A Spatial Analysis of Food Security in Bangladesh based on Climate Change, Management Practices, and Socio-economic Variables

A thesis submitted to the University of Adelaide in fulfilment of the requirements for the degree of Doctor of Philosophy

IFFAT ARA

B.Sc. (Honours) and M.Sc. Geography and Environment, Jahangirnagar University

School of Biological Sciences

The University of Adelaide

April 2017

Dedication

This thesis is dedicated to my beloved parents, the late Md. Arfan Ali and Mrs. Amina Begum

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed: Date: 18th April, 2017

Abstract

Food security has become crucial in many developing countries, especially those with large populations, including Bangladesh. Future uncertainties about environmental and socio-economic changes, including climate change and the spatial variability thereof, need to be addressed. While it is well established that there are spatial differences in production, distribution and socio-economic conditions, no previous study on food security in Bangladesh has explicitly considered the spatial variability of factors that influence food security.

The main objectives of this thesis are: (1) to understand the need and potential for spatially informed policy development; (2) to assess the spatially variable climate effects on three main rice ecotypes (Aus, Aman, and Boro) in Bangladesh during 1981-2010; (3) to evaluate the combined impact of both climate and management factors on total rice yield and (4) to understand the influence of household and regional capitals on food security in the North West region of Bangladesh.

The rice yield data was collated from the Agricultural Statistical Year Book of Bangladesh for the study period of 1981-2010. The climatic and management practices database was collated from the Bangladesh Meteorological Department (BMD) and the Agricultural Statistical Year Book of Bangladesh respectively for the same time period. The present study also used the 2010 Bangladesh Household Income and Expenditure Survey (HIES) dataset from the Bangladesh Bureau of Statistics (BBS).

The results from the review of spatial aspects of food security implies the need to consider a regional food security assessment in the country (Chapter 2). The study indicated a potential way for better research and policy linkages in the country, to improve food security.

The climatic conditions of the growing period have a significant influence on rice yield across Bangladesh. Furthermore, the magnitude of the impact is ecotype-specific. This analysis indicates that any increase in temperature would decrease regional rice yield for

Aus and Aman in many districts of the country. However, regional Boro yield will derive benefit in some of the districts from increases in temperature (Chapter 3).

A more detailed analysis evaluates the relative influence of climate variability and management variables of the rice yield in Bangladesh. The total rice yield was more strongly dependent on management factors than climatic variables. Water management, through various types of irrigation, has become the most important determinant of rice yield (Chapter 4).

The key natural and management determinants were identified by the previous analysis (Chapter 3 and Chapter 4). Additional socio-economic factors were used for the subsequent analysis. Both household socio-economic assets and regional conditions were categorized as livelihood capitals in order to assess the influence of these on household calorie consumption and income. Physical and natural capitals exhibited a much greater share of explained variations in income than in calorie consumption. However, financial and human capitals are the catalysts for determining income. Diverse solutions to the livelihood outcomes will be useful in the long term in the case of the intense use of different household and regional capitals to improve food security (Chapter 5).

Overall, the findings imply that policies to improve food security need to account for regional differences. Climate change, particularly temperature increase need to be considered as important, as this will affect the regional rice yield in most of the districts in Bangladesh. In addition to climate change, the means of irrigation will also impact on rice yield. The high dependence of rice production on the available means of irrigation implies that special attention needs to be given to the optimum use of ground water in order to sustain future use. On the other hand, sustainable socio-economic development may secure food access through an increase in income and nutrition consumption. The present thesis further suggests more region-specific investigations should be undertaken in order to understand spatial responses to food security, more completely, incorporating further climatic variables, natural resources, technological improvements and infrastructural development.

Publications, awards, conference presentations, and research report arising from this thesis

Publications

Ara, I., & Ostendorf, B. 2017. Food security in Bangladesh: Understanding the need and potential for a spatially informed policy development. *South Asian Development*. (**Under review**).

Ara, I., Lewis, M., & Ostendorf, B. 2017. Understanding the spatially variable effects of climate change on rice yield for three ecotypes in Bangladesh during 1981-2010. *Advances in Agriculture*. (**Under review**).

Ara, I., Lewis, M., & Ostendorf, B. 2016. Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh. *Agriculture & Food Security*. 5(1), 1-11, doi10.1186/s40066-016-0061-9. (**Published)**.

Ara, I., Connor, J., Kandulu, J & Ostendorf, B. 2017. An econometric assessment of household calorie consumption and income in Bangladesh: a case study in the Northwest region, using a sustainable livelihood framework. *Food security*. (**Manuscript under preparation**)

Awards

International Postgraduate Research Scholarship (IPRS) 2011

Australian Postgraduate Award (APA) 2011

Graduate Scholar Award 2014 to attend Fourth International Conference on Food Studies in Italy

Participation and travel grant by CGIAR to attend Global Science conference on Climate-Smart Agriculture 2015 in France

Australia-Netherlands Water Challenge participation and travel grant 2015

Awarded training scholarship 2016 and travel grant by Technology and Innovation Centre for South-South Cooperation under the auspices of UNESCO (ISTIC), Malaysia

Conference presentations

Ara, I., Ostendorf, B. & Lewis, M. 2015. Impact of climatic variables on rice yield in Bangladesh: A spatio-temporal analysis. Global Science Conference on Climate Smart Agriculture. Le Corum, Montpellier, France.

Ara, I., J. Connor, J., & Ostendorf, B. 2014. An economic assessment of livelihood outcomes and futures for income and calorie consumption in Bangladesh households. Fourth International Conference on Food Studies. Monash University Prato Centre, Prato, Italy.

Ara, I., J. Connor, J., & Ostendorf, B. 2014. Econometric assessment on vulnerability of Northwest Bangladesh households to food security: A sustainable livelihood based analysis. International Conference on Applied Statistics. University of Dhaka. Bangladesh.

Ara, I., J. Connor, J., Ostendorf, B., & Kandulu, J. 2014. Sustainable livelihood outcome through water resource management: A case study on household character in North West region in Bangladesh. International conference on Conservation Agriculture for Smallholders in Asia and Africa. Bangladesh Agricultural University, Mymensing. Bangladesh.

Ara, I., & Ostendorf, B. 2013. Spatio-temporal Pattern of Rice Production in Bangladesh: Interaction of Climate and Management Practices. 20th International Congress on Modelling and Simulation on 'Adaptation to Change: The Multiple Roles of Modelling'. Adelaide, Australia.

Research report

Ara, I., J. Connor, J., Ostendorf, B., & Kandulu, J. 2014. Econometric assessment on livelihood outcome. In Mainuddin, M., Kirby, M., Walker, G. & Connor, J (Eds). *Sustainable Water Resources for Food Security in Bangladesh* (pp. 69-85). CSIRO Sustainable Development Investment Portfolio Project. CSIRO Land and Water Flagship, Australia.

Statement of Authorship

Chapter 2

Title of Paper	Food security in Bangladesh: Understanding the need and potential for a spatially informed policy development
Publication Status	☐ Published ☐ Accepted for Publication ✔ **Submitted for Publication** ☐ Publication Style
Publication Details	Ara, I., & Ostendorf, B. (2017). Food security in Bangladesh: Understanding the need and potential for a spatially informed policy development. Journal of South Asian Development.

Principal Author

Name of Principal Author	**Iffat Ara**		
Contribution to the Paper	Reviewing articles, interpretation of the results, manuscript preparation and revision. I hereby certify that the statement of the contribution is accurate.		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligation or contractual agreements with a third party that would constraint its inclusion in the thesis. I am the primary author of this paper.		
Overall percentage (%)	95%		
Signature		Date	14/04/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:
i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	**Bertram Ostendorf**		
Overall percentage (%)	5%		
Contribution to the Paper	Supervised writing, reviewed and edited manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14-4-17

Statement of Authorship

Chapter 3

Title	Understanding the Spatially Variable Effects of Climate Change on Rice Yield for Three Eco-types in Bangladesh During 1981-2010
Publication Status	□ Published □ Accepted for Publication ☑ **Submitted for Publication** □ Publication Style
Publication Details	Ara, I., Lewis, M., & Ostendorf, B. (2017). Understanding the spatially variable effects of climate change on rice yield for three eco-types in Bangladesh during 1981-2010. Advances in Agriculture.

Principal Author

Name of Principal Author	**Iffat Ara**		
Contribution to the Paper	Conceived the study idea, data collection, model development, model application, analysis, critical interpretation and manuscript writing. I hereby certify that the statement of the contribution is accurate.		
Overall percentage (%)	90%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligation or contractual agreements with a third party that would constraint its inclusion in the thesis. I am the primary author of this paper		
Signature		Date	14/04/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:
i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	**Megan Lewis**		
Overall percentage (%)	3%		
Contribution to the Paper	Revised the manuscript critically for important intellectual content. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	6-4-17

Name of Co-Author	**Bertram Ostendorf**		
Overall percentage (%)	7%		
Contribution to the Paper	Supervised development of model, data analysis, reviewed and edited manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14-4-17

Statement of Authorship

Chapter 4

Title of Paper	Spatio-temporal Analysis of the Impact of Climate, Cropping Intensity and Means of Irrigation: An Assessment on Rice Yield Determinants in Bangladesh
Publication Status	☑ **Published** ☐ Accepted for Publication ☐ Submitted for Publication ☐ Publication Style
Publication Details	Ara, I., Lewis, M., & Ostendorf, B. (2016). Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh. Agriculture & Food Security. 5(1), 1-11, doi10.1186/s40066-016-0061-9.

Principal Author

Name of Principal Author	**Iffat Ara**		
Contribution to the Paper	Conceived the study idea, data collection, model development, model application, analysis, critical interpretation and manuscript writing. I hereby certify that the statement of the contribution is accurate.		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligation or contractual agreements with a third party that would constraint its inclusion in the thesis. I am the primary author of this paper.		
Overall percentage (%)	90%		
Signature		Date	14/04/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:
i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. Permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	**Megan Lewis**		
Overall percentage (%)	3%		
Contribution to the Paper	Revised the manuscript critically for important intellectual content. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	6.4.17

Name of Co-Author	**Bertram Ostendorf**		
Overall percentage (%)	7%		
Contribution to the Paper	Supervised development of model, data analysis and interpretation, reviewed and edited manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14-4-17

Statement of Authorship

Chapter 5

Title of Paper	An Econometric Assessment of Household Calorie Consumption and Income in Bangladesh: a Case Study in the Northwest Region, Using a Sustainable Livelihood Framework
Publication Status	□ Published □ Accepted for Publication □ Submitted for Publication ✓Publication Style
Publication Details	Ara, I., Connor, J., Kandulu, J & Ostendorf, B. (2017). An econometric assessment of household calorie consumption and income in Bangladesh: a case study in the Northwest region, using a sustainable livelihood framework.

Principal Author

Name of Principal Author	**Iffat Ara**		
Contribution to the Paper	Conceived the study idea, data development, performed analysis, critical interpretation and manuscript writing. I hereby certify that the statement of the contribution is accurate.		
Overall percentage (%)	85%		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligation or contractual agreements with a third party that would constraint its inclusion in the thesis. I am the primary author of this paper.		
Signature		Date	14/04/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:
i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. Permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	**Jeff Connor**		
Overall percentage (%)	5%		
Contribution to the Paper	Supervised writing, reviewed and edited manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14/04/2017

Name of Co-Author	**John Kandulu**		
Overall percentage (%)	5%		
Contribution to the Paper	Contributed in data development and analysis. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14/04/17

Name of Co-Author	**Bertram Ostendorf**		
Overall percentage (%)	5%		
Contribution to the Paper	Revised the manuscript critically for important intellectual content. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14-4-17

Acknowledgements

Very special thanks are offered here to all who have been a great source of inspiration and motivation throughout this long Ph.D. journey for a Ph.D. Firstly, I would like to thank my highly specialized supervision team consisting of Professor Bertram Ostendorf (University of Adelaide), Professor Megan Lewis (University of Adelaide) and Dr Jeffery Connor (CSIRO) for their continuous guidance and support, which went beyond my expectations. Their long-held expertise and experience have been vital sources of intellectual discussion for the development of this thesis, and I am grateful for having had the opportunity to work with all of them.

I appreciate the experience I have gained through these discussions, the companionship and valuable comments from all the members of Spatial Information Group (SIG) at the University of Adelaide: Ken, Ramesh, Adam, Tori, Erica, Dor, Davina, Chitana and Gheneddey. My special thanks go to Gregory Lyle for his critical guidance in the initial stages of the research proposal. I would also like to thank Sofinat Girma Araya, one of my beautiful colleague in the SIG group, for the time that she has spent with me in discussing different aspects of my research and sharing ideas.

I was also fortunate to be guided by the highly accomplished Postgraduate Coordinator for Biological Sciences, Dr Robert Reid. My sincere thanks go to the Integrated Bridging Program (IBP) Lecturer, Richard Warner for his useful notes on the early draft of my Ph.D. proposal. My heartiest acknowledgment shall always be for Dr Margaret Cargill for her proofreading of some of my manuscripts. Special acknowledgment also goes to Ingrid Ahmer and Alison-Jane Hunter, the University of Adelaide, for providing necessary English language editing for this thesis and manuscripts.

Apart from the University of Adelaide, I must mention the Commonwealth Government of Australia and Jahangirnagar University for providing funds and administrative support respectively for the successful completion of this study. I am also grateful to the CSIRO, Land and Water and Water for a Healthy Country National Research Flagship for providing their support. I feel deep gratitude to all of these organizations.

I would like to thank the Bangladesh Meteorology Department (BMD) and the Bangladesh Bureau of Statistics (BBS) for providing me with the necessary data officially. I am grateful to my young colleagues at Jahangirnagar University, namely Rezaul Rony, Mehedi Iqbal and Jahirul Islam for their help, particularly for developing the climate database for my thesis.

I will always remember Professor Maudood Elahi at Stamford University, Bangladesh, who has been the key motivator of this Ph.D. on food security in Bangladesh. I am also thankful to Professor Shahed Rashid and Professor Bashir Ahmed of Jahangirnagar University for their continued cooperation and support throughout the process. I am also thankful to all of my other respected teachers and colleagues at the Department of Geography and the Environment, Jahangirnagar University, Savar, Dhaka, Bangladesh.

My heartiest thanks go to all of my lovely friends in Adelaide for being there for me and for their care during the period of my study. All of their support shall always be remembered.

Finally, I would like to thank my mother, siblings, and relatives for their great love and affection, which has always been a source of inspiration and support for me, enabling me to come to this point in my life.

Iffat Ara

April 2017

Contents

Alphabetic list of abbreviations

ADF	Augmented Dickey-Fullar
AIC	Akaike Information Criterion
BARC	Bangladesh Agriculture Research Council
BBS	Bangladesh Bureau of Statistics
BCA	Bangladesh Country Almanac
BCCSAP	Bangladesh Climate Change Strategy and Action Plan
BDHS	Bangladesh Demographic and Health Survey
BMD	Bangladesh Meteorological Department
BMDA	The Barind Multipurpose Development Authority
BNNC	Bangladesh National Nutrition Council
BR14	Boro Rice Variety 14
BR3	Boro Rice Variety 3
CCCM	Climate and Carbon Cycle Modelling
CEGIS	Centre for Environmental & Geographic Information Services
CERES	Simulation Models Crop Environment Resource Synthesis
DEM	Digital Elevation Model
DFID	Department for International Development
DISSAT	Decision Support System for Agro-technology Transfer
DMIC	Disaster Incidence Database of Bangladesh
DSSAT	Decision Support System for Agro-technology Transfer
DTW	Deep Tube Wells
FAO	Food and Agriculture Organization
FGLS	Feasible Generalized Least Square
FPMU	Food Planning and Monitoring Unit
GCM	General Circulation Model
GDP	Gross Domestic Product
GFDL	Geophysical Fluid Dynamic Laboratory
GFDL-TR	Geophysical Fluid Dynamics Laboratory Transient
GLM	Generalized Linear Model
GIS	Geographic Information System
GoB	Government of Bangladesh
HadCM2	Hadley Centre during 1995 and 1996 using the Second Version of the United Kingdom Meteorology Office's Unified Model
HIES	Household Income and Expenditure Survey

HYV	High Yielding Varieties
IPCC	Intergovernmental Panel on Climate Change
IRRI	International Rice Research Institution
LGED	Local Government Engineering Department
LMM	Linear Mixed Model
LSDVM	Least Square Dummy Variable Model
MoA	Ministry of Agriculture
MoEF	Ministry of Environment and Forest
MoFDM	Ministry of Food and Disaster Management
MoHFW	Ministry of Health and Family Welfare and Bangladesh National Nutrition Council
NAPA	National Adaptation Programme of Action
NFPCSP	National Food Policy Capacity Strengthening Programme
OLS	Ordinary Least square
PFDS	Public Food Distribution System
PRECIS	Providing Regional Climates for Impacts Studies
SRDI	Soil Research Development Institute
STW	Shallow Tube Wells
UKTR	UK Meteorological Office/Hadley Centre Transient with respect to the base year of 1990
UNICEF	United Nations Children's Fund
VIF	Variance Inflation Factor
VME	Vulnerability Mapping Exercise
WARPO	Water Resources Planning Organization
WFP	World Food Program
WHO	World Health Organization

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

1.1.1 Research background

Food security is of global concern. It is necessary to ensure that there is sufficient food for the entire world. Food security has become a crucial issue in many developing countries, especially those with large populations, including Bangladesh. Bangladesh is the tenth most populous country in the world, with 152 million people counted in the last population census in 2011 (BBS 2011). The country has already 60 million undernourished people (WFP 2016). Although Bangladesh has made substantial achievements in food production, especially rice production, there is evidence that the establishment of food security is still facing numerous challenges (Habiba et al. 2015). Both current and future uncertainties of natural and socio-economic changes and the spatial variability of these changes need to be investigated. While it is well established that there are spatial differences in food production, food distribution and social-economic conditions across the country (GoB and WFP 2004), no previous study on food security in Bangladesh has explicitly considered the spatial variability of factors that influence food security there. The present thesis initiates the first step in understanding spatial aspects of food security in Bangladesh and identifies food security determinants at the regional level in order to examine the food security conditions currently extant in order to extrapolate needs into the future for planning purposes.

Climate change is likely to impact food security globally (Parry et al. 1999; Rosenzweig and Parry 1994; Deryng et al. 2011; Iizumi and Ramankutty 2015; Simelton et al. 2012) and in particular, add significant pressure to feeding the large population of Bangladesh (Faisal and Parveen 2004). Several studies have shown potential adverse effects of climate change on agricultural production in Bangladesh (Karim et al. 1996; Sarker et al. 2012; Ruane et al. 2013; Basak and Alam 2013; Rimi et al. 2009; Amin et al. 2015; Sarker et al. 2014). Outside Bangladesh, further evidence from regional climate change impact assessments has identified that in South Asia, agricultural production in a tropical climate was the most vulnerable for food security (Douglas 2009; Tiwari and Joshi 2012; Qin et al. 2013; John and Fielding 2014). These studies have specific relevance to regional food production in Bangladesh, which is also typified by a tropical climate. Several studies have shown climate-yield relationships from empirical evidence in Bangladesh from time series analysis of past records (Sarker et al. 2012; Amin et al. 2015). Prior studies using crop models based on climate change scenarios have predicted the adverse effects of climate change on rice production/rice yield for the three main ecotypes (Aus, Aman, and Boro) (Karim et al. 1996; Basak et al. 2010; Ruane et al. 2013; Rimi et al. 2009; Mahmood et al. 2003). However, the results of these studies do not adequately characterize regional rice production/yield changes due to climatic variables. Some regional assessment of climate change on rice yield has been done, but only for broad climatic and agro-ecological zones (Sarker et al. 2014; Ruane et al. 2013) and so the spatial scales considered in these studies limit the applicability of the results in devising necessary actions for more detailed district-specific adaptation measures.

Management practices, particularly land and water management are also major issues for food security worldwide (Iizumi and Ramankutty 2015; Omoyo et al. 2015; Qin et al. 2013; Li et al. 2011; Bogale 2012; Deryng et al. 2011). In Bangladesh, water management through irrigation has shown a positive contribution in increasing food production (Rahman and Parvin 2009). In particular, groundwater irrigation has led to an increase in rice production in Bangladesh (Ahmad et al. 2014; Rahman and Mahbub 2012). Land management has also a large impact on food security. It is estimated that 1% of the agricultural land will be lost every year due to settlement and other industrial/non-agricultural purposes (Mainuddin et al. 2015). The most promising option for maximum land utilization for agriculture appears to be multiple harvests on the same land, however, there has been no quantitative assessment of the impact of crop production due to cropping intensity in the different districts of Bangladesh. Moreover, the spatial differences of water and land management in various districts may influence food production, hence regional capabilities may face challenges to produce enough food in the future. The available literature has focused on the impact of irrigation and land management on crop production at the national level only, with no regional contexts examined in specific detail. (Mainuddin and Kirby 2015; Parvin and Wakilur 2009; Rahman and Mondal 2015). However, a spatio-temporal assessment is also needed to understand the regional impact of management practices on food security.

Besides climate and management practices, socio-economic conditions also influence food security. The existing literature shows the substantial impact of socio-economic conditions on food security globally (Simelton et al. 2012; Mabiso et al. 2014; Tiwari and Joshi 2012). Likewise, socio-economic conditions play a vital role in Bangladesh's food security (Bose and Dey 2007; Faridi and Wadood 2010; Pitt 1983; Hels et al. 2003; Rahman and Islam 2014). This situation has been reflected in the aims of many household level food security studies, which have investigated the likely impact of socio-economic conditions on food security (Faridi and Wadood 2010; Frongillo et al. 2003; Lewis 1993; Coates et al. 2010; Anik et al. 2013). Although these studies provide some ways to understand the extent of socio-economic impacts on food security at household level, they do not explain the impact of regional heterogeneity of socio-economic conditions on food security across Bangladesh. Therefore, it is important to address the impact of spatially variable socio-economic conditions on food security in the country.

The spatio-temporal variations of climate, management practices and socio-economic variables and the influences of these variations on food security, as stated above, should contribute to the development of food policies in Bangladesh. The current food policy in Bangladesh does not address these important regional details (MoFDM 2006). Most studies on food security in Bangladesh have been non-spatial and failed to assess the impact of spatially variable determinants on food security (Mainuddin et al. 2015; Parvin and Ahsan 2013; Bose and Dey 2007; Faridi and Wadood 2010). GoB and WFP (2004) provided an atlas of thematic maps on food security determinants to understand their regional variations, however, the methodology used was a simple mapping index based on the 2001 Population and Housing Census data and the atlas has not been updated. Furthermore, the study did not consider many important factors affecting food security in the country (e.g. agricultural management and climatic variables). Over the past few years, policymakers have mostly depended on national level data to formulate food policies. Although spatial data on food security is available, the spatial aspect of food security analysis is rarely considered in Bangladesh to improve food policy. There is an urgent need for spatial analysis of food security in the country to fill the gap. The present thesis focuses on the regional context of food security by analyzing spatio-temporal data on climatic variables, management practices, and socio-economic conditions in order to understand the potential impacts of these elements on food security. Finally, the results of the present thesis will contribute to improving food policy in Bangladesh in relation to these aspects. The thesis focuses on the following questions to address the spatial aspects of food security in the country:

(1) What are the existing conditions of food security in Bangladesh and what spatial determinants and national data sources should be used in food security assessment?

(2) How does climate impact on the regional rice yield for the three main ecotypes (Aus, Aman, and Boro)?

(3) How do both climate and management practices regionally combine to influence total rice yield?

4) How does access to household socio-economic assets and regional conditions affect food security in Bangladesh?

1.1.2 Research aim and objectives

The main aim of the thesis is to analyze the impact of spatio-temporal variations of climatic variables, management practices and socio-economic conditions on food security in Bangladesh. The specific objectives are: (1) to review the literature in order to understand the need and potential for a spatially informed food security policy based on available national data sources; (2) to understand the spatially variable impacts of climate on rice yield for the three main rice ecotypes (Aus, Aman, and Boro) across Bangladesh; (3) to evaluate the combined impact of both climate and management factors on total rice yield; (4) to assess the influence of household socio-economic assets and regional conditions on income and nutrition consumption in the North West region of Bangladesh, as a case study.

The analysis presented in this thesis uses spatio-temporal data from government statistics on total rice yield, rice yield for each ecotype, climatic variables (rainfall and temperature), and management practices variables (cropping intensity, types of irrigation) to assess food security in Bangladesh. In addition, the thesis used the Household Income and Expenditure Survey (HIES) 2010 dataset to understand the impact of various socio-economic conditions on food security.

1.1.3 Thesis structure

This thesis is composed of six chapters. Most of the chapters contained here have either been published or submitted to peer-reviewed journals for publication.

The thesis begins with a general introduction and overview of the need for and motivation behind this research and an outline of the composition of the thesis. Chapter 1 also includes a review of the background literature relating to food security, both globally and nationally. The literature review starts with the concepts of food security, highlighting food security analysis relating to climate change and management variables. It then describes regional food security assessments and considers the prospects of using regional data in assessing food security. A brief discussion of the methodological aspects of regional food security assessments suggests possible applications in the case of Bangladeshi food security assessments. Finally, the literature review focuses on possible food security research-policy linkages in the country by incorporating the regional variability of different food security determinants to improve national food policy. In addition to this chapter, a detailed review of the relevant literature is also presented at the start of each individual chapter of this thesis.

Chapter 2 briefly outlines the spatial aspect of food security and food security conditions in Bangladesh, including food availability, food accessibility, and food utilization. The chapter describes the potential geographic impact of climate change on food security and then identifies the national data sources on food security in the country. The chapter ends with a description of a way forward for regional food security assessment that can potentially contribute to developing a spatially-informed food policy in the country. This chapter has been submitted to the *Journal of South Asian Development* as a paper, entitled "Food security in Bangladesh: understanding the need and potential for spatially informed policy development".

Chapter 3 assesses the spatially variable climate effects on rice yield for the three main ecotypes (Aus, Aman, and Boro) in different rice growing seasons across Bangladesh using regression analyses. The models elucidate how seasonal average temperature and rainfall influence regional rice yield at the greater district level. The models further predict rice yield changes due to an overall increase of 1°C temperature in the future in these districts.

The major conclusion from Chapter 3 was presented as a conference poster titled: "Impact of climatic variables on rice yield in Bangladesh: a spatio-temporal analysis" at the Global Science Conference on Climate-Smart Agriculture, March 2015, in Le Corum, Montpellier, France. This chapter has been submitted to the *Journal of Advances in Agriculture* as a paper titled "Understanding the spatially variable effects of climate change on rice yield for three ecotypes across Bangladesh during 1981-2010".

Chapter 4 considers the question: to what extent do both climate and management factors affect total rice yield? The use of the Liner Mixed Model indicates that, overall, management factors appear to have a stronger effect on total rice yield in Bangladesh than climatic variables. The major findings from Chapter 4 were presented as a conference presentation titled: "Spatio-temporal patterns of rice production in Bangladesh: the interaction of climate and management practices" at MODSIM 2013: the 20th International Congress on Modelling and Simulation on 'Adaptation to Change: The Multiple Roles of Modelling', December 2013, Adelaide. This chapter was published on 19 July 2016 in the *Journal of Agriculture and Food Security*, as "Ara, I., Lewis, M., & Ostendorf, B. (2016). Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment of rice yield determinants in Bangladesh. Agriculture & Food Security. 5(1), 1-11, doi10.1186/s40066-016-0061-9".

Chapter 5 focuses on household socio-economic assets and regional conditions as livelihood capitals to assess the influence of these on household food security. The analysis was located in the North West region of Bangladesh to understand the influence of livelihood options on income and nutrition consumption as a means of food security. The methodological aspects of Chapter 5 were presented at a conference titled "An econometric assessment of livelihood outcomes and futures for income and calorie consumption in Bangladeshi households" at the Fourth International Conference on Food Studies, October 2014, Prato, Italy. This chapter was published on 10 November 2014 in the report *Sustainable Water Resources for Food Security in Bangladesh*, as "Ara, I., Connor, J., Ostendorf, B., & Kandulu, J. 2014. Econometric assessment on livelihood outcome. In Mainuddin, M., Kirby, M., Walker, G. & Connor, J. (Eds). Sustainable Water Resources for Food Security in Bangladesh (pp. 69-85). CSIRO Sustainable Development Investment Portfolio Project. CSIRO Land and Water Flagship, Australia".

Finally, Chapter 6 reviews the findings of the present thesis and the extent to which the aims have been achieved. The thesis ends with some recommendations to improve food policy in Bangladesh and identifies important areas for future research based on the outcomes of the present thesis.

1.2 Literature overview

This literature review highlights the published knowledge which surrounds this thesis and informs the reader of current issues relating to food security and food security assessment regionally. Only a broad overview is given in this chapter, as specific literature reviews are included in the relevant chapters of this thesis.

1.2.1 Conceptualizing of food security

The term food security has been expressed in many ways. Although Smith et al. (1993) counted about two hundred and five definitions of food security, the present study uses the definition given by the Food and Agriculture Organization (FAO 1996), which has achieved wide global acceptance: 'Food security exists when all people, at all times, have physical, [social] and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life'. The term *social* was added to the 1996 definition in 2002. The World Food Program (WFP) offers another useful definition: 'Food security is a condition that exists when all people, at all times, are free from hunger' (WFP 2002).

The history of food security was reviewed by Simon (2012). Food Security was originally perceived and defined as the availability of an adequate food supply at all times to feed the world population. This definition was expanded in 1981 by Sen's (1981) 'entitlements approach', which indicated that sufficient food production or food availability was not the only element of food security. Low food security can result from an individual's lack of ability to access enough food because of poor socio-economic conditions or having inadequate food distribution in a place. The access dimension of food security, as highlighted by Sen in 1981, was formally recognized in 1996 and put into practice by food security practitioners only after 2005 (Simon 2012).

Since then, the analysis of food security has broadened to include other issues. For instance, several studies indicate the importance of livelihood choices on food security (Hesselberg and Yaro 2006; Mumuni and Oladele 2016). People’s adaptations in the face of natural disasters and climate change have also become a focus of attention in assessing food security (Atkins 2009; Burke and Lobell 2010). More recently a human development and capabilities approach was included in advancing food security analysis (Burchi and De Muro 2015).

Food security comprises of three main components: food availability, food access and food utilization. These components have been defined individually by the FAO (2006). Food availability is the sufficiency of food that is supplied through domestic production or imports (including food aid). Food access is the economic, social, political and legal rights of individuals to adequate resources for obtaining sufficient food for a nutritious diet. Food utilization is the nutritional wellbeing of a person that comes from adequate food consumption from a diversity of food sources, proper food storage, and processing, including clean water and a healthy environment.

When defining and shaping future food security for a country, many issues need to be considered, such as future population expansion, nutritional changes and preferences, scientific innovations, policies, global economic development and the regional distribution of energy demands, as well as regional impacts of climate changes (Roetter and Keulen 2007).

1.2.2 Food security, climate change, and management variables

The impacts of climate change and other variables on food security are global concerns. Globally, agricultural regions have a varying risk of vulnerability to climate change (Deryng et al. 2014; Iizumi et al. 2010). South Asian agriculture, including Bangladesh, is highly susceptible to low food production due to climate change, natural and socio-economic variables (Tiwari and Joshi 2012; John and Fielding 2014; Douglas 2009). Rice is grown extensively over almost all of Bangladesh in three climatic seasons. A spatially variable impact assessment is necessary for Bangladesh in relation to both climate change and other variables.

Several studies assess climate impact on food production, especially rice production, in Bangladesh (Karim et al. 1996; Sarker et al. 2012; Ruane et al. 2013; Amin et al. 2015).

Simulation studies in Bangladesh predict the decrease in potential rice yields for different ecotypes from the various climate change scenarios (Karim et al. 1996; Basak et al. 2010; Ruane et al. 2013; Rimi et al. 2009; Mahmood et al. 2003). In contrast, empirical studies suggest varied responses for rice yields for these ecotypes from the historical evidence of climate variability (Sarker et al. 2012; Amin et al. 2015; Sarker et al.. 2014). Some studies also analyse the regional variations of climate change impact on rice yields using broad climatic and agro-ecological zones (Sarker et al. 2012; Ruane et al. 2013), however, this scale is too broad to understand the regional impact at district level. Both the National Adaptation Programme of Action (NAPA) and the Bangladesh Climate Change Strategy and Action Plan (BCSSAP) indicate the need for regional impact assessments to target appropriate adaptation measures in the different districts, however current studies are not adequate to understand such regional impacts.

Management variables also influence rice production in Bangladesh. Existing non-spatial studies have shown the impact of water and land management on crop production (Mainuddin and Kirby 2015; Parvin and Wakilur 2009; Rahman and Mondal 2015), but without considering the climate conditions. There is a need for studies that consider regional variations of both climate change and management conditions in order to understand the combined impact of these on rice yield in Bangladesh.

1.2.3 Regional food security assessment

There have been many global studies which have assessed regional food security. These have principally focused on regional agricultural productivity through various modelling approaches, such as crop models (Lobell and Field 2007; Parry et al. 2004; Deryng et al. 2011; Matthews et al. 2013) and empirical assessments (Demeke et al. 2011; Rowhani et al. 2011; Qin et al. 2013; Shi and Tao 2014). Recent analyses are now emphasizing the combined impact of both climate and other variables on food security for different countries (Iizumi and Ramankutty 2015; Omoyo et al. 2015; Qin et al. 2013; Li et al. 2011; Bogale 2012; Deryng et al. 2011), however this type of analysis has not been previously done in case of Bangladeshi food security assessment.

Many international studies have focused on socio-economic determinants for food security assessments (Demeke et al. 2011; Wang 2010; Qi et al. 2013; Sietz et al. 2012; Oluoko-Odingo

2011; Langyintuo and Mungoma 2008). Studies using the livelihood approach have also included a wide range of both natural and socio-economic determinants and indicated the adaptation desires and livelihood choices for improved regional food security (Hesselberg and Yaro 2006; Mumuni and Oladele 2016). The use of regional variations in socio-economic conditions is often overlooked in Bangladesh and needs to be considered for further assessment.

Regional food security assessment relies on spatial data availability. Spatio-temporal data on food security is needed to link food security determinants over space and time (O'Brien et al. 2004). However, major food security studies in Bangladesh have not used spatio-temporal data to understanding the spatio-temporal extent of food security (Mainuddin et al. 2015; G. A. Parvin and Ahsan 2013; Bose and Dey 2007; Faridi and Wadood 2010). Progress has been made in methodology development for regional food security assessment by including new spatial data sources and database management. Managing regional food security data, understanding the regional variation of food security determinants, and then incorporating the regional hereteogenity of these determinants on food security are now the key areas for food security assessment in Bangladesh.

National data sources, including census and survey data, are the most reliable data sources on food security in Bangladesh. Previous food security studies have used these data, considering the temporal trend only, without the spatial extent (Mainuddin et al. 2015; Parvin and Ahsan 2013; Bose and Dey 2007; Faridi and Wadood 2010). A number of challenges are found for developing regional time series using national data sources. The national surveys do not use the same indicator in every survey year, making it difficult to understand the changes in different food security determinants over time and space. The creation of new geographical boundaries for administrative units causes difficulties in linking recent census data to the previous data (23 greater districts and 64 districts were considered for the 1981 and 1991 Population and Housing Census, respectively). It is necessary to give careful attention to regional data availability including the spatial and temporal compatibility to delimit geographic scale for regional food security assessment in Bangladesh. For this, the present thesis uses spatio-temporal data at the greater district level to analyse food security across Bangladesh during 1981-2010.

1.2.4 *Methodological aspects of regional food security assessment*

Various forms of quantitative studies have been used in food security studies globally. For instance, statistical analysis was performed in many studies to understand the regional impact of climate change (Shi and Tao 2014; Qin et al. 2013; Rowhani et al. 2011; Lobell et al. 2007) and other variables (Demeke et al. 2011; Wang 2010; Qi et al. 2013; Sietz et al. 2012; Oluoko-Odingo 2011; Langyintuo and Mungoma 2008). The use of statistical modelling provides a perfect opportunity to understand the magnitude of the impact of different food security determinants from the past records. In Bangladesh, statistical analyses of temporal data on food production have been used to evaluate their impact on food production due to climate change and other variables (Sarker et al. 2012; Sarker et al. 2014; Amin et al. 2015; Mainuddin and Kirby 2015; Parvin and Wakilur 2009). Several studies focus on socioeconomic consequences of food access at a household level in Bangladesh (Bose and Dey 2007; Faridi and Wadood 2010; Coates et al. 2010; Lewis 1993; Hels et al. 2003). These studies overlooked the paradigm of spatially and temporarily variable food security contexts in the country and so are not adequate to understand the spatially variable impacts on food security. The present thesis contributes to a quantitative food security analysis including the spatio-temporal variability of food security determinants across Bangladesh.

Applied statistical procedures were used to quantify the spatial variability of crop production through regression analysis for climatic and other variables (Shi and Tao 2014; Qin et al. 2013; Rowhani et al. 2011; Lobell et al. 2007). Many studies assessed the crop-climate yield relationship alone though regression (Shi and Tao 2014; Tao et al. 2008; Joshi et al. 2011). Lobell and Field (2007) performed a statistical analysis to understand the likely impact of climate change on a range of crops by using past production data. Rowhani et al. (2011) used a Linear Mix Model (LMM) to assess the impact of seasonal climate variability on crop yield in Tanzania. This study showed the significance of the use of regional variability in crop production assessment. Ordinary Least Square (OLS), median regression (Sarker et al. 2012) and Feasible Generalized Least Square (FGLS) regression (Amin et al. 2015) analyses were used in previous studies in Bangladesh, but without considering regional variability. Hence, the results of these studies may not adequately signify the actual impact of the climatic variables used in these studies. Although Sarker et al. (2012) applied a Least Square Dummy Variable Model (LSDVM) to assess the regional climate change impact on different rice-ecotypes at the level of broad agro-climatic zones, the regional scale was too broad to understand the regional impact of climate change on rice production.

