RESEARCH ON IMPACTS OF CLIMATE CHANGE ON BANGLADESH AGRICULTURE: A KGF INITIATIVE

Editors

Jatish C Biswas PhD

M Hazrat Ali PhD

Wais Kabir PhD

KRISHI GOBESHONA FOUNDATION

BARC Complex, Farmgate, Dhaka-1215

Bangladesh

Publication No.: 23

First Edition: 500 copies
May 2019

Published by
Krishi Gobeshona Foundation
BARC Complex
Farmgate-1215, Dhaka
Bangladesh

Cover Design
Jatish C Biswas PhD
Tahsina Naznin

Printed at

CONTENTS

Content	Page
Message	5
Preface	6
Introduction	7
Climate change concerns for agriculture	7
Objectives	10
Approaches	11
Achievements	12
Future climate change scenarios	12
Climatic variability and rice production	13
Extreme climate events	16
Frequency of occurrence	16
Influence on Boro rice yield	17
Waterlogging: anthropogenic or climate change effect?	17
Effect of temperature on soil processes	19
Mineralization	19
Microbial population	20
Development of genetic coefficients for DSSAT	21
Effect of temperature and CO_2 on plant processes	23
Rice	23
Maize	26
Wheat	27
Mungbean	30
Potato	33
Climate change and insect pest	34
Rice yellow stem borer	34
Fecundity of brown plant hopper	35
Greenhouse gas emission	37
Status of water and soil resources	40
Water resources and land surface areas	40
Soil fertility	42
Soil health	43

Economic impact of climate change on selected crops in coastal areas	44
Mitigation and adaptation strategies	45
Organic amendment study at BSMRAU	45
Organic amendment study at BRRI	47
Cultural management and GHG emission patterns	48
Amelioration of soil salinity	50
Cropping pattern based water requirement	51
Wheat planting time adjustments	54
Papers published	55
Outcome/benefit	59
Future plan	60

ABBREVIATIONS

AEZ	Agricultural ecological zone
AWD	Alternate wetting and drying
BARI	Bangladesh Agricultural Research Institute
BBS	Bangladesh Bureau of Statistics
BCCAP	Bangladesh climate change action plan
BoF	Bio-organic fertilizer
BRRI	Bangladesh Rice Research Institute
BSMRAU	Bangabandhu Sheikh Mujibur Rahman Agricultural University
BU	Bangabandhu University
C	Carbon
CC	Climate change
CD	Cow dung
CEC	Cation exchange capacity
CERES	Crop environment resource synthesis
Cfu	Colony forming unit
CH_4	Methane
CO_2	Carbon dioxide
CSDI	Cold spell duration indicator
CSW	Continuous standing water
DAT	Days after transplanting
DSSAT	Decision support system for agro-technology
EC	Electrical conductivity
g	Gram
GDP	Gross domestic product
GENCALC	Genotype coefficient calculator
GHG	Greenhouse gas
GLUE	Generalized likelihood uncertainty estimation
GM	Geometric mean
GWP	Global warming potential
HYV	High yielding variety
INM	Integrated nutrient management
IPCC	Intergovernmental panel on climate change
IPNS	Integrated plant nutrient system
KGF	Krishi Gobeshona Foundation
MAKESENS	Mann-Kendall Test and Sen's Slope Estimates
NARS	National agricultural research system

NBRIP	National botanical research institute phosphate
NECB	Net ecosystem carbon balance
NFB	Nitrogen fixing bacteria
N_2O	Nitrous oxide
OM	Organic matter
OTC	Open top chamber
P	Phosphorus
ppm	Parts per million
PM	Poultry manure
PSB	Phosphate solubilizing bacteria
RCP	Representative concentration pathway
RH	Relative humidity
RHB	Rice husk biochar
RS	Rice straw
SDG	Sustainable development goal
SLR	Sea level rise
SOC	Soil organic carbon
SPI	Standard precipitation index
SPEI	Standardized precipitation evaporation index
TN10	Cold nights
TX10	Cold days
TSP	Triple super phosphate
VC	Vermicompost
YSB	Yellow stem borer

Message

Bangladesh is ranked as the country most vulnerable to climate changes by an international Climate Change Vulnerability Index. For the last two decades, The country has been experiencing an ever-increasing frequency of natural calamities as unwelcome consequences of global warming. Climate adversities have already affected crops, fisheries, livestock and rural livelihoods and incomes in Bangladesh and threaten to cause even greater damages to crops and other agricultural enterprises in the future; at stake are food security and socio-economic wellbeing of the people of Bangladesh. Agricultural scientists and extension specialists need to take stock of the situation and develop stress tolerant crop varieties and breeds of livestock and fish and appropriate production technologies to combat climate change and its impacts. Researchers and extension experts need to keep themselves abreast in respect of scientific information on the current and potential hazards of climate change and possible adaptation and mitigation measures.

This effort by KGF to publish a booklet on *Climate Change Impact Assessment on Bangladesh Agriculture : A KGF Initiative* narrating the outcomes of collaborative research by BARI, BRRI and BSMRAU scientists, sponsored and facilitated by KGF, is a welcome development towards dissemination of scientific information on a pressing national and global issue.

I hope that agricultural researchers and extension specialists, social workers and community leaders, government planners and strategists will find this publication to be engaging and helpful in their collective efforts to combat climate change and its impacts in Bangladesh.

Md Kabir Ikramul Haque PhD
Executive Chairman
Bangladesh Agricultural Research Council

Preface

Climate change (CC) manifestations, such as, rise of temperature, sea level rise (SLR) , increase in frequencies of extreme events like floods, droughts, cyclones, etc. pose as significant challenges to agricultural production, food security and livelihoods in Bangladesh. Grim projections abound regarding flooding and serious salinization of low-lying coastal areas, loss of biodiversity, surface and ground water pollution, substantial damages to agriculture and freshwater fisheries, etc. in the near future. Much warmer and wetter future climate and SLR are predicted, which could result in severe abiotic and biotic stresses to crops, fish and livestock. Due to climate change related stresses, yield reductions in rice, Bangladesh's staple food crop, could be as severe as 15-20% in the southern districts by the 2050s. Overall, agricultural GDP in Bangladesh is projected to be affected negatively each year as a result of CC.

In this backdrop, research and technology generation and dissemination to offset, as much as possible, the adverse effect of climate change need to be expedited. This is also called for by the Bangladesh Climate Change Action Plan (BCCAP) and by Bangladesh's commitment to the United Nations SDG to "Take urgent action to combat climate change and its impacts". ~~(SDG 13).~~

Agricultural researchers and extension specialists need to develop adaptation and mitigation measures comprising climate resilient varieties of crops and breeds of fish and livestock and climate smart production technologies and methods, such as, modifying and fine tuning present cropping patterns, suitable shifts in sowing/transplanting/harvesting dates, zero or minimum tillage, soil, irrigation and nutrient management to reduce greenhouse gas (GHG) emissions from crop fields, rainwater harvesting, floating agriculture, brackish water fish/prawn aquaculture, etc.

The Krishi Gobeshona Foundation (KGF) took up the challenge of promoting and empowering Bangladeshi scientists to conduct research to conduct research on the impacts of climate change on Bangladesh agriculture and develop suitable adaptation and mitigation technologies. KGF organized a series of knowledge boosting and capacity building training sessions during 2014-15 for one hundred and twenty Bangladesh NARS scientists and university professors to build a core of skilled professionals for upcoming research endeavors. Subsequently, in the year 2015, KGF initiated a coordinated project in collaboration with BRRI, BARI and BSMRAU to assess CC impacts on crop agriculture, with plans to expand research to the livestock and fisheries sub-sectors.

Information and data pertaining to past and present climate scenarios and forecasts for the future, climate change impacts on soils and crops, adaptation and mitigation measures including soil organic matter management, shifting crop establishment times, cultural management to reduce GHG emission, etc. gathered through the three-year BARI-BRRI-BSMRAU collaborative research venture have been compiled in this booklet. This booklet may serve as a useful reference for agricultural researchers, extension experts, social workers and policy makers concerned about climate change impacts and mitigation in Bangladesh.

We acknowledge the efforts and contributions of the scientists of BRRI, BARI and BSMRAU in generating important scientific information relating to CC impacts on Bangladesh agriculture. I also hope that they will continue their work to develop suitable adaptation and mitigation techniques to combat the CC threat in Bangladesh agriculture.

Wais Kabir PhD
Executive Director

Introduction

Global warming is a consequence of ~~phenomenon of~~ CC in which average temperature of the Earth increases ~~and thereby~~ modifying the weather balances and ecosystems. ~~for a long time~~ It directly linked to the augmentation of greenhouse gases (GHG) in the atmosphere. The average temperature of the Earth has been already increased by 0.8ºC compared to the end of the 19th century. The last three decades were warmer than all previous decades

The global mean surface temperature has been on the increase during the period 2006–2015 mostly because of anthropogenic activities. Anthropogenic global warming is currently increasing at the rate of 0.2°C per decade. Increased temperatures have already caused damages to many natural resources, and such damage could be irreparable if temperatures increase by more than 1.5^{o}C (IPCC, 2018). However, climate models project strong differences in regional climate characteristics between the present condition and global warming of 1.5°C and between 1.5°C and 2°C. These differences include increases in mean temperature mainly in land and in ocean regions (high confidence), hot extremes in most inhabited regions (high confidence), heavy precipitation in several regions (medium confidence), and the probability of drought and precipitation deficits in some regions (medium confidence). These changes in temperature and CO_2 levels are also related to agriculture because greenhouse gas (GHG) emissions take place from crop fields (Lemke et al, 1998). Thelivestock sector also contributes to the global warming potential (GWP) through GHG emission.

The combination of rising temperatures, severe flooding, droughts and losses of arable lands may cause declines in rice production by 3.9% each year in future (Golub and Golub, 2016). Studies identified Bangladesh as one of the countries most vulnerable to climate change impacts (Allison et al, 2009; Haque et al, 2017) where huge losses occur in most years. The vulnerability is due to the combination of rising temperature, delayed rainfall, drought, etc.

Climate change is expected to decrease agricultural GDP in Bangladesh by 3.1% each year (World Bank, 2018).

Climate change concerns for agriculture

- Declined or stagnant crop productivity in major AEZs
- Reduced factor productivity of inputs, namely, nutrients (NPK)
- Deteriorating soil health
- Changing behavior of insects/pests--emergence of new diseases and insect pests
- Increased frequency of occurrences of extreme climatic events
- High inter- and intra-annual climatic variability
- Depletion and pollution of ground water table
- Rapid land use and land cover changes
- Damages to livestock, poultry and fisheries sub-sectors

During last three decades, the occurrence of extreme climatic events, such as, floods has increased (Fig. 1). Different natural hazards cause huge economic losses in Bangladesh (Fig. 2), crop sub-sector suffering more than livestock and fisheries (Fig. 3). Human sufferings have also been on the increase. There is a need to determine regional vulnerability and identify agronomic management options for sustaining agricultural productivity in the face of extreme climate events.

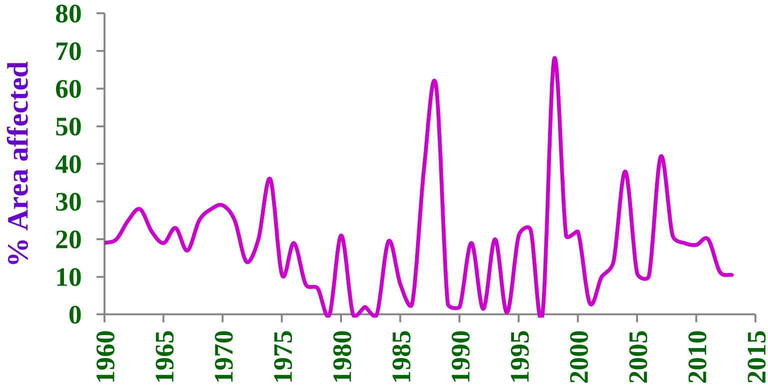

Fig. 1. Flooding frequencies in Bangladesh during 1960 to 2015 (BBS, 2015)

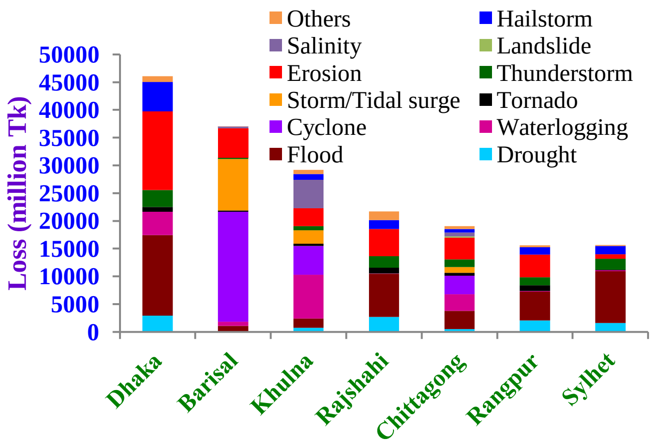

Fig. 2. Economic losses in different regions of Bangladesh due to natural hazards, 2009-2014 (BBS, 2015)

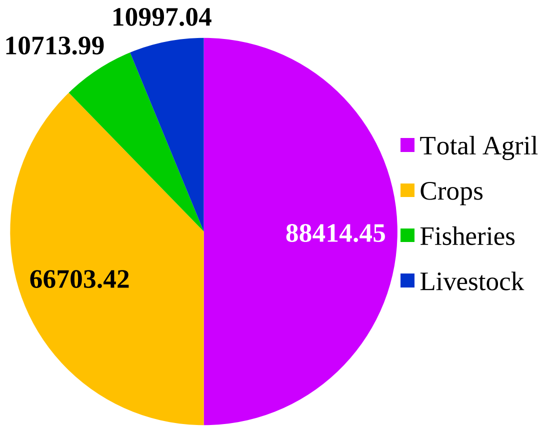

Fig. 3. Economic losses (million Tk) in the agricultural sector of Bangladesh due to natural hazards (BBS, 2015)

Developing climate resilient agriculture through adapting agricultural production practices and management options to changing climate scenarios is urgently needed. This would require prior understanding and mapping out of the risks and impacts of CC on agriculture and also an understanding of various aspects of CC, such as, nature and extent of climate variability, vulnerability of crops, livestock, poultry and fisheries and mechanisms of coping with CC and adaptation strategies. KGF initiated a research project in collaboration with BARI, BRRI and BSMRAU with the following objectives.

