availability

Bangladesh has a distinct dry season which occurs from November to May. This is typically most severe in the northwest portion of the country. Agricultural droughts are associated with the late arrival or the early recession of the monsoon rains and with intermittent dry spells coinciding with critical stages of the t. aman rice season. Droughts in May and June also impact broadcast aman and aus. Similarly, boro, wheat and other crops grown during the dry season are also directly affected by the lack of water availability (both surface and groundwater). The progressive development of groundwater for both rural water supply and agriculture during the last several decades has meant that dry season water availability is not the major threat that it used to be. Indeed, dry season agriculture has been the main source of increased food production over the past 20 years (Bangladesh Bureau of Statistics, 1998). However, declining groundwater tables in some places have begun to constrain production. Moreover, if in the future less water is available in the river systems, groundwater tables may decline even further, increasing the costs of production and limiting overall performance in the sector.

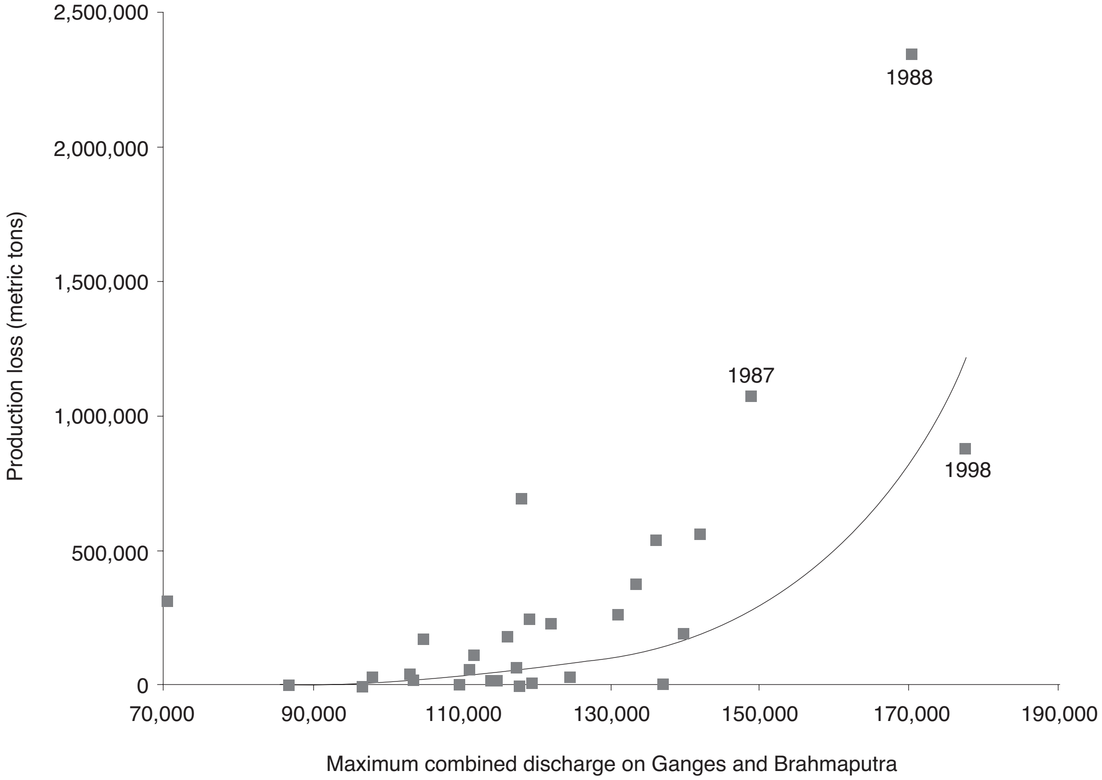


Figure 2.10 Aman crop production loss curve as a function of combined discharge

Bangladesh experienced droughts in 1973, 1978, 1979, 1981, 1982, 1989, 1994 and 1995. The droughts in 1973 were in part responsible for the famine in northwest Bangladesh in 1974. The 1978–9 drought was one of the most severe, resulting in widespread damage to crops (rice production was reduced by about 2Mt), and it directly affected about 42 per cent of the cultivated land. Rice production losses due to drought in 1982 were about 50 per cent more than losses due to floods that same year. Losses in 1997 were about 1Mt and valued at around US$500 million (Selvaraju et al, 2006).

The Bangladesh Agricultural Research Council (BARC) has identified and mapped the drought-prone areas of Bangladesh for the main cropping seasons in the country (based on estimated yield impacts) (Plate 2.7). About 2.7 million ha are vulnerable to annual drought; there is about a 10 per cent probability that 41–50 per cent of the country experiences drought in a given year. Areas of Bangladesh that are affected by drought during the different crop seasons are given in Table 2.7. About 18 per cent of the rabi crops and 9 per cent of the kharif crops are highly vulnerable to annual drought conditions.

Table 2.7 Summary of drought severity areas in Bangladesh by crop season (in Mha)

Drought Class	Rabi	Pre-Kharif	Kharif
Very Severe	0.446	0.403	0.344
Severe	1.71	1.15	0.74
Moderate	2.95	4.76	3.17
Slight	4.21	4.09	2.90
No Drought	3.17	2.09	0.68

2.4 Sea level Rise in Coastal Areas

Rising sea levels are one of the most critical climate change issues for coastal areas. The Intergovernmental Panel on Climate Change (IPCC, 2007a) projected that an average rise of 9 to 88cm could be expected by the end of the century. Recent projections suggest even more substantial rises (Copenhagen Diagnosis, 2009). Increasing temperatures result in sea level rise by the thermal expansion of water and through the addition of water to the oceans from the melting of continental ice sheets. A 1m sea level rise is estimated to impact 13 million people in Bangladesh, with 6 per cent of national rice production lost (Nicholls and Leatherman, 1995). Sea level rise may also influence the extent of the tides (currently the lower third of the country experiences tidal effects) and alter the salinity quality of both surface and groundwater. Currently, because of the low topography in these coastal areas, about 50 per cent typically becomes inundated during the annual monsoons.

Estimating the changes in area that will be inundated due to sea level rise is complicated by the active river morphology. With over a billion tons of sediment being deposited in the alluvial fan of Bangladesh (Goodbred and Kuehl, 2000), a combination of accretion and erosion processes will work to both increase and decrease the land area available in the coastal areas. For instance, satellite images from the coastal zone reveal that some land areas have gained while others have eroded over the last several decades (Plate 2.8). In the Meghna estuary specifically, about 86,000ha of land were lost between 1973 and 2000 (CEGIS, 2009). The relative contribution of these competing processes is largely unknown and an area for future research.

Observed sea level rise trends

Time-series data of daily mean water levels from 13 stations in the coastal zone were statistically examined (the locations are shown in Figure 2.11). Between 12 to 42 years of data are available

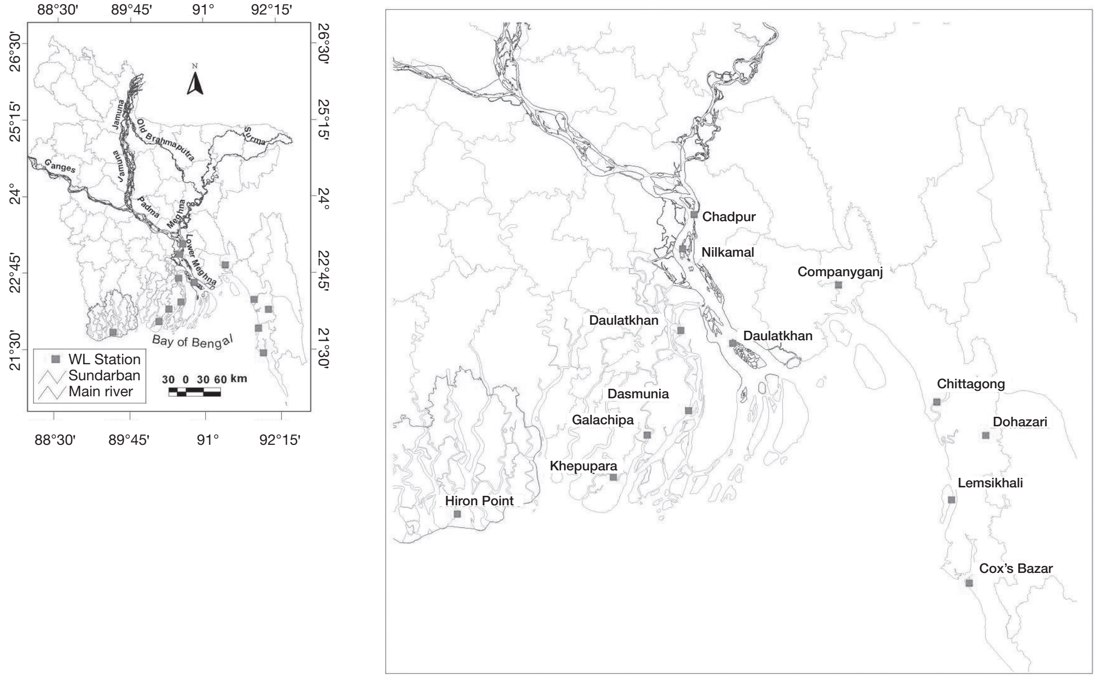


Figure 2.11 Locations of coastal water level stations

Table 2.8 Estimated trends in water level of different stations along the coastline

Station Name	Location of Station	Duration	No. of years	Trend (mm/yr)
Hiron Point	Passur	1977–2002	26	5.6*
Khepupara	Nilakhi	1959–86	22	2.9
Galachipa	Lohalia	1968–88	21	3.3
Dasmunia	Tentulia	1968–86	19	1.3
Kyoyaghat	Tentulia	1990–2002	12	3.6
Daulatkhan	Lower Meghna	1959–2003	31	4.3
Nilkamal	Lower Meghna	1968–2003	33	2.3
Chadpur	Lower Meghna	1947–2002	50	0.0
Companyganj	Little Feni Dakatia	1968–2002	32	3.9
Chittagong	Karnafuli	1968–88	16	3.1
Dohazari	Sangu	1969–2003	32	2.0
Lemsikhali	Kutubdia Channel	1969–2003	27	2.1
Cox's Bazar	Bogkhali	1968–91	22	1.4

*Statistically significant to $p<0.05$.
Source: BWDB, CEGIS (2006)

for these stations. The observed trends for these stations are reported in Table 2.8. These estimates range from a high of 5.6mm/yr at Hiron Point station to no change at the Chadpur station on the Meghna River. At the southeast corner of Bangladesh (Cox's Bazar station) sea level increased at a rate of 1.4mm/yr. In the middle of the south coastal zone (Companyganj station) sea level increased at a rate of 3.9mm/year. Though all of the linear trends are positive, only the trend at Hiron Point is statistically significant with 95 per cent confidence.

Observed salinity changes

Another important factor affecting agricultural productivity is the surface and groundwater salinity distribution. In particular, saline water intrusion along inland rivers is highly seasonal. Using a coastal model (IWM and CEGIS, 2007), it was determined that during the monsoon period (June to September) the Meghna estuary is hardly saline. The maximum salinity variation during the monsoon season in the coastal zone is presented in Plate 2.9. The 5 parts per thousand (ppt) isohaline (line of equal salinity level) intrudes more than 70km landward in the western part of Sundarbans, whereas comparatively higher freshwater flow through the primary Ganges channels pushes the 5ppt saline front towards the estuary mouth.

In contrast, during the dry season (December to March) saltwater intrusion occurs through various inlets in the western part of the coastal zone and through the Meghna estuary. The maximum salinity variation during the dry season is shown in Plate 2.10. The 5ppt isohaline intrudes more than 90km landward at the western part of the coastal area in the Sundarbans. Moreover, with decreases in freshwater flow in the Lower Meghna the saline front can move by as much as 30–40km from the coast. Table 2.9 shows the total area affected by low, moderate and high salinity level for a base condition in 2005 during both the monsoon and dry seasons. During the monsoon, about 12 per cent of the total area is under high salinity levels which increases to 29 per cent during the dry season. With increased sea level rise, drainage gradients may reduce, thereby decreasing the flow to the Bay of Bengal and allowing riverine salinity to move further inland.

Finally, high salinity groundwater is known to threaten drinking water wells in the coastal zone, particularly at shallow depths, and limit the possibility for groundwater irrigation for crop production. However, recent trends in the promotion of aquaculture (shrimp production, for example) have been one local adaptation meas-

Table 2.9 Area affected by low, moderate and high salinity level (in 2005)

Season		Total area (km^2)	Area affected (km^2)	Percentage of area affected (%)
Dry Season	0–1 ppt	Low	25,625	54
(Dec–Mar)	1–5 ppt	Moderate	7808	17
	>5 ppt	High	13,712	29
Monsoon Season (Jun–Sep)	0–1 ppt	Low	37,455	79
	1–5 ppt	Moderate	4063	9
	>5 ppt	High	5707	12

ure for coping with saline surface and groundwater. Deeper in the aquifer, at depths greater than 150m, groundwater is typically fresh, thus much of the groundwater used for drinking water supply is drawn from these depths.

2.5 Regional Hydrology Issues

Due to its location at the confluence of the Ganges, Brahmaputra and Meghna rivers, a discussion of water resources in Bangladesh is not complete without consideration of the broader basin region of which it is a part (Figure 2.12). This invariably requires an examination of its relationship with its neighbours: India, Nepal, China, Bhutan and Myanmar. The hydro-climatic, demographic and socio-economic features that characterize the patterns of water utilization in these shared river basins in the region have important implications for the overall quantity and quality of water resources available as well as for the relationships among and within riparian states.

The annual rate of population growth in each of these riparian nations is similar (about 1 per cent). Population increases throughout the basins, coupled with increased demand for agricultural production, municipal and industrial requirements, environmental flows and energy production, will contribute to increasing water demands. Upstream changes in water demand in the Ganges alone, which currently has a population of 500 million people and contains 82 large cities with populations of 100,000 people or more, will play a significant role in the provision and timing of water downstream in Bangladesh. Moreover, changes in the quality of the water that is returned to the system (e.g. irrigation and municipal return flows) may place further pressures on the gap between supply and demand for Bangladesh.

Balancing these future demands against future supplies may increasingly become difficult. Of particular importance to the region are the greater Himalayas where ten of the largest rivers in Asia begin (Amu Darya, Brahmaputra, Ganges, Indus, Irawaddy, Mekong, Salween, Tarim, Yangtze and Yellow rivers). These river basins are inhabited by over 1.3 billion people. Thus, this water 'tower' is critical to the overall economy of the region. With rising temperatures, it is reported that a rapid reduction in glaciers is being observed (Dyurgerov and Meier, 2005). With this glacier retreat, the rivers that originate at the glacier termini and derive significant volume of annual flow from glacier melt may experience profound downstream impacts on water resources. However, much more research is needed to determine the exact balance among glacier melt, snow and precipitation contributions to the available discharge in each of these rivers. Current estimates of glacier melt contribution to runoff are around 9 and 12 per cent for the Ganges and Brahmaputra respectively (Jianchu et al, 2007).

A major limitation currently is that these mountain systems are poorly understood. The Himalayas are characterized by a complex three-dimensional mosaic of meteorological and hydrological environments, ranging from tropical rainforests to alpine deserts, covering an altitudinal range of more than 8000m. Essential climate and hydrologic data is not readily available. The lack of a basic understanding of runoff sources and timing in these rivers makes it difficult to resolve questions relating to the overall water budget.

This map was produced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and anyother information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

Figure 2.12 Ganges-Brahmaputra-Meghna river basin

Source: World Bank

A final key factor influencing water availability and utilization patterns in the basin are changing water management practices, including the further development of new sources of supply (whether surface or ground) and infrastructure. Demands from the urban, agriculture, industrial and energy sectors will drive the development of new diversions, inter-basin transfers, storage facilities and other infrastructure, as well as further development of groundwater resources where available. This infrastructure may also be developed to strengthen the ability of individual riparian countries to manage floods and droughts, and to better allocate water to higher value uses (e.g. the transfer of water from agriculture to urban areas). In addition to supply management, conservation of water will also play an increasingly major role in changing practices in these basins, particularly with the adoption of micro-irrigation techniques, promotion of artificial groundwater recharge programmes and the planned reuse of water. All of these changing practices may impact the quantity and quality of water available to Bangladesh.

Notes

1 For an excellent historical discussion of floods in Bangladesh please refer to Hofer and Messerli (2007).

2 Bahadurabad, 1956–2004; Hardinge Bridge, 1934–2004; Bhairab Bazar, 1979–93.

3

Future Climate Scenarios

Box 3.1 Key messages

- Projected temperature changes follow a positive trend for all months and seasons from the 2030s onwards. Median warming of 1.1°C, 1.6°C, and 2.6°C by the 2030s, 2050s and 2080s respectively is simulated from a range of plausible scenarios.
- Few months or seasons display clear drying or wetting trends in simulations of the 2030s. By the 2050s, annual and wet season precipitation is projected to trend towards increased precipitation. Only simulations for the dry season do not suggest an increase in precipitation. Across the model experiments, precipitation variations are large. Median annual precipitation increases of 1 per cent, 4 per cent and 7.4 per cent by the 2030s, 2050s and 2080s respectively are projected.
- Greater uncertainty (in terms of magnitude and direction) exists with future precipitation than future temperature.
- A trend toward a warmer and wetter future climate is projected to impact the agriculture sector, particularly if the climate state goes beyond the variations found in the historical record. Projected future temperature changes significantly separate from the background temperature variations. Precipitation is subject to large existing inter-annual and intra-annual variations. Future precipitation projections vary widely amongst models, with small median changes compared to historic variability.
- Using three scenarios of sea level rise (15cm, 27cm and 62cm), total flooded area in the coastal areas is projected to increase 6 per cent, 10 per cent and 20 per cent respectively.

Several climate change scenarios for Bangladesh have been published in recent years. Agrawala et al (2003) examined the performance of 17 global climate models (GCMs)[1] over Bangladesh during the 20th century, then used several top-performing models to simulate future climate using the Intergovernmental Panel on Climate Change (IPCC) B2 emissions scenario (SRES, 2000).[2] The resulting mean annual temperature changes were 1.4°C by 2050 and 2.4°C by 2100, with higher increases in the wintertime. Annual precipitation rose by 5.6 per cent by 2050 and 9.7 per cent by 2100, with indications of winter drying and summer rainfall increases. These projected seasonal changes are consistently found across many studies of the South Asian monsoon region.

Tanner et al (2007) followed a similar approach, identifying 10 out of 18 models from the IPCC Third Assessment Report (TAR) (IPCC, 2001) to project into the future using the IPCC A2 and B1 scenarios. Assessments were made for the 2020s and 2050s for Bangladesh and cover the entire GBM basin. Temperatures in 2050 were projected to increase by an average of 1.6°C and 2.0°C in the B1 and A2 scenarios respectively, with corresponding increases in rainfall of 4 per cent and 2 per cent. An additional analysis was conducted to generate probability distribution functions of climate change in Bangladesh using the climate sensitivities of 23 IPCC TAR models, assuming that each model was an equally likely representation of each future scenario. Again, projected warming was more prevalent in winter

(December–February) than in summer (July–August) and the seasonal monsoon was intensified. Work has also been conducted using regional climate models (RCMs) to more accurately represent local processes and regional variations in Bangladesh. RCM experiments are driven by GCMs under particular emissions scenarios and therefore reflect, at least in part, GCM biases in simulating current and future climates. Islam et al (2005) used the PRECIS regional model to compare regional anomalies of temperature and precipitation. The use of regional models in climate projections for Bangladesh remains a key area for future research.

3.1 Future Estimated Precipitation and Temperature

Sixteen GCMs were analyzed from the Program for Climate Model Diagnosis and Inter-comparison (PCMDI, www-pcmdi.llnl.gov) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al, 2007), each run for three emissions scenarios (A1B, A2 and B1) and a 20th-Century Experiment. Table 3.1 describes the models used, their known climate sensitivities and the resolution of their atmospheric output. The model output consists of monthly averages of simulated precipitation and temperature, with this study using a maximum total of 64 scenario experiments (16 models x 3 emissions scenarios + 16 baseline states). Resolution varies among these models with about five grid boxes typically covering the country. A weighted average was used to calculate national values for the country, with weights determined by the percentage that each grid box overlaps with the country. Variations in space tend to be small relative to variations across models and time. The following time slices are defined as follows and referenced by their central decade:

- GCM Baseline: 1970 to 1999,
- GCM 2030s scenario: 2020 to 2049,
- GCM 2050s scenario: 2040 to 2069,
- GCM 2080s scenario: 2070 to 2099.

Future changes in temperature and precipitation for the decades of the 2030s, the 2050s and the 2080s are calculated for each model relative to

Table 3.1 IPCC AR4 global circulation models

GCM Name	Institution	Atmospheric Resolution (lat, lon, °)	Climate Sensitivity (°C)*
bccr_bcm2.0	Bjerknes Centre for Climate Research, Norway	2.8 x 2.8	–
cccma_cgcm3.1(T63)	Canadian Centre for Climate Modelling and Analysis, Canada	3.75 x 3.75	3.4
cnrm_cm3	CERFACS, Centre National Weather Research, METEO-FRANCE, France	2.8 x 2.8	–
csiro_mk3.0	CSIRO Atmospheric Research, Australia	1.88 x 1.88	3.1
gfdl_cm2.0	Geophysical Fluid Dynamics Laboratory, USA	2 x 2.5	2.9
gfdl_cm2.1	Geophysical Fluid Dynamics Laboratory, USA	2 x 2.5	3.4
giss_model_er	NASA Goddard Institute for Space Studies, USA	4 x 5	2.7
inmcm3.0	Institute for Numerical Mathematics, Russia	4 x 5	2.1
ipsl_cm4	Institut Pierre Simon Laplace, France	2.5 x 3.75	4.4
miroc3.2 (medres)	Center for Climate System Research; National Institute for Environmental Studies; Frontier Research Center for Global Change, Japan	2.8 x 2.8	4.0
miub_echo_g	Meteorological Institute of the University of Bonn, Germany	3.75 x 3.75	3.2
mri_cgcm2.3.2a	Meteorological Research Institute, Japan	2.8 x 2.8	3.2
mpi_echam5	Max Planck Institute for Meteorology, Germany	1.878 x 1.88	3.4
ncar_pcm1	National Center for Atmospheric Research, USA	2.8 x 2.8	2.1
ncar_ccsm3.0	University Corporation for Atmospheric Research, USA	1.4 x 1.4	2.7
ukmo_hadcm3	Hadley Centre for Climate Prediction, Met Office, UK	2.5 x 3.75	3.3

* Climate sensitivity parameter defined as temperature increase for a doubling of atmospheric carbon dioxide.

the same model's 1970–99 baseline period. These 30-year periods are used to reduce the effects of large year-to-year variation that can obscure mean climate changes.

Figure 3.1 shows the projected monthly, annual and seasonal temperature changes. Temperature changes are clearly following a positive trend for all months and seasons from as early as the 2030s, but do not show any obvious seasonal structure. Enhanced warming during the dry winter months is evident by the 2050s, although the model simulations are distributed more widely in these months. Temperature changes are positive for every model experiment and every month by the 2080s, with a clear seasonal variation in magnitude. Median warming of 1.1°C, 1.6°C and 2.6°C by the 2030s, 2050s and 2080s respectively fall into the range of previously published literature for Bangladesh.

The monthly, annual and seasonal precipitation change projections for the 2030s, 2050s and 2080s compared to 1970–99 is shown in Figure 3.2. Deviations for each time period are displayed as the percentage change from their baseline average. Despite only small changes in actual magnitude, rainfall deviations in the dry months of the year appear as very large percentage changes due to the low baseline average. These dry season totals would not have any noticeable impact on the annual rainfall totals, but could still have significant ramifications for the severity of droughts. Conversely, simulated rainfall deviations in the wet season have to be very large to produce high percentage changes.

Few months or seasons display clear drying or wetting trends in simulations of the 2030s. By the 2050s, however, annual and wet season precipitation trend towards increased precipitation in the set of climate change scenarios (though some models do continue to show decreases in precipitation). Only simulations for the post-monsoonal rabi dry season (when boro and wheat are grown) do not suggest a rise in precipitation. An enhancement of the monsoonal circulation (IPCC, 2007a) widens the discrepancy between wet and dry seasons in the 2080s, and by then the annual and monsoon season precipitation changes are clustered around positive trends. Median precipitation enhancements of 1 per cent, 4 per cent and 7.4 per cent by the 2030s, 2050s and 2080s respectively fall into the range of previously published literature for Bangladesh.

Comparison to historical variability

A trend towards a warmer and wetter future climate will impact the agriculture sector in Bangladesh, particularly if the climate state goes beyond the precedent variations found in the historical record. Warming is projected to generally accelerate over the 21st century, although the model-based probability distribution widens. By the 2030s, the median temperatures in July, August and September of the future model distribution surpasses the 90th percentile of the historical temperature variability. Moreover, looking at the monsoon and dry seasons, by the 2080s the 10th percentile of the future model distribution surpasses the 90th percentile of the historical variability. That is, the estimated future temperature significantly separates from the background variations.

The future changes in precipitation are compared to the inter-annual and inter-seasonal variability determined for the 40-year period discussed earlier. Precipitation is subject to large existing variation in the historical record (Table 3.2). Differences in the monsoon structure and the influences of large-scale circulation patterns like the Madden-Julian Oscillation (MJO) and the El Niño-Southern Oscillation (ENSO) contribute to this background variability. Despite the consistently noted enhancement of the monsoonal circulation pattern that leads to a drying trend during the winter months and increased rainfall during the monsoons in the climate scenarios of the 2030s, 2050s and the 2080s, precipitation does not separate itself from the historical variability for any month or season. These findings are consistent with the general finding that greater uncertainty exists with the estimated magnitude of precipitation change than temperature change and that existing rainfall variability is substantial.

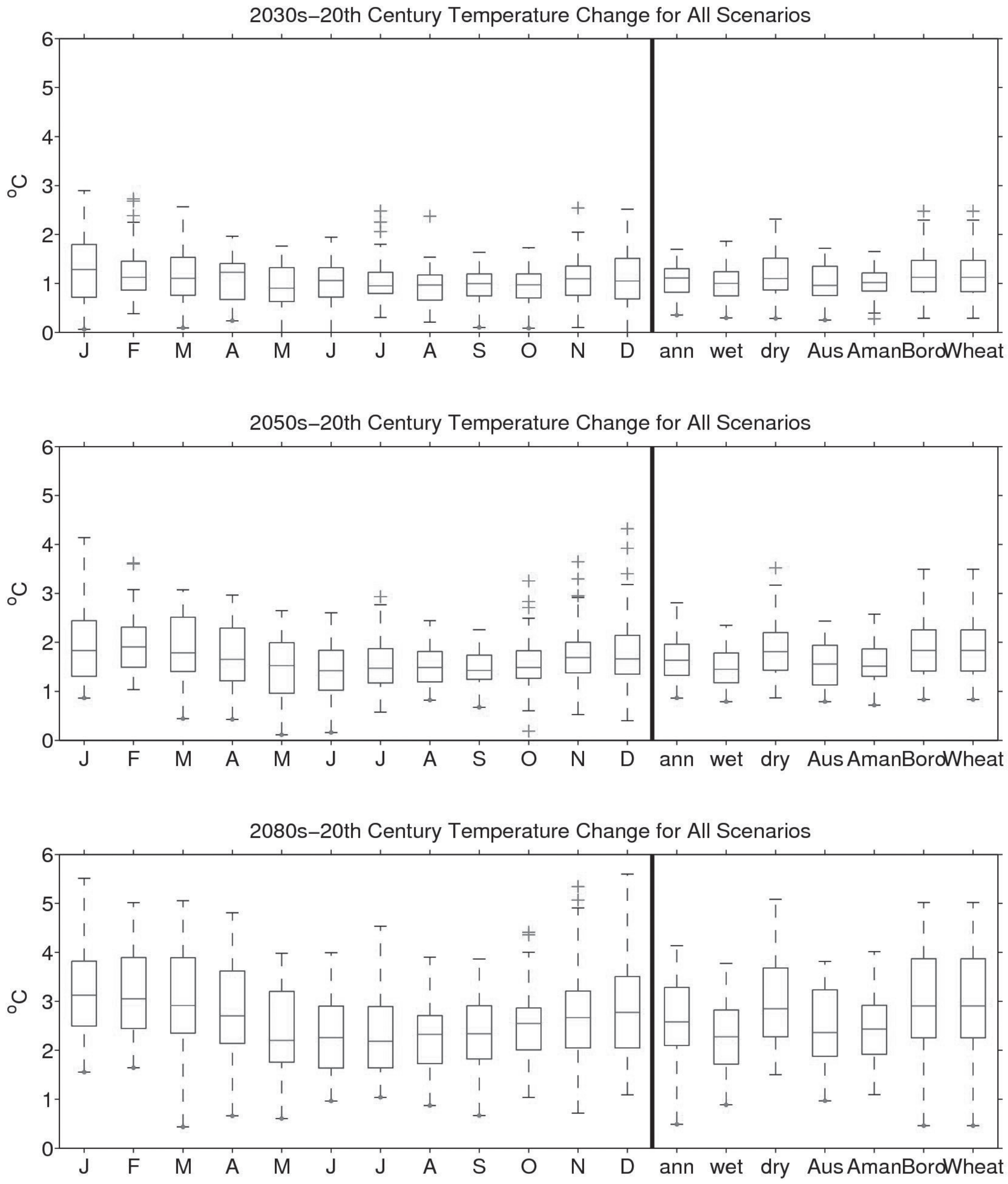


Figure 3.1 Monthly, annual and seasonal temperature changes

Note: The box and whiskers diagram consists of a line representing the median value, a box enclosing the inter-quartile range, dashed whiskers extending to the furthest model that lies within 1.5 times the inter-quartile range from the edges of the box, and plus symbols for additional models that are perceived as outliers.

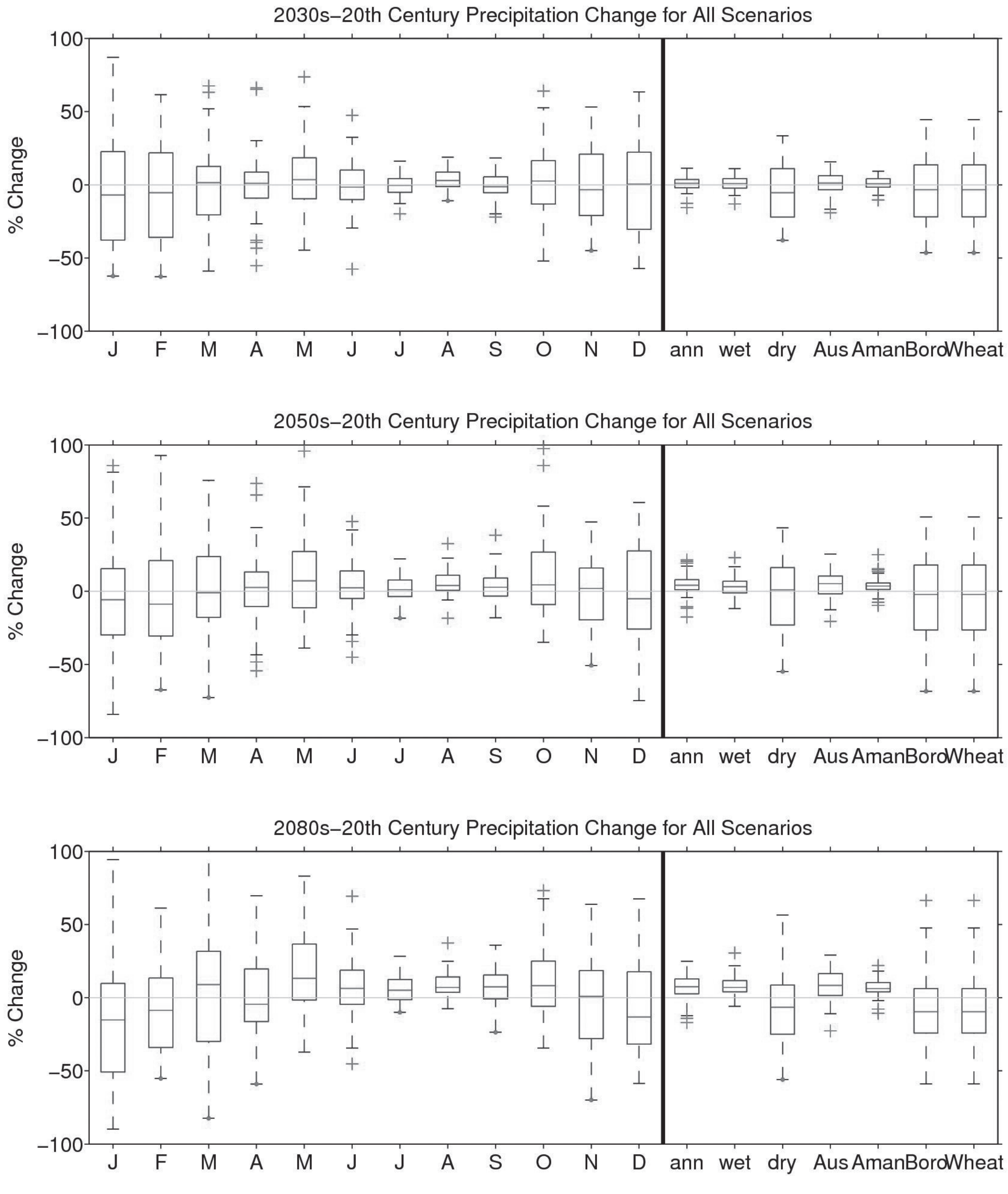


Figure 3.2 Monthly, annual and seasonal precipitation changes

Note: The box and whiskers diagram consists of a line representing the median value, a box enclosing the inter-quartile range, dashed whiskers extending the to the furthest model that lies within 1.5 times the inter-quartile range from the edges of the box, and plus symbols for additional models that are perceived as outliers.

Table 3.2 Summary precipitation statistics averaged across Bangladesh (1960–2001)

	DJF	MAM	JJA	SON	Annual
Average (mm)	53	460	1406	530	2447
Standard deviation (mm)	36	149	216	125	306
Coefficient of variation	68%	32%	15%	24%	12%
90% percentile	118	672	1684	669	2910
75% percentile	72	572	1584	608	2593
10% percentile	21	312	1149	361	2199

Source: Bangladesh Meteorological Department.

Table 3.3 Sea level rise impacts on flood land types

	F0 (0–30cm)	F1 (30–60cm)	F2 (60–90cm)	F3 (90–180cm)	F4 (+180cm)	Flooded Area (F1+F2+F3+F4)	% of total
Base	15,920	4753	4517	5899	1759	16,928	52
15cm	14,841	4522	4705	6765	2015	18,007	55
27cm	14,189	4345	4488	7456	2370	18,659	57
62cm	12,492	3967	3818	8977	3594	20,356	62

Note: Note that the flood land type classes used in IWM and CEGIS (2007) are slightly different than the MPO definitions.

3.2 Future Sea level Rise

This section draws upon a previous coastal zone modelling effort (using the MIKE21 two-dimensional estuary model, IWM and CEGIS, 2007) for 15cm, 27cm and 62cm sea level rise scenarios. Using these scenarios, the changes in total flood land type area is given in Table 3.3. Of a total 33,000km^2 in these coastal areas, over half is annually flooded. With an extreme rise of 62cm, an increase in 10 per cent of flooded area is anticipated. The geographic distribution of this is shown in Plate 3.1. Under the 62cm rise scenario, districts where it is projected that the flooded area will increase by more than 10 per cent include: Bagerhat (22 per cent), Barisal (23 per cent), Bhola (14 per cent), Cox's Bazar (10 per cent), Khagrachhari (13 per cent) and Noakhali (12 per cent). In general, with sea level rise, the total flooded area increases by 6, 10 and 20 per cent for each of the scenarios respectively, with the largest increases observed in the southernmost regions. The largest percentage increases in area are observed for the F4 (+180cm) flood land class.

While these scenarios could be appropriate, more detailed local-scale sea level rise estimates can be developed. One approach is to downscale AR4 GCM simulations to the Bangladesh region using the IPCC four-factor method, which includes: 1) sea level rise components for global thermal expansion; 2) local land processes including accretion, erosion and subsidence; 3) melt-water from glaciers, ice caps and ice sheets; and 4) coastal circulation patterns as affected by currents, tides and weather. This approach has been used by, for example, the University of Washington Climate Impacts Group (2008) and the New York City Panel on Climate Change (2009). Other approaches include the empirical Rahmstorf (2007) method as applied to AR4 climate models (Horton et al, 2008) and the rapid ice-melt scenarios (New York City Panel on Climate Change, 2009). These three approaches are compared in New York City Panel on Climate Change (2009).

Notes

1 Global climate models feature interactions between the atmosphere and oceans and account for forcings from the sun, natural as well as anthropogenic sources of greenhouse gas and aerosols emissions, and internal variability of the climate system.

2 The A1B, A2 and B1 emissions scenarios used in this study each project different developmental paths for global society by forcing the GCMs with greenhouse gas emissions determined by particular developmental storylines. Each represents a unique blend of demographic, social, economic, technological and environmental assumptions. The three scenarios are briefly described as follows: A1B – rapid economic growth is partially offset by rapid introduction of new and efficient technologies and decreases in global population after 2050. This trajectory is associated with relatively rapid increases in greenhouse gas emissions, and the highest overall CO_2 levels for the first half of the 21st century, followed by a gradual decrease in emissions after 2050. A2 – relatively rapid population growth and limited technological change combine to produce the highest greenhouse gas levels by the end of the 21st century, with emissions growing throughout the entire century. B1 – this scenario features what is considered a low population projection, combining low fertility and mortality. Under this scenario, global population peaks at 8.6 billion mid-century and then declines to 7.1 billion by 2100. When combined with societal changes tending to reduce greenhouse gas emissions, the net result is relatively low greenhouse gas concentrations with emissions beginning to decrease by 2040.

4

Future Flood Hydrology

Box 4.1 Key messages

- Primarily driven by increased monsoon precipitation in the GBM basin, models on average demonstrate increased flows in the three major rivers into Bangladesh (by as much as 20 per cent). Larger changes are anticipated by the 2050s compared to the 2030s. Larger changes are observed on average for the Ganges. The exact magnitude is dependent on the month.
- On average, models demonstrate that the flooded area increases in the future (over 10 per cent by the 2050s). This is primarily in the central part of the country at the confluence of the Ganges and Brahmaputra rivers and in the south. Flood area estimates separate from the background variations primarily in August and September at the height of the monsoon.
- Increases in yearly peak water levels are estimated for the northern sub-regions and decreases are estimated for the southern sub-regions. Not all estimated changes are statistically significant. More model experiments demonstrate changes that are significant by the 2050s than by the 2030s. Changes in the peak are in general less than 0.5m from the baseline.
- Across the sub-regions, most GCMs show earlier onset of the monsoon and a delay in the recession of flood waters.

Given the importance of flooding to overall agriculture production, special effort was made to model the future flood hydrology under various climate change scenarios for the flood monsoon months (i.e. May–September). To do this, three sequential steps are taken: (1) a sub-set of climate change scenarios are selected; (2) flows into Bangladesh are generated using a Ganges-Brahmaputra-Meghna (GBM) river basin model; and (3) hydrologic changes within the country are generated using a national river network model.

4.1 GBM Basin Model Development

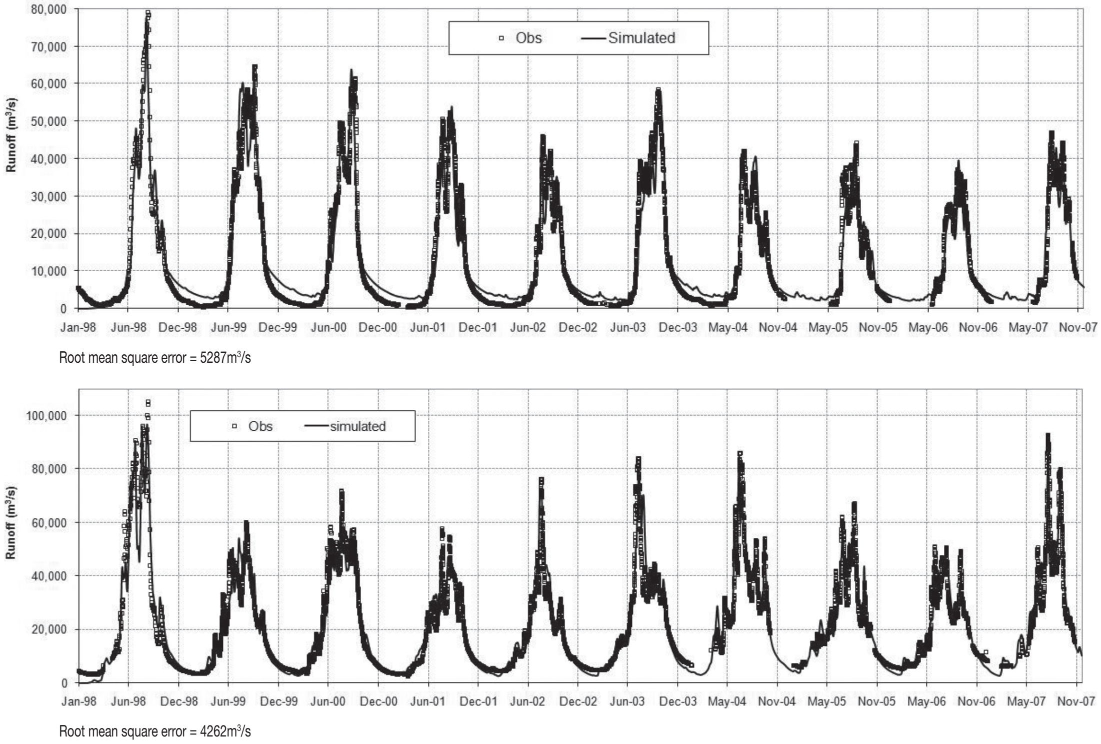
The MIKE BASIN[1] model was used for the GBM basin. Primary input data include topography, meteorology and hydrology information. River alignments for the GBM basin were determined using available physical maps for India and Nepal. For the topography of the basin, data from the Shuttle Radar Topography Mission (SRTM) of the National Aeronautics and Space Administration (NASA) was used (Farr et al, 2007). GTOPO30, a global digital elevation model (DEM) from the United States Geological Survey (USGS), was used to fill in the gaps. The horizontal grid spacing for GTOPO30 is 30-arc seconds (approximately 1km) and for SRTM it is approximately 90m. This data was used to delineate sub-catchments. In total, the GBM basin model comprises 95 sub-catchments: 33 in the Brahmaputra basin, 55 in the Ganges basin and 7 in the Meghna basin.

Rainfall and evaporation data serve as boundary conditions for rain-fed sub-catchments. Irrigation withdrawals and river management controls in upstream catchments were not considered in calibrating the model. Monthly temperature data was available at several stations within the basin. Temperature data was also incorporated as an additional boundary condition for snow-fed catchments. Actual daily rainfall data within the GBM basin was limited to a few stations. However, this information was supplemented with satellite rainfall data (0.25° x 0.25° horizontal resolution) measured by the Tropical Rainfall Measurement Mission (TRMM) and expanded to a 30-year record covering 1978–2008 using a bootstrapping weather generator. Measured evaporation data in the basin was also limited to a few stations. Plate 4.1 shows the map of the modelled GBM basin including the locations of meteorological data inputs.

Average monthly or yearly discharge data is available at several stations along the Ganges and Brahmaputra rivers. Historical data at three locations near the border between India and Bangladesh in the GBM basin are used for calibration purposes (Hardinge Bridge on the Ganges, Bahadurabad on the Brahmaputra, and Amalshid on the Meghna).

Calibration and validation

Only the calibration results for the Ganges and Brahmaputra rivers are shown here as these are the primary drivers of flow in the country. Simulated discharges at Hardinge Bridge on the Ganges and Bahadurabad on the Brahmaputra were calibrated against observed runoff for the time period 2004–2007. Since these models are used primarily for analysis during the monsoon season, the model is calibrated to minimize the sum of the square errors during this period only. There are 11 primary parameters used in calibration (built into the rainfall-runoff model) which are sensitive to the different sub-catchment characteristics and storage zones.[2] The GBM basin



Root mean square error = 5287m³/s

Root mean square error = 4262m³/s

Figure 4.1 Validated discharges from 1998–2007 at (a) Bahadurabad (b) Hardinge Bridge

model was then validated against TRMM data from 1998–2007 (shown in Figure 4.1). The model reasonably replicates the observed peaks.