The socio-economic consequences of food security have been assessed through statistical techniques in Bangladesh, including linear regression (Faridi and Wadood 2010), logistic fixed effect model (Hillbruner and Egan 2008) and mixed model (Hels et al. 2003). Recently, Bashir and Schilizzi (2015) analyzed socio-economic consequences on regional food security in Pakistan by using LSDVM. Further, Bryan et al. (2015) also used the same method to understand regional food security and climate change vulnerability in Australia. However, the regional variation of socio-economic conditions was not considered in the Bangladeshi food security studies mentioned above. The present study further contributes knowledge in this area by using regional variation in the statistical analysis.

1.2.5 *Regional food security assessment and food policy development in Bangladesh*

Bangladesh has initiated policies and actions to improve food security in the past (MoFDM 2006, 2008a, 2008b). The country has achieved self-sufficiency in rice production due to increases in production. However, food security analysis in Bangladesh, as in many other countries, now shows that sufficient food availability does not ensure adequate food consumption. The food security challenge mainly depends on meeting individual food requirements by overcoming problems of inadequate food access and proper food utilization. Natural and socio-economic conditions vary regionally in Bangladesh (GoB and WFP 2004). Therefore, it is possible that these conditions may impact on regional food security to meet individual food requirements. At this point, food policy in Bangladesh and investments in improving food security need to consider the spatio-temporal changes of these conditions across Bangladesh. At present, there are no regional details in the food policy. Thus, NAPA and BCCSAP are unable to initiate necessary adaptation measures at district level due to inadequate knowledge of regional climate change impacts on food production (MoEF 2005 2009). Previous food security studies are not adequate to understand the regional aspect of food security (Bose and Dey 2007; Faridi and Wadood 2010; Pitt 1983; Hels et al. 2003; Rahman and Islam 2014; Rahman and Parvin 2009; Mainuddin and Kirby 2015). Moreover, none of the previous policies (MoFDM 2006; MoEF

2005; MoFDM 2008a) and action plans (MoFDM 2008b, 2010; MoEF 2009) in Bangladesh has provided sufficient regional detail on food security to devise local actions, showing a lack of research-policy linkage in the country. Knowledge of the regional variability of food security determinants has the potential to lead to significant long-term food policy development (Barrett 2002). Likewise, this knowledge will contribute to regional natural resources management, as well as to regional climate change adpatation measures. The present thesis helps in improving food policy in Bangladesh by analysing food security determinants, including the regional variations of climatic variables, management practices and socio-economic conditions.

Chapter 2

Food security in Bangladesh: Understanding the need and potential for spatially informed policy development*

Abstract

Food security in Bangladesh primarily depends on three components (food availability, food access, and food utilization). Regional variations of these components may affect food security via spatial differences in environmental, social, or economic factors. This article provides an overview of food security in Bangladesh in terms of the three main components. The study identifies knowledge gaps in present food security research and highlights both the need and potential for spatially informed policy development. The study indicates a way forward for such a policy development including region-specific deficits, climate change, other future risks, and actions for each food security component in order to improve food security in the country.

* This chapter is based on:

Ara, I., & Ostendorf, B. 2017. *Under review after submission*. Food security in Bangladesh: Understanding the need and potential for a spatially informed policy development. *South Asian Development*.

2.1 Introduction

Food security is a complex and important global issue that is affected by interacting natural factors and human actions (Simelton et al. 2012; Tiwari and Joshi 2012). Many natural variables, including climate change, may influence food production, while socio-economic variables are mostly responsible for food access in a country (Burke and Lobell 2010; Harvey and Pilgrim 2011). One most recent estimate identifies about 795 million undernourished people in the world, with one-third of these people living in South Asia, including Bangladesh (FAO 2015). Bangladesh is facing challenges in attaining and maintaining food security because of its large population, numbering 152 million at the last population census from 2011 (BBS 2011a). In addition, numerous drivers including poverty (Kam et al., 2005), malnutrition (Bose and Dey 2007; Hossain et al. 2005), frequent disasters (Mirza 2002; Ninno and Lundberg 2005), agricultural management practices (Ara et al. 2016) and the effect of climate change (Karim et al. 1996; Sarker et al. 2012; Ruane et al. 2013) influence food security across the country (Habiba et al. 2015a).

According to the Food and Agricultural Organization (FAO), a country achieves food security when it ensures adequate food along with a nutritious diet for the entire population (FAO 2006). Thus, the concept of food security indicates a situation in a particular place and time where people live without hunger or fear of undernourishment. Food security is constituted by the three components of food availability, food access and food utilization (FAO 2006). Until 1980, food availability was seen as the key component to ensure food security in Bangladesh and the government prioritized food production to overcome food shortages (Elahi and Ara 2008). However, Sen's (1981) analysis clearly indicates that food availability is not the only component of food security in the country. Low food security can result from an individual's lack of ability to access enough food because of poor socio-economic conditions or inadequate food distribution in a place. All food security components are now considered as important in existing food policies in Bangladesh (MoFDM 2006; Ahmed 2015).

Globally, several studies have analysed the food security components individually, leading to improved food policies in their respective countries (Ray 2007; Rocha 2009; Bashir and Schilizzi 2015). Similarly, in Bangladesh food security has been analysed in terms of food availability (Mainuddin and Kirby 2015; Parvin and Wakilur 2009), food access (Hossain et al. 2005; Thorne-Lyman et al. 2010, Bose and Dey 2007; Faridi and Wadood 2010) and food utilization (Pitt 1983; Hels et al. 2003; Rahman and Islam 2014). Whilst these findings successfully inform food policy, the full complexity of food security cannot be understood and addressed effectively by using the components individually for a better policy (Pinstrup-Andersen 2009). Some assessments (Mainuddin and Kirby 2015; Parvin and Wakilur 2009) have considered the temporal dimension of food security in Bangladesh, but the spatial aspects of food security have mostly been overlooked. Spatial patterns of food security including these components have received attention from food security scholars globally (Belesky 2014; Ray 2007; Iizumi et al. 2013). However, existing food security studies for Bangladesh are not adequately addressing the spatio-temporal dynamics of food security components in the country. To strengthen food security research in Bangladesh, spatial analysis is required to assess all the components of food security.

Diverse regional conditions affect food security, but these have received insufficient attention in terms of both research and food policy in Bangladesh. Food production varies due to natural conditions (including climate change) and socio-economic conditions (Faisal and Parveen 2004). Climate change may affect food production in a spatial manner in Bangladesh (MoEF 2005; 2009). Many studies have principally focused on crop production to understand the impact of climate change on food availability (Karim et al. 1996; Sarker et al. 2012; Ruane et al. 2013; Parvin and Ahsan 2013; Sarker et al. 2014; Amin et.al. 2015). Hence, these studies have substantial limitations in considering climate change impact on regional food security. Beside climate change, other regional factors such as bio-physical, management, and socio-economic conditions may affect food security. Both the National Food Policy (NFP) (MoFDM 2006) and the National Food Policy Plan of Action (NFPPA) (MoFDM 2008), in particular, do not address regional details to reduce food security challenges. A spatially informed food security assessment is needed to advance the research-policy linkage in the country. The objectives of this paper are: (1) to provide an overview of food security in Bangladesh; (2) to examine the national data sources relevant for food security; and (3) to address a way forward for a spatially informed food security policy.

2.2 Food security in Bangladesh

Bangladesh is located in the Gangetic Delta with an area of 147,570 square kilometres (BBS 2014). At present, the administrative geography of Bangladesh is divided into eight major administrative divisions, 23 greater districts, 64 districts (zilas), 545 sub-districts (489 upazilas and 56 thanas), and 4550 unions (GoB 2016). Figure 2.1 indicates the administrative boundaries of Bangladesh (greater districts, districts, and sub-districts). Food security varies across Bangladesh and administrative levels, particularly sub-districts, are typically used in order to show the regional variations of food security. This section of this paper documents food security in Bangladesh and highlights food security conditions including: (a) spatial variations of food security, (b) food availability, (c) food access, and (d) food utilization.

2.2.1 *Spatial variation of food security*

The Food Security Atlas of Bangladesh compiled by GoB and WFP (2004) represents the first major initiative to assess regional variations of food security at the sub-district level in Bangladesh. The atlas uses indicators such as low agricultural production, limited infrastructure, poverty, seasonal unemployment, limited public and health facilities, unawareness regarding hygiene and sanitation practices, and the frequent occurrence of natural hazards. The data used in the atlas for map production was collected from the Bangladesh Population Census, 2001 (BBS 2001), the Local Government Engineering Department (LGED), and the Bangladesh Agricultural Research Council (BARC). In order to visualize the overall spatial pattern of food security, these indicators were ranked at sub-district level from 1 to 511 (470 upazila and 41 urban thanas included) and summed. The resulting map (Figure 2.2) shows distinct clusters of very low to low levels of food security in the following regions: (a) the Northwest, (b) the Sylhet Basin, (c) the Chittagong Hill Tracts (Chittagong, Bandarban, Rangamati and Khagrachhari), and (d) the Coastal Regions. Whilst the atlas is very useful for understanding the spatial variations of food security determinants across the country, the maps are based on 2001 census data without subsequent updates and without the possibility of understanding the spatio-temporal dynamics of different indicators. The regional context was represented in the atlas by using the household data aggregated to respective sub-districts, but this did not show the variations of food security indicators within individual sub-districts.

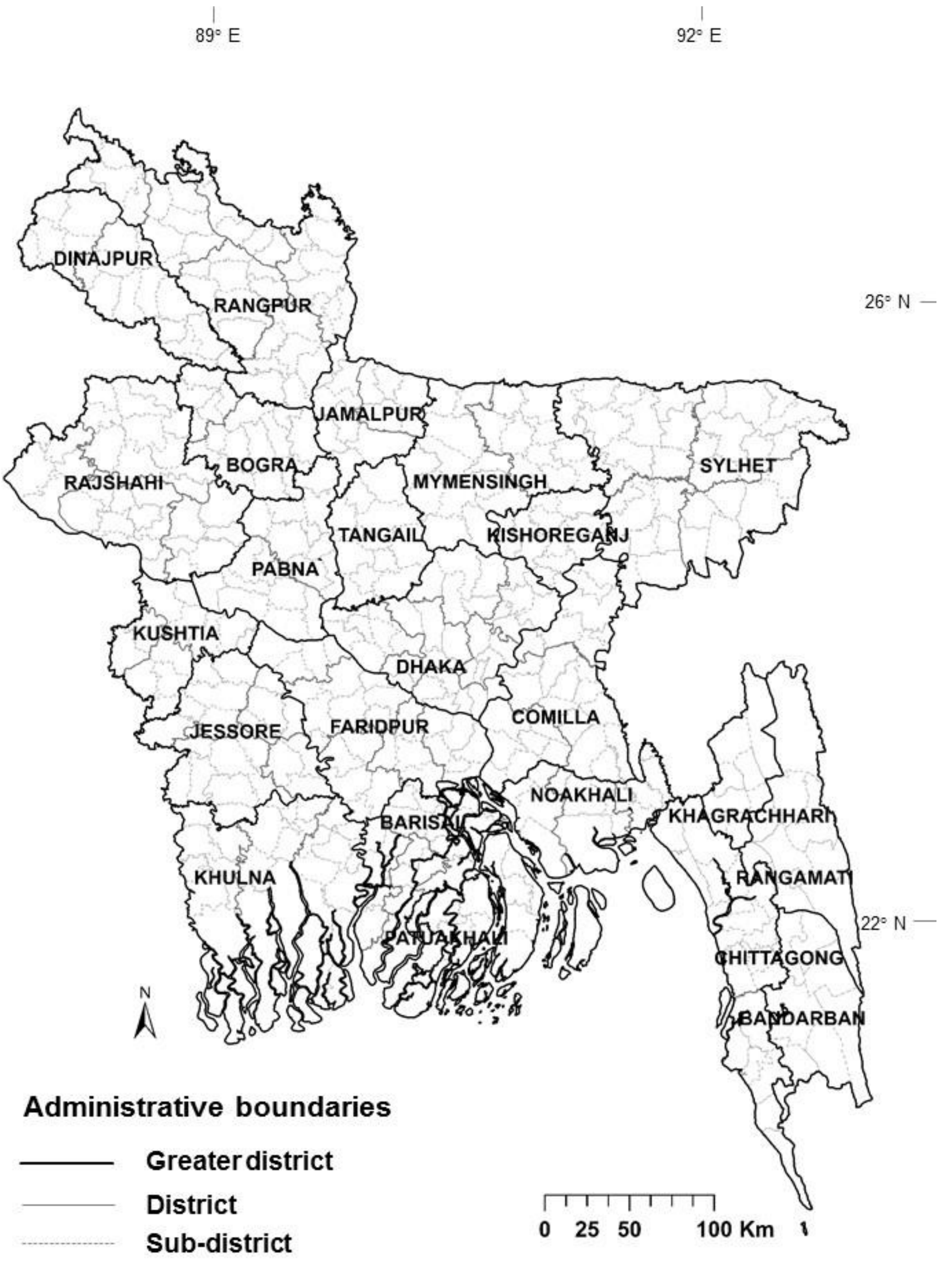

Figure 2.1 Administrative boundaries of Bangladesh

2.2.2 *Food availability*

Food availability refers to the sufficiency of food that is supplied through domestic production or imports (including food aid) (FAO 2006). Both food production and food requirements in Bangladesh have changed over time. Bangladesh typically depends on grain, particularly rice, wheat, and maize, which meet the majority of food requirements. When national food production does not meet the national food requirement, a nation experiences a food gap. The persistence of a food gap in Bangladesh until 1999 can be visualized by comparing the Net total Food Grain Production (NFGP) with the Food Gain Requirement (FGR), shown in Figure 2.3. Net total Food Grain Production is estimated from local food production (particularly rice, wheat, and maize) by assuming national estimates of seed, feed, and wastage, 11.58% (MoF 1991). The Food Gain Requirement can be estimated from population numbers by assuming a constant grain consumption per day per person (here we used, 16 ounces or 453.66 grams; FPMU, 1991). Both the NFGP and FGR increased between 1971 and 2010 (Figure 2.3). Bangladesh closed the food gap in 1999 when the food grain requirement dropped below the net total food grain production (Talukder and Chile 2011). This demonstrates the success of government initiatives to overcome the food gap by raising local food production, particularly rice production.

The national production of rice substantially increased from 9,774 tons in 1971-72 to 33,889 tons in 2011-12 (BBS 2012a). This was primarily due to the introduction of High Yield Varieties (HYV) from the early 1970s (Deb et al. 2009) and an increase in irrigated land for rice cultivation since 1991 (Parvin and Wakilur 2009). The area under irrigation increased from 1.64 to 6.15 million hectares between 1981 and 2012 (BBS 2012b). Approximately 65% of the cultivated land was irrigated in 2012, contributing substantially to increased production; predominantly rice (Rahman and Mondal 2015). Cropping intensity also increased from 151% to 183% for the same period (BBS 2011b). Local food production varies regionally due to biophysical conditions and varied management practices, including cropping intensity and irrigation (Brammer 2000; Rahman 2010; Alauddin and Sharma, 2013). However, these were not considered in previous food security assessments (Mainuddin and Kirby 2015; Parvin and Wakilur 2009) to analyse national food availability. Although Bangladesh now maintains relative self-sufficiency in rice production, this has not been accompanied by substantial rises in the availability of other foods.

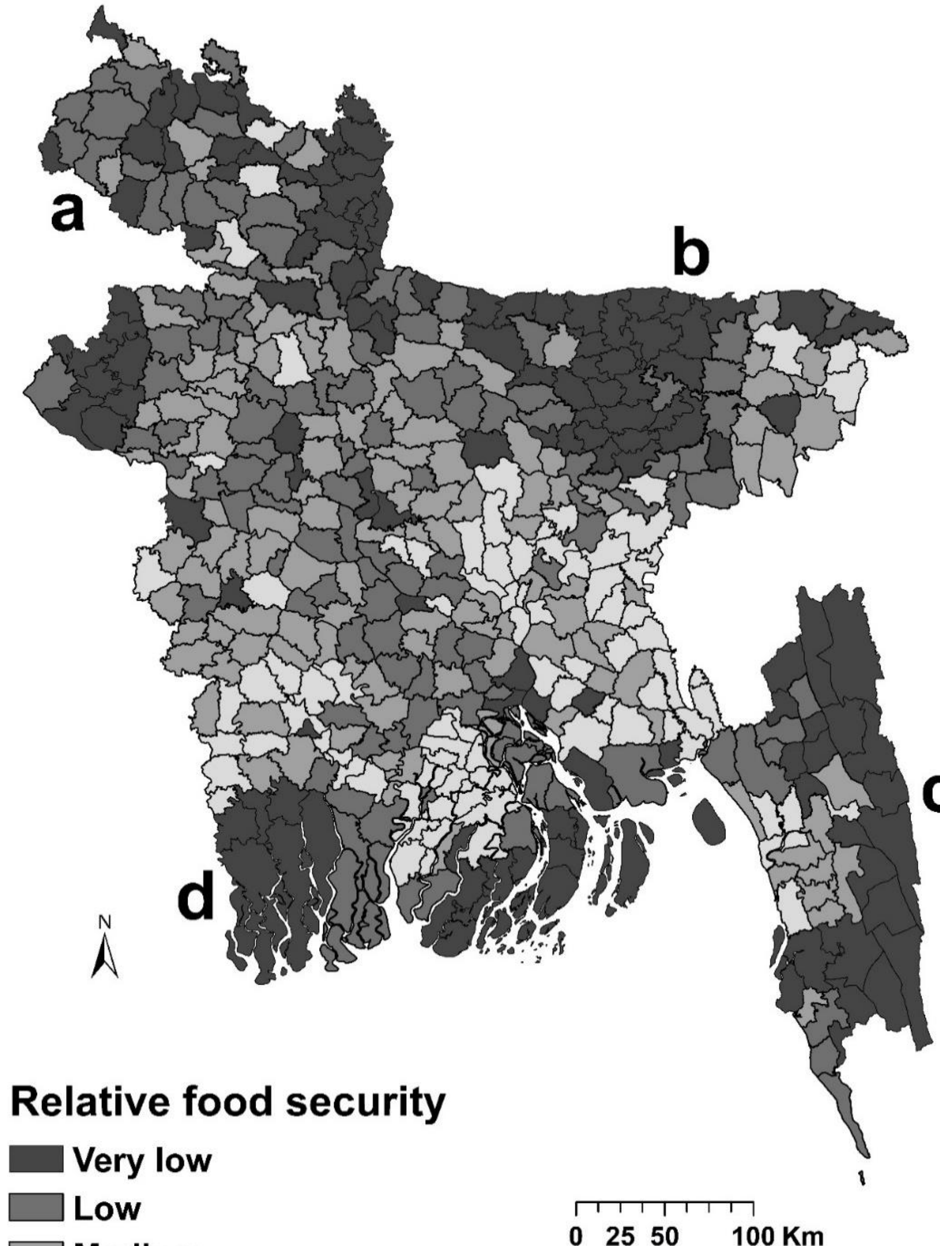

Figure 2.2 Spatial distribution of levels of food security in Bangladesh at sub-district level, 2001 (GoB and WFP 2004).The key areas of very low to low food security, (a) the Northwest, (b) the Sylhet Basin, (c) the Chittagong Hill Tracts (Chittagong, Bandarban, Rangamati and Khagrachhari), and (d) the Coastal region of Bangladesh.

Food availability in Bangladesh may face challenges in the future because of low production of other non-grain foods, import management of food (Bishwajit et al. 2013) and, regional variations of local food production due to climatic and other management variables.

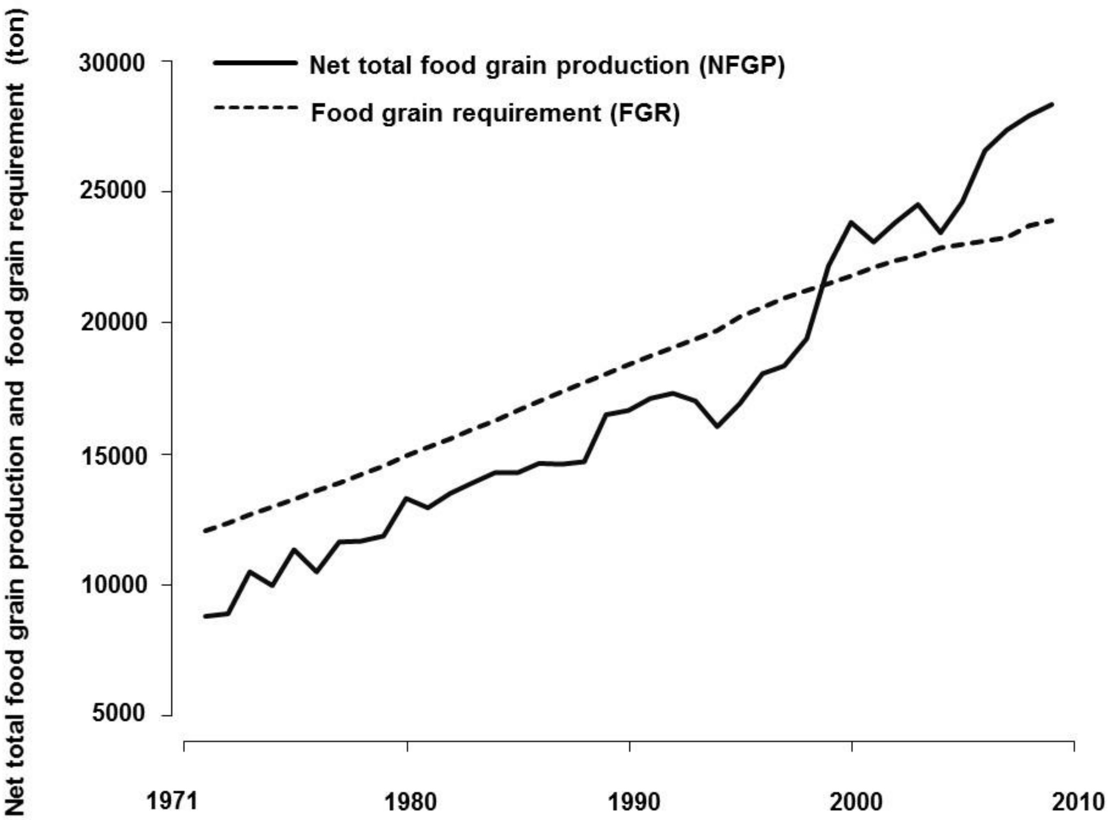

Figure 2.3 Trends in national Net Total Food Grain Production (NFGP) and Food Gain Requirement (FGR) of Bangladesh over the period of 1971 to 2010.

2.2.3 *Food access*

Food access refers to the economic, social, political and legal rights of individuals to adequate resources for getting sufficient food for a nutritious diet (FAO 2006). Poverty has decreased in Bangladesh since 1992 (FAO 2013). Per capita Gross Domestic Production (GDP) (adjusted to US$ in 2014) has increased over the last 52 years from $100 in 1962 to $1,089 in 2014 (BBS 2014). Employment generation has increased through public and private sector programmes and the number of the extreme poor reduced from 44 million in 2000 to 26 million in 2010 (FAO 2013). Regardless of these positive achievements, undernourishment still exists in the country, as 60 million people are not able to consume the minimum daily food intake required for a healthy life (FAO 2013). Furthermore, levels of poverty vary substantially across the country (BBS et al. 2010; Kam et al. 2005). The poorest areas are the Northwest, the Chittagong Hill Tracts and the Coastal Region of Bangladesh, where food security was found to be critically low in 2001 (Figure 2.2). Income inequality exists in Bangladesh (Hossain et al. 2005) and sources of income (agricultural and non-agricultural) and average agricultural wage rates vary geographically in the country (GoB and WFP 2004; BBS et al. 2010).

Food access often varies between rural and urban areas in Bangladesh (Pitt 1983; Hels et al. 2003). Figure 2.4 shows trends in per person per day total food intake (grams) by residence type (rural and urban area) (HIES, various years, BBS 2010b) and required food intake (MoHFW and BNNC 1997) in Bangladesh over the period of 1983-85 to 2010. The national level per person per day food intake was sourced from various Household Income and Expenditure Survey (HIES) reports and BBS (2010) during 1983-2010. The food items considered are rice, other cereals, vegetables and potatoes, pulses, oils and fats, sugar, fruits, fish, meat, eggs, and milk. Figure 2.4 shows the total daily food intake in grams by summing these food items and illustrates the changes of total food intake in rural, compared with urban, areas over the period 1983-2010. Overall, per person per day total food intake has increased in both areas (Figure 2.4). However, food intake in rural and urban areas has always been lower than the required food intake of 934 grams per person per day (MoHFW & BNNC 1997). In rural areas, it has increased from 741 grams in 1983-85 to 906.4 grams in 2010. Food intake in urban areas showed a fluctuating trend during the period, but increased overall from 763 grams in 1983-85 to 871 grams in 2010 (Figure 2.4). These changes may have occurred due to changes in consumption patterns of different types of foods and rural-urban demographic dissimilarities in the country during the period.

Access to infrastructure resources, particularly total delivery distances of food within a region, the location of growth centres, and access to electricity (Scaramozzino 2006; Shin 2010) may impact food access in Bangladesh. Except for the Chittagong Hill Tracts and Coastal Region of Bangladesh, the national average travel time to the nearest growth centre is approximately one hour (GoB and WFP 2004). It is likely that spatial variations of infrastructure development and socio-economic conditions may influence food security, yet little attention has been given to them previously in assessing food security in Bangladesh due to regional infrastructural development and socio-economic conditions, such as demographic contexts, poverty, income, wage rates, labour, employment opportunities, and availability of information (i.e. through increased use of mobiles and the internet).

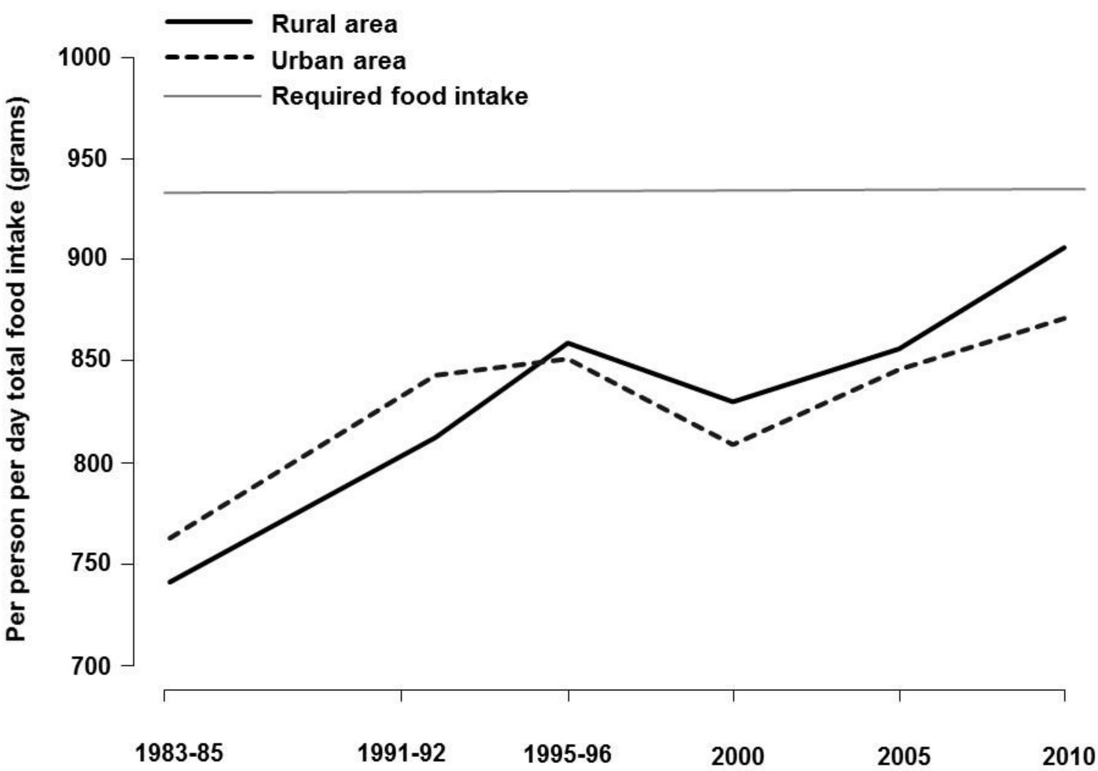

Figure 2.4 Trends in per person per day total food intake (grams) by residence type (rural and urban area) (HIES, various year, BBS 2010b) compared to required food intake (MoHFW and BNNC 1997) in Bangladesh over the period of 1983-85 to 2010.

2.2.4 Food utilization

Food utilization encompasses the nutritional wellbeing of a person that comes from adequate food consumption from a diversity of food sources, food storage, and processing, including clean water and healthy environments (FAO 2006). Utilization of food has always been unsatisfactory nationally in Bangladesh. The national average per person per day nutrition intake from a variety of food sources has only slightly increased over the last 50 years from 2,251 kilocalorie (kcal) during 1962-64 to 2,318 kcal in 2010 (HIES 2010). It remains below the FAO recommended required average calorie consumption of 2,410 kcal per person per day for adults from all sources of food (FAO 2008).

At present, Bangladesh is experiencing a substantial variation in food utilization from different food categories (FAO 2013). Figure 2.5 indicates the national level per person per day calorie consumption and desirable calorie consumption in kcal from 1991-92 to 2010 for rice and other major food items. The national level per person per day food intake was sourced from the reports of the Household Income and Expenditure Survey (HIES) over the period of 1991-92 to 2010 for different food items in grams. The per person per day desirable food intake was given by NFPCSP (2013) for these food items in grams. Data from both sources were converted to kcal for rice and other major food items including wheat, potato, fish, pulses, vegetables, meat, eggs, milk, and fruits by using their nutrition values (Rahman and Islam 2014). However, this estimation did not include food intake from other cereals, oils, and fat. Calorie consumption from major food items other than rice is well below the desirable calorie consumption over the whole period (per capita 1,026 kcal for these items) (NFPCSP 2013). Rice consumption marginally decreased from 1991 (1,518 kcal) to 2010 (1,335 kcal); however, calorie consumption from rice is still higher than the desirable calorie consumption standard (per capita 1,124 kcal from rice) (NFPCSP 2013). This represents a dietary imbalance in food utilization in Bangladesh.

There are several factors influencing the utilization of food. For instance, education levels affect the understanding of the nutritional value of foods (Sajjad et al. 2014). Individual health conditions affect the capacity of the body to absorb food and access to clean, safe drinking water and sanitary facilities are critical in food utilization. In Bangladesh, 70 per cent of the population had access to safe drinking water in 1992. This reached 85 percent by 2012, and the advancement in sanitation has improved (FAO 2013); however, these averages may not be representative for all regions in Bangladesh. A strong geographical association was found in three anthropometric indicators of under-nutrition (stunting, wasting and underweight) at the division level (FAO 2013); with Sylhet division in the North East being the worst affected (BDHS 2013). Regional variations in dietary imbalances and other factors related to food utilization may influence food security in Bangladesh and it is important to evaluate this.

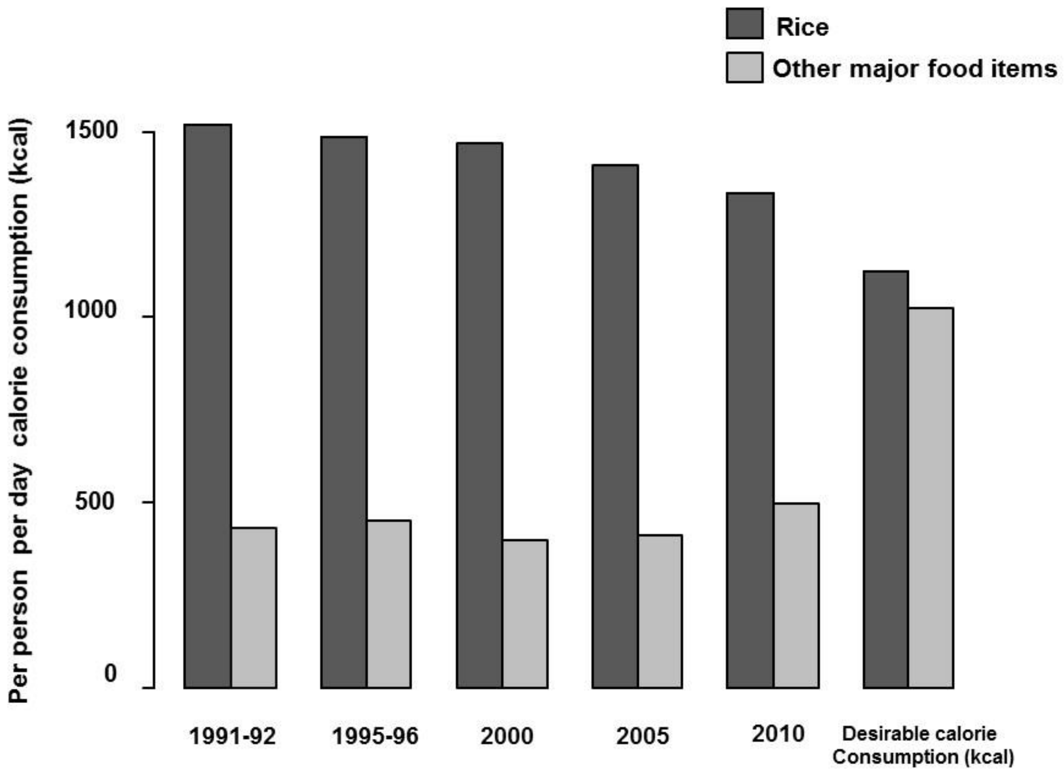

Figure 2.5 Average per person per day calorie consumption (kcal) (BBS, HIES, various year) and desirable food consumption (kcal) (NFPCSP 2013) from rice and other food major items in Bangladesh during 1991-92 to 2010.

2.2.5 *Food security and climate change in Bangladesh*

The impact of climate change on food security is an important concern in Bangladesh (Habiba et al. 2015b). This section of this paper primarily focuses on food security and climate change in order to consider the potential geographic impact of climate change on food security components in the country.

Climatic variables, particularly rainfall and temperature, vary across Bangladesh over the period 1981 to 2010 (Figure 2.6). The station-based rainfall and temperature data (BMD, 2012) were interpolated and aggregated at greater district level using a Geographic Information System (GIS) to shows spatial variations of rainfall (Figure 2.6a) and average temperature (Figure 2.6b) in Bangladesh at the greater district level. Most of the eastern part of the country has high rainfall; averaging 2688 mm to 3192 mm over the period (Figure 2.6a). The southern part of the country has slightly higher temperatures compared with the northern part of the country (Figure 2.6b). Although the spatial variations in long-term temperature are small, the differences may influence food security across the country in the long term and are similar in magnitude to the climate changes predicted to occur during the next decades (Ara et al. 2016).

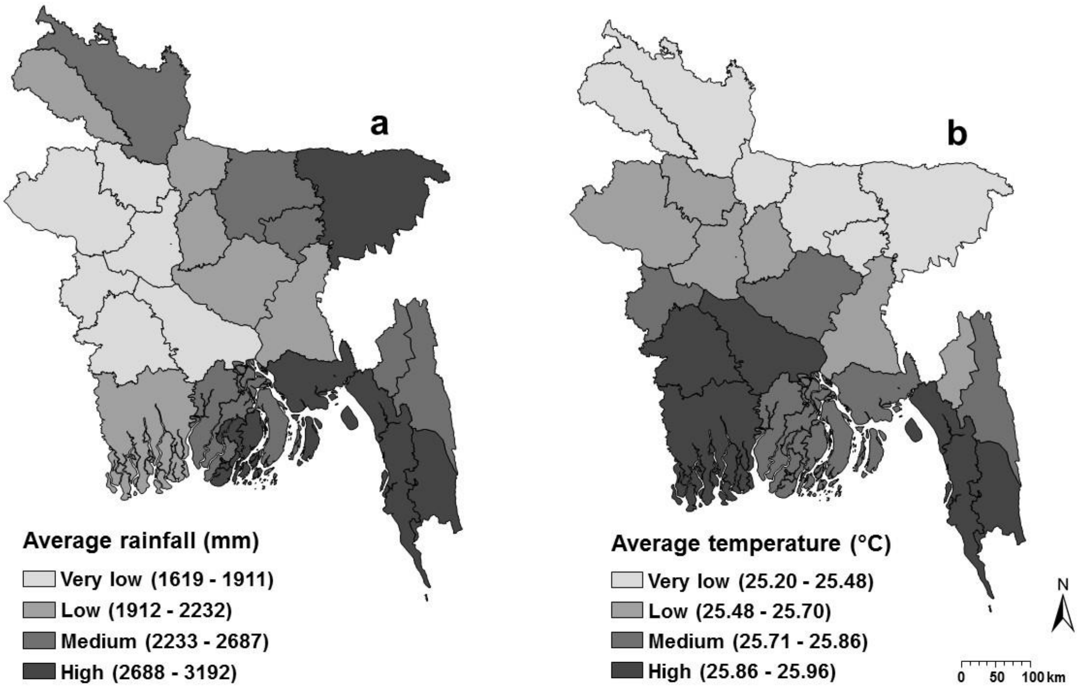

Figure 2.6 Spatial distributions of average rainfall (a) and average temperature (b) at greater districts level in Bangladesh during 1981 to 2010; classes represent quartiles.