Objectives

i. Assessment and characterization of climatic variability and vulnerability of agriculturalproduction to climate change.
ii. Study of the influence of climatic variability and climate change on soil and plant processes.
iii. Compilation of databases for soil, climate, common cultivars, agronomic management practices, other bio-physical and socio-economic scenarios, area and production

delineation, yield gaps and options to narrow them down, dynamics of insects/pests for subsequent use in crop simulation models for application in climate change forecasts, natural resource management, yield forecasts, etc.

iv. Calibration and validation of crop simulation models.
v. Development of mitigation/adaptation strategies for agricultural production.
vi. Vulnerability assessment for agricultural production in relation to climatic variability/climate change.
vii. Establishment of a center for education and research on climate.

Approaches

- Teams were formed for each of the above objectives and team members assigned to each objective were engaged in conducting experiments (field and lab trials), literature search, database management, running crop simulation models (such as, DSSAT, DNDC, FST, INFOCROP, etc.), use of GIS and remote sensing and data analyses and reporting.
- Analysis of the frequency of occurrences of the extreme climatic/episodic events in various growing regions: Future CC scenarios were generated through the generous cooperation of Dr J Furuya, Social Science Division, JIRCAS, Japan.
- Soil and plant processes in relation to CC were evaluated under controlled conditions, followed by field evaluation (wherever applicable).
- Calibrated and validated crop models were used to study CC impacts on the growth and yield of selected crops.
- GHG emissions were measured (both software based and field observation) for identifying suitable agronomic and input management options to adapt to CC impacts and to minimize GHG emission from rice- and non-rice based cropping patterns.
- A few models were developed to study CC impact on mungbean and rice yellow stem borer
- Need based training sessions were organized to accomplish different activities.
- Study on socio-economic vulnerabilities was initiated.

Achievements

The project was designed to study crops and soil processes as influenced by temperature, solar radiation, rainfall, etc. Two other important research topics were, (1) GHG emission from major crop fields, and (2) adaptation and mitigation strategies to minimize CC impacts. Important findings from the three-year (2015-18) research project presented in the following sections.

1. Future climate change scenarios

Future climatic scenario forecasts for Bangladesh were developed. Representative concentration pathway (RCP) based projected data on maximum and minimum temperatures, rainfall and solar radiation were used under five different general circulation models.

Compared with 2010, the monthly maximum temperature increase would be 0.60-0.99^{o}C in 2050 and 0.83-2.93^{o}C in 2100 under different RCPs. The increase in monthly minimum temperature is likely to be 0.98-1.31^{o}C in 2050 and 0.75-2.93^{o}C in 2100compared with 2010. In general, solar radiation is likely to increase during November to February in the central, south-central and south-west regions of Bangladesh. Rainfall is likely to increase compared with that in 1948-2013. Critical maximum temperature limits for maize and rice growth are likely to cross the limit during March to October under RCP8.5. In the winter season, suitable maximum temperature is likely to prevail during December to February in 2050 and 2100 for wheat cultivation. In 2050 and beyond, air temp may exceed the optimum limit for rice, cotton, maize, etc. cultivation in Bangladesh (Fig. 4).

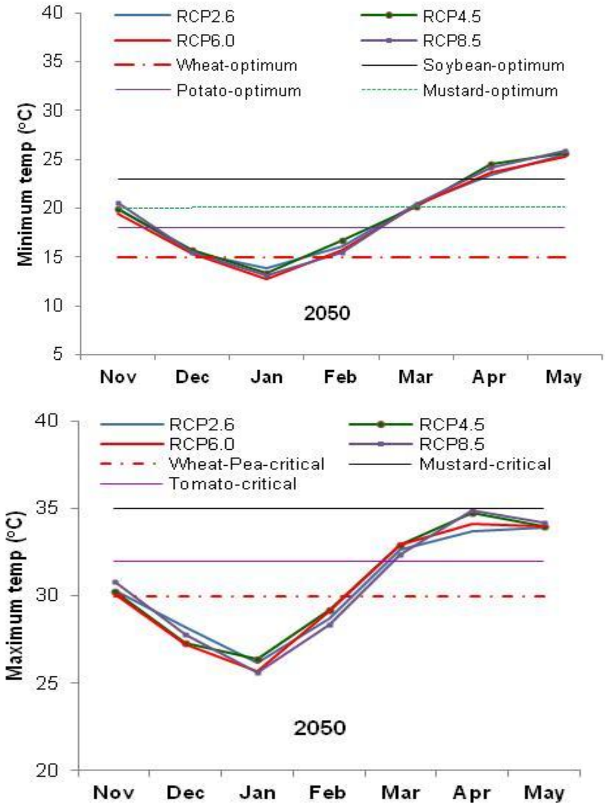

Fig. 4. Minimum and maximum temperature vulnerability for some selected crops by 2050

2. Climatic variability and rice production

Inter-annual climatic variability in Bangladesh is significant and the probability of occurrence of extreme climatic events has increased in the recent decade. The impact of inter-seasonal climatic variability on Boro (dry season irrigated rice) and T. Aman rice (monsoon rice) yields in the north-west part (Rajshahi, Bogura, Dinajpur and Ranpur) of Bangladesh were analyzed using historical weather data (1971 to 2010) and the MAKESENS model. Boro rice yield increased from 1980 onwards and the growth rate peaked with time. Historical average seasonal maximum and minimum temperatures in the study regions were 29.8-31.3°C and 13.4-16.6°C, respectively. The Boro rice seasonal maximum temperature was found to be decreasing by 0.013°C yr^{-1} but minimum and mean temperatures were increasing by 0.024 and 0.006°C yr^{-1}, respectively. Dry season sunshine hours decreased at the rate of 0.035 hr yr^{-1}. If the maximum temperature changed by 1°C, Boro rice yield could be increased by 0.13 t ha^{-1}, but it would decrease by 0.34 t ha^{-1} with a 1° rise in the minimum temperature. Sunshine hours in the study regions were 8.2-9.6 in the dry season and if it is reduced by 1 hr, Boro rice yield would decrease by 0.70 t ha^{-1} at the study locations. The combined effects of maximum and minimum temperatures and sunshine hours appeared to significantly influence grain yield of Boro rice.

Wet season maximum and minimum temperatures were found to increase by 0.0174 and 0.0083°C yr^{-1}, respectively. Sunshine hours have decreased by 0.0259 - 0.027 hr $year^{-1}$. T. Aman rice yield could be reduced by 0.17–0.37 t ha^{-1} if temperature rises by 1°C. If sunshine hours decrease by 1 hr, yield reduction could be 0.20 t ha^{-1}. The increased minimum temperature and decreased sunshine hours will control T. Aman rice yield in the future (Fig. 5) but sunshine hours would be the deciding factor for Boro rice yield reduction.

Seasonal maximum and minimum temperatures and annual rainfall trends for selected districts were analyzed and standard precipitation index (SPI) based on 1, 3, 6, 9 and 12 months and standardized precipitation evapotranspiration index (SPEI) were determined. Variability was observed for 1, 3, 6, 9 and 12-month for Bogura, Patuakhali, Sylhet, Tangail and Teknaf districts. Similarly, the SPEI of 3 and 6 months varied in Dhaka, Barishal, Dinajpur, Jashore and Rajshahi districts. Although demand for water will increase in future agriculture, rainfall is likely to be decrease by 2050 and might increase by 2100 relative to 2010 (Fig. 6)

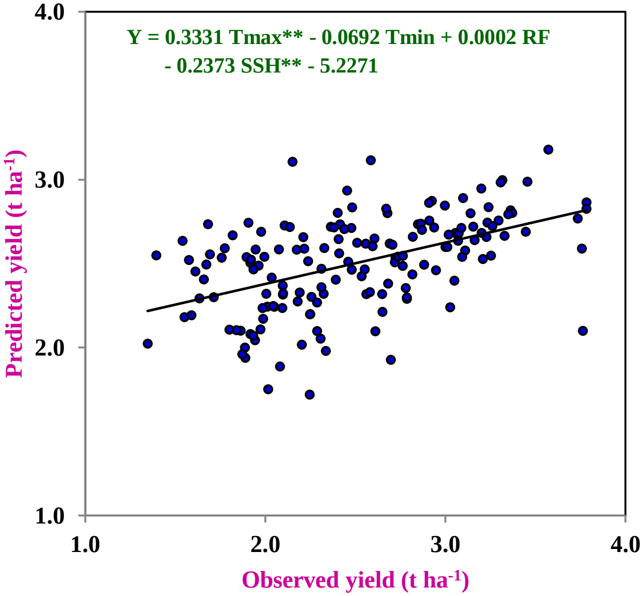

Fig. 5. Influence of T_{max} and T_{min}, total rainfall and sunshine hours on T. Aman rice yield in the north-western region of Bangladesh

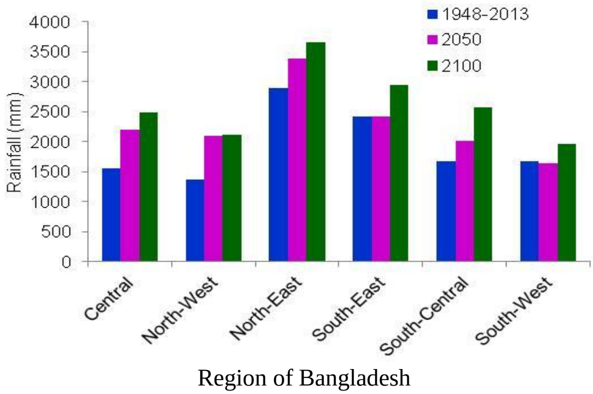

Fig. 6. Total rainfall in different regions of Bangladesh in 2050 and 2100 compared with the average rainfall in 1948-2013

3. Extreme climate events

3.1 Frequency of occurrences

Climate extremes are occurring in increasing frequencies in Bangladesh as indicated by *RClimDex* 1.0 based on historical data. The occurrences of warm days and warm nights are increasing in different parts of Bangladesh (Fig. 7) along with the tropical nights and warm spell duration indicator. The frequencies of cold days and nights, and cold spell duration indicator showed decreasing trends of −0.143, −0.254, and −0.04 day yr^{-1} respectively. These indicate that future agriculture is beset with the risk of extreme climate event vulnerability.

Five years' total numbers of cold and warm spell durations were estimated by *RClimDex* 1.0. Cold spell duration showed a decreasing trend in most regions of Bangladesh except the Rangpur and Rajshahi regions where the cold spell duration was decreasing in 1996–2000 and thereafter it kept increasing. Total number of warm spell duration was also observed in increasing trends in most cases except in Rangpur region. Since warm spell duration is increasing, Boro rice might be exposed to unusual temperature in future and, thus, yield reduction is most likely.

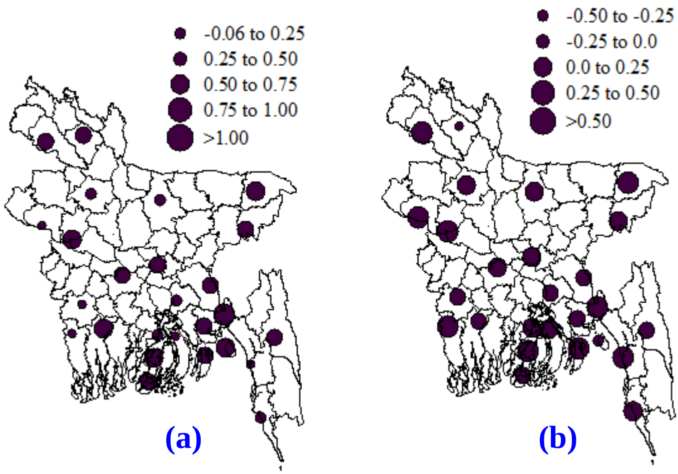

Fig. 7. Distribution patterns of (a) warm days and (b) warm nights based on 1985-2000 data

3.2 Influence on Boro rice yield

Climate extreme events are increasing in Bangladesh. Do they influence crop yields? To answer this question, the relationships of extreme temperature events with rice yields were investigated based on historical data.

