Trade-off analysis of crop residue management for improving conservation agriculture practices under a changing climate in Bangladesh

by

Mohammad Mamunur Rashid Sarker

Submitted in accordance with the requirements for the degree of Doctor of Philosophy

The University of Leeds
School of Earth and Environment

February 2023

Declaration of authorship

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

1. The publication Sarker et al., 2021, A farming system typology for the adoption of new technology in Bangladesh. Food and Energy Security, 10 (3) jointly authored with Galdos MV, Challinor AJ, and Hossain A. The manuscript was solely written by the candidate with comments from co-authors. The candidate conducted field work, performed all data analysis and produced all figures. MG: Supervision, Visualization, and editing; AnC: Supervision, Visualization, and editing and AH: Visualization, and editing

2. The publication Sarker et al., 2022, Conservation tillage and residue management improve soil health and crop productivity—Evidence from a rice-maize cropping system in Bangladesh. Front. Environ. Sci. jointly authored with Galdos MV, Challinor AJ, Huda MS, Chaki AK and Hossain A. The manuscript was solely written by the candidate with comments from co-authors. The candidate conducted the two years field experiment and laboratory analysis, performed statistical analysis and produced all figures. MG: Supervision, Visualization, and editing; AnC: Supervision, Visualization, and editing; MH: Conducted experiment and data collection, ApC: Data collection and Visualization and AH: Visualization, and editing.

3. The publication Sarker et al., Assessing the long-term impact of conservation agriculture on rice-maize systems in Bangladesh under climate change using the APSIM model: jointly authored with Galdos MV, Challinor AJ, Huda MS, Chaki AK, Chandran S, Jennings SA and Hossain A. The manuscript was solely written by the candidate with comments from co-authors. The candidate conducted the two years field experiment and laboratory analysis, performed statistical analysis and produced all figures. MG: Supervision, Visualization, and editing; AnC: Supervision, Visualization, and editing; MH: Conducted experiment and data collection, ApC: Data collection, help to ran the model, and Visualization, CS; help to ran the climate model and Visualization; Jennings SA: Visualization, and editing and AH: Visualization, and editing.

Rationale for thesis by alternative format

This thesis is presented as an alternate format for a doctoral dissertation that includes published content. This style is suitable for this thesis since two of the three data chapters have been published in peer-reviewed journals. The third data chapter publication is now in progress and will be submitted for peer review. This dissertation is accompanied with loose copies of published manuscripts. The thesis is organized into five chapters, in accordance with the Faculty of Environment standard for delivering a doctoral thesis in an alternate format that includes previously published information. Chapter 1 provides a summary of the available literature, which provides background for the thesis and establishes its relevance, as well as research gaps and the justification for the study, research questions and objectives, and a research methodology outline. The three manuscripts consist of chapters 2 - 4. The fifth chapter provides a summary of the major results of the thesis. It summarises the findings from Chapters 2 - 4 and explores their broader implications. Chapter 5 also provides summary of thesis conclusions as well as recommendations for future study.

Acknowledgements

First and foremost, I would like to express my gratitude to Marcelo Valadares Galdos and Andrew Challinor, for being my supervisors throughout my studies and for their ongoing intellectual guidance, affection, ongoing inspiration, useful recommendations, and helpful comments. I felt very comfortable studying at the University of Leeds because of both of them. Without their help, I might not have reached this point in my career. I am extremely lucky to have such a wonderful supervisor. I believe everything you taught me will serve in future.

I would like to thank the National Agricultural Technology Program (NATP-Phase II), Bangladesh Agricultural Research Council (BARC) for sponsoring my study. Additionally, I would like to extend my sincere thanks to the Priestley International Centre for Climate for providing funding for my lab analysis through their climate research bursary programme. This study would not have been possible without their financial support.

My special thanks to the Climate Impacts Group (CIG) for their friendship and assistance in all aspects of my academic life, which made my time at university much easier. Thank you to the laboratory staff in the School of Geography, Rachel Gasior, David Ashley, Martin Gilpin, and David Wilson for ensuring that my experience in the laboratory was great.

I would also like to thank BARI authority for helping me to set up my experiment in the field. I am very grateful to the soil science division, BARI and SRDI, Dinajpur for allowing me to use their lab for my study.

I'm also grateful to the farmers of Birganj Upazilla for their cooperation and assistance with my survey work. I'd like to thank the Khulna and Hajee Mohammad Danesh Science & Technology University students who assisted with data collection and survey conduct. I also want to thank Dr. Md. Khairul Alam, PSO, BARC, for his assistance and support during data collection and analysis.