Several studies have analysed the impact of climate change on food production, particularly rice production in Bangladesh as a means of food security evaluation. Table 2.1 indicates various assessments on the impact of climate change on rice yield/production in Bangladesh for different rice eco-types (Aus, Aman, and Boro). Assessments based on crop models such as Simulation Models, Crop Environment Resource Synthesis (CERES), Decision Support System for Agro-technology Transfer (DSSAT) and Multifactor Impact Analysis predicted a decrease in rice yield due to temperature increase (Karim et al., 1996, Basak et al. 2010; Ruane et al. 2013). On the other hand, empirical assessments showed mixed responses from climate change for different rice eco-types, based on historic evidence (Rimi et al. 2009; Sarker et al. 2012; Sarker et al. 2014; Amin et al. 2015). Some studies primarily focused on the benefit of transplanting date changes for Boro rice alone (Mahmood 1998; Mahmood 2003). Ara et al. (2016) assessed the combined effect of both climatic (rainfall and temperature) and management practices (irrigation and cropping intensity) variables on rice yield. However, there is significant uncertainty concerning changes in rice production/yield associated with climate change (Karim et al. 1996; Ruane et al. 2013) as the effects vary in the different studies (Rimi et al. 2009; Sarkar et al. 2012; Sarkar et al. 2014; Amin et al. 2015). Climate change may also indirectly affect food production in coastal areas because of salinity intrusion and increased yield variability causing reduced food availability (Parvin and Ahsan 2013; Sarwar and Islam 2013).

Table 2.1 shows that some assessments include the location to ascertain the regional variations of climate change impact on rice yield, particularly at the broad climatic zone (Sarker et al. 2014) or agro-ecological zones (Ruane et al. 2013). Using a multifactorial mixed model analysis, temperature significantly decreased yield by 0.14 t/ha rice yield per 1 °C; thus even small spatial differences may have noticeable effects on averages (Ara et al. 2016). Both the National Adaptation Program of Action (NAPA) and the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) recognize the importance of spatially variable climate influences on food security and indicate the need of region-specific adaptation measures to reduce the risk of local low production due to climate change (MoEF 2005; 2009; Islam, et.al 2013a). Unfortunately, the spatial detail in existing understanding of climate change impacts still limits region-specific actions (Islam et al. 2013b). Food security is strongly influenced by natural disasters including flood, drought cyclones, and riverbank erosion, which will likely increase with climate change (Karim et al. 1990; Brammer 1999). Natural disasters can make areas vulnerable to reduced production, can cause damage to infrastructure and communication networks and can lead to a displacement of people (Islam and Sumon, 2013; Coirolo et.al. 2013). In Bangladesh, floods influence the food distribution system through their impact on roads and transport networks. However, the regional influence of natural disasters on food security in Bangladesh is little studied.

Table 2.1 Assessments on impact of climate change on rice production/rice yield in Bangladesh

Authors of the assessments[a,b,c]	Year	Rice	Models	Variables	Impact on Rice eco-types*			Location	Climate Change (scenarios* /historic evidence)	General comment
					Aus	Aman	Boro			
Karim et al.[a] (1996)	1996	Yield	CERES-Rice	Temperature (average)	-	-	-	6 districts	GCM CCCM GFDL	Rice yield changes are varied in six districts due to different simulations
				Temperature (average) and CO_2		-	-			
				Only CO_2	+	+	+			
Mahmood[c] (1998)	1998	Productivity	YIELD CERES	Climate Pedological Hydrological Agronomic Climate station ((lat, long)				2 districts (Mymensing and Barisal)		Comparison of two models for modifying the transplanting date of Boro only
Mahmood et al.[c] (2003)	2003	Yield	CERES-Rice	Climate Pedological Hydrological Agronomic Climate station ((lat, long))				Climate Station locations (16)		Which region would get benefit from a transplanting date change for Boro cultivation
Rimi et al.[b] (2009)	2009	Production	Statistical Analysis	Temperature (seasonal max)	0	-	+	1district (Shatkhira)	GCM-GFDL-TR UKTR HadCM2	Changes in rice yield varied due to different climate scenarios
				Temperature (seasonal min)	0	-	+			
				Rainfall (seasonal total)	+	-	-			
				Soil	-	+/-	+/-			
Basak et al.[c] (2010)	2010	Yield	DSSAT	Temperature (seasonal max) Temperature (seasonal min) Rainfall			-	12 districts	PRECIS	Reduction of Boro rice variety (BR3 and BR14) yield in all locations
Sarker et al.[b] (2012)	2012	Yield	Statistical Analysis	Temperature (seasonal max)	+	0	-	National	Historic evidence	Maximum and minimum temperature are more pronounced compared with rainfall
				Temperature (seasonal min)	0	-	+			
				Total Rainfall (seasonal total)	+	+	0			

Ruane et al. [a] (2013)	2013	Production	Multifactor Impact Analysis	Temperature (seasonal max)	-	-	-	16 agro-ecological zones	GCM	Substantial changes in rice yields for climate scenarios in different zones were measured alone. Sea level rise was not simulated for all regions
				Temperature (seasonal min)	-	-	-			
				Rainfall (seasonal mean)	-	-				
				Co_2	+	+	+			
				Flood	-	-				
				Sea level rise	-	-	-			
Sarker et al. [b] (2014)	2014	Yield	Statistical Analysis	Temperature (seasonal max)	0	+	-	7 climatic zones	Historic evidence	Rice yield changes will be higher for Aman compared with Boro and Aus due to climate change
				Temperature (seasonal min)	-	0	0			
				Rainfall	-	0	0			
				Region	+	+	+			
				Time (year)	+	+	+			
Amin et al. [b] (2015)	2015	Yield	Statistical Analysis	Temperature (seasonal max)	0	-	-	National	Historic evidence	Findings indicated impact of climatic variables on rice yield but regional variations of rice and these climatic variables were overlooked
				Temperature (seasonal min)	0	0	+			
				Rainfall (seasonal mean)	0	-	0			
				Humidity (seasonal mean)	+	+	0			
				Sunshine (seasonal mean)	0	0	+			
				Time (year)	0	+	0			
Ara et al.[c] (2016)	2016	Yield	Statistical Analysis	Temperature (annual average) Rainfall (annual total) Cropping intensity Area under irrigation				23 greater districts	Historic evidence	Analyzed the combined impact of climate and management practices on rice yield. Increase in annual mean temperature and total rainfall will decrease rice yield

Note:

[a]Assesments modelled rice production/yield changes due to changes of climatic variables, (+) = increase, (-) = decrease
[b]Assesments indicated impacts of individual climate variables on rice production/rice yield, (+) = positive effect, (-) = negetive effect, (0) = no significant effect
[c]Assesments do not consider all rice eco-types.
* Climate Scenarios considered : CCCM: Climate and Carbon Cycle Modeling Group; GCM: General Circulation Model; GFDL: Geophysical Fluid Dynamic Laboratory; GFDL-TR: Geophysical Fluid Dynamics Laboratory Transient; HadCM2: Hadley Centre during 1995 and 1996 using the Second Version of the United Kingdom Meteorology Office's Unified Model; PRECIS: Providing Regional Climates for Impacts Studie

In addition to food availability, climate change may also affect food access and food utilization in Bangladesh. As agricultural production becomes susceptible to climate change, disasters, and other socio-economic conditions, farmers adapt by changing preferences for crops (Rosenzweig and Binswanger 1993; Simelton et al. 2012; Iizumi and Ramankutt, 2015). This may influence the availabilty of food for local consumption; all having a potential influence on household income (Burke and Lobell 2010).

Climate change is likely to become an important part of food security in Bangladesh. In certain districts in Bangladesh, farmers are currenly practicing various indigenous techniques to adjust with the local climatic anomalies for crop production (Alauddin and Sarkar 2014). However, national level strategies need to improve for different areas to combat climate change. Although the government has launched several initiatives to facilitate climate change adaptation, more interventions are still required to develop region-specific resilience (MoEF 2009; MoFDM 2008). It is important to understand how to design a long-term food security plan for Bangladesh that includes a consideration of regional climate change impacts on all food security components. Such a plan may reduce the degree and severity of low food security nationally in future. The following section of this paper explores the possible national data sources relevant to food security and climate change which may help to develop such a plan by analyzing this data to improve food security in Bangladesh.

2.3 National data sources on food security in Bangladesh

Data provides the fundamental evidence for assessment of all food security components. But often, data is difficult to obtain and manage. Many factors influence its quality and adequacy, including its use for objectives that were not intended during collection, correlations between determinants, and its derivations for different purposes (Pinstrup-Andersen 2009; Scaramozzino 2006). Food security components often rely on multiple proxies in a country (Alwang et al. 2001). For instance, fertility and mortality (frequently used in demographic research) are relevant in many food security analyses as proxies for population health. The present study explores the availability of directly measured (primary) and proxy determinants for the different food security components. Most determinants were sourced from the recent national and international literature under different food security issues, including production, management practices, climatic variables, disasters, demography, economics, employment, rural-urban differences, infrastructure, calorie consumption, health, education, water, and sanitation.

The study identifies a wide range of possible national data sources on important determinants (primary and proxy) at the spatio-temporal level of Bangladesh. The following sources have been identified for data relevant to food security analysis:

Bangladesh Agricultural Research Council (BARC)
Bangladesh Bureau of Statistics (BBS)
Bangladesh Country Almanac (BCA)
Bangladesh Meteorological Department (BMD)
Bangladesh Household Income and Expenditure Survey (HIES)
Bangladesh Telecommunication Regulatory Commission (BTRC)
Bangladesh Space Research and Remote Sensing Organization (SARRSO)
Centre for Environmental & Geographic Information Services (CEGIS)
Disaster Incidence Database of Bangladesh (DMIC)
Food Security and Nutrition Data Portal (FPMU)
Household Income and Expenditure Survey (HIES)
Local Government Engineering Department (LGED)
Soil Research Development Institute (SRDI)
Water Resource Planning Organization (WARPO)

Administrative boundaries (Figure 2.1) are typically followed by the above-mentioned sources for published spatial data.

Table 2.2 presents the issues and determinants (primary and proxy) of food security under the three food security components and indicates the available national spatio-temporal data on food security determinants for Bangladesh. Geographic data availability varies at different administrative boundaries and selected determinants, like climate and groundwater data, which are station based. In order to be useful in spatial analysis, station based data needs to be prepared using appropriate spatial interpolation techniques. Temporal data availability also varies for different years.

Table 2.2 Components, issues, determinants of food security and the available geographic and temporal data sources on these in Bangladesh nationally. Proxy determinants are indicated in italics.

Components	Issues†	Literature that quotes determinants	Determinants (Primary and *Proxy*)	Possible Data Sources	Geographic data availability	Temporal data availability
Food availability	Production[a]	Mainuddin and Kirby 2015; Moslehuddin et al. 2015	Food production	BBS, BARC	Greater district	1947-2010
			Soil	SRDI, BCA	National	2006
			Seed quality	BBS	Greater district	1991-1997
	Management practices[b]	Abraham et al. 2014; Iizumi and Ramankutty 2015; Hadgu et al. 2009; Tiwari and Joshi 2012; Deryng et al. 2011; Alauddin and Sharma 2013; Rahman 2010; Nasrin et al. 2015; Ahmad et al. 2014; Yengoh 2012; Ara, et al 2016 ; Kirby et al. 2016	Cropped area	BBS	Greater district	1981-2010
			Means of irrigation	BBS	Greater district	1981-2010
			Use of fertilizer	BBS	Greater district	1990,1991
			Use of pesticides	BBS	Greater district	1976-1987
			Groundwater availability	WARPO, IWM	Groundwater well station	1985-2010
	Climatic variables[c]	Rosenzweig and Parry 1994; Parry et al. 1999; Deryng et al. 2014; Aggarwal and Singh 2010; Basak and Alam 2013	Temperature	BMD	Weather station	1948-2012
			Rainfall	BMD	Weather station	1948-2012
			Humidity	BMD	Weather station	1972-2012
			Sunshine	BMD	Weather station	1972-2012
	Disasters[d]	Atkins 2009; Simelton et al. 2012; Ninno and Lundberg, 2005	Flood	DIMC, CEGIS, SPARRSO	National, district, sub-district	Historic record of flood
			Drought	DIMC, CEGIS, SPARRSO	National, district, sub-district	Historic record of drought
			Cyclone	DIMC, CEGIS, SPARRSO	National, district, sub-district	Historic record of cyclone
Food access	Demography[e]	Bose and Dey 2007; Scaramozzino 2006; Felker-Kantor and Wood 2012	*Activity rate*	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
			Sex ratio	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
			Dependency ratio	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
			Age structure	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
			Household structure	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
	Economics[f]	Bose and Dey 2007; Scaramozzino 2006	Land ownership	HIES	District, sub-district	1991-92, 1995-96, 1999-2000, 2004-2005, 2010

			Income	HIES	District, sub-district	1991-92, 1995-96, 1999-2000, 2004-2005, 2010
			Assets	HIES	District, sub-district	1991-92, 1995-96, 1999-2000, 2004-2005, 2010
			Expenditure on food	HIES	District, sub-district	1991-92, 1995-96, 1999-2000, 2004-2005, 2010
	Employment[s]	Scaramozzino 2006	*Labour force structure*	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
			Agriculture vs. non-agriculture activities	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
	Rural-urban differences[h]	Hossain et al. 2005; Thorne-Lyman et al. 2010; Pitt 1983	*Ratio of people lives in urban and rural areas*	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
	Infrastructure[i]	Scaramozzino 2006; Shin 2010	Access to roads	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
				LGED	District, sub-district	2015
			Number of schools	BBS	Greater district	1981
					Districts	1991*, 2001*, 2011**
			Access to electricity	BBS	Greater district	1981*
					District	1991*, 2001*, 2011**
			Access to information technology	BTRC	District	2001-2014
Food utilization	Calorie intake[j]	Bose and Dey 2007; Frongillo et al. 2003; Hels et al. 2003; Hillbruner and Egan 2008; Roetter and Keulen 2007	Food consumption	HIES, FPMU	District, sub-district	1991-92, 1995-96, 1999-2000, 2004-2005, 2010
	Health[k]	Scaramozzino 2006	*Fertility*	BBS	Greater district	1981*
					District	1991*, 2001*, 2011**
			Mortality	BBS	Greater district	1981*
					District	1991*, 2001*, 2011**
			Anthropogenic indicators	HIES	District, sub-district	1991-92, 1995-96, 1999-2000, 2004-2005, 2010
	Education[l]	Sajjad et al. 2014	Literacy rate	BBS	Greater district	1981*
					District, sub-district	1991*, 2001*, 2011**
	Water and sanitation[m]	Sajjad et al. 2014, Roetter and Keulen 2007	*Access to drinking water*	BBS	Greater district	1981*
					District	1991*, 2001*, 2011**
			Access to sanitary facilities	BBS	Greater district	1981*
					District	1991*, 2001*, 2011**

Note:
* Population and housing census year. Administrative boundary changes occurred between 1981 and 1991 census years.
** Note that not all community series for districts from 2011 Population and Housing census were available at the time of thesis publication.

Time series data is available for most of the primary food security determinants but it is only possible to get proxy determinants from Population and Housing Census reports for 1981, 1991 and 2001. Some of the primary determinants have been used in national food security assessments previously (Mainuddin and Kirby 2015; Parvin and Wakilur 2009); however, these assessments overlooked many important primary determinants (Table 2.2). In addition, whilst proxy determinants are considered as important in food security assessment globally (refer to relevant citations in Table 2.2), little attention so far has been given to proxy determinants in Bangladesh. It is important to consider all primary and proxy determinants to strengthen food security research in the country.

Although Table 2.2 shows that spatio-temporal data on food security determinants can be achieved in Bangladesh from past records, such data relevant to food security components are often ignored in food security assessments. Most previous food security assessments were based on primary data (Frongillo et al. 2003; Lewis 1993; Coates et al. 2010,Thorne-Lyman et al. 2010) and HIES data (Faridi and Wadood 2010; Hossain et al. 2005; Bose and Dey 2007), which are collected through questionnaire surveys at household/individual level. However, the studies based on these data do not show the spatio-temporal dynamics of food security in Bangladesh. The data identified in the present study (Table 2.2) allow for the variations of different determinants to be considered over space and time. The following section addresses a way forward for food security analysis that can use spatially explicit data (Table 2.2) to understand the spatial and temporal pattern of each food security component.

2.4 Spatially informed policy: a way forward

The present study addresses a way forward for food security analysis that highlights the need for a potential path that will lead towards a spatially informed policy. Figure 2.7 identifies three separate parts in the process towards improved evidence-based, regional decision making.

2.4.1 Part 1 Food security data analysis and mapping

The approach starts with the traditional data analysis and mapping (Figure 2.7). This has been done before, but new data provides the foundation for substantial improvement. A prominent past example is the National Food Security Atlas using data from the 2001 Population Census (GoB and WFP 2004). Several new datasets have since become available that will allow an update, which in itself is an important contribution to food security policy development as data is available for different epochs, providing the means for a spatial visualisation of changes in critical food security components. In Bangladesh, detailed temporal data has been collected for all three key components of food security (Table 2.2, Figure 2.7, Part 1). Although some harmonisation of data will be necessary because of differences in spatial resolution or temporal availability of the data, the results from the data review above indicate that this is possible.

The mapping of food availability includes food production, management practices, climatic variables, and disasters. Food access analysis is based on the human dimension of food security, including socio-economic conditions, access to resources and communication in different regions. Food utilization analysis mainly considers the food consumption, health, education, water and sanitation of a region. This part results in a visualisation of the geographic variation of components of all of the three food security determinants across the country over time.

2.4.2 Part 2 Considering spatio-temporal evidence for deficits and risks associated with all food security components

The resulting outcomes from different assessments of food security components from part 1 provide the spatio-temporal evidence to identify deficits and risks. For instance, an assessment of food availability will help to identify the biophysical limitations of food production. Food access evaluations will help to ascertain the socio-economic and infrastructure inadequacies of food access. Food utilization assessments may indicate a lack of nutrition and dietary imbalances. All these outcomes will help to understand existing regional risks for food security in a country.

This part includes explicitly spatio-temporal interactions, which have not received sufficient consideration in past policy developments. Examples of possible interactions are off-site effects, i.e. water usage upstream that influences the water availability downstream or potentially unsustainable use of groundwater (Ahmed et al. 2014; Ara et al. 2016) and

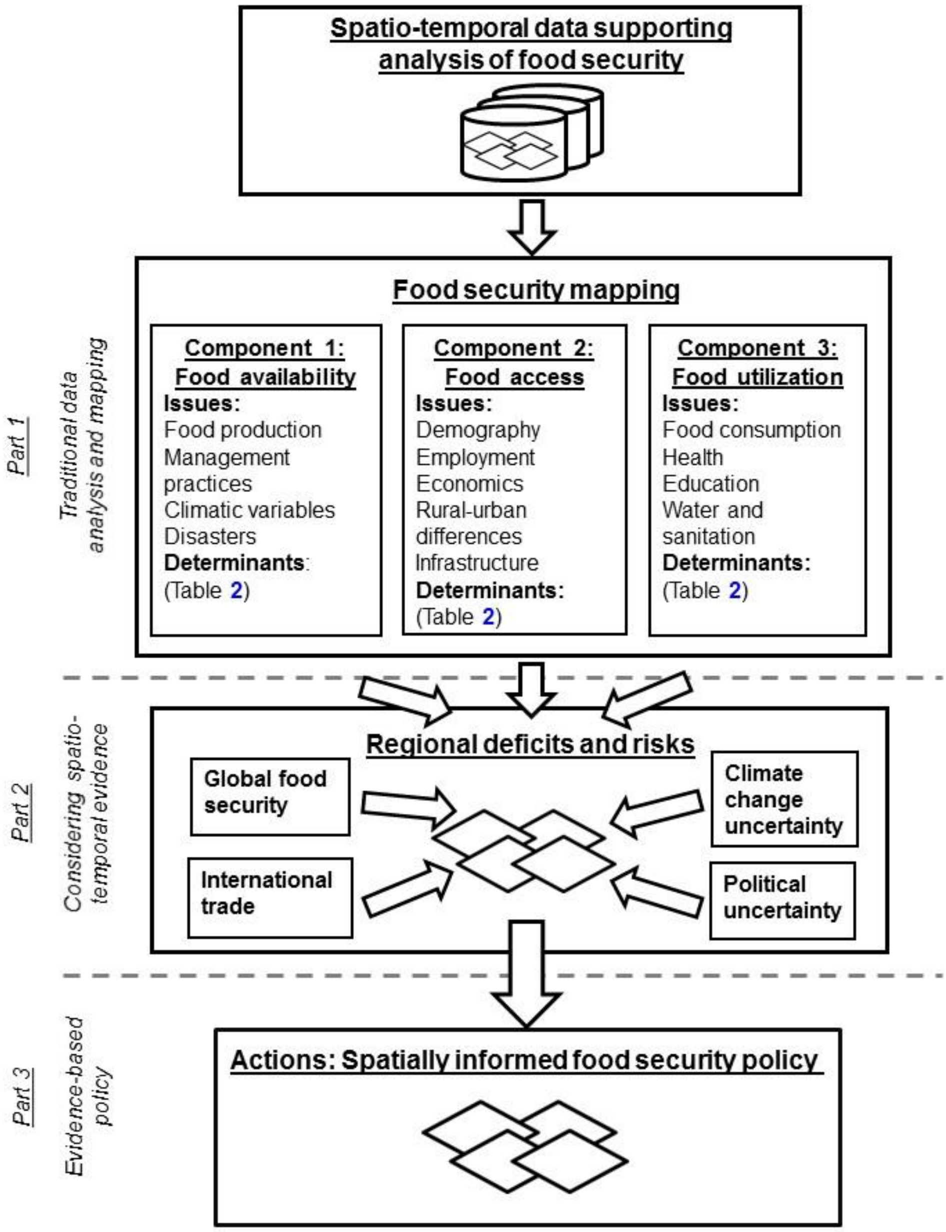

Figure 2.7 A way forward for a spatially informed food policy.

economic development that indirectly influences movement of people and goods with indirect influences on food security. Many of these factors are currently being researched (Mainuddin and Kirby 2015; Kirby et al. 2016) and need to be included in future policies. External factors that are outside of direct government influence include global economic factors such as global annual food production and international trade of agricultural or other commodities that can influence individual food security components (Habiba et al.

2015c). There is also political uncertainty that may cause changes in support and lack of policy continuity. As the complexity in this part is high, it is essential to provide easy access to evidence in the form of spatio-temporal data (Part 2, Figure 2.7).

Climate change uncertainty influences all aspects of food security. Both flooding and cyclones are likely to increase with future climate change and have spatially differing risk profiles associated with all components of food security, production, distribution, housing, and health. Some of these interactions are well understood; others lack evidence, which may successively reduce uncertainties in modelling when it becomes available through research. This research is crucial in order to build and apply quantitative models that use risk appraisals to test policy options for diverse future scenarios.

2.4.3 *Part 3 Development of a spatially informed policy*

The third part (Part 3, Figure 2.7) suggests that regional food security also requires regionally adapted actions in order to address specific food security components. Actions may include but are not limited to region-specific adaptation measures for food availability, varied livelihood options for food access, and diversified diet preferences and awareness building related to health and hygiene environments for proper food utilization. The present study advocates a spatially informed food security policy by considering regional level deficits, future risks, and devises actions related to the respective components to improve food security nationally.

Bangladesh has achieved significant increases in rice production. Calorie consumption has increased marginally at the national level. Both production and consumption have increased, along with imports of food from foreign countries in emergencies, and this has played a vital role in the past for improving food security. Regardless of these positive conditions at national level, the present food policy needs to be improved by incorporating spatial representations of food security components in order to tackle regional food security challenges in Bangladesh (MoFDM 2006; 2008). A comprehensive policy response to food security that fully addresses spatio-temporal variations of food security components is likely to contribute to improving food security.

2.5 Conclusions

The present study has shown that food security is not only an issue of producing food. Food access and food utilization are also very important components of food security in Bangladesh. Most food security determinants vary spatially in Bangladesh and this variation should be considered for regional food security assessment. Similarly, the possible geographic impact of climate change needs to be considered. The study identified available spatio-temporal data on food security in Bangladesh, which has not been used previously for regional food security assessment.

Bangladesh has not yet developed spatial policies to improve its food security, even though there are documented spatial differences in food security (GoB and WFP 2004). Region-specific analysis is required for future evidence-based policy development in Bangladesh. The present study has developed a way forward for regional food security assessment that includes analysis of existing spatio-temporal data but also explicitly stresses interaction of this data with other forms of data. Whereas the first part can be used directly to understand regional variations of factors determining food security, the second part highlights potential connections with factors with high global or national uncertainty. These components need some consideration in order to obtain spatially informed policies in the country. This will contribute to the design of a more appropriate policy and action plans, capable of addressing food security regionally in more effective ways than are possible at present. The government can then give priority to areas where existing food security deficits and future risks are high and devise the necessary region-specific actions to improve food security nationally.

Acknowledgements

The Australian Government and University of Adelaide fund this research through an International Postgraduate Research Scholarship (IPRS) and an Australian Postgraduate Award (APA) for the first author to pursue her Ph.D. The lead author is particularly thankful to Dr. Margaret Cargill, a research communication specialist at the University of Adelaide, and Ingrid Ahmer, the University of Adelaide for review of this manuscript. Special thank goes to Alison-Jane Hunter at the University of Adelaide for assisting in technical language editing.

Chapter 3

Understanding the spatially variable effects of climate change on rice yield for three ecotypes in Bangladesh during 1981-2010*

Abstract

Climate change will impact on rice food security in many parts of the world, including Bangladesh. Bangladesh produces three ecotypes of rice (Aus, Aman, and Boro) in three different climatic seasons. Rice is crucially important for the country's food security as it is considered a staple food and makes up 70 per cent of direct calorie intake. However, little attention has been given to understanding the impact of climate on rice yield for these ecotypes in different areas of the country. Against this backdrop, the main aim of this paper is to analyse the spatio-temporal dynamics of rice yield and climatic variables and the spatially variable climate effects on rice yield for the different ecotypes in Bangladesh during a thirty year period (1981-2010). Rice yield data for three ecotypes and climate data (temperature and rainfall) were sourced from the Bangladesh Bureau of statistics (BBS) and Bangladesh Metrological Department (BMD) respectively. The study used both a Linear Mixed Model (LMM) and a Generalized Linear Model (GLM) to assess climate impacts. The results demonstrated the substantial spatio-temporal variations of rice yield for all ecotypes across the country. The rice yield for all ecotypes was more susceptible to temperature changes than rainfall effects. Modelling of a 1°C temperature increase in the country showed that the regional rice yield would vary for all ecotypes. The decrease in rice yield is higher for Aus and Aman rice in most of the greater districts, whereas the Boro rice yield will increase in some districts. The study concludes that climate change will impact on Bangladesh's food security by affecting the regional rice yield, as future temperature changes are likely to change the rice yield for all ecotypes. These results have important consequences for food security by indicating the need for appropriate region-specific adaptation measures to reduce rice yield variability in the future. Priority should be given to the disadvantaged districts that show lower rice yields in future, due to predicted temperature change

---

* This chapter is based on:

Ara, I., Lewis, M., & Ostendorf, B. 2017. *Under review after submission.* Understanding the spatially variable effects of climate change on rice yield for three ecotypes in Bangladesh during 1981-2010. *Advances in Agriculture*.

3.1 Introduction

Rice is considered as a key food in daily life in many countries and substantial rice production influences global food security. Rice has become a primary concern for national food security in Bangladesh (Ara et al. 2016; Mainuddin and Kirby 2015; Headey and Hoddinott 2016). Climate change may influence rice food security in many parts of the world including Bangladesh (Furuya and Koyama 2005; Yu et al. 2010). Bangladesh primarily produces three ecotypes of rice (Aus, Aman, and Boro) in three different climatic seasons. Changes in seasonal climatic conditions may have an impact on food security (Shi and Tao 2014; Qin et al. 2013; Rowhani et al. 2011) by affecting rice agriculture variability (Belesky 2014) in different areas. Little is known about regional rice yield differences in Bangladesh for these ecotypes as a consequence of climate change.

Rice is fundamentally important for Bangladesh as it is the staple food for its 152 million people (population counted in the last population census, 2011) (BBS 2010). Bangladesh stands fourth in the ratings of per capita rice consumption in the world (FAO 2014). The average annual per capita rice consumption in Bangladesh is 160 kilograms (FAO 2014), which is more than three times higher than the average global rice consumption rate (50 kilograms per capita) (FAO 2015). Production of rice covers nearly 75% of the total cropland and over 80% of the total irrigated area in the country (IRRI 2010). Rice contributes more than 60% of the total crop agriculture and accounts for 18% of the gross domestic product (GDP) in the country (GoB 2010). In addition, the lives and livelihoods of about 13 million farm households and approximately 50 per cent of the workforce, who are engaged in agriculture (BBS 2010) primarily, depend on rice production. Rice production has increased substantially in Bangladesh since independence, which has positively influenced food security. However, the production of rice must continue to increase in order to improve national food security in the future (Mainuddin and Kirby 2015). Due to the significant impact of rice production on agricultural systems, livelihoods and food security in Bangladesh, there is a critical need to understand the spatio-temporal variability of rice agriculture and the spatially variable effects of climate change on rice yield for different ecotypes. Although the scientific and policy recommendations have already covered crop agriculture changes due to climate change (MoFDM 2006), there is still an urgent need to provide additional policy suggestions by understanding regional differences in rice production due to spatially variable climate change effects (Sarker et al. 2014; Amin et al. 2015). Region-specific adaptation measures can then be targeted appropriately for these ecotypes in different areas and so help in increasing farmers' abilities to cope with uncertain climate conditions for rice production in these areas in future.

Bangladesh's rice agriculture typically depends on climatic conditions, particularly temperature and rainfall. Rice grows intensively all over the country in three seasons: Aus season - March to August; Aman season - June to November; and Boro season - December to May (BBS 2012). There is a chance that the extent of the seasonal changes in temperature and rainfall in different areas may influence rice production for various ecotypes. However, the country has few regional adaptation measures yet in place to combat the effects of climate change on rice cultivation (MoEF 2005; 2009). Earlier studies have quantified the impact of climate change on Bangladesh's rice agriculture for different ecotypes through the use of crop models (Karim et al. 1996; Rezaul Mahmood 1998; Mahmood et al. 2003; Basak et al. 2010; Ruane et al. 2013) and empirical models (Sarker et al. 2012; Sarker et al. 2014; Amin et al. 2015). The results of the Decision Support System for Agro-technology Transfer (DSSAT) crop model showed a 35% decrease in the total rice yield in Bangladesh when there is an increase in temperature (Karim et al. 1996). Mahmood et al. (2003) indicated 27% to 75% of Aman rice yield losses were due to the change of transplanting date for local climatic conditions in selected areas. However, crop model studies have placed little emphasis on geographic issues and so further assessment is required to understand regional climate impacts on rice yield. Most of the empirical models explored the climate-rice yield relationship for three rice ecotypes from the historical records without considering any regional variability (Sarker et al. 2012; Amin et al. 2015). Sarker et al. (2014) and Ruane et al. (2013) indicated the considerable climate change impacts on rice yields for three ecotypes for broad climatic and agro-ecological zones respectively. Another study focused on a particular district alone to understand the climate change impact on local rice yield (Rimi et al. 2009). Hence, the results of the existing studies are not adequate to understand the extent of the impact of climate change on rice yields in various districts of the country and therefore to devise necessary adaptation measures across Bangladesh.

Although there are well-established scientific concerns about the impact of climate change on rice yields and possible regional variabilities have also been studied on a broader scale (Ruane et al. 2013; Sarker et al. 2014), district-level assessment is still needed for more specific detail. Some studies have analysed rice agricultural management on the basis of historical trends alone for different ecotypes (Mainuddin and Kirby 2015; Rahman and Parvin 2009), but with no regional context. Recently, Ara et al. (2016) investigated the spatio-temporal effects of climate change and other variables on the total rice yield in Bangladesh at the greater district level but they did not consider such effects for various rice ecotypes grown in different seasons. In general, assessments on climate change impact at a regional scale are rare for Bangladesh's rice agriculture for the three ecotypes. This was acknowledged by Sarker et al. (2012) and Amin et al. (2015), who indicated the need for further district level research on rice yield for these ecotypes in order to address region-specific adaptation measures in different seasons. The present study fills this research gap by focusing on spatially variable climate change effects on Bangladesh's rice ecotypes during the 1981-2010 period at greater districts level. The specific objectives of the study are: (1) to understand the spatio-temporal variations of rice yields for different ecotypes and the spatial variations of growing seasons climatic variability of these ecotypes across Bangladesh; (2) to evaluate the spatially variable impacts of climate on rice yield for three rice ecotypes; and (3) to assess regional rice yield changes due to a 1°C temperature increase in Bangladesh.

3.2 Methods

3.2.1 Rice yield data

Data for rice harvested area in a hectare (ha) for various ecotypes and diverse methods of production of a tonne (t) of rice at greater districts level were obtained from the series of Agricultural Statistical Year Books of Bangladesh, published by the Bangladesh Bureau of Statistics (BBS) for the period between1981-2010. These data were then converted to an annual rice yield (t/ha) for 23 greater districts in the country, dividing the rice production data by the harvested area for the respective ecotype.

3.2.2 *Climate data*

Many studies have used the global gridded climate data set (Rowhani et al. 2011; Shi and Tao 2014), however, this dataset was not used in the present study due to the lack of density of the global climate observation stations (only three) in Bangladesh, so such data may not be reliable for representing the local climate conditions. Instead, we collected the daily rainfall and the maximum and minimum temperature data from the Bangladesh Meteorological Department (BMD 2012). A total of 31 different weather stations were considered for the present study, as these are almost evenly distributed across the country (Figure 3.1). Initially, we calculated the daily average temperature of each station from the maximum and minimum temperatures. Then, we calculated the average monthly temperature for the respective station. Monthly average rainfall data was also calculated from the recorded daily rainfall data for each weather station. The kriging method was applied to interpolate the station-based climate data for temperature and rainfall using a Geographic Information System (GIS). Finally, we derived a 30 year (1981-2010) time series of the seasonal average temperature and rainfall for each ecotype in each greater district. Note that the climatic season calculation for Boro required consideration of two calendar years (for example, from December 1981 to May of 1982 were considered for 1982's Boro yield).

3.2.3 *Analysis*

To assess the impact of climate change on the different ecotypes, we developed statistical models relating yield records from the government statistical yearbooks to the environmental conditions in the districts during the study period. We developed separate models for the three ecotypes (Aus, Aman, and Boro), respectively, and we used two model types to assess the impact of climate change at national and district levels. At national level, we used Linear Mixed Models (LMM, Eqn. 1) with districts as a random effect and at district level we used Generalized Linear Models (GLM, Eqn. 2) with districts as binary dummy variables as

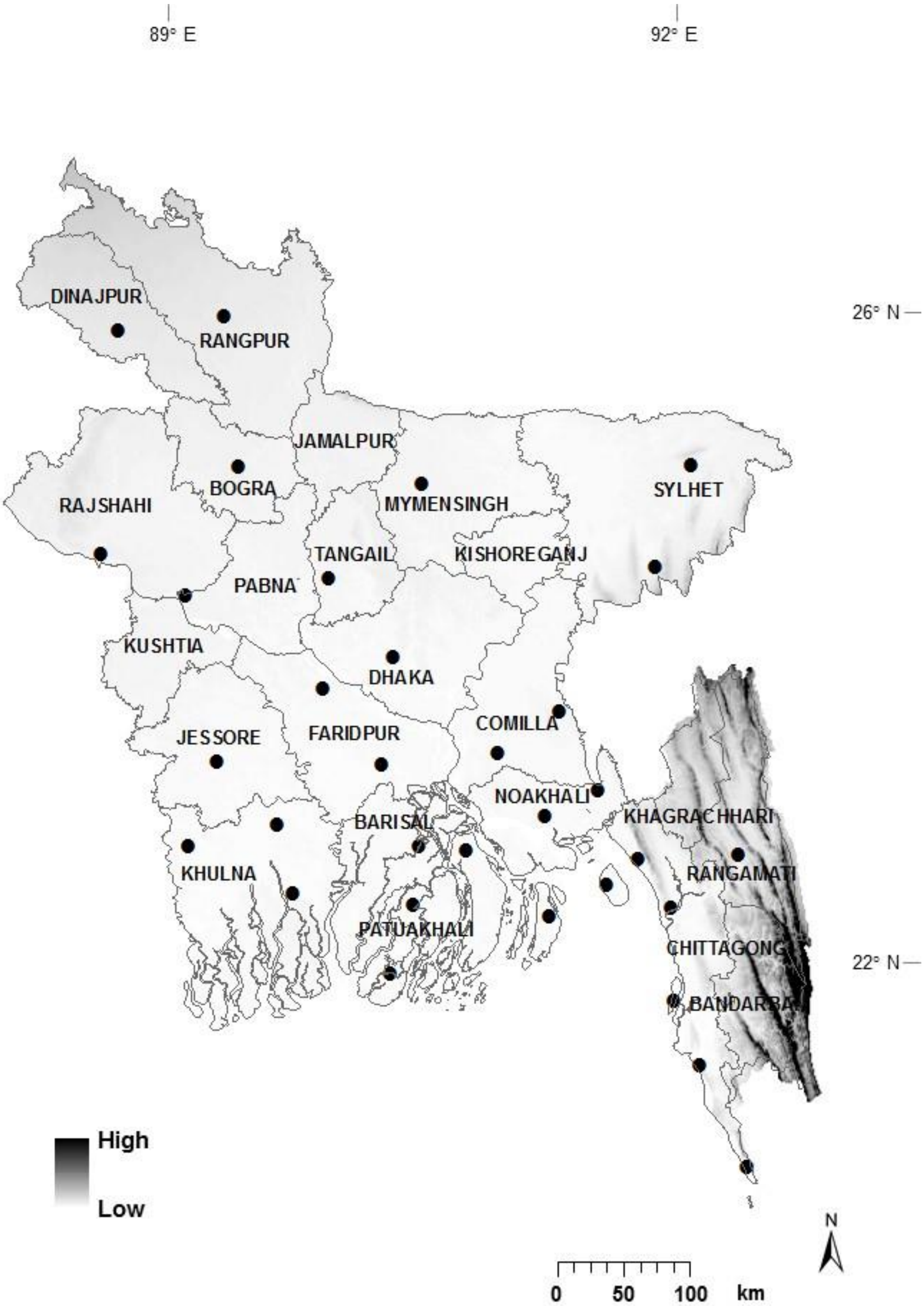

Figure 3.1 Bangladesh's 23 greater districts used in the present study and a Digital Elevation Model (DEM) presenting the topographical landscape. Locations of 31 climate stations (black circles) across Bangladesh are also shown.

$$Y_{ij} = \beta_0 + \beta_1(T_{ij}) + \beta_2(R_{ij}) + \beta_3(year_{ij}) + \sum_{j=2}^{23} a_j (D_{ij}) + \varepsilon_{ij} \text{ .... (1)}$$

and,

$$Y_{ij} = \beta_0 + \sum_{j=1}^{23} \beta_{1j} (T_{ij}: D_{ij}) + \sum_{j=1}^{23} \beta_{2j} (R_{ij}: D_{ij}) + \sum_{j=1}^{23} \beta_{3j} (year_{ij}: D_{ij}) +$$
$$\sum_{j=2}^{23} \beta_{4j} (D_{ij}) + \varepsilon_{ij}. \text{ .... (2)}$$

In both models, Y denotes the rice yield for the respective ecotypes, i represents the different years in the study (e.g. 1981-2010) and j the 23 greater districts in the models. The model coefficients β and a signify the fixed and random effects, respectively. ε denotes the error term. The independent variables in the models are average temperature (T), rainfall (R) and districts (D) for the respective ecotype growing period. The control for unobserved temporal effects was time (*year*) as an explanatory variable in both models. In the models, using both districts (D) and time (*year*) as a variable helped us to omit the effects of the regional variability which may be specific to a certain year or region due to time-variant factors such as disasters, land use intensification, major improvements in technology and government incentives and time invariant district specific characteristics such as the calibre of the soil, topography, and physiography.