Effects of cold extremes on Boro rice are shown in Fig. 8. Boro rice yield decreased with cold days (TX10), cold nights (TN10) and cold spell duration indicator (CSDI).

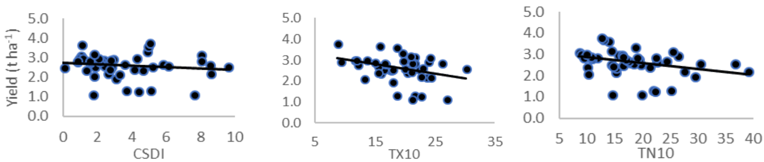

Fig. 8. Effect of cold extreme indices on Boro rice yield in Bangladesh during 1971-2015

4. Waterlogging: anthropogenic or climate change effects?

Waterlogging depends on rainfall intensity, soil type, shape and length of slope along with sea level rise (SLR). Rainfall patterns have changed and SLR is occurring indicating that CC impacts are responsible for waterlogging, although anthropogenic activities also play an important role in this regard. Waterlogging is becoming a major environmental problem and socio-economic challenge for the south-western part of Bangladesh. The Satkhira district was selected to quantify waterlogging areas. Landsat images from 1973, 1989, 1995, 2000, 2005, 2010 and 2015 were used for this purpose. A dataset was generated in ArcGIS and a supervised classification was carried out using the Random Forest algorithm in the R Studio. Post-classification change detection comparisons were made in QGIS to calculate the transformations of the respective land cover areas.

Areas of approximately 832, 3033, 13562, 11547, 27162, 40056 and 35606 ha were observed as waterlogged in test years, respectively, indicating that waterlogged areas have increased approximately 43-fold during the period 1973 to 2015. The most waterlogged upazila was Debhata (38%), while Kolaroa had the lowest (4%) waterlogged area (Fig. 9). Regarding environmental degradation, the government and development agencies should consider these results as a critical issue for the entire south-west part of Bangladesh.

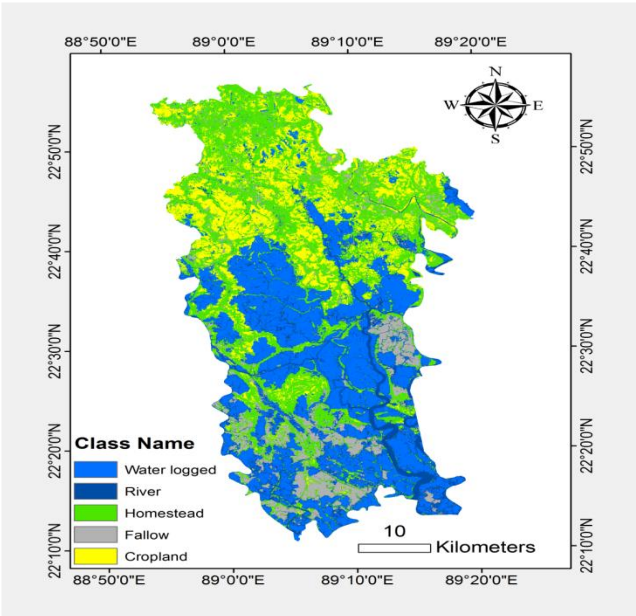

Fig. 9. Waterlogged areas in south-west Bangladesh

5. Effect of temperature on soil processes

5.1 Mineralization

High temperature enhances organic matter (OM) decomposition and nutrient mineralization in soil. An incubation study was conducted at BRRI to determine the effect of temperature on nutrient mineralization and microbial populations in selected soils. Terrace soil was clay loam and saline soil (EC 6 dS m^{-1}) was silty clay loam in texture. Each type of soil (3 kg) was taken in a plastic pot. The treatments were : chemical fertilizers, N-P-K-S @ 135-18-82-20 kg ha^{-1} and integrated nutrient management (INM: cow dung @ 3 t ha^{-1} + N-P-K-S @ 120-13.5-75.1-20 kg ha^{-1}). After mixing fertilizers and OM, soil was moistened and incubated in an incubator at 28±2^{o}C, and 45±2^{o}C. Soil moisture was maintained at the saturation for one month.

High temperature (45^{o}C) enhanced C mineralization by 33% in terrace soil (Table 1) with INM and 41% with chemical fertilizer treatment in saline soil. High temperature significantly influenced NH_4^+-N mineralization (Table 2). Similarly, high temperature significantly enhanced P mineralization in INM compared to chemical fertilizer treatment. In terrace soil at 28^{o}C K release was high in chemical fertilizer amended soil. In another study, it was also found that mineralization was enhanced with higher temperature and followed the order of 50>45>40>35>30>25^{o}C.

Table 1. Effect of temperature and nutrient management practices on carbon mineralization rate (g C soil kg^{-1} day^{-1}) in terrace and saline soil

Soil type	Temp 28^{o}C		Temp 45^{o}C	
	Chemical fertilizer	INM	Chemical fertilizer	INM
Terrace soil	0.011	0.010	0.013	0.015
Saline soil	0.020	0.017	0.034	0.031

Table 2. Effect of temperature and nutrient management practices on NH_4^+-N (ppm) mineralization in terrace and saline soil

Incubation period (day)	Terrace soil				Saline soil			
	28°C		**45°C**		**28°C**		**45°C**	
	Chemical fertilizer	INM	Chemical fertilizer	INM	Chemical fertilizer	INM	Chemical fertilizer	INM
3	31.5ed	29.1ed	26.3e	24.9e	23.5e	22.1e	67.0ab	36.4d
6	26.5e	24.9e	23.1e	28.4ed	25.6e	22.1e	51.8c	53.2c
9	24.3e	22.9e	23.0e	24.5e	25.6e	18.4ef	81.0a	74.7ab
14	21.7ef	18.4ef	22.4e	23.1e	23.1e	23.8e	69.3ab	62.0b
30	14.7f	17.5f	20.1ef	22.4e	20.8ef	18.6ef	27.0e	41.0d

Means followed by the same letter are not statistically significant by DMRT

Since there will be more loss of C as CO_2 because of increased temperature, more OM needs to be added in future to maintain soil health. However, type of OM and N application rate would dictate CO_2 emission from crop fields. It was found that a higher N rate hastened OM decomposition. Moreover, nature of OM also influenced decomposition rate as was found from an investigation at BSMRAU, Gazipur. The C emission loss followed the order of poultry manure (PM)>rice straw (RS)>vermicompost (VC)>cow dung (CD)>rice husk biochar (RHB). This indicates that OM with low decomposition rates would be better as a soil amendment in future.

5.2 Microbial population

Soil samples were collected in plastic bags and kept in an ice box and preserved at 4°C until analyses. Microbial populations were determined following the total plate count method. Total bacteria population was determined using a nutrient agar plate. Potato dextrose agar and actinomycetes isolated media were used to determine fungus and actinomycetes populations, respectively. Free-living N_2 fixing bacteria (NFB) population was determined in N-free media and phosphate solubilizing bacteria (PSB) in national botanical research institute phosphate (NBRIP) media plates. Serial dilution (up to 10^{10}) technique was used for population determination. Inoculated plates were incubated at 28°C temperature for 5 days (d) Population counting was started after 1 d of incubation and completed on day six.

Temperature and nutrient sources affected soil bacteria population significantly compared with fungi and actinomycetes. The PSB were found to be more resistant to high temperature than NFB. In terrace soil at 28^{o}C, microbial population declined sharply after 14 d of incubation. At 45^{o}C, initial bacteria population was greater with INM treatment that decreased after 9 d of incubation (Table 3) and followed a similar pattern for both the nutrient management practices.

In saline soil at 28^{o}C, decrease in bacteria population followed similar patterns with both the nutrient management practices (Table 3). The highest bacteria population (1.1-3.9 x10^{7} Cfu g^{-1} soil) was found at 3 d of incubation and then decreased gradually up to 9 d. At 45^{o}C, bacteria population was low (4.2-4.5x10^{6} Cfu g^{-1} soil) at 3 d of incubation compared with 28^{o}C.

6. Development of genetic coefficients for DSSAT

The DSSAT is a robust model to study the impacts of CC on agriculture, but it requires weather data, soil profile and genetic coefficients. The genetic coefficients of rice, maize, wheat and potato were determined by using the GENCALC (GLUE) module of DSSAT on the basis of field experimental data. Rice varieties used were BRRI dhan28, BRRI dhan29 and BRRI dhan58; maize varieties were BARI Hybrid Maize-7, BARI Hybrid Maize-9, Pioneer 30B07 and NK-40; wheat varieties were BARI Gom-25, BARI Gom-26, BARI Gom-27 and BARI Gom-28 and potato varieties were BARI Alu-7 (Diamant), BARI Alu-8 (Cardinal), BARI Alu-13 (Granola) and BARI Alu-25 (Asterix). Generated genetic coefficients were utilized for CC scenario analysis.

Table 3. Effect of temperature and nutrient management practices on soil bacteria population (Cfu g^{-1} soil) in terrace and saline soil

Incubation time (d)	Terrace soil				Saline soil			
	28°C		45°C		28°C		45°C	
	Chemical fertilizer	INM	Chemical fertilizer	INM	Chemical fertilizer	INM	Chemical fertilizer	INM
3	4.8×10^{7} b	5.0×10^{7} b	6.0×10^{6} c	3.6×10^{7} b	1.1×10^{7} b	3.9×10^{7} b	4.2×10^{6} c	4.5×10^{6} c
6	3.6×10^{7} b	3.5×10^{7} b	4.0×10^{6} b	7.2×10^{6} c	3.1×10^{5} d	4.2×10^{4} e	4.4×10^{5} d	6.2×10^{4} e
9	6.2×10^{7} b	7.2×10^{7} b	4.4×10^{8} a	4.2×10^{8} a	2.8×10^{5} d	3.2×10^{5} d	3.4×10^{5} d	2.2×10^{5} d
14	2.9×10^{7} b	3.6×10^{7} b	3.0×10^{5} d	1.2×10^{5} d	5.1×10^{6} c	2.5×10^{6} c	4.4×10^{4} e	2.9×10^{5} d
30	9.3×10^{4} e	5.8×10^{4} e	2.7×10^{4} e	4.1×10^{4} e	1.2×10^{4} e	1.5×10^{4} e	1.0×10^{4} e	2.7×10^{4} e

Means followed by the same letter are not statistically significant

7. Effect of temperature and CO_2 on plant processes

Both lab and/or model based studies were conducted for determination of plant processes with selected crops (viz. rice, wheat, maize, potato and mungbean). Calibrated and validated DSSAT model was used for determination of the effects of temperature, radiation and CO_2 levels on grain yield and growth duration. Open top chambers with enriched CO_2 levels were also used to study the effect of CO_2 on rice yield.

7.1 Rice

7.1.1 Use of DSSAT model

Crop productivity is affected by air temperature and CO_2 concentration. The relationships among grain yield of Boro rice varieties (BRRI dhan28, BRRI dhan29 and BRRI dhan58) with increased temperatures and CO_2 concentrations were investigated for futuristic crop management in six regions (Gazipur, Rangpur, Rajshahi, Barishal, Cumilla and Habiganj) of Bangladesh using the CERES-Rice model (DSSATv4.6). The aximum and minimum temperature increase rates considered were 0˚C (ambient), +1˚C, +2˚C, +3˚C and +4˚C and CO_2 concentrations were ambient (380), 421, 538, 670 and 936 ppm.

At ambient temperature (no rise in temperature) and CO_2 concentration, Boro rice grain yield varied from 6506 to 8076 kg ha^{-1} depending on variety. Generally, grain yield reduction would be the highest (13–23%) if temperature rises by 4˚C and growth duration would be shortened by 23–33 d. Grain yield reductions with 1˚C, 2˚C and 3˚C rises in temperature are likely to be compensated for by increased CO_2 levels of 421, 538 and 670 ppm, respectively (Table 4). In future, the greatest reductions in grain yield and growth duration would be in cooler regions and the least in the warmer coastal saline region of the country.