I was privileged to share an office with amazing and hardworking friends, Stewart, Isobel, Ioannis, Sam, Joe, Ruth, Chetan, Sachindra, Russ, Jahanzeb, Hellen, Michael, Aikaterini, Laura, Lisma, Rachel and Megan. You made the office a conducive and relaxed environment to work.

My special thanks and appreciation are extended to Dr. Apurbo kumar Chaki, Dr. Shamsul Huda, Dr. Iswar Pun, Dr. Sreejith Aravindakshan for their cordial help during my study.

I am incredibly grateful to my beloved parents for their patience, sacrifices, and support throughout my life and PhD studies. I'm grateful to my beloved brothers for their abundant love and affection, which motivated me to finish this journey. My daughter, Tasika Anan Mitu, has made many sacrifices since her birth because her father has been a PhD student abroad. In monotonous and painful times, she inspired and enthused me with her charming smile and conversation. My gratitude also extends to all my relatives who cared for my daughter in my absence.

What can I say about my wife, Nazneen Ahmed (Bably)?! Thank you for everything. This study could not have been finished without her unending help and strength at every step of this journey. Above all, she handled all of the household duties, leaving me free to focus on my studies.

Abstract

The rice-maize cropping system (RM), which consists of puddled transplanting rice followed by intensively tilled maize has increased markedly in south Asia and provides a lifeline for billions of people, including those in Bangladesh. RM productivity has plateaued, and its sustainability is jeopardised due to a variety of economic (rising labour, irrigation water, and energy costs) and bio-physical (water shortage, soil fertility depletion, and climate variability) limitations. These constraints are all related to traditional agronomic approaches such as tillage in flooded soil during the rice season, suboptimal crop and residue management, and inefficient fertiliser and irrigation water use. Therefore, more effective management strategies for the traditional rice-maize system are urgently required. The application of RM conservation agriculture (CA) practices has the potential to significantly increase productivity. Through a combination of field trials, cropping system modelling and farmer engagement surveys, this dissertation suggests RM management approaches for addressing these issues. The first study investigated the effects of CA based tillage and crop establishment techniques and residue management practices on the physical, chemical, and biological properties of soil along with crop productivity and RM profitability. Results showed that direct seeded rice – strip tillage maize based scenarios led to a decrease in bulk density and soil penetration resistance, but increases in soil porosity, soil organic carbon, yield and profitability. The second study investigated long-term impact of conservation and conventional agriculture in RM in Bangladesh. Results showed that CA is more effective than conventional agriculture in enhancing soil carbon buildup and crop yields. The third study identified four distinct farm types using socioeconomic factors that influence technology adoption, finding that well-resourced farmers who are solely dependent on agriculture are more likely to adopt new CA technologies. Overall, our findings provide holistic evidence that supports CA expansion in RM in Bangladesh.