4.2 National Hydrologic Super Model

Inflows at the validated locations from the GBM basin model are used as boundary inflows into the national hydrologic model. This detailed model is the primary tool used by the government of Bangladesh to make annual flood forecasts and issue warnings. See Hopson and Webster (2007) for an application of this model using satellite imagery to improve the forecast from 3 days to 10 days. This model is combined with gridded precipitation and temperature data and predicts water levels and discharges throughout the country. This model, which uses the MIKE 11 platform,[3] predicts daily water levels and discharges throughout the country covering most of the major river networks (except for some parts in the coastal areas and eastern hills – see Plate 4.2a). A separate coastal model was used for the south-eastern part of the country. Plate 4.2a also shows the network of water levels and discharge points where time-series estimates are produced. With these daily water levels (at 3800 points), the temporal characteristics of the floods can be analysed. Moreover, monthly flood maps can be prepared using a three-dimensional Geographic Information Systems (GIS) tool to interpolate the flood surface while taking into account the presence of flood protection works (e.g. roads, embankments, polders). The area under different flood land type classes (as described in section 2.2) can then be calculated and compared to the baseline.

4.3 Approach to Modelling Future Flood Changes

Rather than use the GCM future scenarios directly in these models, a 'delta' approach was taken to overcome four significant obstacles to climate scenarios generation: (1) GCM outputs may contain significant biases both in the baseline period and in the future period; (2) daily output is required while the GCM output is typically monthly; (3) the GCM spatial resolution reduces extreme events and misses sub-grid scale geographic variability; and (4) year-to-year variability at a particular location in the GCM output tends to be underestimated due to simplified greenhouse forcing scenarios and coarse spatial resolution. Moreover, GCM contributions to the IPCC are designed to capture climatic changes averaged over a long period of time; not to simulate particular events in the future. Therefore, the relevant information that may be taken from a GCM to generate climate scenarios is actually drawn from a comparison between a future projection and a baseline period.

A monthly rainfall and temperature series, averaged over each 30-year time period, is determined for the baseline and 2030s and 2050s scenarios for a particular GCM. By comparing the baseline and future monthly averages, a 'delta' value for both rainfall and temperature can be calculated (i.e. percentage change is used for precipitation and absolute change in degrees Celsius is used for temperature). Because the historical data captures differences between sub-regions and day-to-day and year-to-year variability that is not presented accurately in the GCM historical output, this monthly change is then applied directly to the actual historical observed 30-year precipitation and temperature data.[4] This approach removes much of the bias associated with each of the climate models, assuming that the bias is common to the historical and future periods. The sign and magnitude of remaining biases are unknown.

Selecting a sub-set of global climate models

Not all models could be tested in the flood simulations because of resource limitations. Thus, a sub-set of GCMs was selected for the flood hydrology modelling. In using only a sub-set of models, care must be taken in interpreting the results. The reduction in the number of climate models results in a loss of information about the characteristics of future climate conditions and the statistical significance of those findings.

A major goal, therefore, is to select the climate models that best represent the larger distribution of results and model characteristics in Bangladesh. The use of a statistical representation of additional models was not used, as it would not necessarily represent a physically consistent realization of climate or its potential change. Additionally, combinations of climate models with extreme values in different parameters are especially unlikely to provide sound realizations of future climate, and in fact may lead to the creation of even more extreme climate scenarios than their individual components. To achieve a robust climate signal it was critical that multiple years and multiple emissions scenarios be simulated.

Several criteria were used to narrow the sub-set of GCMs. First, the selected GCM must perform well in the GBM region and adequately capture the dynamics of the monsoon. Second, the sub-set of models must capture the range of climate sensitivity found in the IPCC models. Third, the resolution of the GCM must be adequate for this hydrologic application. Fourth, the subset of models should capture the range of IPCC changes. Fifth, the selected GCMs must have a substantial basis in the literature. Based on this, it was decided that two future time periods (each for a 30-year record), two emission scenarios (A2 and B1 – A1B are omitted because for the time period of analysis, there is not much difference between A1B and A2), and the following five GCMs would be most suitable for this analysis (i.e. ten model experiments for each time period):

- University Corporation for Atmospheric Research – CCSM
- Max Planck Institute for Meteorology – ECHAM5
- Hadley Centre for Climate Prediction – UKMO
- Center for Climate System Research – MIROC
- Geophysical Fluid Dynamics Laboratory – GFDL

Delineating agro-climatic sub-regions

To capture regional variations in both flooding characteristics and overall agriculture performance, Bangladesh is divided into 16 sub-regions (see Plate 4.2b). These sub-regions will be used throughout the study. The criteria used to delineate these boundaries include: flooding characteristics (e.g. riverine, tidal, flash), watershed catchments (e.g. Ganges dependent), planning units (e.g. administrative, crop, flood land type), agro-climatic (e.g. floodplain, drought areas, coastal zone, hilly region) and the presence of climate station data. The sub-regions are defined in Table 4.1.

4.4 Future Changes over the Ganges-Brahmaputra-Meghna Basin

Across the models and scenarios, a clear consensus on a trend towards warming (between 1 to 3°C) in the larger GBM basin is observed (Figure 4.2). This is consistent with the estimated national changes. Greater warming during the dry winter months is estimated. Moreover, the incremental increase in temperatures between the 2030s and the 2050s is less than 1°C. Temperature increases are greater for the A2 than B1 scenarios across all models.

For precipitation in the GBM basin, estimated changes differ widely across models. Plates 4.3 and 4.4 show the estimated monthly percentage change in precipitation over the Ganges and Brahmaputra sub-basins respectively for the 2050s for all ten model experiments (5 GCMs x 2 IPCC Special Report on Emissions Scenarios [SRES]). Note that the large percentage changes estimated during the non-monsoon months primarily reflect little baseline rainfall during this period. Most GCMs estimate increases in rainfall during the monsoon season (both in the 2030s and the 2050s) – up to 20 per cent more from July to September. Large changes at the onset of the monsoon (during May and June) particularly in the Ganges may reflect an earlier arrival of the monsoon season. During the dry season, some

Table 4.1 The sub-regions with hydrological region, agro-ecological zone and districts

Sub-region	Area (km^2)	Hydrologic region	Agro-ecological zone*	Districts
SR-01	13,157	NW	10, 11a, 11b, 11c, 1a, 1b, 1c, 25a, 26, 27a, 27b, 3a, 3b, 3e, 3f, 3g, 5, 6, River	Dinajpur, Joypurhat, Naogaon, Natore, Nawabganj, Panchagarh, Rajshahi, Thakurgaon
SR-02	17,301	NW	11a, 11b, 12b, 2, 25a, 25b, 27a, 27b, 27c, 3a, 3b, 3c, 3d, 3e, 3f, 3g, 4a, 4b, 4c, 5, 7, 8a, River	Bogra, Dinajpur, Gaibandha, Joypurhat, Kurigram, Lalmonirhat, Naogaon, Natore, Nilphamari, Rangpur, Sirajganj
SR-03	3336	NW	10, 11a, 12a, 12b, 4a, 4b, 4c, 5, 7	Natore, Pabna, Sirajganj
SR-04	7794	NC	10, 12b, 15, 19f, 28a–e, 4b, 7, 8a, 8c, 8d, 9a, 9b, 9c, 9d, 9e, River	Dhaka, Jamalpur, Manikganj, Munshiganj, Sirajganj, Tangail
SR-05	2302	NC	19f, 19g, 28a–e, 28f, 8d, 9b, 9e, River	Dhaka, Gazipur, Narayanganj
SR-06	12,424	NC, NE	16, 19f, 19g, 21a, 22a, 22b, 22d, 28a-e, 29b, 29c, 7, 8a, 8b, 8d, 9a, 9b, 9d, 9e, River	Gazipur, Jamalpur, Kishoreganj, Kurigram, Munshiganj, Mymensingh, Narayanganj, Narsingdi, Netrakona, Sherpur
SR-07	12,158	NE	16, 19b, 19c, 19h, 19i, 20, 21a, 21b, 21c, 22a, 22b, 22c, 22d, 29a, 29b, 29c, 8b, 9b, 9d, 9e, River	Brahamanbaria, Habiganj, Kishoreganj, Maulvibazar, Netrakona, Sunamganj, Sylhet
SR-08	2559	NE	20, 21b, 22b, 22c, 29a, 29b, 29c	Habiganj, Maulvibazar
SR-09	8756	SE	10, 16, 17a, 17b, 17c, 17d, 18f, 19a, 19b, 19c, 19d, 19e, 19i, 21b, 22b, 22c, 22d, 23a, 23b, 29a, 29b, 29c, 30, 7, 8d, River	Brahamanbaria, Chandpur, Comilla, Feni, Habiganj, Lakshmipur, Noakhali
SR-10	4574	EH	18e, 18f, 23a, 23b, 23c, 23d, 29a, 29b, 29c	Chittagong, Cox's bazaar
SR-11	15,217	EH	23a, 29a, 29b, 29c, KP-LK, River	Bandarban, Chittagong, Khagrachhari, Rangamati
SR-12	2521	SE	17d, 18f, 19a, 19e, 23b	Feni, Lakshmipur, Noakhali
SR-13	8443	SW	10, 11a, 12a, 12b, 14a, 14b	Chuadunga, Jessore, Jhenaida Kushtia, Magura, Meherpur, Satkhira
SR-14	10,580	SC, SW	10, 11a, 12a, 12b, 13a, 13b, 13c, 13d, 13e, 14a, 14b, 19f, 19j, 7	Bagerhat, Barisal, Faridpur, Gopalganj, Jessore, Khulna, Kushtia, Madaripur, Magura, Narail, Pirojpur, Rajbari, Shariatpur
SR-15	9346	SC	10, 12b, 13a, 13b, 13d, 14a, 18a, 18b, 18c, 18d, 18e, 18f, 19f	Barguna, Barisal, Bhola, Jhalokathi, Patuakhali, Pirojpur, Shariatpur
SR-16	9346	SW	11a, 13a, 13c, 13d, 13e, 13f, 13g, 14a, River	Bagerhat, Khulna, Pirojpur, Satkhira

*Agro-ecological zones as used by the BBS. These are defined on the basis of physiography, soils, land levels in relation to flooding and agro-climatology. There are 30 agro-ecological zones in the country.

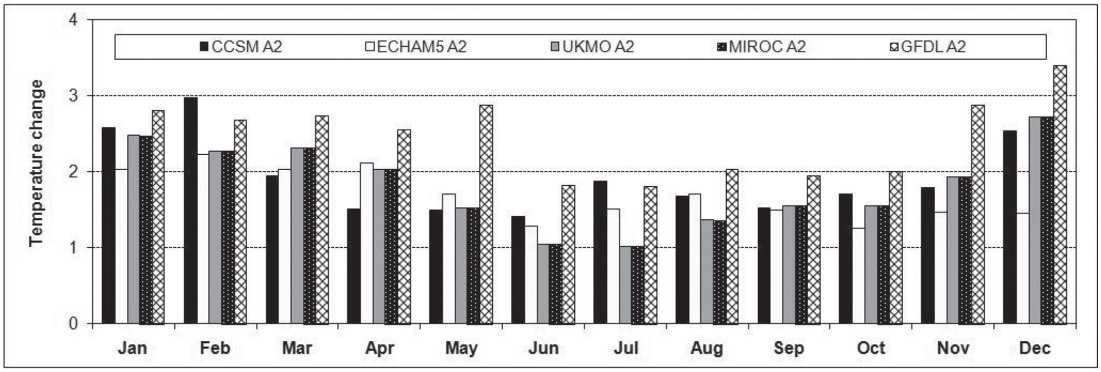


Figure 4.2 Temperature changes for A2 scenario over GBM basin (the 2050s)

models show increased precipitation while others show decreased precipitation. Moreover, there is not even necessarily agreement on the direction of rainfall change between emissions scenarios for individual models (e.g. in January, ECHAM A2 estimates decreases, ECHAM B1 estimates increases).

4.5 Future Flood Characteristics and Analysis

Future estimated discharges

The future transboundary inflows of the three major rivers (Ganges, Brahmaputra and Meghna) during the monsoon period are simulated. For all three rivers, across the different global circulation models, inflows into Bangladesh are on average projected to increase over the monsoon period (driven primarily from increased basin precipitation). Not much difference is observed between the A2 and B1 scenarios. Larger changes are anticipated by the 2050s compared to the 2030s. Larger changes are observed on average for the Ganges. The magnitude of change from the baseline is dependent on the month (Table 4.2). For the Ganges and Brahmaputra, the average discharges increase for all months.

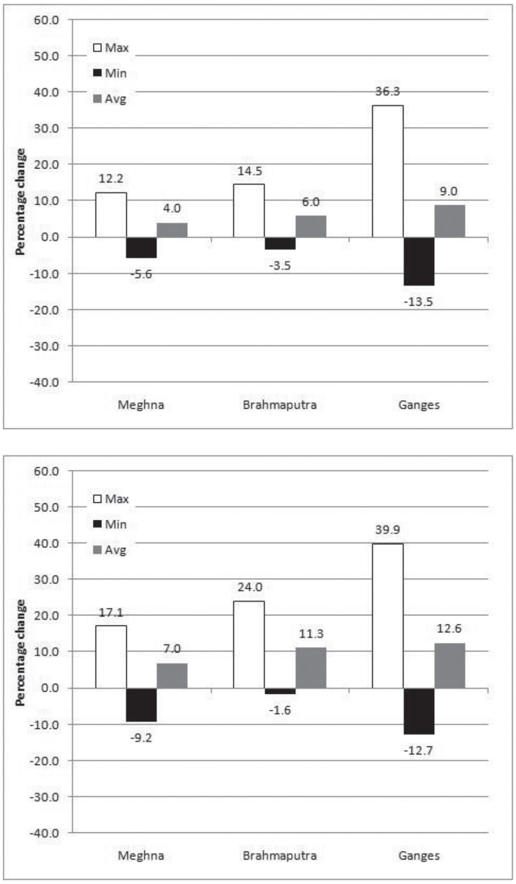


Figure 4.3 Percentage change in discharges in (a) the 2030s and (b) the 2050s for A2 scenario in August

Not all model experiments predict increases in discharge. For example (Figure 4.3), for the month of August the largest increases are estimated on average for the Ganges River (9 per cent to 13 per cent for the 2030s and the 2050s respectively). The GFDL model, though, estimates a reduction in Ganges flow of almost 13 per cent by the 2050s. In contrast, for the month of May (Figure 4.4) larger average increases are observed for the Meghna and Brahmaputra flows by the 2050s (17 per cent and 20 per cent respec-

Table 4.2 Estimated average change (per cent) in discharge across all model experiments*

	2030s			2050s		
	Brahmaputra	Ganges	Meghna	Brahmaputra	Ganges	Meghna
May	7.5	9.3	0.0	17.4	11.8	12.3
June	5.4	11.9	3.1	10.9	16.7	7.7
July	3.4	13.5	0.0	6.9	15.0	3.6
August	5.5	8.8	3.7	9.5	12.0	7.8
September	3.7	7.3	–2.0	9.7	12.5	5.9

* 5 GCM x 2 SRES = 10 model experiments

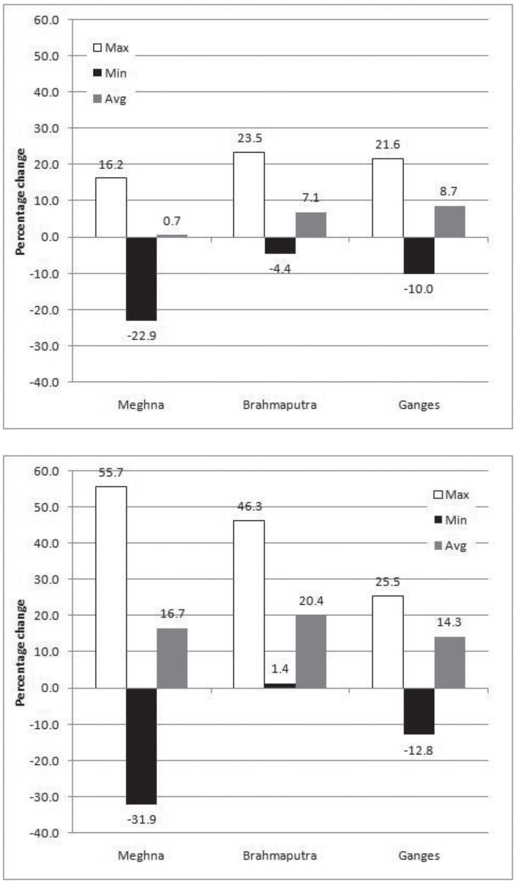


Figure 4.4 Percentage change in discharges in (a) the 2030s and (b) the 2050s for A2 scenario in May

tively). The model range is largest for the Meghna (55 per cent increase to 32 per cent decrease) in this scenario, however, reflecting less baseline discharge at the onset of the monsoon.

Changes in discharge could also be estimated at each of the water level points in the hydrologic model. Four geographically diverse locations were selected to illustrate the findings. These are: the Old Brahmaputra River at Mymensingh, the Kushiyara River at Sherpur, the Teesta River at Kaunia and the Gorai River at Gorai Railway Bridge. Similar to the major inflows in Bangladesh, most of the models and scenarios predict average increases in discharges ranging from 2 to 50 per cent by the 2050s. Larger changes are anticipated by the 2050s compared to the 2030s. For instance, all the model experiments indicate that the monsoon flow of the Teesta River will increase by the 2050s (Plate 4.5). For some river locations, direction of change varies among experiments (e.g. the Kushiyara River – Plate 4.6).

Changes in spatial extent of land flooding

Given that most model experiments indicate an increasing trend of monsoon rainfall and greater inflows into Bangladesh, if all else is equal the extent of flooding is likely to increase. Among the 16 sub-regions described earlier, only 11 were covered by the national hydrologic model (SR-01 to 08, SR-13 to 15). Using the generated water level time-series at each grid point in these regions, average monthly water levels are calculated for the baseline and two future time periods. With these, the distribution of flood land types (F0, F1, F2, F3 and F4 described in section 2.2) can be determined. The locations of flood protection infrastructure (e.g. roads, embankments, polders) are incorporated. The national baseline flood maps are shown in Plate 4.7 and summary statistics given in Table 4.3. These maps and statistics are produced for every month and for every sub-region.

It is important to note that this baseline distribution of flood land types is different from that reported in the MPO (1987). This is in part due to the fact that since the early MPO analysis, the government has invested substantially in polders and flood protective works (Table 4.4).

Of a total modelled area of about 9940km^2, the total area that is flooded ranges from 6.9 per cent (in May) to 36.7 per cent (in August). In general, the total flooded area peaks in August, coinciding with the peaks of the major rivers. This pattern of flooding varies across sub-regions.

Comparison of total change in flooded area (sum of F1, F2, F3 and F4) is presented in Figure 4.5. Under climate change, across most models the flooded area is estimated to increase for most of the flood season. An average increase of flooded area of 3 per cent in 2030s and 13 per cent in 2050s for A2 scenario is projected (with the largest changes simulated during the months of May

Table 4.3 Modelled baseline season flood land type distribution for each month (ha)

Flood land type	May	Jun	Jul	Aug	Sep
F0 (flood free)	9,300,316	8,665,915	7,491,199	7,270,645	7,391,137
F1	292,437	490,887	835,497	835,533	828,990
F2	207,657	407,457	825,183	923,472	899,145
F3	118,944	315,819	645,453	762,957	710,262
F4	20,628	59,904	142,650	147,375	110,448
Total flooded (F1+F2+F3+F4)	639,666	1,274,067	2,448,783	2,669,337	2,548,845
% Flooded	6.9%	14.7%	32.7%	36.7%	34.5%

Table 4.4 Protected areas flood control and drainage infrastructure (FCDI)

Sub-region	FCDI area	
	km2	% area
SR-01	5860	45
SR-02	8314	48
SR-03	2541	76
SR-04	1179	15
SR-05	214	9
SR-06	2167	17
SR-07	3337	27
SR-08	570	22
SR-09	3900	45
SR-10	1407	31
SR-11	319	2
SR-12	1461	58
SR-13	3498	41
SR-14	4064	38
SR-15	4467	48
SR-16	3246	35

and June). Some models indicate a decrease in flooding during the month of May, June, and July. The GFDL model, for instance, shows the largest decrease of 17 per cent in flooded area in the month of May for the A2 scenario in the 2050s. The maximum observed increase in flooding occurs during May (about 50 per cent) for the MIROC model under the A2 scenario in the 2050s. The B1 scenarios show smaller changes than the A2 scenarios, though in the same direction.

Increases in flooded area vary by sub-region (Table 4.5). Most models demonstrate agreement in changes in sub-regions 3, 4, 5, 13, 14 and 15. These are primarily in the central part of the country at the confluence of the Ganges and Brahmaputra rivers and in the south. Moreover, to determine whether or not these estimated changes are large in comparison to the year-to-year variations a one-standard deviation flood surface was also calculated. Table 4.5 shows for each sub-region the number of model experiments (total of 10) for the 2030s (numerator) and the 2050s (denominator) that exceed these bounds in each month. This is an indication of significance. In many sub-regions (1, 2, 6, 7 and 8), though increases in flooded areas are estimated, these fall mostly within one-standard deviation bounds. By the 2050s, more model experiments estimate changes that exceed these bounds. Most significant changes occur later in the flood season, primarily in August and September at the height of the monsoon, and in the south and central parts of the country.

Changes in temporal flood characteristics

To compare the characteristics of the future and baseline hydrographs, 36 locations were selected (at least 3 locations in each of the 11 sub-regions) for temporal analysis (locations shown in Plate 4.8). Using the approach outlined in Hassan et al (2007), the time-series of the annual peak values, onset date of the flood (with respect to May 15) and recession date of the flood (with respect to September 15) were analysed. Here, only mean characteristics will be compared. Note that incorporating future variability changes is addressed through a Monte Carlo simulation in the economic modelling section of this study and is exogenous to the hydrologic modelling.

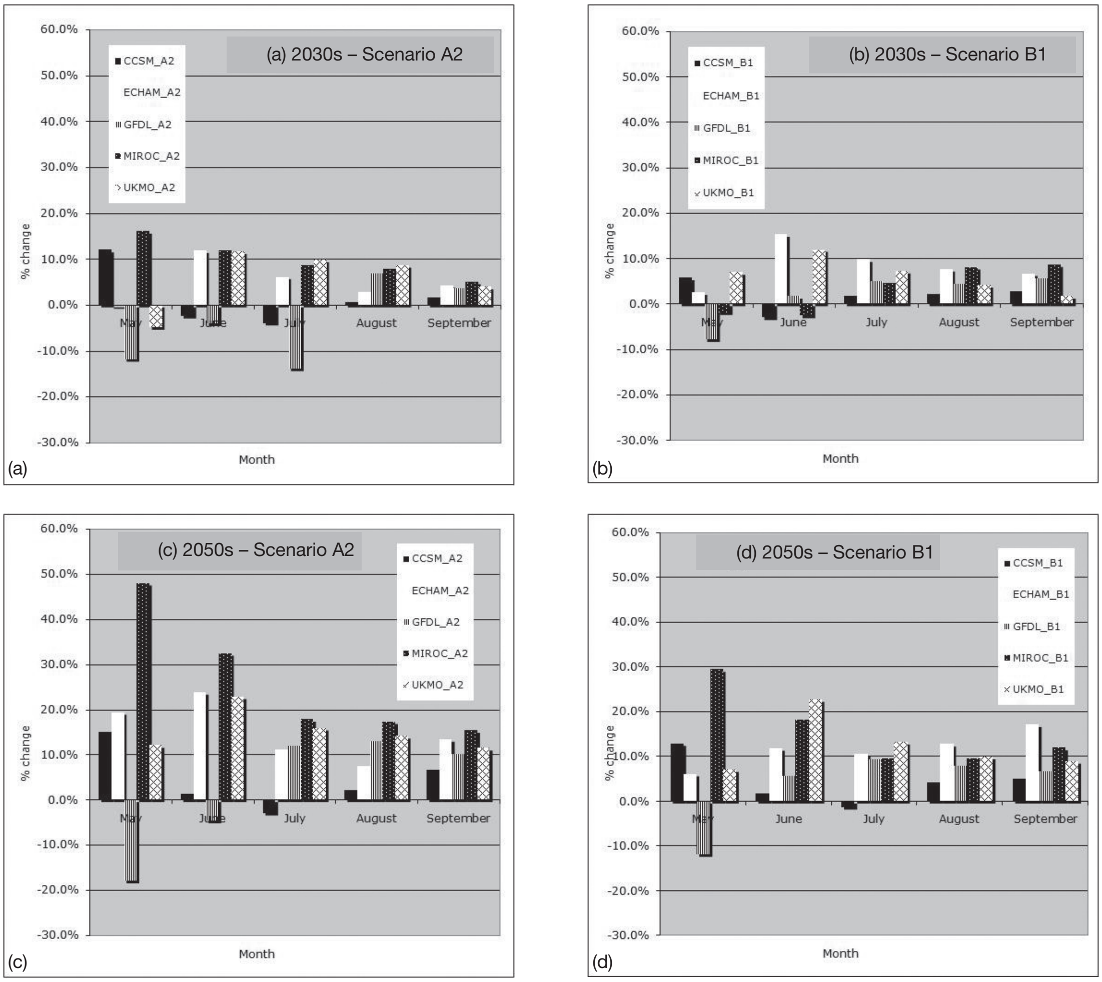


Figure 4.5 Total change in national flooded area for (a) 2030s A2, (b) 2030s B1, (c) 2050s A2, (d) 2050s B1

Table 4.5 Number of model experiments exceeding one-standard deviation bounds on baseline (2030s/2050s) and 2050s average estimated change in area flooded

Sub-region	2030s/2050s no. of model experiments exceeding one-standard deviation*					2050s average change (%) in flooded area				
	May	June	July	Aug	Sept	May	June	July	Aug	Sept
SR-01	2/4	0/1	0/0	0/1	0/0	23	25	14	19	19
SR-02	0/2	0/0	0/0	0/2	0/2	23	33	18	15	8
SR-03	5/9	0/5	5/5	4/5	1/6	460	77	15	15	56
SR-04	2/6	2/5	2/6	3/7	0/2	76	49	17	14	16
SR-05	1/3	0/5	6/8	5/8	0/5	44	28	10	7	9
SR-06	0/2	0/1	1/4	3/5	0/3	20	19	10	12	14
SR-07	0/1	0/0	1/3	0/2	0/0	11	5	1	2	3
SR-08	0/0	0/0	0/0	0/0	1/0	4	2	1	2	2
SR-13	8/6	3/2	4/6	7/7	2/7	–10	13	44	65	63
SR-14	3/1	0/5	3/3	3/4	0/2	–6	15	11	9	10
SR-15	0/9	7/9	8/9	9/9	9/9	54	69	38	31	24

* numerator 2030s/denominator 2050s.

Annual peak flows

To estimate whether or not the peak flows are statistically changing under the climate change scenarios, the peak values at each of the 36 locations are recorded for each year for the baseline and future time periods. Summary statistics (max, mean, min, standard deviation) are calculated. Hypothesis testing is performed to determine whether or not observed differences are statistically significant (null hypothesis that average peaks in the baseline and future time periods are not different). This is necessary because peak levels vary naturally from year to year. For instance, Figure 4.6 shows the observed peak water levels during the hydrologic baseline period (1978–2008) at one location on the Jamuna in addition to the estimated peak water levels for the different model experiments for the 2030s. The baseline inter-annual variation is itself almost 0.5m (average value of 11.6m). Thus, any observed change in average yearly peak levels must be considered in relation to this background variability.

Not all estimated changes in peak water levels are statistically significant. More model experiments demonstrate changes that are statistically significant (at the $p < 0.01$ level) by the 2050s. By the 2050s, many of the northern sub-regions (2–9) show statistically significant increases in the annual peak while many in the southwest (13–16) show decreases. Table 4.6 summarizes the observed changes in yearly peak levels, the number of model experiments that are statistically significant and the average change anticipated for the 2050s. The greater the number of model experiments, the greater the agreement. Changes are in general less than 0.5m from the baseline. Estimated changes in sub-regions 3 and 15 are statistically the most robust. Estimated changes in sub-regions 1 and 9 are statistically the least robust.

Table 4.6 Peak water level summary for the 2050s

Sub-region	No. model experiments*	Average change (m)
SR-01	2	0.47
SR-02	10	0.33
SR-03	17	0.27
SR-04	6	0.31
SR-05	11	0.28
SR-06	8	0.30
SR-07	10	0.43
SR-08	6	0.87
SR-09	2	0.27
SR-13	10	–0.41
SR-14	8	–0.19
SR-15	22	–0.28
SR-16	8	–0.28

*Number of model experiments where the estimated change is statistically different from the historical average peak level. Total number of model experiments is 30 (5 GCMs x 2 SRES x 3 stations per sub-region).

Onset and recession times

Average hydrographs were generated for each of the 36 locations for the baseline period and two future climate change futures to compare the

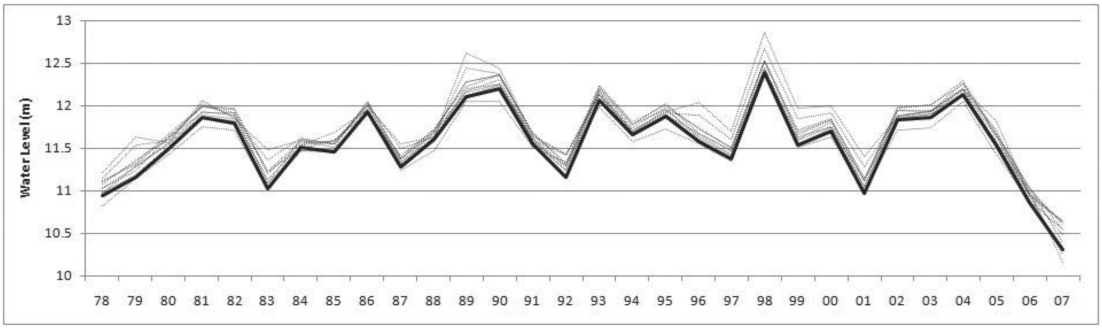


Figure 4.6 Yearly peak levels at Jamuna station for the baseline and model experiments (2030s)

Note: Solid line is historical baseline and dashed lines are all future model experiments.

timing of the onset and recession of the yearly monsoon. Using 15 May and 15 September as the baseline onset and recession dates respectively, the future dates when the baseline water level is reached can be determined. Figure 4.7 shows an example for a location on the Teesta River in SR-02 using the MIROC GCM for the A2 scenario. The baseline water level on 15 May is 49.55m. This same water level occurs earlier under the two future scenarios – around 6 May in the 2030s and 28 April in the 2050s. That is, the onset of the flood is early by almost two weeks by the 2050s. Averaged over all of the model experiments for this location, the estimated date of onset is earlier by five days (2030s) and ten days (2050s). Similarly, the baseline water level on 15 September is 50.97mm. This same water level occurs later under the two future scenarios – around 19 September in the 2030s and 21 September in the 2050s. That is, the recession of the flood waters is delayed by about five to six days. For this location, this delay is consistent across the range of scenarios.

In some locations the onset of the flood is delayed. For instance, for a location on the Meghna River in SR-15 the 15 May water level is 1.79m (Figure 4.8). This same water level for the GFDL GCM A2 scenario does not occur till

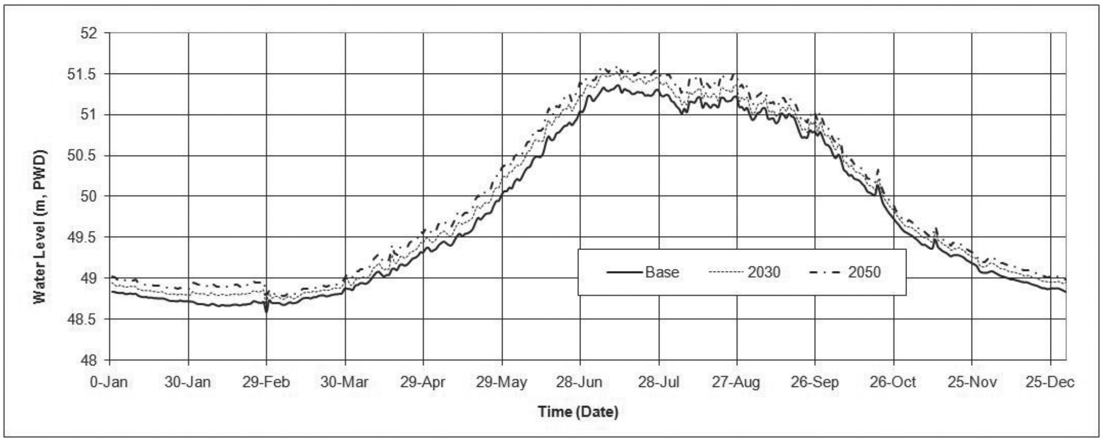


Figure 4.7 Average hydrographs (baseline, 2030s, 2050s) for MIROC GCM and A2 scenario on Teesta River

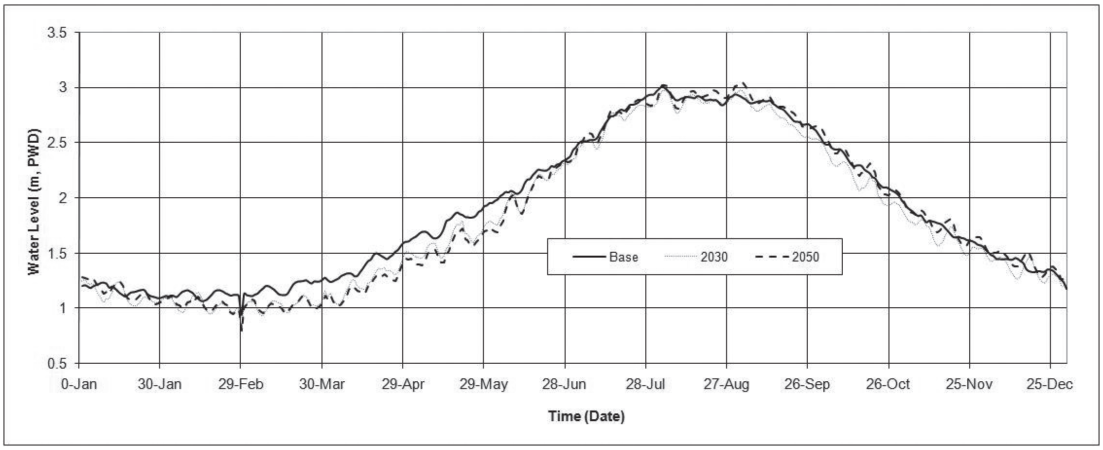


Figure 4.8 Average hydrographs (baseline, 2030s, 2050s) for GFDL GCM and A2 scenario on Meghna River

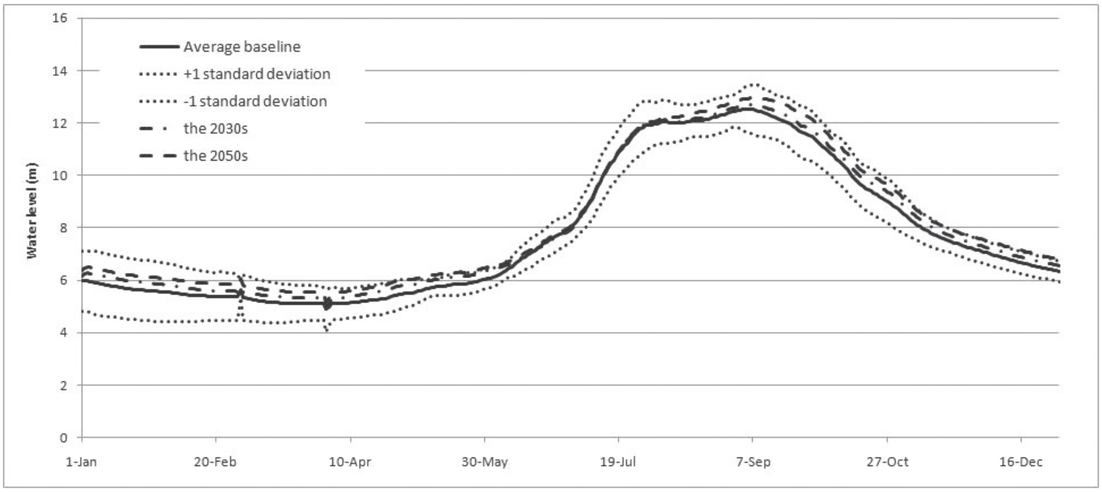


Figure 4.9 Average hydrographs on the Gorai River (baseline, 2030s, and 2050s – for CCSM A2 scenario) and plus/minus one-standard deviation bounds

around 4 June in both the 2030s and 2050s. When averaged over all the model experiments, a delay of approximately ten days is estimated. The recession of the flood waters at this location shows no significant change from the baseline.

Across the sub-regions, most model experiments estimate an earlier onset (as compared to the baseline) of the monsoon and a delay in the recession. This is more apparent by the 2050s and driven in large part due to the increased flows and flooding under these climate change scenarios. Some caution must be exercised, however, when interpreting these results as the range of dates across the model experiments can be as much as 1–2 weeks. Moreover, in many cases the year-to-year variation in the annual hydrograph is larger than the predicted changes. Figure 4.9 shows, for a location on the Gorai River, the baseline and two future estimated average hydrographs for the CCSM A2 scenario. Here, the two estimated future time-series fall within the one-standard deviation bounds, thus not separating from the historical variability.

Notes

1 MIKE BASIN is a versatile Geographic Information Systems-based water resource and environmental modelling package from DHI Water and Environment. MIKE BASIN represents all elements of water resource modelling: users, reservoirs, hydropower, surface water, groundwater, rainfall-runoff and water quality.

2 U_{max} = Maximum water content in surface storage; L_{max}= Maximum water content in root zone storage; CQ = Overland flow runoff coefficient; CK_{IF} = Time constant for routing interflow; CK_{OF} = Time constant for routing overland flow; T_{OF} = Root zone threshold value for overland flow; T_{IF} = Root zone threshold value for interflow; T_G = Root zone threshold value for groundwater recharge; CK_{BF} = Time constant for routing base flow; C_{snow} = Constant degree day coefficient; T_0 = Base temperature (snow/rain).

3 MIKE 11 is a system for the one-dimensional, dynamic modelling of rivers, channels and irrigation systems, including rainfall-runoff, advection-dispersion, morphological and water quality. The complete St Venant equations can be solved, so the model can be applied to any flow regime where the flow can be assumed one-dimensional. Diffusive wave, kinematic wave and quasi-steady state options are also available. Flow over weirs,

through culverts and user-defined structures, and over the flood plain can be simulated. Output from the hydrodynamic module can be routed to additional modules that simulate the transport of cohesive and non-cohesive sediment, dissolved oxygen, nutrients, heavy metals and eutrophication.

4 The baseline climate period (1979–99) differs slightly from the baseline hydrologic period (1978–2008) which introduces slightly higher baseline conditions for the 'delta' method. However, changes between 1999 and 2008 are the smallest of the 20th century.

5

Future Crop Performance

Box 5.1 Key messages

- Elevated CO_2 concentrations are projected to have a substantial positive effect on crop yield for all crops and locations.
- Considering only temperature, precipitation and CO_2 changes, aus and aman median production is projected to increase by 2 per cent and 4 per cent by the 2030s and the 2050s respectively. Wheat also increases, reaching a maximum of 4 per cent by 2050 before following a downward trend. These distributions range approximately +/– 2 per cent.
- Boro production is projected to decline under climate change scenarios, around 8 per cent by the 2080s. Changes for boro and wheat are conservative as it is assumed that farmers have unconstrained access to irrigation.
- Shifts in the average floods are projected to reduce production of aus and aman by between 1 per cent and 4 per cent. The narrow model distribution of flood impacts projected by different GCMs suggest a robust change, although changes are small in comparison to year-to-year variability.
- The area lost to production due to sea level rise can be substantial. Maximum crop losses of nearly 40 per cent are projected by the 2080s for the south.
- Considering all climate impacts for the 2050s, the median of all rice crop projections show declining national production, with boro showing the largest median losses. However, for aus (–1.5 per cent) and aman (–0.6 per cent), the range of model experiments covers both gains and losses and does not statistically separate from zero. Most GCM projections estimate decline of boro production with a median loss of 3 per cent by the 2030s and 5 per cent by the 2050s. Wheat production increases up to the 2050s (3 per cent).
- In each sub-region, production losses are estimated for at least one crop. The production in the southern sub-regions is most vulnerable to climate change. For instance, average losses in SR-16 (containing Khulna) are –10 per cent for aus, aman and wheat, and –18 per cent for boro by the 2050s.
- The current large gap between actual and potential yields suggests substantial on-farm opportunities for growth and poverty reduction. Expanded availability of modern rice varieties, irrigation facilities, fertilizer use and labour could increase average yields at rates that could potentially more than offset the climate change impacts.

This section describes the use of a Decision Support System for Agrotechnology Transfer model (DSSAT v4.5, Hoogenboom et al, 2003; Jones et al, 2003) to simulate agricultural yields under a range of climate change scenarios in Bangladesh. The DSSAT model covers 16 sentinel locations in Bangladesh (to correspond to each sub-region described in the previous section) and focuses on yields of rice (primarily three seasons) and wheat. Simulations of changes in crop yield include impacts from climate only (CO_2, temperature and precipitation), floods and coastal inundation, both separately and in combination. For the climate only simulations, probabilistic distributions of yield changes are generated across the set of global climate models, several emissions scenarios (A1B, A2, and B) and future time slices (2030s, 2050s and 2080s). Together, these 16 locations, 3 growing seasons, 3 emissions scenarios, 16 GCMs, 3 time-slices and 30-year periods for each simulation required the simulation of more than 200,000 individual DSSAT cropping seasons. The sensitivity of various individual climate parameters was also extensively tested. The number of individual runs for the flood-damaged yields is significantly reduced as only a sub-set of model experiments are used (as described in section 4.3). The results of these simulations are reported here.

5.1 Development of the Baseline Period

CERES crop models

Crop simulations for this project utilized the Crop Environment Resource Synthesis (CERES) Rice and Wheat models, which are components of the DSSAT cropping systems model (Hoogenboom et al, 2003). These dynamic biophysical crop models simulate plant growth on a per hectare basis, maintaining balances for water, carbon and nitrogen. CERES models have been applied previously in Bangladesh to model rice (Hussain, 1995; Mahmood et al, 2003) and rice-wheat systems (Timsina and Humphreys, 2006a,b; Timsina et al, 1998). Studies examining climate change impacts on agricultural production in Bangladesh have also employed the CERES models (Karim et al, 1994; Hussain, 2006).

CERES models require information about the plant environment (weather and soils), cultivar genetics and agricultural management practices. Daily maximum and minimum temperatures, precipitation, carbon dioxide concentrations and solar radiation determine respiration and photosynthesis rates, available water and evapotranspiration rates. A soil profile provides information about available nutrients and root-zone moisture processes. Cultivar genetics determine the type of crop that is grown, including biophysical characteristics determining development and vulnerability to environmental stresses. Management practices dictate the date, method and geometry of planting, as well as any applications of irrigation, fertilizer or chemicals.

As discussed in section 2.1, actual yields are much lower than the potential yields observed at experimental stations under controlled conditions. The model outputs for this study are potential yields as simulated by the CERES models under recommended agricultural practices, and so validation of the potential yields is complex. Insects and rodents, which may severely damage infested areas, were not modeled. Thus, crops were assumed to be disease- and weed-free. Historically, shortages or prohibitive costs of irrigation, fertilizer and labour reduce yields, while variation in management practices exists across the country. In addition, many farmers have not yet adopted modern rice varieties. For this study, as the main concern is to estimate the *changes* from the baseline, replicating the actual observed yields is of secondary importance. This, of course, assumes that crop response functions will be similar for high-input and low-input cropping systems.

The ability of the CERES models to accurately represent the agricultural impacts of anthropogenic climate change is hindered by considerable uncertainty in the magnitude of CO_2 effects (Easterling et al, 2007; Long et al, 2006; Tubiello et al, 2007a, b; Ainsworth et al, 2008; Hatfield et al 2008) and the location of temperature thresholds for crop damage. CO_2 is a primary element of photosynthesis, and plants respond to elevated levels by increasing the rate of primary production. High CO_2 concentrations also increase root densities and allow a plant to make more efficient gaseous transfers with its environment, collecting sufficient CO_2 in shorter periods of open leaf stomata. This has the added effect of increasing water use efficiency in the plant as the duration that stomata are open is lessened and stomatal resistance is increased, reducing the loss of moisture to transpiration. Biophysical crop models, controlled chamber experiments, and Free Air CO_2 Enrichment (Hendry and Kimball, 1994) experiments have demonstrated these effects, but the extent to which large-scale field crops will respond to CO_2 is uncertain. The CERES-Rice and CERES-Wheat models use a simple look-up table to relate growth coefficients with CO_2 levels, and produce responses that are relatively optimistic. In addition, high temperatures can damage crop development if sharp events occur during key phenological stages (particularly the grain setting period), but these stresses are not modelled in the CERES simulations.