Table 4. Influence of temperature rise (^oC) and CO_2 level (ppm) on change (%) of grain yield for BRRI dhan28 in different regions of Bangladesh

CO_2 level/Temp rise	Gazipur					Rangpur				
	0	+1	+2	+3	+4	0	+1	+2	+3	+4
380	0.0	-4.2	-9.7	-11.9	-17.5	0.0	-5.1	-8.7	-18.3	-21.3
421	2.8	-1.5	-7.2	-9.6	-15.2	2.9	-2.3	-6.1	-16.0	-19.3
538	11.7	7.1	0.8	-1.8	-8.1	11.7	6.6	1.8	-8.7	-12.5
670	20.6	15.7	8.7	6.1	-0.4	22.6	16.3	10.5	-1.0	-4.9
936	36.6	31.3	21.4	18.8	11.7	40.6	32.6	26.6	10.8	6.5
	Rajshahi					Barishal				
380	0.0	-2.4	-10.3	-17.2	-19.6	0.0	-4.0	-8.5	-10.3	-16.4
421	2.9	0.3	-7.6	-14.9	-17.4	2.7	-1.3	-6.0	-7.9	-14.3
538	11.8	9.2	0.5	-7.6	-10.4	11.3	7.2	2.1	0.1	-7.0
670	22.0	17.7	8.6	0.2	-2.9	20.9	15.6	10.2	8.4	0.9
936	40.0	34.8	23.1	12.8	8.6	37.3	29.5	23.0	21.4	13.0
	Cumilla					Habiganj				
380	0.0	-3.6	-8.5	-12.3	-16.4	0.0	-5.2	-11.7	-18.1	-19.5
421	2.8	-0.9	-6.0	-9.8	-14.2	2.8	-2.3	-9.1	-15.7	-17.1
538	11.3	7.5	2.3	-1.8	-6.7	12.5	6.9	-0.2	-8.0	-9.7
670	20.4	16.2	10.4	6.5	1.1	22.8	17.1	8.3	0.5	-1.7
936	36.7	32.5	24.3	18.6	12.8	41.1	33.4	23.7	15.0	12.1

7.1.2 Study with open top chamber

A greenhouse pot experiment was conducted at BSMRAU, Gazipur in the wet season (T. Aman) to study the effect of elevated CO_2 levels and N scheduling on the yield of BU dhan1. Nitrogen (195 kg urea ha^{-1}) was applied in three equal splits at (a) N1:10, 25 and 40 days after transplanting (DAT), (b) N2: 10, 40 and 50 DAT and (c) N3: 10, 40 and 60 DAT. The CO_2 levels were 380, 400, 450 and 500 ppm. The rice crop for elevated CO_2 levels was grown under open top chamber (OTC) conditions (Fig. 10). Carbon dioxide gas was supplied to the chamber from a gas cylinder using a manifold gas regulator, pressure gauge and underground pipeline for supplying natural air with the help of a blower. The concentration of CO_2 in the chamber was monitored using an infrared gas analyzer (Model LI-6400xt, Lincoln, USA).The rice plants were grown in plastic pots containing approximately 13kg clayey soil. Thirty-day old seedlings of BU dhan1were transplanted on 08 August 2017. Phosphorus, K, S and Zn were applied at the rates of 20, 60, 20 and 3.5 kg/ha in the forms of triple super phosphate, muriate of potash gypsum and zinc sulfate, respectively.

Fig. 10. Open top chamber for studying enriched CO_2 levels in rice, BSMRAU, Gazipur

One thousand grain weight did not vary significantly due to N scheduling under elevated CO_2. The highest grain yield was recorded from N applications at 10, 40 and 60 DAT with 450 ppm CO_2 level (Table 4). This result needs to be confirmed in future.

Table 4. Effect of timing of N application on grain yield of rice under elevated CO_2

CO_2 conc. (ppm)	1000-grain weight (g)			Grain yield (g hill^{-1})		
	N1	N2	N3	N1	N2	N3
500	21.71	21.71	20.87	31.97	35.47	28.40
450	21.74	22.02	22.07	35.49	36.75	36.83
400	22.39	20.31	21.23	31.46	31.74	28.12
Open air	20.32	20.46	22.98	31.26	31.18	35.21
$LSD_{0.05}$						
CO_2		NS			2.61	
N		NS			NS	
$CO_2 \times N$		NS			4.52	

7.2 Maize

Maize is an important cereal crop next to rice and wheat in Bangladesh. To study the growth and development of maize under changing climate, calibrated and validated DSSAT model was used. Genetic coefficients of BARI Hybrid Maize-7, BARI Hybrid Maize-9, Pioneer 30B07 and NK-40 were determined using GENCALC of DSSAT. After calibration, the model was tested for its performance through validation procedures. The model performed satisfactorily in terms of phenology, biomass and grain yield.

It was found that, if temperature increases yield will be reduced irrespective of the CO_2 level. For example, if temperature is increased by 2°C at ambient CO_2 level, yield reduction would 9–13% in different regions of Bangladesh (Fig. 11). In that situation, the north-western and south-eastern parts will be affected more compared with other parts of Bangladesh. If temperature is increased by 2°C with increased CO_2 levels, the central and south-eastern parts will be affected more than other parts of the country and yield reduction would be 2 to > 7% indicating that increased CO_2 levels would have some positive effect on maize production.

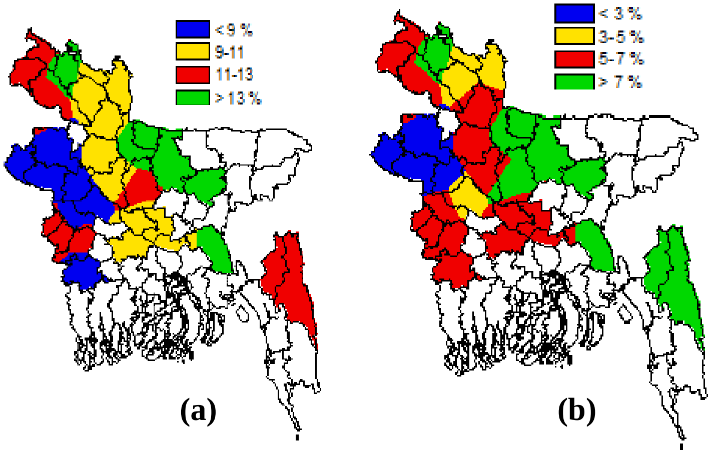

Fig. 11. Changes in maize production in different parts of Bangladesh as influenced by (a) 2°C rise in temperature at ambient CO_2 levels and (b) 2°C rise in temperature at 550 ppm CO_2 level

7.3 Wheat

7.3.1 Effect of temperature, CO_2 and solar radiation

Wheat is likely to be the greatest sufferer in the tropical region because of increased temperature in the future. The effect of rising temperature on wheat was investigated with DSSAT v.4.6 model (CERES-Wheat). Datasets used were soil file, weather file, genetic coefficients file, experimental file, annual file and time-course file. Calibrated and validated DSSAT model was used to study the effect of temperature and CO_2 concentration on the wheat varieties, BARI Gom-25, BARI Gom-26, BARI Gom-27 and BARI Gom-28 at Gazipur. Temperature rises considered were 0, 1, 2 and 3 °C and CO_2 levels were 380 and 450 ppm. Effects of increased temperatures (0, 1, 2 and 3°C) and CO_2 concentration (380, 450 and 550 ppm) on BARI Gom-28 were studied at Dinajpur. Effect of solar radiation change on BARI Gom-26 yield was simulated by considering both reduction and increase in solar radiation by 5% and 10% and compared with the no-change situation. Interaction effect of rising temperature and solar radiation on grain yield of BARI Gom-26 was studied considering 0, 1 and 2^{o}C rise in temperature and 0 and 10% reduction in solar radiation.

The highest grain yield of 5194 kg ha^{-1} was obtained from BARI Gom-28 followed by BARI Gom-27 (4866 kg ha^{-1}) and BARI Gom-26 (4573 kg ha^{-1}) under existing temperature conditions (Fig. 12). Wheat yield at Gazipur increased with elevated atmospheric CO_2 concentration but decreased with the increase in temperature. About 11–23% yield reductions were observed with 1–3^{o}C rise in temperatures under ambient CO_2 level at Gazipur; 2–4% yield compensations are likely if the CO_2 level is increased up to 550 ppm. In the Dinajpur area, grain yield of BARI Gom-28 was reduced by about 6–25% depending on temperature rise. BARI Gom-28 gave the highest grain yield (5006 kg ha^{-1}) with 10% increase in solar radiation, but decreased to 4182 kg ha^{-1} with 10% reduction of solar radiation. Reduction in solar radiation and rise in temperature would reduce wheat yield in Bangladesh, although increased atmospheric CO_2 levels might cut down, to some extent, the yield penalty.

7.3.2 Effect of temperature, nitrogen rate and irrigation

The effects of temperature, N rates and irrigation scheduling on grain yield of BARI Gom-26 were evaluated through the use of DSSAT v4.6 model. Thirty years' historic weather data were used. Nitrogen rates tested were 0, 40, 80 and 120 kg ha^{-1}; number of irrigation was 0, 1, 2, and 3; temperature rise considered was 0, 1, 2 and 3^{o}C.

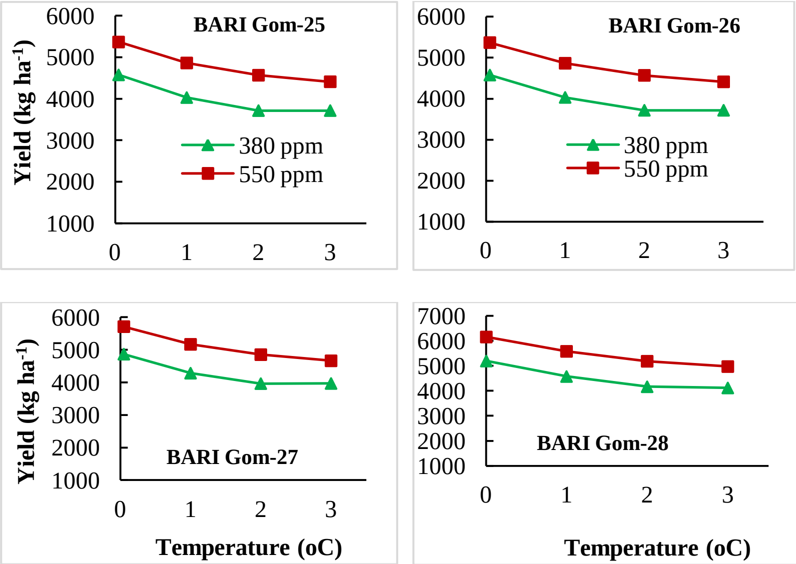

Fig. 12. Effect of increased temperature and CO_2 concentration on grain yield of wheat varieties at Gazipur, Bangladesh

Simulation results indicated that wheat yield increased with an increase in N application rate, but the increase was higher with reduced N rate under increasing temperatures (Fig. 13). In general, wheat yield reductions were about 8%, 17% and 25% because of rise in temperature by 1˚C, 2˚C and 3˚C, respectively compared with no temperature rise. The predicted wheat grain yield increased with greater number of irrigations. However, the benefit of increased irrigation scheduling diminished significantly with temperature rise compared with the ambient condition (Fig. 14). Irrigation use efficiency decreased with a rise in temperature. Crop growth duration decreased by about 5 d for each degree rise in temperature, irrespective of irrigation level and N rate. These simulation studies indicate that appropriate management, especially growing heat tolerant wheat varietieswould be needed for sustained wheat production in Bangladesh under changing climate in the future.

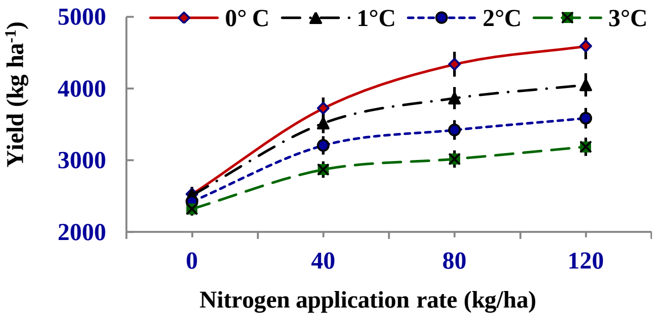

Fig. 13. Grain yield of wheat as influenced by temperature and N rate

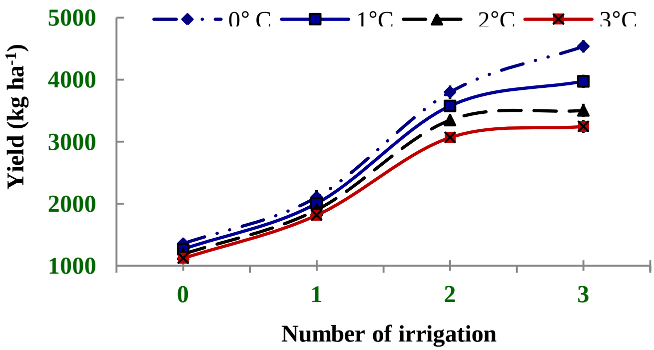

Fig. 14. Grain yield of wheat as influenced by temperature and irrigation level

7.4 Mungbean

Mungbean (*Vigna radiata* L. Wilczek) is an important pulse crop in South Asia, although its productivity is low. Moreover, growth and yield of mungbean is highly sensitive to waterlogging at any growth stage. A simple mungbean growth model (*MungGro*) was developed to study its growth following the principles of SUCROS2 using the Fortran Simulation Translator program. Water balance sub-routine was incorporated along with G × E interaction. The flow diagram of different components is shown in Fig. 15. The model was successfully calibrated and validated to evaluate the effects of increased temperatures and CO_2 level. Generally, grain yield decreased with rise in temperature (Fig. 16) because of growth duration shortening and reduced seed weight gain. Increased CO_2 levels compensated to some extent the deleterious effects of increased temperatures. Waterlogging at the beginning of the maturity stage reduced seed yield drastically. In the present model, N uptake and its fixation at the terminal stage of the crop were calculated. The model needs to be improved by including N balance and insect-pest sub-routines in future.