Table of Contents

List of Figures

List of Tables

Abbreviations

SOC - Soil Organic Carbon

SOM - Soil Organic Matter

CA- Conservation Agriculture

DSR- Direct Seeded Rice

STM- Strip till Maize

BD- Bulk Density

SPR- Soil Penetration Resistance

PCA- Principal Component Analysis

CA- Cluster Analysis

DAE- Department of Agricultural Extension

EGP- Eastern Gangetic Plains

C - Carbon

CV - Coefficient of Variation

DOC - Dissolved Organic Carbon

GHG - Greenhouse Gas

IPCC - Intergovernmental Panel on Climate Change

K - Potassium

MAP - Mean Annual Precipitation

MAT - Mean Annual Temperature

MBC - Microbial Biomass Carbon

Mg - Magnesium

N - Nitrogen

Na - Sodium

NO3 - Nitrate

OM - Organic Matter

P - Phosphorus

POC - Particulate Organic Carbon

PTR - Puddled Transplanted Rice

DOC- Dissolved Organic Carbon

POM- Particulate Organic Matter

MBC - Microbial Biomass Carbon

REY- Rice Equivalent Yield

ST- Strip Tillage

CO_2- Carbon dioxide

GCMs- Global Climate Models

APSIM - Agricultural Production Systems sIMulator

BMD- Bangladesh Meteorological Department

FST- Farming System Typology

TLU - Tropical Livestock Unit

FT- Farm Types

IGP- Indo-Gangetic Plains

CTM- Conventional Tillage Maize

Na2-EDTA -Disodium ethylene diamine tetra acetic acid

GR- Gross Returns

BCR - Benefit-Cost Ratio

ANOVA- Analysis of Variance

SMC- Soil Moisture Content

DAS- Days After Sowing

ZT- Zero Tillage

BP- Bed Planting

NT- No Tillage

Chapter 1

Introduction

Providing food security for a growing population is the greatest obstacle facing the majority of Asian nations (Bhan & Behera, 2014; Gathala et al., 2011b). This is because the current system of food production is unable to meet rising demand due to rapid population expansion, climate change, deteriorating soil fertility, and water accessibility issues (Rahut et al., 2022). An example of the challenge is in Bangladesh, a South Asian nation with a high population density and a per capita agricultural land allocation of 485 m^2 (World bank, 2022), which is continuing to shrink at a rate of 1% annually (Quasem, 2011). To meet domestic demand, the Bangladesh government imports significant amounts of food each year (Bangladesh Economic Review, 2021). To feed its growing population without relying on ever-increasing food imports, Bangladesh needs to increase the amount of food that is produced per unit of land (Bakr et al., 2011) without depleting resources and further degrading the environment.

This chapter explores the importance of conservation agriculture (CA) for ensuring sustainability of Bangladesh rice and maize systems in the context of climate change. First, an outline of climate and farming systems in Bangladesh (1.1-1.2) and the importance of rice-maize cropping systems in Bangladesh (1.3) are discussed. The concept of conventional agriculture is then introduced in Section 1.4, along with crop residue utilisation in Bangladesh (1.5). The current challenges in rice-based systems are described in (Section 1.6). Following that (1.7), the concept and importance of CA on soil health and crop productivity are described, including the global status of CA and the constraints to CA implementation (1.8-1.13). Section 1.14 offers an overview of crop modelling and applications for assessing CA. Finally, Section 1.15 discusses the socioeconomic factors that influence the adoption of new CA technologies.

1.1 Climate in Bangladesh

Bangladesh shares its border with India to the west and Myanmar to the east. The climate is classified as sub-tropical monsoon, and is characterised by humid summers and mild, cool winters. In general, Bangladesh has four seasons: pre-monsoon (March-

May), monsoon (June-early October), post-monsoon (late October to November) and winter (December-February). The average annual rainfall is 2200 mm, but this varies by region, ranging from 1200 to 3500 mm (Biswas et al., 2018). For example, the mean annual rainfall in the Western region of Bangladesh is about 1400 mm, whereas it is 3300 mm in the east (Caesar et al., 2015). Eighty percent of the annual precipitation occurs during the monsoon season, particularly from May to September. In terms of temperature, pre-monsoon has the highest average temperature of the four seasons, at around 32.5°C, and can reach as much as 41°C in some regions (Islam et al., 2022). Because of this, Bangladesh has experienced numerous droughts (e.g. in the years 1981, 1982, 1984, 1989, 1994 and 2000), which affected 53% of the population and 47% of the total area of the country (BBS, 2018). At the same time, natural disasters such as floods and salinity are widespread in Bangladesh (Islam et al., 2022) and it is predicted that these will soon get worse (IPCC, 2013).

The North-Western region of Bangladesh has regularly experienced extreme maximum temperatures of approximately 35°C to 40°C from March to June, with even higher temperatures possible (43°C), making it a region that is vulnerable to drought and crop heat stress (BARC, 2016). Although this area is a significant agricultural hub for the nation, this extreme weather can be damaging to crops, leading to reduced food consumption and even the possibility of starvation (Karim et al., 2020).

1.2 Farming system in Bangladesh

Farming systems in Bangladesh are mostly focused on crop production, livestock, fisheries and agroforestry, and are highly diversified, heterogeneous and dynamic (Sreejith et al., 2020; Sarker et al., 2022). Additionally, household farming is regarded as a substitute for generating essential vegetables, fish, poultry and cattle (Islam et al., 1999; Hossain, 1996).

The rice cropping system (R-R) in Bangladesh is practiced by including monsoon (T.aman) rice (*Oryza sativa*) in the rainy Kharif season, followed by the next rice (boro) crop during the winter season when irrigation water is available (Sarker et al., 2022). However, rice covers 81% of the total cultivated land (BBS, 2020), whether planted as a monoculture or in rotation. Where there is a shortage of water, maize, wheat, potato, vegetables or others crop are grown instead of boro (winter rice) in order to achieve greater profits or fulfil dietary and nutritional needs.