Sub-region production totals

The CERES models simulate crop development and yield on a single hectare. Production totals are determined by multiplying the yield by cropped area in a particular sub-region. The agricultural areas in each sub-region producing aus, aman, boro and wheat are presented in Table 5.1 below.

Table 5.1 Sub-regional agricultural information

Sub-region	Aus area (ha)	Aman area (ha)	Boro area (ha)	Wheat area (ha)
1	65,401	613,853	543,438	174,969
2	42,491	815,334	976,956	149,176
3	21,165	116,985	86,369	53,228
4	46,826	239,834	261,113	48,131
5	13,458	51,661	32,107	8225
6	100,018	610,184	561,919	39,339
7	124,288	350,173	589,900	10,034
8	24,304	64,558	19,294	541
9	129,498	330,897	426,250	33,260
10	38,209	23,194	74,850	39
11	30,320	14,628	71,881	17
12	45,945	121,579	26,894	103
13	98,834	359,053	333,375	67,317
14	167,592	351,018	286,413	49,575
15	240,201	198,407	162,463	6399
16	14,809	215,747	78,225	1794

Note: Aus and wheat areas come from the 2003–2004 season, based on Bangladesh Bureau of Statistics (2005), while 2003 aman and 2008 boro areas come from CEGIS.

Climate data used

Each sub-region was required to have a Bangladesh Meteorological Department (BMD) observation station covering a 1970–99 baseline period. Table 5.2 shows the BMD station selected for each sub-region, as well as the mean climate conditions for variables required by the CERES models. The weather generator component of DSSAT was used to fill in gaps in the observational climate record and to convert the BMD sunshine hours measurements to solar radiation data needed by the CERES models

Soil data

Soil profile data were not available at all of the sentinel BMD locations, but suitable matches were located for every sub-region (see Table 5.3). Soil profiles for some regions are available in DSSAT-compatible formats from Hussain (1995) and others were generated drawing from Brammer (1996). If multiple profiles existed, the profile closest to each sentinel site was selected, provided it had soil information down to at least 1m depth. When no profiles existed within a region, profiles from neighbouring sub-regions or sub-regions with similar surface soil conditions were used. Following Mahmood et al (2003), paddy rice percolation rates for all sub-regions were set at 4mm/day.

Cultivar information

Genetic information for the CERES models was drawn from existing and estimated coefficients for cultivars used in Bangladesh (BRRI, 2007). For the aus season, the Bangladesh Rice Research Institute (BRRI) BR3 cultivar was selected. Known locally as *biplab*, BR3 is a combination of a foreign rice, the International Rice Research Institute (IRRI) IR-506-1-133 and a local rice variety. BR3 grows quickly and may be planted late, leading to productive aus seasons. Cultivar information was not available for the more popular BR24, 26 and 27 varieties. BR11, known locally as *mukta*, was used for the aman season. Cultivar information was not available for the more popular BR31 variety. CERES

Table 5.2 Climate information for each sub-region: the representative BMD station, its code and annual mean climate statistics during the 1970–99 baseline period

Sub-region	BMD Station Location	BMD Station Code	Mean Tmax (°C)	Mean Tmin (°C)	Mean Rainfall (mm)	Mean Sunshine (MJ/m^2/day)
1	Dinajpur	10,120	30.1	19.7	2003	16.9
2	Rangpur	10,208	29.7	19.9	2239	17.2
3	Ishwardi	10,910	31	20.3	1652	17.3
4	Tangail	41,909	30.3	20.8	1902	16.7
5	Dhaka	11,111	30.6	21.6	2148	17.6
6	Mymensingh	10,609	30	20.5	2255	16.4
7	Sylhet	10,705	29.6	20.2	4150	16.7
8	Srimangal	10,724	30.4	19.4	2421	17
9	Comilla	11,313	30.1	20.9	2054	17.2
10	Chittagong	11,921	30.2	21.6	2931	18
11	Rangamati	12,007	30.2	21.4	2532	17
12	Maijdee Court	11,809	29.8	21.6	3103	16.9
13	Jessore	11,407	31.4	20.9	1600	17.2
14	Faridpur	11,505	30.4	21.1	1967	17.2
15	Patuakhali	12,103	30.3	21.9	2704	15.6
16	Khulna	11,604	31.1	21.6	1812	17.4

Table 5.3 Soil profile information for each sub-region

Sub-region	Soil Location	Soil Description	Soil Type	Soil Depth (cm)	Percolation Rate (mm/day)	Initial Moisture (mm)	Initial NO_3 (kg N/ha)	Initial NH_4 (kg N/ha)
1	Dinajpur		Aeric Endoaquepts	130	4	243	44.7	4.11
2	Rangpur		Aeric Endoaquepts	84	4	142	47.2	2.16
3	Jessore		Aeric Endoaquepts	137	4	332	44.5	4.78
4	Karatia	Silty Loam	Aeric Endoaquepts	107	4	290	46.6	2.86
5	Ghatail		Typic Dystrudepts	122	4	375	42.6	7.53
6	Phulpur	Loam	Aeric Endoaquepts	116	4	187	44.1	5.86
7	Biani Bazar		Typic Dystrudepts	107	4	162	42.9	7.04
8	Srimangal	Very fine sandy loam	Udic Ustochrept	185	4	397	41.1	8.49
9	Shalpur		Hyperthermic Typic Endoaquept	160	4	353	43.1	5.99
10	Chittagong		Aeric Endoaquepts	216	4	378	39.6	9.78
11	Srimangal	Very fine sandy loam	Udic Ustochrept	185	4	397	41.1	8.49
12	Hatiya	Silty	Aeric Fluvaquent	165	4	543	41.6	8.01
13	Jessore		Aeric Endoaquepts	137	4	332	44.5	4.78
14	Jessore		Aeric Endoaquepts	137	4	332	44.5	4.78
15	Satkhira	Clay Loam	Typic/Aeric Hapluquept	142	4	603	36.8	13.1
16	Satkhira	Clay Loam	Typic/Aeric Hapluquept	142	4	603	36.8	13.1

coefficients for BR11 transplanted aman and BR3 are distributed with DSSAT v4.5 (Hoogenboom et al, 2003). BR29, introduced in 1994, was selected as a more current variety for the boro season, with genetic information provided by Dr Sk. Ghulam Hussain (at BARC). *Kanchan*, the most common variety of wheat grown in Bangladesh, is not packaged with DSSAT v4.5. However, *kanchan* genetic coefficients exist for the CERES-Wheat model in DSSAT v3.0 and for the CropGro Wheat model in DSSAT v4.5. Using the coefficients from these model versions, genetic coefficients were estimated for CERES-Wheat in DSSAT v4.5 format, with modifications necessary to capture appropriate season length. These cultivars have been commonly used in crop modelling studies of Bangladesh.

Agricultural management practices assumed

CERES-Rice and CERES-Wheat require information about the management practices governing crop cultivation during the growing season. Planting dates, planting geometry and planting environment are necessary, as well as any fertilizer or irrigation applications. These simulations were initiated with 75 per cent initial moisture for two weeks of fallow period before the planting/transplanting date, with no crop residue left on the field. Nitrogen and water cycle processes and limitations were included in these experiments. Tables 5.4 and 5.5 show the management characteristics selected for the rice and wheat simulations respectively. Management practices may vary considerably across any given sub-region and between sub-regions across Bangladesh. For the purposes of this study, management practices for a given crop were assumed to be the same across all locations to allow sub-regional comparisons.

Characteristics of farm-level management practices for the cultivation of rice and wheat were selected for the CERES models according to the recommendations of the Bangladesh Rice Research Institute (BRRI, 2007), annual reports from the Bangladesh Agricultural Research Institute (BARI) and published studies examining rice and wheat systems in Bangladesh. Rice seedlings are commonly raised in a seedbed before they are transplanted to the wider field, with aus plants spending 25 days in a seedbed, aman 30 days and boro 35 days (BRRI, 2007). The transplant environment temperature was set as the mean temperature for Bangladesh for the 30 days prior to transplanting, approximating the seedbed temperature that determines initial development. Aus and aman are dependent on local rainfall, but boro and wheat are aided in the simulations by an automatic irrigation routine that applies irrigation whenever the soil moisture in the top 30cm of soil falls below 50 per cent of saturation. Water availability for irrigation was assumed to be limitless. 120kg/ha of urea fertilizers were added in the simulations to all rice crops, and 100kg/ha were added to wheat. These totals far exceed the current average application, but fertilizer use is expected to expand with development in future periods and thus optimistic scenarios are used. Finally, these management options were maintained for future scenarios, allowing a direct comparison of the climate impacts on yield.

Table 5.4 Agriculture management options for simulations of the three main rice varieties

	Aus	Aman	Boro	Source
Cultivar	BR3	BR11	BR29	Hussain, 1995
Local name	Biplab	Mukta		BRRI, 2007; Hussain, personal communication, 2008
Simulation date	1 Apr	1 Jul	1 Dec	Two weeks before planting
Planting date	15 Apr	15 Jul	15 Dec	Hussain, 1995; Mahmood, 1997; Gomosta et al, 2001; Hussain, personal communication, 2008
Plant population (plants/m^2)	50	50	50	Latif et al, 2005; BRRI, 2007
Row spacing (cm)	20	20	20	Hussain, 1995
Sowing depth (cm)	6	6	6	Mahmood et al, 2003; Hussain, 1995
Transplant age (days)	25	30	35	BRRI, 2007; Mahmood et al, 2003
Transplant temperature (°C)	27	28.5	21.9	BMD observations
Bund height (mm)	100	100	n/a	Hussain, 1995
Irrigation	Rainfed	Rainfed	Automatic	BBS, 2005b
Fertilizer type	Urea	Urea	Urea	Hussain, 1995
Fertilizer amount (kg N/ha)	40, 40, 40	40, 40, 40	40, 40, 40	Latif et al, 2005; BRRI, 2007
Applications (days after transplanting)	1, 30, 60	1, 30, 60	1, 30, 60	

Table 5.5 Agriculture management options for wheat simulations

	Wheat	Source
Cultivar	Kanchan	Timsina et al, 1998
Simulation date	1 Dec	
Planting date	15 Dec	Two weeks before planting
Plant population (plants/m^2)	220	Timsina et al, 1998
Row spacing (cm)	20	
Sowing depth (cm)	3.5	
Irrigation	Automatic	
Fertilizer type	Urea	
Fertilizer amount (kg N/ha)	66, 34	
Applications (days after transplanting)	1, 21	

5.2 Developing Flood Damage Functions

The CERES-Rice model simulates water stress for both photosynthesis and growth during water shortages, but assumes that excess rainfall (that cannot be absorbed by the soil or puddle in a bund) is lost as runoff without any damages inflicted. As simulations occur on a single hectare, water that flows on to agricultural areas from flash floods or rising rivers cannot be seen by the model. Thus, the CERES-Rice model does not model the flood damages that affect Bangladesh. Instead, in this work flood damages were separately assessed and applied to CERES-Rice output using information gleaned from potential rice yield simulations and the hydrologic models described in Chapter 4.

The assessment of flood damages for aus and aman rice was based on the methodology developed for Bangladesh by Hussain (1995; herein referred to as the Hussain method). Boro rice and wheat, which are grown during the dry season, are assumed to be free from flood impacts. Flood damages are assessed according to the depth of a flood (as a percentage of the plant height), the duration of the flood and the developmental stage of the rice plant when the flood occurs. Table 5.6 presents the crop damage inflicted under various flood scenarios. These damages assume clear flood waters, which are slightly less damaging than water with a high silt content, and do not account for damages from flood water currents (Hussain, 1995). Similar approaches to estimating flood damages based on comparisons between water level and rice plant height are reported in Yoshida (1981) and Kotera and Nawata (2007).

To characterize the phenological stage and height of rice crops during the flooding season, daily CERES-Rice output was analysed for the baseline period. Although dates of some phenological transitions are available, plant height is not recorded as a variable in CERES-Rice. Dates for key developmental milestones (transplanting, end of juvenile development, panicle initiation, heading, beginning of grain filling and maturity) were calculated across all crops, with results showing only minor changes between years and sub-regions. The date of maximum tillering, which is required by the Hussain method, was not available and therefore was estimated. Plant height at each developmental milestone was estimated according to published reports and the height at maturity for BR3 and BR11 cultivars, with daily height in any given stage interpolated from its endpoints (Yoshida, 1981; Hussain, 1995; Chen et al, 2007; Kotera and Nawata, 2007).

For each of the 11 sub-regions where future floods were modelled, flood damages were determined separately for crops grown on each flood land type (see Table 2.6). To determine flood depths, the mean baseline hydrograph of a representative location (typically the upstream-most point; see Table 5.7) was used as a reference to determine the base of the rice plants (to ensure, for example, that F1 rice plants really flooded between 30 and 90cm on average). Each daily hydrograph was then compared to plant heights estimated according to phenological stages from the CERES model output and known harvest heights for the BR3 and BR11 cultivars (Yoshida, 1981; Hussain, 1995; Chen et al, 2007; Kotera and Nawata, 2007). The Hussain (Hussain, 1995) damages were then assessed according to flood depths as a percentage of plant height, flood durations and phenological stage (Table 5.6). The rise and fall of flood waters to different percentages of the plant heights often led to overlapping damaging events from long-duration low floods and

Table 5.6 Flood damages (percentage yield) according to submergence depth, duration and phenological stage

Submergence of 25–50% of plant height

	Days of Submergence			
Phenological Stage	**3 to 6**	**7 to 9**	**10 to 14**	**15 or greater**
10 days after transplanting	10	15	20	30
Maximum tillering	10	15	25	40
Panicle initiation	0	0	30	40
Heading	0	0	30	40
Early grain filling	0	0	30	40
Maturity	0	25	40	40

Submergence of 50–75% of plant height

	Days of Submergence			
Phenological Stage	**3 to 6**	**7 to 9**	**10 to 14**	**15 or greater**
10 days after transplanting	10	40	50	60
Maximum tillering	5	50	60	70
Panicle initiation	15	40	50	60
Heading	15	40	50	60
Early grain filling	20	40	60	70
Maturity	20	40	60	70

Submergence of 75% or more of plant height

	Days of Submergence			
Phenological Stage	**3 to 6**	**7 to 9**	**10 to 14**	**15 or greater**
10 days after transplanting	40	80	100	100
Maximum tillering	40	60	80	100
Panicle initiation	50	70	100	100
Heading	40	80	100	100
Early grain filling	30	60	80	100
Maturity	30	60	80	100

Source: from Hussain, 1995.

brief high waters. In such cases only the more damaging element was recorded. If flood waters receded entirely before a later flood occurred, that event could inflict further damages.

Sub-regional damages for a particular year were then aggregated according to the area of each flood land type in that sub-region, which could change from season to season as the flooded areas are larger during high flood seasons. Inter-annual variations in flooded areas were determined from monthly maps of the mean flooded area (e.g. Plate 4.7 for the baseline period) and a +/- one standard deviation flood map. For each sub-region, a second-order polynomial was used to describe the land area covered by each flood land type according to the anomaly of the annual maximum hydrograph reading for each season. Therefore, years with higher than average annual maximum floods would have more land classified as flooded (and deeply flooded). This approach produced slightly larger flood damages than those estimated by simply examining the damage caused by the average annual hydrograph over a given scenario. The baseline flood damage factors (between 0 and 100 per cent) for each sub-region is given in Figure 5.1.

Uncertainties with flood damages

There are several uncertainties that lead to likely biases in the flood damage assessment approach conducted for this study. These biases are offset

Table 5.7 Representative hydrographs

Sub-region	River Name
1	Upper Karatoya
2	Teesta
3	Atrai
4	O Brahmaputra
5	Turag
6	O Brahmaputra
7	Surma
8	Juri
13	Ganges
14	Gorai
15	Southern Meghna

to an extent, but there are areas where additional information could improve projections. First, the location of agricultural areas in each sub-region is only measured on a *thana* (precinct) administrative level, which is not fine enough to determine the actual amount of agricultural area that falls under each flood classification. Farms are located disproportionately in regions that are slightly elevated to avoid flood damages and low-lying areas may grow taller rice varieties in anticipation of floods, so the assumption that agricultural land is situated without regard to flood land type leads to a likely overestimate of flood damages. Second, taking only the maximum damage during an event where waters rise underestimates flood damages that would accrue from lower water levels and inundation periods. Finally, defining water levels in each flood classification according to the maximum annual flood extent underestimates the damages caused by early-season and late-season floods that rise to a deeper flood classification during peak flow.

5.3 Incorporating Coastal Inundation Effects

As discussed in section 3.3, coastal zone models were used to simulate baseline conditions, as well as 15cm, 27cm and 62cm of mean sea level rise. These future simulations were designed to represent the B1 2080s, A2 2050s and A2 2080s respectively. In this study we also attributed the 15cm level to the A2 2030s. B1 and A1B sea levels would be lower. For the B1 scenario, which was given a 15cm rise for the 2080s, we estimated a 5cm and 8cm rise for the 2030s and 2050s

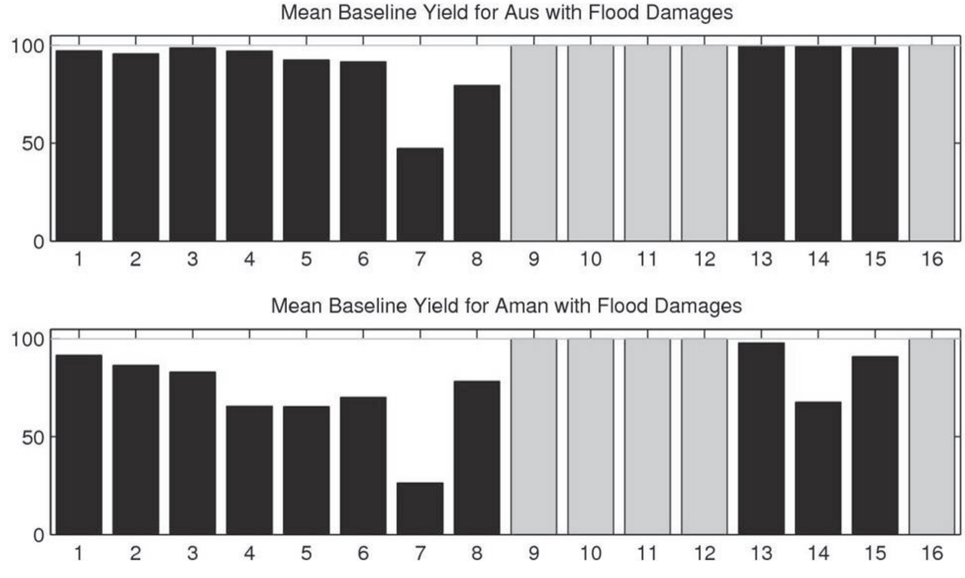


Figure 5.1 Baseline sub-regional yields with flood damages applied (as a percentage of undamaged yields)

Light grey bars represent sub-regions that were not simulated by the hydrologic model. Flood damages for the boro and wheat seasons were not modelled.

respectively. Since these lower values were not explicitly modelled, we estimated that their inundations were approximately linear proportions of the 15cm inundation maps. Since the publication of the IPCC Fourth Assessment Report (AR4), new research into ice dynamics in a warming climate suggest that sea level rise may occur more rapidly than previously thought (Alley et al, 2005; Copenhagen Diagnosis, 2009). As noted in Chapter 3, improved methods are available for re-estimating sea level rise.

Even with current sea levels, many coastal areas are periodically flooded with seawater due to tidal oscillations and river floods (see Plate 3.1). Areas that are classified as experiencing coastal floods of 30cm or more during the baseline period are assumed to have already abandoned grain production. Thus, impacts of sea level rise on agriculture can be assessed by removing sub-regional production according to the proportion of additional land lost under the future flooding scenarios.

Future agricultural impacts of sea level rise are likely biased by somewhat offsetting factors that were not modelled. Only mean sea level rise and tidal fluctuations were considered for this study, representing an optimistic scenario of coastal inundation. Additional land lost to extreme tidal and storm surges that can penetrate further up the distributaries along the Bangladesh coast were not considered, nor were the effects of salinity increases on soil, ground and irrigation water. However, agricultural land in these areas was assumed to be distributed without regard for potential coastal inundation, leading to a likely overestimate of sea level rise damage. Also not considered was the salinity impact of farmers who convert their fields to aquaculture (e.g. shrimp) by inundating their land with saltwater.

5.4 Projections of Future Potential Unflooded Production (Climate Only)

As discussed in section 4.3, a 'delta' approach is used for generating future climate scenarios whereby climate changes from a particular model experiment are applied directly to the BMD observational data. This adjusted observational climate data is used directly in DSSAT. Thus, these scenarios are plausible climate conditions that retain the day-to-day and year-to-year characteristics of the 1970–99 baseline period, with monthly mean temperatures and precipitation that reflect the mean climate changes simulated by the GCM/emissions scenarios for the 2030s, 2050s and 2080s. By adjusting according to monthly means, changes in seasonality simulated by a given model experiment are also captured. The entire set of GCMs (Table 3.1), all three emissions scenarios and all future time slices are utilized.

In the initial simulations of future changes in potential unflooded yield (before the application of flood and sea level damages), crops are affected by CO_2 concentration, temperature and precipitation changes. These factors interact in a non-linear manner, but an estimate of the relative contribution of the CO_2 concentration compared to the effects of changing temperature and precipitation may be attained through test simulations. Both rice and wheat are C3 crops, and thus both react strongly to changes in temperature and CO_2 concentrations (Kimball and Bernacchi, 2006; Hatfield et al, 2008). The isolated impacts of changing CO_2 concentrations, as well as of changing precipitation and temperature, are described in this section, along with their combined direct effect of changing climate in each sub-region. Figure 5.2 summarizes the results as changes in national potential production due to isolated and combined direct climate effects.

CO_2 impact experiments

To isolate the agricultural effects of increased CO_2 concentration predicted by climate change, future climate scenarios were generated that used the baseline temperature and precipitation data but used CO_2 levels to match the future scenarios (see Table 5.8). Thus, the only difference between the future experiments and the baseline conditions was an elevated CO_2 concentration. Because the same CO_2 levels were used for all GCMs in a particular emissions scenario, a single 30-year simulation for each crop in each sub-region

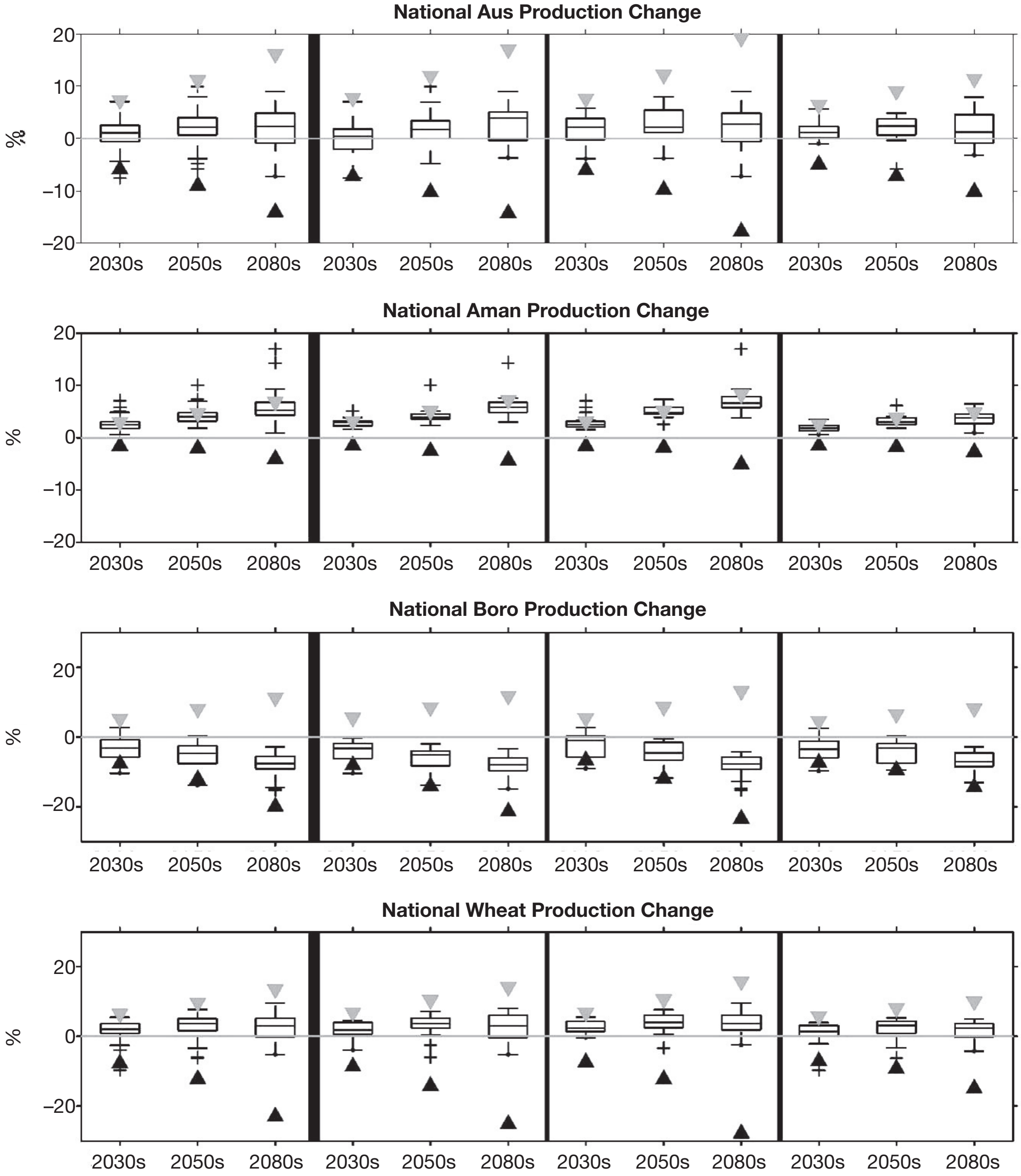


Figure 5.2 Percentage change (versus the baseline undamaged simulation) in national potential production of a) aus, b) aman, c) boro and d) wheat

Note: Each panel has four sections, each containing the three future time periods and presenting (from left to right) the combination of all emissions scenarios, the A1B, the A2 and the B1 scenario. The results of the CO2 impact experiments are displayed as upside-down triangles, while the median of the temperature and precipitation impact experiments is shown as an upside triangle. The distribution of undamaged potential yields projected by GCMs are presented as a box and whiskers diagram, consisting of a line representing the median value, a box enclosing the inter-quartile range (the middle 50 per cent of models), dashed whiskers extending to the furthest model that lies within 1.5 times the inter-quartile range from the edges of the box, and plus symbols for additional models that are perceived as outliers.

Table 5.8 Carbon dioxide concentrations (ppm) for baseline period and future climate scenarios

	B1	A1B	A2
1980s	345	345	345
2030s	450	472	470
2050s	498	552	556
2080s	541	667	734

allowed the contribution of CO_2 enhancement to be explored.

Elevated CO_2 concentrations have a positive effect on crop yield for all crops and locations in the simulations. Presented as upside-down triangles in Figure 5.2, the CO_2 impact experiments simulate an effect that can raise potential production by up to 20 per cent for 2080s A2 aus and 12 per cent in the 2080s B1 aus. CO_2 effects generally follow an upward trajectory in the future for each scenario. Potential production increases are least for aman, not quite reaching 10 per cent for the A2 2080s. These simulations may be optimistic about the beneficial effects of CO_2 on rice and wheat production, as research continues into the impact of CO_2 on open field crops, particularly in tropical areas (Hatfield et al, 2008).

Temperature and precipitation impact experiments

To examine the effects of future temperature and precipitation on potential yield without the influence of elevated CO_2, future scenarios for each GCM were created using the 'delta' approach but with CO_2 levels fixed at their baseline level (345ppm). The results are summarized as the upside triangles in Figure 5.2, representing the median change in national potential production (across all GCMs) due only to changes in temperature and precipitation.

Without the beneficial effect of CO_2, future climate changes reduce crop production. The most strongly affected crop is wheat, with potential production declining almost 30 per cent in the A2 2080s and 15 per cent in the B1 2080s. Large potential production losses are also seen in the boro and aus crops. Because they are irrigated, the decline in wheat and boro production is driven by temperature increases. Although the medians are all negative, some GCMs produce slightly positive changes even when the CO_2 is fixed to baseline levels, as temperature or precipitation changes may be favourable for a particular season in a given GCM. Regardless of the uncertain (although positive) magnitude of CO_2 effects, including future CO_2 concentrations increases potential production from the baseline levels seen in these experiments.

Unflooded (climate only) potential production projections

Simulations of crop production with changes in temperature, precipitation and CO_2 concentrations reveal large differences between crops, GCMs and emissions scenarios. Results are presented as box-and-whisker diagrams of national production changes in Figure 5.2, capturing the range of changes produced from the full set of IPCC GCM outputs relevant to Bangladesh. Changes largely depend on the interplay between CO_2 enhancement and the detrimental effects of temperature and precipitation. Their combined effect is clearly complex.

Aus production

Aus production increases under climate change scenarios, although the range of GCMs indicates some uncertainty in these projections. There is also a clear shift in trend in the latter half of the 21st century that suggests that the effects of temperature and precipitation stresses are more pronounced. For all scenarios and time periods at least one GCM produces a decline in production, but median production changes rise from 1.1 per cent in the 2030s to 2.2 per cent in the 2050s and 2.4 per cent in the 2080s. The central half of the GCM distribution suggests a range of about +/- 2 per cent in the 2030s and 2050s, with the centre of the distribution expanding to +/- 3 per cent in the 2080s. The 2030s A1B results are approximately distributed around zero change, but the 2080s A1B are the most positive of any scenario (4 per cent). Both the A2 and B1 scenarios begin with a larger change. Only the 2050s period has the entire central range of each scenario simulation higher than zero change. Aus production changes are fairly evenly distributed between the CO_2 impact and the temperature and precipitation impact experiment results.

Aman production

Aman production rises under all future time periods, emissions scenarios and GCM simulations. Following rising CO_2 concentrations, median production changes increase with time to 2 per cent in the 2030s to 4 per cent in the 2050s and to 5 per cent in the 2080s. Aman rice has the most robust changes of any crop, showing remarkably low variability between different scenarios. Overall changes are relatively small, however, with only a few GCM scenarios causing rises of 10 per cent or more. The centre half of the simulation distributions range around +/- 0.5 per cent in the 2030s, rising to +/- 1 per cent by the 2080s when emissions scenarios are combined. This increase in range is due mostly to the diverging emissions scenarios, which drive significantly different CO_2 enhancement impacts. Aman rice is grown at the height of the monsoon season, which provides plenty of rain even in simulations where mean rainfall decreases slightly. Monsoon clouds and high humidity also keep temperatures lower than in the pre-monsoon period. These factors reduce the temperature and precipitation impacts of climate change, and cause the production to be influenced most strongly by the beneficial CO_2 enhancement. Some scenarios even produce better production gains than the CO_2 enrichment alone, suggesting that the temperature and precipitation characteristics are more favourable for aman production. These results are in the absence of flood impacts discussed in subsequent sections.

Boro production

Boro production declines under climate change scenarios, with median national production losses across all emissions scenarios reaching 3 per cent in the 2030s, 5 per cent in the 2050s and 8 per cent in the 2080s. Several simulations project decreases in production of more than 10 per cent, with one GCM projecting a 15 per cent decline in the 2080s A1B. The central portion of the boro distributions ranges around +/- 2 per cent, and the distributions grow tighter at the end of the 21st century. Boro production changes are more responsive to the temperature changes than the CO_2 enhancement, with irrigation offsetting any precipitation change. Note that these estimates are conservative given that groundwater irrigation is assumed to be unconstrained. Currently, with evidence of declining groundwater tables in many parts of the northwest, future water availability may pose a serious additional constraint on boro production.

Wheat production

Wheat production increases under most climate change scenarios, although there is a clear shift in trend at the end of the 21st century towards lower yields. Median increases across all scenarios are 2 per cent, 4 per cent and 3 per cent for 2030s 2050s, and 2080s respectively. The largest median increases in yield for all emission scenarios occur in the 2050s, with A2 production rising 4 per cent, B1 production rising 3 per cent and the centre of the distribution ranging +/- 2 per cent. Potential production tracks more closely with the CO_2 enhancement than with the detrimental temperature increases (irrigation negates precipitation changes), but toward the end of the century production begins to move away from the CO_2 influence toward the much lower temperature impacts.

5.5 Projections of Future Projected Flood Damages

Production changes due to flood damages are presented in Figure 5.3 for aus and aman rice (boro and wheat are assumed to be un-impacted by floods). Flood damages are projected to increase in most scenarios, particularly for the 2050s time period and for the aman crop grown at the height of the monsoon. Median additional losses across all scenarios are 1 per cent and 2 per cent in the 2030s and 2050s respectively. Maximum median flood losses occur in the 2050s A2, with national aman production falling 4 per cent

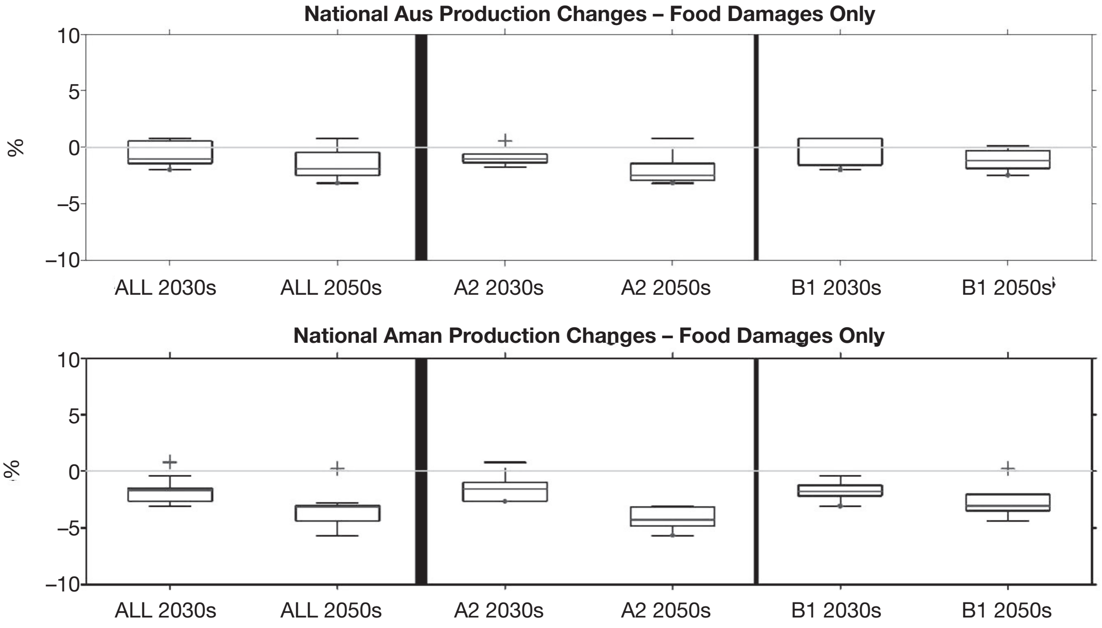


Figure 5.3 Percentage change (versus the baseline flood-only simulation) in national potential production affected by basin floods of a) aus and b) aman (boro and wheat are assumed to be flood-free)

Note: Each panel has three sections, each containing the two future time periods and presenting (from left to right) the combination of all emissions scenarios, the A2 scenario and the B1 scenario. The distribution of flood-damaged potential yields projected by GCMs is presented as a box and whiskers diagram, consisting of a line representing the median value, a box enclosing the inter-quartile range (the middle 50 per cent of models), dashed whiskers extending to the furthest model that lies within 1.5 times the inter-quartile range from the edges of the box, and plus symbols for additional models that are perceived as outliers.

and national aus production dropping 2.4 per cent. More modest crop losses are projected for the B1 scenario, reaching only 1 per cent of aus production and 3 per cent of aman production in the 2050s. The narrow distribution of flood damages projected by different GCMs suggests a robust change, although changes are small compared to the year-to-year variability in each time period. These results are likely to be optimistic, as changes in inter-annual variability between the baseline and future time periods are likely to produce larger flood damages and several sub-regions were not modelled.

5.6 Projections of Potential Coastal Inundation Damages

The percentage of production lost to coastal inundation associated with sea level rise in each sub-region is presented in Figure 5.4. Coastal sub-regions experience impacts that increase with time as sea levels rise, with maximum crop losses of nearly 40 per cent projected for the 2080s in sub-region 16 in the southwest. Sub-region 15 also loses a substantial portion of agricultural production, while more modest losses are simulated in sub-regions 10 and 12. Even without considering the effects of increased frequency of cyclones and increasing groundwater salinity, these simulations still project considerable production losses.

5.7 Projections of Integrated Damages

National production changes

The combined impacts of climate change on potential national cereal production are presented in Figure 5.5, including the effects of CO_2

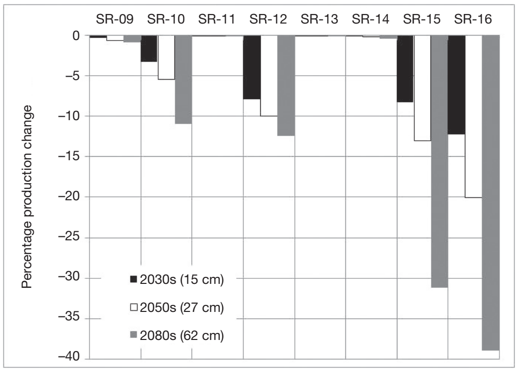


Figure 5.4 Percentage of production lost to coastal inundation associated with sea level rise in each coastal region sub-region (9–16) for three future scenarios, as compared to the baseline period (for A2 SRES)

Note: Depths in the legend refer to the mean sea level rise associated with each future scenario.

enhancement, temperature and precipitation changes, river basin flooding and coastal flooding. The median of all rice crop projections show declining national potential production in future decades, with boro production showing the largest median losses. Wheat production increases out to the 2050s period. Median value production losses are given in Table 5.9.

Aus production

Changes in aus production are mostly negative, but median losses are only 1.5 per cent of the baseline potential production by the 2050s for all scenarios. Significant projections, however, indicate anywhere from 9 per cent losses to 3.5 per cent gains. A substantial number of GCMs project slight increases, especially in the A2 scenario where CO_2 levels are higher. The added effects of basin and coastal flooding result in production losses in national aus. This is despite the CO_2 enhancement slightly exceeding the damage caused by temperature and precipitation changes (see Figure 5.2). Losses reach 3.5 per cent in the 2050s A2, although the range in GCM projections covers both positive gains and losses of nearly 10 per cent. In all, the aus production changes do not separate themselves convincingly from zero, suggesting that the aus crop, on balance, will not be strongly affected by climate change up to the 2050s. The role of aus in total production is expected to decline over time.

Table 5.9 Median integrated production change (per cent) for the 2030s and 2050s

	2030s All SRES	2050s All SRES	2030s A2	2050s A2	2030s B1	2050s B1
Aus	−0.27	−1.52	−1.11	−3.51	−0.14	0.01
Aman	−0.37	−0.62	−0.42	−1.49	−0.37	−0.40
Boro	−3.06	−4.74	−1.68	−5.54	−3.76	−3.54
Wheat	2.05	3.44	2.23	3.74	1.33	3.03

Note: All SRES refers to both the A2 and B1 emissions scenarios

Aman production

Aman production is substantially impacted by basin and coastal flood effects where projected yield changes are overwhelmingly negative by the 2050s. The tight distribution between GCM projections allows a more definitive assessment that losses are expected, but the magnitude of the median change is only losses of 0.4 per cent in the 2030s and 0.6 per cent in the 2050s. The largest median decrease is -1.5 per cent projected for the 2050s A2 scenario. Thus, aman production will also not experience strong effects due to climate change. Note that this only reflects mean changes in flood impacts and not changes in the future frequency of extreme events and inter-annual variability.

Boro production

Projections for boro production are entirely negative by the 2050s, with substantial losses likely. Boro is not affected by river floods, and most production occurs away from the coastal sub-regions; thus, integrated damages are similar to the climate-only production estimates (Figure 5.2). Boro production declines with time, with median losses across all emissions scenarios reaching 3 per cent by the 2030s and 5 per cent by the 2050s, although some GCMs project losses of greater than 10 per cent. The robust loss projections suggest that boro is the major Bangladeshi crop that is most at-risk to climate change impacts.

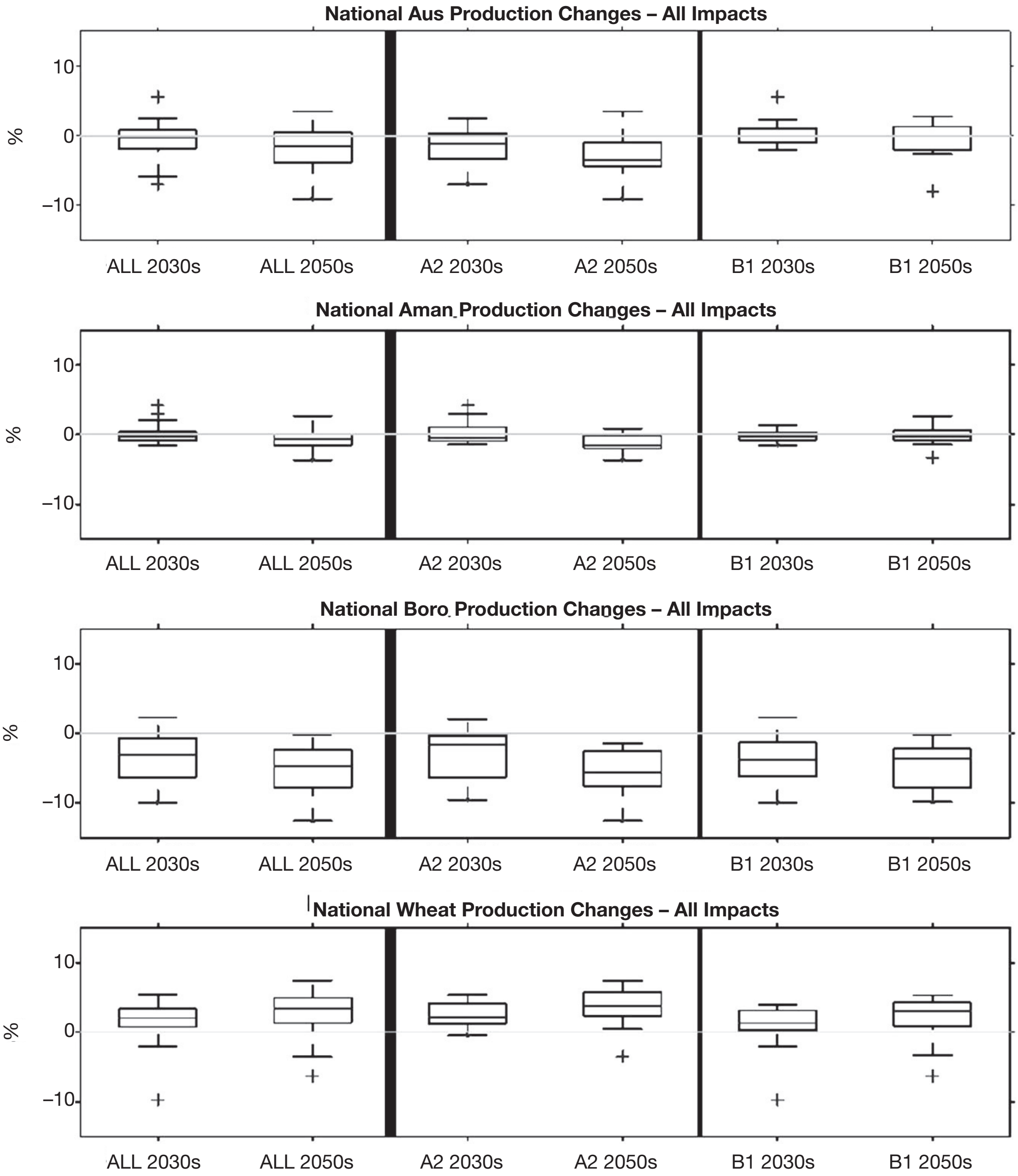


Figure 5.5 Percentage change (versus the baseline flood-affected simulation) in national potential production with the combined effects of CO_2, temperature and precipitation changes, basin flooding and coastal flooding

Note: Each panel has three sections, each containing two future time periods and presenting (from left to right) the combination of all emissions scenarios, the A2 scenario and the B1 scenario. The distribution of potential yields projected by GCMs are presented as a box and whiskers diagram, consisting of a line representing the median value, a box enclosing the inter-quartile range (the middle 50 per cent of models), dashed whiskers extending to the furthest model that lies within 1.5 times the inter-quartile range from the edges of the box, and plus symbols for additional models that are perceived as outliers.