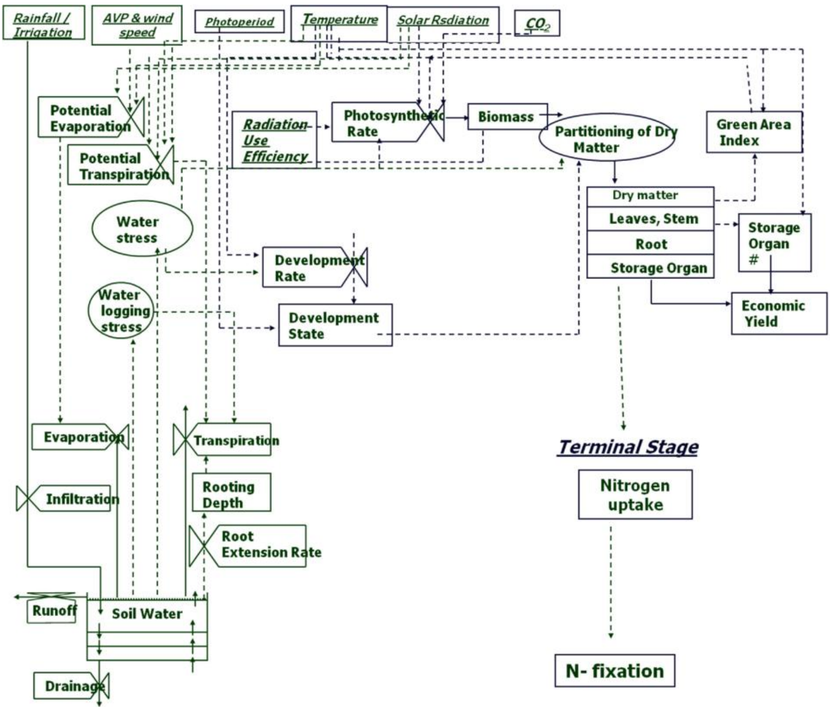

Fig. 15. Flow diagram of *MungGro* model

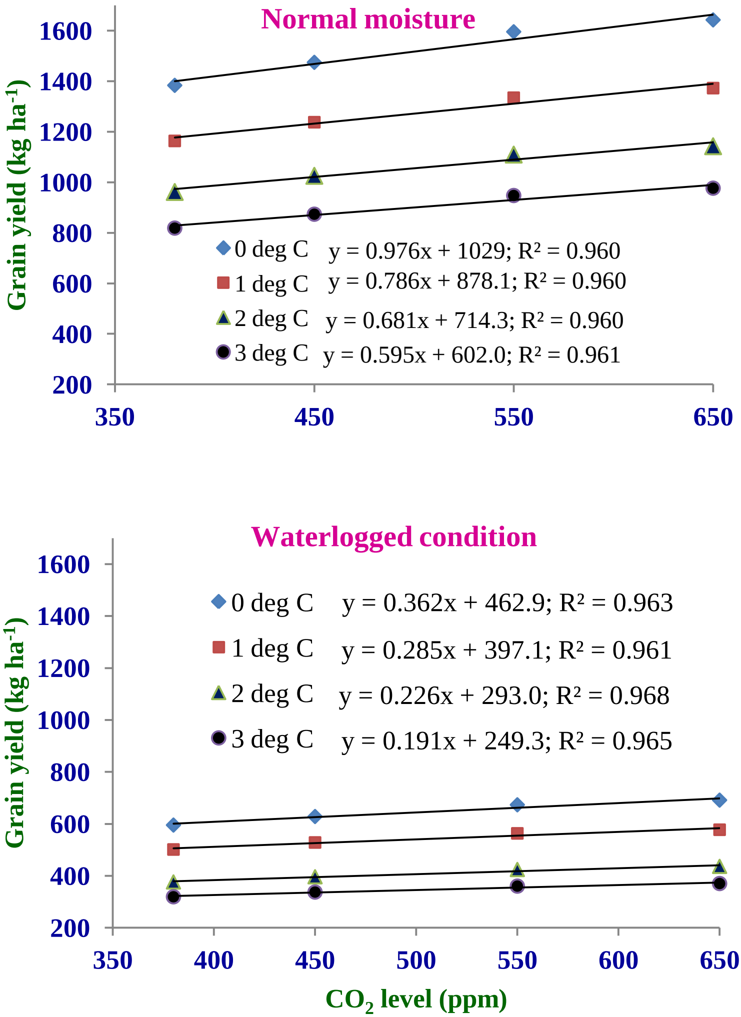

Fig. 16. Grain yield of mungbean as influenced by increased temperature and CO_2 level under normal and waterlogged (at 65-66 days after sowing) conditions

7.5 Potato

Calibrated and validated DSSAT model was used to study the effect of rising temperatures on tuber yield of potato. Potato varieties used were: V1 = BARI Alu-7 (Diamant), V2 = BARI Alu-8 (Cardinal), V3 = BARI Alu-25 (Asterix) and V4 = BARI Alu-13 (Granola); temperature rise considered was T0 = ambient, T1 = 1^{o}C and T2 = 2^{o}C and CO_2 levels considered were: C1 = 380 ppm and C2 = 550 ppm. The model was run to simulate for 30 years.

Yield of all tested varieties decreased gradually with an increase in temperature (Fig. 17). BARI Alu-13 (Granola) was the best yielder in all temperature regimes. About 8-15% yield could be reduced if temperature rose by1–2^{o}C compared with the historical average. About 22.5% tuber yield increased when CO_2 concentration was raised from 380 ppm to 550 ppm.

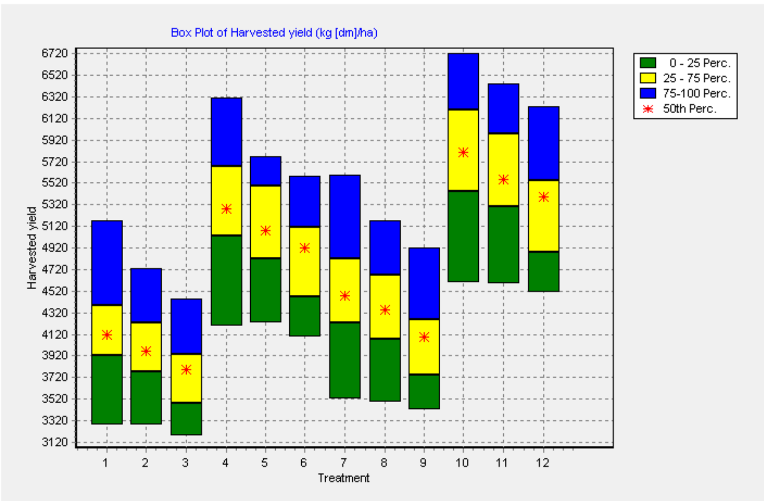

Fig. 17. Influence of temperature and CO2 level on potato tuber yield, Dinajpur.

T1=V1T0C1, T2=V1T1C1, T3=V1T2C1, T4=V1T0C2, T5=V1T1C2, T6=V1T2C2, T7=V4T0C1, T8=V4T1C1, T9=V4T2C1, T10=V4T0C2, T11=V4T1C2, T12=V4 T2C2

8. Climate change and insect pest prevalence

8.1 Rice yellow stem borer

Models to study the impacts of CC on insect pests and diseases are either lacking and/or not easily available in Bangladesh. Therefore, a simple model was developed using the Fortran Simulation Translator to study the influence of increased temperature on duration of various life cycle phases of YSB in the Bangladesh environment. The model was primarily based on growing degree day concept and by also including cardinal temperatures sensitive for specific growth stages of YSB. After successful calibration and validation of the model, it was taken for CC (only temperature rise in the present study) impact analysis on the growing cycle of YSB. Temperature rises considered were: 1, 2, 3 and 4^{o}C that were compared with the control (no temperature rise), by using historic weather data of representative locations in eight divisions of Bangladesh.

Differential spatial responses in the life cycle of YSB under various temperature rise treatments were observed and in general, the growing cycle hastened with rising temperatures. The life cycle of YSB is likely to be reduced by about 2 days for each degree rise in temperature, when averaged over locations. This means that there will be 2.0–2.5 additional generations of YSB in the pre-monsoon season and about 2.9–3.2 in the wet monsoon season of Bangladesh. There is a need to include the phenology in the module for studying population dynamics of YSB in future.

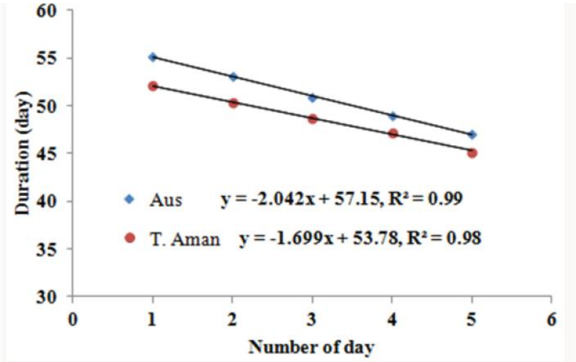

Fig. 18. Total life cycle duration of rice yellow stem borer as influenced by temperature rise during Aus and T. Aman seasons.

8.2 Fecundity of brown plant hopper

The fecundity of any insect depends on mostly temperature and humidity. The effects of temperature and humidity on the fecundity of the female brown plant hopper (BPH) and its nymphal development were studied under nethouse conditions at BRRI, Gazipur (Fig. 19). A 35 day-old seedling of the host (rice variety, BR3) was transplanted in pot. Five gravid females were enclosed in the mylar with a fine mesh net at the top. Treatments used were: T1= gravid female enclosed by mylar in the nethouse, T2= gravid female enclosed by mylar under shadow, T3= gravid female enclosed by mylar in sunshine and T4 = gravid female enclosed by fine mesh net in sunshine (almost ambient conditions). Data on egg deposition and nymphal developments were recorded for making inferences.

Fig. 19. Nethouse study on development of BPH nymph at BRRI, Gazipur, 2016-17

Depending on study period and exposure pattern, the highest number of nymphs/females was 51 per pot when temperature ranged in between 32°C and 42°C and relative humidity (RH) was 80–87% relative humidity in October 2016 (T2) and the least with T4 (Table 5). However, such scenarios were changed during the months of November and February depending on air temperature and RH. Nymphal development and temperature relationships showed both positive and negative effects on development of nymphs/females. Higher temperature at 9:00 AM and 5:00 PM showed higher nymphal development but reduced growth with higher temperature at 3:00 PM. This study needs further evaluation for conclusion.

Table 5. Fecundity of BPH as influenced temperature and humidity

Expt time	Treat	Nymph/female (no.)	Temp range	% RH range
October/2016	T1	49	30-41	81-88
	T2	51	32-42	80-87
	T3	45	28-40	36-64
	T4	40	27-44	42-76
November/2016	T1	33	22-36	84-88
	T2	24	21-29	82-84
	T3	46	28-36	67-80
	T4	35	22-29	47-70
February/2017	T1	108	21-32	82-93
	T2	55	20-26	71-88
	T3	35	27-38	60-80
	T4	114	25-31	39-45

T1= gravid female enclosed by mylar in the nethouse, T2= gravid female enclosed by mylar under the shadow, T3= gravid female enclosed by mylar in sunshine and T4 = gravid female enclosed by fine mesh net in sunshine

9. Greenhouse gas emission

Data on greenhouse gas (GHG) emissions from different crops fields of Bangladesh are not available in most cases. A study was conducted using the Cool Farm Tool Beta-3 was to determine GHG emissions from rice and no-rice based cropping patterns and its actual measurements of GHG emission from rice, wheat, maize, potato and mustard crops were done during 2015-2018. The static close chamber technique was employed. Emitted CH_4, CO_2 and N_2O were measured by gas chromatography equipped with FID detector for CH_4, TCD for CO_2 and ECD for N_2O and Porapak NQ (Q 80-100 mesh) column. Temperature ranges used were 80^{o}C, 100^oC and 110^{o}C for FID, 65^{o}C, 150^{o}C and 300^{o}C for TCD and 125^{o}C, 150^{o}C and 300^{o}C for ECD.

Software based GHG emission patterns and global warming potential (GWP) showed that non-rice based cropping patterns had a lower GWP than rice-rice based patterns (Table 6). Onion-jute-fallow, jute-rice-fallow, wheat-mungbean-rice and maize-fallow-rice patterns are relatively more suitable for minimizing GHG emission and subsequent GWP. There were spatial variations in CH_4 emission; greater emissions were found in Mymensingh and Dinajpur districts of Bangladesh because of greater rice area coverage (Fig. 20). On an average, about 1.39-1.56 Tg year^{-1} CH_4 emission took place from paddy fields in Bangladesh during 2012–2015. Among 64 districts, the lowest CH_4 emission was found in Ramgati and Bandarban districts because of relatively low rice acreage. The emission rates varied from 89 to 148 kg ha^{-1} year^{-1} depending on location in the country and type of rice culture and variety used.

Actual measurement of CH_4 and N_2O emissions from rice-rice-rice spattern at Gazipur showed that GHG emission patterns varied with season and nutrient management practices (Table 7). This indicates that GHG emissions could be moderated by changing crop production practices. Moreover, pattern based GHG emissions need to be measured from different regions of the country.