1.3 Importance of rice-maize cropping systems in Bangladesh

Historically, rice-rice and rice-maize (RM) crop rotations have played a significant role in establishing food security in South Asia as well as Bangladesh (BBS, 2018; Timsina et al., 2010; Timsina & Connor, 2001). Currently, repeated monoculture rice cultivation with inefficient land management over long periods of time reduces soil fertility, posing a serious threat to sustainable agriculture (Chaki et al., 2021a; Jat et al., 2012a). In addition, winter rice e.g. "boro rice'' which requires 3,000 L of water per kg of rice grain and causes serious groundwater depletion (Karim et al., 2014). For wheat, 1,000 L of water are needed per kg of wheat grain (typically 2–4 irrigation treatments). Likewise, maize requires significantly less water than boro rice, requiring approximately 850 L of water per kg grain production (typically 2–4 irrigation treatments). Additionally, maize has fewer insect and disease vulnerabilities compared with boro rice and wheat (Timsina et al., 2010). Furthermore, maize can be grown during both the winter and summer periods, especially in rainfed regions (Timsina et al., 2010). Maize demand is increasing due to rising demand for poultry, fisheries, and human foods (BBS, 2018; Ali et al., 2008). Given this, the amount of land used to grow maize increased dramatically during the last decade, rising from 0.31 million ha in 2012 to 0.4 million ha in 2020 (BBS, 2022).

1.4 Current conventional agriculture: basic concepts

1.4.1 Concept of tillage

Tillage is the mechanical modification of soil for planting crops (Siemens et al., 1992). Farmers in South Asia cultivate their fields with a moldboard plough, a traditional desi-plough, or mechanical power and tractors. Repeated tillage can help farmers prepare seed beds and make planting easier. However, it has been demonstrated that repeated tillage without crop residue retention and reduced fertilizer application decreases SOC stock in the upper 10 to 15 cm of soil, increases soil erosion and damages soil structure, resulting in reduced crop yields (Gathala et al., 2015).

1.4.2 Crop residue management options under the conventional system

Farmers in the IGP (Indo-Gangetic plain) can use crop residue in a variety of ways, including removing all residue from the field, burning it, or retaining it for the subsequent crop. In a study in Bangladesh, it was found that few residues were recycled in agricultural fields, with the majority being used for animal feed, fuel, or bedding, or being burned in the field (Singh et al., 2008). The common practices of crop residue management are as follows:

i. Residue burning

Rice residues are burned in the field in the Western IGP to save labour costs (Akteruzzaman et al., 2012). Additionally, burning is a simple technique that can help farmers reduce pest and disease transmission (Kirkby, 1999). Several studies have recently indicated that crop residue burning has become a serious health issue due to a rise in air pollution (NPMCR, 2019) and global greenhouse gas emissions (GHGs) (Grace et al., 2002).

Figure 1.1: crop residue burning in Bangladesh (Islam et al., 2018).

ii) Residue incorporation

Most of the nutrients in the straw are returned to the soil when crop residues are incorporated into the soil and allowed to decay (Sarker et al., 2022). This is better for restoring organic matter to the soil and protecting the land from erosion (Seitz et al., 2019; Chaki et al., 2022).

1.5 Crop residue utilisation in Bangladesh

Crop residues are the leftover (or stubble) parts of crops, such as roots leaves, and stalks. The majority of crop residue in Bangladesh comes from rice, maize, lentils and oilseeds, with rice accounting for almost 70% (Islam et al., 2020). Crop residues are mostly used in Bangladesh to feed animals (67.30%) and cooking fuel (10-25%) (Islam et al., 2020; Akteruzzaman et al., 2012).

A number of researches on conservation agriculture (CA) based systems have been conducted in South Asia (Chaki et al., 2021a; Sarker et al., 2022). In CA systems, keeping at least 30% of the residue on the land is essential in order to prevent soil degradation (Giller et al., 2009). The distribution of agricultural residue for various purposes such as animal feeding, fuel, construction, and burning, poses a significant obstacle in the promotion of CA in mixed crop-livestock production systems (Bhan and Behera, 2014). Particularly in Bangladesh, the application of CA is inadequate (Das, 2013) due to feeding livestock instead of keeping crop residue on the field. As a result, there is declining soil health which can lead to reduced crop yields (Sarker et al., 2022; Islam et al., 2022). To solve this problem, priority should be given to future research that clarifies the implications of crop residue use trade-offs related to CA use in Bangladesh (Islam et al., 2019).