Wheat production

Wheat production increases under climate change, reaching nearly 4 per cent in the 2050s A2. Some GCMs project gains as high as 7 per cent in that period, but some B1 scenarios project production losses when CO_2 levels are not as high. Wheat does not experience river flooding and most production occurs away from coastal regions affected by sea level rise, so integrated estimates are very similar to the undamaged production estimates above (Figure 5.2). In all, wheat production is projected to be positively affected by climate change out to the 2050s, but strong temperature effects (represented as upside triangles in Figure 5.2d) and uncertain benefits of enhanced CO_2 concentrations suggest that these wheat gains may be overly optimistic. These simulations also indicate that wheat production may decline rapidly as temperature changes pass key thresholds.

Sub-regional production changes

Figure 5.6 and Table 5.10 show the production changes by crop, by climate impact factor and by sub-region for the 2050s for a combined A2 and B1 scenarios. Production losses compared to the baseline are estimated for at least one crop in each sub-region. For sub-regions including Maijdee Court (SR-12), Patuakhali (SR-15) and Khulna (SR-16), the yields for all four crops are reduced. These southern areas are the most vulnerable to climate change due primarily to both sea level rise and riverine flooding. The largest observed decreases in yields are in Khulna (SR-16) (approximately 10 per cent reduction in aman, aus and wheat yields, and 18 per cent reduction in boro yields). For five sub-regions – Tangail (SR-4), Sylhet (SR-7), Maijdee Court (SR-12), Patuakhali (SR-15) and Khulna (SR-16) – both the aman and aus crops demonstrate negative changes in yields. That is, any potential gains from CO_2 effects on the aus and aman will be more than offset by the negative impacts of temperature and precipitation changes, and inland and coastal flooding. For the wheat crop, only five sub-regions show decreases in yields. These are concentrated in the south where wheat production is lower. For the boro crop, all but one sub-region, Sylhet (SR-7), show decreases in yields (primarily due to CO_2 fertilization effects). The largest decrease in yield from basin flooding is observed in sub-region 7 (approximately 9 per cent for both the aman and aus crop). For coastal flooding, the largest decreases in yield are observed in SR-12, SR-15 and SR-16 (7 per cent, 9 per cent and 13 per cent reductions respectively). The yield impacts of temperature and precipitation changes vary by sub-region depending on the crop. The largest declines in aman, aus, boro and wheat are in SR-3 (4 per cent), SR-4 (13 per cent), SR-8 (16 per cent) and SR-1 (19 per cent) respectively.

5.8 Using the Crop Model to Simulate Adaptation Options

Vulnerabilities to and potential adaptation strategies for climate change have been identified in Bangladesh for agriculture and many other sectors (Karim et al, 1994; Huq et al, 1999; Ali, 1999; NAPA, 2005; Ahmed, 2006; Tanner et al, 2007). The IPCC also devoted chapters to global climate change impacts on the agricultural sector (Easterling et al, 2007) and coastal regions (Nicholls et al, 2007) as well as adaptation options (Adger et al, 2007). Thomalla et al (2005) detail some of the historical efforts to implement widespread adaptation strategies in Bangladesh utilizing local, regional, governmental and non-governmental entities. Much of the international effort for adaptation has focused on reducing the threats of floods and tropical cyclones following devastating events in the 1980s and 1990s. Some agricultural adaptation is already being tested in the field, e.g. dried hyacinth used as a basis for floating agriculture during flooding in Barisal and salinity-tolerant cultivars introduced to adapt to salinity intrusion (Sarwar, 2005). But widespread efforts in the agricultural sector are not yet prominent. Moreover, the current large gap between actual and potential yields suggests substantial on-farm opportunities for growth and poverty reduction. Expanded availability of modern rice varieties, irrigation facilities, fertilizer use

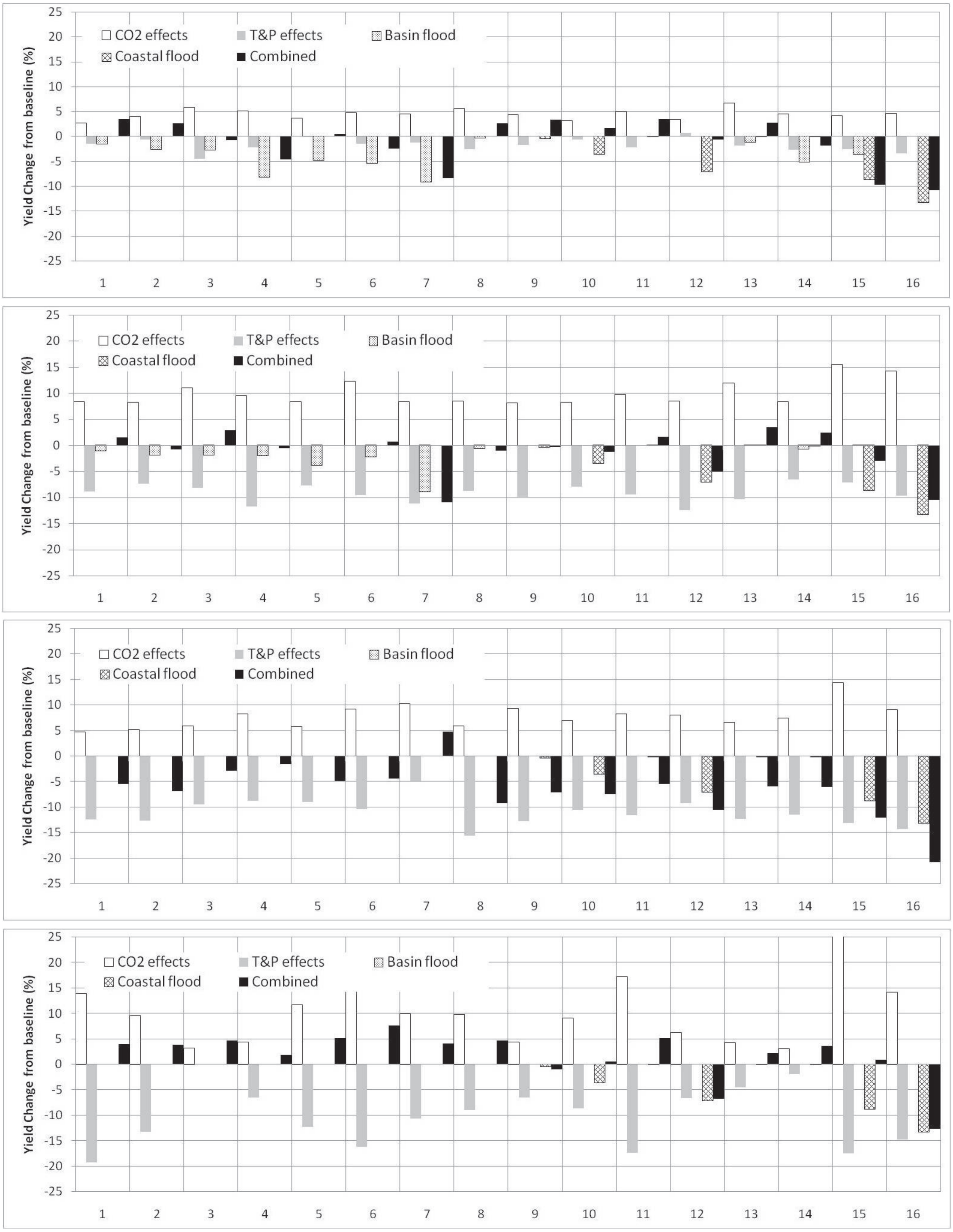


Figure 5.6 Regional median potential production changes from baseline (per cent) for 2050s (a) aman, (b) aus, (c) boro and (d) wheat

Note: Numbers refer to sub-region.

Table 5.10 Sub-regional average production changes (per cent) disaggregated by crop (aman, aus, boro, wheat) and climate risk for 2050s – all scenarios

	Aman					Aus					Boro[1]					Wheat[1]				
SR	CO_2	T&P	FLD	SLR[2]	COM	CO_2	T&P	FLD	SLR	COM	CO_2	T&P	FLD	SLR	COM	CO_2	T&P	FLD	SLR	COM
1	2.72	–1.46	–1.57	0	3.5	8.37	–8.89	–1.12	0	1.47	4.66	–12.43	0	0	–5.43	14.04	–19.26	0	0	3.96
2	4.11	–0.64	–2.69	0	2.71	8.31	–7.4	–1.95	0	–0.75	5.16	–12.57	0	0	–6.81	9.69	–13.24	0	0	3.88
3	5.83	–4.43	–2.8	0	–0.78	11.06	–8.23	–1.91	0	2.93	5.91	–9.4	0	0	–2.78	3.25	0.15	0	0	4.76
4	5.2	–2.21	–8.24	0	–4.57	9.54	–11.74	–2.05	0	–0.55	8.22	–8.75	0	0	–1.49	4.48	–6.44	0	0	1.91
5	3.7	–0.16	–4.83	0	0.5	8.37	–7.7	–3.89	0	–0.12	5.73	–8.96	0	0	–4.83	11.78	–12.23	0	0	5.2
6	4.8	–1.42	–5.38	0	–2.37	12.35	–9.55	–2.28	0	0.68	9.18	–10.37	0	0	–4.32	16.59	–16.15	0	0	7.61
7	4.59	–1.22	–9.16	0	–8.31	8.39	–11.23	–8.94	0	–10.97	10.25	–4.88	0	0	4.83	9.98	–10.59	0	0	4.11
8	5.63	–2.51	–0.31	0	2.68	8.56	–8.73	–0.6	0	–1.07	5.88	–15.57	0	0	–9.2	9.87	–9.02	0	0	4.73
9*	4.38	–1.66	0	–0.41	3.39	8.14	–9.96	0	–0.41	–0.3	9.31	–12.74	0	–0.41	–7.08	4.49	–6.49	0	–0.41	–0.94
10*	3.24	–0.57	0	–3.56	1.68	8.32	–7.92	0	–3.56	–1.22	6.97	–10.46	0	–3.56	–7.38	9.13	–8.65	0	–3.56	0.61
11*	5.06	–2.17	0	–0.02	3.49	9.76	–9.5	0	–0.02	1.67	8.23	–11.59	0	–0.02	–5.41	17.28	–17.34	0	–0.02	5.14
12*	3.44	0.78	0	–7.09	–0.66	8.53	–12.48	0	–7.09	–5.09	8	–9.21	0	–7.09	–10.49	6.38	–6.6	0	–7.09	–6.68
13	6.69	–1.82	–1.25	–0.03	2.79	11.99	–10.36	–0.04	–0.03	3.44	6.63	–12.27	0	–0.03	–5.85	4.37	–4.46	0	–0.03	2.19
14	4.56	–2.62	–5.17	–0.12	–1.83	8.43	–6.58	–0.75	–0.12	2.43	7.44	–11.39	0	–0.12	–5.98	3.19	–1.85	0	–0.12	3.64
15	4.19	–2.51	–3.67	–8.73	–9.64	15.58	–7.09	–0.04	–8.73	–3.05	14.37	–13.09	0	–8.73	–12.05	27.97	–17.51	0	–8.73	0.96
16*	4.61	–3.4	0	–13.26	–10.76	14.3	–9.71	0	–13.26	–10.5	9.07	–14.3	0	–13.26	–20.79	14.26	–14.76	0	–13.26	–12.56

Notes: CO_2 = Carbon dioxide enhancements are estimated from the CO_2 impact experiments and differ from the baseline period only in their atmospheric CO_2 concentration; T&P = Temperature and precipitation effects are estimated from the range of scenarios simulated by the temperature and precipitation impact experiments and differ from the baseline period only in their temperature and precipitation series; FLD = Basin flood effects are estimated from changing flood magnitudes and extent without regard for direct climate effects (CO_2, temperature, or precipitation); SLR = Sea level rise damages are estimated from the changing coastlines projected as mean sea levels rise of the A2 scenario, with no other factors differing from the baseline period; COM = Combined effects include all climate risks described above.

*Sub-regions 9–12 and 16 were not modelled in the future flood analysis.

**Sea level rise only impacts sub-regions 9–16.

***Boro and wheat crop is assumed not impacted by the flood.

and labour could increase average yields at rates that dwarf the climate change impacts.

An important follow-on to the present study is the use of the crop simulation approach developed here to evaluate adaptive responses themselves. There are many elements of cropping for which adaptations can be studied; these are described in detail in Annex 1. The elements for potential evaluation include: cultivar selection; adjustments in planting and harvesting dates and crop sequence; changes in planting systems, including crop density; and input adjustments including irrigation, fertilizer and farm-level environmental modifications. Studying these elements will enable the development of additional adaptation options such as those detailed in Chapter 7.

6

Economy-wide Impacts of Climate Risks

Box 6.1 Key messages

- Economy-wide adjustments will to some extent mitigate the physical losses predicted.
- Existing climate variability has a pronounced detrimental economy-wide impact. Compared to an 'optimal' climate simulation with the highest simulated yield and no inter-annual variations, climate variability is estimated to reduce long-term rice production by an average 7.4 per cent each year during 2005–50, primarily by lowering production of the aman and aus crops. Average annual rice production growth is lowered in all sub-regions.
- Simulated climate variability is projected to cost the agriculture sector (in discounted terms) US$26 billion in agricultural GDP during the 2005–50 simulation period (US$0.57 billion per year in 2005 US$) compared with optimal production and growth. This climate variability has economy-wide implications beyond simply the size-effect of the lost agricultural GDP. Existing climate variability is estimated to cost Bangladesh US$121 billion in lost national GDP during the same period (US$3 billion per year).
- Climate change exacerbates the negative impacts of existing climate variability for food security by further reducing rice production by a projected cumulative total of 80Mt over the 2005–50 simulation period (3.9 per cent each year), driven primarily by reduced boro crop production. This is equivalent to almost two years' worth of rice production lost over the next 45 years as a result of climate change. Uncertainty about future climate change means that annual rice production losses range between 3.6 per cent and 4.3 per cent.
- Climate change primarily impacts boro rice and thus limits its ability to compensate for lost aus and aman rice production during extreme events.
- Agricultural GDP is projected to be 3.1 per cent lower each year as a result of climate change (US$8 billion in lost value-added in 2005 US$). Average loss in agricultural GDP due to climate change is estimated to be a third of the agricultural GDP losses associated with existing climate variability. This is projected to cost Bangladesh US$26 billion in total GDP over the 2005–50 period. This is equivalent to US$570 million overall lost each year to climate change, or alternatively an average annual 1.15 per cent reduction in total GDP by 2050.
- Uncertainty surrounding GCMs and emission scenarios means that costs may be as high as US$1 billion per year over 2005–50 under less optimistic scenarios.
- These climate risks will have severe implications for household welfare. For both the climate variability and climate change simulations, around 80 per cent of these losses fall directly on household consumption (cumulative total consumption losses of US$441.7 billion and US$104.7 billion for climate variability and climate change respectively).
- About 80 per cent of the projected economic losses from existing climate variability and climate change occur outside of the agriculture sector (from a national accounts perspective), particularly in the upstream and downstream agriculture value-added processing sectors. This means that both rural and urban households may be adversely affected.

Chapter 5 provides estimates of changes in production for four different crops (aus, aman, boro and wheat) due to various climate risks. Though informative, this information should be supplemented by economic responses to these production shocks (e.g. land and labour reallocation, price effects). These economic adjustments will to some degree mitigate the physical losses predicted. What is described in this section is the development and use of a dynamic computable general equilibrium model to assess the economy-wide impacts from these projected losses. The focus here is on rice production economic impacts only since this dominates agricultural and household food consumption.

6.1 Integrating Climate Effects in an Economy-wide Model

Conceptual framework of the methodology

A dynamic computable general equilibrium (CGE) model was developed to estimate the impacts of existing climate variability and future climate change in Bangladesh on the agriculture sector. The yield change estimates from the hydro-crop models described earlier are passed down to the CGE model to estimate their economy-wide implications, including changes in production and household consumption for different sectors, household groups and sub-regions in the country. A detailed description of the model is provided in Annex 2.

Three impact channels, apart from crop yield changes estimated from the hydro-crop models, are captured in the CGE model. First, the CGE model includes the additional impacts that occur under extreme climatic events, such as during the major floods of 1988 and 1998. These comprise, for example, major losses of cultivatable land due to floodwater inundation, which occurs over and above the average flood yield losses described in previous sections. The second additional impact channel considered in the CGE analysis is the change in the frequency of these extreme events caused by climate change. It is expected that major floods in Bangladesh will become more frequent, thus exacerbating economic losses through heightened climate variability. Finally, though sea level rise impacts on yields were determined earlier (see section 5.6) changes in cultivable land are explicitly incorporated in the CGE. The CGE analysis, therefore, builds on the hydro-crop modelling analysis by incorporating the predicted crop yield changes, while also extending the analysis by including the impact and frequency of extreme climate events.

Climate simulations

Three sets of simulations are run using the CGE model.

Optimal Climate

The first simulation is the 'Optimal Climate Simulation', in which Bangladesh is unaffected by existing climate variability or future climate change. This means that the highest simulated crops yields are used and sector productivity and factor supplies increase smoothly at long-term growth rates with no inter-annual variations. 'Optimal' is defined as the best simulated crop yield achieved in each sub-region during the 30-year baseline period 1970–99. This scenario reflects a hypothetical trajectory for Bangladesh in which there are no yield losses caused by climate variability. This simulation provides a hypothetical baseline scenario against which other climate-affected simulations can be compared. Since climate conditions are always assumed to be 'optimal' (i.e. no crop yield losses or major floods), it is not necessary to run multiple baseline simulations to account for climate uncertainty (i.e. there is only one optimal scenario).

Existing Variability

The second set of simulations is the 'Existing Variability Simulation'. These simulations include the yield losses associated with the historical climate data series. The CGE model is run forward over 45 years (2005–50) and for each year a random observation is drawn from the historical data series (1970–99). The crop yield changes estimated by the hydro-crop models (relative to the potential yields) for that particular baseline historical year are imposed on the CGE model, which then estimates the economy-wide impacts. Moreover, years in the historical record during which major floods took place (i.e. 1970, 1974, 1984, 1987, 1988 and 1998) are identified. If one of these years is drawn during the random selection, then additional impacts are imposed on the CGE model (discussed later in this section). Together these random selections from the historical climate data produce a single 45-year climate scenario based on existing climate variability and patterns (i.e. without the effects of climate change). This Monte Carlo process is repeated 50 times in order to produce a series of 45-year climate scenarios. The average economy-wide outcomes for these 50 simulations provide an estimate of the economic impact of existing climate variability since all Monte Carlo runs are considered equally likely.

Climate Change

The third set of simulations is the 'Climate Change Simulation'. As described earlier, the hydro-crop models estimate crop yield changes for future 30-year time slices around the 2030s and 2050s based on a range of model experiments. As the CGE model is run forward over the 2005–50 period, yield impacts are drawn initially from the historical series and then gradually from the future series. For example, there are 30 years separating the 2005 base year of the CGE model and the mid-point of the 2030s time slice. Thus, in 2010, which is year 5, 25/30 of the yield impact from the randomly selected year in the historical dataset and 5/30 of the yield impact from the same year in the 2030s time slice are used[1]. A similar linear transition from the 2030s to the 2050s time-series is used. As with the Existing Variability Simulation, this Monte Carlo process is repeated 50 times and the average is taken to provide an overall estimate of economic outcomes under climate change. Finally, this whole process is repeated for the two emissions scenarios and five GCMs described earlier.

These three sets of simulations can be used to decompose the impacts of existing climate variability and future climate change. The difference between the results from the CGE model for the Existing Variability Simulation and the Optimal Climate Simulation is the estimated economic impact of existing climate variability. Similarly, the difference between the results for the Existing Variability and Climate Change simulations is the estimated economic impact of climate change.

Bangladesh CGE model

A CGE model is a representation of the structure and workings of an economy. CGE models are often called 'economy-wide' models because they include all sectors and households as well as a country's government and its interactions with the rest of the world (i.e. imports and exports). They are also called 'macro-micro' models because they estimate how changes in macro-level conditions, such as the external shocks caused by climate variation, influence micro-level outcomes, including sector production and household incomes and spending. This macro-micro linkage is achieved by simulating the functioning of factor and commodity markets, and thus captures how changes in economic conditions are mediated through prices. Economic decision-making in CGE models is the outcome of decentralized optimization by producers and consumers within a coherent economy-wide framework. The outcomes of a CGE model are therefore determined by the structure of the economy and by the behavioural assumptions. This section briefly describes the main characteristics of the Bangladesh model and the way in which the results from earlier sections are incorporated within this analytical framework to assess climate variability and change.

In order to capture the heterogeneity of producers and households, the Bangladesh CGE model is based on a highly disaggregated 2005 social accounting matrix (SAM).[2] The model distinguishes between 36 productive activities/commodities (17 in agriculture, 14 in industry and 5 in services). Agricultural production in each crop or sub-sector is further disaggregated across the

16 sub-regions described in earlier sections. Each of the 36 sectors in each of the 16 sub-regions is represented by a production function, which combines factor and intermediate inputs to produce a certain level of output. This output is supplied to either domestic or foreign markets based on relative prices.

In Bangladesh the size of agricultural landholdings is an important determinant of the activities and technologies that are available to farmers. Agricultural land in the model is thus disaggregated into marginal, small, medium and large-scale holdings based on the 2005 Agricultural Census (BBS, 2006a). Similarly, education is important in determining employment opportunities for workers. The CGE model therefore separates workers into four education-based categories taken from the 2005 Household Income and Expenditure Survey (HIES) (BBS, 2006b). Labour in each category is assumed to be fully mobile across sectors and regions. A flexible wage then adjusts to ensure total labour demand equals supply. Agricultural land, by contrast, is region-specific, but can be reallocated to different crops and sub-sectors depending on their relative profitability. Finally, capital in the model is immobile and earns region/sector-specific returns. The model's detailed treatment of producers and factors allows it to capture Bangladesh's unique production structure and resource constraints, as well as some of the 'autonomous' adaptation to climate variation that is driven by economic forces (i.e. prices and profitability).

The Bangladesh model separates households into 52 groups based on the region where they are situated; whether they are engaged in farming; the size of farmers' land holdings; and, for non-farm households, their land-ownership status and the educational attainment of the household head. Households in the model earn incomes from producers' use of the factors of production. These returns are paid to households based on their factor endowments, which are drawn from the 2005 household survey. Households use their incomes to pay taxes, save, and purchase domestic and imported goods in national commodity markets. Tax revenues are paid to the government where they are used for recurrent spending. Private and public savings are pooled and used to finance investment.

The CGE model is run over the simulation period 2005–50. During this time the model's parameters are updated based on long-term demographic trends and rates of technical change. For example, population and labour supply growth is assumed to diminish over time from 2 per cent per year in 2005. Agricultural land expansion also declines over time. Long-run growth in total factor productivity (TFP) starts at 2 per cent per year and falls to 0.5 per cent by 2050. However, land availability and technology outcomes vary from year to year depending on climate conditions. In the CGE model, climate variability and future change affect the growth and development of Bangladesh through three primary mechanisms:

1. Crop yield changes. The impact of climate variables on agricultural productivity are obtained from the hydro-crop models, which estimate yield changes for different crops and sub-regions (relative to a potential yield). Specifically, the CGE model first determines how much land, labour, capital and intermediate inputs are allocated to a crop. This gives an estimated level of production under the assumption of 'optimal' climatic conditions. The hydro-crop models then determine deviations from this level as a consequence of realized climate. These short-term deviations are imposed on the technology parameters of the production functions. Together the long-term resource allocations determined by the CGE model and the short-term deviations in crop yields obtained from the hydro-crop models determine the level of production in each sector and region during a particular year.
2. Extreme events. Additional impacts occur during extreme climate events, such as the major floods of 1988 and 1998. During major flood years it is assumed that long-term rates of land expansion and technology accumulation cease and there is a short-term decline in available agricultural lands due to particularly severe and persistent flooding. These land

losses are based on historical production data. While crop yields and agricultural lands may return to 'normal' after an extreme event, the loss in productive assets and forgone technical improvements will have lasting implications in the CGE model. Climate change is also predicted to increase the frequency of extreme events and this is also captured in the model. The return periods for the 1988 and 1998 flood years are reduced by one-third. In other words, 1988 and 1998 are characterized as the 1/33 and 1/50 year floods respectively (in relation to water discharges). The frequency of these floods in the sample for the random selection of years for the future climate change sequences is increased to 1/25 and 1/33 for the 1988 and 1998 floods respectively.

3. Sea level rise. Certain parts of Bangladesh are particularly vulnerable to rising sea levels, including crop land salinization from tropical cyclones. This is captured in the CGE model by permanently reducing the supply of cultivable land in the affected sub-region. These land losses are based on the results from the hydrological models described in earlier sections. For all climate change scenarios, the CGE model simulates a gradual 15cm sea level rise by the 2030s and a 27cm sea level rise by the 2050s.

Climate change is projected to take place over the course of the next century. The analysis in this section only considers the implications of climate change to 2050 even though climate change is expected to be most severe towards the end of the century. Nevertheless the relatively long timeframe considered (45 years into the future) means that dynamic processes are important. Economic development is in many ways about the accumulation of factors of production such as physical capital, human capital and technology. These factors, combined with the necessary institutional frameworks to make them productive, determine the material wellbeing of a country. The CGE model captures these dynamic processes. To the extent that climate change reduces agricultural output in a given year, it also reduces income and hence savings. Reduced savings translate into lower levels of investment, which in turn lower potential future production. Extreme events, such as flooding, can destroy assets and infrastructure in the period in which the event occurs and with lasting effects. Generally, even small differences in rates of accumulation can lead to large differences in economic outcomes over long time periods. The CGE model used in this section is designed to capture these accumulation effects.

Limitations of the CGE model

As with any economic modelling there is uncertainty over the accuracy of underlying data and the values of behavioural parameters. For example, the social accounting matrix (SAM) to which the CGE model is calibrated captures current production technologies and linkages. While the CGE model allows for some endogenous change from existing technologies, it cannot predict the emergence of entirely new technologies or economic sectors. Similarly, the model uses estimated elasticities for various functions, such as factor substitution possibilities in the production function, or the ease at which consumers can shift between domestic and foreign goods depending on relative prices. Although the CGE model is based on the best available data on Bangladesh's economic structure and institutional behaviour, both of these characteristics could change substantially over the long time periods simulated in this chapter. Thus, while the analysis in Chapter 6 provides the best estimate based on existing knowledge on Bangladesh's economy, some caution should be exercised when interpreting the absolute magnitudes of estimated economic losses.

6.2 Economic Impacts of Existing Climate Variability

An optimal climate scenario without climate variability

Economic growth in the Optimal Climate Scenario (Table 6.1) is driven by assumptions about

Table 6.1 Summary of the Optimal Climate Scenario

	Average annual growth rate (%)				Share of total GDP (%)			
	2005–50	2005–25	2025–40	2040–50	2005	2025	2040	2050
Total GDP	4.65	4.47	4.80	4.78	100.00	100.00	100.00	100.00
Agriculture	3.46	3.50	3.47	3.39	20.17	16.71	13.79	12.06
All rice crops	3.03	3.21	2.97	2.75	6.61	5.18	3.98	3.27
Aus variety	3.07	3.24	3.02	2.80	0.38	0.30	0.23	0.19
Aman variety	3.02	3.20	2.97	2.75	2.63	2.06	1.58	1.30
Boro variety	3.03	3.21	2.97	2.74	3.60	2.82	2.17	1.78
Industry	5.15	4.88	5.40	5.29	29.34	31.72	34.57	36.27
Rice processing	2.94	3.17	2.87	2.59	1.99	1.55	1.17	0.95
Services	4.71	4.59	4.81	4.79	50.48	51.57	51.63	51.66

the accumulation of factors of production and technical change with no inter-annual variations. A gradually declining rate of population growth from around 2 per cent per year and a constant dependency ratio, such that the labour force and the population grow at the same rate, are assumed. However, the supply of higher skilled labour grows faster than the supply of illiterate and unskilled workers, reflecting expected improvements in the Bangladesh educational system and changing labour demands over time. Land expansion rates are initially set at 1 per cent per year, but declines to 0.5 per cent per year by 2050. This is below rural population growth, thus capturing existing and future increases in agricultural land scarcity. Finally, it is assumed that total factor productivity growth rates are higher in industry and services than in agriculture, with the former set at 2.5 per cent per year and the latter at 2 per cent per year. Together these assumptions determine the Optimal Climate Scenario and provide a benchmark growth path against which the economic losses from existing climate variability can be measured.

Under the Optimal Climate Scenario, total GDP grows at an average rate of 4.65 per cent per year during 2005–50, with a slight acceleration in the average growth rate from the beginning to the end of the period (see Table 6.1). As observed in most countries' development paths, economic growth is not evenly balanced across all sectors, with a declining contribution of agriculture to total GDP and a rising contribution from industry. Thus, agriculture's share of total GDP falls from 20.17 per cent in 2005 to 12.06 per cent by 2050. By contrast, industry's share rises from 29.34 to 36.27 per cent during the same period. This declining role of agriculture has implications for estimating the economic cost of climate variability and change, since the sector is expected to be the primary impact channel. Thus, any adverse impacts to the agricultural sector will be offset by the sector's declining importance in the overall economy.

Production losses from existing variability

As described in section 6.1, the Existing Variability Scenario imposes crop yield losses observed during the 1970–99 baseline period. These yields reflect 'sub-optimal' climate conditions (i.e. rainfall, temperature and flooding). The average of the Monte Carlo economic outcomes is termed the Variability Scenario. Figure 6.1 shows the estimated losses in national rice production caused by existing climate variability. Under the Optimal Climate Scenario, national rice production grows at 3.03 per cent per year during 2005–50. In physical terms, rice production rises from 22.36Mt in 2005 (162kg per capita) to 85.56Mt by 2050 (255kg per capita). The impact of existing climate variability is a reduction in rice production, with its average annual growth rate falling from 3.03 to 2.71 per cent per year. Under the Variability Scenario, rice production rises to 74.6Mt by 2050 (222kg per capita), which is almost 11Mt (33kg per capita) below what would have been achieved without the adverse

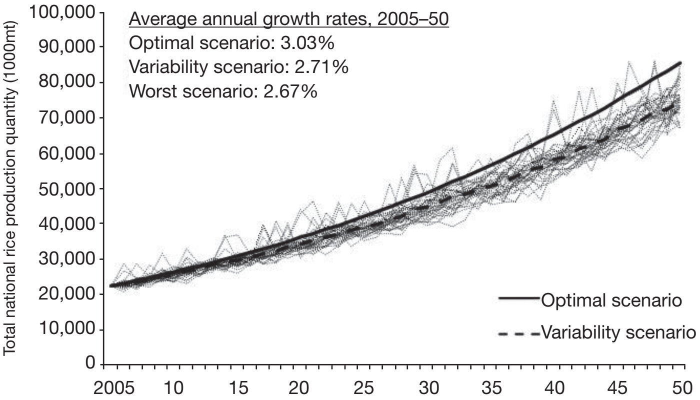


Figure 6.1 Losses in total national rice production due to existing climate variability, 2005–50

Table 6.2 National rice production losses due to existing climate variability, 2005–50

	Average annual growth rate (%)				Rice production quantities (1000 tonnes)			
	2005–50	2005–25	2025–40	2040–50	2005	2025	2040	2050
All rice crops								
Optimal Scenario	3.03	3.21	2.97	2.75	22,355	42,038	65,226	85,563
Variability Scenario	2.71	2.84	2.69	2.51	22,355	39,123	58,232	74,596
Worst Case Scenario	2.67	2.43	2.98	2.69	22,355	36,122	56,105	73,186
Aus rice								
Optimal Scenario	3.07	3.24	3.02	2.80	897	1697	2652	3497
Variability Scenario	2.46	2.49	2.47	2.37	897	1467	2115	2673
Worst Case Scenario	2.34	2.21	1.36	4.12	897	1388	1699	2544
Aman rice								
Optimal Scenario	3.02	3.20	2.97	2.75	11,687	21,950	34,042	44,668
Variability Scenario	2.41	2.53	2.39	2.22	11,687	19,262	27,443	34,196
Worst Case Scenario	2.27	1.81	2.74	2.51	11,687	16,725	25,079	32,125
Boro rice								
Optimal Scenario	3.03	3.21	2.97	2.74	9772	18,392	28,532	37,398
Variability Scenario	3.05	3.21	3.00	2.78	9772	18,393	28,674	37,728
Worst Case Scenario	3.09	3.10	3.30	2.76	9772	18,010	29,328	38,517

impacts of climate variability (see Table 6.2). This means that Bangladesh will lose on average 7.4 per cent of its optimal rice production each year if the existing climate variability patterns remain unchanged into the future. Moreover, this share of lost production increases throughout the period, as the effects of climate variability are compounded.

The Worst Case Scenario is defined as the randomly drawn climate series resulting in the largest overall economic losses for the country as a whole.[3] Under the Worst Case Scenario, rice production averages 2.67 per cent growth per year. By 2050, this implies an additional loss of 1.41Mt.

Changes in national rice production hide differential impacts for specific rice crops (see Figure 6.2). Under the Variability Scenario, most of the lost rice production is due to reduction in production for the aus and aman crops. These crops are adversely affected by yield declines from flooding during the wet season. For example, the average annual growth rate for aman rice production is 3.02 per cent under the Optimal Climate

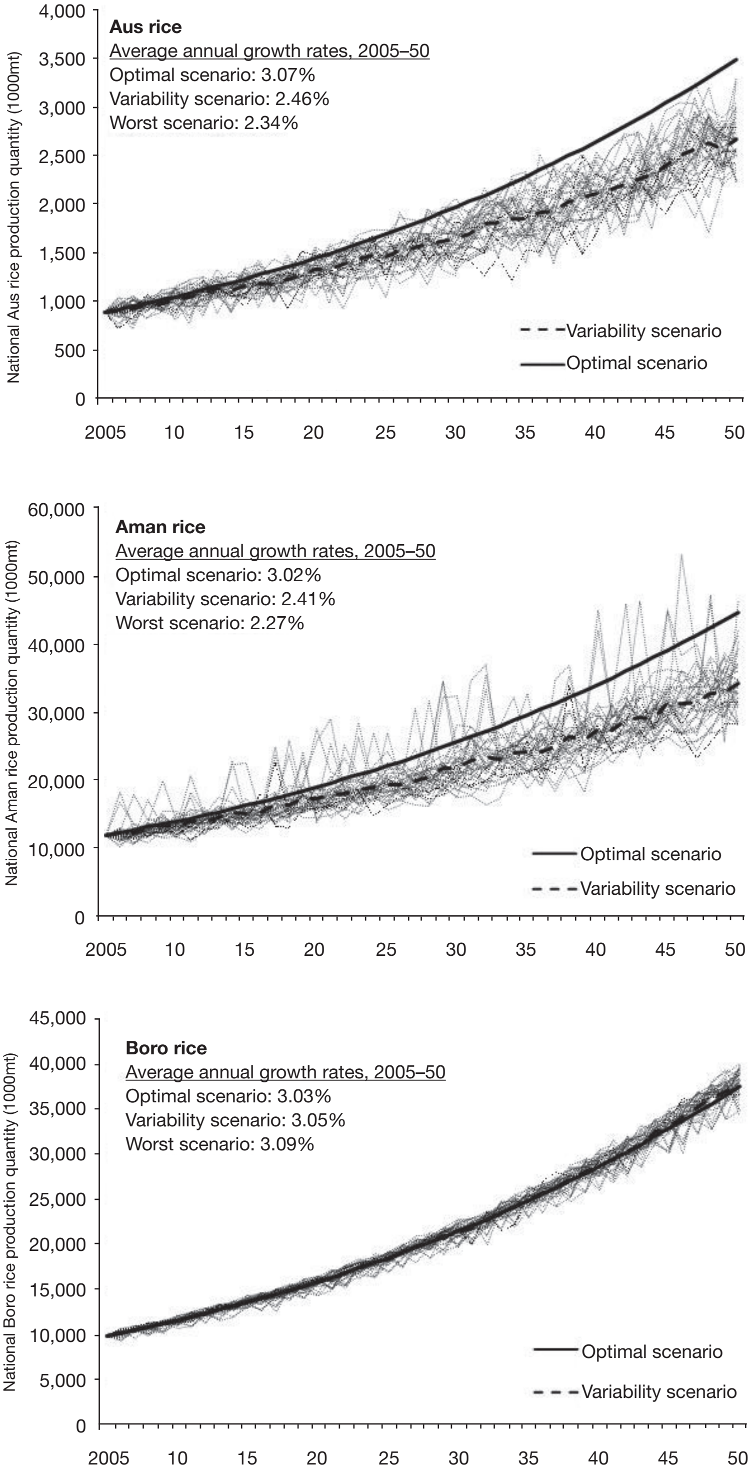


Figure 6.2 Losses in national rice production by crop due to existing climate variability, 2005–50, (a) aus, (b) aman, (c) boro

Scenario. This falls to 2.41 per cent under the Variability Scenario and to 2.34 per cent under the Worst Case Scenario. By 2050, this reduced growth means that aman production is 23 per cent below the production levels achieved without the effects of climate variability (see Table 6.2).

By contrast, the impact of existing climate variability on boro rice production is negligible. This is because the boro is an irrigated crop and largely independent of the annual floods. Moreover, the CGE model allows economic forces to shift farmers' incentives away from producing those rice crops that face the largest yields declines. More specifically, existing climate variability greatly reduces aus and aman production, which reduces overall rice supply in the country and causes the average price of rice to rise. Farmers thus shift production towards the boro rice to take advantage of higher rice prices. These economic forces coupled with smaller yield impacts encourage greater boro production. By 2050, boro rice production is 0.881Mt higher under the Variability Scenario than it was under the Optimal Climate Scenario. These model results highlight the crucial compensating role that dry season boro rice plays in Bangladesh as a result of climate variability. This role was also empirically observed in the historical production data (see Figure 2.2).

Production losses across sub-regions

The economy-wide model also captures rice production losses for the 16 different sub-regions. Two factors determine the overall loss in rice production at the sub-region level. First, some regions face more severe climate variability causing production of specific crops to decline more than elsewhere in the country. Second, some regions rely more heavily on crops that are severely affected by climate variability. This can be seen in Table 6.3, which shows changes in average annual rice crop production growth from the Optimal Climate Scenario during 2005–50. Figure 6.3 shows the weighted contribution of each crop to the overall change in regional rice production.

Mymensingh (6) and Tangail (4) in the central region are the worst affected sub-regions since they face amongst the largest declines in aus and aman production due to climate variability effects, while also being regions that are most reliant on aus and aman for their overall rice production.

Table 6.3 Regional rice production losses due to existing climate variability, 2005–50

	Deviation in average annual production growth rate from optimal scenario (%-point)				Share of rice crop in total regional rice production (%)			
	Aus	Aman	Boro	All crops	Aus	Aman	Boro	All crops
National	–0.61	–0.61	0.02	–0.31	4.01	52.28	43.71	100.00
Dinajpur (SR-1)	–0.57	–0.57	0.04	–0.31	5.21	55.87	38.92	100.00
Rangpur (SR-2)	–0.68	–0.52	0.07	–0.27	5.67	54.04	40.29	100.00
Ishwardi (SR-3)	–0.56	–0.50	0.00	–0.29	5.48	53.84	40.67	100.00
Tangail (SR-4)	–0.66	–0.77	–0.01	–0.42	4.57	54.14	41.30	100.00
Dhaka (SR-5)	–0.70	–0.63	0.02	–0.34	2.82	56.18	41.00	100.00
Mymensingh (SR-6)	–0.77	–0.76	0.01	–0.40	2.71	55.51	41.79	100.00
Sylhet (SR-7)	–0.52	–0.53	0.03	–0.28	1.39	56.85	41.76	100.00
Srimangal (SR-8)	–0.65	–0.66	–0.05	–0.37	1.92	52.98	45.10	100.00
Comilla (SR-9)	–0.62	–0.66	0.04	–0.32	2.78	52.86	44.36	100.00
Chittagong (SR-10)	–0.58	–0.61	0.01	–0.32	4.06	52.49	43.44	100.00
Rangamati (SR-11)	–0.66	–0.64	0.02	–0.33	4.03	51.58	44.39	100.00
Maijdee Court (SR-12)	–0.57	–0.51	0.05	–0.23	4.19	49.09	46.71	100.00
Jessore (SR-13)	–0.60	–0.55	0.03	–0.26	4.83	46.60	48.58	100.00
Faridpur (SR-14)	–0.53	–0.62	0.01	–0.27	4.71	43.67	51.61	100.00
Patuakhali (SR-15)	–0.66	–0.64	0.07	–0.27	6.18	44.91	48.90	100.00
Khulna (SR-16)	–0.54	–0.65	0.00	–0.30	5.37	44.96	49.66	100.00

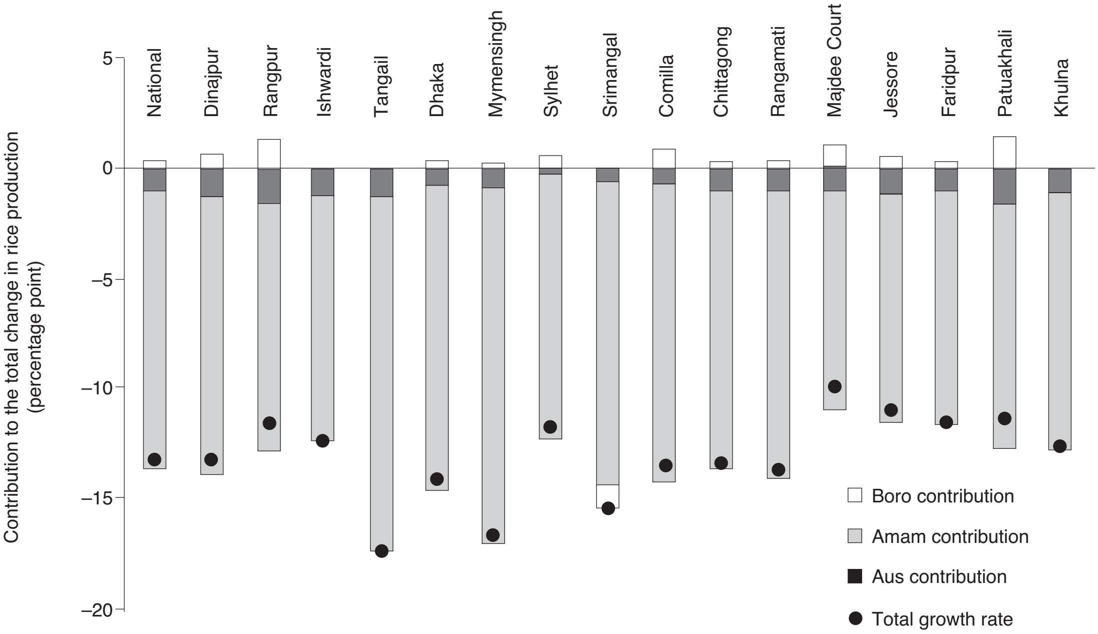
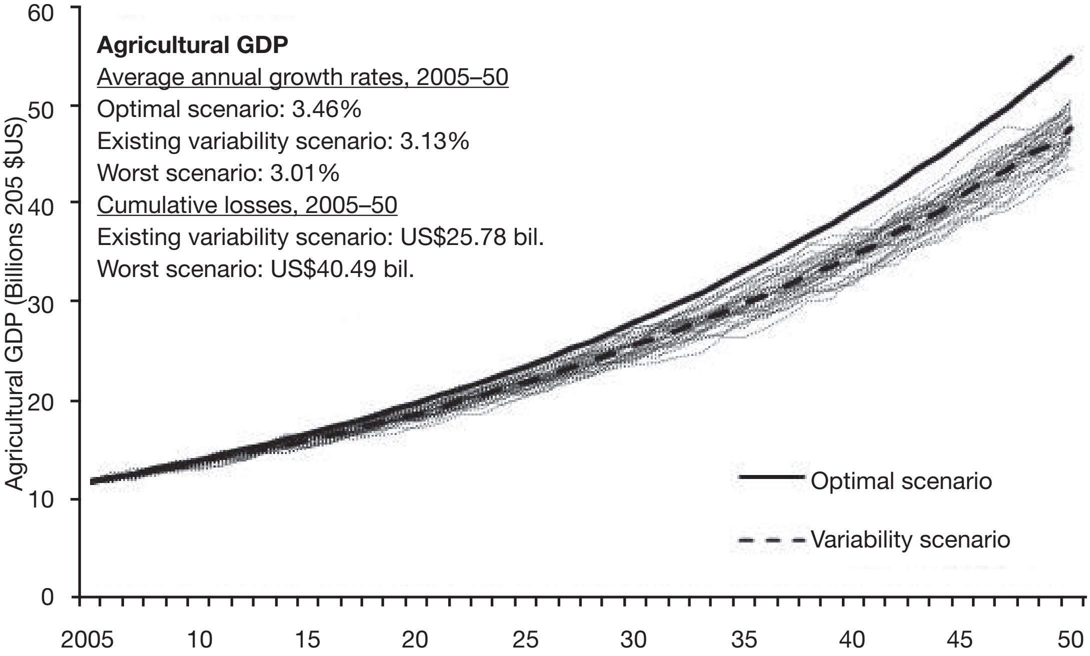


Figure 6.3 Decomposing regional rice production losses due to existing climate variability, 2005–50

Note: Total percentage changes in rice production are weighted by each rice crop's contribution to total regional rice production (see Table 6.3).