Table 6. Greenhouse gas emission and GWP for selected cropping patterns in Bangladesh

Name of pattern	CO_2 (kg ha^{-1})	CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})	GWP (CO_2 eq kg ha^{-1})
Onion-jute-fallow	836.6i	0f	4.3bcd	2125k
Jute-T. Aman-fallow	668.4k	40.17e	4.2cd	2923j
Boro (ID)-T. Aman-fallow*	1114.2ef	163.17b	3.9d	6355d
Boro (CF)-T. Aman-fallow	1141de	245.18a	3.9d	8432b
Mustard-Boro (ID)-T. Aman	1516.1c	163.17b	4.8abc	7026c
Mustard-Boro (CF)-T. Aman	1543.1c	244.85a	4.8abc	9131a
Mustard-Boro-fallow	1082.6gh	148.2c	3.8d	5746e
Wheat-T. Aus-T. Aman	1109.1fg	80.34d	2.5f	4180f
Potato-Boro-T. Aman	1871.3b	163.17b	3.5de	6975c
Maize-fallow-T. Aman	1167.5d	40.17e	5.5a	3782h
Potato-maize-T. Aman	1924.9a	40.17e	5.1ab	4412f
Wheat-Mungbean-T. Aman	1080.9h	40.17e	3.5de	3109i
Grass pea-T. Aus-T. Aman	799.2j	80.34d	2.8ef	3643

*ID = Intermittent drainage, CF = Continuous flooding
Small letters in a column compare means at 5% level of probability by LSD

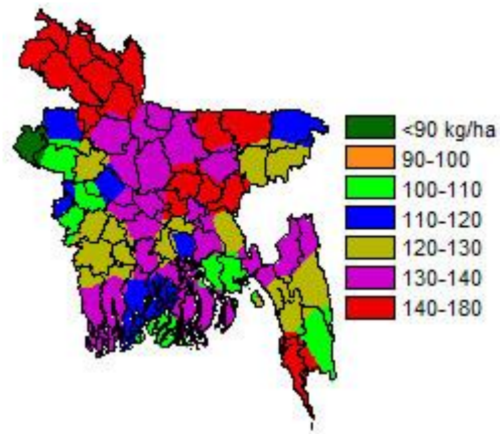

Fig. 20. Methane emission rate from rice fields in Bangladesh

Table 7. Fluxes (kg ha^{-1}) of CH_4 and N_2O from rice fields in Aus-T. Aman-Boro pattern with organic amendment, Gazipur

Treatment	CH_4	N_2O
	T. Aus season	
NPKSZn	307	0.07
Poultry manure	508	0.212
Control	243	0.038
$LSD_{0.05}$	8.06	0.01
	T. Aman season	
NPKSZn	326	0.247
Poultry manure	679	0.556
Control	240	0.170
$LSD_{0.05}$	9.44	0.02
	Boro season	
NPKSZn	232	0.265
Poultry manure	568	0.530
Control	147	0.110
$LSD_{0.05}$	10.07	0.02

10. Status of water and soil resources

Water and soil resources in Bangladesh are under tremendous pressure for growing crops, and, also, their demand for industry is increasing rapidly. On the other hand, CC impacts are playing negative roles in respect of rejuvenation of these vital resources. I such a situation, it is necessary to understand the status of water and soil resources in Bangladesh for adaptation strategies against CC impacts in future agriculture.

10.1 Water resources and land surface areas

Sixteen scenes of Landsat MSS, TM and OLI imagery from path 135–139 and row 42–46 to cover entire Bangladesh were downloaded from USGS archives and analyzed digitally. A mosaic of these scenes was done to derive an image of entire Bangladesh. Since water scarcity prevails in the dry season, space-borne satellite imageries (Landsat, MSS/TM/OLI) available between February to April of the years 1975, 1989, 2005 and 2015 were used to identify available water and to quantify its changes. Both supersized and unsupervised classification techniques were applied for water and land mapping. Unsupervised classification used information from the image itself to identify spectral clusters, which were interpreted as classes. Supervised classification was used on the basis of region of interest (ROIs), where the training areas (collected from Google maps) are regions of terrain with known properties or characteristics. Besides, an index was used to identify water bodies namely Normalized Different Water Index (NDWI). Remote sensing image analysis was done using ENVI (version 4.3) and ArcGIS software (version 9.3) was applied to digitize and analyze all the classified maps.

In four decades (1975–2015), surface water availability shoed a decreasing trend (Fig. 22). Surface water availabilities were 5.76, 4.34, 3.92 percent in March of 1975, 1989 and 2005, respectively, which was reduced to 3.62% in 2015. This gradual change in surface water availability indicates that scope for mitigating drought using surface water is diminishing in Bangladesh. On the other hand, land surface area was 93.81, 93.47, 96.53 and 96.01 percent in March of 1975, 1989, 2005 and 2015, respectively. The increased land surface area, if under cultivation, might have helped increase total production in Bangladesh.

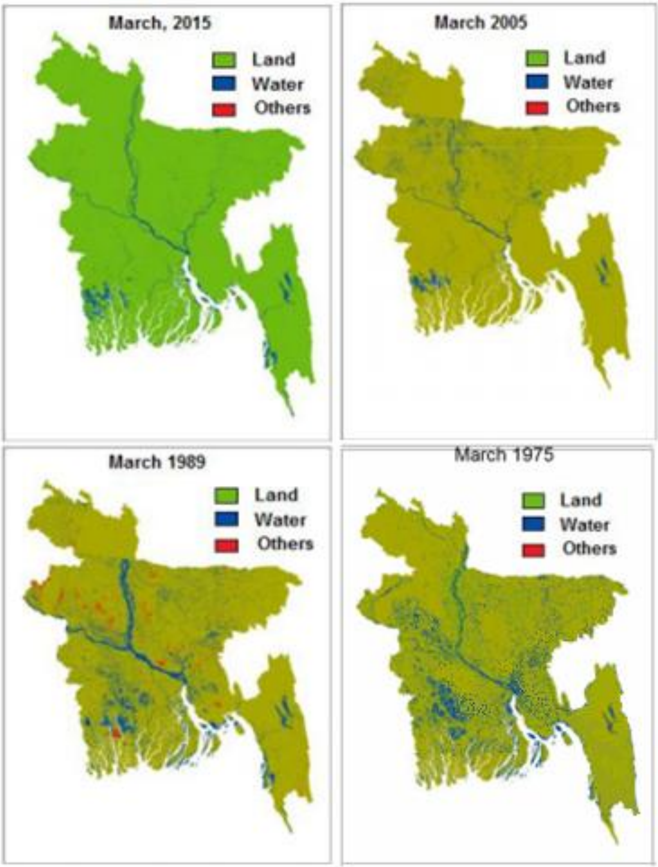

Fig. 22. Spatial water availability in Bangladesh during March

10.2 Soil fertility

Soil fertility is one of the important driving forces of crop production. It is essential to understand the spatial distribution of soil fertility. A simple and cost effective method of soil fertility evaluation for Bangladesh was developed by using soils pH, soil organic carbon (SOC), available phosphorus (P), sulphur (S), zinc (Zn), boron (B), exchangeable K and cation exchange capacity (CEC) values. . Soil nutrient status was considered for assigning scoring values at 0–100. Attribute-wise soil fertility ratings over different locations of Bangladesh were made by using MS-Excel Macros and IDRISI3.2. Soil fertility scores, as determined by arithmetic mean (AM), geometric mean (GM), weighted mean and (WM) and most minimum attribute ($MAtrib_{score}$) techniques, were used to find out their relationships with Boro rice yields (64 districts of Bangladesh from 2007 to 2013) through regression analyses (data not shown). Considering higher R^2 values, final soil fertility rating maps were prepared (all maps are not shown here) based on weighted mean scores and scores of the most minimum of eight parameters for each district.

Soil fertility status combining all tested attributes was <35 (very low), 35-45 (low), 45-55 (medium) and >55 (fertile) indicating that 10–12 and 39–52 percent areas of the country represent very low and low soil fertility, respectively (Fig. 23). Medium fertile and fertile soils are distributed in 17–41% and in about 8% areas of the country, respectively. These findings clearly indicate that special care will be needed for efficient and profitable crop production in major areas of Bangladesh.

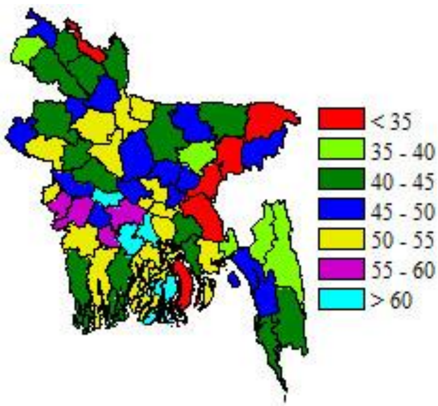

Fig. 23. Soil fertility variation in Bangladesh as per weighted mean score

10.3 Soil health

Soil quality assessment methods are available, but not well validated for subsequent operational applications. A simple method for soil quality index assessment was developed based on soil texture, SOC, pH, available water, CEC, bulk density, total porosity, saturated hydraulic conductivity, salinity, aggregate stability, slope and soil depth and scoring of attributes on a 0–100 scale. The lowest score was assigned to the most limiting factor of crop growth and development. Attribute-wise rating was made by using Macros developed in MS-Excel and IDRISI3.2 was used to delineate the rating maps.

About 64.6% soils scored more than 60 and the best soil group (score >70) was only about 15% (Fig. 24) indicating that soil quality needs to be improved in Bangladesh. As it has been seen from other studies that C loss will be intensified due to increased temperature in future, it will be necessary to take judicious steps to improve soil health for sustained crop production. It is also concluded that geometric mean approach for soil health scoring can be utilized in similar environments around the globe with or without further improvement.

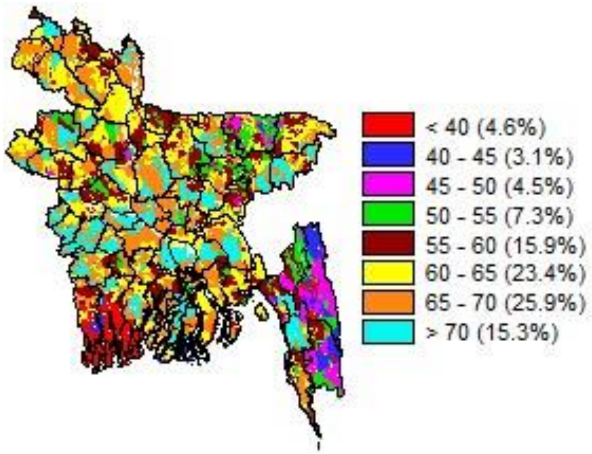

Fig. 24. **Soil health quality index in Bangladesh; figures in parentheses indicate percent of the total of 13.83 million ha**

11. Economic impact of climate change on selected crops in coastal areas

Household vulnerability because of exposure to natural hazards depends on many factors, such as, economy, education, knowledge in disaster management, etc. Four villages each from Subarna Char (Noakhali) and Botiaghata (Khulna) were selected for an investigation. The total numbers of households and farm households were 1202 and 922, respectively. A stratified random sampling method was used to determine the sample size for the study. Total sample population was distributed according to two sampling variables, namely, name of selected village and education level of head of farm household for ensuring the representative sample. Depending on these two sampling variables, 12 strata were developed for selecting sample from the total sample population. From the total sample population, 35 percent was selected as sample for the study. The study was conducted based on both primary and secondary data related to temperature, rainfall, and net revenue from crop production, soil salinity, socioeconomic and demographic information on farm households. Assessment of economic impact because of CC on crop production was determined by applying Ricardian Net Revenue Model for rice, watermelon, mungbean and sesame. Production vulnerability at farm household levels by analyzing adaptive capacity, sensitivity and exposure of crop production systems was done partially.

Economic vulnerabilities for rice, watermelon, mungbean and sesame production increased because of changes in temperature, rainfall and salinity patterns in southern Bangladesh. The estimated net losses per ha were 28886/-, 48380/-, 17330/- and 17105/- for Boro rice, watermelon, mungbean and sesame productions, respectively.

12. Mitigation and adaptation strategies

The project activities continued only for three years. So, this section should be considered as indicative of findings for CC adaptation and mitigation strategies for Bangladesh agriculture. However, some of the findings were from repeated measurements that can be practically used in future.

12.1 Organic amendment

It is well established that organic matter (OM) not only improves soil quality, but also increases crop production. An experiment was conducted at the field research plots of the Soil Science Department, BSMRAU, Gazipur that have been receiving different organic manures for the last 28 years (1988-2016). The two-factor (organic material and N fertilizer) experiment was laid out in a factorial RCB design with two replications. No manure, CD, compost, green manure (GM) and RS were applied at the rates of 0, 25, 25, 7.5 and 1.5 t ha^{-1}, respectively in a yearly sequence. Urea-N was applied @ 0, 55 and 80 kg ha^{-1} for rice and 0, 80 and 120 kg ha^{-1} for wheat. Individual plot size was 12 m x 7 m. Soil samples were collected from 0–15, 15–30, 30–45, 45–60, 60–90, 90–120 cm depths under each treatment and analyzed following standard protocols.

Compared to the control (no organic amendment), there was C sequestration under compost treated soils (Fig. 25). Such findings are also reported by many researchers. Therefore, continuous application of OM is recommended to maintain a good C stock in order to keep the soil alive and productive. Nitrogen rates showed significant influence on soil C stock (Fig. 26). The highest amount of total and SOC contents were found under no added N and the lowest under 55 kg N ha^{-1}. Carbon contents steadily decreased with greater N rates. Thus, judicious use of N not only helps in maintaining soil C, but also is beneficial in terms of economy of crop production.