1.6 Current challenges in rice-based systems

The RR cropping pattern plays an important role in the food systems of south Asia, since it ensures food security for over a billion people (40 percent of whom live in extreme poverty); (Timsina et al., 2018). However, current study indicates that the system sustainability is jeopardized because yields are declining, reducing their profitability (Chaki et al., 2021a, Bhatt et al., 2021). These are mostly caused by (i) a heavy tillage-induced decline in soil organic matter, (ii) inefficient input use (fertilizer, water, and labour), (iii) an insufficient return of organic material, (iv) the rising cost of cultivation, (v) an increasing scarcity of water and labour and (vi) climate change (Chaki et al., 2021a; Sarker et al., 2022; Gathala et al., 2011a; Bhan & Behera, 2014).

It is well known that healthy soils should have at least 2% organic matter (FRG, 2015), but Bangladesh soils have less than 1.2% organic matter, with some even below 1% (FRG, 2018). This is due to the adoption of unsuitable intensive agricultural practices, such as heavy ploughing with a two-wheel tractor, the use of cow dung as a fuel, crop residue removal, and residue burning (Krupnik et al., 2013; Sudha et. al., 2003; Timsina & Connor, 2001; Kafiluddin and Islam, 2008).

Rice and non-rice (upland) crops are produced in the Eastern Gangetic plains (EGP) with regular cycles of wetting and drying under anaerobic and aerobic conditions, which have a negative impact on soil C and N cycles (Zhou et al., 2014; Chaki et al., 2021). Rice growing in flooded conditions typically contributes 9–11% of agricultural GHG emissions (IPCC, 2014).

However, puddling for wetland rice has resulted in the loss of soil structure, which may be suitable for continuous rice but could be a problem for crop rotations that alternate between rice and aerobic crops (Timsina et al., 2010). In addition, puddling breaks down aggregates, destroys macrospores, and causes subsurface compaction (Sharma et al., 2005). This subsurface compaction restricted root development, water uptake and nutrient absorption, which in turn reduces the yield of the subsequent dryland crop, including maize and wheat (Bajpai and Tripathi, 2000; Pagliai et al., 2004).

In addition, planting traditional varieties of monsoon rice under rainfed circumstances with conventional tillage delays the establishment of the maize crop (Islam et al., 2022). Since farmers often use conventional tillage, which requires additional 2-3 weeks after the rice harvest to do tillage operations prior to planting maize, which severely delays planting (Gathala et al., 2015). It is noted that conventional tillage, which needs up to 3-5 passes of slow-speed rotating tillage with a two-wheeled, tractor-driven power tiller (Gathala et al., 2015). Consequently, a late-planted maize crop is affected by heat stress during the reproductive stage, which causes a 12–22% decrease in yield (Ali et al., 2006).

1.7 Conservation agriculture is a potential key part of the solution

The adoption of climate-smart techniques such as zero, strip and reduced tillage may be especially relevant in the context of delayed planting and deteriorating soil health (FAO, 2017). CA practices are increasing throughout the EGP (Eastern Gangetic plains), particularly in rice-based systems, due to a wide range of benefits including improved soil fertility, carbon sequestration, and reduced GHGs (Reicosky and Saxton, 2007).