We ran several diagnostic tests in the *R* statistical packages to develop our models. For this we typically considered the yield data for each rice ecotype individually, including the average seasonal temperature and rainfall variables for the respective ecotype. First, we checked the distribution of both dependent and independent variables for each ecotype used in the model by using the ladder approach developed by Tukey (1977), finding no transformation was required for any variable. Secondly, we assessed the stationarity of these variables for all the ecotypes by following the Augmented Dickey-Fullar (ADF) test (Dickey and Fuller 1979) and all variables were stationary. Therefore, the GLM models can be applied to district data without pre-processing. Third, we evaluated the co-linearity between temperature and rainfall for each season in the LLM models. The resultant R^2 were insignificant for all ecotypes.

To assess the overall performance of the models, we estimated a Pseudo-R-squared value for Generalized Mixed-Effect models using the 'r.squaredGLMM' function from the MuMIn package (Barton 2014). We report both the marginal and conditional R2 estimates to distinguish the variance explained for fixed effects compared to both fixed and random factors in the models, respectively.

In order to assess the spatial pattern of rice yield changes across Bangladesh, as affected by a temperature increase, we applied a temperature increase (ΔT) to the GLM models by using the standardized relative changes equation (Eqn. 3). These changes are the product of the temperature coefficients β_{1j} from GLM models for the separate ecotypes multiplied by ΔT =1, to assess the impact of a 1°C temperature increase. Standardized rice yield changes (Δy_j) for all j districts are estimated as:

$$\Delta y_j = \Delta T * \beta_{1j} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

3.3 Results

3.3.1 Summary statistics

The summary statistics of the rice yields are presented in Table 3.1. This table illustrates the fundamental features of the rice yield and climatic variables (temperature and rainfall) during three rice-growing periods in Bangladesh over 30 years. The highest mean value is observed for Boro yield. Aus' growing period average temperature is the highest of the three growing periods. The Boro growing period received less rainfall than the Aus and Aman periods. However, both rice yield and climatic variables vary across Bangladesh and the following sections describe the spatio-temporal variations of these variables during the study period.

Table 3.1 Summary statistics of the rice yields and growing period's average temperature and rainfall for three ecotypes

Statistics	**Variables**								
	Rice yield (t/ha)			**Temperature (°C)**			**Rainfall (mm)**		
	Aus	***Aman***	***Boro***	***Aus***	***Aman***	***Boro***	***Aus***	***Aman***	***Boro***
Mean	1.32	1.73	2.79	28.11	27.87	23.46	1777	1850	465
Std. dev.	0.39	0.45	0.63	0.47	0.32	0.62	477	497	185
Maximum	2.44	2.79	4.29	29.40	28.66	25.23	3211	3392	1338
Minimum	0.61	0.69	1.03	26.55	27.03	21.77	1034	898	110

3.3.2 *Spatio-temporal variations of rice yields for the three ecotypes*

The average rice yield varies across Bangladesh for the three ecotypes over the period from 1981 to 2010 (Figure 3.2). Khulna, Chittagong, and Khagrachari were the highest yielding Aus regions in Bangladesh (Figure 3.2a). The average Aus yield for these districts was 1.54 to 1.90 t/ha. Other important Aus yielding areas are Rajshahi, Bogra, Kustia, Sylhet, Kishoreganj, Comilla, Rangamati, and Bandarban. The low yielding (on average 0.81 to 1.32 t/ha) Aus regions are mostly in the middle of the country. The Chittagong hill tracts (Chittagong, Kahrachari, Rangamati, and Bandarban) were observed to have the highest average yield of Aman, 1.97 to 2.50 t/ha, during the study period (Figure 3.2b).

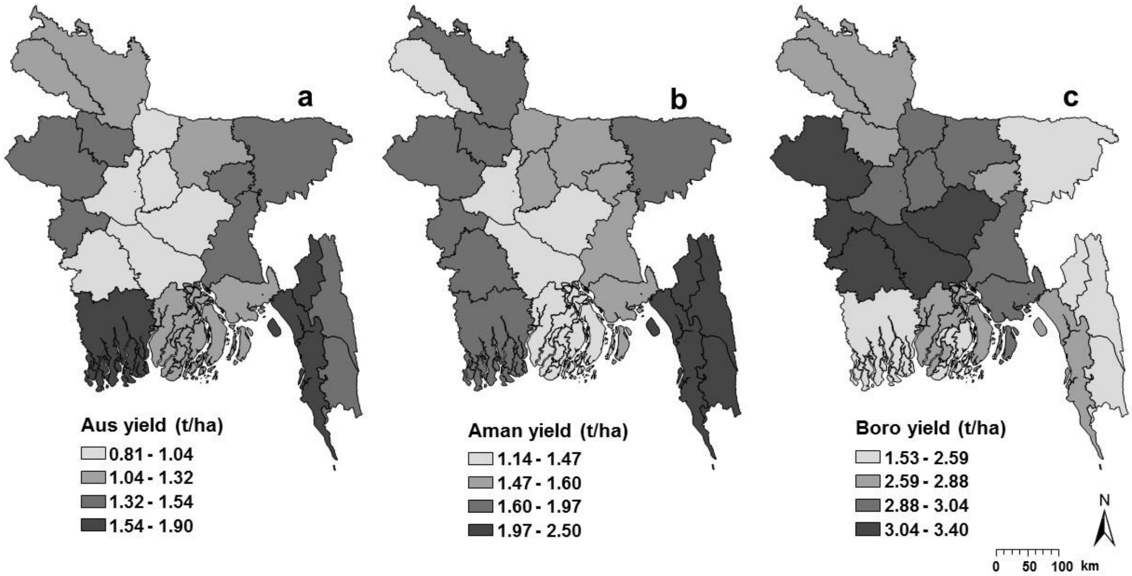

Figure 3.2 The spatial distribution of rice yield (t/ha) in Bangladesh averaged over the 1981-2010 period; classes represent quartiles; (a) Aus yield, (b) Aman yield, and (c) Boro yield.

Most of the western districts, including Rangpur, Bogra, Rajshahi, Kustia, Jessore and Khulna, along with Sylhet in the East, showed 1.60 to 1.97 t/ha Aman yield over the period. The remaining areas had low Aman yields; on average 1.14 to 1.60 t/ha. The regions with the highest yield of Boro rice (on average 3.04 to 3.40 t/ha) were Dhaka, Faridpur, Jessore, Kustia and Rajshahi (Figure 3.2c). On the other hand, all districts associated with the coast and Chittagong hill tracts had the lowest Boro yield: on average 1.53 to 2.88 t/ha. Other districts, including Pabna, Tangail, Jamalpur, Mymensing, Comilla and Noakhali, were considered to have a medium Boro yield (on average 2.88 to 3.04 t/ha).

Temporal data on the rice yield in Bangladesh is available from 1972 and shows an increase for all ecotypes during the period 1972 to 2010 (Figure 3.3). Of the three varieties of rice considered in the present study, Boro yield significantly increased over the period from 1972 to 2010, when compared with the Aus and Aman yields. In 1972, the average Boro yield was 2.01 t/ha but this rose to 3.7 t/ha in 2010. The Aman yield fluctuated over the period but overall showed a gradual increase from 1.05 t/ha in 1972 to 2.19 t/ha in 2010. The Aus yield increased slowly over the period from 0.78 t/ha in 1972 to 1.64 t/ha in 2010.

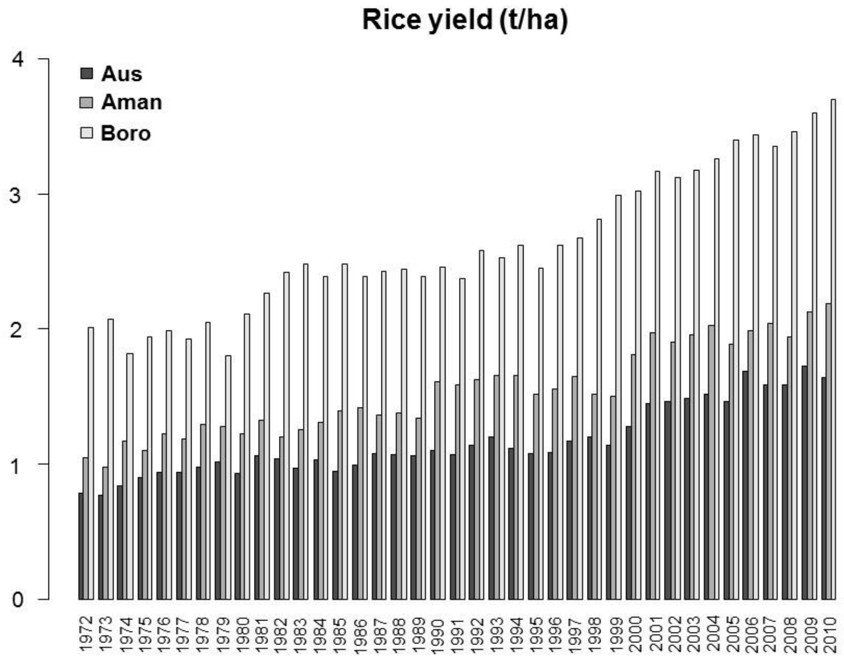

Figure 3.3 The temporal trend in rice yield (t/ha) for three rice ecotypes during the 1972-2010 period in Bangladesh.

3.3.3 *Climate variability in different rice growing seasons*

Temperature and rainfall vary across the Bangladesh for the different rice growing seasons (Figure 3.4). During the Aus growing season (March to August) most of the north western part of the country had high average temperatures (on average 28.04 to 28.74 °C) but received relatively low rainfall (on average 1228 to 1715 mm). For the Aman growing season

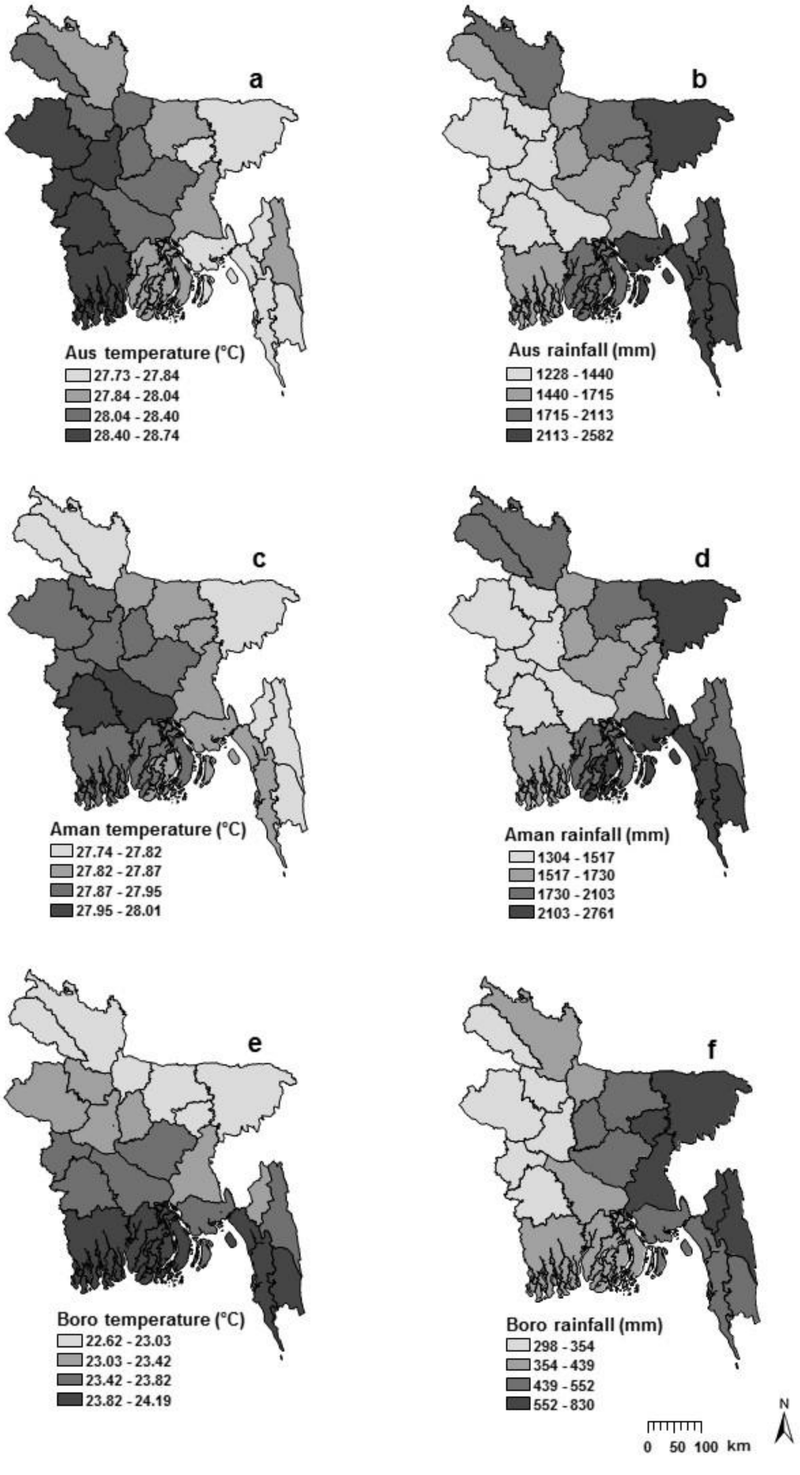

Figure 3.4 The spatial distribution of temperature (°C) and rainfall (mm) of three rice-growing periods in Bangladesh, averaged over the 1981-2010 period for three rice growing seasons; classes represent quartiles; (a) Aus temperature, (b) Aus rainfall, (c) Aman temperature, (d) Aman rainfall, (e) Boro temperature, and (f) Boro rainfall.

(June to November), Western areas had high temperatures, on average 27.87 to 28.01 °C temperatures during the study period. However, these areas received lower rainfall (on average 1304 to 1730 mm) compared with eastern areas (on average 1730 to 2761 mm). In the Boro growing season (December to May) most of the southern areas and Chittagong hill tracts in Bangladesh had high temperatures (on average 23.42 to 24.19 °C). During this season the Southern and entire north western areas of Bangladesh received low rainfall (on average 298 to 439, whereas the eastern areas and Chittagong hill tract received high rainfall (on average 439 to 830 mm). To understand the quantitative justification of climate impacts on Aus, Aman and Boro ecotypes individually, we estimated statistical models. The results are given below.

3.3.4 *Climate impacts on Aus yield*

The Linear Mixed Model results (Table 2) show the temperature and rainfall effects on Aus yield in Bangladesh nationally. These results show that temperature does not influence Aus yield whereas rainfall has a slightly positive correlation with rice yield ($p<0.08$). The marginal and conditional R2 values are 0.12 and 0.75, respectively. The fixed effects factors only account for 12% of the variance explained, the full model that includes districts as a random effect explains 75%. This demonstrates that the improvement of R2 is due to spatial differences.

Table 3.2 Results of mixed model analysis for Aus yield and climatic variables.

Variables	**Estimate**	**Standard error**	***p*-value**
Intercept	-30.530	1.744435	<0.001
Temperature	-0.003408	0.023035	0.882
Rainfall	0.000051	0.000029	0.078
Year	0.015963	0.000932	<0.001

3.3.5 *Climate impacts on Aman yield*

The influence of the growing season average climatic variables on the Aman rice yield is shown in Table 3. The impacts of both temperature and rainfall are negative, with temperature showing high significance at a p-value <0.001. The rainfall effect is not significant with a p-value of 0.28. Total 26% (marginal R2) and 90% (overall R2) of the variability in Aman rice yield is explained by the fixed factors and both fixed and random factors used in the model, respectively.

Table 3.3 Results of mixed model analysis for Aman yield and climatic variables

Variables	**Estimate**	**Standard error**	***p*-value**
Intercept	-56.05271	1.376545	<0.001
Temperature	-0.15090	0.025146	<0.001
Rainfall	-0.00002	0.000018	0.277
Year	0.03108	0.000900	<0.001

3.3.6 *Climate impacts on Boro yield*

The LMM results show the contributions of the climatic variables on the Boro yield and are presented in Table 4. Increased temperature has a positive impact on Boro yield (p-value = 0.05) whereas increased rainfall shows a small negative influence ($p < 0.1$). The fixed effects factors explain 49% of Boro yield variation with an overall R2 value of 91%.

Table 3.4 Results of mixed model analysis for Boro yield and climatic variables.

Variables	**Estimate**	**Standard error**	***p*-value**
Intercept	-97.83967	1.726650	<0.001
Temperature	0.03460	0.017666	0.050
Rainfall	-0.00010	0.000057	0.088
Year	0.05005	0.000871	<0.001

3.3.7 *Climate impacts on regional rice yield*

The results from the GLM model demonstrate the individual impact of temperature and rainfall on regional rice yields for the three ecotypes (Table 3.5). In general, Aus shows both positive and negative influence of temperature in different districts, Aman is mostly negative, whereas Boro has a more positive response to temperature. The impact of seasonal rainfall is negligible for the three ecotypes in all districts. As expected, there is a significant change of yield over time in all districts due to changes or improvements in regional rice cultivation management during the time of the study.

Table 3.5 Results of the generalized linear model analysis showing the coefficient of temperature effects on Aus, Aman, and Boro yields in the greater districts in Bangladesh.

Districts	**Aus**		**Aman**		**Boro**	
Bandarban	-0.06		-0.17	.	-0.04	
Barishal	0.05		-0.00		0.07	
Bogra	-0.14		-0.23	*	0.07	
Chittagong	-0.13		-0.16		-0.07	
Comilla	0.22	.	-0.12		0.06	
Dhaka	0.02		-0.15		0.06	
Dinajpur	-0.08		-0.33	***	0.20	***
Faridpur	-0.11		-0.02		0.05	
Jamalpur	0.01		-0.16		0.12	.
Jessore	-0.03		0.06		0.00	
Khagrachari	-0.11		-0.32	**	0.10	
Khulna	0.24	*	0.19		0.02	
Kishoregong	-0.00		-0.36	***	0.13	.
Kushtia	-0.06		-0.09		-0.04	
Mymensing	-0.05		-0.33	***	-0.00	
Noakhali	0.14		0.03		0.00	
Pabna	-0.06		-0.21	*	0.08	
Patuakhali	0.03		-0.16		-0.07	
Rajshahi	-0.04		-0.11		0.05	
Rangamati	0.01		-0.04		0.06	
Rangpur	-0.09		-0.11		0.09	
Sylhet	0.00		-0.24	**	0.00	
Tangail	-0.03		-0.04		0.05	

. Represents the 10% level of significance
* Represents the 5% level of significance
** Represents the 1% level of significance
*** Represents the 0.1% level of significance

The coefficients of the temperature effects on regional Aus yield are positive in nine districts. The *p*-values for two of these districts were statistically significant (Comilla and Khulna). The impact is negative in the other 14 districts, although the results for these districts were not statistically significant.

The coefficients of the temperature effects on regional Aman yields are negative in 20 districts. The *p*-values for eight of these districts were statistically significant: Bandarban, Bogra, Dinajpur, Khagrachari, Kishoreganj, Mymensing, Pabna, and Rangpur. The impact is positive in the remaining three districts, however the results for these districts were not statistically significant.

The impact of temperature is positive for the Boro yield in the 18 districts whilst the p-values for only three districts were statistically significant (Dinajpur, Jamalpur, and Kishoregong). The temperature effects are negative in five districts, none being statistically significant.

3.3.8 Regional variation of rice yield changes due to a 1°C temperature increase

The impact of the growing season average temperature on national rice yields for different ecotypes in the LMM models can be envisaged by calculating the rice yield changes in the model rice yield due to a 1°C temperature increase in Bangladesh. Figure 3.5 illustrates the rice yield changes in Bangladesh for three ecotypes nationally. The Aman yield change (-0.15 t/ha) is higher than the Aus and Boro yield changes, -0.003 t/ha and 0.03 t/ha respectively. This result demonstrates that, in the future, the national Aman yield will be more vulnerable to temperature increases than the Aus and Boro yields.

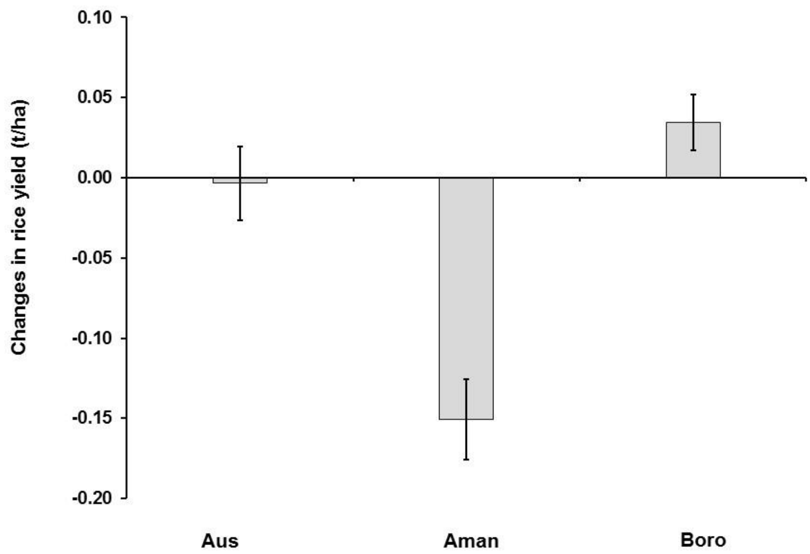

Figure 3.5 Changes in the modelled rice yield (t/ha) that arise from a 1°C temperature increase.

The regional variations of changes in the modelled rice yield for a 1°C temperature increase for Aus, Aman, and Boro in the greater districts is shown in Figure 3.6. The effect of seasonal temperature on the regional Aus rice yield is small in many districts, as is shown by the yellow areas on the map (Figure 3.6, Aus). The Aus yield is expected to decrease in four districts: Borga (-0.14 t/ha); Chittagong (-0.13 t/ha); Faridpur (-0.11 t/ha); and Khargrachari (-0.11 t/ha). The Aus yield is expected to increase in seven districts, and the largest increases will be observed in Comilla (0.22 t/ha) and Khulna (0.24 t/ha) where the temperature effect is statistically significant at the 5% and 1 % level respectively (Table 3.5). The Aman yield will decrease in all districts except Khulna, Jessore, and Noakhali (Figure 3.6, Aman). The temperature effect is statistically significant in Dinajpur, Kishoregang and Mymensing at the 0.1% level and the Aman yield will decrease by 0.33 t/ha, 0.34 t/ha and 0.33 t/ha respectively in these districts. Similarly, the Aman yield will decrease in Khagrachari (0.22 t/ha), in Sylhet (0.24 t/ha) at a 1% level of significance, in Bogra (0.23 t/ha) and Pabna (0.21t/ha) is at the 5% level of significance (Table 3.5).

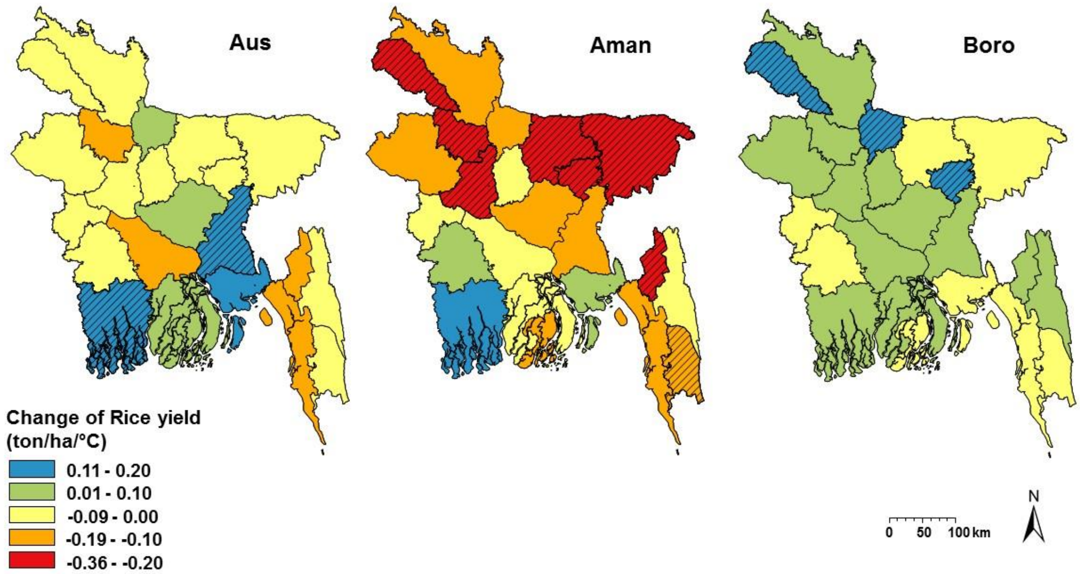

Figure 3.6 Regional variations in changes to the modelled rice yield (t/ha) for three ecotypes Aus, Aman, and Boro due to a 1°C temperature increase across Bangladesh. Districts with statistically significant temperature effects are highlighted with a diagonal line pattern.

The Boro yield, in contrast, will increase in most districts (Figure 3.6, Boro). The temperature effect is statistically significant for the Boro yield in the three districts of Dinajpur, Kishoreganj and Jamalpur and the Boro yield will increase at 0.20 t/ha, 0.13 t/ha and 0.12 t/ha respectively. The Boro yield is expected to decrease in Kustia, Chittagong, Bandarban, Sylhet, Mymensingh, Jessore, and Noakhali districts, however the temperature effects are statistically insignificant (Table 3.5).

3.4 Discussion

The present study has analysed the spatially variable climate impact on the rice yield for three ecotypes in Bangladesh using 30 years of historical records. There were strong differences in the growing season temperature and rainfall for the three ecotypes. We investigated the relationship between the climatic variables and the government rice yield statistics and our analysis showed that climatic variables have a substantial influence on rice yield. The temperature changes correlated more strongly with the rice yield than the rainfall. In addition, our results reveal different climatic influences for the three ecotypes and strong regional variations of rice yields across the country.

3.4.1 Regional variability of rice yield and climatic variables

The results from our analysis of the spatio-temporal changes to the rice yield indicated that rice yield varies in different areas for Aus, Aman, and Boro. Overall, there was a significant spatial pattern in the rice yield for these ecotypes, with the Aus and Aman yields being more favorable in the north western, eastern and Chittagong hill tracts in Bangladesh than in other areas. Most of the central part of the country was unfavorable for Aus and Aman yields. In contrast, Boro has mostly been grown in the western and central parts of the country. There are many possible factors contributing to rice yield variations across Bangladesh. These include many natural variables (e.g. topography, soil, drought/flood and climatic conditions), management factors (e.g. irrigation, use of fertilizer/pesticides) and agricultural technologies [e.g. ploughing methods and the use of High Yielding Varieties (HYV) /hybrid seeds].

The present study shows that the rice yield has increased over the period from 1971-2010 and that the Boro yield has increased to a greater extent, when compared with Aus and

Aman yields during this period. This increase in the Boro yield in Bangladesh is primarily due to the shift in Boro production from being rain-fed to using irrigation during the dry season (MoA 2014; Rahman and Mondal 2015).

3.4.2 Spatially variable climate effects

To assess the relative importance of the climatic variables on the rice yield, particularly temperature and rainfall, the coefficients resulting from the LLM model for each rice ecotype were used. Overall, our results demonstrate that temperature has a much stronger impact on rice yield than rainfall. These findings of the impact of climate on rice yield variability are consistent with the findings of the previous empirical study by Sarker et al (2012), using the time series data alone from the historic records to assess the impact of climate on rice yield nationally. However, our analysis is more robust than the previous study as our study also considers spatio-temporal variations. We found that when regional variations were considered in the GLM model, there were significant differences in the regional estimates, both in sign and size. Hence, the present study demonstrates more precise results about the impact of climate changes on rice yields than studies based on historic national records alone.

Our study shows the spatially variable climate impact on rice yield for three ecotypes individually. The LMM model firstly indicates the negative temperature impact on Aus, confirming previous studies that used climate scenarios to assess Aus yield changes (Karim et al. 1996; Ruane et al. 2013). On the other hand, rainfall impacted on the Aus yield positively, which is also consistent with previous results (Rimi et al. 2009; Sarker et al. 2012). Secondly, our results demonstrate that the Aman yield would be the most susceptible to climate change of the three rice ecotypes. We found a statistically significant relationship between the average temperature and the Aman yield with the impact being negative. Rainfall impact was also negative for the Aman yield. These results are consistent with the results of Amin et al. (2015). Similar results were found in the previous study based on climate change scenarios by MoEF (2005), which indicate that the rice yield variability would be higher for Aman due to climatic change. Thirdly, the growing season temperature was statistically significant for the Boro yield, with a positive impact. However, the impacts of temperature on the Boro yield were not consistent in previous studies, with some finding a positive impact for minimum temperatures (Amin et al. 2015; Sarker et al. 2012) and others finding a negative impact for maximum temperatures (Sarker et al. 2012; Rimi et al. 2009). Our results show that the impact of rainfall on the Boro growing season was statistically insignificant, as expected, since the Boro growing season usually receives little rainfall (Rimi et al. 2009; Basak et al. 2010).

3.4.3 Regional variations in future rice yield changes

The present study shows the regional rice yield changes in the greater districts of Bangladesh. Our results from the GLM model (Table 5) are based on the historic records of last 30 years and were used to predict regional rice yield changes in the future due to a 1°C temperature increase. Figure 3.6 presents the expected regional variations of rice yield changes for Aus, Aman, and Boro for this scenario. The Aman rice yield will decrease in most of the districts. Previous simulation studies produced similar results, showing that Aman rice would reduce in many areas in the country (Karim et al. 1996; Rimi et al. 2009; Ruane et al. 2013). Similarly, growing season average temperatures negatively impacted on the Aus rice yield in many districts, as found in previous studies (Rimi et al. 2009; Ruane et al. 2013; Karim et al. 1996). However, the Boro yield will gain benefit from increases in temperature in many districts, as found by Basak et al. (2010), whereas in some districts the Boro yield will reduce. The present study did not show the rainfall effects on regional rice yields as these effects were insignificant for all districts, with very little or no impact (the coefficients were too small to consider). Ruane et al. (2013) also indicated that the regional Aus and Aman yields were not impacted by the growing season rainfall levels. The Boro yield was typically influenced by irrigation management, rather than by the dry season's rainfall regimes (MoA 2014; Rahman and Mondal 2015).

3.4.4 Data limitations and uncertainties

Our study principally focuses on statistical analyses, using government records on rice yields and climate at a spatio-temporal level, with considerable uncertainties. We found the effect of the individual year was quite noticeable in the GLM model, which clearly indicates that there are several unobserved factors which increase the rice yield in different districts. We tried to control these unobserved factors by using the year effect in our models. The spatio-temporal data on many natural and management variables are unavailable for different rice ecotypes. For instance, spatial data is unavailable for management variables associated with rice cultivation for the ecotypes. Likewise, there was no record of the seasonal irrigation demands for different rice ecotypes by region during the study period. Moreover, time series data on the use of pesticides, fertilizer and improved seeds are limited for particular years. We tried to develop soil data on the basis of the category of soil profile including soil nutrients, soil moisture, and soil organic matter, at aggregated districts level by using GIS techniques. However, we found the soil data was too variable for different categories in various districts to use in the models. The present study considers climatic variables, particularly the average growing season temperature and rainfall. However, the impacts of extreme weather events, including drought and floods, which may become more frequent in many districts, were not quantified in the present study due to the lack of spatio-temporal data on these elements.

Climate impacts on agriculture are ambiguous because of the complex processes of both direct and indirect effects of weather on the rice yield (Sarker et al. 2012; Sarker et al. 2014; Amin et al. 2015), which may vary for different stages of growing seasons for all ecotypes (Basak et al. 2010; Mahmood et al. 2003). Moreover, using spatially weighted growing season average climate data at district level overlooked local micro-climate conditions in the present study. There is already evidence that a shortening of the rainy season, or heavy rainfall, high temperatures, cold waves or more frequent dry spells can all influence rice yields locally in certain districts in Bangladesh (Alauddin and Sarker 2014; Sarker et al. 2013). Disaster, regional management (Ara et al. 2016) and local microclimatic conditions (Alauddin and Sarker 2014) have become important indicators of change, which need further local investigation.

3.4.5 Policy implications for food security in terms of climate change

Climate-related changes may impact on food security, especially in regions with low agricultural inputs and highly variable climatic conditions. Our study modelled regional rice yield changes for a 1°C temperature increase across Bangladesh. The study illustrates a substantial variation in regional rice yield changes in the future for different ecotypes across the 23 greater districts of Bangladesh. Although climate change influence had been assessed previously at a broad scale in Bangladesh (Ruane et al. 2013; Sarker et al. 2014), the district-level assessment in this study will help to understand more details about future rice yield changes, so as to enable the taking of necessary actions, with different districts potentially employing different adaptation measures. Therefore, the present study cautions against country or state level general adaptation measures for climate change (MoEF 2005), which may be ineffective, and consequently suggests that there is a requirement for region-specific adaptation policies.

Improved governmental policies can certainly balance some of the adverse effects of climate change in different areas. Public and private investment in action-oriented adaptive research is required to support regional rice agriculture in the face of climate change. Priority should be given to research on varietal improvement, particularly in terms of temperature or drought tolerant rice varieties. Agricultural extension departments in Bangladesh can play a vital role in publicizing information about the use of newly developed rice varieties among farmers. Furthermore, the various adaptation measures should be monitored by the agriculture research and extension services in each districts.

Food security and rice agriculture are intimately linked to growing period trends. At present, farmers are trying to devise locally appropriate practices for rice cultivation in many districts of Bangladesh, to deal with local climate variability (Alauddin and Sarker 2014). Crop models suggest that adjustments to planting dates would increase rice yields in many districts (Basak et al. 2010; Mahmood et al. 2003). Therefore, technological improvements for the continued dissemination of this research to local farmers are necessary in Bangladesh. Region-specific adaptation measures, along with well-timed local climate information, will help farmers to cope with uncertain climate dependencies in the different districts of Bangladesh. Furthermore, various regional developments, including sustainable irrigation combining use the of both groundwater and surface water (Ara et al., 2016), moving rice production to other less intensively cultivated areas (Mainuddin and Kirby 2015) and various improved management practices are all needed to increase rice yields in the districts, which will in turn improve food security in the country as a whole.

3.5 Conclusions

The objective of the present study was to understand the spatially variable effects of climate change on rice yields for three ecotypes across Bangladesh. The overall findings reveal that the impact of climatic variables on rice yields were ecotype specific. The results demonstrate that the Aman yield was the worst affected ecotype, when compared with the

Aus and Boro yields. Based on past records, we estimate that there will be variable rice yield changes due to a 1°C temperature increase in the 23 greater districts. The temperature increase will adversely impact Aus and Aman yields in most of the districts, relative to Boro yield. Given this sensitivity to regional rice yield variations in the future, ecotype specific adaptation strategies need to be adopted urgently in different districts to combat climate change. Priority should be given to the disadvantaged districts where the rice yield will decrease noticeably. Adaptation strategies include the improved dissemination of climate information along with the development and introduction of new temperature-tolerant varieties in the different districts. However, substantial use of new varieties in different districts needs to be monitored continuously. For this, adequate investment and public-private sector involvement will be necessary over a significant time period. The spatially aggregated time series data used in the present study has primarily focused on climate variables alone. Due to a lack of data, the study did not consider other important variables, which contributed to higher yields in many districts during the study period. Therefore, future research should focus on both climate change and other variables to capture a more robust picture of regional rice yields for the ecotypes favoured across Bangladesh.

Acknowledgements

This research is funded by the Australian Government and the University of Adelaide through an International Postgraduate Research Scholarship (IPRS) and an Australian Postgraduate Award (APA) for the first author to pursue her Ph.D. Special thanks go to Ingrid Ahmer and Alison-Jane Hunter at the University of Adelaide for assisting in technical language editing. Acknowledgment is also made of the support from the Bangladesh Bureau of Statistics (BBS) and the Bangladesh Meteorological Department (BMD) in providing rice yield and climate data respectively, both of which were used as the basis of this research.