Agricultural GDP

Average annual growth rates, 2005–50

Optimal scenario: 3.46%

Existing variability scenario: 3.13%

Worst scenario: 3.01%

Cumulative losses, 2005–50

Existing variability scenario: US$25.78 bil.

Worst scenario: US$40.49 bil.

Figure 6.4 Losses in national agricultural GDP due to existing climate variability, 2005–50

Table 6.4 Losses in GDP due to existing climate variability, 2005–50

	Agricultural GDP				Total GDP			
	2005–50	2005–25	2025–40	2040–50	2005–50	2005–25	2025–40	2040–50
Average annual growth rate (%)								
Optimal Scenario	3.46	3.50	3.47	3.39	4.65	4.47	4.80	4.78
Variability Scenario	3.13	3.11	3.13	3.19	4.44	4.20	4.59	4.69
Worst Case Scenario	3.01	2.78	3.12	3.29	4.36	4.01	4.47	4.91
Cumulative economic loss (2005 US$ billion)								
Variability Scenario	120.96	14.78	45.80	60.38	594.06	61.81	213.64	318.61
Worst Case Scenario	189.24	20.76	81.27	87.20	929.98	77.35	397.88	454.76
Discounted cumulative economic loss (2005 US$ billion)								
Variability Scenario	25.78	7.17	10.71	7.90	120.66	29.59	49.53	41.54
Worst Case Scenario	40.49	10.09	18.94	11.46	187.74	36.14	91.96	59.64
Average annual discounted economic loss (2005 US$ billion)								
Variability Scenario	0.57	0.36	0.71	0.79	2.68	1.48	3.30	4.15
Worst Case Scenario	0.90	0.50	1.26	1.15	4.17	1.81	6.13	5.96
Discounted economic loss average share of total optimal GDP (%)								
Variability Scenario	1.10	0.64	1.43	1.62	5.14	2.66	6.61	8.51
Worst Case Scenario	1.72	0.91	2.53	2.35	7.99	3.25	12.28	12.21

Agricultural GDP impacts from existing variability

Rice production accounted for about one-third of total agricultural GDP in Bangladesh in 2005. Reductions in rice production will therefore have a significant impact on overall value-added results in the sector. Model results estimate that the agricultural GDP growth rate will decline from 3.46 per cent per year during 2005–50 under the Optimal Scenario to 3.13 per cent per year under the Variability Scenario (see Figure 6.4). This drop in the growth rate causes substantial economic losses over the 45-year period 2005–50. For example, existing climate variability results in a loss of US$120.96 billion in agricultural GDP during 2005–50 (measured in 2005 prices), which is an average economic loss of US$2.63 billion per year (see Table 6.4).[4] If we discount future economic losses at 5 per cent per year,[5] then the total loss in agricultural GDP due to climate variability is US$25.78 billion during 2005–50, or an annual loss of US$0.57 billion. This means that 1.10 per cent of agricultural GDP is lost on average each year as a result of existing climate variability. However, this average hides compounding economic losses over time. Economic losses resulting from existing climate variability average 0.64 per cent of agricultural GDP during 2005–25, rising to 1.62 per cent during 2040–50.

The agricultural GDP growth rate falls even further under the Worst Case Scenario to 3.01 per cent per year, implying the climate variability reduces agricultural GDP by almost 0.5 per cent each year during 2005–50. The discounted cumulative loss in agricultural GDP under this scenario reaches US$40.49 billion or an annual average loss of US$0.9 billion (both measured in 2005 prices). This is equivalent to 1.72 per cent of agricultural GDP lost each year. Existing climate variability will therefore have a profoundly negative impact on the future growth of Bangladesh's agricultural GDP.

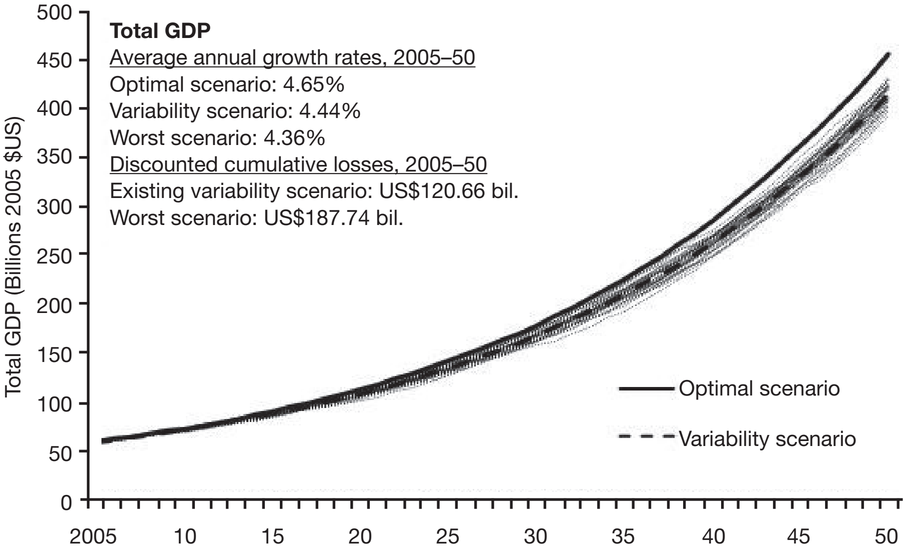


Figure 6.5 Losses in national total GDP due to existing climate variability, 2005–50

National GDP impacts from existing variability

Agriculture is a key sector in Bangladesh, accounting for one-fifth of total GDP in 2005. However, the impact of climate variability on the agriculture sector has economy-wide implications beyond simply the size-effect of the lost agricultural GDP. For example, declining rice production causes a contraction of upstream rice-milling industries, which lowers manufacturing GDP. Since much of the value-addition for rice production occurs during processing, a significant share of these impacts occurs in manufacturing rather than agriculture. Climate variability also has direct impacts on non-agricultural sectors through depreciated capital assets during major flood years. Falling farm incomes also reduce households' demand for non-agricultural products and hence production in these sectors. Finally, by reducing overall economic growth, these climate effects lower investment and capital accumulation, which affects all sectors of the economy, especially those in more capital-intensive non-agriculture sectors. The impact of total GDP is therefore expected to be significantly larger than the impact on agriculture alone. Figure 6.5 shows that this is true for Bangladesh.

Model results estimate that climate variability reduces total GDP annual average growth rate by 0.21 percentage points each year during 2005–50 (i.e. from 4.65 per cent per year under the Optimal Scenario to 4.44 per cent under the Variability Scenario). Average GDP growth rates decline further under the Worst Case Scenario. Over the 45-year 2005–50 period, climate variability will cost Bangladesh US$594.06 billion in lost real GDP at the national level, or an annual average decline of US$12.91 billion (both measured in 2005 prices). Again, if future losses are discounted at 5 per cent, then climate variability will generate a real economic loss of US$120.66 billion during 2005–50, or an annual loss of US$2.68 billion. This substantial decline in national income is, on average, equal to 5.14 per cent of the national GDP that could be achieved under optimal climate conditions (see Table 6.4).

Household consumption impacts from existing variability

The impact of climate variability on household per capita consumption is shown in Table 6.5. Climate variability reduces private consumption spending by a cumulative US$89.8 billion during 2005–50 discounted at 5 per cent per year.[6] This

Table 6.5 Losses in national households' consumption spending due to existing climate variability, 2005–50

	Average annual growth rate (%)	Deviation from optimal (%-point)	Discounted cumulative losses, 2005–50 (2005 US$ billion)	Average annual discounted consumption losses as a share of discounted average annual total consumption spending (%)				National population share in 2005 (%)	Per capita consumption in 2005 (2005 US$)
	Optimal scenario	Variability scenario		2005–50	2005–25	2025–40	2040–50		
All Households	2.37	–0.21	89.8	2.54	1.17	3.20	4.40	100.0	365
Agricultural Households	2.38	–0.20	56.1	2.51	1.17	3.16	4.33	72.4	320
Farm Households	2.44	–0.21	48.4	2.62	1.23	3.30	4.52	57.3	332
Marginal Farms	2.26	–0.17	7.4	2.12	0.98	2.68	3.68	20.3	181
Small-scale Farms	2.42	–0.21	25.0	2.63	1.23	3.32	4.55	28.7	340
Large-scale Farms	2.59	–0.23	16.1	2.91	1.38	3.66	4.99	8.2	675
Landless Workers	2.08	–0.17	7.7	1.98	0.90	2.51	3.46	15.2	275
Non-farm Households	2.35	–0.21	33.7	2.59	1.18	3.27	4.50	27.6	486
Low Education	2.23	–0.18	11.8	2.21	1.00	2.79	3.85	19.3	289
Some Education	2.23	–0.24	12.4	2.94	1.35	3.72	5.09	5.7	784
High Education	2.65	–0.22	9.6	2.75	1.26	3.47	4.79	2.7	1,277

Note: Marginal Farms are less than 0.5 acres; Small-scale Farms are between 0.5 and 2.5 acres; and Large-scale Farms are larger than 2.5 acres. Low Education households have household heads that are illiterate or have completed some primary schooling; Some Education households' heads have completed primary schooling and some secondary schooling; and High Education households' heads have completed secondary schooling. For more information see Annex 2.

Source: Results from the Bangladesh CGE model.

is an average annual reduction of US$2 billion or 2.54 per cent of consumption spending each year. Economic losses compound themselves, starting at 1.17 per cent per year in 2005–25 and rising to 4.4 per cent in 2040–50. The welfare losses caused by existing climate variability therefore become more pronounced over time, thus underlining the importance of addressing climate variability in the near-term in order to avoid long-term welfare losses.

Both farm and non-farm households experience declining real per capita consumption compared to the Optimal Scenario (see column 2 in Table 6.5). Large-scale farm households are the worst affected amongst households engaged in agricultural production, due in part to their greater reliance on the returns from agricultural land and capital as sources of incomes. In contrast, marginal farmers and landless farm workers rely more heavily on non-farm labour incomes, and are thus less adversely affected by existing climate variability. Marginal farmers and landless farm workers do, however, have the lowest average per capita incomes and are therefore likely to be more vulnerable to even small changes in per capita consumption. Similarly, amongst non-farm households it is the higher-educated households that are hurt the most by climate variability, since these households earn a greater share of the returns to economic growth and hence suffer more when the size of the economy contracts. However, it is lower-educated non-farm households that are likely to be more vulnerable to small income changes than higher-educated households.

6.3 Additional Economic Impacts of Climate Change

The additional economic costs of climate change over and above the costs of existing climate variability is estimated here. As described in section 6.1, the Climate Change Scenario imposes crop yield losses from the hydro-crop models. The average of the Monte Carlo economic outcomes is termed the Climate Change Scenario. To isolate the economic impact of climate change we compare the results of the Climate Change Scenario to the Variability Scenario described in the previous section. To account for climate and model uncertainty, the Monte Carlo process of

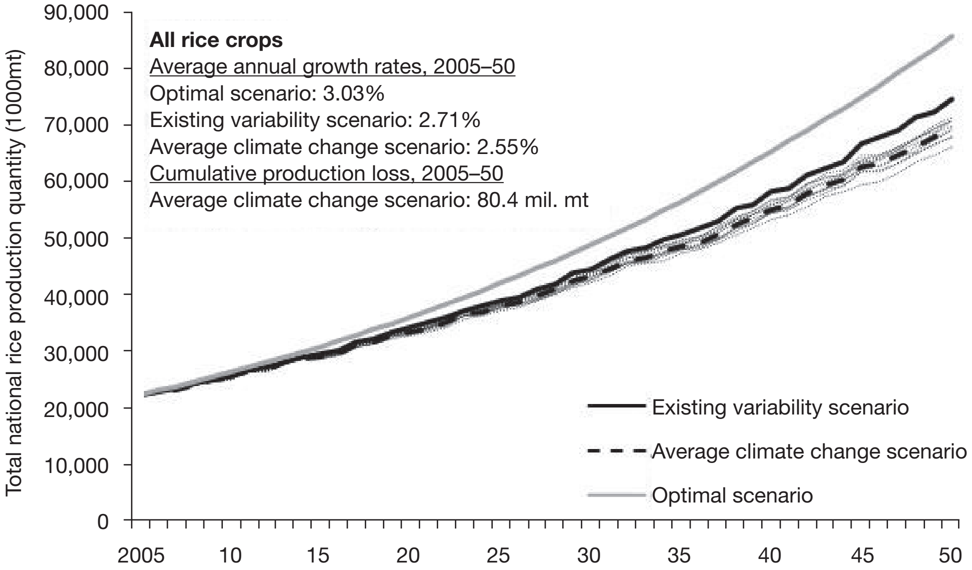


Figure 6.6 Losses in total national rice production due to climate change, 2005–50

randomly constructing future climate patterns is repeated for five GCMs and two emissions scenarios.

Figure 6.6 shows total national rice production for the Variability Scenario and the average outcomes for each of the GCMs and emissions scenarios (light curves). In other words, they are the average outcomes for each of these Climate Change Scenarios after conducting 50 Monte Carlo simulations for each scenario. The darker broken curve is then the simple average or arithmetic mean of all the various Climate Change Scenarios. The figure shows that national rice production declines under all of the Climate Change Scenarios and that the annual growth rate is reduced from 2.71 per cent under the Variability Scenario to 2.55 percent under the Average Climate Change Scenario. This reduction in the annual rice production growth rate by 0.17 percentage points causes final year rice production to be 5.243Mt below what would have been achieved under existing variability and without the additional negative effects of climate change (see Table 6.6). This is equivalent to an average 8kg per capita reduction in rice production (i.e. 4.9 per cent reduction of current per capita production levels). Moreover, the average cumulative loss is 3.9 per cent of total rice production each year during 2005–50 (i.e. relative to the rice production achieved under the Variability Scenario). This suggests that climate change will exacerbate food availability and security in Bangladesh over the coming decades.

Even though national rice production falls under all GCMs and emissions scenarios there are significant differences in outcomes across these Climate Change Scenarios (see Table 6.6). First, as expected, the A2 emissions scenarios lead to larger rice production losses on average than do the B1 scenarios. However, this is not the case for two of the GCMs: MPI ECHAM5 and UKMO HADCM3. Second, some GCMs produce much larger impacts than others. For example, the rice production losses from GFDL 2.1 under the less severe B1 emission scenario (i.e. 6.7Mt) is larger than the economic losses obtained for most of the other GCMs even under the more severe A2 emission scenario. UKMO HADCM3 similarly produces larger impacts relative to the remaining three GCMs considered in this analysis. Therefore, reduced national rice production by an average 3.9 per cent per year hides considerable model uncertainty. For example, just considering emission scenario uncertainty, the average annual

Table 6.6 National rice production losses due to climate change, 2005–50

	Deviation in average annual growth rate from Existing Variability scenario, 2005–50 (%)				Deviation in final year production from Existing Variability scenario, 2050 (1000 tonnes)			
	Aus	Aman	Boro	All rice	Aus	Aman	Boro	All rice
Average scenario	–0.10	–0.16	–0.18	–0.17	–114	–2270	–2862	–5246
A2 average	–0.11	–0.17	–0.20	–0.18	–122	–2431	–3174	–5728
GFDL 2.1	–0.02	–0.22	–0.34	–0.27	–25	–3198	–5205	–8428
MIROC3.2 MEDRES	–0.26	–0.20	–0.09	–0.15	–293	–2936	–1419	–4649
MPI ECHAM5	–0.08	–0.14	–0.06	–0.10	–95	–2074	–1056	–3224
NCAR CCSM3	–0.13	–0.15	–0.20	–0.17	–143	–2148	–3166	–5457
NCAR CCSM3	–0.05	–0.12	–0.33	–0.22	–55	–1800	–5026	–6881
B1 average	–0.09	–0.14	–0.16	–0.15	–107	–2109	–2549	–4765
GFDL 2.1	–0.02	–0.14	–0.30	–0.22	–29	–2069	–4616	–6714
MIROC3.2 MEDRES	–0.13	–0.15	–0.09	–0.12	–152	–2248	–1386	–3786
MPI ECHAM5	–0.15	–0.22	–0.03	–0.12	–175	–3219	–483	–3878
NCAR CCSM3	–0.08	–0.07	–0.18	–0.12	–90	–1010	–2799	–3899
NCAR CCSM3	–0.08	–0.14	–0.22	–0.18	–87	–1999	–3463	–5549

production loss ranges from 4.3 per cent for the more severe A2 scenarios to 3.6 per cent for the less severe B1 scenarios. Moreover, allowing GCM uncertainty widens the range of rice production losses to between 2.0 and 6.5 per cent (i.e. A2 emissions scenarios for MPI ECHAM5 and GFDL 2.1 respectively).

Figure 6.7 and Table 6.6 show production losses associated with the three rice varieties. Boro rice is the most severely affected by climate change. Annual boro rice production growth rates fall from 3.05 per cent under the Variability Scenario to 2.87 per cent under the Average Climate Change Scenario. Over the 45-year period 2005–50, cumulative losses in boro rice production equal 52.507Mt or an average 1.166Mt per year. This loss in boro production is driven primarily by declining crop yields due to climate change, rather than by the increase in the frequency of major floods. Aus and aman production is also negatively affected by climate, albeit less severely and more as a result of the increased frequency of major floods. Climate change therefore has adverse implications for boro production and undermines its compensating role in offsetting the aus and aman production losses caused by existing climate variability. Climate change will therefore exacerbate existing climate-related food insecurity as well as Bangladesh's vulnerability to extreme climate events.

Production losses across sub-regions

Figure 6.8 shows the change in rice production in each of the 16 agro-climatic sub-regions. Differences in predicted climate changes and initial production patterns result in varying growth-effects at the regional level. The southern agro-climatic regions of Patuakhali (15) and Khulna (16) experience the largest decline in total rice production due to climate change. This is for three reasons. First, these two regions already experience significant declines in aus and aman rice production due to climate variability, which now worsens under the Climate Change Scenario. Secondly, boro yields are severely affected by the effect of climate change on mean rainfall, temperature and CO_2 levels. Finally, these two regions are the worst affected by rising sea levels, which permanently reduce cultivable land. Overall rice production losses are therefore most pronounced in these southern coastal regions. Moreover, this ranking of regions according to their vulnerability to climate change is consistent across the two emissions scenarios considered in this analysis (see Figure 6.9).

Agricultural GDP impacts from climate change

Figure 6.10 shows the decline in agricultural GDP caused by climate change. Agriculture

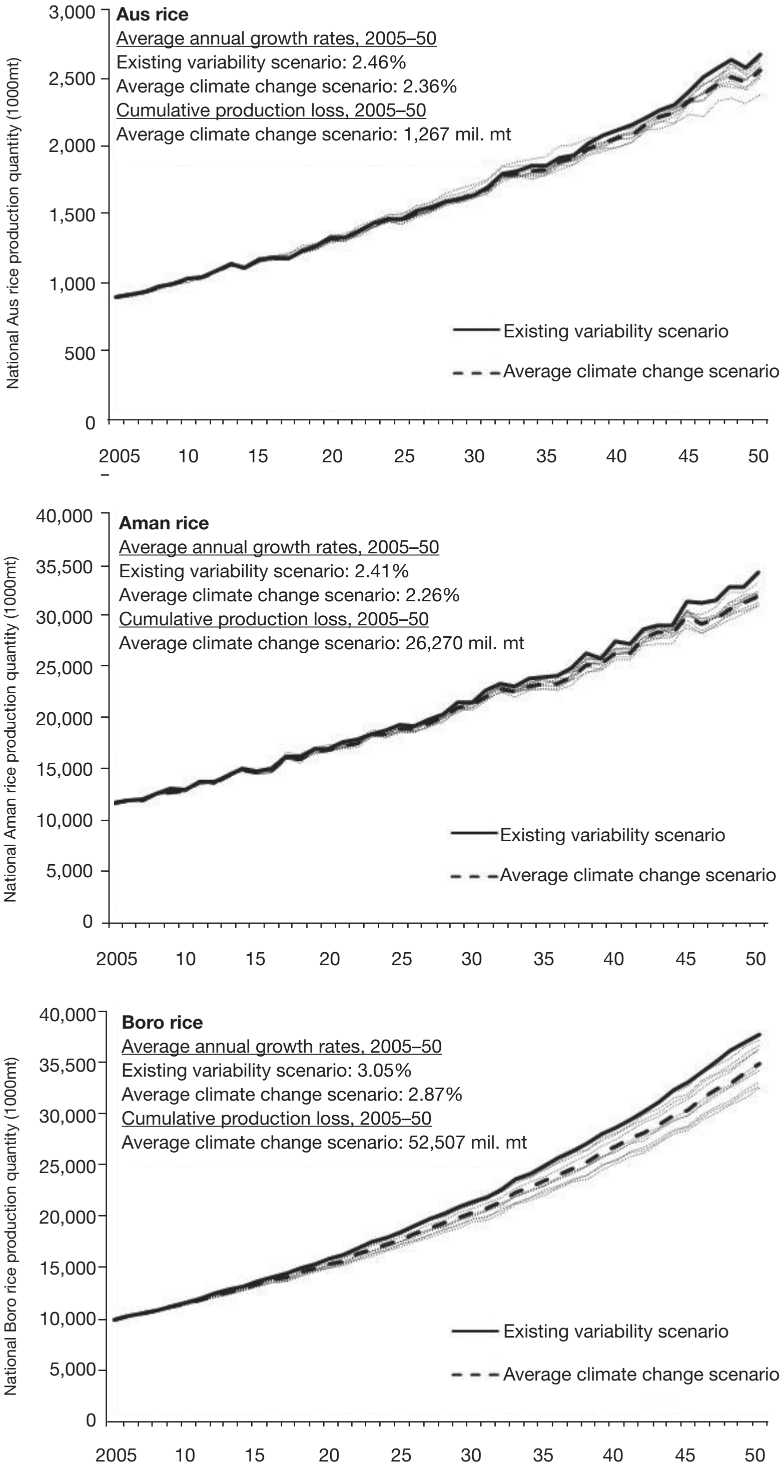


Figure 6.7 Losses in national rice production by crop due to climate change, 2005–50

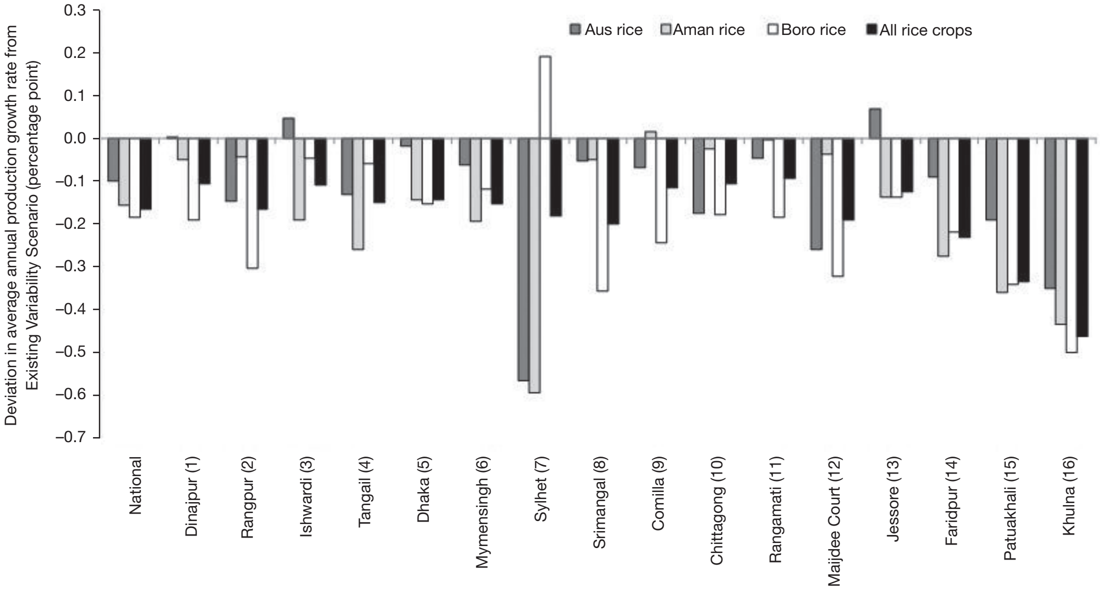


Figure 6.8 Deviation in average final year rice production from the Existing Variability Scenario under the Average Climate Change Scenario, 2050

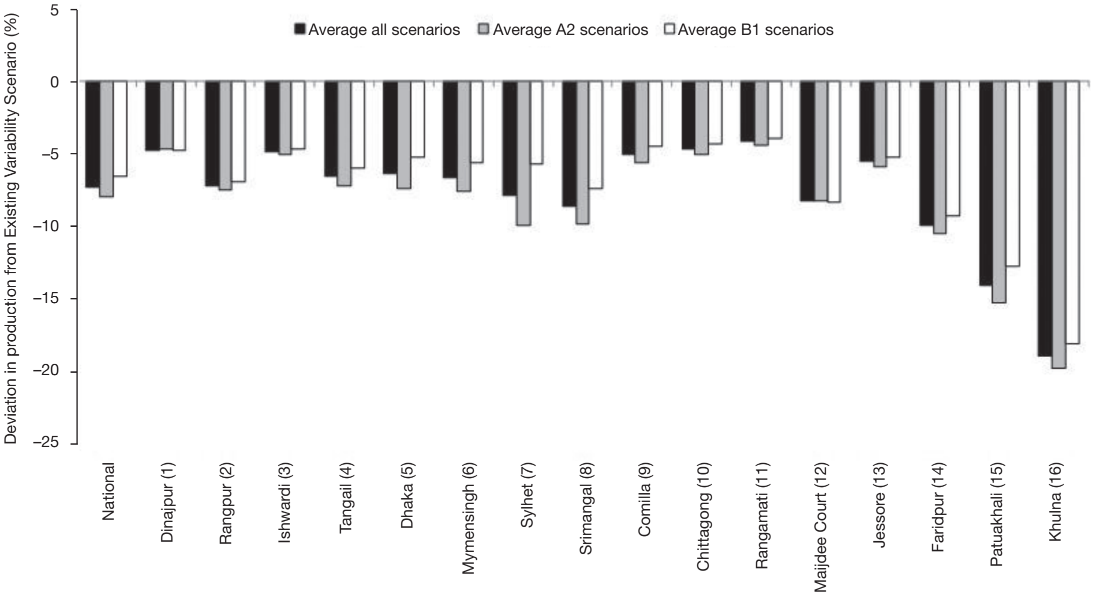


Figure 6.9 Deviation in average final year rice production from the Existing Variability Scenario under different emissions scenarios, 2050

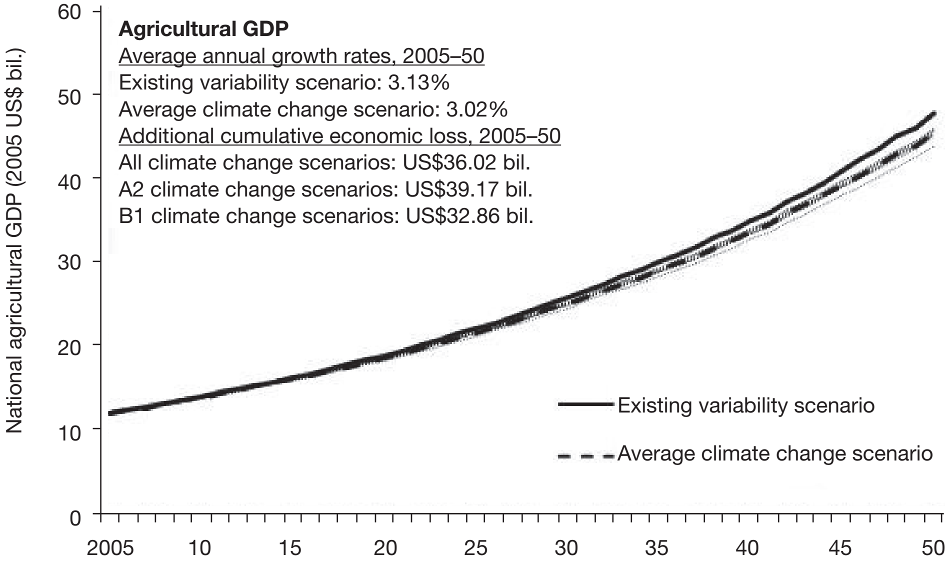


Figure 6.10 Losses in national agricultural GDP due to climate change, 2005–50

growth rate declines from 3.13 per cent per year under the Existing Variability Scenario to 3.02 per cent under the Average Climate Change Scenario. Cumulating these losses over the 45-year period means that climate change costs Bangladesh's agricultural sector a total of US$36 billion in lost value-added during 2005–50. Discounting future losses at 5 per cent produces a present value of foregone real agricultural GDP of US$7.7 billion, which is an average annual reduction in discounted agricultural GDP of 0.17 per cent during 2005–50 (see Table 6.7). Uncertainty regarding future emissions scenarios means that the cumulative loss in agricultural GDP ranges from US$7.11 billion under the less severe B1 scenario to US$8.29 billion under the more severe A2 scenario. Comparing Tables 6.7 and 6.4, the average loss in agricultural GDP due to climate change is a third of the agricultural GDP losses associated with existing climate variability. Climate change will thus substantially reduce agricultural GDP beyond the losses already caused by existing climate variability. These average losses in agricultural GDP compound themselves over time, starting at US$10.86 per capita in 2005–25 and rising to US$22.95 per capita in 2040–50. Reducing the impacts of climate change in the near-term will therefore reduce larger long-term economic costs.

Model uncertainty implies that discounted agricultural GDP losses may range from around US$0.1 billion under the MPI ECHAM5 GCM to US$0.29 billion per year under the GFDL 2.1 GCM (see Table 6.8). On average the GCMs indicate that agricultural GDP losses in the A2 emissions scenario will be almost 20 per cent higher than in the B1 scenario.

National GDP impacts from climate change

Figure 6.11 shows the losses in national total GDP caused by climate change. The annual GDP growth rate declines by 0.06 per cent per year over the 45-year period. This results in a cumulative loss in total value-added of US$128.55 billion over 2005–50 (measured in 2005 prices), which is 21 per cent of the losses already caused by existing variability. Discounted economic losses are lower at US$25.73 billion. This is equivalent to an average drop in national GDP of US$570 million per year or 1.15 per cent of total GDP compared to the Existing Variability Scenario (see Table 6.7). This is the aver-

Table 6.7 Average GDP losses due to climate change, 2005–50

	Agricultural GDP				Total GDP			
	2005–50	2005–25	2025–40	2040–50	2005–50	2005–25	2025–40	2040–50
Average annual growth rate (%)								
Variability Scenario	3.13	3.11	3.13	3.19	4.44	4.20	4.59	4.69
Average Scenario	3.02	2.99	3.02	3.06	4.38	4.14	4.54	4.62
A2 average	3.01	2.98	3.01	3.05	4.37	4.13	4.52	4.63
B1 average	3.03	3.00	3.04	3.07	4.39	4.15	4.55	4.62
Cumulative economic loss (2005 US$ billion)								
Average Scenario	36.02	4.51	13.36	18.15	128.55	12.96	44.38	71.21
A2 average	39.17	4.70	14.45	20.02	146.79	14.33	50.74	81.73
B1 average	32.86	4.31	12.27	16.28	110.31	11.60	38.02	60.69
Discounted cumulative economic loss (2005 US$ billion)								
Average Scenario	7.70	2.22	3.12	2.36	25.73	6.33	10.24	9.17
A2 average	8.29	2.32	3.37	2.60	29.21	6.99	11.66	10.56
B1 average	7.11	2.13	2.88	2.11	22.26	5.66	8.82	7.78
Average annual discounted economic loss (2005 US$ billion)								
Average Scenario	0.17	0.11	0.21	0.24	0.57	0.32	0.68	0.92
A2 average	0.18	0.12	0.22	0.26	0.65	0.35	0.78	1.06
B1 average	0.16	0.11	0.19	0.21	0.49	0.28	0.59	0.78
End of period per capita discounted economic loss (2005 US$)								
Average Scenario	22.95	10.86	19.42	22.95	76.69	30.94	60.17	76.69
A2 average	24.71	11.34	20.67	24.71	87.04	34.20	67.76	87.04
B1 average	21.20	10.39	18.17	21.20	66.34	27.68	52.59	66.34

Table 6.8 GDP losses under different climate change scenarios, 2005–50

	Discounted average annual GDP losses, 2005–50 (2005 US$ bil.)							
	Agricultural GDP				Total GDP			
	2005–50	2005–25	2025–40	2040–50	2005–50	2005–25	2025–40	2040–50
Average Scenario	0.17	0.11	0.21	0.24	0.57	0.32	0.68	0.92
A2 average	0.18	0.12	0.22	0.26	0.65	0.35	0.78	1.06
GFDL 2.1	0.29	0.19	0.35	0.39	1.02	0.59	1.20	1.63
MIROC3.2 MEDRES	0.15	0.09	0.18	0.22	0.58	0.31	0.69	0.96
MPI ECHAM5	0.10	0.06	0.12	0.16	0.45	0.23	0.55	0.74
NCAR CCSM3	0.19	0.13	0.24	0.26	0.67	0.37	0.82	1.04
UKMO HADCM	0.19	0.11	0.23	0.27	0.52	0.25	0.62	0.91
B1 average	0.16	0.11	0.19	0.21	0.49	0.28	0.59	0.78
GFDL 2.1	0.19	0.12	0.23	0.25	0.50	0.28	0.62	0.77
MIROC3.2 MEDRES	0.13	0.09	0.16	0.18	0.41	0.24	0.46	0.68
MPI ECHAM5	0.10	0.06	0.12	0.17	0.44	0.19	0.54	0.79
NCAR CCSM3	0.18	0.13	0.21	0.22	0.54	0.36	0.63	0.79
UKMO HADCM	0.19	0.13	0.23	0.25	0.58	0.35	0.70	0.87

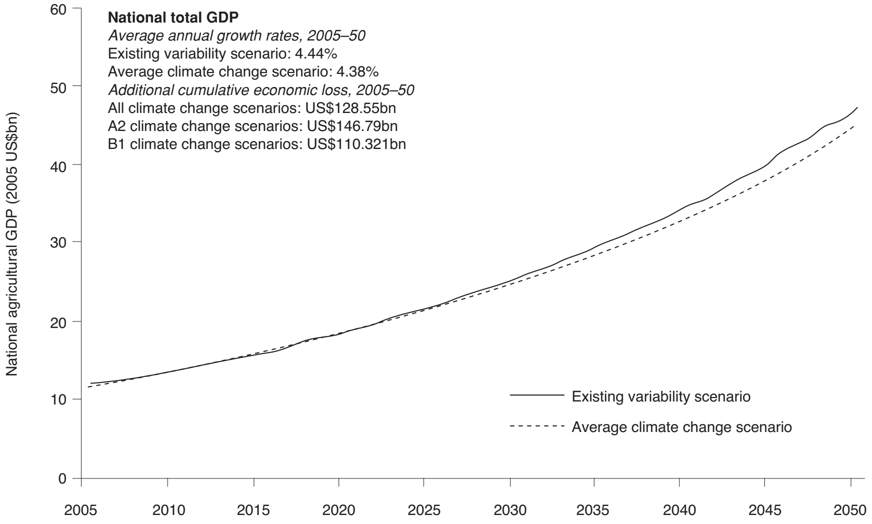


Figure 6.11 Losses in national total GDP due to climate change, 2005–50

age annual economy-wide cost of climate change in Bangladesh during 2005–50, and is equal to about 8 per cent of foreign aid transfers to Bangladesh in 2005. In per capita terms this is equivalent to a discounted US$76.69 per capita during the full 2005–50 period (i.e. taking population and income growth into account). The economic cost of climate change also rises over time from US$0.57 billion per year during 2005–25 to US$0.92 billion per year during 2040–50.

Economic costs are higher under the average A2 scenario (US$29.21 billion overall; US$0.65 billion per year) than under the average B2 scenario (US$22.26 billion overall; US$0.49 billion per year). This uncertainty over future emission scenarios causes a wide divergence in the estimated economic cost of climate change over the coming decades (see Figure 6.12). Model uncertainty implies that average total GDP losses range from US$0.41 billion per year under the MIROC3.2 MEDRES GCM (B1 scenario) to over US$1 billion per year under the GFDL 2.1 GCM (A2 scenario) (see Table 6.8). Despite this uncertainty, however, climate change will impose a substantial economic cost on future development in Bangladesh, thus justifying significant investments to curb its long-term impacts.

Household consumption impacts from climate change

Table 6.9 shows the reduction in real household consumption spending as a result of climate change. The total loss in consumption spending over the 2005–50 period is US$104.77 billion (measured in 2005 prices), which suggests that over 80 per cent of the total economic cost of climate change will be passed onto households (i.e. compared to the US$128.55 billion loss in total GDP). The remaining economic cost will be borne by the public sector and private investment. Two-thirds of the decline in private consumption will be experienced by households working in the agricultural sector, including landless farm workers. However, the largest declines are for larger-scale farmers, who rely more heavily on agricultural incomes. By contrast, marginal farm households and landless farm workers rely more on labour incomes and non-farm employment, and are thus less directly affected by the economic losses from climate change. However, these households' initial incomes are much lower than larger-scale farmers, and so their welfare will be more vulnerable to even small changes in per capita incomes (see Table 6.9). Similarly, non-farm households' consumption spending also declines,

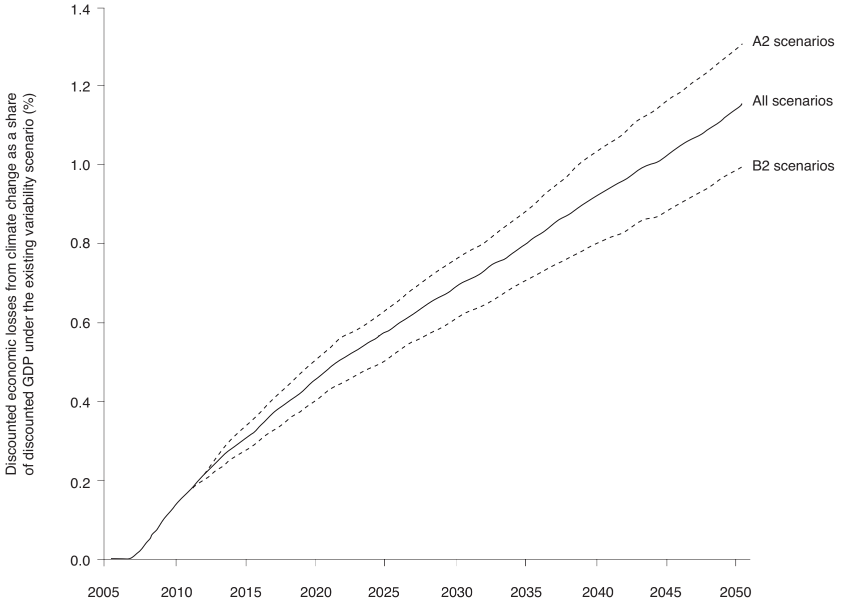


Figure 6.12 Cumulative discounted losses due to climate change as a share of total GDP, 2005–50

Table 6.9 Losses in national households' consumption spending due to climate change, 2005–50

	Population share in 2005 (%)	Cumulative loss in consumption spending, 2005–50 (2005 US$ billion)			Average per capita loss in consumption, 2005–50 (US$)			Share of lost consumption in total household consumption (%)		
		All scenarios	A2 scenarios	B1 scenarios	All scenarios	A2 scenarios	B1 scenarios	All scenarios	A2 scenarios	B1 scenarios
All Households	100.00	104.77	118.30	91.24	10.47	11.82	9.12	1.62	1.83	1.40
Agricultural Households	72.42	65.82	74.41	57.23	9.08	10.27	7.90	1.59	1.81	1.38
Farm Households	57.26	56.39	63.83	48.94	9.84	11.14	8.54	1.64	1.86	1.42
Marginal Farms	20.32	8.87	10.01	7.73	4.36	4.92	3.80	1.38	1.56	1.20
Small-scale Farms	28.74	29.56	33.42	25.70	10.27	11.61	8.93	1.68	1.91	1.46
Large-scale farms	8.19	17.95	20.40	15.51	21.90	24.89	18.92	1.72	1.95	1.48
Landless workers	15.16	9.43	10.58	8.29	6.22	6.97	5.46	1.38	1.55	1.21
Non-farm Households	27.58	38.95	43.89	34.01	14.11	15.90	12.32	1.65	1.87	1.44
Low Education	19.26	14.53	16.31	12.76	7.54	8.46	6.62	1.52	1.71	1.33
Some Education	5.67	13.67	15.36	11.99	24.11	27.08	21.14	1.83	2.06	1.60
High Education	2.65	10.74	12.22	9.26	40.48	46.07	34.90	1.64	1.87	1.41

Note: Marginal Farms are less than 0.5 acres; Small-scale Farms are between 0.5 and 2.5 acres; and Large-scale Farms are larger than 2.5 acres. Low Education households have household heads that are illiterate or have completed some primary schooling; Some Education households' heads have completed primary schooling and some secondary schooling; and High Education households' heads have completed secondary schooling. For more information see Annex 2.

especially for higher-educated households, who are affected negatively by the deceleration in economic growth and rising food prices.

Consumption impacts across sub-regions

Per capita consumption declines in all sub-regions (see Table 6.10). However, the least

Table 6.10 Losses in regional farm households' consumption spending due to climate change, 2005–50

	Population share in 2005 (%)	Cumulative loss in consumption spending, 2005–50 (2005 US$ billion)			Average per capita loss in consumption, 2005–50 (US$)			Share of lost consumption in total household consumption (%)		
		All scenarios	A2 scenarios	B1 scenarios	All scenarios	A2 scenarios	B1 scenarios	All scenarios	A2 scenarios	B1 scenarios
Farm Households	57.26	56.39	63.83	48.94	9.84	11.14	8.54	1.64	1.86	1.42
Dinajpur (1)	5.71	5.01	5.70	4.32	8.77	9.98	7.56	3.25	3.71	2.80
Rangpur (2)	7.17	5.94	6.64	5.25	8.28	9.25	7.31	1.73	1.94	1.52
Ishwardi (3)	1.70	1.41	1.62	1.20	8.31	9.55	7.07	1.79	2.06	1.52
Tangail (4)	4.05	3.79	4.37	3.21	9.37	10.80	7.93	1.26	1.46	1.07
Dhaka (5)	2.01	1.66	1.89	1.44	8.26	9.38	7.13	1.38	1.58	1.19
Mymensingh (6)	4.90	4.86	5.58	4.13	9.89	11.37	8.42	1.46	1.68	1.24
Sylhet (7)	3.41	2.71	3.19	2.24	7.95	9.33	6.57	1.13	1.33	0.93
Srimangal (8)	1.81	2.17	2.50	1.85	12.01	13.81	10.22	1.74	2.01	1.48
Comilla (9)	5.60	6.19	7.02	5.37	11.04	12.52	9.56	1.73	1.97	1.49
Chittagong (10)	2.60	2.82	3.18	2.47	10.85	12.23	9.48	1.75	1.97	1.52
Rangamati (11)	0.81	1.15	1.31	0.98	14.11	16.14	12.08	1.60	1.83	1.37
Maijdee Court (12)	2.01	2.32	2.58	2.05	11.50	12.81	10.19	1.91	2.14	1.69
Jessore (13)	4.28	3.73	4.25	3.21	8.71	9.93	7.49	1.64	1.88	1.41
Faridpur (14)	3.00	3.58	4.00	3.16	11.92	13.31	10.53	1.73	1.94	1.53
Patuakhali (15)	5.72	6.48	7.08	5.87	11.31	12.36	10.25	2.07	2.26	1.87
Khulna (16)	2.47	2.55	2.91	2.19	10.31	11.76	8.86	1.52	1.74	1.30

affected regions are Sylhet (7) and Dhaka (5). The latter is partially insulated from climate change in our analysis since the share of agriculture in this regions' total GDP is below that of most other regions. Many of the southern coastal regions experience significant declines in per capita consumption and bear a substantial share of the total cumulative cost of climate change for farm households. This is because these regions experienced large declines in rice production due to sea level rises. However, if the initial per capita consumption level is controlled, then the largest percentage declines in per capita consumption are in Maijdee Court (12) and Patuakhali (15) in the south and Dinajpur (1) in the northwest. These regions are the most vulnerable from an economic perspective.