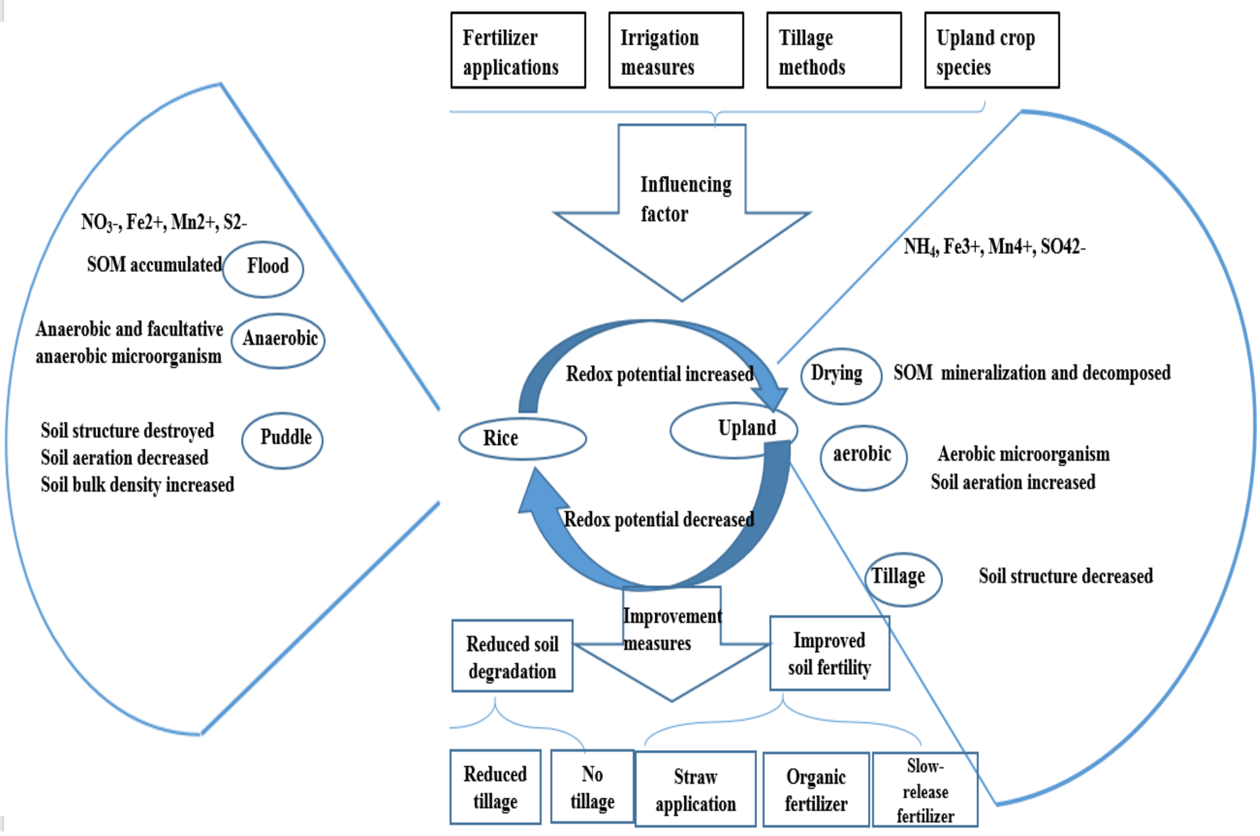

Figure 1.2: Schematic describing both conventional and conservation management options. Adapted from Zhou et al. (2014).

1.8 Conservation agriculture: basic concepts

Conservation agriculture (CA) is a new method that maintains a permanent soil cover with no or minimal tillage. The three pillars of conservation agriculture are: no or minimal tillage, maintaining soil cover with mulch on the soil surface and crop diversity (FAO, 2017). The practice of conservation agriculture is a holistic approach, allowing farmers to increase their production and profits (Dumanski et al., 2006).