Statement of Authorship

Title of Paper	Spatio-temporal Analysis of the Impact of Climate, Cropping Intensity and Means of Irrigation: An Assessment on Rice Yield Determinants in Bangladesh
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Publication Style
Publication Details	Ara, I., Lewis, M., & Ostendorf, B. (2016). Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh. Agriculture & Food Security. 5(1), 1-11, doi10.1186/s40066-016-0061-9.

Principal Author

Name of Principal Author	**Iffat Ara**		
Contribution to the Paper	Conceived the study idea, data collection, model development, model application, analysis, critical interpretation and manuscript writing. I hereby certify that the statement of the contribution is accurate.		
Certification	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligation or contractual agreements with a third party that would constraint its inclusion in the thesis. I am the primary author of this paper.		
Overall percentage (%)	90%		
Signature		Date	14/04/2017

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:
i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. Permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	**Megan Lewis**		
Overall percentage (%)	3%		
Contribution to the Paper	Revised the manuscript critically for important intellectual content. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	6.4.17

Name of Co-Author	**Bertram Ostendorf**		
Overall percentage (%)	7%		
Contribution to the Paper	Supervised development of model, data analysis and interpretation, reviewed and edited manuscript. I hereby certify that the statement of the contribution is accurate.		
Signature		Date	14-4-17

Chapter 4

Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh*

Abstract

Rice (Oryza sativa) is the most important staple food for almost half of the global population. Improvement of rice yield is of global concern and is influenced by a wide variety of regional factors including climate and agricultural management. This research addresses the need to understand the relative influence of these factors and develop geographically-explicit determinants of rice yield across Bangladesh. The specific objectives of this study were (a) to assess spatial and temporal variation of rice yield, cropping intensity and means of irrigation, and (b) to evaluate the relative importance of spatio-temporal change of climate, cropping intensity and means of irrigation on rice yield. A database on rice yield, management practices (cropping intensity, and means of irrigation) and climate was collected from the Bangladesh Bureau of Statistics (BBS) and Bangladesh Meteorological Department (BMD) respectively for the years of 1981 to 2010. Linear mixed models were used to assess the influence of different determinants on rice yield. The results indicate that irrigation, particularly groundwater irrigation, had a stronger influence on rice yield than climatic conditions and cropping intensity in Bangladesh during the study period. Temperature and rainfall showed negative impacts on yield. Rice yield also declined when cropping intensity increased. Both climate and groundwater extraction need to be considered in future policy development. However, the current extraction rate of groundwater may not be sustainable in the future to increase rice yield. The study concludes that spatio-temporal differences in observed yield allow interpretation of potential determinants that are important for food policy development in Bangladesh.

---

* This chapter is based on:

Ara, I., Lewis, M., & Ostendorf, B. 2016. Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh. *Agriculture & Food Security* 5(1), 1-11, doi10.1186/s40066-016-0061-9.

4.1 Introduction

The effective management of natural resources and agricultural production depends on solid, geographically-explicit evidence (Ostendorf 2011). In order to devise regional development plans and successful agricultural policies, it is important to understand which factors influence the complex agriculture system in a region (Nasrin et al. 2015). The effects of climate variability and natural resources management are the key determinants for production in many agricultural systems (Qin et al. 2013; Iizumi and Ramankutty 2015; Omoyo et al. 2015). Resources management, mainly land and water management, seem to be the most influential determinants in many countries (Tong et al. 2003; Kumar et al. 2012; Diagne et al. 2013; Smilovic et al. 2015). It is acknowledged that variation of climate and agricultural management practices influence crop yield (Deryng et al. 2011). However, there is little systematic analysis on which factors determine regional agricultural production. In particular, little is known about the spatially variable determinants of crop yield and production for rice in South Asia, including Bangladesh.

Rice is the most important staple food for almost half of the global population (FAO 2011). Around 90 percent of the world's rice grows and is consumed in Asian countries and of them, Bangladesh is the fourth-highest rice producing country in the world (IRRI 2015). Rice is vital for Bangladesh as 150 million people depend on it for 70 percent of direct calorie intake (BBS 2005). Rice occupies 77 percent of the arable land in Bangladesh (BBS 2010) and the country contributed nearly 9 percent of the world's total rice in 2010 (IRRI 2015). Understanding of factors that influence rice yield in Bangladesh is critical because food security primarily depends on food availability through rice production.

There is substantial uncertainty about how climate and other variables affect rice yield and production in Bangladesh (MoEF 2005; 2009). Simulation models, such as Crop Environment Resource Synthesis (CERES) and Decision Support System for Agro-technology Transfer (DSSAT) generally predict a reduction of yield under future climate scenarios (Karim et al. 1996; Basak et al. 2010; Ruane et al. 2013). The response is dependent on rice eco-type, with rain-fed types showing negative temperature responses and mixed results for the irrigated variety Boro (Karim et al. 1996; Rimi et al. 2009; Basak and Alam 2013). At the broad scale, production will likely be reduced by an expected future increase in flooding events and potentially be increased by CO_2 fertilization (Ruane et al. 2013). In contrast, empirical analyses of government statistics relating rice yield historic records to climatic variables show positive past response of yield to higher temperatures for Aus and Aman varieties (Sarker et al. 2012; Sarker et al. 2014). However, the effect of rainfall in these empirical models is highly variable and differs significantly among regions and eco-types (Sarker et al. 2014).

Bangladesh has made remarkable achievements in rice production. Water management and cropping intensity have substantially influenced rice production in the country (Rahman 2010; Alauddin and Sharma 2013) and these may possibly impact rice production in future (Ahmad et al. 2014; Mainuddin and Kirby 2015; Mainuddin et al. 2015). During the 1990s, rain-fed agriculture shifted to irrigation-based agriculture utilizing both surface and groundwater. Presently, nearly 8.52 million hectares (64 percent of the total land area) are arable and of them, 6.15 million hectares are cultivated under different types of irrigation (power pumps, tube wells, canals and other forms) (BBS 2012). Bangladesh is now one of the highest users of groundwater irrigation in the world (Shah et al. 2006), delivered through power pumps and tube wells (Rahman and Parvin 2009). At present, groundwater irrigation covers 77 percent of the total irrigated area (BBS 2012). Furthermore, there is potential to intensify agriculture by increasing the number of annual crop harvest cycles using groundwater and surface water irrigation (Mainuddin et al. 2015; Rahman and Parvin 2009). However, how the area under different types of irrigation and the cropping patterns in different districts of Bangladesh has changed rice production has not been analyzed yet, although it is known that water requirement for rice production varies regionally (Alauddin and Sharma 2013). In addition, the combined effects of climate change, irrigation, and cropping intensity on rice yield have not been assessed, which has implications for food policy in the country (Rahman and Parvin 2009; MoFDM 2008). It is crucial to evaluate the factors which have influenced yield in the past in order to predict possible future trends in rice production for effective food policy development.

In the present study, we analyse the spatial and temporal variation of rice yield in Bangladesh for 30 years as influenced by the three important potential determinants climate, cropping intensity, and means of irrigation. The specific objectives of the study are (a) to assess spatial and temporal variation of rice yield, cropping intensity and irrigation types, and (b) to evaluate the relative importance of spatio-temporal change of climate, cropping intensity and means of irrigation on rice yield.

4.2 Methods

The geographic extent for the analysis is the entire country of Bangladesh at the level of 23 greater districts (Figure 4.1). Annual data of rice production, management (cropping intensity and irrigation), and climatic conditions were compiled for these districts for the period 1981 to 2010. The key sources of data are the Bangladesh Bureau of Statistics (BBS) and the Bangladesh Meteorological Department (BMD).

4.2.1 Rice production and yield

Bangladesh produces three eco-types of rice: Aus, Aman, and Boro. These three eco-types are grown in different seasons (BBS 2012) with varying needs for irrigation. Aus varieties are grown during the Kharif-I season (typically March to August) and potentially require irrigation water around planting time (Mainuddin et al. 2015). Aman varieties are grown during the Kharif-II season (typically June to November), and are predominantly rain-fed, although benefit from supplementary irrigation in case of shortage of water (R. Rahman and Mondal 2015). Boro rice is entirely dependent on irrigation and is grown during the Rabi season from December–March. Rice production and area under rice cultivation data for all eco-types for the 23 greater districts were sourced from Agricultural Statistical Year Books of Bangladesh, published by BBS from 1981 to 2010. Annual average rice yield (in t/ha) used in the models was then calculated as the sum of rice production for all eco-types divided by the sum of total area planted to rice in a year. It needs to be noted that the total cultivation area is generally larger than the geographic extent used for cropping (net cropped area) because different eco-types can be grown in sequence within a year, allowing multiple annual harvests. This is indicated by cropping intensity, as described below.

Figure 4.1 Spatial distribution of the 23 greater districts across Bangladesh and locations of climate stations (triangles) used in this study.

4.2.2 *Cropping intensity*

Cropping intensity indicates the number of harvest cycles that are undertaken per year in a given area. For each district and year, data is collected by the BBS about the geographic extent under single, double, or triple cropping regimes. The sum of areas under these different management regimes is net cropped area. Unfortunately, this statistic is only available aggregated for all types of crops and not for rice, but it is possible to assume that the data is representative for rice, because rice is the predominant crop in Bangladesh. Total cultivation area is estimated a weighted sum of single, double, and triple cropping areas with weights of 1, 2, and 3 respectively. Cropping intensity is then calculated as a percentage of total cultivation area divided by net cropped area.

4.2.3 *Irrigation*

Area under irrigation for each year was sourced for four categories: 1) power pumps/low lift pumps (methods used to lift surface water); 2) deep, shallow and hand tube wells (methods which pump groundwater); 3) canals (surface water irrigation using gravity) and 4) other methods (indigenous methods of surface water irrigation). This data was sourced from reports of Agricultural Statistical Year Books of Bangladesh, published by the Bangladesh Bureau of Statistics (BBS).

4.2.4 *Climate*

Station-based climate data was obtained from the Bangladesh Meteorological Department (BMD 2012). We used Kriging (implemented in ArcGIS) to interpolate the climate data spatially on a monthly basis for the years 1981-2010. Monthly rainfall and monthly mean minimum and maximum temperature was sourced for 31 weather stations (Figure 4.1) based on data availability for both rainfall and temperature during the study period. The monthly average temperature was estimated as the average of minima and maxima for the interpolation procedure. Spatially and temporally averaged annual rainfall (mm) and mean annual temperature (°C) were then extracted for each district and year during 1981 to 2010.

4.2.5 *Analysis*

Summary statistics of the data are presented in Table 4.1, illustrating the broad climatic characteristics and management practices (cropping intensity and means of irrigation as a percentage of area per total district land area) for the time period 1981 to 2010 at greater district level. However, these descriptive statistics do not provide any evidence of the influence of geographical variations in climate and management practices on rice yield. To build deeper understanding of how regional variations in climate and management practices influence rice production, the present study developed linear mixed model. For the models, we lumped the three categories 'power pump/ low lift pump', 'canals', and 'other' to represent surface water irrigation. All types of tube wells represent groundwater irrigation. We used percentage area per district of these two broad irrigation categories for the statistical analysis.

Table 4.1 Summary statistics for all variables used in the models (mean, standard deviation, minimum, and maximum.

Statistics	Mean	Std.dev.	Min	Max
Rice yield (t/ha) (Y)	1.96	0.53	0.85	3.25
Average temperature (°C) (T)	25.67	0.38	24.68	26.66
Total rainfall (mm) (R)	2319.7	563.8	1218.0	3873.3
Cropping intensity (% area) (CI)	170.3	22.9	125.0	222.0
Area under groundwater irrigation (% area) (GW)	17.26	18.80	0.00	73.00
Area under surface water irrigation (% area) (SW)	7.36	6.11	0.24	29.22

In the mixed model, rice yield (Y) was used as the dependent variable (eqn. 1); where i denotes different years (e.g. 1981-2010), j identifies the 23 greater districts, β and a represent the fixed and random effects regression coefficients, respectively, and ε_{ij} is the error term in the model. The independent variables in the model are average temperature (T), total rainfall (R), cropping intensity (CI), area as a percentage of district area under surface water irrigation (SW), area as a percentage of district area under groundwater irrigation (GW), and year. The greater districts are represented as binary dummy variables D_2 to D_k.

$$Y_{ij} = \beta_0 + \beta_1(T_{ij}) + \beta_2 sqrt(R_{ij}) + \beta_3 log(CI_{ij}) + \beta_4 log(GW_{ij}) + \beta_5 log(SW_{ij}) + \beta_6(year_{ij}) + a_2(D_{i2}) + \cdots + a_j(D_{ik}) + \varepsilon_{ij} \quad (1)$$

Prior to model development, we tested the distribution of both dependent and independent variables using the ladder approach (Tukey, 1977) and applied the most appropriate transformations (square root for R, and log transformation for CI, GW, and SW). The transformed variables were assessed for co-linearity using the Variance Inflation Factor (VIF) test in the R statistical package. None of the variables showed a VIF value above 5.

We also developed simple diagnostic linear models to assess the proportion of variance in yield that can be explained by different groups of determinants: climate (T, R) and management (CI, GW, SW). In addition, we tested the level of geographic variation that can be explained by districts (D).

In order to assess how much the change in rice yield was affected by the different determinants during the study period, we estimated rice yield change (Δy) relative to the change in the observations of independent variables (Δx_i) in the models. In order to standardize the magnitude of the variability of the predictor variables, we used one standard deviation for each predictor variable $s(x_i)$ (eqn. 2; see Table 1 for standard deviation of the independent variables). The standardized relative effect is then the product of the model coefficient β_i for any determinant multiplied by the standard deviation (transformed if appropriate) of x_i.

$$\Delta y = s(x_i) \cdot \beta_i \quad (2)$$

4.3 Results

4.3.1 Spatial and temporal variation of rice yield, cropping intensity, and irrigation types

Rice yield in Bangladesh gradually increased during the study period from 1.4 t/ha around 1980 to 2.7 t/ha in 2010 (Figure 4.2). Cropping intensity also increased initially but remained relatively constant between 1990 and 2005 (Figure 4.2).

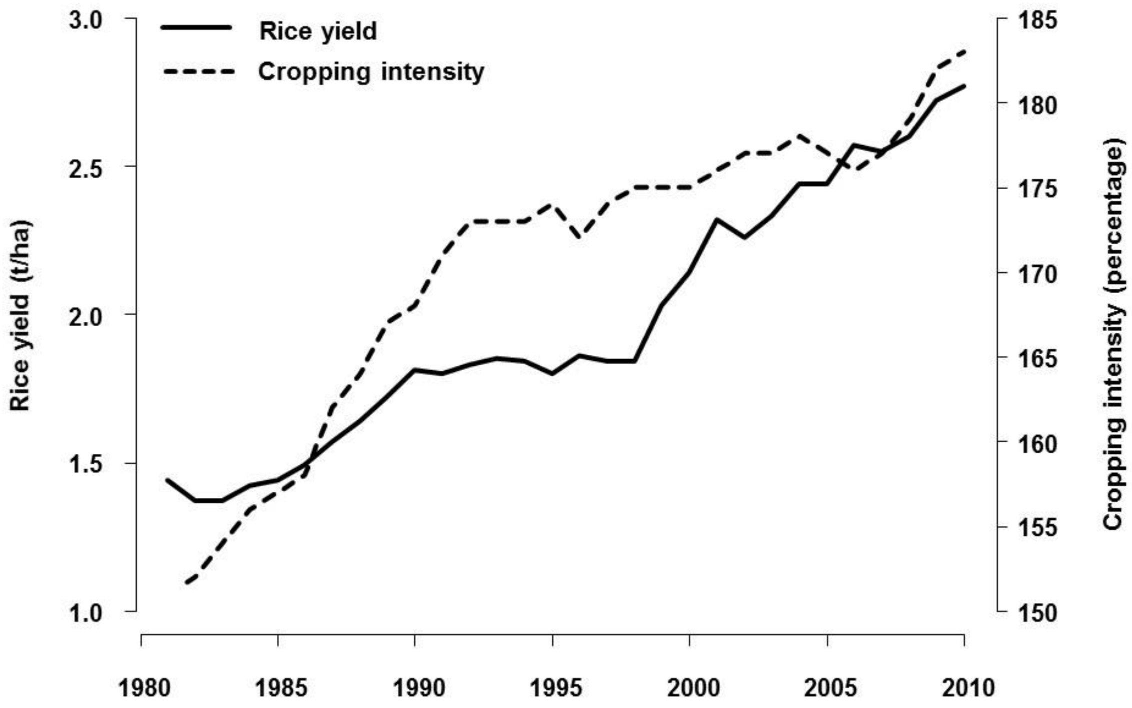

Figure 4.2 Temporal trends in rice yield and cropping intensity in Bangladesh over the periods of 1981-2010.

Total annual average rice yield, as averaged over the entire time period 1981 to 2010, shows high spatial variation across Bangladesh (Figure 4.3a).The highest yield was observed in western districts including Rajshahi, Bogra, and Jessore and the two hilly regions Chittagong and Khagrachari. These areas produced more than 2.12 t/ha rice on average over the period. Some eastern districts, the centre of the country and one of the southern districts (Khulna) had low to medium yields with 1.57 to 2.12 t/ha. Only Patuakhali and Faridpur districts had very low average rice yields of less than 1.57 t/ha.

Cropping intensity (average of 1981-2010) showed a different pattern (Figure 4.3b). It was highest in some of the northern districts including Comilla and low to very low in hilly regions (Rangamati, Bandarban, and Khagrachari), forested areas (Khulna) and coastal districts of Bangladesh. Other districts, mostly covering the centre of the country, had medium to high cropping intensities (Figure 4.3b).

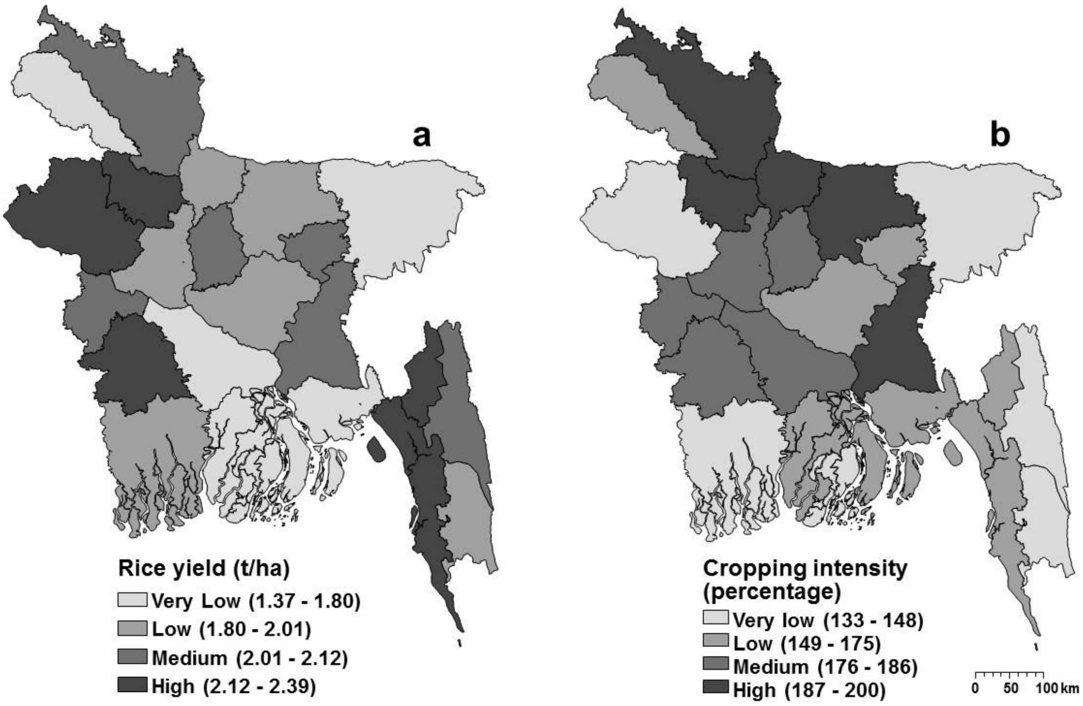

Figure 4.3 Rice yield (a) and cropping intensity (b) in Bangladesh averaged over the 1981-2010 period; classes represent quartiles.

Bangladesh experienced considerable changes in water management for irrigation during the study period with a substantial increase in the area equipped with motorized irrigation through tube wells (Figure 4.4). This was largely due to the dramatic increase in percentage of the land area irrigated by tube wells in Bangladesh, which increased from 1.73 to 27.65 (Figure 4.4). The area covered by power pumps/low lift pumps showed a slight increase while the area under canals remained constant over the time period. The percentage of area under 'other' means of irrigation gradually decreased as old indigenous water lifting methods were replaced by modern irrigation technologies.

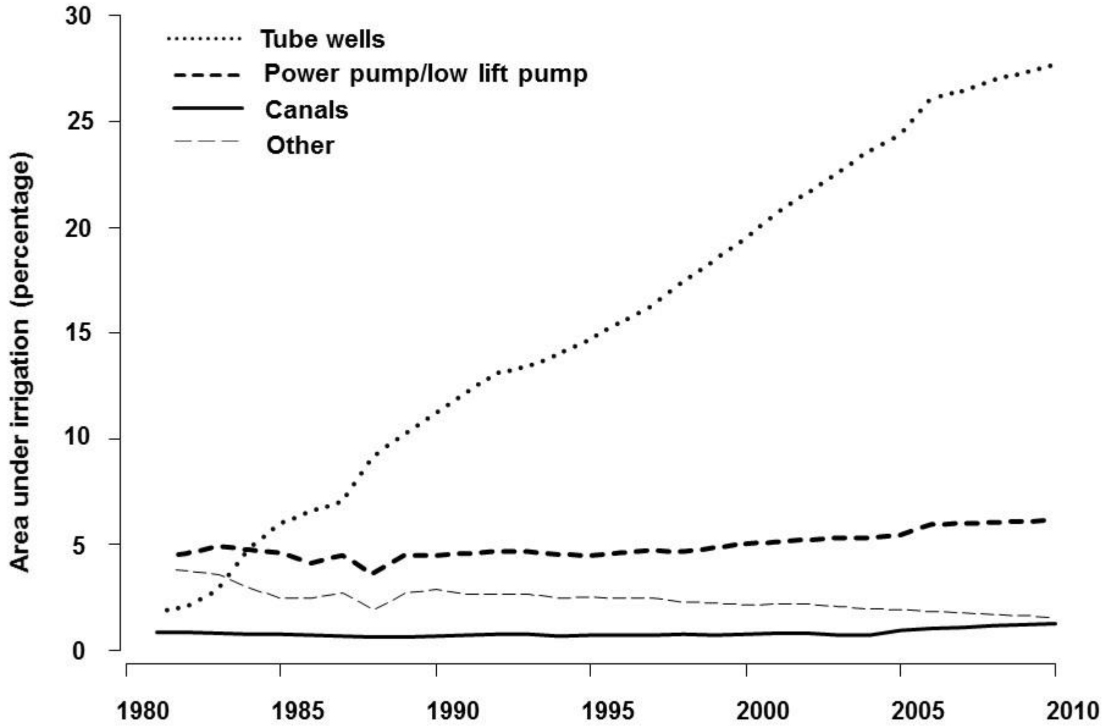

Figure 4.4 Temporal trends in different means of irrigation as a percentage of area under irrigation relative to the total land area of Bangladesh, 1981-2010.

Water management through different types of irrigation also varied regionally in Bangladesh in the study period. Most of the eastern and middle parts of the country were found to have high to very high proportions of area under power pump/low lift pump irrigation, except for three hilly districts (Rangamati, Bandarban, and Khagrachari) (Figure 4.5a). Other districts including the coastal areas had low to very low areas under power pump/low lift pump irrigation. Most of the northern and western districts have medium to high percentages of land under tube wells irrigation (Figure 4.5b). A different geographic pattern can be observed for surface water irrigation through canals: it was very low to low in most of the northern, northwest and central districts of the country (Figure 4.5c). Kustia, Jessore, and Chittagong districts were observed to be high for this category. Areas under other traditional forms of irrigation were generally low for the entire country except for Sylhet, Kishoreganj, Comilla, Rangpur and Rajshahi districts (Figure 4.5d).

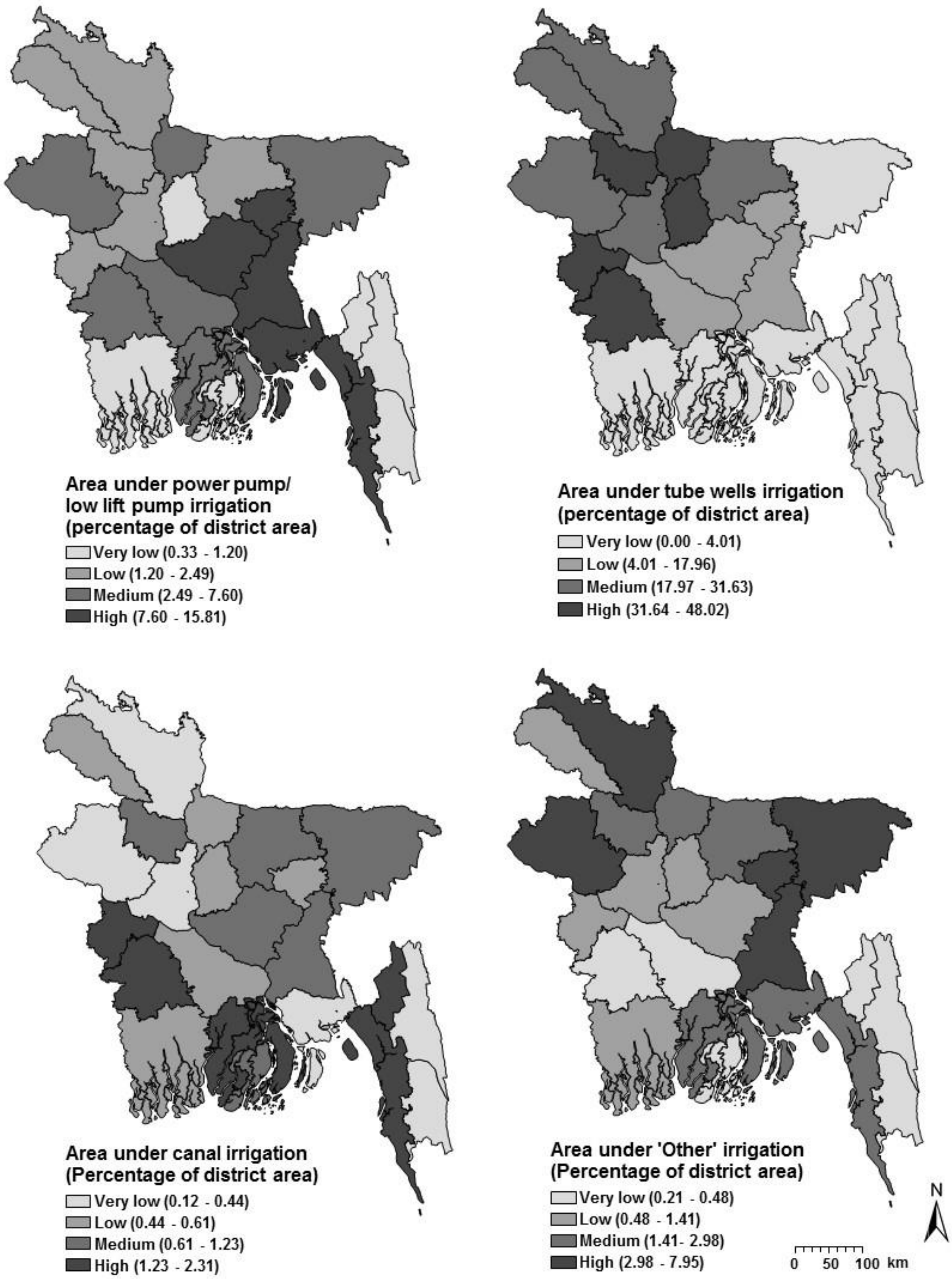

Figure 4.5 Percentage of district area under different types of irrigation in Bangladesh: power pump/low lift pump (a), tube wells (b), canals irrigation (c), and other (d), averaged over the 1981-2010 period; classes represent quartiles.

4.3.2 *Relative importance of rice yield determinants*

The results of the mixed model are shown in Table 4.2. Rice yield is negatively impacted by the climatic variables temperature and rainfall. Cropping intensity also has a significant negative effect. The contribution of water management through different types of irrigation to rice yields is prominent. Area under both groundwater and surface water irrigation exhibit strong positive effects in the model.

Table 4.2 Coefficients of the linear mixed model predicting rice yields from climatic and management variable.

Determinants	**Estimate**	**Standard error**	***p*-value**
Intercept	-68.380	2.631	0.000
Temperature	-0.134	0.031	0.000
Rainfall	-0.005	0.002	0.012
Cropping intensity	-0.989	0.149	0.000
Area under groundwater irrigation	0.584	0.036	0.000
Area under surface water irrigation	0.223	0.069	0.001
Year	0.038	0.001	0.000

The effect plots for rice yield show the model response to the determinants and illustrate the response and variability of rice yield in the model (Figure 4.6). Temperature and rainfall have a negative effect on rice yield, but the large error bands indicate a high level of uncertainty in the model. Increasing cropping intensity reduces yield in the model. Irrigation through groundwater has the strongest positive influence with the largest effect at low rates of the area under this category. Increased area of surface water irrigation also impacts positively on rice yield.

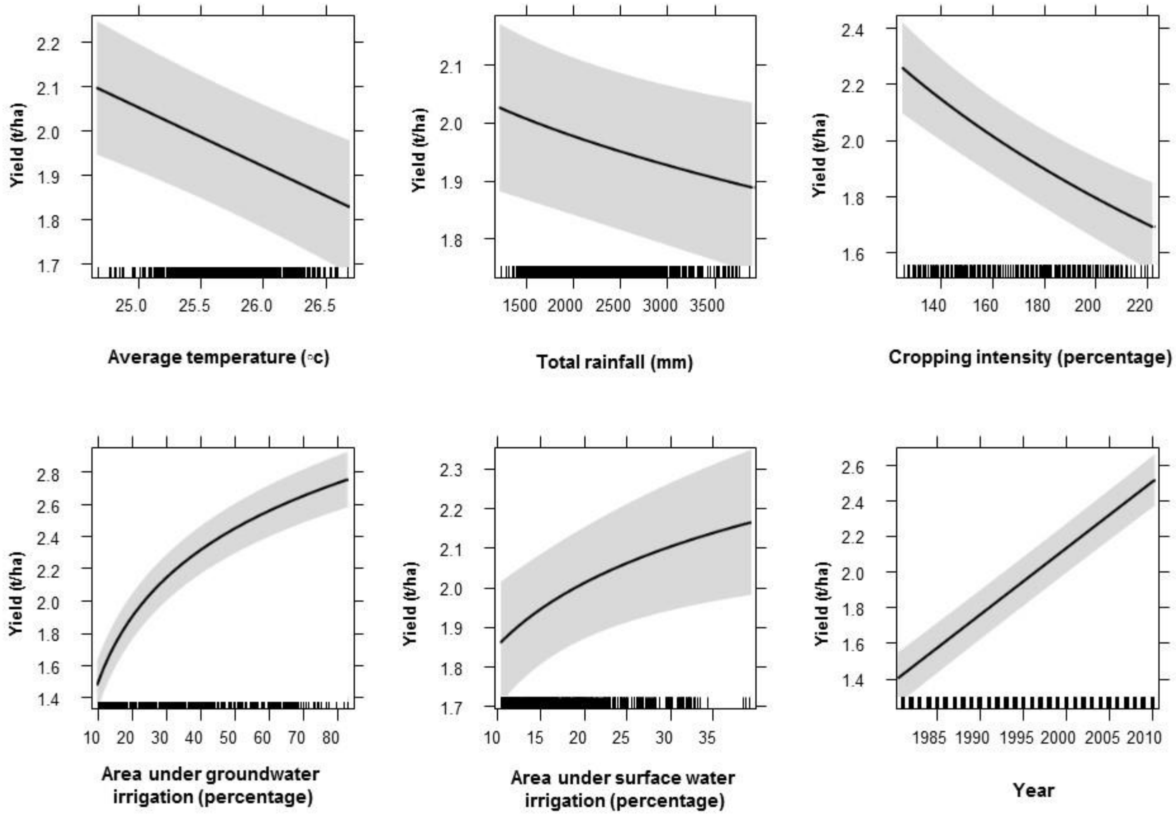

Figure 4.6 Effect plots for rice yield determinants in Bangladesh (1981-2010). The shaded bands show 0.95 confidence limits for the effects.

In addition to the mixed model, we also used simple linear models to assess the variability that can be explained by different groups of determinants (Table 4.3). The simplest model using only climatic variables explains 62 percent of the variation in rice yield. Using only management, the R^2 of the linear model is 66 percent. Combining climatic and management determinants produces a model that can explain 67 percent of the rice yield variation. A further 22 percent of the variation can be explained including different districts, suggesting a remarkable impact of districts on yield through regional conditions. The model comparison (Table 4.3) shows a substantial reduction of AIC (Akaike Information Criterion) values with increasing model complexity. This demonstrates that the improvement in R^2 is not simply due to an increase in the number of model variables but that 'Management' and particularly 'Districts' are important determinants of rice yield.

Table 4.3 Comparison of separate models predicting yield using different indicator categories

Models	**Adjusted R^2**	***p*-values**	**AIC**
Climate	0.62	0.000	407.16
Management	0.66	0.000	317.55
Climate + Management	0.67	0.000	307.46
Climate + Management + Districts	0.89	0.000	-453.70

The relative influence of the determinants of yield in the model can be effectively visualized by showing the changes in the modeled rice yield that arise from changes in the predictor variables, shown in Figure 4.7. Average temperatures show a small negative impact on rice yield, with a 0.05 t/ha decrease of rice yield observed for a temperature change of 0.38 °C. Rainfall produces a very small reduction of 0.03 t/ha in yield. Also, increasing cropping intensity corresponds to a slightly reduced rice yield. Increasing the area under groundwater irrigation show the strongest effect of an increase of yield 0.17 t/ha and Increasing the area under surface water irrigation was also beneficial, contributing to a small increase of 0.03 t/ha rice yield.

4.4 Discussion

The present study has analysed the factors that have influenced the spatial and temporal variation of rice yield in Bangladesh from 1981-2010. The results show substantial changes in space and time that can be correlated with climate variables, cropping intensity, and water management practices through groundwater and surface water irrigation. Our analysis shows that management of water resources under groundwater irrigation had the strongest positive effect on rice yield during the study period. Climate variables and increased cropping intensity show a negative relationship.

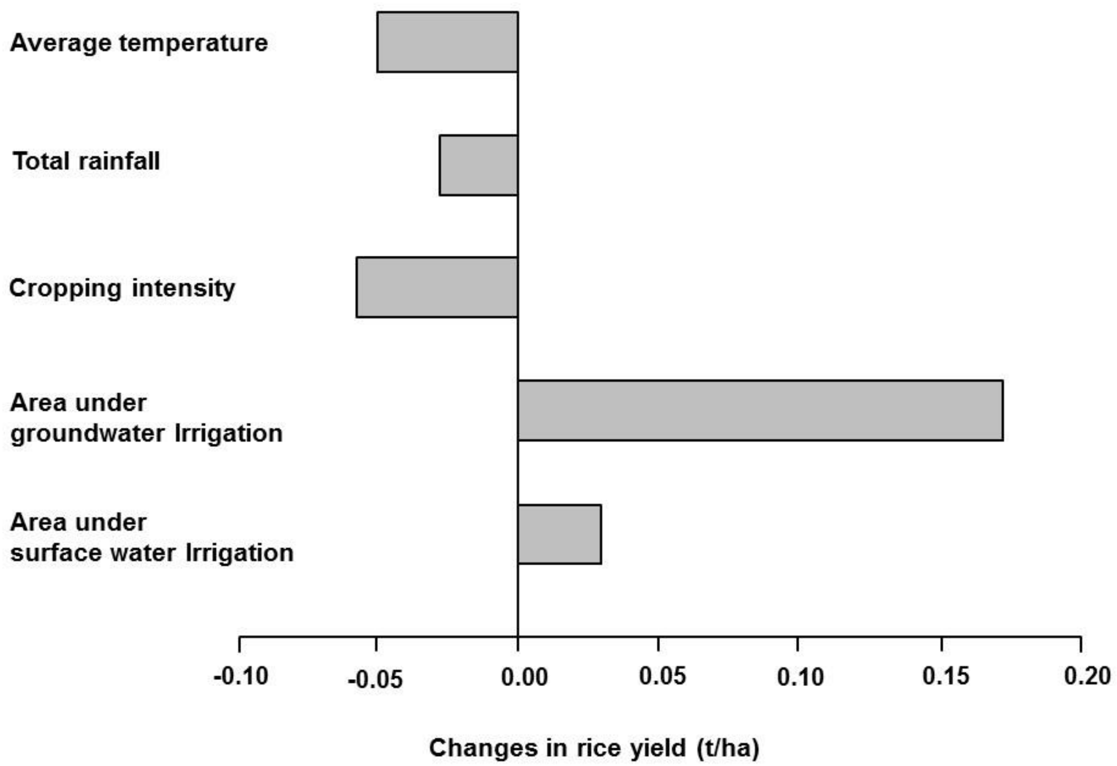

Figure 4.7 The relative effect of rice yield determinants. This figure shows the changes in the modelled rice yield (t/ha) that arises from standardized changes in the predictor variables.

4.4.1 Irrigation

Overall, the results demonstrate that water management affected rice yield very strongly in Bangladesh during the study period. Increased area under groundwater irrigation is most influential in our models. The area under surface water irrigation also positively influences rice yield, but the effect is smaller because of a limited increase in the area in this category during the study period. Further, the present study illustrates that means of irrigation varied regionally (Figure 4.5). Tube well irrigation had the highest area (up to 48%, Figure 5b) with distinct geographic differences because groundwater is more accessible in North Western districts (Jahani and Ahmed 1997; Rahman and Mahbub 2012). In contrast, southern districts are more susceptible to salinity intrusion than any other parts of the country (Habibullah et al. 1998; Mondal et al. 2001), resulting in a lower use of tube-wells (Figure 5b).