Notes

1 By starting the transition from historical to 2030s data in 2005 we assume that the mean of the historical 1970-1999 period did not change from the mid-point of the historical period (1984) to the base year of the CGE model (2005). The effect is to compress climate change effects for the period 1984-2035 into the shorter period 2005-2035. However, this assumption will not greatly affect our conclusions since the effects of climate change during 1984-2004 are fairly small, especially relative to future climate change projections for the 2030s and 2050s.

2 The estimation procedure of the 2005 SAM is described in Annex 3.

3 This is measured by the cumulative loss in total or national GDP during 2005–50.

4 All dollar values reported in this chapter are in constant 2005 US$.

5 A lower or higher discount rate will not qualitatively change the results presented. A higher rate will result in lower estimated losses and a lower rate will result in higher estimated losses. The relative losses across simulations and model experiments will largely be unchanged.

6 This is lower than total GDP losses since private consumption is only part of national income, which also includes government consumption, investment demand and net exports.

7

Adaptation Options in the Agriculture Sector

Vulnerability to climate risks and overall economic development are intricately linked, as is shown in the preceding sections. Therefore, adaptation in the agriculture sector must be well integrated with both the broad national development goals and livelihood priorities at the local level. Not surprisingly, though, farmers and rural households have long adapted to a variety of climate risks. These coping strategies vary by geographic region and depend on the range of prevailing socio-economic conditions. As the climate changes, more and different adaptations will be required. An approach to studying cropping adaptations through the crop simulation approach of Chapter 5 is given in detail in Annex 1. In this chapter, a series of adaptations for which field trials exist and farmer feedback is reported are described. These descriptions provide templates for the development of other adaptations for farm-level implementation.

The presence of both formal and informal sources of support can play a critical role in minimizing climate risks. For instance, substantial public-sector investments in agriculture and water have been made to help protect farmers from a variety of existing climate risks. These measures include investments in water infrastructure (e.g. embankments in floodplain and coastal areas to protect against floods and storm surges) and irrigation.

Groundwater irrigation has provided a means for farmers to adapt to soil moisture deficits, particularly in drought-prone areas. This has resulted in changes in cropping pattern, greater diversification of agriculture, promotion of high-yielding varieties and increased cropping intensity. Embankments in flood-prone areas (both coastal and inland) have also played a major role in reducing flood risks and protecting key household assets. Over the last three decades, the Bangladesh government has invested over US$10 billion (at constant 2007 prices) for flood management embankments, coastal polder and cyclone shelters (BCAS, personal communication). With this protection, substantial increases in production have been made possible. These collective investments have resulted in significant improvements in meeting national objectives of food-grain self-sufficiency. Substantial investments in early warning and preparedness systems (primarily improvements in flood forecasting and cyclone warnings) have also minimized (though not entirely eliminated) the risk from natural disasters. The Bangladesh Disaster Management Bureau plays a critical role in responding to droughts and floods. Lastly, in addition to this direct support from the government departments, non-government organizations and other donors have played an important role in supporting alternative livelihood activities.

Agriculture research and technology development has been essential to achieving higher and more stable crop yields. An active network of agriculture research institutes exists in Bangladesh. These include the Bangladesh Agriculture Research Institute (BARI), Bangladesh

Rice Research Institute (BRRI), Bangladesh Institute of Nuclear Agriculture (BINA) and the Bangladesh Agriculture University (BAU). These groups, among other things, develop and test new crop varieties to increase national total production and resilience against climate risks. Extensive testing and field trials are undertaken before new varieties are released to extension organizations for dissemination. The Department of Agriculture Extension (DAE) plays a vital role in disseminating new technologies down to the farmer level through demonstration plots, by providing critical inputs and through training. Typically, DAE undertakes 5–10 demonstrations on a new crop variety at each block each year depending on budget resources. The DAE is one of the largest governmental departments working with approximately 60 per cent of the population directly involved with crop production. The Department of Agricultural Information Service (AIS) under the DAE is instrumental in preparing materials on specific technology. These institutions will continue to be active in helping Bangladesh achieve food security.

In Bangladesh, though there is no specific drought-tolerant rice variety, DAE does promote particular paddy varieties that are short durational to avoid the effects of drought. These include BR25, BRRI Dhan 33 and BRRI Dhan 39. BARI has also promoted some vegetables and crops like chilli, tomato, okra, cucumber, aubergine (brinjal/eggplant), potato, cowpea, barley, maize, chickpea, linseed and sesame as drought tolerant. BRRI has developed some flood-tolerant varieties of paddy including BR11, 20, 21, 22, 23 and 24, and BRRI Dhan 31, 32, 33 and 34. Moreover, as was mentioned earlier, the boro crop plays an important role in offsetting flood losses. Finally, BRRI has developed some saline-resistant paddy varieties including BR10 and 23, and BRRI Dhan 32, 41 and 47. Some vegetables and other crops like chilli, tomato, okra, cucumber, potato, cowpea, soybean and barley are promoted as salt tolerant. These evolving new varieties will continue to play a major role in helping farmers adapt to changing and uncertain conditions.

Despite these innovations, poor adoption of technologies and innovations can be common. The current large gap between actual and potential yields suggests substantial on-farm opportunities to increase incomes and production. For many communities, adoption of new technologies can represent high downside risks unless options are well tested in the field. Efforts to provide financial and technical support to ensure sustainable production systems are thus required. Government agriculture extension officers play an important role in these regards. At the household and farm level, private-level adaptations to climate risks have included, inter alia: crop adjustments in terms of crop mix and planting dates; supplementary irrigation from ponds; moisture conservation approaches; adoption of new seed varieties (e.g. drought and saline resistant), diversifying to fisheries and shrimp production; and flood protection and drainage works. Some current and past adaptation programmes for the agriculture sector in Bangladesh are given in Table 7.1.

7.1 Identifying and Evaluating Adaptation Options

Adaptation options can address several different types of climate risks. Broadly speaking, adaptations can focus on increasing crop productivity, improving irrigation efficiency or expanding water supply, crop diversification and intensification, generating alternative enterprises (either farm or non-farm sector) to diversify household income sources, and expanding access to training and credit. Existing strategies to deal specifically with drought risks include: full irrigation for dry season boro and supplementary irrigation for t. aman from groundwater and surface water sources, crop adjustments (e.g. replanting), moisture conservation practices and promotion of horticultural crops. Existing strategies to deal specifically with flood risks include: construction of embankments and drainage canals, harvesting of crops from under water, changing the crop calendar (e.g. late or early planting), raising seedlings in a safe and dry place, double transplanting of seedlings and floating vegetable gardens. Existing strategies to deal with coastal zone risks (e.g. tidal

Table 7.1 Sample of past and present programmes on adaptation in the agriculture sector

Project Name	Agency	Location	Sample Activities
Reducing Vulnerability to Climate Change	CARE	Satkhira, Gopalganj, Rajshahi	Drought-tolerant crop cultivation; Tree and plant nursery activities; Floating gardens and homestead vegetable gardens
Livelihood Adaptation to Climate Change (LACC) Phase I	FAO, DAE,	Chapai, Nawabganj, Natore, Naogaon, Pirojpur, Khulna	Homestead gardening; Drought-tolerant fruit tree gardening; Rainwater harvesting in mini ponds for supplementary irrigation for t. aman
Livelihood Adaptation to Climate Change (LACC) Phase II	FAO, DAE	Rajshahi, Chapai Nawabganj, Natore, Naogaon, Pirojpur, Khulna	Adaptation options have been identified but not implemented yet
Disappearing Lands: Supporting Communities Affected by River Erosion	Practical Action Bangladesh	Gaibandha	Sand bar vegetable cultivation in char lands; Floating bed vegetable cultivation
Assistance to Local Community on Climate Change Adaptation and DRR in Bangladesh	Action Aid Bangladesh	Naogaon, Sirajganj, Patuakhali	Homestead vegetable gardening; Rice demonstrations; Chickpea cultivation; Community based pond management for supplementary irrigation
Barind Integrated Area Development Project	BMDA	Northern part of Bangladesh	Groundwater irrigation; Management of surface water for crop production; Excavation of mini ponds
Asia-Pacific Forum for Environment and Development	BCAS	Rajshai, Naogaon, Sirajganj, Gaibandha, Kurigram Shunamganj, Faridpur, Pirojpur, Cox's Bazar, Satkhira, Patuakhali, Barisal	Zero-tillage maize cultivation; Chickpea cultivation; Relay cropping of sweet gourd; Floating bed vegetables cultivation

inundation and salinity intrusion) include: coastal embankments and introduction of saline resistant crops and bio-saline aquaculture (e.g. shrimp cultivation).

The following 14 sample adaptation options (Table 7.2) were identified through a series of workshops with participation from a variety of research institutes, government agriculture extension officers, donor community representatives and practitioners in the field. These adaptations represent promising adaptation approaches to increasing production (both existing and new crops) under constrained and changing environments. For all of these options, field trials exist and farmer feedback is reported. Thus, these options have the potential for replication and scalability.

The effectiveness and suitability of each of these options will be dependent on a wide range of location-specific factors. These may cover a range of institutional, socio-economic, financial and environmental issues. Sustainability will in

Table 7.2 Sample adaptation options in the agriculture sector

Adaptation Option	
1	Zero or minimum tillage to cultivate potato, aroid and groundnut with water hyacinth and straw mulch
2	Zero-tillage cultivation of mashkalai, khesari, lentil and mustard
3	Modified sorjan system (zuzubi garden) with vegetable cultivation in char land
4	Floating bed vegetable cultivation
5	Cultivating foxtail millet (kaon) in char land
6	Parenga practice of t. aman cultivation system
7	Relay cropping of sprouted seeds of aman rice in jute fields
8	Raising vegetables seedlings in polythene bags homestead trellises
9	Zero-tillage maize cultivation
10	Chickpea cultivation using a priming technique
11	Supplementary irrigation of t. aman from mini ponds
12	Year-round homestead vegetable cultivation
13	Pond-water harvesting for irrigation to cultivate rabi vegetables
14	Sorjan system for cultivating seasonal vegetables, fruits and fish

Table 7.3 Estimated costs and benefits of selected adaptation options

Adaptation Option No.	Cost per hectare (Tk)	Benefit per hectare (Tk)	Profit per hectare (Tk)
1 potato	196,270	342,000	145,730
1 aroid	97,700	250,000	152,300
1 groundnut	79,095	90,000	10,905
2 mashkalai	29,950	52,500	22,550
2 khesari	26,010	56,000	29,990
2 lentil	30,531	75,000	44,469
2 mustard	37,540	67,500	29,960
3	262,500	535,000	272,500
4	34,025	59,750	25,725
5	233,469	487,500	254,031
6	49,880	79,000	29,120
7	49,830	78,000	28,170
8	165,575	432,000	266,425
9	98,315	129,000	30,685
10	57,325	90,000	32,675
11	76,705	100,875	24,170
12	125,000	372,000	247,000
13	151,575	294,000	142,425
14	253,084	573,052	319,968

Note: US$1 = Tk69

part be dependent on the local capacity and the capacity of the implementing support agency (both government and non-government) at the national and sub-national levels to provide both technical and material assistance. Potential for economic return will be a critical determinant of overall adoption. Detailed indicative cost and financial benefit estimates were prepared (see Table 7.3) for each of the identified options. The unit costs are limited to those costs that would be borne by the farmer to implement the adaptation option. That is, the cost to the government agency to implement such options more widely is not included here. These 14 adaptation options represent potential no-regret strategies for increasing incomes and building resilience to climate risks.

Detailed factsheets follow, describing each adaptation option (numbered above), including information about the production package, geographical suitability, major advantages and disadvantages and the costs and financial benefits of implementation. More detailed information can be found either through the Department of Agriculture Extension or the FAO Livelihood Adaptation to Climate Change (LACC) programme.

1 Zero or minimum tillage to cultivate potato, aroid and groundnut with water hyacinth and straw mulch

Summary

This practice can produce several different types of crops (e.g. potato, aroid, groundnut, chickpea, onion, garlic) with minimum tillage required. This practice is done on mostly medium high land in flood-prone areas during the rabi season. Farmers are already practising this approach when land is unfavourable to normal practices. Farmers sow seeds on moist soil just after the recession of flood water. The land is then mulched with water hyacinth of about 30cm thick. The mulching conserves soil moisture and decreases evaporation from the soil. The process is as follows for potato, and similar for the others:

- Clear grasses and debris from the field;
- Sowing/planting time is November–December;
- Apply fertilizers at the rate of 165kg–100kg–130kg–40kg/ha of urea-TSP-MOP-gypsum;
- Place germinated seed tubers in rows at 60cm apart and 25cm intervals within a row;
- Cover the potato seeds with 30cm thick mass of water hyacinth;
- Depending on the market price the crop can be harvested partially or fully 70 days after sowing.

Potato is a photo-sensitive, succulent crop that needs more soil moisture during the vegetative period. The water hyacinth is used as a mulch layer to preserve soil moisture as well as increase production. During periods of dense fog and moist weather there is the potential for fungal diseases (like late blight and early blight) that can severely affect potato yield. If this infection happens during the early stages of potato cultivation, production could decrease tremendously.

Most suitable geographic area

Coastal areas (saline and non-saline) and the central floodplains, depending on the degree of flooding and tidal surge, and areas where mulch materials are readily available are the most suitable. This is currently practised in Rangpur, Kurigram, Gaibandha, Bogra, Sirajgang, Rajshahi, Nawabganj, Natore, Pabna, Kushtia, Faridpur, Munsiganj, Madariganj and Barisal.

Major advantages

This option provides an additional crop and income for farmers. Farmers can also generate mulch materials as a byproduct of this option which can generate material for household fuel. This byproduct can be sold in the local market. Mulch materials also have the added benefit of protecting soils from high temperatures and high evaporation which increases both microbial activity and soil productivity. Finally, this approach can help to control the population of weeds.

Major disadvantages

This option will not be feasible without mulch materials such as water hyacinth or straw. Moreover, thin application of mulching materials may not fully protect the tubers from sunlight, resulting in decreased quality of potato.

Approximate benefits

This option only requires land, potato seeds, water hyacinth or straw, fungicide and insecticides, fertilizers and labour. Approximately a total of Tk196,270 (US$2785) (including land-lease cost) is required to cultivate potato in 1 hectare of land by using this option and farmers can harvest 19.0t of potato at a market price of approximately Tk18 per kg (total Tk342,000 or US$4854). Moreover, farmers can harvest green potatoes as cattle fodder and mulch material as well as fuel for family consumption. Farmers can thus earn a net profit of Tk145,730 (US$2068) from 1 hectare of land which would normally remain fallow during the rabi season. Per unit hectare cost of producing aroid and groundnut is Tk97,700 and Tk79,095 (US$1386–1122) respectively. Per hectare profits would be approximately Tk152,300 and Tk10,905 (US$2161–154) respectively.

2 Zero-tillage cultivation of mashkalai, khesari, lentil and mustard

Summary

In some cases, after the harvesting of the t. aman crop, the delay in the recession of flood water results in excessive soil moisture and unsuitable conditions for planting. Given this situation, this adaptation option broadcasts mustard, mashkalai or khesari in the t. aman field 10–15 days before harvest using zero tillage approaches to generate an extra crop.

Production package

Zero-tillage cultivation of mustard, khesari and mashkalai is currently being practised by farmers in flood-prone areas. Farmers sow seeds in the aman paddy fields 10–15 days before harvest time. This is also being grown in previously fallow fields in mid-October to November after recession of flood waters. The process is as follows for mustard, and similar for the others:

- Method of seed sowing: broadcast;
- If possible, supplemental irrigation may produce better yields (one irrigation during flowering stage and another one during fruiting stage);
- For mustard cultivation the following doses of fertilizer might be used for better yield. Urea-TSP-MOP-gypsum-zinc sulphate-boric acid = 225kg–160kg –75kg–140kg–4kg–12kg per hectare;
- Seed rate: Mustard 8–10kg/ha;
- Time of harvest: January–February;
- Yield: Mustard 1.0–1.5t/ha.

Most suitable geographic area

Coastal areas (saline and non-saline) and central floodplains, depending on the degree of flooding and tidal surge, are the most suitable. This is currently practised in Kurigram, Sirajganj, Bogra, Joypurhat, Noagaon, Rajshahi, Jamalpur, Tangail, Manikganj, Nawabganj, Rajshahi, Pabna, Kushtia, Meherpur, Jessore, Chuadunga, Jhenaida, Faridpur, Barisal and Narail.

Major advantages

This option provides an additional crop and income for farmers. Farmers get byproducts that can be used as fodder and for family fuel consumption. Pulse crops are also leguminous family crops which improve soil nutrients through the release of nitrogen. This helps to increase soil productivity. Extension officers, in fact, often advise farmers to harvest the crop from the stem, careful not to uproot the plant. These pulses can add 40–80kg per hectare of nitrogen, i.e. provide about 87–174kg of urea which will decrease fertilizer costs.

Major disadvantages

Early harvest during the vegetative stages may reduce crop yields. During the production period, most of the land remains fallow and may disrupt cattle-grazing practices. Finally, the degree of soil moisture is an important determinant of seed germination. Excess soil moisture could damage seedlings.

Approximate benefits

Land, seeds, fertilizers and labour are required. Approximately a total of Tk37,540 (US$532) is needed to cultivate one hectare of mustard. Farmers can harvest 1.5t of mustard at a market price of approximately Tk45 per kg (total Tk67,500 or US$958). Farmers also get the mustard plant as cattle fodder and fuel for family consumption. Farmers can earn a net profit of Tk29,960 (US$425) from one hectare of land which normally would have been fallow. The per hectare cost of cultivating khesari, lentil and mashkalai is Tk26,010, Tk30,531 and Tk29,950 (US$369, US$433, US$425) respectively. The net profit is Tk29,990, Tk44,469 and Tk22,550 (US$425, US$631, US$320) for khesari, lentil, and mashkalai respectively.

3 Modified sorjan system (zuzubi garden) with vegetable cultivation in char land

Summary

In many places, flood waters remain on crop fields and char lands for an extended period of time. In the absence of uplands, vegetables and fruits cannot be grown. Most of the char lands remain fallow after the recession of flood water during the rabi and kharif 1 seasons. Normally vegetables and fruits must come from outside of the char lands to meet local demands. Moreover, the communities in these areas typically are unable to afford the high price of vegetables and fruits and thus cannot incorporate these items into their regular diets. The result is malnutrition from lack of minerals and vitamins. A modified sorjan system with vegetable cultivation can help to increase production in these places.

Production package

Farmers in char land areas can produce vegetables and fruit (zuzubi) during the rabi and kharif 1 season by using a modified sorjan system. A dedicated area of land (33 decimal) of loamy type soil is required for the modified sorjan system. This soil is best for making these beds and ditches. January to February is the best time for preparation. Specifically, the provisions are as follows:

Raised bed

3m breadth x 0.5m height x (10m length or considering length of plot size).

Ditches

2m breadth x 0.5m depth x (10m length or considering length of plot size).

Crops on beds

zuzubi (variety Apel kul/BAU kul), recommended spacing (plant to plant and row to row) should be followed.

Crops on ditches

Seasonal vegetables (cabbage, cauliflower, tomato, aubergine, amaranth, Indian spinach, kang kong,

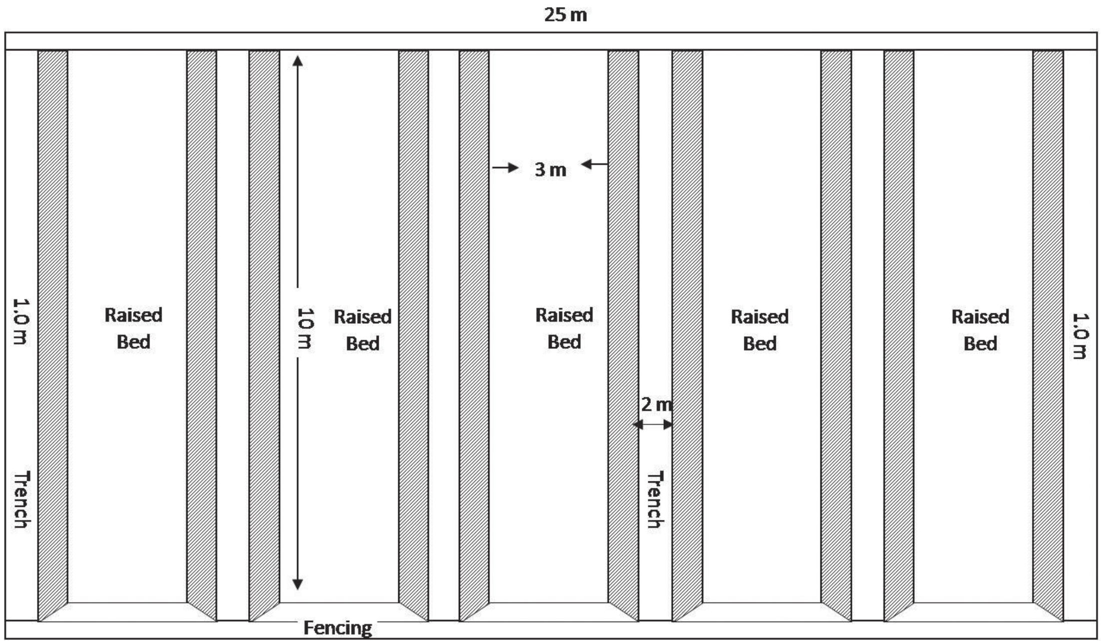


Figure 7.1 Layout of modified sorjan system

chilli, red amaranth, cucumber, bitter gourd, snake gourd , bottle gourd, sweet gourd, etc.) can be cultivated round the year if trellises are made on the ditches.

Fruits

Papaya, lemon, etc. may be planted near the edge of the beds.

Design and layout

- Top soil of middle 2m ditch is removed and kept aside;
- Soil from the 2m plot (ditch) is dug at a depth of 0.5m and placed on the 3m plots;
- The 3m plots are raised to 0.5m high beds to measure three beds at the top;
- The 2m plots at the ends are also dug at a depth of 0.5m and the soil is placed on the beds;
- Slope of the bed is made uniform and compact by pressing;
- Top soil kept aside is spread uniformly on the raised bed. Thus the sorjan beds and furrows are made.
- Trellises are made with bamboo and other local materials on the furrows to support creeper vegetables.

Cropping patterns

- The five beds (or more based on the size of the plot) are numbered from 1 to 5 or more. Two beds at either the east or south are earmarked for vegetables cultivation and the rest for fruits and vegetables.
- The edge of the beds is planted with creeper vegetables, which is supported by the trellis over the furrows.
- Zuzubi should be planted on raised beds following standard spacing. Seasonal creeper vegetables can be cultivated on the edges to make trellises on the ditches.

Most suitable geographic area

The char lands or coastal areas are most suitable depending on the degree of flooding and tidal surges. This is currently being practised in Sirajganj.

Major advantages

This option helps to diversify the crop mix and increases the production of vegetables and fruits (both for household consumption and for sale in local markets which increases income). This may also have positive nutritional impacts on communities in the char lands. The zuzubi plant is a flood-tolerant crop.

Major disadvantages

Depending on the flood frequency and intensity, the ditches may silt with clay and sand. Moreover, large floods may damage the layout of the modified sorjan system. Though the zuzubi plant is a flood-tolerant crop, prolonged exposure to flood waters may still damage the crop and result in disease.

Approximate benefits

The modified sorjan system requires vegetables seeds, fruits saplings, fertilizers, bamboo, jute sticks, spades and other resources. Approximately a total of Tk233,469 (US$3313) is required to cultivate fruits and vegetables using this approach. A farmer can typically harvest 16,500kg of vegetables and 3150kg of fruits (zuzubi) where the potential revenue generated is Tk487,500 (US$6920) (assuming Tk20 per kg vegetables and Tk50 per kg of zuzubi). In addition, household consumption of these crops can help to supplement family nutritional requirements. Farmers can also use pruned materials for home fuel. In summary, farmers can earn a potential net profit of Tk254,031 (US$3605) from one hectare of char land that would have otherwise remained fallow during the rabi season.

4 Floating bed vegetable cultivation

Summary

During high floods, land is water-logged and seedlings are easily damaged. In these areas, production of crops is difficult. Moreover, delayed recession of flood waters can create a scarcity of necessary cereals and vegetables. Considering this, floating vegetable beds (*baira*) can help to meet the daily requirements for vegetables such as lalshak, data, kang kong, okra, spinach, Indian spinach, cucumber, bitter gourd, bottle gourd, sweet gourd, radish, aubergine, onion and garlic and spices such as chilli and turmeric etc.

Suitable crops for floating beds

Amaranth (both leaf and stem), okra, aubergine, kang kong, etc. can be grown under wet conditions on floating substrata made of water hyacinth. Water hyacinth is abundantly available in flood-prone and submerged areas. This is already being practised in certain locations. Bottle and sweet gourds also can be grown on floating substrata, but require that the floating beds touch the ground after the recession of flood water for continued rooting.

Production packages

- Make a bamboo frame of 10m long and 1m wide on water near the land and fix the location with a bamboo pole;
- Add floating piles of water hyacinth within the bamboo frame and repeat several times at five to seven day intervals on the same piles until a heavy floating bed (about 60cm thick) is made;
- Apply a small dose of TSP and MP on the bed mixed with previously made compost of water hyacinth;
- Mix seeds of red amaranth, stem amaranth, kang kong, okra and a few bottle gourd and sweet gourd seeds in a proportionate quantity, mix with soil and broadcast on the floating bed after five to seven days of application of fertilizers;
- Single crop vegetable seeds with recommended spacing may be sown on the floating bed;
- In a few days the seeds will germinate and grow;
- Apply a little urea depending on the growth of the vegetables;
- Continue to harvest the vegetables by thinning to allow the remaining seedlings to grow.
- When the water recedes the bed will touch the ground and the gourd plants will take root on the field and start fruiting.
- When the bed is about to touch the ground other winter vegetables like cabbage, cauliflower, etc. can also be planted on the bed ahead of the scheduled planting date and can be grown as a field crop with some fertilizer as needed.

Most suitable geographic area

The coastal areas (both saline and non-saline areas) and central floodplains are the most suitable. The northeast region of the country may also introduce this practice as well. This is currently being practised in Faridpur, Barisal, Gopalganj, Khulna and Gaibandha.

Major advantages

Floating beds (*baira*) are a low-cost farmer innovation that can play a vital role in generating vegetables for the family. During the dry season, *baira* can also result in compost to increase soil fertility as well as crop productivity. Farmers can also practise growing tree saplings on *baira* to generate additional income.

Major disadvantages

Heavy rainfall and strong winds may damage *bairas*. Sometimes damaged *bairas* may result in the loss of harvest vegetables. If heavy rains come before germination, seeds may wash away.

Approximate benefits

Bamboo for making the *baira* frame, water hyacinth, vegetables seeds and some fertilizers are needed for this option. It is estimated that farmers can harvest 175kg of vegetables per *baira* and that about 150 *baira* can be built on one hectare of land. Total harvested vegetables would be approximately 26,250kg. At a market price of about Tk20 (US$0.30) per kg, this results in a total sale value of Tk525,000 (US$7451). Moreover, assuming the generation of 20t of water hyacinth which can be sold in the market for about Tk10,000 (US$142), the farmer in total will generate Tk272,500 (US$3867) net on land that otherwise would remain fallow. Furthermore, farmers will consume some vegetables to meet the basic family requirements.

5 Cultivating foxtail millet (koan) in char land

Summary

Most of the char lands remain fallow after recession of flood water in rabi and kharif 1 seasons. Foxtail millet (kaon) is a drought-tolerant, short duration crop that can be grown with minimum tillage during the rabi season immediately after the recession of flood water.

Production technology

Currently, farmers plough their char land two or three times and then sow kaon seeds (10kg per hectare) following a broadcasting or line system. After two to three weeks, seeds germinate and the removal of weeds is needed for better growth and increased yields. Farmers are using urea-TSP-MP fertilizer at the rate of 100kg–75kg–40kg per hectare. If irrigation facilities are available then farmers use half the urea and the total amounts of TSP and MP fertilizer during ploughing of the land; the remainder of the urea may be applied 35–40 days after germination of seed. When irrigation facilities are not available then farmers use all the fertilizer during ploughing of the land. Irrigation is needed if drought conditions are prolonged. Normally 2–2.5t of kaon may be produced per hectare of char land.

Most suitable geographic area

This is most suitable on char lands depending on the occurrence and intensity of the floods. This is currently being practised in Nilphamari, Rangpur, Lalmonirhat, Kurigram, Gaibandha, Sirajganj and Jamalpur.

Major advantages

Kaon is a low-cost cereal crop that farmers can easily grow on char lands that otherwise would remain fallow during the rabi season. Kaon is also a shallow-rooted crop which can decrease soil erosion and increase organic matter in the soil if, at the time of harvesting, cuttings are made at 20–30cm from the ground.

Major disadvantages

During seed germination and seedling stages, prolonged droughts during the rabi season may severely affect the crop. Sometimes, early floods and heavy water-logging may also impact the production.

Approximate benefits

This is a low-cost activity that needs only minimum tillage to prepare the land, kaon seeds and some fertilizer. Farmers can harvest 2.25t of millet from one hectare of char land and generate Tk59,750 (US$848) in income. The production cost is Tk34,025 (US$482). Thus, the farmer gets Tk25,725 (US$365) as net profit from one hectare of land by using this option. Farmers can also use straw from the millet as fodder for cattle and fuel. This material can be sold in the local market.

6 Parenga practice of t. aman cultivation system

Summary

Prolonged flooding can damage aman seedlings and also the existing transplanted aman. Moreover, if aman seedlings are damaged, there is often not enough time to re-raise seedlings for transplanting. Farmers in some places are currently addressing this issue by sowing sprouted aman seeds in moist soil on medium-high or medium-low land after recession of flood waters.

Production package

In this approach, farmers first clear weeds and other debris from the land. Farmers then soak aman seeds for 24 hours till they sprout and then broadcast (or directly sow) in moist soil during the month of August.

Under this option farmers use urea-TSP-MP-gypsum fertilizers at the rate of 200kg–125kg–85kg–65kg per hectare of land. Farmers apply all of the TSP and gypsum and half of the MP fertilizer after field clearing and then the remainder of the MP and one-third of the urea three to four weeks after sowing. During the tilling stage, the second dose of urea (one-third of the total dose) may be applied with the remainder of the urea and MP applied immediately before the panicle initiation stage. During the production period, one to two weedings are needed to decrease infestation of insects and pests. Farmers can harvest 3.5t of paddy from one hectare of land and also get straw that can be used for cattle fodder.

Most suitable geographic area

This option is most suitable in floodplain areas where flood water recession is late. This option is currently being practised in Kurigram, Gaibandha and Sirajganj.

Major advantages

This option helps to increase the likelihood of harvesting an additional cereal crop. Farmers also get straw as a byproduct which can be used as fodder for household cattle with the remainder sold in local markets for cash. Finally, because of the increased cropping intensity, the population of weeds is reduced and thus weeding costs for the following crop cycle are reduced.

Major disadvantages

This option is vulnerable to heavy rainfall and prolonged flooding (especially just after seeds are sown in the field).

Approximate benefits

The main requirements are medium-to-high land, quality seeds of aman rice, fertilizers, insecticides and pesticides. A total of Tk49,880 (US$708) is needed to cultivate aman rice using the parenga system on one hectare of land. Farmers can harvest 3.5t of aman rice which at a market value of Tk20 (US$0.30) per kg will gross Tk70,000 (US$993). Furthermore, farmers can get straw for cattle fodder and fuel for family consumption. The remainder can be sold in the local market for cash (approximately Tk9000 or US$128). Farmers thus can earn Tk29,120 (US$413) from one hectare of land which would normally remain fallow.

7 Relay cropping of sprouted seeds of aman rice in jute fields

Summary

Farmers normally cultivate jute on medium-high land from mid-April to mid-September. Typically after harvest, sowing or transplantation of aman is not possible and so kharif 2 crops are typically not planted and the land remains fallow. To address this, farmers in the southeastern part of Bangladesh are practising relay cropping of sprouted aman seeds in jute fields. This approach results in an additional short duration crop on the same field where cultivation of transplanted aman rice would not have been possible.

Production package

Farmers sow jute seeds on medium-high land from mid-April to mid-May and normally harvest mid-August to mid-September. Sprouted aman seeds are sown on the jute field 15–20 days before harvest/cutting of jute. Farmers select medium-high land where drainage facilities are sufficient and control of water application depth is possible. Before the sowing of aman seeds in the jute fields, the land is cleared of weeds and others debris. Farmers will soak aman seeds for 24 hours for sprouting and then broadcast in the jute field when standing water depth is not more than 2.5–5cm. It is very important to control the water depth of the jute field while the seeds sprout over the next seven days. If water depth cannot be controlled then seeds could be damaged.

Farmers use urea-TSP-MP-gypsum fertilizers at the rate of 200 kg–125kg–85kg–65kg. All the TSP and gypsum and half of the MP fertilizer dose are applied after the jute field is cleared. The remainder of the MP and one-third of the urea is applied three to four weeks after sowing. During the tillering stage, the second dose of urea (one-third of total dose) may be applied and the rest of the urea and MP may be applied immediately before the panicle initiation stage. During the production period, one to two weedings are required to decrease the susceptibility to insects and pests.

Most suitable geographic area

This option is most suitable for medium-high land where sufficient drainage exists. This can also be extended to saline, non-saline and central floodplain areas where proper infrastructure exists. This option is currently being practised in Faridpur and Barisal.

Major advantages

This option results in an additional crop which helps to increase total cereal production and generate income for households. Farmers also get straw which can be used as fodder and family fuel consumption.

Major disadvantages

Under this option it is important to control the water depth during the sowing of seeds in the jute field. If the water depth increases (more than 2.5–5cm of water) and no measures are taken, seeds may get damaged. Also, during the jute cutting period, caution must be taken to not damage the aman seedlings. For instance, in some places, the jute plant is left on the fields after cutting which damages the seedlings and reduces overall rice production.

Approximate benefits

Resources required include medium-high land, quality seeds of aman rice, fertilizers, insecticides and pesticides. A total of Tk49,830 (US$707) is needed to cultivate aman rice on one hectare of jute field. Farmers can harvest 3.5t of rice which at market price of Tk20 (US$0.30) per kg results in Tk70,000 (US$993) gross. Farmers also get straw byproducts that can be used as cattle fodder and fuel for family consumption. Remainder material can be sold in the local market for about Tk8000 (US$113). Farmers thus can earn Tk28,170 (US$400) from one hectare of land that would normally remain fallow after harvest of the jute.

8 Raising vegetable seedlings in polythene bags on homestead trellises

Summary

The floodplain region can sometimes be characterized by early floods, prolonged water-logging and even late recession of flood water. These problems affect vegetable production during the rabi season. Communities typically need vegetable seedlings for early plantation to harvest before a regular season. Farmers in these areas cannot cultivate winter vegetables due to the unavailability of vegetables seedlings. To overcome this, farmers therefore raise vegetable seedlings in polythene bags on trellises near the homestead for early rabi and kharif 1 vegetable production on medium-high land.

Production system

Farmers make covered trellises to overcome the impacts of heavy rainfall and late floods. These are typically located near the homestead. Soil from high lands is mixed with cow dung following the recommended ratio (60:40) and then kept for seven to ten days for decomposition. After that, the mixture is placed in polythene bags (7.5 x 12.5cm) and two to three seeds are sown per poly bag in June to mid-July. These poly bags are then set up on the trellis. Within a few days, seeds are germinated and kept in the trellis for 30–45 days before transplanting on the main land. This coincides with the flood water receding and land thus becomes favourable for ploughing. Farmers prepare the field and transplant the seedlings in August to September or as early as possible. Farmers typically cultivate tomato, aubergine, cabbage, etc. using this approach.

Fertilizer doses for some common vegetables:

- Tomato: Urea-TSP-MP and cow dung = 550kg–450kg–250kg–10000kg;
- Aubergine: Urea-TSP-MP and cow dung = 375kg–150kg–250kg–10000kg;
- Cabbage: Urea-TSP-MP and cow dung = 250kg–150kg–200kg–15000 kg.

During land preparation, farmers apply half the cow dung and the total amount of TSP fertilizers. After preparation, beds are raised by about 1m width, 25–30cm height and 25–30cm length depending on land size; 30cm to 35cm of space is kept as a trench between the two beds to use for irrigation water and to drain excess rainwater. Beds are levelled and then seedlings are transplanted during mid-August to September following the spacing for specific vegetables (tomato = 60cm x 40cm; aubergine = 75cm x 60cm; cabbage = 60cm x 45cm). The remainder of the cow dung is used during plantation of the seedlings and the rest of the fertilizer doses may be applied in the field three to five weeks after plantation. Farmers can harvest on average 36–50t of tomato, aubergine and cabbage on one hectare of land.

In some floodplain regions, farmers are also producing other vegetables (e.g. cucumber, sweet gourd, ash gourd and bitter gourd) in poly bags during the early kharif l season and transplanting on to raised pits of water hyacinth and soil.

Most suitable geographic area

The most suitable area for this practice is in flood-prone areas and coastal areas where irrigation is available. This is currently being practised in Faridpur, Gopalganj, Barisal and Habiganj.

Major advantages

This option helps to increase the overall production of vegetables. This technique helps to overcome the typical water-logging situation which constrains early vegetable production during the rabi season. Farmers also get byproduct materials that can be used as cattle fodder. Farmers can sell the vegetable seedlings themselves in the local markets at a high price.

Major disadvantages

Significant delay in water recession on medium-high land may delay the transplant time which can decrease yields. Long-lasting drought conditions during the rabi season might increase irrigation costs and decrease yields.

Approximate benefits

The resources required include quality vegetable seeds, fertilizers, insecticides, pesticides and sufficient medium-high land. A total of Tk165,575 (US$2350) (including land-lease value) is needed to cultivate early rabi vegetables on one hectare of land using this option. Farmers on average can harvest 36–50t of vegetables at a market price of Tk12 (US$0.17) per kg, grossing a total of Tk432,000 (US$6131). Thus, farmers can earn a net profit of Tk266,425 (US$3781) from one hectare of land which normally would not be cultivated due to the late recession of flood waters.

9 Zero-tillage maize cultivation

Summary

Maize is a crop that grows all year. The yield of maize is comparatively higher than rice, wheat or any other cereal crops. In the Barind tract areas, farmers often harvest and keep t. aman rice on the field to dry for two to three weeks. This is then collected for threshing to separate the rice from the straw. During this time, the soil loses its moisture due to the high rate of evaporation and the land becomes hard. This situation makes it difficult for farmers to plough the land and therefore in many cases the land remains fallow. Farmers can easily cultivate maize by using the existing soil moisture in the fallow land during the rabi season following a zero-tillage system.

Production package

For cultivating maize using the existing soil moisture on fallow lands, a crop calendar needs to be identified. The exact period of transplantation of t. aman seedlings and harvesting during the kharif 2 season must be determined and coordinated with the maize cultivation. Maize is typically cultivated during the rabi season (seed-sowing time in mid-November to early December). Harvested t. aman rice should not be kept on the field. Maize seeds are sown immediately after harvest using a 'dribbling' approach whereby a few seeds are sown using a sharp stick or finger. The following steps need to be followed for zero-tillage maize cultivation:

- Weeds and other debris are cleared from the field before sowing seeds;
- Two to five maize seeds are dribbled per hill on no-till muddy soil in 25cm intervals in rows 70cm apart;
- Fertilizers are applied at the following doses: 250kg–200 kg–185 kg–105kg nitrogen-phosphorus-potassium-sulphur (NPKS) per ha land in bands along the maize rows. Fertilizers rate for hybrid varieties is 250kg–50kg–140kg–40kg–4kg–2kg/ha of nitrogen-phosphorus-potassium-sulphur-zinc-boron (NPKSZnB) for high yields and 175kg–40kg–100kg–20kg–2kg–1kg/ha for moderate yields;
- Apply all of the PKS and 50 per cent N as the base dose and the remaining N in two equal instalments at 30 and 55 days after sowing along the maize rows;
- Keep single maize seeding per hill at 20 days after sowing and use thin plants as fodder;
- Green maize cobs can be harvested depending on need. Mature cobs are harvested at 127 days after sowing;
- Yields of about 4t/ha can be harvested with local composite. Hybrid yields are almost double.

It is to be noted that the land should have the necessary residual moisture to germinate maize seeds. Otherwise, a minimum irrigation may be needed before sowing the maize seeds or after germination. After germination of maize seeds, farmers plough the land by using a spade/hoe and then apply organic and chemical fertilizer mixed with soil. Farmers may irrigate the field according to the degree of soil moisture and availability of irrigation water to increase the production of maize.

Most suitable geographic area

In addition to drought-prone areas, the zero-tillage maize cultivation option is also suitable in the coastal saline and non-saline areas and the central floodplains. This is currently being practised in Rajshahi and Nawabganj.

Major advantages

This option helps to increase the cropping intensity and decrease the area of fallow land. This system also helps to increase family income and consumption. Farmers also get byproducts (e.g. stem and cob) which can be sold in the market and/or used to meet family fuel demands. Some farmers also use the stem to make fences to protect homestead-based vegetable gardens. Finally, during the vegetative stage of maize, the leaves can be used as cattle fodder.

Major disadvantages

Maize can uptake many nutrients, which decreases overall soil fertility and productivity. Therefore, it should not be used as a mono crop. Presently maize is used only in the poultry sector for poultry feed.

Approximate benefits

Quality seeds, hoe/spade, labour, fertilizers and pesticides are required. A total of approximately a Tk98,315 (US$1395) (including land-lease cost) is required to cultivate maize per hectare of land. Farmers can harvest 7.5t of maize. Thus, farmers can earn net Tk30,685 (US$435) from one hectare of land that normally would remain fallow during the rabi season.

10 Chickpea cultivation using a priming technique

Summary

Farmers typically sow chickpea seeds directly in the field. However, this is not optimal under low soil-moisture conditions. Priming is one approach to address this. In the priming technique, seeds are soaked in water for a period of time based on the thickness of the seed coating. In drier areas, chickpea seeds are soaked at night for a period of six to eight hours. Then the soaked chickpea seeds are spread in a shaded place where there is enough air movement for air drying before sowing in the field. After sowing/seeding, the land is ploughed and levelled to preserve the moisture. Good tillage is essential for moisture preservation. Primed seeds will be germinated after four to five days.

Most suitable geographic area

Priming is practised throughout the country depending on the antecedent soil-moisture conditions, recession of flood water and seed-sowing time. In addition to drought-prone areas, this option is most suitable in the central floodplain, coastal saline and non-saline areas. This is currently being practised in Rajshahi, Nawabganj and Naogaon.

Major advantages

This option helps to increase pulse production and increase the cropping intensity. In addition to the crop, farmers also get plant and pulse husk byproducts which can be used to meet fodder and fuel demand and can potentially be used to generate extra income. The chickpea is also a leguminous family plant which absorbs nitrogen and can help increase overall soil productivity. For this reason, the chickpea plant should only be cut after harvest and not entirely uprooted. Moreover, continuous cultivation of chickpeas helps to decrease demand for urea for the next crop. Finally, up to 10–15 crop days are saved by priming.

Major disadvantages

In the Barind tract areas, farmers are spreading cut t. aman paddy on the fields for prolonged periods thereby increasing the loss of soil moisture. This affects the germination of seeds. Moreover, in some cases, land cannot be ploughed due to heavy soil and, as a result, most of the land remains fallow.