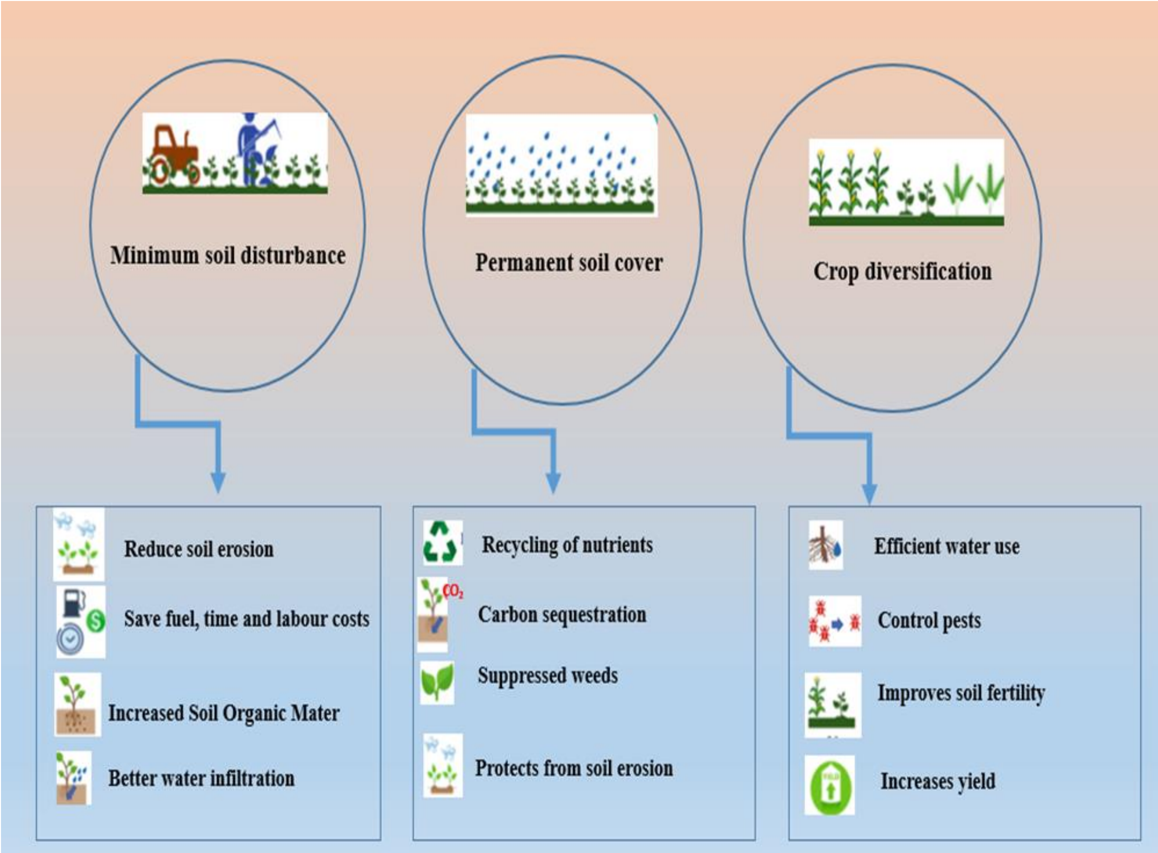

Figure 1.3: The potential advantages of Conservation Agriculture (CA). Adapted from Naorem et al. (2021).

1.8.1 Minimum soil disturbance

Conservation agriculture relies on the concepts of minimum tillage, strip tillage and no-tillage, which are described below.

i. Minimum tillage

The term minimum tillage refers to the agricultural practice of preparing the land for planting seeds and fertilizer with little soil disturbance (Busari et al., 2015). The emphasis of minimum tillage is to reduce the number of tractors passes, which makes the soil less compacted, improves its structure, and maintains soil moisture.

ii. Strip tillage

Strip tillage (ST) is characterised by Luna et al. (2003) as a system with a seeding zone and a soil management zone. The seeding zone requires sowing at a depth and width of 6 to 12 inches and 8 to 16 inches, respectively, in order to preserve the soil and microclimate, improve crop germination, and establish new seedlings. The area of soil management in between the strips is untouched and covered in crop residue. This technique decreases soil erosion and compaction while minimizing labour and fuel expenses. In addition, ST is a form of conservation tillage in which the seedbed is tilled in narrow strips while at least 30 percent of crop residue is retained (Trevini et al., 2013)

iii. No-tillage

To meet CA requirements for rice-based cropping on the EGP, a new rice planting method called non-puddled transplanting (NP) has been created (Alam et al., 2016; Haque et al., 2016). With NP, ST (about 2–4 cm wide and 4–5 cm deep) are tilled while keeping about 80% of the soil untilled. No-till is an agricultural technique that allows a small hole to be made in the soil for successful seed placement for crop production (Lal, 1983). The no-till system, also called direct drilling, zero tillage, or conservation tillage, is a tool that allows seeds to be planted at the right depth in the soil without any cultivation other than a shallow disturbance (5 cm) with narrow tines or coulters and then covered with soil. Additionally, the previous crop residue should remain undisturbed at the soil surface (Derpsch et al., 2011).

Figure 1.4: A Versatile Multi-Crop Planter is used for strip tillage. Adapted from experimental plot, November 2019.

1.8.2 Maintenance of soil cover: crop residue management

One of the key tenets of CA is the incorporation or retention of residue in the soil, which has a positive effect on the soil physical, chemical, and biological properties. Mulching with crop residue improves soil health by modifying soil aggregate stability, increasing SOC, and ultimately increasing production (Choudhury et al., 2014). Additionally, residue retention in the soil can increase water-soluble carbon, microbial biomass carbon, and potentially mineralizable carbon (Alam et al., 2019). It also helps to enhance the overall amount of carbon in the soil by reducing the amount of carbon emissions.

However, it is necessary to estimate the threshold levels of crop residue removal in order to improve SOC, maintain soil moisture, and increase crop production (Graham et al., 2007). It is important to keep in mind that the optimal cutting height is crucial for successful crop establishment (Anderson et al., 2009). Furthermore, standing crop residue - especially when mechanization was used - is considerably better for crop establishment than flattened crop residue in the field.