4.4.2 *Climatic variables*

Yield shows a negative correlation with temperature and rainfall during the study period. This corresponds with findings from simulation models, which indicated a decreased rice yield under temperature increase in future scenarios of climate change (Karim et al. 1996; Rimi et al. 2009; Basak et al. 2010; Basak and Alam 2013; Ruane et al. 2013). The temperature effect in the model is not strong, with a slope in the model of approximately 0.14 t/ha rice yield per 1 degree °C. The effect of rainfall on yield is also negative. Whereas the intensity of disasters, especially drought, and flooding may affect rice yield regionally (Shah et al. 2006; Ruane et al. 2013), data was not available at the spatial and temporal resolution and extent of the present study. Hence, our results need to be treated with some level of caution. There is also a strong unexplained temporal trend in yield as indicated by the significant effect of time in the model. Temperature has increased during the study period and this could potentially cause spurious effects in the model.

4.4.3 *Cropping intensity*

Cropping intensity increased substantially during the study period from 151% in 1981 to 183% in 2010 with relatively stable conditions during 1990 to 2005. Cropping intensity had a small but significantly negative effect on yield during the study period. This may initially seem counterintuitive, as clearly, the increase in cropping intensity was a major contributor to food security nationally (Ahmad et al. 2014). Whilst we find that cropping intensity has a negative effect on yield in the models, this does not contradict the fact that production is positively influenced by cropping intensity because cropping intensity implies an increase in the number of harvests. Also, cropping intensity and yield are positively correlated in one-dimensional models, but once irrigation is included as covariate in multivariate models based on our dataset, the correlation between cropping intensity and yield changes. Our results show that the effect of irrigation on yield outweighs the effects of cropping intensity and, in fact, turns it slightly negative. A possible explanation may be that in those districts with a low cropping intensity, where production depends on one or two crops per year, farmers may consider a more intensive cultivation. However, there is little data to underpin this possibility and the effect in the models is small.

4.4.4 Modelling issues and data limitation

The results also indicated that the empirical models developed in this study are underspecified since we were not able to include several variables that are known to influence regional rice yield because information is unavailable. A large amount of additional variance was explained by simply adding districts as an independent variable to the model. This indicates that there are strong regional differences in rice yield, which cannot be quantified due to lack of spatio-temporal data on these variables. Likely candidates for these variables are biophysical environmental conditions such as soils and management factors that relate to intensification. Potentially important are the use of fertilizer and pesticides, ploughing practices, the quality of seeds, or the record of adoption of high-yielding rice varieties in different areas in Bangladesh. This lack of additional spatio-temporal information is likely the most critical weakness in our models.

4.5 Conclusions

The present study has analysed the combined impact of climate and management practices on rice yield in Bangladesh. Area under irrigation had a far stronger effect on rice yield in Bangladesh than climatic variables and cropping intensity during the study period.

Our study indicates that in particular groundwater dependent irrigation through tube wells appears to be the dominating factor for rice yield differences in space and time. The result is alarming because it indicates that the recent production level is only sustainable if the area under groundwater irrigation can be maintained. Therefore it is crucial to continue to utilize groundwater for irrigation. However, there is already evidence of over-exploitation of groundwater in some areas and there are concerns that the current pumping rates may not be sustainable (Ahmad et al. 2014). Further increasing of area under groundwater irrigation is a challenging task and some areas may even need a reduction in groundwater irrigation because aquifers are overused. In contrast, surface water irrigation was relatively constant during the study period. Both groundwater and surface water salinity are a major concern for irrigation development in coastal areas, limiting further expansion of land under irrigation in these areas that make up 30 percent of the total cultivable land (Rahman and Mondal 2015) of Bangladesh. In addition, groundwater extraction through tube wells increases the risk of arsenic contamination in many parts of the country and industrial pollution may deteriorate surface water quality for irrigation (Rahman and Monda 2015). Worse, production needs to be increased to compensate future population growth in Bangladesh (Mainuddin and Kirby 2015). Therefore, policies need to incorporate water management options critically in different districts by combining groundwater with the use of other water sources for irrigation. This puts substantial pressure on policy development because of the need to consider conflicting interest on the use of water resources, supporting more efficient and sustainable use of water and environmental stewardship (Rahman and Mondal 2015) to ensure future food security.

Although the effect of climatic variables was much smaller than water management variables, it is an important consideration for the future sustainability of rice production in Bangladesh. Whilst future weather conditions cannot be controlled, adaptation to changes in climate may be possible through different varieties or space-specific changes in management practices (i.e. irrigation, fertilization, timing, etc.) in order to compensate for the negative effects on food security in a long run (MoEF 2005; 2009; MoFDM 2008). Climate change effects such as extreme events (flooding, drought), not considered in the present study, may also influence rice production in different areas. However, climate change may impact seasonal climatic conditions, affecting the rice eco-types differently (Sarker et al. 2012) highlighting the need to assess rice eco-types specific impacts explicitly in future studies.

The importance of region-specific effects (only crudely incorporated as districts in the present study) may also be seen as evidence that regional conditions should be considered importantly in food policy. Our results indicate that the best management practices and adaptation measures will likely vary spatially, requiring region-specific policies in order to sustain the country's food security. Specific regional differences due to bio-physical, infrastructure, and management variables may also impact rice cultivation regionally, but could not be included into our study. Furthermore, cultivable area of the country is declining at a rate of 1 percent per year (Mainuddin and Kirby 2015) further increasing pressures from different conflicting potential land uses.

The study underpins the important role that water management has played in food security for Bangladesh and it indicates that there is scope for improvement in rice yield by understanding the region-specific limitations and how they can be overcome.

Acknowledgements

This research is funded by the Australian Government and University of Adelaide through an International Postgraduate Research Scholarship (IPRS) and Australian Postgraduate Award (APA) for the first author to pursue her Ph.D. The lead author is particularly thankful to Dr Margaret Cargill, a research communication specialist at the University of Adelaide, for review of this manuscript. Special acknowledgment goes to the Bangladesh Meteorological Department (BMD) for providing climate data.

Chapter 5

Econometric assessment on household calorie consumption and income in Bangladesh: a case study in Northwest region, using sustainable livelihood framework *

Abstract

There are growing concerns about food security and sustainable livelihoods in developing countries. However, attempts to quantify sustainable livelihood outcomes for food security are limited and tend to relate their outcomes to human activities offered by household and natural resources, particularly in the North West region of Bangladesh. In this study, the spatial variations of household socio-economic conditions and regional resources were assessed to understand the impact of these factors on food security by using a sustainable livelihood framework. The household socio-economic data was collected from the Bangladesh Household Income and Expenditure Survey for the year 2010. The study also used spatial information characterizing variations in regional resources across the North West districts from multiple sources. The Least Square Dummy Variable Model (LSDVM) is applied to measure calorie consumption and income as a means of food security assessment. The results of the study help to identify key household and regional capitals of nutrition consumption and income. The outcomes also compare the natural, financial, human, social and physical capitals that influenced the calorie consumption and income variations. The physical and natural capitals exhibited a much greater share of explained variations in nutrition than in income. Financial and human capitals are the catalysts for determining household income. The study recommends policy responses for food security in terms of sustainable livelihoods, focusing particularly on income-generating opportunities and the development of human resources and controls for bio-physical limitations, so that people can achieve better livelihood choices in the North West region of Bangladesh. These solutions will help to advance household socio-economic conditions and regional abilities, as well as improve access to necessary capitals for food security in the North West region of Bangladesh.

---

* This chapter is based on:

Ara, I., Connor, J., Kandulu, J & Ostendorf, B. 2017. *Manuscript under preparation*. An econometric assessment of household calorie consumption and income in Bangladesh: a case study in the Northwest region, using a sustainable livelihood framework. *Food Security*.

Ara, I., J. Connor, J., Ostendorf, B., & Kandulu, J. 2014. Econometric assessment on livelihood outcome. In Mainuddin, M., Kirby, M., Walker, G. & Connor, J (Eds). Sustainable Water Resources for Food Security in Bangladesh (pp. 69-85). CSIRO Sustainable Development Investment Portfolio Project. CSIRO Land and Water Flagship, Australia.

5.1 Introduction

Food security in developing countries is a major global concern. The difference in the standard of living and food consumption between rich and poor nations is increasing. Both global and national level initiatives are necessary to reduce this gap. Hence understanding the causes behind this gap is important in many developing countries including Bangladesh, where food security problems are still unresolved because of a lack of knowledge of human wellbeing to get enough food. Many studies, globally, show that human wellbeing depends on having a sustainable livelihood, including financial, human, physical, natural and social capitals (Hesselberg and Yaro 2006; Jansen et al. 2006; Soini 2005; Soltani et al. 2012). These capitals may also influence human wellbeing as well as food security in Bangladesh. However understanding the key capitals and the influence of these capitals on food security is still unaddressed in the country.

Livelihood capitals are considered as important in many countries for policy development, in order to manage these elements appropriately for human wellbeing. For instance, natural and human capitals were found to be the most influential determinants for livelihood outcomes in Tanzania (Soini 2005). Natural capitals, such as forest resources, contribute positively to livelihood (Babulo et al. 2008; Kristjanson et al. 2005; Soltani et al. 2012). Although natural capital has a positive impact on livelihood outcomes (Fang et al. 2014), the livelihood strategies based on natural resources, like topography and forest degradation, are hard to manage. On the other hand, human capitals, which have the strongest impact on livelihood, can potentially be improved through substantial investment in making people more efficient for different economic activities through training (Jansen et al. 2006). Livelihood is also impacted by the physical capitals, such as remoteness (Hesselberg and Yaro 2006) and access to irrigation (Sellamuttu et al. 2014), which are also possible to organize though government level policies. Previously, many studies have focused on national and household level food security in Bangladesh and provided relative solutions in terms of policy development (Hossain et al. 2005; Thorne-Lyman et al. 2010; Bose and Dey 2007; Faridi and Wadood 2010; Mainuddin and Kirby 2015; Rahman and Parvin 2009). However, none of the previous studies applied a sustainable livelihood framework to understanding livelihood outcomes in Bangladesh in order to improve food security. A few studies focus on livelihood and food security based on social capital alone

(Ali 2005), which is inadequate to understand livelihood outcomes. Understanding livelihood outcomes has the potential to contribute knowledge to food policy development (Haidar 2009; Burchi and De Muro 2015). Although the Bangladesh government has initiated policies and action plans to improve food security in the past (MoFDM 2006, 2008a, 2008b), financial, human, physical, social, and natural resources limit the outcomes of these initiatives. Identifying key livelihood capitals for food security and decisions about investment on the sustainable use of these capitals through policies may potentially improve livelihoods as well as food security throughout the country.

Understanding livelihood determinants under various forms of livelihood capitals is challenging because many aspects of spatial setting, household character, natural resources and broad economic drivers influence livelihood outcomes. A number of studies globally have focused on various livelihood determinants (Scoones 1998; Jansen et al. 2006; Senaratna et al. 2014; Soini 2005; Soltani et al. 2012; Hesselberg and Yaro 2006), but provided very limited accounting for geography as a determinant of livelihood outcomes. The regional variations of these determinants need further attention to advance livelihood outcomes. There is limited investigation globally on how spatially heterogeneous geographical characteristics influence livelihood outcomes. A spatial analysis may help in understanding the impact of regional variations of different determinants on livelihood outcomes and this has not yet been completed in many developing countries, including Bangladesh.

Most livelihood analysis globally to date has only considered household assets to assess livelihood outcomes; in particular, income and poverty as measures of household wellbeing (Kristjanson et al. 2005; Senaratna et al. 2014; Soltani et al. 2012). However, as many households in developing countries attain substantial livelihood resources from their own production of food (Bushamuka et al. 2005), fibre and income may not be good indicators of livelihood outcomes. How nutritional outcomes could be used as another means of better livelihood analysis remains unaddressed globally. In Bangladesh, many studies analyse household calorie consumption (Faridi and Wadood 2010; Bose and Dey 2007; Thorne-Lyman et al. 2010). Household income variations have also been assessed in the country (Hillbruner and Egan 2008; Hels et al. 2003; Frongillo et al. 2003). However, both calorie consumption and income could be used as important indicators of livelihood outcomes that have yet to be considered. An assessment is therefore necessary in order to understand livelihood outcomes relative to calorie consumption and income.

In Bangladesh, the North West (NW) region in particular is highly productive in terms of agriculture. The area is considered as one of the key low food security regions (GoB and WFP 2004), where livelihoods primarily depend on agricultural activities. The NW is often affected by the recurrence of "*Monga*' events (local food security incidents) because of the seasonal unemployment of agricultural day labourers and disadvantaged socio-economic groups for specific periods within each year since 1990 (Elahi and Ara 2008; Zug 2006). The region is frequently affected by natural disasters, including flood and drought (Shahid 2008; Shahid and Behrawan 2008; Shahid and Hazarika 2010), and these may possibly influence livelihoods. The influence of disaster on livelihood choices has been observed and it has been found that hurricanes affect livelihood outcomes in Nicaragua (Van den Berg 2010). Very few studies have evaluated the impact of disasters as a factor of livelihood analysis globally. Studies have been done in Bangladesh to understand the impact of flood on poverty (Brouwer et al. 2007), agricultural income (Banerjee 2007) and child nutrition (Ninno and Lundberg 2005). However, little attention has been given to understanding the impact of natural disasters on livelihood outcomes. Natural disasters should be included in livelihood analysis as a variable to determine the livelihood outcomes appropriately in the country.

A sustainable livelihood framework is recommended for application to food security assessments in a region where a community lives with high level of commonality (FAO 2015). Thus the present study has considered the North West region of Bangladesh as a test site. The study uses a sustainable livelihood framework and considers regional variations of household socio-economic assets and regional resources. The study aims to examine the potentials of the food policy development by recognizing key household and regional resources for better livelihood outcomes. The specific objectives of the study are: (1) to identify key livelihood capitals and determinants for calorie consumption and income; (2) to understand and compare the influence of key livelihood determinants on calorie consumption and income and (3) to provide recommendations for policy developments for sustainable livelihoods, in order to improve food security.

5.2 Methods

5.2.1 Study area

The study area comprises of 16 districts of the NW in Bangladesh (Figure 1), encompassing 3.45 million ha (BBS 2010a). The area is bounded by the river Jamuna to the east and the Ganges to the south. The physiography of the area is principally covered by the river floodplain, old Himalayan piedmont plain and Barind tract. Of these, the Barind tract is an uplifted terrace of Pleistocene sediments that is at a higher elevation (37 meters above sea level) (Figure 1) than the rest of the country (Harun-ur-Rashid 1991; Brammer 1996). The economy of the area heavily depends on agriculture: nearly 75 per cent of the land is used for agriculture in the NW. About 59 per cent of the cultivatable land is under irrigation and nearly 75 per cent of irrigation water comes from groundwater (BADC 2005). Livelihoods in the NW depend on agriculture, especially groundwater irrigation. The Barind Multipurpose Development Authority (BMDA) has been operating about 13,000 Deep Tube Wells (DTW), together with another 1,34,884 Shallow Tube Wells (STW), which together provide irrigation facilities in the region (BMDA 2006). The installation of pumps by local farmers is inappropriate and water is lifted without care and consideration of the ground sources due to a lack of proper knowledge and modern technologies. These errors may impact on livelihood as the water table is declining at an alarming rate in the NW of Bangladesh. To further understand the spatial differences of its topography, the NW area is divided into three sub-regions and these are used as dummy variables: the Northern part of the North West (Pachangarh, Thakurgaon, Nilphamari, Lalmonirhat, Kurigram, Rangpur, and Gaibandha); the central part (Barind Tract) of North West (Dinajpur, Joypurhat, Bogra, Naogaon, Nawabganj, and Rajshahi); and the Southern part of the North West districts (Sirajganj, Nator and Pabna).

5.2.2 Data Sources

The present study used the 2010 Bangladesh Household Income and Expenditure Survey (HIES) data to consider household socio-economic assets. Spatial information from a number of sources and was compiled to characterize district geographical features.

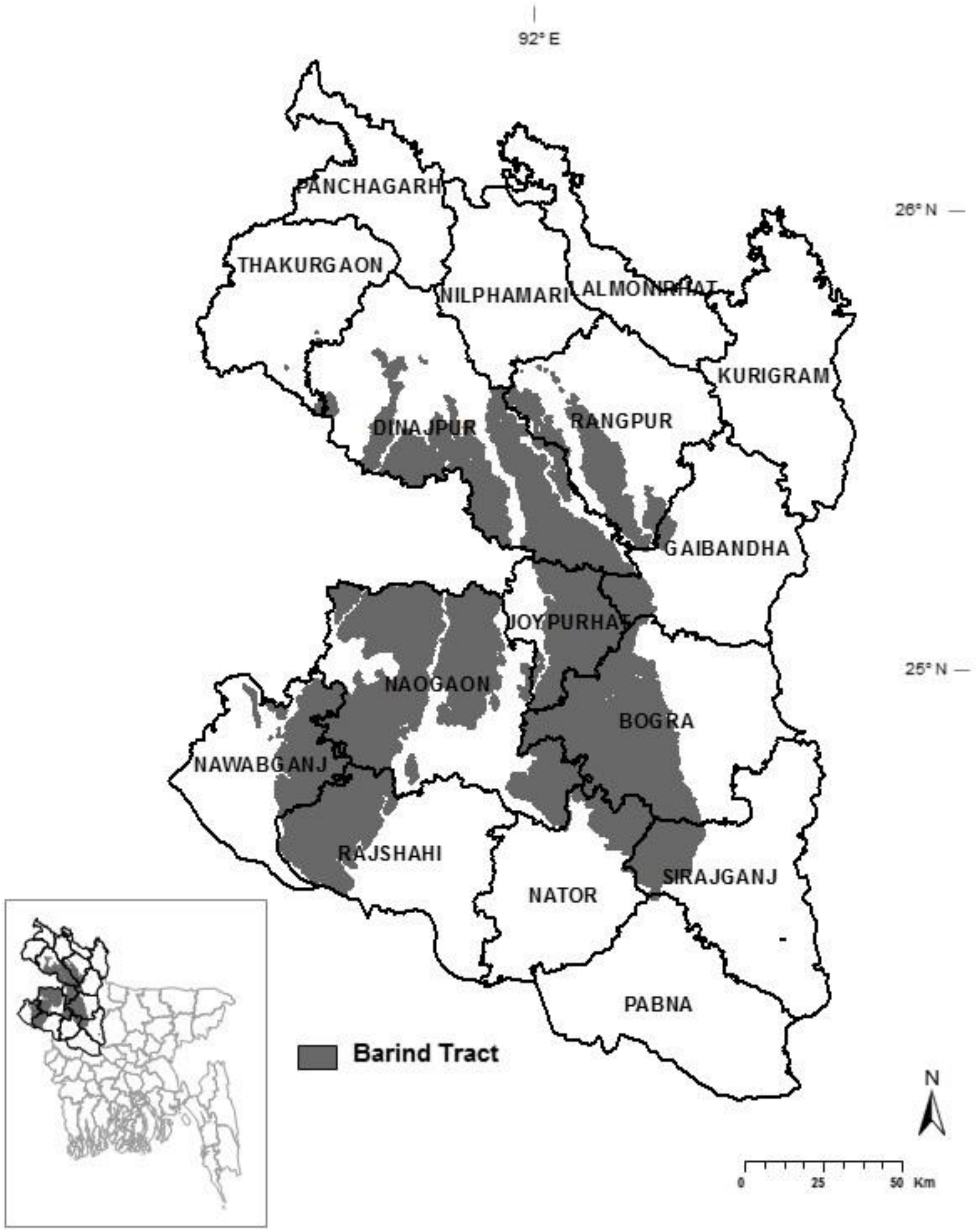

Figure 5.1 Location of the study area in Bangladesh with the grey areas representing the Barind tract in the North West region of Bangladesh

5.2.3 *Household data*

The HIES (2010) data provided information on household assets including demographic characteristics, income, health, education, assets, employment, micro-credit, migration, remittance, the social safety net and exposure of the household to natural disasters, including flood and drought (BBS 2010b). The national sample of over 12,240 households is stratified geographically and the present study focuses on the sub-sample of surveyed households that are located in the North West districts of Bangladesh, as shown in Figure 5.1.

5.2.4 *Regional data*

District biophysical data was collected from different sources. This included measures of the extent and depth of land inundation during major flood events and the proportion of the area under severe drought conditions. Information on the extent and depth of land inundation during major flood events in 1998 was collected from the Centre for Geographic and Information Services (CEGIS 2009). A flood area inundated deeper than 360 cm was considered in this study. The magnitude (severe, moderate, low and no drought) of the drought events in 2004 was collected from the BCA data (BCA 2006). GIS techniques were used to assemble the extent of the drought area for 16 districts in the North West region. The present study considered severe drought alone, which was calculated as the average area under severe drought for three seasons (*pre-kharif*, *kharif* and *rabi*) in 2004 for these districts. Irrigation data was sourced from the Bangladesh Bureau of Statistics (BBS 2010a) and then sorted for the North West districts. The area under DTW and STW irrigation in 2010 was considered for the present study. The ratio of DTW and STW was calculated by dividing the area under deep tube wells by the area under shallow tube wells and vice versa for each of these districts.

A set of determinants to be considered as independent variables in the present study, along with the data sources, is presented in Table 5.1. Livelihood frameworks (Scoones 1998; Jansen et al. 2006; Senaratna Sellamuttu et al. 2014; Soini 2005; Soltani et al. 2012; Hesselberg and Yaro 2006) were used to categorize determinants into various forms of livelihood capitals, including natural, social, financial, human, and physical capitals (Table 5.1).

Table 5.1 Data description, unit, mean, SD., independent variables use in calorie consumption (DCal) and income (AI) regression, and the sources of data

Variable definition	Unit	Mean	SD	*DCal*	*AI*	Data source
Dependent variables						
Daily average household food calories consumed per capita (*Dcal)*	kcal	2312	713			HIES, 2010
Log of annual household income from all sources *(AI)*	taka	10.89	0.98			HIES, 2010
Independent variables						
(1) Financial capital						
Household remittances received from overseas (*Ros)*	taka	4355	37814		√	HIES, 2010
Proportion of household members with non-agricultural paid employment (*Pern*)	percentage	0.32	0.18	√	√	HIES, 2010
Proportion of household members with paid employment working in agriculture *(Pag)*	percentage	0.44	0.45	√	√	HIES, 2010
Proportion of household members with paid employment working as agricultural day labour *(Pagdl)*	percentage	0.22	0.38	√		HIES, 2010
Taka value of all household credit *(Tcd)*	taka	13905	94391	√	√	HIES, 2010
Average interest rate on all household loans *(HHl)*	taka	16.97	40.18	√	√	HIES, 2010
(2) Human capital						
Proportion of household members reporting chronic illness *(Psck)*	percentage	0.16	0.23		√	HIES, 2010
Proportion of household members reporting untreated illness *(Puntr)*	percentage	0.02	0.10		√	HIES, 2010
Head of household's years of formal education *(HHedu)*	year	3.65	4.42	√	√	HIES, 2010
Households with female head as binary variable *(HHf)*	female head (1) or not (0)	0.06	0.24	√	√	HIES, 2010
(3) Physical capital						
Taka value of household crop production for own consumption *(Cc)*	taka	4677	17516	√		HIES, 2010
Taka value of household fish production for own consumption *(Fc)*	taka	1622	15145	√		HIES, 2010
Taka value of household livestock production for own consumption *(Lc)*	taka	2087	16084	√		HIES, 2010
Area of agricultural land operated *(Agop)*	hector	70	134	√	√	HIES, 2010
(4) Natural capital						
Major flooding: District area proportion inundated deeper than 360 cm*(Fm)*	percentage	0.09	0.10		√	CEGIS,2009
Household flooding: binary variable reporting exposure to flood *(Fex)*	exposure to flood (1) or not (0)	0.05	0.21	√	√	HIES, 2010
Household drought: binary variable reporting exposure to drought *(Dex)*	exposure to drought (1)or not (0)	0.03	0.18	√	√	HIES, 2010
Proportion of district area under severe drought *(Pdsd)*	percentage	3.68	5.23	√	√	BCA,2004
Ratio of Deep Tube Well (DTW) area to Shallow Tube Well (STW) area*(Rdsi)*	ratio	0.38	0.46	√	√	BBS,2010
(5) Social capital						
Proportion of household members receiving social safety net assistance *(Pssn)*	percentage	0.08	0.17	√	√	HIES, 2010

5.2.5 *Analysis*

The present study provides a statistical assessment of the relevant data in order to understand the influence of livelihood capitals on calorie consumption and income as a means of determining food security in the North West region of Bangladesh. Calorie consumption and income were used as dependent variables in the regression analysis. Various household assets and district resources were considered as livelihood capitals (Table 5.1).

The combined database contains a total of 120 conditions; determinants of 1556 households in the NW. Daily calorie consumption was calculated from all the food items consumed per capita (per person per day) in a household in kcal (called the '*DCal*' model, below). The annual average income was derived from all sources of income for a household for all members in taka (called the '*AI*' model, below).

In order to reduce the dimensionality of the independent variables dataset for statistical analysis, the present study removed those variables that were deemed unimportant. The choice was based on prior findings, common sense and qualities such as the type of house construction, broad binary subjective classifications of poverty, or the types of drinking water sources. The study also excluded categorical variables that were rare in the study area, such as the ability of a household to sell forest products. The rest of the variables were then tested for deviations from normality and if necessary, a transformation to the variables was applied by using a ladder approach (Tukey 1977) (a log transformation was performed for income). Multicollinearity and variance inflation were assessed for both models individually by using the VIF test in STATA. The results of the VIF test further reduced the set of independent variables in the models. Variables with a VIF > 5 were removed from both models. The result of this process finally produced a set of 20 independent variables, which were used for the calorie consumption and income regression data (Table 5.1).

Initial tests indicated a large proportion of unobserved regional heterogeneity in the models. This was not surprising because the database lacks regional information such as soil conditions and land suitability for agricultural production, differences in infrastructure (i.e. roads or schools) or distances to markets. Consequently, the study added districts as a fixed effects variable and found a large improvement in the models. The present study finally ran the models including 16 districts of the North West and three regions based on topographic variation (Figure 5.1) (e.g. the northern part of the North West (north), the central part of North West (central) and the Southern part of North West (south)), as dummy regional variables. They were used to account for any regional effects associated with topographic variations or other unobserved variables in the North West districts of Bangladesh.

Income is considered as one of the key elements in calorie consumption, however, the present study does not consider 'income' as an individual variable in understanding calorie consumption contexts. The study followed the livelihood framework to categorize various determinants and household income was determined indirectly through various forms of livelihood capitals to assess calorie consumption regimes. The study finally developed two separate Least Square Dummy Variable Models (LSDVM), calorie consumption (*'Dcal'*, Eq. 1) and income (*'AI'*, Eq. 2), to identify the effect of important household and regional resources on livelihood outcomes as functions of financial, human, physical, natural and social capitals. To estimate the influence of livelihood determinants on calorie consumption and income, the study used one standard deviation greater than the mean value of each of the statistically significant determinants considered for calorie consumption and income regression (Table 5.1). The standardized relative influence is then achieved from the modelled calorie consumption and income coefficients for each statistically significant determinant and multiplied by the standard deviation values of these.

5.3 Results

Regression coefficient estimates are presented in Table 5.2 and Table 5.3 for calorie consumption and income respectively. The relative influences on calorie and income outcomes of statistically significant factors influencing the NW of Bangladesh are presented in Figure 5.2 and Figure 5.3.

$$\boldsymbol{DCal_{ij}} = \alpha_0 + \alpha_1 (Pern)_{ij} + \alpha_2 (Pag)_{ij} + \alpha_3 (Pagdl)_{ij} + \alpha_4 (Tcd)_{ij} + \alpha_5 (HHl)_{ij} + \alpha_6 (HHedu)_{ij} + \alpha_7 (HHf)_{ij} + \alpha_8 (Cc)_{ij} + \alpha_9 (Fc)_{ij} + \alpha_{10} (Lc)_{ij} + \alpha_{11} (Agop)_{ij} + \alpha_{12} (Fex)_{ij} + \alpha_{13} (Dex)_{ij} + \alpha_{14} (Pdsd)_{ij} + + \alpha_{15} (Rdsi)_{ij} + \alpha_{16} (Pssn)_{ij} + a_{kn} (D)_{kij} + a_{rn} (R)_{ri} + \varepsilon_{ij} \quad \ldots\ldots (1)$$

Where:

DCal	Daily average i^{th} household food calories consumed per capita in j^{th} district
Pern	Proportion of i^{th} household members with paid employment in j^{th} district
Pag	Proportion of i^{th} household member with paid employment working in agriculture in j^{th} district
Pagdl	Proportion of i^{th} household member with paid employment working as agricultural day labour in j^{th} district
Tcd	Taka value of all i^{th} household credit in j^{th} district
HHl	Average interest rate on all i^{th} household loans in j^{th} district
HHedu	Head of i^{th} household years of formal education in j^{th} district
HHf	Households (i^{th}) with female head as binary variable in j^{th} district
Cc	Taka value of i^{th} household crop production for own consumption in j^{th} district
Fc	Taka value of i^{th} household fish production for own consumption in j^{th} district
Lc	Taka value of i^{th} household livestock production for own consumption in j^{th} district
Agop	Area of agricultural land operated for i^{th} household in j^{th} district
Fex	Household (i^{th}) flooding: binary variable reporting exposure to flood in j^{th} district
Dex	Household (i^{th}) drought: binary variable reporting exposure to drought in j^{th} district
Pdsd	Proportion of district area under severe drought in j^{th} district
Rdsi	Ratio of area under Deep Tube Well (DTW) area to Shallow Tube Well (STW) irrigation in j^{th} district
Pssn	Proportion of i^{th} household members receiving social safety net assistance in j^{th} district
D	Districts of Northwest region used as a dummy variable in the regression
R	Regions used as a dummy variable in the regression
$a_{1\text{-}16}$	Coefficients of the variables used in the regression
a_{kn}	Co-efficient of districts (dummy)
a_{rn}	Coefficients of the regions (dummy)
e	Error term

$$\boldsymbol{AI_{ij}} = \beta_0 + \beta_1 (Ros)_{ij} + \beta_2 (Pern)_{ij} + \beta_3 (Pag)_{ij} + \beta_4 (Tcd)_{ij} + \beta_5 (HHl)_{ij} + \beta_6 (Psck)_{ij} + \beta_7 (Puntr)_{ij} + \beta_8 (HHedu)_{ij} + \beta_9 (HHf)_{ij} + \beta_{10} (Agop)_{ij} + \beta_{11} (Fm)_{ij} + \beta_{12} (Fex)_{ij} + \beta_{13} (Dex)_{ij} + \beta_{14} (Pdsd)_{ij} + + \beta_{15} (Rdsi)_{ij} + \beta_{16} (Pssn)_{ij} + \beta_{kn} (D)_{kij} + \beta_{rn} (R)_{ri} + \varepsilon_{ij} \quad \ldots\ldots (2)$$

Where:

YI	Natural log of yearly average i^{th} household income in j^{th} district
Ros	Household (i^{th}) remittances received from overseas in j^{th} district
Pern	Proportion of i^{th} household members with paid employment in j^{th} district
Pag	Proportion of i^{th} household member with paid employment working in agriculture in j^{th} district
Tcd	Taka value of all i^{th} household credit in j^{th} district
HHl	Average interest rate on all i^{th} household loans in j^{th} district
Psck	Proportion of i^{th} household members reporting chronic illness in j^{th} district
Puntr	Proportion of i^{th} household members reporting untreated illness
HHedu	Head of i^{th} household years of formal education in j^{th} district
HHf	Households (i^{th}) with female head as binary variable in j^{th} district
Agop	Area of agricultural land operated for i^{th} household in j^{th} district
Fm	Major flooding: district area proportion inundated deeper than 360 cm
Fex	Household (i^{th}) flooding: binary variable reporting exposure to flood in j^{th} district
Dex	Household (i^{th}) drought: binary variable reporting exposure to drought in j^{th} district
Pdsd	Proportion of district area under severe drought in j^{th} district
Rdsi	Ratio of area under Deep Tube Well (DTW) area to Shallow Tube Well (STW) irrigation *in j^{th} district*
Pssn	Proportion of i^{th} household members receiving social safety net assistance in j^{th} district
D	Districts of Northwest region used as a dummy variable in the regression
R	Regions used as a dummy variable in the regression
$\beta_{1\text{-}16}$	Coefficients of the variables used in the regression
β_{kn}	Co-efficient of districts (dummy)
β_{rn}	Coefficients of the regions (dummy)
e	Error term

5.3.1 *Key livelihood capitals and determinants for calorie consumption*

The LSDVM results show the contribution of the livelihood capitals on daily calorie consumption and are presented in Table 5.2. Four forms of financial capitals, two forms of physical capitals and one form of natural capital are statistically significant (Table 5.2).Financial capitals, in particular the proportion of household members with paid employment, were statistically significant (*p*-value 0.00) and impacted positively on calorie consumption. The proportion of the household with paid employment working in agriculture is also statistically significant (*p*-value 0.04) and impacted on calorie consumption positively.

Table 5.2 Results of LSDVM analysis for household calorie consumption

Variables	Estimate	Standard error	*p*-value
Intercept	1696.00	128.59	0.00***
Financial capital			
Proportion of household members with paid employment	961.99	212.37	0.00***
Proportion of household with paid employment working in agriculture	379.54	187.25	0.04***
Proportion of household with paid employment working as agricultural day labour	-310.68	142.66	0.03***
Taka value of all household credit	0.0002	0.0002	0.37
Average interest rate on all household loans	-4.11	2.19	0.06**
Human capital			
Households with female head as binary variable	-67.00	211.68	0.75
Head of household's years of formal education	9.05	10.13	0.34
Physical capital			
Taka value of household crop production for own consumption	0.0005	0.0031	0.86
Taka value of household fish production for own consumption	0.013	0.006	0.02***
Taka value of household livestock production for own consumption	0.0001	0.0004	0.74
Area of agricultural land operated	0.65	0.36	0.07**
Natural capital			
Household flooding: binary variable reporting exposure to flood	-258.97	164.43	0.11
Household drought: binary variable reporting exposure to drought	2.81	129.36	0.98
Proportion of district area under severe drought	-6.80	3.07	0.02***
Ratio of Deep Tube Well (DTW) area to Shallow Tube Well (STW) area	-48.29	123.98	0.96
Social capital			
Proportion of household members receiving social safety net assistance	289.48	280.45	0.30

** Represents the 1% level of significance

*** Represents the 0.1% level of significance

In contrast, two financial capitals, the proportion of household with paid employment working as an agricultural day labourer and the average interest rate on all household loans, impacted negatively and these are statistically significant, with a p-value of 0.03 and 0.06 respectively. Physical capitals, including the taka value of household fish production for their own consumption and the area of agricultural land operated, are statistically significant and impacted on household calorie consumption positively. However, natural capitals, such as the proportion of the district area under severe drought, influenced calorie consumption negatively and were statistically significant, with a p-value of 0.02. All other remaining determinants under various livelihood capitals are statistically insignificant and showed both positive and negative impacts on household calorie consumption in the NW region. Overall, the regression had a moderate explanatory power with an R2 square value of 0.26, which means only 26 per cent of the variation in calorie consumption can be explained by the determinants considered in the present study.

5.3.2 Key livelihood capitals and determinants for income

The LSDVM results show the effects of livelihood capitals on the household annual averaged income in the NW of Bangladesh (Table 5.3). Five forms of financial capitals, three forms of human capitals, one form of physical capital, two forms of natural capitals, and one form of social capital are statistically significant (Table 5.3). All financial capitals are statistically significant and influence household income positively, except for the proportion of the household with paid employment working in agriculture, which has a negative impact. Three forms of human capitals are statistically significant; the head of household's years of formal education (*p*-value 0.00) showed a positive impact, whereas the proportion of the household reporting chronic illness (*p*-value 0.05) and households with a female head (*p*-value 0.00) influence income negatively. Physical capital, including the area of agricultural land operated per household, was statistically significant with a *p*-value of 0.00, natural capital, particularly the proportion of the district area inundated by deeper than a 360 cm flood, was also statistically significant (0.05) and both impacted on household income positively. In contrast, household flooding and reporting exposure to flood in 2010 affected income negatively with a *p*-value of 0.09. Social capital, such as the proportion of household members receiving social safety net assistance, was statistically significant (a *p*-value of 0.00) and impacted on household income negatively. Other determinants are statistically insignificant and showed mixed impacts on household income. Income regression also had a moderate explanatory power with an R^2 value of 0.29, based on the household and district capitals considered in the present study.

Table 5.3 Results of LSDVM analysis for household income.

Variables	Estimate	Standard error	*p*-value
Intercept	10.96	0.10	0.00
Financial capital			
Household remittances received from overseas	0.00004	0.00006	0.00***
Proportion of household members with paid employment	0.47	0.10	0.00***
Proportion of household with paid employment working in agriculture	-0.66	0.05	0.00***
Taka value of all household credit	0.00009	0.00002	0.00***
Average interest rate on all household loans	0.001	0.0004	0.01***
Human capital			
Proportion of household reporting chronic illness	-0.17	0.09	0.05***
Proportion reporting untreated illness	-0.25	0.17	0.13
Head of household's years of formal education	0.03	0.004	0.00***
Households with a female head as a binary variable	-0.81	0.11	0.00***
Physical capital			
Area of agricultural land operated	0.0008	0.0002	0.00***
Natural capital			
Major flooding: district area proportion inundated deeper than 360 cm	0.54	0.28	0.05***
Household flooding: binary variable reporting exposure to flood	-0.12	0.07	0.09**
Household drought: binary variable reporting exposure to drought	0.11	0.14	0.42
Proportion of district area under severe drought	0.001	0.001	0.24
Ratio of Deep Tube Well (DTW) area to Shallow Tube Well (STW) area	0.02	0.07	0.77
Social capital			
Proportion of household members receiving social safety net assistance	-0.83	0.13	0.00***

*** Represents the 0.1% level of significance
** Represents the 1% level of significance

5.3.3 *Influences of livelihood determinants on calorie consumption and income*

Out of the five livelihood capitals, only three influence calorie consumption (Figure 5.2). The financial capitals influence calorie consumption critically, as two forms of financial capitals impact positively whereas the other two impact negatively. The proportion of households with paid employment working in agriculture and the proportion of the household with paid employment working in agriculture boost household calorie consumption by 8 and 7 per cent respectively. On the other hand, the proportion of the household with paid employment working as an agricultural day labour and the average interest rate on all household loans decreases by 6 and 5 per cent of the household's daily calorie consumption. Physical capitals in the form of their own caught fish consumption were the most influential livelihood determinants of household calorie outcomes. A household with one standard deviation above the sample mean level of access to fisheries achieves an additional 11 per cent of the calorie consumption per day on average. Likewise, the area of agricultural land operated would increase 3 per cent of the per capital daily calorie consumption. Natural capital, particularly the proportion of the district area under severe drought, decreases household calorie consumption by 1 per cent.