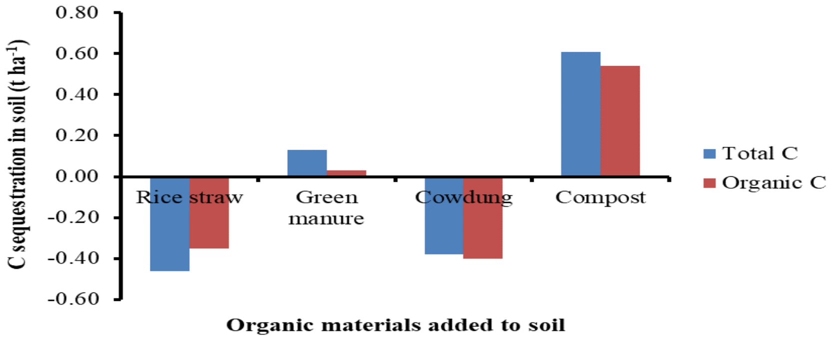

Fig. 25. Carbon sequestration in soils under different organic material application

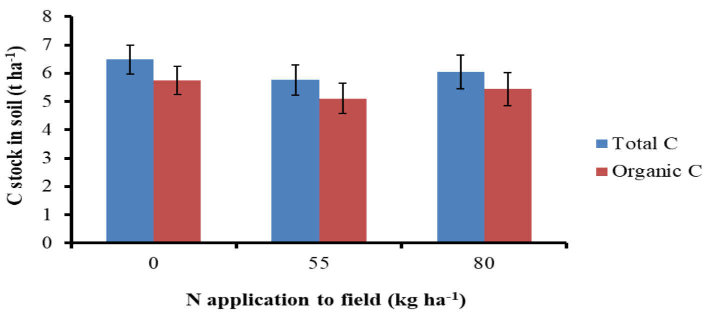

Fig. 26. Carbon stock in soil under application of N fertilizer (vertical bar indicates standard deviation)

A similar experiment was established at BRRI experimental farm, Gazipur, Bangladesh. The treatments imposed were: chemical fertilizers (NPKSZn), cow dung (CD), poultry manure (PM) and vermicompost (VC) on the basis of integrated plant nutrient system (IPNS) and control, arranged in a completely randomized block design with three replications. Unit plot size was 6 m x 7m. BRRI dhan49 was grown under irrigated conditions. Top soil sample was analyzed following standard techniques. Greenhouse gas emission was measured based on static closed chamber method (discussed in section 9). Net ecosystem carbon balance (NECB) was calculated by C balance analysis (Ciais et al., 2010; Smith et al., 2010; Jia et al., 2012; Haque et al., 2015).

The NECB was positive with VC, CD and PM (Fig. 27). In control and chemical fertilizer treatments, C sequestration was negative, but organic amendments showed positive C sequestration. Organic amendment significantly increased soil C sequestration capacity by around 58–66% compared with chemical fertilization. The IPNS based fertilizer management also improved soil aggregate stability. These findings clearly indicate that INM is beneficial not only for the environment, but also for energy and production cost savings.

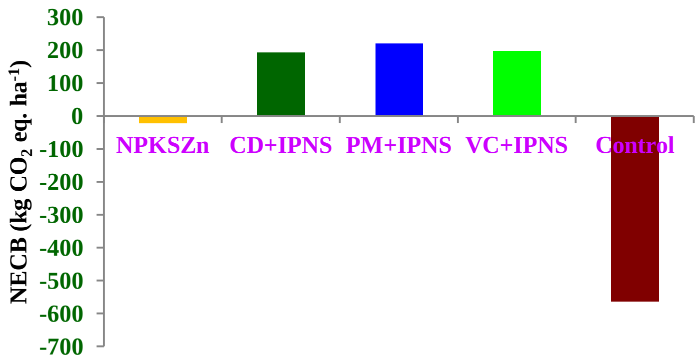

Fig. 27. Carbon sequestration as influenced by organic amendment in wet season rice cultivation

12.3 Cultural management and greenhouse gas emission patterns

The Cool Farm Tool Beta3 was utilized for determination of CH_4 and CO_2 emission from rice fields. Treatments were: intermittent drainage (ID), continuous standing water (CSW), local rice varieties (LV) and modern high yielding varieties (HYV). The emissions of GHG from rice field under CSW and AWD treatments and mustard crop established after conventional tillage (CT) and reduced tillage (strip tillage-ST) were measured using gas chromatography system (discussed in section 9).

Methane emission from rice field was reduced when ID irrigation was employed relative to CSW, although no appreciable changes were observed for CO_2 levels (Fig. 28). Similar results were found from AWD vs CSW trial at BRRI, Gazipur (Table 8). Use of HYV is beneficial in terms of CH_4 emission mostly because of the shorter growth duration of HYV than that of LV. In case of mustard, ST reduced N_2O and CO_2 emissions by about 45% and 54%, respectively, and GWP with ST was 59% of that with CT (Fig. 29). These findings clearly indicate that GHG emission can be reduced significantly without yield penalty by adopting suitable crop production technologies.

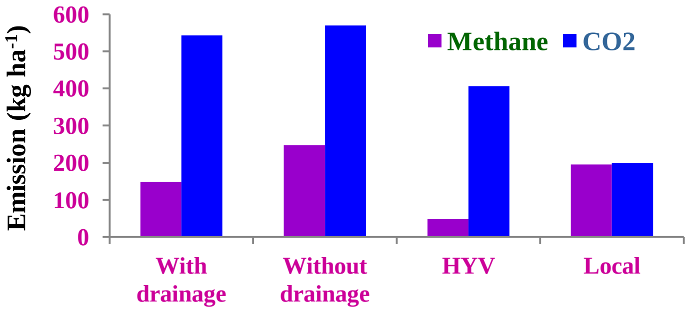

Fig. 28. Methane and CO_2 emission patterns as influenced by water management and rice variety

Table 8. Total CH_4 flux and Boro rice yield under continuous flooding and AWD

Treatments	Continuous flooding		AWD	
	CH_4 flux (kg ha^{-1})	Rice yield (t ha^{-1})	CH_4 flux (kg ha^{-1})	Rice yield (t ha^{-1})
NPKSZn	232	6.68	164	6.56
CD+IPNS	439	7.19	282	6.95
PM+IPNS	568	7.03	411	6.91
VC+IPNS	345	7.25	266	7.08
Control	147	2.51	102	2.60

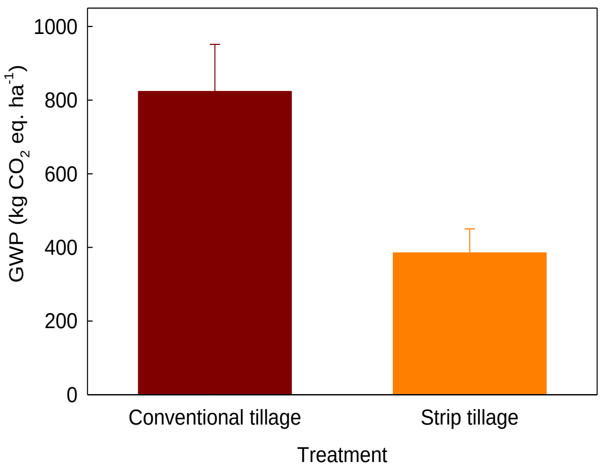

Fig. 29. Global warming potential of mustard under different tillage systems

12.4 Amendment of saline soils

Soil and water salinity impair crop production in the coastal region of Bangladesh. Besides, saline soil areas are increasing due to the SLR effect. Adaptation mechanisms are needed for crop production in the coastal saline environment. Use of salinity tolerant varieties, soil amendment and fertilizer management could be possible adaptation strategies. The performance of a bio-organic fertilizer (containing a group of growth promoting bacteria, rice husk biochar and rock phosphate) was evaluated along with chemical fertilizers in farmer's fields at Amtali (Borguna) and Dacope (Khulna) in the Boro season of 2017-18. BRRI dhan67 was used as the test variety. The treatment combinations were: T_1= bio-organic fertilizer (2 t ha^{-1}) + 70% NK (100%), T_2 = full chemical fertilizer (N-P-K-S @ 140-20-80-10 kg ha^{-1}).

The application of bio-organic fertilizer improved rice yield by about 1 t ha^{-1}, which was 15.3–22.3% higher than that achieved with the full chemical fertilizer dose (Table 9). Bio-organic fertilizer was found to be capable of improving rice yield in saline soil where irrigation water salinity was EC 0.65–2.53 dS m^{-1} and soil salinity was EC 6.59–8.96 dS m^{-1}. It is worthy to mention here that bio-organic fertilizer improved rice yield by 3–16% compared to conventional fertilizer management in T. Aman season at the same location. These findings clearly indicate that dissemination of this technology can reduce subsidy greatly for urea and TSP fertilizers. The overall benefit would be reduced use of chemical fertilizers, saving in energy for production of urea and TSP along with reduction of GHG emission related to their manufacture.

Table 9. Influence of bio-organic and chemical fertilizers on Boro rice (BRRI dhan67) yield in farmers' fields during 2017-18

Place/management	Yield (t/ha)	Yield increase (%)
Amtali, Barguna		
T_1= BoF (2 t ha^{-1}) + 70% NK	**5.59**	**22.3**
Chemical fertilizer (N-P-K-S @ 140-20-80-10 kg ha^{-1})	4.57	-
Dacope, Khulna		
T_1= BoF (2 t ha^{-1}) + 70% NK	**6.71**	**15.3**
Chemical fertilizer (N-P-K-S @ 140-20-80-10 kg ha^{-1})	5.82	-

12.5 Cropping pattern based water requirement

Availability of irrigation water is likely to dictate future agriculture in Bangladesh because surface water resources are deteriorating. This important natural resource should be utilized judiciously for crop production. The CROPWAT 8 modelbased irrigation water requirements for different cropping patterns in north-west and south-west (non-saline) regions of Bangladesh were determined. The study region comprised 20 districts (8 from Rangpur division, 7 from Rajshahi division and 5 from Khulna division). This study was performed with five selected cropping patterns. BRRI dhan28 and BRRI dhan49 were grown in Boro and T. Aman seasons, respectively. Boro ice was transplanted at the optimum time, i.e.,January 15, in a Boro-fallow-T. Aman cropping pattern. BARI recommended irrigation scheduling was followed for non-rice crops. In rice, 50 mm irrigation was applied at 20% desaturation.

Since rice is a water loving crop and its growth duration is comparatively longer than other crops, it requires more water. Net irrigation requirement of major cropping patterns was calculated and shown in Table 10. The highest amount of 1251 mm net irrigation water was estimated for Boro-T. Aus-T. Aman pattern, whereas the lowest amount of 369 mm water was required for wheat-jute-T. Aman pattern. Average estimated net irrigation water requirement was 897 mm for Boro-fallow-T. Aman pattern in the study region; the highest amounts of 1056 mm was found in Bogura and the lowest amounts of 765 mm in Rangpur regions. Since T. Aus rice received much rainfall in its later stage, T. Aus based pattern required comparatively less water than Boro based pattern. CROPWAT model estimated the highest (734 mm) and the lowest (380 mm) amounts of irrigation water requirement for Rajshahi and Rangpur region respectively under potato-T. Aus-T. Aman cropping pattern. Mustard-Boro-T. Aman cropping pattern required 915 mm average net irrigation water in the study area. In general, farmers applied more water than required. So, there is a need to develop irrigation and water management practices for crop production with minimum water use.

Table 10. CROPWAT model based net irrigation requirements of major cropping patterns in north-west and south-west regions of Bangladesh with normalized weather data

Cropping pattern	Bogura	Rangpur	Rajshahi	Ishurdi	Chuadanga	Jessore	Dinajpur	Average
Boro-fallow-T. Aman	1056	765	923	871	868	874	923	897
Potato-T. Aus-T. Aman	477	380	734	629	607	644	512	569
Wheat-jute-T. Aman	426	321	503	391	340	312	290	369
Mustard-Boro-T. Aman	887	790	970	905	931	1036	889	915
Boro-T. Aus-T. Aman	1363	998	1374	1332	1210	1244	1235	1251

12.6 Adjustment in wheat planting time

Sowing date is a crucial factor for wheat (*Triticum aestivum* L.) production in Bangladesh. It is possible to find out an optimum sowing date for a cultivar from traditional field experiments, but such experiments do not allow prediction of suitable futuristic sowing dates to address CC impacts. Crop simulation models can play an important role in this regard. A study was conducted at the Regional Wheat Research Center, BARI, Gazipur, Bangladesh to evaluate the CERES-wheat model in simulating an optimum sowing window for wheat. Thirteen sowing dates starting from 21 October to 20 December at five-day intervals were tested using the wheat variety, BARI Gom-26. The model was calibrated and validated with one field experimental data followed by 30 years seasonal runs.

The optimum sowing window for wheat is 15 November–30 November in Bangladesh (Fig. 30). On an average, grain yield of wheat was reduced by 30–40 kg day^{-1} ha^{-1} when sown from 1 December to 20 December. On the other hand, with early sowing, i.e., from 21 October–14 November, grain yield reduction was about 148–102 kg day^{-1} ha^{-1}. .