Approximate benefits

Chickpea seeds, fertilizers, bio-fertilizer and insecticides are the major inputs for this practice. Approximately, a total of Tk57,325 (US$813) (included land-lease cost) is needed to cultivate chickpeas on one hectare of land. A farmer can typically harvest 1.8t of chickpeas at a sale value of Tk50 (US$0.70) per kg. Thus, farmers can generate about Tk90,000 (US$1280) in revenues. Farmers also get dry plant and husk byproducts that can be used as cattle fodder and fuel for family needs. The remainder can be sold in the market for cash. Farmers, thus, can earn net Tk32,675 (US$463) from one hectare of land during the rabi season.

11 Supplementary irrigation of t. aman from mini ponds

Summary

In the absence of water for irrigation, rainwater harvesting in mini ponds for supplementary irrigation of t. aman during the dry period is an option. These mini ponds are typically excavated within the crop land. Farmers use comparatively lower areas to dig these ponds.

Most suitable geographic area

In addition to the Barind tract areas, this practice can be implemented in char land and coastal areas depending on the availability of water for irrigation from other sources. This is currently being practised in Rajshahi.

Major advantages

This option helps to decrease the loss of t. aman production by providing supplemental irrigation. This decreases the dependency on groundwater for irrigation. It is reported that having access to supplemental irrigation can improve rice yields by up to 23 per cent and net economic profit by 75 per cent (FAO LACC Project). Farmers can also cultivate rapid-growth varieties of fish in these ponds from July to November for both household consumption and market sales. This is an important source of protein for rural communities.

Major disadvantages

Excavation of a pond within the crop land reduces the area for crop cultivation. Moreover, due to the soil erosion in the Barind tract, these ponds may become silted in a few years, requiring re-excavation.

Approximate benefits

Rice seeds, fertilizers, insecticides, pesticides and land are the major inputs to implement this option. Approximately a total of Tk76,705 (US$1088) (included land-lease cost) is needed to cultivate t. aman rice on one hectare of land using this option. Farmers can harvest 4.5t of t. aman and straw (14,500 bundles) for a sale value of Tk90,000 and Tk10,875 (US$1277, US$154) respectively when the unit prices are Tk20 (US$0.30) per kg and Tk0.75 (US$0.01) per bundle. Farmers can also harvest fish. Thus, farmers can earn net Tk24,170 (US$343) from one hectare of land which would normally not be possible.

12 Year-round homestead vegetable cultivation

Summary

Each farm family typically has about 30 decimals of land around the homestead. Farmers can easily use this fallow land for cultivating vegetables around the year to fulfil family requirements. Any surplus can be sold in the market to increase family income. Homestead vegetable cultivation is an employment-generation activity for women and children, a source of additional income and also increases vegetable and fruit consumption.

Production package

Cultivation of vegetables in open space of the homestead (bed method)

Five beds, each 3m in length, 1m wide and 20cm in height, should be prepared in a sunny and open space near the homestead. Three kg of decomposed cow dung or recommended fertilizers of specific vegetables should be applied thoroughly to each bed before the sowing of seeds or planting of seedlings. The cultivation pattern of year-round vegetables is shown in Table 7.4.

The farmer needs only Tk1500 (US$21) per year to cover all cost related to vegetable cultivation in these five beds. Typically, Tk2500 (US$35) extra can be generated after the family requirements are fulfilled.

Cultivation of runner-type vegetables on a platform (trellis)

A trellis (5m x 4m) is made with bamboo, jute sticks and string and located in a sunny space near the homestead. Country bean, long yard bean, ash gourd, bottle gourd, bitter gourd, snake gourd, cucumber and other runner-type vegetables can be cultivated on this trellis all year round. The farmer needs approximately Tk600 (US$8.50) for the bamboo, necessary fertilizers and seeds to cultivate vegetables. The farmer can earn about Tk1800 (US$25) per year by selling extra vegetables after the family requirements are fulfilled.

Table 7.4 Common vegetable cultivation patterns

Bed No.	Rabi (Mid Oct–Mid Mar)	Kharif 1 (Mid Mar–Mid July)	Kharif 2 (Mid July–Mid Oct
1	Tomato	Okra	Data (katua data)
2	Lalshak, aubergine	Indian spinach	Indian spinach
3	Lalshak, aubergine	Kang kong	Jute vegetable
4	Radish	Okra, lalshak	Onion, lalshak
5	Batishak, country bean	Chilli, lalshak	Chilli

Note: No. of beds no. of crops may vary depending on space availability

Cultivation of runner-type vegetables on the roof

Sweet gourd, bottle gourd, ash gourd, country bean and other runner-type vegetables can be cultivated on the roof of the house. A farmer can earn about Tk1000 (US$14) per year from the sale of excess vegetables. Only Tk200 (US$2.80) is required for seeds and materials.

Cultivation of runner-type vegetables at edge/bank of pond

Bamboo poles can also be planted at a distance of about 1.5–2m from the banks/edge of a homestead pond to make a trellis for the cultivation of runner-type vegetables. This method has some advantages of utilizing unused spaces near a pond as well as providing shade for fish. The farmer typically needs about Tk500–700 (US$7.10–9.90) for the total cost of materials. About Tk2500 (US$35) can be earned from the sale of extra vegetables in local market after the family requirements are fulfilled.

Cultivation of papaya in land surrounding the homestead and edges/banks of pond

Papaya can be cultivated on the edges/banks of a pond or surrounding the homestead by digging holes with the dimension 60 x 60 x 60cm, 2m apart from each other. 10kg cow dung, 500g TSP, 250g MP, 50g boron fertilizer and 20g zinc sulphate mixing are used with the soils. After plantation of saplings, 50g urea and MOP fertilizer should be applied to each plant per month, with this doubled during the flowering stages. Farmers can earn about Tk5000 (US$70) from 100 plants. Initial production costs are about Tk2200 (US$31).

Most suitable geographic area

This adaptation option is suitable in many different areas. In particular, flood-prone, drought-prone, *haor* (wetland system) and *beel* (floodplain pond) areas are most suitable. This is currently being practised to varying degrees throughout the country, but limited in scale.

Major advantages

This option increases family consumption of vegetables and fruits and improves family income.

Major disadvantages

Due to the intensive use of land for cultivating vegetables and fruits, this option may reduce the overall area devoted to cattle grazing. This may result in decreases in the availability of cow dung.

Approximate benefits

Vegetable seeds, fertilizers, bio-fertilizer, insecticides, bamboo, jute sticks and rope are the major materials needed to implement this option. Approximately a total of Tk10,000 (US$142) (considering a 20 decimal homestead area for each family) is needed to cultivate different seasonal runner-type vegetables, leafy vegetables and fruits. The farmer will typically get Tk25,000 to Tk35,000 (US$354–496) from the sale of extra vegetables. Farmers may also get plant material that can be used as cattle fodder. Farmers can earn Tk15,000 to Tk20,000 (US$212–283) net from a single farm homestead.

13 Pond-water harvesting for irrigation to cultivate rabi vegetables

Summary

From October to May, rainfall is very low. The demand for vegetables during the rabi season is high. Winter vegetables require irrigation for maintaining soil moisture at different stages (especially during the vegetative, flowering and fruit-bearing stages). Supplementary irrigation can play a vital role in production of vegetables. In the Barind areas, some farmers are cultivating rabi vegetables with irrigation from mini ponds. Typically, rainwater is harvested or surface water is diverted into mini ponds during the monsoon and then used to grow vegetables during the rabi season. This practice helps to harvest vegetables earlier in the season.

Production package

The fertilizer dose for tomato is

> Urea-TSP-MP and Cow dung = 550kg–450kg–250kg–10,000kg;
>
> for aubergine it is urea-TSP-MP and Cow dung = 375kg–150kg–250kg–10,000kg.

Farmers select land nearest to the pond and prepare the land by ploughing and applying half of the cow dung and the total amount of TSP fertilizers. After preparation of the land, beds are raised with a width of 1m, a height of 25–30cm and a length depending on land size; 30–40cm of space is kept between beds for irrigation and drainage of excess rainwater. After levelling the beds, farmers transplant the seedlings, usually from mid-September to November, following the suggested spacing for specific vegetables (tomato = 60cm x 40cm; aubergine = 75cm x 60cm). The remainder of the cow dung is used during transplanting of seedlings. Urea and MP fertilizers are applied three weeks and five weeks after planting of the vegetable seedlings. Given that these are high value crops, farmers must pay attention to weeding, irrigation, insecticide and pesticide use. About 36–40t of tomato can be harvested from one hectare of land.

Most suitable geographic area

The flood-prone and coastal areas are the most suitable. This is currently being practised in Rajshahi, Nawabganj, Naogaon and Natore.

Major advantages

This option helps to increase vegetable production and consumption for the family. In drought-prone areas, it is very difficult to cultivate early rabi vegetables without following this option. This reduces the area of fallow land. After the harvest of vegetables, farmers can grow boro rice or high value horticultural crops (e.g. onion, garlic). Farmers can also culture fish in these ponds for both household consumption and for sale in local markets.

Major disadvantages

In the absence of rainfall and the unavailability of surface water, farmers may fail to harvest rainwater in the mini pond. Prolonged droughts may dry out the pond.

Approximate benefits

The resources required for this option include quality vegetables seeds or seedlings, fertilizers, insecticides, pesticides and land with a mini pond. Tk151,575 (US$2151) is needed to cultivate early vegetables during the rabi season on one hectare of land. A farmer can harvest 24.5t of vegetables which, at a market price of about Tk12 (US$0.17) per kg, will gross Tk294,000 (US$4173). Thus, farmers can earn net Tk142,425 (US$2021) from one hectare of land.

14 Sorjan system for cultivating seasonal vegetables, fruits and fish

Summary

Tidal surges, water-logging, saline water intrusion and soil salinity increases due to sea level rise make the production of vegetables and fruits difficult. Demand for these crops is typically met from outside supply. For this option, farmers can grow vegetables and fruits on raised beds and creeper vegetables on the edges to meet day-to-day demands. In addition, farmers can earn extra cash from the sale of remainder vegetables and fruits at the local market.

Production techniques

- A model sorjan has five raised beds (3m wide each) and six ditches (2m wide and 1.5m deep). It may be increased or decreased based on land size and shape. Normally a 28m x 11m piece of land and clayey soil is most suitable for making these raised beds and ditches. The dry months (January–March) are best for preparing the sorjan (see Figure 7.1, Plate 7.3).
- Slope of the bed is made uniform and compact;
- Trellises are made with bamboo and other local materials on the furrows to support creeper vegetables.
- Fish may be cultured in the ditches during wet months.

Cropping patterns

Two beds can be earmarked for vegetable cultivation and the rest for fruits and vegetables. The edge of the beds can be planted with creeper vegetables, which can be supported by the trellis over the furrows. The cropping patterns in Table 7.5 could be used for the five beds (as an illustration).

Most suitable geographic area

The coastal areas (both saline and non-saline), depending on the degree of flooding and tidal surges, are the most suitable. This is currently being practised in Barisal, Gopalganj, Pirojpur and Jhalokathi.

Table 7.5 Common vegetable cropping patterns for sorjan system

Bed No.	Cropping patterns on bed tops	Crops on bed edge
1	Amaranth, okra, red amaranth, tomato	Bitter gourd, hyacinth bean
2	Indian spinach, vegetables seedlings for cabbage, cauliflower	Bitter gourd, hyacinth bean
3	Papaya, chilli, red amaranth	Ribbed gourd, hyacinth bean
4	Banana, kang kong, red amaranth, aubergine	Ribbed gourd, marma
5	Banana, amaranth, red amaranth, aubergine	Snake gourd, bitter gourd

Major advantages

This option increases the cropping intensity and decreases the area of fallow land. Family consumption of fruits and vegetables will increase, as will income.

Major disadvantages

Various extreme events may increase the risk of inundation and affect the layout of the sorjan system. Bed heights consequently may need to be raised, which increases the production costs.

Approximate benefits

In the sorjan system the following resources may be required: vegetable seeds, fruit saplings, fertilizers, bamboo, jute sticks, a spade and others. A total of Tk7795 (US$110) is needed to cultivate vegetables, fruits and fish in the coastal zone using this system. Farmers can typically harvest 400–20kg, 130kg and 18kg of vegetables, fruits and fish respectively. This results in a gross value of Tk17,650 (US$250) when the market price per kg is Tk20 for vegetables, Tk125 (US$1.80) for fish and Tk55 (US$0.78) for fruit (zuzubi). Each year, farmers can also get some fuel each year from pruning the zuzubi stem. Thus, farmers can earn net Tk9855 (US$139) from one model sorjan (11m x 28m) in the coastal zone which would normally remain fallow. Over a hectare of land, the production costs are Tk253,084 (US$3592), gross income is Tk573,052 (US$8133), and the net income is Tk319,968 (US$4541).

8

The Way Forward – Turning Ideas into Action

The year 2007 was indicative of the challenges that Bangladesh faces to achieving food security. Severe flooding from July to September 2007 affected over 13 million people in 46 districts and caused extensive damage to agricultural production and physical assets (e.g. housing, embankments). With hardly any time to recover, on 15 November 2007 Cyclone Sidr made landfall across the southern coast of the country, causing over 3000 deaths. The total economic damages of these two events amounted to over US$1 billion US (World Bank, 2008). Moreover almost 2 million tonnes of rice were lost, putting government cereal stocks in a precarious situation. Finally, that same year the unabated increase in the international prices of oil and food, of which Bangladesh is a net importer, put further strains on both government budgets and household livelihoods.

What these events demonstrated was the inherent vulnerability of Bangladesh to climate risks. It also showed the degree to which food security remains a challenge for the country. Climate change has the potential to significantly affect Bangladesh's efforts to provide food to a growing nation. The challenges that the agriculture sector will face as it adapts to climate change, however, coincide well with the needs required to address the climate variability risks of today. Both processes of adapting to climate change and stimulating the agriculture sector to achieve rural growth and support livelihoods require efforts to, among other things: diversify household income sources; improve crop productivity; support greater agricultural research and development; promote education and skills development; increase access to financial services; enhance irrigation efficiency and overall water and land productivity; strengthen climate risk management; and develop protective infrastructure. Continued developmental planning and investment is needed to build resilience at both national and local scales.

This study is largely focused on the impacts of climate risks (both climate variability and climate change) on food security in Bangladesh. The risks from climate change include higher temperatures and changing precipitation patterns, increased flood intensity and frequency, droughts and sea level rise effects on agriculture production. The future is also expected to bring elevated CO_2 concentrations, which have a beneficial effect on crop growth. A suite of models is used to approach the complex questions of climate variability and change and food security in Bangladesh. In this study, future climate is projected using the most recent climate science available. Detailed hydrologic models project changes in future flooding. Country specific data is used to derive more realistic and accurate agricultural impact functions and simulations. Finally, a dynamic CGE is used to better understand the degree to which economic effects will buffer against the physical losses predicted from climate variability and climate change. Significant impacts on growth and household consumption are projected.

The models used here are among the best mathematical representations available of the physical and economic responses to these exogenous climate changes. However, like all modelling approaches, uncertainty exists as parameters may not be known with precision and functional forms may not be fully accurate. Thus, careful sensitivity analysis and an understanding and appreciation of the limitations of these models are required. Further collection and analysis of critical input and output observations (e.g. climate data, farm-level practices and irrigation constraints) will enhance this integrated framework methodology and future climate impact assessments.

Some key messages that emerge from this study include:

The impacts of existing climate variability are enormous. A no-regret strategy is to focus first on the near-term climate risks to build future resilience

Bangladesh is clearly one of the most vulnerable countries to climate risks today. The agriculture sector is impacted by annual flooding, water shortages during the dry season and frequent coastal cyclones and storm surges. Though the relative severity of these disasters has decreased substantially since the 1970s, these remain critical challenges to rural poverty and growth. Thus, continued substantial public investment in protective infrastructure (e.g. cyclone shelters, embankments), early warning and preparedness systems and programmes to build resilience at the household level (e.g. income diversification, identified adaptation options in this study) can play a critical role in minimizing these impacts.

The impacts of future changes in temperatures and precipitation, increased CO_2 levels, flooding, droughts and sea level rise are highly uncertain. In some cases not only is the magnitude of change not known with precision, but also the direction of change. Despite this, the simulation estimates in this study suggest that the simulated cumulative economy-wide impacts of existing climate variability alone (US$594 billion) are almost five times that of climate change (US$129 billion). That is, the existing inter- and intra-annual variation is significantly larger than the projected uncertain future changes. This, however, is not a cause for inaction. Rather, a no-regrets strategy is to promote activities and policies that help the national government and households build resilience in the agriculture sector to existing climate risks today. This aligns well with existing development strategies and plans. By doing so, the country and households will be better prepared for whichever future outcome materializes. The adaptation options identified are only a small sub-set of what can be done today.

The southern and northwestern regions are the most vulnerable. This is due to the confluence of several different climate risks and existing poor baseline conditions

From a socio-economic perspective, the south and northwest regions have long been areas of extensive poverty. As these communities currently in many cases exist on the margins, both climate variability and climate change threaten to increase these vulnerabilities. The sub-regions in the south sit at the confluence of multiple climate risks. These areas experience the largest decline in rice production due to climate change. This is for three reasons. First, these regions already experience significant declines in aus and aman rice production due to climate variability, which is expected to worsen under climate change. Second, boro yields are severely affected by the effects of changes in mean rainfall and temperature. Thus, reductions in boro production limit the ability for these regions to compensate for lost aus and aman rice production during extreme events. Projections, moreover, are conservative as access to irrigation is assumed limitless. Third, the south is also affected the most by rising sea levels, which permanently reduces cultivable land. The largest percentage declines in per capita consumption will be in these regions. Similarly, the northwest region is particularly vulnerable as impacts have a disproportionate share relative to the low existing household consumption. These two areas are where priority must be given and where substantial opportunities for adaptation are possible.

Increased investments in adaptation in the agriculture sector are critical to ensuring continued growth and poverty alleviation

Bangladesh will continue to depend on the agriculture sector for economic growth. Rural households will continue to depend on the agriculture sector for income and livelihoods. Floods, droughts and cyclones will continue to affect the performance of the agriculture sector. Though the government has made substantial investments to increase the resilience of the poor (e.g. new high-yielding crop varieties, protective infrastructure, disaster management), as has been shown these variability impacts may be exacerbated by long-term effects of climate change.

Households have for a long time adapted to these dynamic conditions to maintain their livelihoods. The nature of these adaptations and the determinants of success depend on the availability of assets, resources, labour, skills, education and social capital. The adaptation options identified, in fact, are currently being implemented in many locations with assistance from both the government and donor community. However, the scale of these efforts remains limited and is not commensurate with the probable impacts. Moreover, the current large gap between actual and potential yields suggests substantial on-farm opportunities for growth and poverty reduction. Expanded availability of modern rice varieties, irrigation facilities, fertilizer use and labour could increase average yields at rates that could potentially more than offset the climate change impacts. Significant additional planning and investments in promoting these types of adaptations are still needed.

8.1 A Framework for Assessing the Economic Impacts of Climate Change

The precise impact of climate change on countries in the developing world remains to be seen. This much is known, however: climate change poses additional risks to many developing countries in their efforts to reduce poverty, promote livelihoods and develop sustainably. As populations grow, the ability for many countries to meet basic food requirements and effectively manage future disasters will be critical for sustaining long-term economic growth. These are challenges above and beyond those that many countries are already currently facing. Moreover, most developing countries lack the financial and technical capacities to manage these increasing risks. Thus, strategic prioritization and improved planning and management of existing assets and budget resources are critical. Largely, these strategic choices will be dependent on the economics of these impacts.

The integrated framework used in this analysis provides a broad and unique approach to estimating the hydrologic and biophysical impacts of climate change, the macro-economic and household-level impacts and an effective method for assessing a variety of adaptation practices and policies. The framework presented here can serve as a useful guide to other countries and regions faced with similar development challenges and objectives of achieving food security. In assessing the impacts, several different modelling environments must be integrated to provide a more nuanced and complete picture of how food security may be impacted by climate change. This approach is needed to better understand the relative impacts from multiple climate risks (e.g. floods, droughts, climate change) and how these relate in the context of an evolving socio-economic baseline (e.g. population, prices, international trade). Moreover, such a framework allows for extensive scenario analysis to identify and understand key sensitivities. This is critical to making decisions in a highly uncertain future. Finally, through this integration of multiple disciplines, a richer and more robust set of adaptation options and policies for the agriculture sector can be identified and tested. Continued refinements to the assessment approach developed in this volume will further help to sharpen critical policies and interventions by the Bangladesh government.

Annex 1 – Using DSSAT to Model Adaptation Options

The following sections detail adaptive responses that may be tested according to the capabilities of the DSSAT models (Hoogenboom et al, 2003). Arranged to approximate the planning process for any given year, farm-level practices are described that may affect the selection of the crop and variety to grow, the sequence and timing of the cropping calendar, decisions relating to how each field is planted and what types of applications are made to adjust for mid-season deficiencies. The benefits of regional-scale programmes to reduce external hazards from damaging crops are also explored and additional factors are identified that will affect the interpretation of DSSAT simulation results.

Cultivar Selection

Biology

In addition to deciding which species (rice, wheat, etc.) to grow, specific cultivars within that species may be more or less adapted to future climate in a particular location. The DSSAT CERES-Rice model contains 46 different cultivars (Table A1.1), including some known to be currently used in Bangladesh.

Each of these cultivars is represented as a collection of 8 genetic coefficients affecting different aspects of growth and environmental resilience (Table A1.2). Similarly, the DSSAT CERES-Wheat model contains 10 cultivars (Table A1.3) described by 40 genetic coefficients (Table A1.4). In addition to testing the range of known cultivars for a particular location, the sensitivity of any particular genetic coefficient may be assessed using hypothetical cultivars that may serve as models in the engineering of new breeding programmes. Additional biological resilience may be simulated by adjusting salinity levels or

Table A1.1 Cultivars available in the DSSAT v4.5 CERES-Rice model

1	IRRI Originals	24	RD 23 (cal.)
2	IRRI Recent	25	CICA8
3	Japanese	26	Low Temp. Sen
4	N. American	27	Low Temp. Tol
5	IR 8	28	**17 BR11, t. aman**
6	IR 20	29	**18 BR22, t. aman**
7	IR 36	30	**19 BR3, t. aman**
8	IR 43	31	**20 BR3, boro**
9	Labelle	32	CPIC8
10	Mars	33	Lemont
11	Nova 66	34	RN12
12	Peta	35	TW
13	Starbonnett	36	IR 64
14	UPLRI5	37	Heat Sensitive
15	UPLRI7	38	**BR14**
16	IR 58	39	IR 72
17	SenTaNi	40	**BR11**
18	IR 54	41	Pant-4
19	IR 64	42	Jaya
20	IR 60 (Est)	43	BPRI10
21	IR 66	44	Zheng Dao 9380
22	IR 72x	45	CL-448
23	RD 7 (cal.)	46	PR114

Note: Cultivars known to be grown in Bangladesh are in bold. The Dhan-29 was added to DSSAT for this study based upon calibrations at the Bangladesh Agricultural Research Council.

Table A1.2 Genetic coefficients in the DSSAT v4.5 CERES-Rice model

1	P1	Time period for basic vegetative phase
2	P20	Longest day length at which the development occurs at a maximum rate
3	P2R	Extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P20
4	P5	Time period from beginning of grain filling to physiological maturity
5	G1	Potential spikelet number coefficient
6	G2	Single grain weight under ideal conditions
7	G3	Tillering coefficient
8	G4	Temperature tolerance coefficient

Table A1.3 Cultivars available in the DSSAT v4.5 CERES-Wheat model

1	Spring – High Lat	6	Spring – Low Lat
2	Winter – Europe	7	Maris Fundin
3	Winter – USA	8	Newton
4	Winter – Ukraine	9	Manitou
5	Facultative	10	Chelsea SRW-US

Note: The Kanchan and Sowgat cultivars were added to DSSAT for this study based upon calibrations at the Bangladesh Agricultural Research Council.

the amount of water available for root uptake. The simulated direct response function of each species' growth to carbon dioxide fertilization is independent of their particular cultivars in the models, although growth rates may be handled differently by each cultivar. The DSSAT CERES models do not directly simulate pests and diseases.

Location

The same agricultural practices may also be tested in numerous divisions with varying soil types and water regimes to determine where a specific crop can be grown productively. Areas whose yield underperforms may be tested with alternative cultivars or crops in order to maximize utility for local residents.

Calendar Adjustment

Planting and harvesting dates

The cropping calendar used by farmers in Bangladesh has been developed to take advantage of

Table A1.4 Genetic coefficients in the DSSAT v4.5 CERES-Wheat model

1	P1V	Days at optimum vernalizing temperature required to complete vernalization
2	P1D	Percentage reduction in development rate in a photoperiod 10 hours shorter than the threshold relative to that at the threshold
3	P5	Grain filling (excluding lag) phase duration
4	G1	Kernel number per unit canopy weight at anthesis
5	G2	Standard kernel size under optimum conditions
6	G3	Standard, non-stressed dry weight of a single tiller at maturity
7	PHINT	Time interval between successive leaf tip appearances
8	AWNS	Awn score
9	ECONO	Code for the ecotype
10	GRNMN	Minimum grain N
11	GRNS	Standard grain N
12	HTSTD	Standard canopy height
13	KCAN	PAR extinction coefficient
14	LAWRS	Lamina area to weight ratio of standard first leaf
15	LAWR2	Lamina area to weight ratio, phase 2
16	LA1S	Area of standard first leaf
17	LAVS	Area of standard vegetative phase leaf
18	LARS	Area of standard reproductive phase leaf
19	LLIFE	Life of leaves during vegetative phase
20	LT50H	Cold tolerance when fully hardened
21	NFGL	N stress factor, growth, lower
22	NFGU	N stress factor, growth, upper
23	NFPL	N stress factor, photosynthesis, lower
24	NFPU	N stress factor, photosynthesis, upper
25	PARUV	PAR conversion to dm ratio, before last leaf stage
26	PARUR	PAR conversion to dm ratio, after last leaf stage
27	P1	Duration of phase end juvenile to double ridges
28	P2	Duration of phase double ridges to end leaf growth
29	P3	Duration of phase end leaf growth to end spike growth
30	P4	Duration of phase end spike growth to end grain fill lag
31	P4SGE	Stem growth end stage
32	RDGS1	Root depth growth rate, early phase
33	RDGS2	Root depth growth rate, later phases
34	RSFRS	Reserves fraction of assimilates going to stem
35	TI1LF	Tillering threshold (leaf number to start tillering)
36	WFGU	Water stress factor, growth, upper
37	WFPU	Water stress factor, photosynthesis, upper
38	WFPGF	Water factor, genotype sensitivity to stress when grain filling
39	TBGF	Temperature base, grain filling
40	P1DPE	Day length factor, pre-emergence

current climate. As climate shifts occur, however, so may the optimal planting and harvesting schedules. In order to determine the sensitivity of the yield to the planting date, a series of DSSAT model simulations may be run with incremental planting dates over the course of several weeks to months. Harvest dates may be determined automatically by the models or specified according to local requirements.

Sequence

Bangladesh is one of the few countries in the world that is able to have three planting seasons in a given year. In the future, however, the sequence of crops and fallow periods may need to be adjusted to maximize yield. The DSSAT models allow crop sequences to be tested over an annual period or even in multi-year cycles. Future stresses may require increased crop rotation with legumes to replenish nutrients in the soils, and the treatment of crop residuals and fallow periods may have large effects on nitrogen and water-cycle processes. The potential for changing crop sequence and rotations in response to the climate change scenarios may therefore be tested using DSSAT models.

Planting Systems

Method

In addition to the planting date discussed in the previous section, the DSSAT CERES-Rice model recognizes several planting options that may be adapted to future climates. Rice may be planted according to ten different options (Table A1.5), ranging from dry seed to inclined sticks to transplants (as is common for aman production in Bangladesh). The environment in which the transplants are grown and their age and weight may be adjusted. Thirty-four tillage options may also be tested for optimization (Table A1.6).

Density

Planting may be done at varying density in a uniform distribution, in rows or on hills. The row spacing and planting depth may also be determined. Together, there is a wide range of potential planting methods that may be tested under climate change scenarios.

Table A1.5 Planting method options in the DSSAT v4.5 models

1	Bedded	6	Nursery
2	Cutting	7	Pre-germinated seed
3	**Dry Seed**	8	Ratoon
4	Horizontally planted sticks	9	**Transplants**
5	Inclined (45°) sticks	10	Vertically planted sticks

Note: Known common practices in Bangladesh is in bold.

Table A1.6 Tillage implements available in the DSSAT v4.5 models

1	Animal-drawn implement	18	Fertilizer applicator, anhydrous
2	Bedder	19	Harrow, spike
3	Blade cultivator	20	Harrow, tine
4	Chisel plough, straight point	21	Lister
5	Chisel plough, sweeps	22	Manure injector
6	Chisel plough, twisted shovels	23	Matraca hand planter
7	Cultivator, field	24	Moldboard plough
8	Cultivator, ridge till	25	Mulch treader
9	Cultivator, row	26	Plank
10	Disk plough	27	Planter, no-till
11	Disk, 1-way	28	Planter, row
12	Disk, double disk	29	Planting stick (hand)
13	Disk, tandem	30	Rod weeder
14	Drill, deep furrow	31	Roller packer
15	Drill, double-disk	32	Rotary hoe
16	Drill, no-till	33	Subsoiler
17	Drill, no-till into sod	34	V-Ripper

Inputs

Irrigation

If irrigation is available, simulated applications may be made according to a set schedule or automated according to need – defined according to the percentage of saturation in a soil layer extending down to a particular depth. An option exists to build a bund around rice plots to retain water, and an application may be made according to any of 11 methods; applied either as a given quantity or until the soil reaches a particular level of saturation (Table A1.7). An efficiency factor may be adjusted to represent lost runoff, and irri-

Table A1.7 Irrigation options in the DSSAT v4.5 models

1	Alternating furrows	7	Furrow
2	**Bund height**	8	Percolation rate
3	**Constant flood depth**	9	**Puddling (for rice only)**
4	Drip or trickle	10	Sprinkler
5	**Flood depth**	11	Water table depth
6	**Flood**		

Note: Options that may be appealing for use in Bangladesh are in bold.

gation can be exclusively scheduled for particular growth stages if necessary. Regardless of the types of irrigation provided, the largest difference will be between irrigated and rainfed fields. The gap that exists between these two options will have profound implications on potential grain yield, demand for surface water resources, and stresses on the water table.

Fertilizer

In addition to incorporating crop residuals from a previous season's harvest, the DSSAT models allow fertilizer applications to be made according to a schedule or in an automated manner. Twenty-five different chemical fertilizers (Table A1.8) and 19 application methods (Table A1.9) are available in the DSSAT models and may be automated depending on the nitrogen stress at a given soil level. Fourteen organic amendments may also be simulated (Table A1.10). Like irrigation, the price and availability of fertilizers will largely determine their use in the future, so any gains in yield need to be weighed against increases in cost.

Environmental modifications

The DSSAT models also allow farm-level environmental modifications that may reduce plant stresses. For example, water stresses may be ameliorated by adjusting the rate of soil drainage (e.g. by simulating the addition of a semi-permeable material at the base of the soil column), and scheduled periods of shading may reduce heat stress.

Independent options

Baseline experiments that are calibrated to historical division level yields can be run with the adjustment of a single practice, allowing the

Table A1.8 Fertilizer types in the DSSAT v4.5 models

1	Ammonium nitrate	13	Liquid phosphoric acid
2	Ammonium nitrate sulphate	14	**Monoammonium phosphate**
3	Ammonium polyphosphate	15	Potassium chloride
4	Ammonium sulphate	16	Potassium nitrate
5	Anhydrous ammonia	17	Potassium sulphate
6	Aqua ammonia	18	Rhizobium
7	Calcitic limestone	19	Rock phosphate
8	Calcium ammonium nitrate solution	20	**Single super phosphate**
9	Calcium hydroxide	21	**Triple super phosphate**
10	Calcium nitrate	22	**Urea**
11	**Diammonium phosphate**	23	Urea ammonium nitrate solution
12	Dolomitic limestone	24	Urea super granules

Note: Fertilizers known to be in use in Bangladesh are in bold (*Yearbook of Agricultural Statistics of Bangladesh*, 2005).

Table A1.9 Fertilizer and organic amendment application options in the DSSAT v4.5 models

1	Applied in irrigation water
2	Band on saturated soil, 2cm flood, 92% in soil
3	Banded beneath surface
4	Banded on surface
5	Bottom of hole, deep placement
6	Broadcast on flooded/saturated soil, 15% in soil
7	Broadcast on flooded/saturated soil, 30% in soil
8	Broadcast on flooded/saturated soil, 45% in soil
9	Broadcast on flooded/saturated soil, 60% in soil
10	Broadcast on flooded/saturated soil, 75% in soil
11	Broadcast on flooded/saturated soil, 90% in soil
12	Broadcast on flooded/saturated soil, none in soil
13	Broadcast, incorporated
14	Broadcast, not incorporated
15	Deeply placed urea super granules/pellets, 100% in soil
16	Deeply placed urea super granules/pellets, 95% in soil
17	Foliar spray
18	Injected
19	On the seed

Table A1.10 Organic amendments available in the DSSAT v4.5 models

1	Barnyard manure	8	Maize residue
2	Bush fallow residue	9	Macuna residue
3	Compost	10	Peanut residue
4	Cowpea residue	11	Pearl millet residue
5	Crop residue	12	Pigeon pea residue
6	Green manure	13	Sorghum residue
7	Liquid manure	14	Soybean residue

sensitivity of yield to each particular approach to be evaluated. Yield sensitivity for each of the following management practices (as applicable) may then be assessed for any given location and climate scenario:

- Crop selection
- Known cultivar selection
- Genetic coefficient values
- Soil profile
- Tillage schedule
- Tillage implement
- Tillage depth
- Planting date
- Planting density
- Planting geometry
- Planting depth
- Planting method
- Temperature of transplant environment (if applicable)
- Transplant age (if applicable)
- Transplant weight (if applicable)
- Irrigation calendar
- Irrigation type
- Irrigation amount
- Fertilizer calendar
- Fertilizer type
- Fertilizer implementation option
- Organic amendment calendar
- Organic amendment type
- Organic amendment implementation option
- Harvest date
- Environmental modifications
- External flood control
- External salinity control.

Combined practices

Once sensitive practices are identified, strategies may be developed to combine adapted practices for maximum seasonal yield. If multiple strategies produce similar shifts in yield, the cost-effectiveness of each approach may be evaluated along with the extent to which the new management departs from traditional practices. Assumptions about water management may also be incorporated to determine irrigation availability and develop strategies to maintain scarce resources. This allows a projected benefit to be associated with the cost of each simulated adaptation option. Some potential combined practices include modifications to:

- Cultivar selection and irrigation calendar
- Planting density and planting depth
- Tillage implement and fertilizer implementation option
- Cultivar selection, irrigation amount and fertilizer type
- Cultivar selection, planting date, and irrigation amount
- Genetic coefficient values, planting date, planting method, planting geometry, planting depth, irrigation calendar, irrigation amount, irrigation type, fertilizer calendar, fertilizer type, fertilizer amount and fertilizer implementation option.

Sequential adjustments

The DSSAT crop modelling system allows for simulations of crop cycling that allows evaluation of multi-seasonal adaptation strategies. The inclusion of a legume cycle or a multi-seasonal strategy of fertilizer application may be a cost-effective way to maximize yield from a particular plot of land. The effect of changing one season's practices may be assessed for lingering impacts on the following seasons using this crop modelling framework. Thus, the cropping strategy of a particular location may be analysed throughout an annual or multi-year cycle of cultivation and fallow periods to maximize sustainability and yields.

Annex 2 – Description of the CGE Model

Tables A2.1 and A2.2 present the equations of a simple closed-economy computable general equilibrium (CGE) model that is used at this stage to illustrate how climate change affects the economic outcomes examined in this analysis. The model is recursive dynamic and can therefore be separated into a static 'within-period' component wherein producers and consumers maximize profits and utility, and a dynamic 'between-period' component wherein the model is updated based on the demographic model and previous period results, thereby reflecting changes in population, labour supply, and the accumulation of capital and technology.

In the static component of the model, producers in each sector *s* and agro-climatic region *r* produce a level of output *Q* in time period *t* by employing the factors of production *F* under constant returns to scale (exogenous productivity α) and fixed production technologies (fixed factor shares δ) – Equation 1. Profit maximization implies that factor payments *W* are equal to average production revenues – Equation 2. Labour supply *L*, land supply *N* and capital supply *K* are fixed within a given time period, implying full employment of factor resources. Land and labour market equilibrium is defined at the regional level, so land and labour is mobile across sectors but wages and rental rates vary by region – Equation 6. National capital market equilibrium implies that capital is mobile across both sectors and regions, and earns a national rental rate (i.e. regional capital returns are equalized) – Equation 8.

Factor incomes are distributed to households in each region using fixed income shares based on the households' initial factor endowments – Equation 3. Total household incomes *Y* are then either saved (based on marginal propensities to save υ) or spent on consumption *C* (according to marginal budget shares β) – Equation 4. Consumption spending includes a 'subsistence' component λ that is independent of income and determined by household population *H*. Savings are collected in a national savings pool and used to finance investment demand *I* (i.e., savings-driven investment closure) – Equation 5. Finally, a single price *P* equilibrates national product markets, thus avoiding the necessity of modelling inter-regional trade flows – Equation 9.

The model variables and parameters are calibrated to observed data from a regional social accounting matrix (SAM) (described in Annex 3) that captures the initial equilibrium structure of the economy in 2005. Parameters are then adjusted over time to reflect demographic and economic changes and the model is resolved for a series of new equilibriums for the 45-year period 2005–50. Three dynamic adjustments occur between periods: changes in land and labour supply; capital accumulation; and technical change.

Between periods the model is updated to reflect long-term growth rates in land supply *N* and labour supply *L*. These are imposed through the parameters σ and ϕ – Equations 10 and 11 – which remain unchanged across simulations. For capital supply *K*, the model endogenously determines the national rate of accumulation – Equation 12.

Table A2.1 Simple CGE model equations

Static model equations			
Production function	$Q_{srt} = \alpha_{srt} \cdot \prod F_{fsrt}^{\delta_{fsr}}$		1
Factor payments	$W_{frt} \cdot \sum_{s} F_{fsrt} = \sum_{s} \delta_{fsr} \,.\, P_{st} \,.\, Q_{srt}$		2
Household income	$Y_{hrt} = \sum_{fs} \theta_{hf} \cdot W_{frt} \,.\, F_{fsrt}$		3
Consumption demand	$P_{st} \cdot D_{hsrt} = \beta_{hsr} \cdot (1 - \upsilon_{hr}) \cdot Y_{hrt}$		4
Investment demand	$P_{st} \cdot I_{st} = \rho_{s} \cdot \sum_{hr} \upsilon_{hr} \cdot Y_{hrt}$		5
Labour market equilibrium	$\sum_{s} F_{fsrt} = L_{frt}$	*f* is labour	6
Land market equilibrium	$F_{fsrt} = N_{fsrt} \cdot (1 + \varepsilon_{fsrt}) \cdot \lambda_{frt}$	*f* is land	7
Capital market equilibrium	$\sum_{rs} F_{fsrt} = K_{ft} \quad and \quad W_{frt} = W_{fr't}$	*f* is capital	8
Product market equilibrium	$\sum_{hr} D_{hsrt} = \sum_{r} Q_{srt} + I_{st}$		9
Recursive dynamic equations			
Labour supply	$L_{frt} = L_{frt-1} \cdot (1 + \sigma_{fr})$	*f* is labour	10
Land expansion	$N_{fsrt} = N_{fsrt-1} \cdot (1 + \varphi_{fsr} - \eta_{fsrt})$	*f* is land	11
Capital accumulation	$K_{ft} = K_{ft-1} \cdot (1 + \pi - \tau_{t}) + \sum_{s} \frac{P_{st-1} \cdot I_{st-1}}{K}$	*f* is capital	12
Technical change	$\alpha_{srt} = \alpha_{srt-1} \cdot (1 + \gamma - \mu) \cdot (\omega \cdot \nu)$	*f* is labour	13

The level of investment *I* from the previous period is converted into new capital stocks using a fixed capital price κ. This is added to previous capital stocks after applying a fixed long-term rate of depreciation π. New capital is allocated to regions and sectors endogenously in order to equalize capital returns. Finally, the model captures total factor productivity through the production function's shift parameter α. The rate of technical change γ is exogenously determined based on long-term trends and is applied to all simulations.

Table A2.2 Simple CGE model variables and parameters

Subscripts		Static model exogenous parameters	
f	Factor groups (land, labour and capital)	α	Production shift parameter (factor productivity)
h	Household groups	β	Household average budget share
m	GCMs and emission scenarios	δ	Factor input share parameter
r	Regions (agro-climatic)	θ	Household share of factor income
s	Economic sectors	ρ	Investment commodity expenditure share
t	Time periods	υ	Household marginal propensity to save
Endogenous variables		**Dynamic updating exogenous parameters**	
D	Household consumption demand quantity	γ	Long-run unbiased productivity growth rate
F	Factor demand quantity	κ	Base price per unit of capital stock
I	Investment demand quantity	π	Long-run capital depreciation rate
K	National capital supply	σ	Long-run labour supply growth rate
L	Regional labour supply	ϕ	Long-run land expansion rate
P	Commodity price		
		Climate-related exogenous parameters	
Q	Output quantity	w	Yields: climate-affected deviation from base
W	Average factor return	v	Yields: flood-affected deviation from base
Y	Total household income	τ	Major flood: additional capital depreciation
		ε	Major flood: land loss from inundation
		η	Major flood: decelerating land expansion
		μ	Major flood: decelerating productivity growth
		λ	Sea level rise: long-run land deviation from base

Climate Impact Channels in the Economy-wide Model

Climate variability and change is imposed on the simple economy-wide model via various climate-related exogenous parameters (see Table A2.3). The first impact channel is changes in rice crop yields (wheat is not considered here). The hydro-crop models produce two parameters that reflect deviations in annual crop yields from its exogenously-determined long-term trend.[1] The first parameter w is the yield deviations caused by changes in climate conditions, including temperature, rainfall and CO$_2$ levels (see Equation 13). This climate-affected yield parameter w varies around a base year value of one depending on the year selected randomly from the climate data series (i.e. values greater than one represent better-than-base-year yields). The second parameter v taken from the hydro-crop models is the crop yield deviation caused by changes in mean flooding (see Equation 13). When there are no changes in mean flooding the flood-affected yield parameter is equal to one and there is no yield loss. In the presence of changes, the parameter falls below one and the yield in a particular year is below its long-term trend. The climate- and flood-affect yield deviations can compound each other, causing yields in a particular year to fall below long-term trends. However, there are no permanent yield losses caused by climate variability during a typical year (i.e. yields can return to long-term trend rates in subsequent years).

The second impact channel is the additional economic losses associated with extreme climate events. When a major flood year is randomly drawn from the climate datasets then there are four additional 'extreme event' impacts that take place over and above the climate- and flood-affected yield changes described above. First, there is a deceleration in long-term rate of land expansion, which is governed by the parameter ϕ – Equation 11. This is achieved by assigning the offsetting parameter η with the negative value of the long-term land expansion rate (i.e. $-\phi$), thus reducing land expansion during a major flood year to zero. Second, there are land losses from severe water inundation during major floods.

Table A2.3 Summary of climate impact channels in economy-wide model simulations

Impact channel		Affected sectors	Description of impact
For each year in the Monte Carlo experiment (during the 45-year repeated draws in each simulation)			
Climate-affected yield impacts	ω	Aus, aman and boro rice	Deviation in rice crop yields from base value due to changes in rainfall, temperature and CO_2 levels ($0 < \omega < \infty$).
Climate-affected yield impacts	ν	Aus and aman rice	Decline in rice crop yields caused by water-logging ($0 < \nu < 1$). Optimal year has no water logging (i.e. $\nu = 1$).
For major flood years when drawn in the Monte Carlo experiment (reflecting conditions in 1970–71, 1974–75, 1984–85, 1987–88, 1988–89, 1998–99)			
Decelerating crop land expansion	η	All crops and shrimp fisheries, except for irrigated boro rice, wheat, and pulses	Long-term rate of annual land expansion is reduced to zero during major flood year ($\eta = -\phi$). Land expansion continues in subsequent period (i.e. η returns to zero).
Land inundation from flooding	ε	Aus and Aman rice	Flooding reduces land supply according to observed crop land losses from historical crop production data ($\varepsilon < 0$). Crop land returns to cultivation in subsequent year (i.e. ε returns to zero).
Capital stock losses	τ	All non-heavy-industry sectors	Capital depreciation rates increase during major flood year reducing the physical stock of capital ($\tau < 0$). Normal depreciation rates resume in subsequent period (i.e. τ returns to zero).
Decelerating productivity growth	μ	All agricultural sectors	Long-term rate of annual land expansion is reduced to zero during major flood year ($\mu = -\gamma$). Productivity growth continues in subsequent period (i.e. μ returns to zero).
Shocks only taking place in the climate change simulations			
Rising sea levels	λ	All crops and shrimp fisheries	Crop land gradually and permanently declines due to rising sea levels in affected regions ($0 < \lambda < 1$).