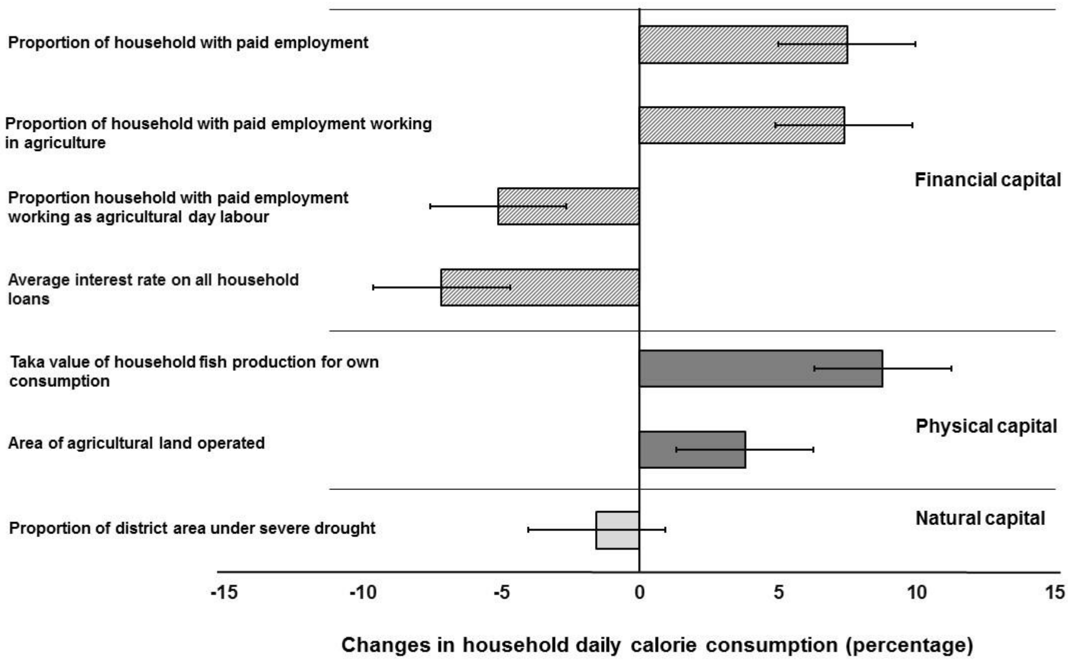

Figure 5.2 Comparison of statistically significant determinants under livelihood capitals influencing household daily calorie consumption by percentage in the NW of Bangladesh.

All livelihood capitals impact on income (Figure 5.3). Financial capitals had a large influence on household income. The income was highly influenced by the household remittances received from overseas and such income could change the yearly household income by nearly by 47 per cent of that achieved by an average household. The proportion of household members with paid employment, the taka value of all household credit, and the average interest rate on all household loans could increase the household income by 9, 8 and 7 percent respectively.

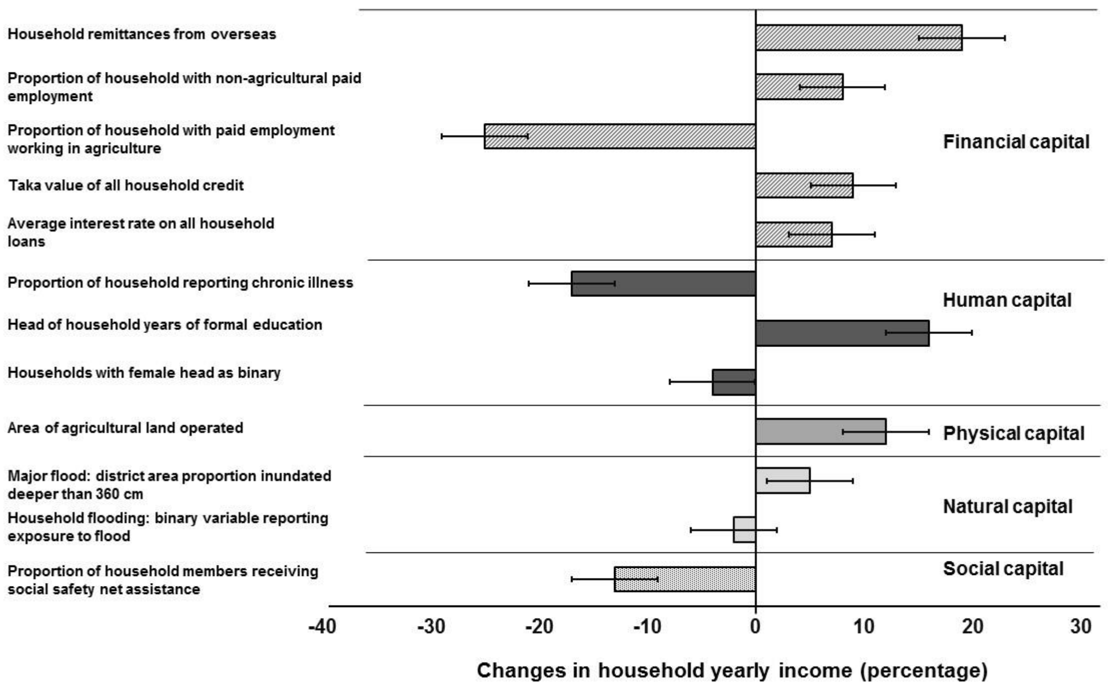

Figure 5.3 Comparison of statistically significant determinants under livelihood capitals influencing household annual income by percentage in the NW of Bangladesh.

The proportion of household members with paid employment working in agriculture, in contrast, could lower the household annual income by 25 per cent. The head of household's completed years of formal education impacted on income positively as it could increase the yearly income by 17 per cent. On the other hand, human capitals, including the proportion of the household reporting chronic illnesses and households with a female head, decreased the annual income by 4 and 20 per cent respectively. The present study indicates that, on average, households with one standard deviation above the mean agricultural land holding enjoyed an additional 11 per cent of annual income. A household exposed to flood in the survey year (2010) could expect nearly 2 per cent less income on average in that year. On the other hand, major flood prevalence appears to impact on household annual income positively, as a household that faced a major flood earned, on average, 7 percent more than the average household income. The proportion of household members receiving social safety net assistance could decrease the household's annual income by 13 per cent.

5.4 Discussion

The present study has identified the key livelihood determinants of calorie consumption and income. The study has found that household assets are more aligned to calorie consumption and income outcomes, when compared with regional conditions. The results show that different determinants influence household's calorie consumption and income substantially.

5.4.1 *Financial capital*

Financial capitals demonstrate a large influence on household calorie consumption and income. The proportion of household members with paid employment increased both the household's calorie consumption and income. A similar result was found in a previous study, which indicates that the higher the proportion of employed members there are in a household, the better they enjoy good nutritional choices in Bangladesh (Thorne-Lyman et al. 2010). Households with more of their working members relying on agricultural day labour enjoy worse nutritional outcomes, similar to those who can only borrow loans with high interest rates. The proportion of the household with paid employment working in agriculture, decreases income. This is consistent with some other findings, indicating that seasonality can affect agricultural day laborers critically: they suffer from lower incomes and greater malnutrition when compared with others in Bangladesh (Abdullah 1989; Thorne-Lyman et al. 2010; Elahi and Ara 2008; Zug 2006). Nargis and Hossain (2006) indicate that overseas migration, particularly when it is the main source of remittances, makes a significant contribution to income growth in Bangladesh at a national level and the present study shows such remittances make similar contributions to household incomes in the NW of Bangladesh. The influence of taking credit has already been analysed and the evidence shows that credit substantially improves livelihoods in Northern Bangladesh (Amin et al. 2003). The present study indicates a comparable impact from the amount of credit that household members receive from different sources leads to their enjoying greater annual income.

5.4.2 *Human capital*

Three forms of household human capitals are statistically significant for income, whereas no human capital is found to be statistically significant for calorie consumption. The head of a household's level of formal education contributes to generating an income 17 per cent higher than the average household income. Available evidence indicates that education has positively impacted on income in Bangladesh (Kam et al. 2005; Nargis and Hossain 2006). Many international studies indicate that education has a positive impact on food security (Sajjad et al. 2014; Soltani et al. 2012), however this was not statistically significant in the present study because the level of formal education considered is reserved for the head of the household alone. Having a household with a female head has a significant impact on livelihood outcomes. Our study found that female-headed households earned 20 per cent less income. Previous studies show that female homeowners have less access to higher income levels because they are not able to compete for resources as effectively as male members of a household (Lewis 1993; Koppen and Mahmud 1995; Karim et al. 2012; Pitt and Khandker 1998). A household with a proportion of the household reporting chronic illnesses has a moderate impact, delivering a 4 per cent lower income than that of a typical household income, on average. Human capital has become an important indicator for household income, whereas it has no impact on calorie consumption, based on the variables considered in the present study.

5.4.3 *Physical capital*

Our findings show that physical capital and the taka value of a household's fish production for their own consumption increase calorie consumption in the NW of Bangladesh. This was revealed in a previous study where inland fishery access was shown to influence nutritional outcomes in the country positively (Thompson et al. 2002). Many studies show that land holding impacts significantly on the socio-economic development of Bangladesh (Indra and Buchignani 1997; Abdullah and Murshid 1986). Rahman and Manprasert (2006) also observe that landlessness has become a key indicator of poverty in rural Bangladesh. However, the present study demonstrates that all kind of households (both rural and urban) with their own agricultural land enjoy an extra 3 per cent and 11 per cent calorie consumption and income respectively, when compared with the average household. Thus, land ownership impacts noticeably on livelihood outcomes in the NW of Bangladesh.

5.4.4 Natural capital

The present study considers most regional conditions as natural capital. Interestingly, the study found, on average, that households in the most drought exposed district (where 15% of the area had been exposed to severe drought) can expect to consume 1 per cent fewer calories per capita than people in a zero drought exposed area, when all other household assets are considered equal. There is no previous study in Bangladesh that assesses the regional impact of drought on calorie consumption to which to compare our results. Ninno and Lundberg (2005) observe the adverse effects of flood on child nutrition. The present study did not demonstrate any relationship between flood and calorie consumption. However, the proportion of the district area inundated by deeper than 360 cm of flood, increases annual household incomes by 7 per cent. This may indicate that the value of soil renewal from major floods translates into greater yields and agricultural income. Households that reported exposure to flood in the survey year, 2010, experienced lower incomes and this was also revealed by previous studies which indicate the immediate adverse impacts of flood on socio-economic development and the environment in Bangladesh (Banerjee 2007; Chanda Shimi et al. 2010; Brouwer et al. 2007).

5.4.5 Social capital

The present study considers one determinant (the proportion of household members receiving social safety net assistance) under social capital in order to assess household calorie consumption and income. The results show that this form of capital had no impact on calorie consumption, but it could reduce the household's yearly average income by 13 per cent. It is also difficult to say whether receiving the social safety net increases household consumption and income levels or has a beneficial impact on human wellbeing and longer-term income generation, as the available evidence in Bangladesh shows a mixed picture of the impact of social safety net programs (Barkat-e-Khuda 2011; Pradhan et al. 2013; Morshed 2009).

5.4.6 Limitations of the study and future research

The present study considers a set of determinants under the livelihood framework (Table 5.1) to understand the influence of these on household calorie consumption and income. However, many important determinants were excluded because of the selection of the determinants under this framework. We have also excluded many determinants for statistical model selection. The results show that broad-scale district variables have a substantial effect on household wellbeing, but here the study can only hypothesise about what factors may be responsible. We tried to avoid the impact of regional heterogeneity on the model by using districts and regions as dummy variables. There are still many unobserved factors in the districts, which we were not able to consider in the present study due to the lack of regional data. The study demonstrates that the marginal effects of household capital measures from the HIES survey could be more accurately identified than those of the spatial (e.g. district resources, disaster) effects. We tried to identify regional impacts by using two other regional conditions, including the proportion of the net cultivation area irrigated and the proportion of ground water irrigation individually for each of the North West districts instead of using the ratio of the area under DTW and STW irrigation in both of the models (the results were not included in the present study). The results showed no significant impact on livelihood outcomes by using the individual impacts of the net cultivation area irrigated and the proportion of ground water irrigation along with the other variables considered in the study. This is likely to be because spatial attributes were only available on a district average basis for the district in which each household in the study is located.

There are various conditions that may influence household wellbeing. There is a need for future analysis in order to understand these conditions. More integrated research is required in the North West region, which should incorporate spatially varying factors such as ground water recharging, irrigation facilities, land type and utilization as well as the extent of other disasters. In addition, infrastructure facilities, like transport, the length of roads and the number of schools, for example, should also be included in future analysis. Spatially explicit analysis at a finer scale (e.g. upazilla, thana and village) in the North West may also help us to understand the detailed impact of regional heterogeneity on livelihood outcomes. In-depth local level research is highly recommended at district level, sampling one or two villages in each district to assess livelihood outcomes by collecting primary data together with more household and more spatially aggregated variables, rather than depending on HIES data alone.

5.4.7 Policy recommendations for food security in terms of sustainable livelihoods

Policy development on different livelihood capital endowments may improve food security (Burchi and De Muro 2015). According to the results found by the present study, the following recommendations are emphasized to improve food policy in terms of sustainable livelihoods in the NW of Bangladesh:

Financial capital impacts more on household income and calorie consumption than other capitals. Our results support prior findings that socio-economic development, such as industrialization, that creates wage income, is a major contributor to both household income and nutritional well-being (Khandker et al. 1998; Nargis and Hossain 2006) due to the fact that the proportion of household members with paid employment increases livelihood outcomes. Both public and private investment is required to set up new industries, particularly agro-based industries, which may well increase employment opportunities in the area and lead to better livelihoods.

Remittance has been found to be a key driver of economic growth and poverty reduction in Bangladesh (Nargis and Hossain 2006) and our results show that it impacts significantly on household income. Government initiatives should give more importance to migrant workers and international migrants who are sending back money for the benefits of their family as it reduces poverty in the country.

Improvements in human capital may increase income through different training and youth development programs. Physical capital vulnerability presents a much greater share of explained variations in nutrition than in income. Physical capital in the form of households' own fish production increased calorie consumption significantly. Regional level inland fish culture may possibly increase nutritional outcomes: this is possible to implement at a local level through various programs and through greater awareness of the benefits of this kind of physical capital. Proper land distribution among disadvantaged people can potentially lead to improved household livelihood outcomes. People may achieve benefits though appropriate government land management policies.

We found greater drought vulnerability reduced household per capita calorie consumption, whereas major flood increased income as a result of its cumulative influences on soil fertility. The government of Bangladesh has undertaken several initiatives on disaster management. However, in many cases, it is difficult to control disasters through these initiatives. Natural capital is an unpredictable determinant for livelihood outcomes. A long term vision for disaster management preparedness may help to reduce the adverse impact of disaster on livelihoods in the country.

The government has initiated different safety net programs across the country. However, our findings show that these impact negatively on household annual income in the long run. Existing safety net programs should be monitored and evaluated, so appropriate, consistent and effective improvements can be made. Some programs should be abandoned after reviewing their prospects of improving livelihoods in the NW of Bangladesh.

Household level data collection has a lack of spatial entity, as the HIES survey has no record of the geographical location of each household. A Government level policy should now be enacted to collect more accurate data, which considers both household and spatial data. This will help to fill up the data vacuum, as well as help in our understanding of the impact of regional determinants on livelihood outcomes more accurately. In future, HIES surveys should consider household geographical coordinates and be merged with more detailed spatially explicit data and thus, more statistically significant geographical changes can be achieved for the benefit of livelihood outcomes.

5.5 Conclusions

The objective of the present study was to understand the spatially variable influences of household assets and regional resources on calorie consumption and income in the NW of Bangladesh, as a means of developing food security assessments, using the sustainable livelihood framework. The findings demonstrate that marginal effects of household assets measured from the HIES survey could be more accurately identified than spatial (e.g. district resources, disaster) effects. The present study found that various forms of livelihood capitals influence calorie consumption and income. Furthermore, the study compares the influence of these capitals on calorie consumption and income. Physical and natural capitals exhibit a much greater share of the explicable variations in nutrition than on income.

Financial and human capitals are the catalysts for determining household income. Social capital shows a negative impact on household income. The results of the present study indicate that household socioeconomic conditions need to improve in order to achieve better livelihood outcomes. The study shows lower impacts from regional conditions than other conditions, however disaster (flood and drought) should be considered as important when planning to manage natural capitals appropriately. The study suggests diverse solutions which need to be incorporated into improving policies for the sustainable use of the significant determinants found in the present study, focusing particularly on income-generating opportunities, the development of human resources and the control of bio-physical limitations. Moreover, access to better livelihoods based on household assets and regional conditions is not enough to understand food security: there is further need for a broader analysis than that currently undertaken, including data showing greater details of regional divergence, economic drivers, natural resources management and infrastructural development.

Acknowledgements

The author would like to acknowledge the Government of Australia for their support and funding, enabling the researcher to undertake the whole study using her IPRS and APA Scholarship. This research is also funded by the Commonwealth Scientific and Industrial Research Organization (CSIRO) under the auspices of the "Water for a Healthy Country" flagship project. The lead author is particularly thankful to Alison-Jane Hunter, a professional English language editor, at the University of Adelaide for assisting in technical language editing.

Chapter 6

Conclusion and recommendations

6.1 Overall summary

Food security determinants vary across Bangladesh, yet very little systematic research exists to assess the potential impact of such variation on food security in the country. Food security assessments have often ignored spatial aspects at administrative levels and associated future changes that may influence food security in the country. This thesis narrows this gap, developing an understanding of the spatio-temporal variability of key food security determinants and the impact of these determinants on future food security, particularly by evaluating the influences of climate change, management and socio-economic circumstances.

The aim of the present thesis was to assess food security by using spatio-temporal data from the government statistics on climate change, management, and socio-economic conditions in order to improve food security. The objectives of this thesis were: (1) to understand the need and potential for a spatially informed food policy, (2) to assess the spatially variable climate change effects on rice yield for the three main ecotypes (Aus, Aman and Boro) in Bangladesh, (3) to evaluate the combined impact of both climate change and management factors on rice yield and (4) to understand the influence of household socio-economic assets and regional conditions on food security.

The salient findings of this research can be summarized as follows:

- The present project initially enhances understanding of the spatial aspects of food security and the status of food security components in Bangladesh, including food availability, food access, and food utilization. It helps with the understanding of possible geographic impacts of climate change on food security. It identifies a wide range of national data sources on food security. Finally, it suggests a way forward for the development of a spatially informed food policy in the country to improve food security, including offering advice on region-specific deficits, climate change, other future risks, and actions for each food security component (Chapter 2).

- The present thesis shows that climatic variables influenced rice yield for the three main eco-types (Aus, Aman, and Boro) grown in Bangladesh, based on the past records. An empirical assessment of climate impact indicates that rice yield has become more susceptible to temperature effects, when compared with rainfall effects, over the period from 1981 to 2010. The study demonstrates that climate impact on Bangladeshi rice agriculture is ecotype-specific and shows different spatial pattern. Aus and Aman yield are negatively correlated with temperature in most of the districts in Bangladesh. In contrast, Boro yield may increase with temperature (Chapter 3).

- The study further assesses the combined influence of climatic variables and management practices on total rice yield. The clear result from this analysis demonstrates that management has a much stronger effect on rice yield than climatic variables. However, climate impact on total rice yield is still observable from the past records. More importantly, the Liner Mixed Model results show that water management through ground water irrigation affected rice yield significantly in Bangladesh over the study period (1981-2010). This is alarming because dependence on ground water for rice cultivation may not be sustainable in the future (Chapter 4).

- The present thesis considered the 2010 HIES data from. This analysis mainly focuses on the sub-region (North West) in Bangladesh because of the region's importance for rice production and its particular vulnerability to groundwater depletion for irrigation. Econometric assessments are performed to understand household income and nutrition consumption as a means of food security. Livelihood capitals (financial, human, physical, natural, and social) are used to understand the influence of these on household food security. The results show that physical and natural capitals exhibit a much greater share of explained variations in nutrition consumption than in income. Financial and human capitals are the catalyst for determining household income. The results show multiple capitals will be useful in the long term to improve food security in the area. The sustainable use of these capitals needs to manage appropriately. This will improve regional ability as well as improve access to capitals for food security (Chapter 5).

6.2 Recommendations for food policy development

The results of this thesis potentially make a contribution to a number of areas of policy development to improve food security in Bangladesh. Although food security is dependent on many factors, the present study was limited to key natural and socio-economic factors. Many factors could not be included because of the lack of spatio-temporal data at either regional or district administrative levels. However, the study acknowledges these factors in order to develop a spatially informed food policy in the country. Several recommendations are raised by the present thesis that should be considered in future food policy reform. These recommendations are –

a) The present thesis shows that there is a lack of regional food security assessment in Bangladesh. The regional aspects of food security are not addressed in current food policy. The thesis indicates a way forward for spatially informed food policy developments in the country by using the spatio-temporal data from the national sources.

b) This project was focused on food availability by indicating the impact of both climatic variables and management practices on regional rice yield. Although it was found that the means of irrigation had stronger effects than climatic conditions, still the impacts of climate change need to be addressed in the national food policy due to their diverse impact on the three main rice ecotypes (Aus, Aman, And Boro) grown in Bangladesh. Climatic variables, particularly temperature increases, will decrease regional Aus and Aman yields. However, the Boro yield may potentially benefit from future temperature increases in some districts. The results of the thesis help to develop detailed, district-specific, adaptation measures to combat climate change and reduce the regional rice yield variability in the disadvantaged districts in the future.

c) The national food policy needs to consider regional prospects of irrigation as important. Past records show that irrigation using motorized pumps, which is highly dependent on ground water, has become a key determinant of rice yield in Bangladesh. However, groundwater extraction at the current rate may not be sustainable in the future. Therefore, it is critical that policies incorporate water management options in different districts by combining ground water with the use of other water sources for irrigation.

d) The study indicates that the current level of food security in Bangladesh may not be sustainable if the dependence on unsustainable factors remains high. Moreover, it also shows that there are substantial spatial differences in yield across the districts studied. This may be an indication that there is room for improvement in the agricultural sector at a regional level and that food security for the larger population may be achieved with a solid understanding of current limitations and potentials.

e) Household socio-economic and regional conditions need to be considered critically in future food policies in Bangladesh. Special consideration should be given to the different forms of livelihood capitals (financial, social, physical, human and social), which influence household calorie consumption and income to the greatest extent. However, the influence of household assets (sourced from HIES) is accurately identified along with the spatial (e.g. district resources and disasters) attributes. The spatial attributes might not associate appropriately with the household data because of the missing geographic location of households within a district. In this regard, the present study recommends future HIES surveys at national level should include each household's geographic coordinates. This will help to merge the household data with detailed spatially explicit conditions in the future, to make better food security research-policy linkages.

6.3 Future research

The present thesis answered a number of questions related to the influence of spatially variable natural and socio-economic determinants on food security in Bangladesh. However, the study further indicates the prospects of future research on food security and these are:

a. The results of the present thesis indicate that the trends in yield and productivity cannot be fully explained by the present data, indicating that the past trends contain important information that can only be obtained from longer time series. More spatially detailed data is needed, however, this is not available for longer time periods at present. Various spatial techniques will need to be applied in the future to develop such data at an aggregated level for different food security determinants.

b. The present study considers spatially variable climatic variables, particularly rainfall and temperature, to assess the impact of these on rice yield for the main three ecotypes. However, other climatic variables (e.g. humidity, sunshine, and evapotranspiration) may impact on rice yield. Future research should consider these elements in order to understand the impact of climatic variables on regional rice yield in greater detail. On the other hand, the climatic conditions themselves may vary due to numerous local circumstances, which should be considered in detail by applying either crop models or other methods locally in the country.

c. The present study suggests a critical need for improvements in regional management of agriculture. Emphasis should be focused on spatially explicit information of various agricultural management practices, as these might influence the trends in yield that our models were not able to explain. Furthermore, the intensity of disasters affects rice yield regionally but data was not available at the spatial and temporal resolution and so went beyond the extent of the present study. More investigation is necessary for different regional management indicators (e.g. application of fertilizer and pesticides), technological improvement (e.g. ploughing methods, tools, investments etc.) and disasters.

d. The present study considers the household socio-economic assets and some district conditions in order to assess income and nutrition consumption as a means of assessing food security in the North West region of Bangladesh, as a case study. In future, the study should be extended to identify distribution options for food access. Food distribution factors such as roads and water transport networks within the country.

List of References

Abdullah, A. A., & Murshid, K. A. S. 1986. Inter District Changes and Variations in Landlessness in Bangladesh. *The Bangladesh Development Studies*. 14(3), 97-108.

Abdullah, M. 1989. The Effect of Seasonally on Intra household Food Distribution and Nutrition in Bangladesh. *The Bangladesh Development Studies*. 16(6), 67-81.

Abraham, B., Araya, H., Berhe, T., Edwards, S., Gujja, B., Khadka, R. B., et al. 2014. The system of crop intensification: reports from the field on improving agricultural production, food security, and resilience to climate change for multiple crops. *Agriculture & Food Security*. 3(1), 1-12.

Aggarwal, P. K., & Singh, A. K. 2010. Implications of Global Climatic Change on Water and Food Security. In C. Ringler, A. K. Biswas, & S. Cline (Eds.), Global Change: Impacts on Water and food Security (pp. 49-63, Water Resources Development and Management). Springer Berlin Heidelberg.

Ahmad, M. U., Kirby, M., Islam, M., Hossain, M. J., & Islam, M. M. 2014. Groundwater use for irrigation and its productivity: status and opportunities for crop intensification for food security in Bangladesh. *Water Resources Management*. 28(5), 1415-1429.

Ahmed, F. R. S. 2015. Policy Support and Institutional Dimensions of Food Security. In Food Security and Risk Reduction in Bangladesh (pp. 135-155). Springer.

Alauddin, M., & Sarker, M. A. R. 2014. Climate change and farm-level adaptation decisions and strategies in drought-prone and groundwater-depleted areas of Bangladesh: an empirical investigation. *Ecological Economics*. 106, 204-213.

Alauddin, M., & Sharma, B. R. 2013. Inter-district rice water productivity differences in Bangladesh: An empirical exploration and implications. *Ecological Economics*. 93(0), 210-218.

Ali, A. 2005. Livelihood and food security in rural Bangladesh: the role of social capital. Wageningen, WU thesis, no. 3853. http://edepot.wur.nl/121729. Accessed 07 Sep 2014.

Alwang, J., Siegel, P. B., & Jorgensen, S. L. 2001. Vulnerability: a view from different disciplines. 0115. Washington, USA. Available at: worldbank.org/curated/en/2001/06/1637776/vulnerability-view-different-disciplines. Accessed 15 Mar 2016.

Amin, M. R., Zhang, J., & Yang, M. 2015. Effects of climate change on the yield and cropping area of major food crops: A case of Bangladesh. *Sustainability Science*. 7, 898-915.

Amin, S., Rai, A. S., & Topa, G. 2003. Does microcredit reach the poor and vulnerable? Evidence from northern Bangladesh. *Journal of Development Economics*. 70(1), 59-82.

Anik, A., Manjunatha, A. V., & Bauer, S. 2013. Impact of farm level corruption on the food security of households in Bangladesh. *Food Security*. 5(4), 565-574.

Ara, I., Lewis, M., & Ostendorf, B. 2016. Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh. *Agriculture & Food Security*. 5(1), 1-11.

Ara Parvin, G., & Reazul Ahsan, S. 2013. Impacts of climate change on food security of rural poor women in Bangladesh. *Management of Environmental Quality: An International Journal*. 24(6), 802-814.

Atkins, P. J. 2009. Famine. In R. Kitchin, & N. Thrift (Eds.), International Encyclopedia of Human Geography (Vol. 4, pp. 14-20). Oxford: Elsevier.

Babulo, B., Muys, B., Nega, F., Tollens, E., Nyssen, J., Deckers, J., et al. 2008. Household livelihood strategies and forest dependence in the highlands of Tigray, Northern Ethiopia. *Agricultural Systems*. 98(2), 147-155.

BADC. 2005. The Minor Irrigation Survey Report 2004-2005. Dhaka, Bangladesh. Available at: http://books.google.com.au/books/about/Minor_irrigation_survey_report_2004_05.html?id=XnYmAQAAMAAJ&redir_esc=y. Accessed 22 Jan 2017.

Banerjee, L. 2007. Effect of Flood on Agricultural Wages in Bangladesh: An Empirical Analysis. *World Development*. 35(11), 1989-2009.

Barkat-e-Khuda. 2011. Social safety net programmes in Bangladesh: A Review. *The Bangladesh Development Studies*. 34(2), 87-108. 32.

Barton, K. 2014. MuMIn: Multi-model inference, R package version 3.0.0.

Barrett, C. B. 2002. Food security and food assistance programs. Handbook of agricultural economics. 2, 2103-2190.

Basak, J. K., & Alam, K. 2013. Impacts of carbon dioxide emission and subsequent rise of temperature on rice production in Bangladesh: implications for food security. *International Research Journal of Environment Sciences*. 2, 60-67.

Basak, J. K., Ali, M. A., Islam, M. N., & Rashid, M. A. 2010. Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model. *Journal of Civil Engineering*. 38(2), 95-108.

Bashir, M., & Schilizzi, S. 2015. Food security policy assessment in the Punjab, Pakistan: effectiveness, distortions and their perceptions. *Food Security*. 7(5), 1071-1089.

BBS. 2001. Bangladesh Population Census Report, 2001. Dhaka, Bangladesh: Government of Bangladesh.

BBS. 2005. Household Income and Expenditure Survey. Dhaka, Bangladesh: GoB.

BBS. 2010a. Agricultural Statistical Year Book of Bangladesh. Dhaka, Bangladesh: GoB.

BBS. 2010b. Household Income and Expenditure Survey. Dhaka, Bangladesh: GoB.

BBS. 2010c. Report of the Household Income & Expenditure Survey 2010. Dhaka, Bangladesh: Ministry of Planning, GoB.

BBS. 2011a. Agricultural Statistical Year Book of Bangladesh. Dhaka, Bangladesh: GoB.

BBS. 2011b. Bangladesh Population Census Report, 2011. Dhaka, Bangladesh Government of Bangladesh.

BBS. 2012a. Agricultural Statistical Yearbook of Bangladesh. Dhaka, Bangladesh: GoB.

BBS. 2012b. Statistical Year Book of Bangladesh. Dhaka, Bangladesh GoB.

BBS. 2014. Statistical Year Book of Bangladesh. Dhaka, Bangladesh: GoB.

BBS, WFP, & WB. 2010. Poverty Maps of Bangladesh: Key Findings. Dhaka, Bangladesh: GoB, World Food Program and The World Bank .

BCA. 2006. Bangladesh Country Almanac. (Vol. BCA v.2.0.). Dhaka, Bangladesh: CIMMYT Bangladesh.

BDHS. 2014. Demographic and Health Survey. Dhaka, Bangladesh: National Institute of Population Research and Training (NIPORT), Mitra and Associates, and ICF International.

Belesky, P. 2014. Regional governance, food security and rice reserves in East Asia. *Global Food Security*. 3(3–4), 167-173.

Bishwajit, G., Sarker, S., Kpoghomou, M.-A., Gao, H., Jun, L., Yin, D., et al. 2013. Self-sufficiency in rice and food security: a South Asian perspective. *Agriculture & Food Security*. 2(1), 1-6.

BMD. 2012. Climate Database. Dhaka, Bangladesh: Bangladesh Meteorological Department.

BMDA. 2006. Groundwater model study for deep tube well installation project in barind area. Dhaka, Bangladesh: GoB.

Bogale, A. 2012. Vulnerability of smallholder rural households to food insecurity in Eastern Ethiopia. *Food Security*. 4(4), 581-591.

Bose, M. L., & Dey, M. M. 2007. Food and nutritional security in Bangladesh: Going beyond carbohydrate counts. *Agricultural Economics Research Review*. 20(2), 203-225.

Brammer, H. 1996. The Geography of Soils of Bangladesh. Dhaka, Bangladesh: University Press Limited.

Brammer, H. 1999. Agricultural Disaster Management in Bangladesh. Dhaka: University Press Limited.

Brammer, H. 2000. Agro-ecological Aspect of Agricultural Research in Bangladesh. Dhaka: University Press Limited.

Brouwer, R., Akter, S., Brander, L., & Haque, E. 2007. Socioeconomic vulnerability and adaptation to environmental risk: a case study of climate change and flooding in Bangladesh. *Risk Analysis*. 27(2), 313-326.

Bryan, B. A., Huai, J., Connor, J., Gao, L., King, D., Kandulu, J., et al. 2015. What actually confers adaptive capacity? Insights from agro-climatic vulnerability of Australian wheat. *PLoS ONE*. 10(2), e0117600.

Burchi, F., & De Muro, P. 2015. From food availability to nutritional capabilities: Advancing food security analysis. *Food Policy* (in press).

Bushamuka, V. N., de Pee, S., Talukder, A., Kiess, L., Panagides, D., Taher, A., et al. 2005. Impact of a homestead gardening program on household food security and empowerment of women in Bangladesh. *Food & Nutrition Bulletin*. 26(1), 17-25.

CEGIS. 2009. Major flood inundation Dhaka, Bangladesh.

Chanda Shimi, A., Ara Parvin, G., Biswas, C., & Shaw, R. 2010. Impact and adaptation to flood: A focus on water supply, sanitation and health problems of rural community in Bangladesh. *Disaster Prevention and Management: An International Journal*. 19(3), 298-313.

Coates, J., Webb, P., Houser, R., Rogers, B., & Wilde, P. 2010. "He said, she said": who should speak for households about experiences of food insecurity in Bangladesh? *Food Security*. 2(1), 81-95.

Coirolo, C., Commins, S., Haque, I., & Pierce, G. 2013. Climate change and social protection in Bangladesh: are existing programmes able to address the impacts of climate change? *Development Policy Review*. 31(s2), 074-090.

David, L., & Marshall, B. 2010. Climate change and food security: adapting agriculture to a warmer world (Advances in global change research, Vol. 37). London: Springer.

Deb, U. K., Hossain, M., & Jones, S. 2009. Rethinking food security strategy: self-sufficiency of self-reliance. Dhaka, Bangladesh. Available at: http://econpapers.repec.org/paper/esswpaper/id_3a3458.htm. Accessed 10 Mar 2016.

Demeke, A. B., Keil, A., & Zeller, M. 2011. Using panel data to estimate the effect of rainfall shocks on smallholders food security and vulnerability in rural Ethiopia. *Climatic Change*. 108(1), 185-206.

Deryng, D., Conway, D., Ramankutty, N., Price, J., & Warren, R. 2014. Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters*. 9(3), 034011.

Deryng, D., Sacks, W., Barford, C., & Ramankutty, N. 2011. Simulating the effects of climate and agricultural management practices on global crop yield. *Global biogeochemical cycles*. 25(2), 1-18.

Diagne, M., Demont, M., Seck, P., & Diaw, A. 2013. Self-sufficiency policy and irrigated rice productivity in the Senegal River Valley. *Food Security*. 5(1), 55-68.

Dickey, D. A., & Fuller, W. A. 1979. Distribution of the Estimators for Autoregressive Time Series With a Unit Root. *Journal of the American Statistical Association*. 74(366), 427-431.

Douglas, I. 2009. Climate change, flooding and food security in south Asia. *Food Security*. 1(2), 127-136.

Elahi, K. M., & Ara, I. 2008. Understanding the Monga in Northern Bangladesh (1st ed.). Dhaka, Bangladesh: Academic Press and Publishers Library.

Faisal, I. M., & Parveen, S. 2004. Food Security in the Face of Climate Change, Population Growth, and Resource Constraints: Implications for Bangladesh. *Environmental Management*. 34(4), 487-498.

Fang, Y.-p., Fan, J., Shen, M.-y., & Song, M.-q. 2014. Sensitivity of livelihood strategy to livelihood capital in mountain areas: Empirical analysis based on different settlements in the upper reaches of the Minjiang River, China. *Ecological Indicators*. 38, 225-235.

FAO. 2006. The state of food insecurity in the world 2006: eradicating world hunger—taking stock ten years after the world food summit. Rome, Italy: Food and Agriculture Organization Available at: ftp://ftp.fao.org/docrep/fao/009/a0750e/a0750e00.pdf. Accessed 23 Dec 2015.

FAO. 2008. Supplements to the report on the 1990 World census of agriculture. 9a. Rome, Italy: Food and Agriculture Organization Available at: http://www.fao.org/es/ess/census/wcahome.htm. Accessed 27 Feb 2014.

FAO. 2011. Looking Ahead in World Food and Agriculture: Perspective to 2050. Rome, Italy. Available at http://www.fao.org/docrep/014/i2280e/i2280e.pdf. Accessed 05 Jan 2017

FAO. 2013. A Compendium of Country Reports on Metadata for National Agricultural Statistics. Available at http://faorap-apcas.org/rdes/PPT/Compendium2.pdf. Accessed 04 Jan 2014.