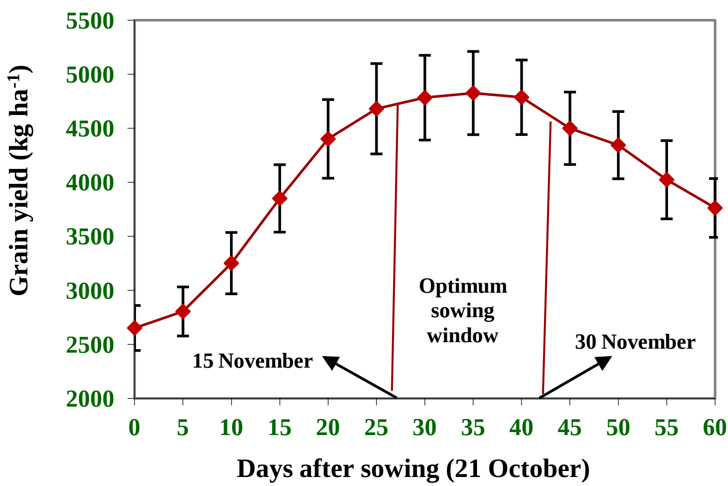

Fig. 30. Effect of sowing date on grain yield of wheat

13. Publications produced from the project findings

Publications made using research results from the project, under Modeling CC Impacts in Bangladesh Agriculture (CRP-II) are listed below.

Sl #	Title of paper	Authors	Name of journal/year
1	Extreme climate events and fish production in Bangladesh	J. C. Biswas, M. Maniruzzaman, M. M. Haque, M. B. Hossain, M. M. Rahman, U. A. Naher, M. H. Ali & W. Kabir	Environment Natural Resource Res., 9(1)/2019
2	Extreme temperature events and rice production in Bangladesh	M. Maniruzzaman, J. C. Biswas, M. B. Hossain and N. Kalra	Environment Natural Resource Res., 8(4)/2018
3	Development of mungbean model (*MungGro*) and its application for climate change impact analysis in Bangladesh	J. C. Biswas, N. Kalra, M. Maniruzzaman, A. K. Choudhury, M. A. H. S. Jahan, M. B. Hossain, S. Ishtiaque, M. M. Haque, W. Kabir	Ecological Modelling, 384: 1–9/2018
4	Effect of elevated air temperature and carbon dioxide levels on dry season irrigated rice productivity in Bangladesh	M. Maniruzzaman, J. C. Biswas, M. B. Hossain, M. M. Haque, U. A. Naher, A. K. Choudhury, S. Akhter, F. Ahmed, R. Sen, S. Ishtiaque, M. M. Rahman and N. Kalra	American J. Plant Sci., 9: 1557-1576/2018
5	Model Development for Life Cycle Assessment of Rice Yellow Stem Borer under Rising Temperature Scenarios	J. C. Biswas, M. Maniruzzaman, M. B. Hossain, H. Ali1, W. Kabir and N. Kalra	Curr Inves Agri Curr Res 2(4): 1-7/2018
6	Calibration and Validation of DSSAT Model for Simulating Wheat Yield in	A. K. Choudhury, S. Ishtiaque, R. Sen, M.A.H.S. Jahan, S. Akhter, F. Ahmed1, J. C.	Haya: The Saudi J. Life Sci., 3 (4): 356-364/2018

	Bangladesh	Biswas, M. Manirruzaman, M. B. Hossain, M. M. Miah, M. M. Rahman, T. Zahan, A.S.M.M.R. Khan and N Kalra	
7	Climatic Change Concerns in Bangladesh Agriculture	J. C. Biswas, A. K. Choudhury, M. M. U. Miah, M. Maniruzzaman, F. Ahmed, S. Akhter, M. M. Rahman, M. A. Aziz, M. A. Hamid, Wais Kabir, N Kalra	Haya: The Saudi J. Life Sci., 3: 329-338/2018
8	Simulating wheat yield under changing temperature, carbon dioxide and solar radiation levels in Bangladesh	S. Ishtiaque, R. Sen, M. A. H. S. Jahan, A. K. Choudhury, S. Akhter, F. Ahmed, J. C. Biswas, M. Manirruzaman, M. Muinnuddin Miah, M. M. Rahman, A. S. M. M. R. Khan, Naveen Kalra & M. B. Hossain	Global J. Sci. Frontier Res. D: Agric Veterinary, 18 (2): 27-36/2018
9	Co-composting urban waste, plant residues and rock phosphate: Biochemical characterization and evaluation of compost maturity	U. A. Naher, M. I. U. Sarkar, A. Jahan and J. C. Biswas	Communications Soil Sci. Plant Anal DOI:10.1080/00103624.2018.1435799/2018
10	Optimizing sowing window for wheat cultivation in Bangladesh using CERES-wheat crop simulation model	M. A. H. S. Jahan, R. Sen,, S. Ishtiaque, A. K. Choudhury, S. Akhter, F. Ahmed, J. C. Biswas, M. Manirruzaman, M. M. Miah, M. M. Rahman, N. Kalra	Agric. Ecosys Environ, 258: 23-39/2018
11	Monitoring the spatiotemporal dynamics of waterlogged area in southwestern	M. R. Islam, H. M. Abdullah, Z. U. Ahmed, I. Islam, J. Ferdush, M. G. Miah, M. M. U. Miah	Remote Sensing Applications: Society and Environment

	Bangladesh using time series Landsat imagery		9:52–59/2018
12	Greenhouse gas emissions from selected cropping patterns and adaptation strategies in Bangladesh	M. M. Haque, J. C. Biswas, M. Maniruzzaman, A. K. Choudhury, U. A. Naher, M. B. Hossain, S. Akhter, F. Ahmed and N. Kalra	Intl. J. Dev. Res. 07 (11): 6832-16838/2017
13	Future climate change scenarios and anticipated performance of major cereals in Bangladesh	J. C. Biswas, M. Maniruzzaman, U. A. Naher, M. M. Haque, M. B. Hossain, M. M. Rahman, M. M. U. Miah, A. K. Choudhury, S. Akhter, F. Ahmed, M. A. Hamid, N. Kalra and J. Furuya	Intl. J. Agric. Environ. Res. 3(6): 4123-4148/2017
14	Carbon mineralization and carbon dioxide emission from organic matter added soil under different temperature regimes	M. B. Hossain, M. M. Rahman, J. C. Biswas, M. M. U. Miah, S. Akhter, M. Maniruzzaman, A. K. Choudhury, F. Ahmed, M. H. K. Shiragi and N. Kalra	Intl. J. Recycl Organic Waste Agric. DOI 10.1007/s40093-017-0179-1/2017
15	Climatic Variability and Wet Season Rice (*Oryza sativa* L.) Production in North-West Bangladesh	J. C. Biswas, M. B. Hossain, A. K. Choudhury, N. Kalra and M. Maniruzzaman	The Agriculturists 15(1): 68-80/2017
16	Effect of Tillage Practices and Rice Straw Management on Soil Environment and Carbon Dioxide Emission	M. M. Rahman, J. C. Biswas, M. Maniruzzaman, A. K. Choudhury and F. Ahmed	The Agriculturists 15(1):127-142/2017
17	Evaluating the CERES-Rice model under dry season irrigated rice in Bangladesh: Calibration and validation	M. Maniruzzaman, J. C. Biswas, M. B. Hossain, M. M. Haque, U. A. Naher, A. Biswas, A. K. Choudhury, S. Akhter, F. Ahmed, M. M. Rahman and N Kalra	J. Agril. Crop Res., 5(6): 96-107/2017

18	Irrigation Scheduling of Rice (*Oryza sativa* L.) Using CROPWAT Model in the Western Region of Bangladesh	M. B. Hossain, S. Yesmin, M. Maniruzzaman and J.C. Biswas	The Agriculturists 15(1): 19-27/2017
19	Advanced computational procedures for the understanding of agricultural processes	N. Kalra, J. C. Biswas, M. Maniruzzaman, A. K. Choudhury, S. Akhter, F. Ahmed, M. A. Aziz, M. M. Rahman and M. M. Miah	Current Sci., 113(2): 208-209/2017
20	Calibration and Validation of Decision Support System for Agro-Technology Transfer Model for Simulating Growth and Yield of Maize in Bangladesh	F. Ahmed, A. K. Choudhury, S. Akhter, M. A. Aziz, J. C. Biswas, M. Maniruzzaman, M. Main U. Miah, M. M. Rahman, M. A. H. S. Jahan, I. M. Ahmed, R. Sen, S. Ishtiaque, A. F. M. T. Islam, M. M. Haque, M. B. Hossain, N. Kalra and M. H. Rahman	American J. Plant Sci., 8, 1632-164/2017
21	Simulating nitrogen and irrigation effects on wheat production in Bangladesh under changing climate	R. Sen, A. K. Choudhury, S. Akhter, S. Ishtiaque, M. A. H. S. Jahan, F. Ahmed, J. C. Biswas, M. Maniruzzaman, M. M. U. Miah, M. M. Rahman, N. Kalra, M. A. Aziz and A. S. M. M. R. Khan	American J. Plant Sci., 8: 1593-1606/2017
22	Characterization of Inter-seasonal Climatic Variability through Dry-season Rice productivity in the North-west Region of Bangladesh	M. Maniruzzaman, M. A. Muttaleb, A. K. Choudhury, S. Akhter, F. Ahmed, M. A. Aziz, M. M. Rahman, M. M. Miah, J. C. Biswas, M. A. Hamid, N. Kalra	Italian J. Agrometeorol., 1/2017, DOI:10.19199/2017.1.2038-5625.005/2017

14. CONCLUSIONS AND RECOMMENDATIONS

- Climatic variability in different regions and seasons need to be addressed separately by choosing variety and other crop production technologies.
- As temperature is rising differentially in various regions of the country, plant breeders should think of specialized varieties to be grown regionally/zonally.
- Waterlogging has expanded in area in some parts of the country expanded which needs to be considered in crop production planning and measures to prevent further waterlogging need to be taken quickly.
- Crop area coverage is changing rapidly, preventive measures should be taken.
- Irrigation scheduling has been developed to save water.
- Climate extreme events are increasing variably; production zones can be delineated based on the findings of the project.
- Future climatic scenarios have been developed, which can be utilized for the improvement of future agriculture.
- Soil organic matter decomposition may be hastened by increasing temperature in the future. This can be decelerated by adding sparingly decomposable organic matter. Data on response of rice to elevated CO_2 levels and N management may be useful in future planning to combat CC.
- Responses of wheat to elevated CO_2 levels, temperature and solar radiation along with irrigation and N scheduling were determined; the data provide insight into the type of wheat variety needed for future agriculture in Bangladesh.
- The mungbean model and life cycle assessment model for rice yellow stem borer have been developed. These models can be useful in future climate change impact studies in Bangladesh.
- Carbon and nitrogen mineralization patterns in soil under expected elevated temperature regimes have been determined which indicate the need for increased addition of organic materials in future for maintaining soil health.

- Carbon sequestration techniques are available from the project output.
- Crop productivity in the coastal saline zone can be improved with the use of bio-organic fertilizer. Soil health and soil fertility have been ranked. Based on these findings, crop zoning and fertilizer management strategies can be adopted.
- Some preliminary findings on GHG emissions from different crop fields are available which can be useful in adopting soil-crop-water management practices to minimize GHG emission.

15. Future plan

This paper presents the results of research during 2015-2018 with some selected crops and soil processes. In future, some of the experiments and tests need to be repeated including in the studies other important crops, livestock and poultry and fisheries to gain a complete picture of CC impacts on Bangladesh agriculture. The following points need to be considered by agricultural scientists in future R&D work related to CC impacts on agricultural production in Bangladesh.

I. Characterization of inter- and intra-annual climatic variability for important crops under various production environments;
II. Delineating vulnerable regions for major crops/cropping systems under future climatic scenarios;
III. Effect of temperature on soil and plant processes with special emphasis on important field and horticultural crops;
IV. Identification of agronomic and other management options to sustain agricultural production under extreme/episodic climatic conditions;
V. Evaluating the effects of rising temperature and atmospheric CO_2 concentrations on yields of selected crops/cropping systems;
VI. Assessing the impact of climatic variability/CC on soil water, N and carbon balances;

VII. Dynamics of insect/pests build up in relation to climate variability/change, agricultural intensification and human interventions;

VIII. Calibration/validation of relevant models for simulating crop/soil processes and subsequent growth and yield of crops;

IX. Conducting field experiments with test crops/cropping systems for addressing knowledge gaps;

X. Assessment of GHGs emission from important cropping systems in various production environments;

XI. Determination of suitable agronomic and management options (cultivars, crops/cropping system, irrigation/ nutrients management, other agronomic management, policy issues for adoption) to sequester C, best management practices to reduce GHGs emission;

XII. Identifying suitable adaptive measures to sustain agricultural production under climate change scenarios;

XIII. Options to safeguard soil health (soil fertility, soil physical conditions, soil biota, soil physic-chemical aspects);

XIV. Climate change impact on livestock and poultry and adaptation strategies with emphasis on heat stress and enteric CH_4 emission; adaptation strategies to address heat stress reduction in enteric CH_4 emission; development of prediction model for CC impact assessment on livestock;

XV. Climate change impact on freshwater fisheries and brackish water aquaculture and adaptation strategies; water temperature effects on hatching and larvae/fry/fingerling/adult fish; quality seed production and adaptation strategy towards CC;

XVI. Socio-economic vulnerability to climate change and adaptation strategies in Bangladesh.