Historical data suggests that the land cultivated for aus and aman are severely affected during major flood years (see Figure 2.3). Accordingly, the land inundation parameter ε is set equal to the land declines observed in each region from official agricultural production data – Equation 7. Third, productive capital stocks are lost during major flood years, which limit both agricultural and non-agricultural production. This is captured in the model by doubling the exogenous economy-wide rate of depreciation π during major flood years (1988 and 1998) and increasing it by 50 per cent during the other less severe flood years. In other words, the additional depreciation parameter τ – equation 12 – rises from zero in typical climate years to 0.5 when the 1988 and 1998 flood years are drawn from the climate datasets. Finally, there is a deceleration in long-term technical progress, which is governed by the parameter γ – Equation 13. This is achieved by assigning the offsetting parameter μ with the negative value of the exogenous rate of technical change (i.e. $-\gamma$), thus reducing the growth rate of total factor productivity to zero during a major flood year to zero.

The third climate impact channel captured in the CGE model is the rise in sea levels caused by climate change. Independent analysis estimates the amount of land lost in each of the 16 sub-regions resulting from increases in sea levels by the 2030s and the 2050s. These are imposed on the total supply of agricultural land through the parameter λ – equation 7. The base year reflects current conditions and λ has a value of one. As sea levels gradually rise, the land area in particular regions decline and λ has a value less than one. Since the rising sea level is only associated with climate change it is only imposed on the climate change simulations.

The CGE therefore captures three climate-related impacts:

1. Yield losses each year resulting from potential sub-optimal climate conditions (including temperature, rainfall, CO_2 and mean flood changes) as estimated by the hydro-crop models;
2. Lost land, capital and productivity growth during major flood years as observed in historical production data;
3. Lost cultivable land resulting from rising sea levels caused by climate change.

The economy-wide model also accounts for the predicted increase in the frequency of major flooding resulting from climate change. The return period for the 1988 and 1998 flood years are reduced by one-third. In other words, 1988 and 1998 are characterized as the 1/33 and 1/50 year floods respectively (in relation to water discharges). The frequency of these floods in the sample for the random selection of years for the future climate sequences is increased to 1/25 and 1/33 for the 1988 and 1998 floods respectively.

Extensions in the Full Bangladesh Model

The simplified model illustrates how climate variability and change affects economic outcomes in our analysis. However, the full Bangladesh model drops certain assumptions.[2] Constant elasticity of substitution (CES) production functions allows factor substitution based on relative factor prices (i.e. δ is no longer fixed). The model identifies 36 sectors in each of the 16 agro-climatic regions (i.e. 17 in agriculture, 14 in industry and 5 in services). Intermediate demand in each sector (excluded from the simple model) is determined by fixed technology coefficients. Based on the 2005 household income and expenditure survey, labour markets are further segmented across four skill groups:

1. Illiterate or uneducated workers;
2. Workers with primary education;
3. Workers with some secondary schooling;
4. Workers with secondary or higher schooling.

Farm land is divided into:

1. Marginal farms with less than 0.5 acres;
2. Small-scale farms with between 0.5 and 2.5 acres;
3. Large-scale farms with more than 2.5 acres.

All factors are assumed to be fully employed, and capital is immobile across sectors. New capital from past investment is allocated to regions/sectors according to profit rate differentials under a 'putty-clay' specification.

The full model still assumes national product markets. However, international trade is captured by allowing production and consumption to shift imperfectly between domestic and foreign markets, depending on the relative prices of imports, exports and domestic goods. Since Bangladesh is a relatively small economy, world prices are assumed to be fixed and the current account balance is maintained by a flexible real exchange rate (i.e. the price index of tradable-to-non-tradable goods). Production and trade elasticities are econometrically estimated.

A linear expenditure system determines household consumption levels and permits non-unitary income elasticities. Households are disaggregated across agricultural and nonagricultural groups. Agricultural households are separated into landowners and landless agricultural workers. Landowning farm households in each of the 16 agro-climatic regions are separated into marginal, small-scale and large-scale farm households. Non-agricultural households are disaggregated according to the education level of their household head (i.e. uneducated or illiterate, primary-school educated and secondary-school educated or higher). There are a total of 52 distinct household groups in the full CGE model. These household groups pay taxes to the government based on fixed direct and indirect tax rates. Tax revenues finance exogenous recurrent spending, resulting in an endogenous fiscal deficit.

Notes

1. The base year crop yields in the CGE model (i.e. 2005) are set as the average yield achieved

for a given agro-climatic region and crop during the 1970–99 baseline. These then grow at an exogenous rate reflecting the long-term rate of technical change without the effects of climate variability or change.

2 A mathematical specification of the underlying recursive dynamic CGE model is presented in Thurlow (2004). The CGE model used in the current study falls within the broader class of structural neo-classical models described in Dervis et al (1982) and Robinson (1989).

Annex 3 – Constructing the Social Accounting Matrix for Bangladesh

Key Features of the 2005 Bangladesh SAM

A social accounting matrix (SAM) is a consistent data framework that captures the information contained in the national income and product accounts and the input-output table, as well as the monetary flows between institutions. A SAM is an ex-post accounting framework because, within its square matrix, total receipts must equal total payments for each account contained within the SAM. Since the required data is not drawn from a single source, information from various sources must be compiled and made consistent. This process is valuable since it identifies inconsistencies among Bangladesh's statistical sources and highlights areas where data reliability is weakest. SAMs are economy-wide databases which are used in conjunction with analytical techniques to strengthen the evidence underlying policy decisions. The 2005 SAM extends previous SAMs constructed by the International Food Policy Research Institute (IFPRI) by including more agricultural sectors, and disaggregating agricultural production across 64 districts/zilas and non-agricultural production across the 6 major regional divisions/states of the country.

General structure of SAMs

A SAM is an economy-wide data framework that usually represents the real economy of a single country.[1] More technically, a SAM is a square matrix in which each account is represented by a row and column. Each cell shows the payment from the account of its column to the account of its row – the incomes of an account appear along its row, its expenditures along its column. The underlying principle of double-entry accounting requires that, for each account in the SAM, total revenue (row total) equals total expenditure (column total). Table A3.1 shows an aggregate SAM (with verbal explanations in place of numbers).

The SAM distinguishes between 'activities' (the entities that carry out production) and 'commodities' (representing markets for goods and non-factor services). SAM flows are valued at producers' prices in the activity accounts and at market prices (including indirect commodity taxes and transactions costs) in the commodity accounts. The commodities are activity outputs, either exported or sold domestically, and imports. In the activity columns, payments are made to commodities (intermediate demand) and factors of production (value-added comprising operating surplus and compensation of employees). In the commodity columns, payments are made to domestic activities, the rest of the world and

Table A3.1 Basic structure of a SAM

	Activities	Commodities	Factors	Households	Government	Investment	Rest of the World	Total
Activities		Marketed output						Activity income
Commodities	Intermediate inputs			Private consumption	Government consumption	Investment, change in stocks	Exports	Total demand
Factors	Value-added							Factor income
Households			Factor income to households		Transfers to households		Foreign remittances received	Household income
Government		Sales taxes, import tariffs	Factor and corporate taxes	Direct household taxes			Government transfers from rest of world	Government income
Savings				Household savings	Government savings		Foreign savings	Savings
Rest of the World		Imports	Repatriated earnings		Government transfers to rest of world			Foreign exchange outflow
Total	Activity expenditures	Total supply	Factor expenditures	Household expenditures	Government expenditures	Investment	Foreign exchange inflow	

various tax accounts (for domestic and import taxes). This treatment provides the data needed to model imports as perfect or imperfect substitutes vis-à-vis domestic production.

The government is disaggregated into a core government account and different tax collection accounts, one for each tax type. This disaggregation is necessary since otherwise the economic interpretation of some payments is often ambiguous. In the SAM, direct payments between the government and households are reserved for transfers. Finally, payments from the government to factors (for the labour services provided by public-sector employees) are captured in the government services activity. Government consumption demand is a purchase of the output from the government services activity, which in turn pays labour.

The SAM contains a number of factors of production, which earn incomes from their use in the production process and then pay their incomes to households, government and the rest of the world. Capital earnings or profits are taxed according to average corporate tax rates and some profits may be repatriated abroad. The remaining capital earnings, together with other factors' earnings (e.g. land and labour) are paid to households. Households use their incomes to pay taxes, save, and consume domestically produced and imported commodities.

Structure of the 2005 Bangladesh SAM

The new SAM extends previous Bangladesh SAMs produced by IFPRI by: (1) updating the previous 2002/03 SAM to 2004/05; (2) disaggregating the agricultural sector across a greater number of crops; (3) disaggregating agricultural production and land and livestock markets across 64 districts or zilas; and (4), disaggregating non-agricultural production and labour and capital markets across 6 divisions. The next section describes the various data sources used to produce the new 2005 SAM, while this section describes its overall structure.

The SAM identifies 62 sectors, of which 23 are in agriculture (see Table A3.2). Agricultural production is divided into crop agriculture (18 sub-sectors), livestock (2 sub-sectors), fisheries (2 sub-sectors) and forestry. With the exception of forestry and 'other fisheries', which are disaggregated across divisions, all agricultural sub-sectors are disaggregated across Bangladesh's 64 districts or zilas. Given severe land constraints in Bangladesh, agricultural land is disaggregated across three categories: (1) marginal farmers (farm households with less than 0.5 acres of cultivated land); (2) small-scale farmers (households with between 0.5 and 2.5 acres of cultivated land); and (3) medium- and large-scale farmers (household with more than 2.5 acres of cultivated land – equivalent to 1 hectare of land). Land allocation across crops varies across different parts of the country and across farm households with different land endowments (see Table A3.3). Farm households' land endowments are typically small in Bangladesh, with the average farm household cultivating just over 1 acre of land. This varies significantly across divisions, with the largest average cultivated land sizes in Rajshahi and the smallest in Chittagong and Dhaka. This aggregation hides even greater variation across districts. All farm households devote a majority of their land to rice production, although most households produce a diverse range of crops. This regional and sectoral heterogeneity justifies the detailed spatial disaggregation of crops in the new Bangladesh SAM.

The 2005 SAM retains non-agriculture sectoral detail from the 2002/03 IFPRI SAM, but these non-agricultural sectors are now disaggregated across six regional divisions (see Table A3.4). The Dhaka division is the largest in terms of its contribution to gross domestic product (GDP), accounting for two-fifths of the overall economy. Agriculture is least important in the Dhaka division, accounting for 10 per cent of its economy, which is substantially below the national average contribution of agriculture of 20 per cent of GDP. Agriculture is especially important for the smaller divisions of Barisal, Khulna and Sylhet, where the sector accounts for around a third to a half of divisional GDP.

Factors markets are defined at various levels of spatial aggregation. Land and livestock capital are specific to each zila and, as mentioned above, agricultural land in each zila is further disag-

Table A3.2 Sectors in the 2005 Bangladesh SAM

Sector no.	Activity code	Commodity code	Description	Disaggregation
Agriculture				
1	arausl	cauric	Rice Aus (local)	Zila
2	araush		Rice Aus (hyv)	Zila
3	aramnl	camric	Rice Aman (local & trans)	Zila
4	aramnh		Rice Aman (hyv & hybrid)	Zila
5	arborl	cboric	Rice Boro (local)	Zila
6	arborh		Rice Boro (hyv & hybrid)	Zila
7	awheat	cwheat	Wheat	Zila
8	aocere	cocere	Other cereals	Zila
9	ajutef	cjutef	Jute	Zila
10	asugar	csugar	Sugarcane	Zila
11	aocash	cocash	Other cash crops	Zila
12	apulse	cpulse	Pulses	Zila
13	arapes	crapes	Rapeseed	Zila
14	aooilc	cooilc	Other oil crops	Zila
15	aspice	cspice	Spices	Zila
16	apotat	cpotat	Potatoes	Zila
17	aveges	cveges	Vegetables	Zila
18	afruit	cfruit	Fruits	Zila
19	alives	clives	Livestock	Zila
20	apoult	cpoult	Poultry	Zila
21	ashrmp	cshrmp	Shrimp farming	Zila
22	aofish	cofish	Other fishing	Division
23	afores	cfores	Forestry	Division
Industry				
24	amines	cmines	Mining & quarrying	Division
25	aaumll	caumll	Rice milling (Aus)	Division
26	aammll	cammll	Rice milling (Aman)	Division
27	abrmll	cbrmll	Rice milling (Boro)	Division
28	aocmll	cocmll	Other cereal milling	Division
29	aedoil	cedoil	Edible oils	Division
30	asugrp	csugrp	Sugar processing	Division
31	aofood	cofood	Other food processing	Division
32	abevtb	cbevtb	Beverages and tobacco	Division
33	aleath	cleath	Leather and footwear	Division
34	ajtext	cjtext	Jute textiles	Division
35	ayarns	cyarns	Yarn	Division
36	amclth	cmclth	Mill cloth	Division
37	aoclth	coclth	Other cloth	Division
38	agarms	cgarms	Ready-made garments	Division
39	aknitw	cknitw	Knitwear	Division
40	aotext	cotext	Other textiles	Division
41	awoodp	cwoodp	Wood and paper	Division
42	achems	cchems	Chemicals	Division
43	aferts	cferts	Fertilizers	Division
44	apetrl	cpetrl	Petroleum products	Division
45	anmetl	cnmetl	Non-metallic minerals	Division
46	ametal	cmetal	Metal products	Division
47	amachs	cmachs	Machinery	Division
49	aconst	cconst	Construction	Division
50	antgas	cntgas	Natural gas	Division
51	aelect	celect	Electricity	Division
52	awater	cwater	Water	Division
Services				
53	atrade	ctrade	Retail and wholesale trade	Division
54	ahotel	chotel	Hotels and catering	Division
55	atrans	ctrans	Transport	Division
56	acomms	ccomms	Communications	Division
57	abusre	cbusre	Business and real estate	Division
58	afsrvs	cfsrvs	Financial services	Division
59	acsrvs	ccsrvs	Community and social services	Division
60	apadmn	cpadmn	Public administration	Division
61	aeduca	ceduca	Education	Division
62	aheals	cheals	Health and social works	Division

Source: 2005 Bangladesh SAM.

gregated into marginal, small-scale and large-scale farms. Capital and labour are defined at the divisional level. Labour is further disaggregated across four education-based categories: (1) illiterate landless workers whose households still derive incomes from agriculture (i.e. farm labourer families); (2) low-skilled workers (i.e. primary schooling or less) and illiterate workers whose households derive incomes from wage employment and/or non-farm enterprises; (3) semi-skilled workers (i.e. some secondary schooling); and (4) high-skilled workers (i.e. completed secondary schooling and/or tertiary qualifications). These factor incomes are paid to households and are supplemented by social security payments from the government and remittances received from abroad.

The model identifies 'agricultural' and 'non-agricultural' households depending on whether the household receives any income from working in the agricultural sector. However, even agricultural households derive at least some of their incomes from non-farm enterprises and off-farm wage employment. Agricultural households are separated into the three land endowment categories discussed above (i.e. marginal, small and medium/large) within each district. The SAM also identifies households who are landless but derive some of their income from working in the agricultural sector. These landless households are only disaggregated across divisions because labour markets are identified at the division level. Finally, non-agricultural households are disaggregated across divisions and according to the education level of the head of the household (i.e. low-skilled, semi-skilled and high-skilled).[2]

Table A3.5 shows the share of different households' incomes derived from factor and non-factor sources as reflected in the 2005 SAM. Table A3.6 shows the income shares taken directly from the 2005 Household Income and Expenditure Survey (HIES) (Bangladesh Bureau of Statistics, 2005a). A comparison shows that the SAM captures the relative importance of factors in generating different households' incomes.[3]

From Table A3.5, labour income is most important for non-agricultural households, which are in turn most dependent on the type of

Table A3.3 Average cultivated crop land allocation across divisions and scale of production

	National	Divisions						Farm size		
		Barisal	Chitta-gong	Dhaka	Khulna	Rajshahi	Sylhet	Marginal farms	Small farms	Large farms
Population	137,649	9164	27,019	43,727	15,879	33,026	8835	27,971	39,567	11,274
Households	28,166	1760	4816	9200	3479	7406	1505	5829	7523	1738
Average cultivated land (ac)										
All crops and shrimp	1.06	1.37	0.82	0.82	1.10	1.40	1.19	0.38	1.98	7.36
Rice	0.80	1.09	0.65	0.60	0.74	1.02	1.12	0.26	1.48	5.60
Aus (local)	0.05	0.23	0.09	0.02	0.05	0.02	0.11	0.02	0.10	0.42
Aus (high yield)	0.04	0.05	0.06	0.03	0.04	0.03	0.08	0.02	0.08	0.25
Aman (local)vv	0.18	0.62	0.15	0.13	0.19	0.16	0.23	0.05	0.31	1.45
Aman (high yield)	0.19	0.06	0.13	0.11	0.20	0.35	0.18	0.07	0.36	1.28
Boro (local)	0.04	0.02	0.02	0.03	0.02	0.03	0.22	0.01	0.06	0.30
Boro (high yield)	0.29	0.11	0.21	0.28	0.24	0.43	0.31	0.11	0.58	1.89
Wheat	0.03	0.01	0.01	0.02	0.05	0.06	0.01	0.01	0.06	0.21
Other cereals	0.01	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.02	0.07
Jute	0.04	0.01	0.01	0.05	0.07	0.05	0.00	0.02	0.08	0.23
Sugar cane	0.01	0.00	0.00	0.01	0.01	0.02	0.00	0.00	0.02	0.09
Other cash crops	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.02
Pulses	0.03	0.10	0.01	0.02	0.04	0.03	0.00	0.01	0.04	0.22
Rapeseed	0.03	0.01	0.01	0.04	0.02	0.04	0.00	0.01	0.06	0.17
Other oil crops	0.01	0.03	0.03	0.01	0.01	0.01	0.00	0.00	0.02	0.12
Spices	0.04	0.06	0.04	0.03	0.03	0.04	0.01	0.02	0.07	0.22
Potatoes	0.03	0.01	0.02	0.01	0.01	0.07	0.02	0.01	0.06	0.17
Vegetables	0.02	0.02	0.03	0.01	0.02	0.01	0.02	0.01	0.03	0.10
Fruits	0.01	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.02	0.07
Shrimp farming	0.01	0.00	0.00	0.00	0.06	0.00	0.00	0.01	0.01	0.07

Source: Authors' calculations using the 2005 Agricultural Census and 2005 Bangladesh SAM

labour category in which their household head falls. Marginal farmers and landless agricultural households are more dependent on illiterate and lower-skilled labour incomes. By contrast, large-scale farmers derive a greater share of their income from capital earnings and land earnings and less from labour.

Household expenditure patterns are shown in Table A3.7 and are mainly determined by income levels. Per capita consumption is lowest for marginal and landless agricultural households, and almost three times as high on average for high-skilled non-agricultural households. Food consumption as a share of total consumption spending is lowest for higher-income large-scale farm and high-skilled non-agricultural households. However, these household groups form only a small share of the total population of Bangladesh, with most households relying on small-scale agriculture and allocating more than two-fifths of the total consumption spending to food products.

In summary, the 2005 Bangladesh SAM makes full use of available data sets to produce a SAM with a stronger focus on agriculture but with the retained non-agricultural detail of previous SAMs. Moreover, the SAM reflects the spatial heterogeneity of the country, both in terms of agro-ecological conditions and cropping patterns, as well as the varying concentrations of non-agricultural production. Since the SAM captures in detail Bangladesh's sub-national and sectoral characteristics, it is an ideal tool for examining agricultural investment policies, rural-urban linkages and transformation and environmental and climate-related scenarios.

Table A3.4 National and divisional per cent of gross domestic product (GDP)

	National	Barisal	Chittagong	Dhaka	Khulna	Rajshahi	Sylhet
GDP shares across divisions	100.0	6.9	21.7	39.3	9.7	13.7	8.7
GDP shares within divisions	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Agriculture	20.2	40.8	16.7	10.4	31.7	24.1	37.8
Mining & quarrying	1.2	0.1	1.4	1.1	2.0	0.2	2.6
Manufacturing	15.8	8.6	19.7	18.1	6.6	18.2	7.3
Grain milling	2.1	1.6	1.5	2.3	1.1	4.2	0.7
Edible oils	0.3	0.3	0.3	0.4	0.2	0.7	0.1
Sugar processing	0.2	0.1	0.1	0.2	0.1	0.3	0.1
Other food processing	1.0	0.8	0.7	1.1	0.5	2.0	0.3
Beverages /tobacco	0.3	0.2	0.2	0.3	0.1	0.5	0.1
Leather/footwear	0.2	0.0	0.2	0.4	0.0	0.1	0.1
Jute textiles	0.1	0.0	0.1	0.2	0.0	0.2	0.0
Yarn	1.0	0.4	1.7	1.2	0.3	0.4	0.2
Mill cloth	0.7	0.3	1.3	0.9	0.2	0.3	0.1
Other cloth	0.7	0.3	1.2	0.8	0.2	0.3	0.1
Ready-made garments	3.3	1.3	5.7	4.2	1.1	1.3	0.7
Knitwear	1.7	0.7	2.9	2.1	0.6	0.7	0.3
Other textiles	0.2	0.1	0.3	0.2	0.1	0.1	0.0
Wood & paper	1.0	1.1	1.0	1.2	0.8	0.7	0.4
Chemicals	0.6	0.2	0.1	0.1	0.0	3.5	0.0
Fertilizers	0.1	0.0	0.0	0.0	0.0	0.8	0.0
Petroleum products	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Non-metallic minerals	0.7	0.5	0.3	0.4	0.1	1.0	3.2
Metals products	0.9	0.4	1.2	1.3	0.1	0.4	0.1
Machinery	0.2	0.2	0.2	0.1	0.2	0.3	0.0
Other manufacturing	0.6	0.1	0.8	0.5	0.7	0.5	0.6
Construction	10.6	15.8	8.5	7.6	12.8	13.0	19.3
Natural gas	0.1	0.1	0.3	0.1	0.0	0.0	0.0
Electricity	1.5	0.1	3.5	1.5	0.4	0.5	0.6
Water	0.1	0.0	0.2	0.1	0.0	0.0	0.0
Private services	42.8	29.3	42.1	52.1	36.7	38.3	27.4
Retail & wholesale trade	12.7	7.7	12.2	18.3	11.4	6.9	3.2
Hotels & catering	0.5	0.2	1.7	0.1	0.2	0.4	0.1
Transport	9.4	8.1	8.6	8.7	12.1	12.1	8.2
Communications	1.2	1.4	1.9	0.9	0.4	1.4	0.8
Business & real estate	7.5	4.7	7.6	7.6	5.6	11.2	5.9
Financial services	1.9	1.7	2.6	1.9	1.6	1.6	1.7
Community services	9.6	5.5	7.4	14.6	5.5	4.7	7.5
Public and related services	7.7	5.2	7.5	8.9	9.8	5.7	5.0
Public administration	2.8	1.7	4.0	3.3	2.0	1.5	1.6
Education	2.6	2.0	2.3	2.3	5.8	2.8	1.5
Health and social work	2.2	1.4	1.2	3.2	1.9	1.5	1.9

Source: Authors' calculations using the 2005 Bangladesh SAM.

The initial task in building a SAM involves compiling data from various sources into the SAM framework. This information is drawn from national accounts, household and agricultural surveys, foreign trade statistics, government budgets, balance of payments and various other publications. This information often uses: (1) different disaggregation of sectors, production factors, and socio-economic household groups; (2) different years and/or base-year prices; and (3) different data collection and compilation techniques. Consequently, the initial or prior SAM

Table A3.5 Household factor income shares from the 2005 Bangladesh SAM

	Labour				Capital		Agriculture		All factors	Per capita income (US$)
	Illiterate	Low-skilled	Semi-skilled	High-skilled	Physical capital	Cattle	Land	Adjusted revenues*		
All households	14.8	7.8	14.4	10.0	38.6	1.8	12.6	17.4	100.0	366
Agricultural	16.6	6.9	11.3	7.5	37.9	2.5	17.3	23.8	100.0	317
Farm households	8.8	5.8	11.6	8.7	41.5	3.0	20.6	28.3	100.0	337
Marginal	24.1	11.4	14.2	4.1	30.6	4.0	11.6	18.3	100.0	160
Small-scale	9.0	6.7	11.6	7.6	41.5	3.3	20.3	28.3	100.0	331
Large-scale	0.9	1.7	10.2	12.6	46.9	2.1	25.5	33.4	100.0	796
Landless	57.5	12.8	9.5	1.0	19.2	0.0	0.0	0.0	100.0	244
Non-agricultural	15.8	10.5	21.2	14.9	37.7	0.0	0.0	0.0	100.0	526
Low-skilled	41.4	24.4	2.5	0.3	31.3	0.0	0.0	0.0	100.0	280
Semi-skilled	1.3	4.2	59.1	0.7	34.6	0.0	0.0	0.0	100.0	826
High-skilled	0.0	0.0	3.8	47.5	48.7	0.0	0.0	0.0	100.0	1672

*Adjusted agricultural revenues include labour and capital earnings from the agricultural sector as well as land returns.

Source: 2005 Bangladesh SAM. Social security payments, foreign remittance earnings and other non-factor incomes are excluded from this table.

Table A3.6 Household factor income shares from the 2005 Household Income and Expenditure Survey

	Labour wages and in-kind receipts				Non-farm enterprise revenues	Livestock product revenues	Agriculture		All factors	Per capita income (US$)
	Illiterate	Low-skilled	Semi-skilled	High-skilled			Land	Revenues		
All households	14.6	4.6	8.9	12.2	37.8	1.1	–	20.7	100.0	250
Agricultural	15.3	3.9	7.6	10.2	36.0	1.4	–	25.5	100.0	246
Farm households	6.8	3.1	7.7	11.9	38.2	1.7	–	30.7	100.0	281
Marginal	19.3	6.6	10.6	5.9	31.2	1.8	–	24.5	100.0	185
Small–scale	5.4	3.0	8.3	11.1	40.0	1.8	–	30.3	100.0	269
Large–scale	0.5	0.6	4.7	17.2	40.1	1.4	–	35.6	100.0	485
Landless	57.4	8.3	7.1	2.2	25.0	0.0	–	0.0	100.0	153
Non-agricultural	20.4	7.8	13.2	16.9	41.7	0.0	–	0.0	100.0	234
Low–skilled	40.2	14.4	2.8	0.8	41.8	0.0	–	0.0	100.0	166
Semi-skilled	1.2	2.4	46.7	1.8	48.0	0.0	–	0.0	100.0	286
High-skilled	0.0	0.0	1.1	63.5	35.4	0.0	–	0.0	100.0	644

Source: Authors' calculations using the 2005 Household Income and Expenditure Survey (Bangladesh Bureau of Statistics, 2005a). Social security payments, foreign remittance earnings and other non-factor incomes are excluded from this table. Note that household population weights differ between SAM (census-based) and the HIES.

inevitably includes imbalances between row and column account totals.

The prior macro SAM is based on national and government accounts and balance of payments. The disaggregated SAM is built so that the totals from the macro SAM are preserved (i.e. shares are used from other sources not actual numbers). This section explains how each macro SAM entry is derived and disaggregated to arrive at the prior micro SAM. Table A3.8 shows the 2005 macro SAM for Bangladesh. Each entry in the SAM is discussed below. The notation for SAM entries is (row, column) and the values are in millions of 2005 Bangladesh taka.

Factors, Activities: 3,388,539

This is the value of gross domestic product (GDP) at factor cost or alternatively, total value-added generated by labour, capital and land. Sectoral GDP is drawn from national accounts and contains information on 20 aggregate sectors (Bangladesh Bureau of Statistics, 2008b). GDP is then

Table A3.7 Household consumption

	Consumption share (%)		Population (1000s)	Per capita consumption	
	Food	Non-food		Taka per year	US$ per year
All households	41.6	56.0	137,649	21,543	335
Agricultural	40.9	57.1	99,685	20,069	312
Farm households	39.5	58.5	78,811	21,129	328
Marginal	42.4	52.8	27,971	16,876	262
Small-scale	40.6	58.8	39,567	20,708	322
Large-scale	33.7	65.1	11,274	33,158	515
Landless	47.8	49.8	20,873	16,067	250
Non-agricultural	42.9	53.9	37,965	25,414	395
Low-skilled	45.3	49.5	26,518	19,074	297
Semi-skilled	49.4	50.1	7799	35,262	548
High-skilled	26.7	71.5	3648	50,447	784

Source: Authors' calculations using the 2005 Bangladesh SAM. Per capita consumption differs from Table A3.5 due to additional income sources missing from that table (i.e. social security and foreign remittances) and additional expenditure items missing from this table (i.e. direct taxes and savings).

further disaggregated across the full 62 sectors using shares from the 2001/02 Bangladesh SAM (Arndt et al, 2002). Value-added is further divided into the returns to labour; capital and land using the 2001/02 SAM.

Labour income is split across four educational groups: 'illiterate' refers to workers without any education and living in landless agricultural households; 'low-skilled' includes workers with primary schooling or less (Class I to V); 'semi-skilled' includes workers with some secondary schooling (Class VI to IX); and 'high-skilled' includes workers who have completed secondary school or higher education (SSC/HSC and above). Workers' incomes from wage and non-farm enterprises are drawn from the 2005 Household Income and Expenditure Survey (HIES) (Bangladesh Bureau of Statistics, 2005a). Capital is split into non-livestock physical capital and livestock capital.

Each activity is then disaggregated across zilas (for agricultural sectors) or divisions (for non-agricultural sectors). Agricultural land allocation by crop and zila was taken from the 2005 Agriculture Sample Survey (ASS) (Bangladesh Bureau of Statistics, 2005b). The ASS interviewed 2.8 million households and asked them to indicate whether they cultivated any agricultural land during the 2004/05 season and to identify how much of the land was allocated to different crops. This cultivated land area information was then combined with official regional crop yield estimates for 1999/2000 (Bangladesh Bureau of Statistics, 2002) – the year for which these estimates were most available – to derive an estimate of total production in each crop and zila. This was then scaled to match the level of production and land area observed at the national level in official agricultural production data for the 2004/05 season (Bangladesh Bureau of Statistics, 2008c). Thus, in estimating agricultural production in each region, the full range of available data was employed. The land used in each agricultural activity was further disaggregated according to the land size of the farm household. The three land sizes include: (1) marginal landholders (less than 0.5 acres); (2) small-scale farmers (between 0.5 and 2.5 acres); and (3) medium- and large-scale farmers (more than 2.5 acres). The same production technology was assumed for the same crops in different zilas.

Non-agricultural GDP was disaggregated across six regional divisions based on labour and non-farm enterprise earnings reported in HIES. This assumes that the same sector in each region employs the same production technology.

Commodities, Activities: 3,558,916

This is the value of intermediate inputs used in the production process. The aggregate value is

Table A3.8 2005 macro SAM for Bangladesh (millions of Taka)

	Activities	Commodities	Factors	Households	Government	Taxes	Investment	Rest of World	Total
Activities		6,947,454							
Commodities	3,558,916			2,892,513	206,985		777,864	613,880	3,558,916
Factors	3,388,539								3,388,539
Households			3,300,422		109,625			226,043	
Government						364,169		25,837	
Taxes		243,196	49,772	71,201					
Savings				672,375	73,396			32,094	
Rest of World		859,508	38,345						
Total		6,947,454							

derived at the sector-level using GDP estimates described above. The technical coefficients used in the SAM are derived from the 2001/02 SAM (Arndt et al, 2002).

Activities, Commodities: 6,947,454

This is the value of total marketed output. Since all output is assumed to be supplied to markets, this value is equivalent to gross output, where gross output is the sum of intermediate demand and GDP at factor cost. The SAM distinguishes between regional activities and national commodities. Regional producers therefore supply their output into a national commodity (i.e. there is no explicit treatment of inter-divisional trade).

Taxes, Commodities: 243,196

While the macro SAM in Table A3.8 shows only a single row and column for taxes, this account actually consists of a number of distinct tax accounts. These include specific accounts for direct, indirect and trade taxes as reported in government accounts (International Monetary Fund, 2007). The commodity tax entry can therefore be disaggregated to include indirect sales taxes (92,752) and import tariffs (150,446). These aggregate values were taken from government accounts for 2005 (International Monetary Fund, 2007). Aggregate tax revenues were disaggregated across commodities using information on value-added tax and import tariff rates from the 2001/02 SAM (Arndt et al, 2002).

Rest of World, Commodities: 859,508

The value of total imports of goods and services was initially taken from national accounts (Bangladesh Bureau of Statistics, 2008b). Goods imports were disaggregated using 2007 foreign trade data (Bangladesh Bureau of Statistics, 2008a) and services trade from the balance of payments (International Monetary Fund, 2007).

Commodities, Households: 2,892,513

The payment from households to commodities is equal to household consumption of marketed production. The total level of private consumption is taken from national accounts (Bangladesh Bureau of Statistics, 2008a). Total private consumption was distributed across commodities and different household groups using information from HIES (Bangladesh Bureau of Statistics, 2005a). However, HIES only sampled 10,080 households out of a total population of 137 million people. The survey is thus strictly representative at the divisional level and its estimates of consumption are unreliable at the zila level. Accordingly, per capita expenditures were estimated for different household groups at the divisional level and then multiplied by zila level population estimates from the Agricultural Sample Survey (Bangladesh Bureau of Statistics, 2005b). These estimates were then scaled to match national consumption aggregates for each commodity from HIES.

Commodities, Government: 206,985

The total value of government consumption spending is taken from government accounts (International Monetary Fund, 2007) and disaggregated across commodities using information from the 2001/02 SAM (Arndt et al, 2002), adjusted for observed changes in public administration, education and health in national accounts (Bangladesh Bureau of Statistics, 2008b).

Commodities, Investment: 777,864

The aggregate value of investment demand is taken from national accounts (Bangladesh Bureau of Statistics, 2008b) and disaggregated across commodities using information from the 2001/02 SAM (Arndt et al, 2002). Note that this aggregate value includes both public and private investment.

Commodities, Rest of World: 613,880

The value of total exports of goods and services was taken from national accounts (Bangladesh Bureau of Statistics, 2008b). Goods exports were disaggregated using 2007 foreign trade data (Bangladesh Bureau of Statistics, 2008a) and services exports from the balance of payments (International Monetary Fund, 2007).

Households, Factors 3,300,422

This is the total labour value-added generated during production as well as livestock and land returns. The distribution of labour income across households is determined using household labour income shares as reported in HIES (Bangladesh Bureau of Statistics, 2005a). Land and livestock returns were based on land and stock holdings reported in the 2005 Agricultural Sample Survey (Bangladesh Bureau of Statistics, 2005b). Capital returns were distributed using non-farm enterprise earnings and returns to assets (e.g. imputed rent, interest earnings and property rents).

Taxes, Factors: 49,772

These are corporate taxes paid on the profits earned by capital. It is paid to the government and is derived from government accounts (International Monetary Fund, 2007). The same corporate tax rate is assumed across all divisions.

Rest of World, Factors: 38,345

These are remitted profits by the capital factor and are equal to the value of foreign factor payments in the balance of payments (International Monetary Fund, 2007).

Taxes, Households: 71,201

The value of direct taxes on households is equivalent to PAYE taxes and is taken from government accounts (International Monetary Fund, 2007). Tax payments are distributed across households using information on tax and deduction payments from HIES (Bangladesh Bureau of Statistics, 2005a).

Savings, Households: 672,375

This is value of domestic private savings and is calculated as a residual to balance aggregate household income and expenditure accounts when constructing the macro SAM. Household groups in the SAM are assumed to have savings rates in proportion to the share of capital earnings in total household earnings (scaled to match the macro SAM control total).

Households, Government: 109,625

This is social security and other transfers paid by the government to households. The total level of social transfers was taken from government accounts (International Monetary Fund, 2007). This was disaggregated across households using social security incomes reported by households in HIES (Bangladesh Bureau of Statistics, 2005a).

Households, Rest of World: 226,043

This is foreign workers' remittances to domestic households as reported in the balance of payments (International Monetary Fund, 2007). This was disaggregated across households using reported foreign remittance incomes in HIES (Bangladesh Bureau of Statistics, 2005a).

Government, Taxes: 364,169

The tax accounts in the micro SAM are separated into import tariffs, export taxes, sales taxes and direct taxes. Each account adds up tax revenue from all sources and then transfers these funds to the government. The entries correspond to government accounts (International Monetary Fund, 2007).

Government, Rest of World: 25,837

Government income from the rest of the world is equivalent to the value of foreign grants and official transfers in the balance of payments (International Monetary Fund, 2007).

Savings, Government: 73,396

This is value of public savings. It is the sum of the fiscal surplus (after receiving foreign grants) and the value of public investment or capital expenditure. It is equal to the fiscal surplus in government accounts (International Monetary Fund, 2007).

Savings, Rest of World: 32,094

This is the current account deficit or the total value of foreign savings. It is derived from the balance of payments (International Monetary Fund, 2007).

Balancing the Prior SAM

The range of datasets used to construct the prior micro SAM implies that there will inevitably be imbalances (i.e. row and column totals are unequal). Cross-entropy econometrics is used to reconcile SAM accounts (see Robinson et al, 2001). This approach begins with the construction of the prior SAM which, as explained in the previous section, used a variety of data from a number of sources of varying quality. This prior SAM provided the initial 'best guess' for the estimation procedure. Additional information is then brought to bear, including knowledge about aggregate values from national accounts and technology coefficients. A balanced Bangladesh SAM was then estimated by minimizing the entropy 'distance' measure between the final SAM and the initial unbalanced prior SAM, taking into account of all additional information.

Balancing procedure for the Bangladesh SAM

The balancing procedure takes places in two stages. First, a national SAM and supply-use table is constructed using primarily national accounts, government budgets and balance of payments. This was disaggregated across activities and commodities using sectoral GDP estimates from the agricultural census, HIES and previous SAMs for Bangladesh. The SAM contains aggregate entries for factors and households. This aggregate national SAM was then balanced using cross-entropy. Larger standard errors were applied to non-agricultural production estimates, since this is less recent data, and on household demand because total consumption from the household survey is 25 per cent below the aggregate figure reported in national accounts (making a shares approach to estimating commodity consumption less accurate). Smaller standard errors were imposed on agricultural production because a number of data sources, including the large sample agricultural survey, reported similar land area and production levels.

After balancing the aggregate national SAM, the SAM was disaggregated across regions, factors and households. Since the aggregate national SAM is balanced, this results in imbalances for the household accounts only. These household accounts were again balanced using cross-entropy, but holding all other non-household-related entries of the national SAM constant. Given the imbalances in the household survey between incomes and expenditures, and then the additional imbalances caused by different household factor income shares in the macro SAM, the target household income/expenditure total for the final balanced SAM was an average of the income and expenditure totals in the unbalanced prior SAM.

Cross-entropy estimation of the balanced SAM

Table A3.9 summarizes the equations defining the SAM estimation procedure. Starting from an initial estimate of the SAM, additional information is imposed in the form of constraints on the estimation. Equation 1 specifies that row sums and corresponding column sums must be equal, which is the defining characteristic for a consistent set of SAM accounts. Equation 2 specifies that sub-accounts of the SAM must equal control totals, and that these totals are assumed to be measured with error (Equation 3). An example would be the estimate of GDP provided by national accounts, which is the total value of the Factor-Activity matrix in the prior SAM. The matrix G is an aggregator matrix, with entries equal to 0 or 1. The index k is general and can include individual cells, column/row sums and any combination of cells such as macro aggregates. Equation 4 allows for the imposition of information about column coefficients in the SAM rather than cell values, also allowing for error (Equation 5).

The error specification in Equations 2 and 3 describes the errors as a weighted sum of a specified 'support set' (the V parameters). The weights (W) are probabilities to be estimated, starting from a prior on the standard error of measurement of aggregates of flows (Equation 8) or coefficients (Equation 9). The number of elements in the error support set (w) determines

Table A3.9 Cross-entropy SAM estimation equations

Index	Definition
i, j	row (i) and column (j) entries
k	set of constraints
w	set of weights
Symbol	Definition
$T_{i,j}$	SAM in values
$A_{i,j}$ and $\overline{A_{i,j}}$	SAM in column coefficients
$G_{k,i,j}$	aggregator matrix for each constraint k
γ_k and $\overline{\gamma}_k$	aggregate value for constraint k
e_k	error on each constraint k
$e^A_{i,j}$	error on each cell coefficient
W and $\overline{W}$	weights and prior on error term for each constraint k or cell coefficient i,j
$\overline{V}$	error support set indexed over w for each constraint k or cell coefficient i,j

Equations

$$\sum_i T_{i,j} = \sum_j T_{i,j} \tag{1}$$

$$\sum_i \sum_j G_{k,i,j} \cdot T_{i,j} = \gamma_k \tag{2}$$

$$\gamma_k = \overline{\gamma}_k + e_k \tag{3}$$

$$A_{i,j} = \frac{T_{i,j}}{\sum_i T_{i,j}} \quad \text{with} \quad \sum_i A_{i,j} = 1 \; \forall \, i \tag{4}$$

$$A_{i,j} = \overline{A}_{i,j} + e^A_{i,j} \ \text{ for some i, j} \tag{5}$$

$$e_k = \sum_w W_{k,w} \cdot \overline{V}_{k,w} \tag{6}$$

$$e^A_{i,j} = \sum_w W^A_{i,j,w} \cdot \overline{V}^A_{i,j,w} \tag{7}$$

$$\sum_w W_{k,w} = 1 \quad \text{with} \quad 0 \leq W_{k,w} \leq 1 \tag{8}$$

$$\sum_w W^A_{i,j,w} = 1 \quad \text{with} \quad 0 \leq W^A_{i,j,w} \leq 1 \tag{9}$$

$$\min \left[\sum_k \sum_w W_{k,w} \cdot \left(\ln W_{k,w} - \ln \overline{W}_{k,w} \right) + \sum_i \sum_j \sum_w W^A_{i,j,w} \left(\ln W^A_{i,j,w} - \ln \overline{W}^A_{i,j,w} \right) \right] \tag{10}$$

how many moments of the error distribution are estimated. The probability weights must be non-negative and sum to one (Equations 8 and 9). The objective function is the cross-entropy distance between the estimated probability weights and their prior for the errors in both coefficients and aggregates of SAM flows. It can be shown that this minimand is uniquely appropriate and that using any other minimand introduces unwarranted assumptions (or information) about the errors.

Various constraints were imposed on the model according to the perceived reliability of the Bangladesh data. Certain values that appeared in national accounts were maintained in order to remain consistent with the overall macro structure of the economy. The macro-economic aggregates that were maintained in the micro-SAM include: total labour value-added; total capital value-added; household final demand; government spending; investment demand; exports; imports; government borrowing/saving; current account balance; sales taxes; import tariffs; direct taxes on enterprises; government transfers to enterprises; enterprise transfers to the rest of the world; enterprise transfers to government; household transfers to government; government transfers to the rest of the world; and household foreign transfers received. Since the household survey (HIES) and the agricultural production and GDP estimates from national accounts were taken from data for the same year, the standard errors applied to the various components were uniform.

Notes

1 For general discussions of SAMs see Pyatt and Round (1985) and Reinert and Roland-Holst (1997); for perspectives on SAM-based modelling see Pyatt (1988) and Robinson and Roland-Holst (1988).

2 Note that 'low-skilled non-agricultural' households include both household heads who are illiterate and those who completed some level of primary schooling

3 There are differences in the interpretation of factor income sources in the SAM and survey. The SAM separates land returns from agricultural labour and capital earnings, while the HIES reports agricultural revenues after subtracting production costs (i.e. returns to all agricultural factors). Survey agricultural income shares are therefore larger than land returns in the SAM. Similarly, non-farm enterprise earnings are a form of 'mixed income'. In other words, they include both labour and capital earnings, and are therefore typically higher than capital earnings alone.

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