FAO. 2014. Country Nutrition Paper Bangladesh Rome, Italy. Available at: http://www.fao.org/3/a-at608e.pdf. Accessed 05 Jan 2017.

FAO. 2015a. Food Security and Livelihoods Rome, Italy. Available at: ftp://ftp.fao.org/docrep/fao/010/aj033e/aj033e00.pdf. Accessed 15 Jan 2016.

FAO. 2015b. The state of food insecurity in the world, 2015. Rome, Italy. Available at: http://www.fao.org/3/a-i4646e.pdf. Accessed 02 Sep 2016.

Faridi, R., & Wadood, S. N. 2010. An Econometric Assessment of Household Food Security in Bangladesh. *The Bangladesh Development Studies*. XXXIII(3).

Felker-Kantor, E., & Wood, C. 2012. Female-headed households and food insecurity in Brazil. *Food Security*. 4(4), 607-617.

FPMU. 1991. Study on the estimation of seed, feed and post-harvest wastage of food grain crops in Bangladesh Dhaka, Bangladesh: Food Planning and Monitoring Unit, Ministry of Food, GoB.

Frongillo, E. A., Chowdhury, N., Ekström, E. C., & Naved, R. T. 2003. Understanding the experience of household food insecurity in rural Bangladesh leads to a measure different from that used in other countries. *The Journal of Nutrition*. 133(12), 4158.

Furuya, J., & Koyama, O. 2005. Impacts of climatic change on world agricultural product markets: estimation of macro yield functions. *Japan Agricultural Research Quarterly*. 39(2), 121-134.

GoB. 2010. Bangladesh Economic Review Dhaka, Bangladesh Ministry of Finance.

GoB. 2016. Bangladesh National Portal. Available at: http://www.bangladesh.gov.bd/. Accessed 26 August 2016.

GoB, & WFP. 2004. The Food Security Atlas of Bangladesh. Dhaka, Bangladesh: Bangladesh Planning Commission and the United Nations World Food Programme.

Habiba, U., Abedin, M. A., Hassan, A. W. R., & Shaw, R. (Eds.). 2015a. Food Security and Risk Reduction in Bangladesh. Japan: Springer.

Habiba, U., Abedin, M. A., & Shaw, R. 2015b. Future Approaches of Food Security, Sustainable Development, Environment and Resource Management and Risk Reduction. In Food Security and Risk Reduction in Bangladesh (pp. 255-273). Springer.

Habiba, U., Abedin, M. A., & Shaw, R. 2015c. Introduction and Overview of Food Security and Risk Reduction Issues. In U. Habiba, R. A. W. Hassan, A. M. Abedin, & R. Shaw (Eds.), Food Security and Risk Reduction in Bangladesh (pp. 1-17). Tokyo: Springer Japan.

Habibullah, M., Ahamad, A. U., & Karim, Z. 1998. Assessment on Food Grain Production Loss Due to Climate Induced Enhanced Soil Salinity. In S. Huq, Z. Karim, M. Asaduzzaman, & F. Mahtab (Eds.), Vulnerability and Adaptation to Climate Change for Bangladesh (pp. 55-70). Dordrecht, Netherlands: Kluwer Academic Publishers.

Hadgu, K., Rossing, W. H., Kooistra, L., & van Bruggen, A. C. 2009. Spatial variation in biodiversity, soil degradation and productivity in agricultural landscapes in the highlands of Tigray, northern Ethiopia. *Food Security*. 1(1), 83-97.

Haidar, M. 2009. Sustainable livelihood approaches: The framework, lessons learnt from practice and policy recommendations. Beirut: United Nations: Economic and Social Council.

Harun-ur-Rashid. 1991. Geography of Bangladesh. Dhaka, Bangladesh: University Press Ltd.

Harvey, M., & Pilgrim, S. 2011. The new competition for land: Food, energy, and climate change. *Food Policy*. 36, Supplement 1, S40-S51.

Headey, D. D., & Hoddinott, J. 2016. Agriculture, nutrition and the green revolution in Bangladesh. *Agricultural Systems*. 149, 122-131.

Hels, O., Hassan, N., Tetens, I., & Thilsted, S. H. 2003. Food consumption, energy and nutrient intake and nutritional status in rural Bangladesh: changes from 1981–1982 to 1995–96. *European Journal of Clinical Nutrition*. 57(4), 586-594.

Hesselberg, J., & Yaro, J. A. 2006. An assessment of the extent and causes of food insecurity in northern Ghana using a livelihood vulnerability framework. *GeoJourna*l. 67(1), 41-55.

HIES. 2010. Household Income and Expenditure Survey. Dhaka, Bangladesh: GoB.

Hillbruner, C., & Egan, R. 2008. Seasonality, household food security, and nutritional status in Dinajpur, Bangladesh. *Food and Nutrition Bulletin*. 29(3), 221-231.

Hossain, M., Naher, F., & Shahabuddin, Q. 2005. Food security and nutrition in Bangladesh: progress and determinants. *Journal of Agricultural and Development Economics*. 2(2), 103-132.

Iizumi, T., & Ramankutty, N. 2015. How do weather and climate influence cropping area and intensity? *Global Food Security*. 4, 46-50.

Iizumi, T., Yokozawa, M., & Nishimori, M. 2010. Probabilistic evaluation of climate change impacts on paddy rice productivity in Japan. *Climatic Change*, 1-25.

Indra, D. M., & Buchignani, N. 1997. Rural landlessness, extended entitlements and inter-household relations in south Asia: A Bangladesh case. *The Journal of Peasant Studies*. 24(3), 25-64.

IRRI. 2010. International Rice Research Institute. www.irri.org. Accessed 17 December 2014.

IRRI. 2015. International Rice Research Institute. Available at: http://irri.org/our-impact/increase-food-security. Accessed 23 Dec 2015.

Islam, A., Shaw, R., & Mallick, F. 2013a. Bangladesh Climate Change Strategy and Action Plans. In Climate Change Adaptation Actions in Bangladesh (pp. 107-118). Springer.

Islam, A., Shaw, R., & Mallick, F. 2013b. National adaptation programme of action. In Climate Change Adaptation Actions in Bangladesh (pp. 93-106). Springer.

Islam, A., & Sumon, A. 2013. Integration of Climate Change Adaptation, Disaster Risk Reduction and Social Protection in Bangladesh: Contemporary Views and Experiences. In Climate Change Adaptation Actions in Bangladesh (pp. 71-89). Springer.

Jahan, C. S., & Ahmed, M. 1997. Flow of groundwater in the Barind area, Bangladesh: implication of structural framework. *Journal of Geological Society of India*. 50(6), 743-752.

Jansen, H. G., Pender, J., Damon, A., Wielemaker, W., & Schipper, R. 2006. Policies for sustainable development in the hillside areas of Honduras: a quantitative livelihoods approach. *Agricultural Economics*. 34(2), 141-153.

John, A., & Fielding, M. 2014. Rice production constraints and 'new' challenges for South Asian smallholders: insights into de facto research priorities. *Agriculture & Food Security*. 3(1), 1-16.

Joshi, N. P., Maharjan, K. L., & Piya, L. 2011. Effect of climate variables on yield of major food-crops in Nepal -A time-series analysis. *Journal of Contemporary India Studies: Space and Society*. 1(March 2011), 19-26.

Kam, S.-P., Hossain, M., Bose, M. L., & Villano, L. S. 2005. Spatial patterns of rural poverty and their relationship with welfare-influencing factors in Bangladesh. *Food Policy*. 30(5–6), 551-567.

Karim, K. M. R., Emmelin, M., Resurreccion, B. P., & Wamala, S. 2012. Water Development Projects and Marital Violence: Experiences from Rural Bangladesh. *Health Care for Women International*. 3(33).

Karim, Z., Hussain, S., & Ahmed, M. 1996. Assessing impacts of climatic variations on foodgrain production in Bangladesh. *Water, Air, & Soil Pollution*. 92(1), 53-62.

Karim, Z., Ibrahim, A. M., Iqbal, A., & Ahmed, M. 1990. Drought in Bangladesh Agriculture and Irrigation Schedule for Major Crops. Dhaka, Bangladesh.

Khandker, S. R., Samad, H. A., & Khan, Z. H. 1998. Income and employment effects of micro-credit programmes: Village-level evidence from Bangladesh. *The Journal of Development Studies*. 35(2), 96-124.

Kirby, J., Mainuddin, M., Mpelasoka, F., Ahmad, M., Palash, W., Quadir, M., et al. 2016. The impact of climate change on regional water balances in Bangladesh. *Climatic Change*. 135(3-4), 481-491.

Koppen, B. v., & Mahmud, S. 1995. Women and water-pumps in Bangladesh: the impact of participation in irrigation groups on women's status.

Kristjanson, P., Radeny, M., Baltenweck, I., Ogutu, J., & Notenbaert, A. 2005. Livelihood mapping and poverty correlates at a meso-level in Kenya. *Food Policy*. 30(5), 568-583.

Kumar, M. D., Sivamohan, M. V. K., & Narayanamoorthy, A. 2012. The food security challenge of the food-land-water nexus in India. *Food Security*. 4(4), 539-556.

Langyintuo, A. S., & Mungoma, C. 2008. The effect of household wealth on the adoption of improved maize varieties in Zambia. *Food Policy*. 33(6), 550-559.

Lewis, D. J. 1993. Going it alone: Female-headed households, rights and resources in rural Bangladesh. *The European Journal of Development Research*. 5(2), 23-42.

Li, X., Waddington, S., Dixon, J., Joshi, A., & de Vicente, M. C. 2011. The relative importance of drought and other water-related constraints for major food crops in South Asian farming systems. *Food Security*. 3(1), 19-33.

Lobell, D., Cahill, K., & Field, C. 2007. Historical effects of temperature and precipitation on California crop yields. *Climatic Change*. 81(2), 187-203.

Lobell, D. B., & Field, C. B. 2007. Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters*. 2(1), 014002.

Mabiso, A., Cunguara, B., & Benfica, R. 2014. Food (In) security and its drivers: insights from trends and opportunities in rural Mozambique. *Food Security*. 6(5), 649-670.

Mahmood, R. 1998. Air temperature variations and rice productivity in Bangladesh: a comparative study of the performance of the YIELD and the CERES-Rice models. *Ecological Modelling*. 106(2-3), 201-212.

Mahmood, R., Meo, M., Legates, D. R., & Morrissey, M. L. 2003. The CERES-Rice model-based estimates of potential monsoon season rainfed rice productivity in Bangladesh. *The Professional Geographer*. 55(2), 259-273.

Mainuddin, M., & Kirby, M. 2015. National food security in Bangladesh to 2050. *Food Security*. 7(3), 633-646.

Mainuddin, M., Kirby, M., Chowdhury, R., & Shah-Newaz, S. 2015. Spatial and temporal variations of, and the impact of climate change on, the dry season crop irrigation requirements in Bangladesh. *Irrigation Science*. 33(2), 107-120.

Mark M. Pitt, & Shahidur R. Khandker. 1998. The Impact of Group-Based Credit Programs on Poor Households in Bangladesh: Does the Gender of Participants Matter? *Journal of Political Economy*. 106(5), 958-996.

Md. Abdur Rashid, S., Khorshed, A., & Jeff, G. 2012. A comparison of the effects of climate change on Aus, Aman and Boro rice yields in Bangladesh: Evidence from panel data. Paper presented at the 41st Australian Conference of Economists, Melbourne, July 8-11.

Mirza, M. Q. 2002. Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environmental Change*. 12(2), 127-138.

MoA. 2014. Handbook of Agricultural Statistics. http://www.moa.gov.bd/statistics/statistics.htm. Accessed 03 Mar 2014.

MoEF. 2005. National Adaptation Programme of Action (NAPA). Dhaka, Bangladesh: Ministry of Environment and Forest, GoB.

MoEF. 2009. Bangladesh Climate Change Strategy and Action Plan (BCCSAP). Dhaka, Bangladesh: Ministry of Environment and Forest, GoB.

MoF. 1991. The Estimation of Seed, Feed and Post-harvest Wastage of Food Grain Crops in Bangladesd. Dhaka, Bangladesh Ministry of Food, GoB.

MoFDM. 2006. National Food Policy. Dhaka, Bangladesh: Ministry of Food and Disaster Management, GoB.

MoFDM. 2008a. National Food and Nutrition Policy. Dhaka, Bangladesh: Ministry of Food and Disaster Management, GoB.

MoFDM. 2008b. National Food Policy Plan of Action (NFPPA). Dhaka, Bangladesh Food Planning and Monitoring Unit (FPMU), Ministry of Food and Disaster Management, GoB.

MoFDM. 2010. Bangladesh Country Investment Plan: A Road Map towards Investment in Agriculture, Food Security and Nutrition Dhaka, Bangladesh Ministry of Food and Disaster Management, GoB.

MoHFW, & BNNC. 1997. Bangladesh National Plan of Action for Nutrition. Dhaka, Bangladesh: Ministry of Health and Family Welfare and Bangladesh National Nutrition Council.

Mondal, M. K., Bhuiyan, S. I., & Franco, D. T. 2001. Soil salinity reduction and prediction of salt dynamics in the coastal rice lands of Bangladesh. *Agricultural Water Management*. 47(1), 9-23.

Morshed, K. 2009. Social safety net programmes in Bangladesh. Dhaka: United Nations Development Program.

Moslehuddin, A. Z. M., Abedin, M. A., Hossain, M. A., & Habiba, U. 2015. Soil Health and Food Security: Perspective from Southwestern Coastal Region of Bangladesh. In Food Security and Risk Reduction in Bangladesh (pp. 187-212). Springer.

Nargis, N., & Hossain, M. 2006. Income dynamics and pathways out of rural poverty in Bangladesh, 1988–2004. *Agricultural Economics*. 35, 425-435. doi:10.1111/j.1574-0862.2006.00188.x.

Nasrin, S., Bergman Lodin, J., Jirström, M., Holmquist, B., Andersson Djurfeldt, A., & Djurfeldt, G. 2015. Drivers of rice production: evidence from five Sub-Saharan African countries. *Agriculture & Food Security*. 4(1), 1-19.

NFPCSP. 2013. Desirable Dietary Pattern for Bangladesh Dhaka, Bangladesh: National Food Policy Capacity Strengthening Programme, Bangladesh Institute of Research and Rehabilitation in Diabetes, Endocrine and Metabolic Disorders (BIRDEM) and GoB.

Ninno, d. C., & Lundberg, M. 2005. Treading water: The long-term impact of the 1998 flood on nutrition in Bangladesh. *Economics & Human Biology*. 3(1), 67-96.

Oluoko-Odingo, A. A. 2011. Vulnerability and Adaptation to Food Insecurity and Poverty in Kenya. *Annals of the Association of American Geographers*. 101(1), 1-20.

Omoyo, N. N., Wakhungu, J., & Oteng'i, S. 2015. Effects of climate variability on maize yield in the arid and semi arid lands of lower eastern Kenya. *Agriculture & Food Security*. 4(1), 1-13.

Ostendorf, B. 2011. Overview: Spatial information and indicators for sustainable management of natural resources. *Ecological Indicators*. 11(1), 97-102.

Parry, M., Rosenzweig, C., Iglesias, A., Fischer, G., & Livermore, M. 1999. Climate change and world food security: a new assessment. *Global Environmental Change*. 9(Supplement 1), S51-S67.

Parvin, G. A., & Ahsan, S. M. R. 2013. Impacts of climate change on food security of rural poor women in Bangladesh. *Management of Environmental Quality: An International Journal*. 24(6), 802-814.

Parvin, L., & Wakilur, R. M. 2009. Impact of irrigation on food security in Bangladesh for the past three decades. *Journal of Water Resource and Protection*. 3, 216-225.

Pinstrup-Andersen, P. 2009. Food security: definition and measurement. *Food Security*. 1(1), 5-7.

Pitt, M. M. 1983. Food Preferences and Nutrition in Rural Bangladesh. *The Review of Economics and Statistics*. 65(1), 105-114.

Pradhan, M. A. H., Mohd, S., & Sulaiman, J. 2013. An investigation of social safety net programs as means of poverty alleviation in Bangladesh. *Asian Social Science*. 9(2).

Qi, X., Liu, L., Liu, Y., & Yao, L. 2013. Risk assessment for sustainable food security in China according to integrated food security—taking Dongting Lake area for example. *Environmental Monitoring and Assessment*. 185(6), 4855-4867.

Qin, Y., Liu, J., Shi, W., Tao, F., & Yan, H. 2013. Spatial-temporal changes of cropland and climate potential productivity in northern China during 1990–2010. *Food Security*. 5(4), 499-512.

Rahman, K. M. M., & Islam, M. A. 2014. Nutrition-sensitive agriculture in Bangladesh: a review. *Food Security*. 6(5), 671-683.

Rahman, M., & Manprasert, S. 2006. Landlessness and its impact on economic development: A case study on Bangladesh. *Journal of Social Sciences*. 2 (2): 54-60.

Rahman, M. M., & Mahbub, A. 2012. Groundwater depletion with expansion of irrigation in Barind Tract: a case study of Tanore Upazila. *Journal of Water Resource and Protection*. 4(08), 567.

Rahman, M. W., & Parvin, L. 2009. Impact of Irrigation on Food Security in Bangladesh for the Past Three Decades. *Journal of Environmental Protection*. 1, 40-49.

Rahman, R., & Mondal, M. S. 2015. Role of Water Resource Management in Ensuring Food Security. In Food Security and Risk Reduction in Bangladesh (pp. 213-234). Springer.

Rahman, R., & Mondal, S. M. 2015. Role of Water Resource Management in Ensuring Food Security. In U. Habiba, R. A. W. Hassan, A. M. Abedin, & R. Shaw (Eds.), Food Security and Risk Reduction in Bangladesh (pp. 213-234). Tokyo: Springer Japan.

Rahman, S. 2010. Six decades of agricultural land use change in Bangladesh: Effects on crop diversity, productivity, food availability and the environment, 1948–2006. *Singapore Journal of Tropical Geography*. 31(2), 254-269.

Ray, R. 2007. Changes in food consumption and the implications for food security and undernourishment: India in the 1990s. *Development and Change*. 38(2), 321-343.

Rimi, R. H., Rahman, S. H., Karmakar, S., & Hussain, S. G. 2009. Trend analysis of climate change and investigation on its probable impacts on rice production at Sathkhira, Bangladesh. *Pakistan Journal of Meteorology*. 6, 37-50.

Rocha, C. 2009. Developments in national policies for food and nutrition security in Brazil. *Development Policy Review*. 27(1), 51-66.

Roetter, R. P., & Keulen, H. 2007. Food Security. In R. P. Roetter, H. Keulen, M. Kuiper, J. Verhagen, & H. H. Laar (Eds.), Science for Agriculture and Rural Development in Low-Income Countries (pp. 27-56). Springer Netherlands.

Rosenzweig, C., & Parry, M. 1994. Potential impact of climate change on world food supply. *Nature*. 367(6459), 133-138.

Rosenzweig, M. R., & Binswanger, H. P. 1993. Wealth, weather risk and the composition and profitability of agricultural investments. *The Economic Journal*. 103(416), 56-78.

Rowhani, P., Lobell, D. B., Linderman, M., & Ramankutty, N. 2011. Climate variability and crop production in Tanzania. *Agricultural and Forest Meteorology*. 151(4), 449-460.

Ruane, A. C., Major, D. C., Yu, W. H., Alam, M., Hussain, S. G., Khan, A. S., et al. 2013. Multi-factor impact analysis of agricultural production in Bangladesh with climate change. *Global Environmental Change*. 23(1), 338-350.

Sajjad, H., Nasreen, I., & Ansari, S. A. 2014. Assessment of Spatio-Temporal Dynamics of Food Security Based on Food Security Index Analysis: A Case from Vaishali District, India. *Journal of Agriculture and Sustainability*. 5(2).

Sarker, A. R., Alam, K., & Gow, J. 2013. Assessing the determinants of rice farmers' adaptation strategies to climate change in Bangladesh. *International Journal of Climate Change Strategies and Management*. 5(4), 382-403.

Sarker, M. A. R., Alam, K., & Gow, J. 201). Assessing the effects of climate change on rice yields: An econometric investigation using Bangladeshi panel data. *Economic Analysis and Policy*. 44(4), 405-416.

Sarker, M. A. R., Khorshed, A., & Jeff, G. 2012. Exploring the relationship between climate change and rice yield in Bangladesh: An analysis of time series data. *Agricultural Systems*. 112(0), 11-16.

Sarwar, M. G. M., & Islam, A. 2013. Multi hazard vulnerabilities of the coastal land of Bangladesh. In Climate change adaptation actions in Bangladesh (pp. 121-141). Springer.

Scaramozzino, P. 2006. Measuring Vulnerability to Food Insecurity. ESA Working Paper No. 06-12. Rome. Available at http://www.fao.org/3/a-ah630e.pdf. Accessed 3 Mar 2015.

Scoones, I. 1998. Sustainable rural livelihoods: a framework for analysis. IDS Working Paper 72. Brighton: Institute of Development Studies. Available at: https://www.staff.ncl.ac.uk/david.harvey/AEF806/Sconnes1998.pdf. Accessed 15 Dec 2015.

Sen, A. 1981. Poverty and Famine: An Essay on Entitlement and Deprivation. (pp. 1-257). Delhi: Oxford University Press Limited.

Senaratna S., Aida, T., Kasahara, R., Sawada, Y., & Wijerathna, D. 2014. How Access to Irrigation Influences Poverty and Livelihoods: A Case Study from Sri Lanka. *Journal of development studies*. 50(5), 748-768.

Shah, T., Sing, O. P., & Mukherji, A. 2006. Some aspect of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. *Hydrogeology Journal*. 14, 286-309.

Shahid, S. 2008. Spatial and temporal characteristics of droughts in the western part of Bangladesh. *Hydrological Processes*. 22(13), 2235-2247.

Shahid, S., & Behrawan, H. 2008. Drought risk assessment in the western part of Bangladesh. *Natural Hazards*. 46(3), 391-413.

Shahid, S., & Hazarika, M. 2010. Groundwater Drought in the Northwestern Districts of Bangladesh. *Water Resources Management*. 24(10), 1989-2006.

Shi, W., & Tao, F. 2014. Vulnerability of African maize yield to climate change and variability during 1961–2010. *Food Security*. 6(4), 471-481.

Shin, M. 2010. A geospatial analysis of market integration: the case of the 2004/5 food crisis in Niger. *Food Security*. 2(3), 261-269.

Sietz, D., Mamani Choque, S. E., & Lüdeke, M. K. B. 2012. Typical patterns of smallholder vulnerability to weather extremes with regard to food security in the Peruvian Altiplano. *Regional Environmental Change*. 12(3), 489-505.

Simelton, E., Fraser, E. G., Termansen, M., Benton, T., Gosling, S., South, A., et al. 2012. The socioeconomics of food crop production and climate change vulnerability: a global scale quantitative analysis of how grain crops are sensitive to drought. *Food Security*. 4(2), 163-179.

Smilovic, M., Gleeson, T., & Siebert, S. 2015. The limits of increasing food production with irrigation in India. *Food Security*. 7(4), 835-856.

Soini, E. 2005. Changing livelihoods on the slopes of Mt. Kilimanjaro, Tanzania: Challenges and opportunities in the Chagga homegarden system. *Agroforestry Systems*. 64(2), 157-167.

Soltani, A., Angelsen, A., Eid, T., Naieni, M. S. N., & Shamekhi, T. 2012. Poverty, sustainability, and household livelihood strategies in Zagros, Iran. *Ecological Economics*. 79, 60-70.

Talukder, D., & Chile, L. 2011. Estimation of Population and Food Grain Production in Bangladesh by 2020: A Simple Moving Average Approach to a Time Series Analysis. Bangladesh e-*Journal of Sociology*. 8(2), 4.

Tao, F., Yokozawa, M., Liu, J., & Zhang, J. 2008. Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Climate Research*. 38, 83-94.

Thompson, P., Roos, N., Sultana, P., & Thilsted, S. H. 2002. Changing Significance of Inland Fisheries for Livelihoods and Nutrition in Bangladesh. *Journal of Crop Production*. 6(1-2), 249-317.

Thorne-Lyman, A. L., Valpiani, N., Sun, K., Semba, R. D., Klotz, C. L., Kraemer, K., et al. 2010. Household Dietary Diversity and Food Expenditures Are Closely Linked in Rural Bangladesh, Increasing the Risk of Malnutrition Due to the Financial Crisis. *The Journal of Nutrition*. 140(1), 182S-188S.

Tiwari, P., & Joshi, B. 2012. Natural and socio-economic factors affecting food security in the Himalayas. *Food Security*. 4(2), 195-207.

Tong, C., Hall, C. A. S., & Wang, H. 2003. Land use change in rice, wheat and maize production in China (1961–1998). *Agriculture, Ecosystems & Environment*. 95(2–3), 523-536.

Tukey, J. W. 1977. Exploratory Data Analysis. Reading MA: Addition-Wesley.

Van den Berg, M. 2010. Household income strategies and natural disasters: Dynamic livelihoods in rural Nicaragua. *Ecological Economics*. 69(3), 592-602.

Wang, J. T. 2010. Food Security, Food Prices and Climate Change in China: a Dynamic Panel Data Analysis. International Conference on Agricultural Risk and Food Security 2010. 1, 321-324.

WFP. 2016. World Food Programme: Fighting Hunger Worldwide. Available at: https://www.wfp.org/countries/bangladesh/overview. Accessed 27 May 2016.

Yengoh, G. T. 2012. Determinants of yield differences in small-scale food crop farming systems in Cameroon. *Agriculture & Food Security*. 1(1), 1-17.

Yu, W. H., Alam, M., Hassan, A., Khan, A. S., Ruane, A. C., Rosenzweig, C., et al. 2010. Climate change risks and food security in Bangladesh. London. Available at http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2012/05/24/000426104_20120524164749/Rendered/PDF/690860ESW0P1050Climate0Change0Risks.pdf. Accessed 27 June 2016.

Zug, S. 2006. Monga - seasonal food insecurity in Bangladesh - bringing the information together. *Journal of Social Studies*. 111.

Appendices

Appendix 1

Poster presented at the 2nd Global Science Conference on Climate Smart Agriculture, Le Corum, Montpellier, France, 16-18 March 2015.

Impact of Climatic Variables on Rice Yield in Bangladesh: a Spatio-Temporal Analysis

Ara Iffat[1]*, Ostendorf Bertram[2], Lewis Megan[2]

[1] Ph.D. Candidate, School of Biological Sciences, University of Adelaide, SA-5005, Adelaide, Australia. (*Corresponding author: iffatara.ju@gmail.com)
[2] Professor, School of Biological Sciences, University of Adelaide, SA-5005, Adelaide, Australia.

Abstract

Climate change may impact on rice food security in many parts of the world, including Bangladesh. Bangladesh may lose nearly 28 percent of its total rice production due to climate change. Rice is the main staple food of Bangladesh, covering 70 percent of direct calorie intake. In addition, 77 percent of all agricultural land is used for rice cultivation in the country. At present, Bangladesh contains 150 million people. A further 75 million people are estimated to be added to this number by 2050. The country needs sufficient rice production to feed this huge number of people. The relationship between climatic variables and rice yield has become an important indicator in assessing any changes in rice yield that may occur due to climate change. Little attention has been given to understanding spatially variable climate impacts on rice yield for the three main ecotypes (Aus, Aman, and Boro) in Bangladesh. Against this backdrop, the main aim of this paper is to analyze the effects of climatic variables on rice yield. The study analyzed 30 years (1981 to 2010) of spatio-temporal data on rice yield and climatic variables (temperature and rainfall). Multiple linear regressions were used to understand the climate-yield relationship. The resultant R^2 of each rice ecotype indicates that variations in different rice yield can be explained by climatic variables. Moreover, Aus and Aman yield became more susceptible to climate change when compared with Boro across this period. Some of the variations in rice yield were related to climatic variability, but a large proportion of the variance was related to district characteristics. The variances may therefore depend on other issues like biophysical conditions or the management of rice cultivation in the districts. Further research is needed to understand the influences of biophysical and management practices on rice yield across Bangladesh in terms of climate change alone.

Keywords: Climate change, rice yield, rainfall, maximum temperature, minimum temperature.

Appendix 2

Paper presented at the Fourth International Conference on Food Studies. Monash University Prato Centre, Prato, Italy, 20-21 October 2014.

An Economic Assessment of Livelihood Outcomes and Futures for Income and Calorie Consumption in Bangladesh

Iffat Ara, Biological Sciences, University of Adelaide, Adelaide, Australia
Jeff Connor, CSIRO Ecosystem Sciences, CSIRO, Australia, Adelaide, Australia
Bertram Ostendorf, Biological Sciences, University of Adelaide, Adelaide, Australia.

Overview: An econometric assessment of income and calorie consumption indicates how economic development, educational improvement and a greater level of household workforce participation will positively influence livelihood outcomes for Bangladeshi households.

Abstract

Food security has emerged as an important concern in recent times because of the high prices for all staple foods globally. Changes in price adversely affects food consumption in many parts of the world, including Bangladesh. The country has experienced high food prices since 2007. Food consumption in Bangladesh is mainly influenced by household socio-economic assets. An assessment is necessary to understand the influence of both household and regional conditions on food consumption in Bangladesh. The aim of the present study is to assess household calorie consumption and income under livelihood capital (natural, social, financial, human and physical), alongside any changes in these capital endowments that are likely to impact future calorie consumption and income. The present study used the 2010 Bangladesh Household Income and Employment survey (HIES) data set. The study tested two sets of regressions and included districts as a fixed effect. It was found that future trends related to general economic development, especially growth in non-agricultural employment and improved education, are likely to be the greatest and most positive influences on household income. The calorie consumption outcomes are also likely to be positively influenced by general economic development: a greater level of household workforce participation in paid employment is likely to improve nutritional outcomes.

Appendix 3

Paper presented at the International Conference on Applied Statistics (ICAS), University of Dhaka. Bangladesh, 27-29 December 2014.

Econometric Assessment of the Vulnerability of North West Bangladesh Households to Food Security: A Sustainable Livelihood-based Analysis

Iffat Ara, University of Adelaide, Australia
Jeff Connor, CSIRO, Australia
Bertram Ostendorf, University of Adelaide

Abstract

The North West region of Bangladesh is considered as a key source of national food production. Livelihoods depend on agriculture in the area primarily. Moreover, the area is vulnerable to flood and drought. Spatially varied natural resources and household characteristics affect livelihood outcomes. The present study analyzed determinants of nutrition consumption and income through a sustainable livelihood approach, which influences overall food security in the North West region. The study used the Bangladesh Household Income and Expenditure Survey (HIES) dataset and the spatially aggregated data on regional conditions for 16 districts in the North West region of Bangladesh. The data was then characterized into five capitals (physical, financial, human, natural, and social) to understand the influence of each of these on household calorie consumption and income. Two separate sets of statistical tests were used to assess livelihood determinants. The nutrition and income model generated moderate explanatory power, as the R-square values are 0.26 and 0.29 respectively. Different forms of capital were statistically significant for two of the models. The key finding was that it was the proportion of the area under severe drought in each district that impacted on calorie consumption negatively. On the other hand, major floods impacted positively on the income.

Keywords: Food security, sustainable livelihood, calorie consumption, income.

Appendix 4

Poster presented at the conference on Conservation Agriculture for Smallholders in Asia and Africa, Bangladesh Agricultural University, Mymensingh. Bangladesh, 7-11 December 2014.

Sustainable Livelihood Outcomes through Water Resource Management: A Case Study of Household Character in the North West Region of Bangladesh

Iffat Ara[1*], Jeff Connor[2], Bertram Ostendorf[1], John Kandulu[2]

[1]School of Biological Sciences, University of Adelaide, SA-5000, Australia (*Corresponding author: iffatara.ju@gmail.com)
[2]The Commonwealth Scientific and Industrial Research Organization (CSIRO), SA-5064, Australia

Introduction

Water resource management has become a key element for improved livelihood globally (Rockström, Lannerstad and Falkenmark 2007). Also, each household's demographic and socio-economic character impacts on the possibility of a sustainable livelihood for the smallholder. Bangladesh is an agrarian country where agriculture contributes 23.5 percent of the national GDP and offers 60 percent of rural employment (BBS 2012). The present study covered the North West (NW) region of Bangladesh, which represents a major source of national food production. Livelihoods and the economy in the NW region are heavily dependent on natural resources as 75 percent of the land is used for agriculture (BBS 2012). Moreover, 59 percent of the cultivable land is under irrigation and nearly 75 percent of irrigation water comes from groundwater in the NW (ASB 2003). Moreover, this area is frequently affected by flood and drought, which sometimes adversely affect livelihoods. Understanding the impact of water resources on livelihood outcomes is challenging because many aspects of spatial setting, household character, and broad economic drivers affect livelihoods. There is no investigation that features an evaluation of how spatially heterogeneous natural resources, including water resources and household character, influence livelihood outcomes such as income and nutrition consumption in Bangladesh.

Materials and methods

The present study included detail household characteristics with spatial information characterizing natural resource determinants of those districts where the households were located. The present study used the 2010 Bangladesh Household Income and Expenditure Survey (HIES) dataset and different secondary sources. It further aggregated geographic information as per each district in the NW. It was then categorized into five capitals, namely physical, financial, human, social and natural, for analysis and interpretation. The study examined two separate sets of statistical (multiple linear regression) tests for both nutrition and income to evaluate the influences of each capital on livelihood outcomes in the NW of Bangladesh.

Results and Discussion

Overall the nutrition and income model had moderate explanatory power with an *R*-square value of 0.26 and 0.29 for calorie consumption and income respectively. Different forms of capitals were statistically significant for two of those models. However, the study did not obtain any positive relationships between livelihood outcomes and water resources management in a district. This may be due to merges between the district water resource management data and the household data, which are located in the respective districts. The key finding was that the proportion of the area under severe drought impacted on calorie consumption negatively. On the other hand, the proportion of the district area where the household is located which was inundated by a major flood impacted on income positively. However, households reporting exposure to flood in the survey year were impacted on negatively in terms of their average yearly income in the short term.

Conclusion

The present study shows that socio-economic developments through industrialization mechanisms that create wage income are major contributors to both household income and nutritional well-being. Also, disaster management needs to consider to improve livelihood outcomes.

References

Rockström, J., M. Lannerstad & M. Falkenmark (2007) Assessing the water challenge of a new green revolution in developing countries. Proceedings of the National Academy of Sciences, 104, 6253-6260

ASB. 2003. National encyclopedia of Bangladesh. Dhaka, Bangladesh: Asiatic Society of Bangladesh

2012. Yearbook of Agricultural Statistics of Bangladesh 2012. Dhaka, Bangladesh: Government of Bangladesh

Appendix 5

Paper presented at the 20th International Congress on Modelling and Simulation on 'Adaptation to change: the multiple roles of modelling', Adelaide, South Australia, 1-6 December 2013.

Spatiotemporal Patterns of Rice Production in Bangladesh: Interactions of Climate and Management Practices.

Iffat Ara[1], Bertram Ostendorf[2]

[1]Ph.D. Candidate, School of Biological Sciences, The University of Adelaide, SA-5005. email: iffatara.ju@gmail.com
[2]Professor, School of Biological Sciences, the University of Adelaide, SA-5005

Abstract

The people of Bangladesh mostly depend on rice for their dietary requirements and it is the country's the main staple food. Rice occupies 77% of agricultural land and about 70% of direct human calorie intake comes from rice in Bangladesh. Rice production is variable in space and time and depends on biophysical conditions, climate, and management practices. Because of the importance of rice for Bangladesh, it is necessary to assess which factors cause regional differences in production. This is then the basis for the development of spatial indicators that show if a region produces rice at full potential or if there are improvements that can be achieved through changes in management.

Bangladesh has a long-term (30 year) record of rice yield and biophysical and climatic data. Station base climate data was obtained from the Bangladesh Meteorological Department (BMD). Rice yield, cropping intensity and irrigation data was collated by the Bangladesh Bureau of Statistics (BBS) from 1981 to 2010 and was extracted from the annual reports. The government reports distinguish three varieties of rice (e.g. Aus, Aman, and Boro) that are grown in different seasons. Aus mostly covers the pre-monsoon period (March to August), Aman is typically rain fed (June to November) and Boro is generally irrigated (December to May).

The main aim of this study was to analyze the direct effects of climate and management factors on rice yield. Specific objectives were to evaluate the data quality, to assess the spatial and temporal changes from climate and management influences as well as yield values and to evaluate the relative importance of these factors on the yield itself. We harmonized the data by spatially interpolating climate station data for rainfall and temperature at monthly time intervals and summarized the outcomes by region. Cropping intensity is estimated based on the proportion of the land use multiplied by the number of harvests per year. We used linear mixed models to differentiate between climatic and management influences.

The results show an overall increase in rice for three varieties at national level but rates differ substantially amongst the regions. Cropping intensity increased until 1991 but has been relatively steady during the last 20 years of the study period. The areas under means of irrigation (e.g. power pumps, tube wells, canals and others) are variable regionally but groundwater irrigation has increased. The Linear Mixed Model was used to assess the influence of variable combinations on rice yields. The irrigation management appears to

have a stronger influence on rice yield than climatic conditions. A large proportion of the variance is related to districts and cannot be explained by the data. Furthermore, there is an increase over time that remains unexplained.

The present study shows that some of the improvements are related to groundwater extraction, which may not be sustainable over time. However, there are spatial differences that indicate that there is further potential for improvement. More investigation of other management issues (e.g. application of fertilizers and pesticides, ploughing methods and tools etc.) will improve our understanding of the regional variations in rice yield in Bangladesh. This spatial analysis has contributed to an improved understanding of the biophysical and management limitations to date.

Keywords: Rice production, climatic variables, cropping intensity, means of irrigation, spatial analysis

H15. Spatial indicators for ecosystem pattern and processes