Figure 1.5: Residue retention for maize crops in Bangladesh. Adapted from experimental plot, February 2020.

1.8.3 Crop rotation

Crop rotation is a basic principle of conservation agriculture that involves growing different crops in the same field throughout the year. This method reduces soil erosion and discourages the growth of pest populations by disrupting their life cycles (Kassam and Friedrich, 2009). These processes not only provide a diverse "diet" to the soil microorganisms but also release access to different nutrients that have been leached to deeper layers and later on "recycled" by the crops in rotation. Moreover, the rotation of crops not only releases different nutrients, but also contributes to the development of soil structure through crop residue recycling (Ball et al., 2005; Pokhrel, 1995).

1.9 Effect of conservation agriculture on soil properties

i. Soil bulk density and porosity

Root penetration is highly influenced by soil bulk density and plays an important role in crop growth and development. Furthermore, increasing bulk density tends to increase soil strength and decrease soil porosity, which can result in negative effects on root growth (Marahatta et al., 2014).

Soil and crop management influenced bulk density and porosity (Singh & Kaur, 2012). A five-year CA study in Bangladesh found that strip planting with residue retention resulted in lower bulk density than regular tillage (Alam et al., 2018). Another study from Bangladesh, permanent beds with high residue retention provide higher porosity and lower bulk density than ploughed soil (Rashid et al., 2019). According to Choudhury et al. (2018), vigorous tillage with no residue retention produced the highest bulk density (1.47 Mg m^{-3}) in comparison to zero tillage with residue retention (1.34 Mg m^{-3}).

ii. Soil water content

Soil moisture conservation is very important in agricultural production, particularly in dryland areas where rainfall is limited. There is a significant correlation between soil water content and the presence of mulch cover, and once mulch cover is removed, soils rapidly lose moisture (Islam et al., 2022; Chaki et al., 2021a). Puddling of soil is currently practiced during rice farming, and intensive tillage of maize destroys the physical soil conditions and delays maize planting, which leads to reduced yields in rice-based systems (Gathala et al., 2015). Moreover, Mcdonald et al. (2006) also found that puddled transplanted rice and wheat grown under the conventional system degrades the soil structure, and leads to lower yields in rice-wheat rotations. The reason for this is that it is not possible to allow the use of machinery for succeeding crop establishment when the soil is wet (Islam, 2017).

Intensive tillage changes porosity, which influences the total infiltration rate and results in decreased infiltration, according to Marahatta et al. (2014). A ten-year study found that straw mulching increases soil porosity, which has positive impacts on water retention (Blanco-Canqui and Lal, 2007). In their investigation, they observed that the addition of straw mulch (16 Mg ha^{-1} yr^{-1}) led to a 40% increase in soil water retention compared to non-mulch treatments.

iii. Soil organic carbon

SOC is the most important component of soil organic matter and it is an important indicator of soil quality because of its positive effects on the soil physical, chemical, and biological properties, which increase crop yield (Panakoulia et al., 2017). As a result, increasing and preserving soil organic carbon is essential for crop productivity (Corning et al., 2016). Soil organic carbon is affected by tillage and residue management strategies. For instance, Alam et al. (2018) observed that on the EGP, CA techniques using minimum tillage (strip tillage) with residue retention had higher soil organic carbon levels than those using heavy tillage with no residue retention. In a three-year study on sandy clay loam soil in the IGP, permanent broad bed with residue techniques produced higher soil organic carbon at 0-30 cm soil compared to conventional tillage. Similar findings were made by Chivenge et al. (2007), who found that CA methods involving mulch ripping had higher SOC content 6.8 mg C g^{-1} than conventional tillage 4.2 mg C g^{-1} in sandy soil. In contrast, in clay soil, soil organic matter increased with reduced tillage (57.6 t C ha^{-1}) compared to conventional tillage (54.9 t C ha^{-1}), while there was no noticeable difference for the sandy soil (Swanepoel et al., 2018). In maize-based rotations, combining residue with reduced tillage had a significant influence on soil organic carbon, but tillage and residue practices alone had limited impact (Paul et al., 2013).

1.10 Changes of soil organic carbon in rice-rice and rice-maize systems:

Rice and maize, which were successively grown each year, had quite different edaphic requirements. Rice cultivation involved the process of puddling the soil and maintaining it in a flooded state, which induces anaerobic conditions that promote organic carbon accumulation (Haefele et al., 2022; Sanchez, 1973). According to Kirk and Olk's (2000), when compared to aerobic (upland) conditions, the process of decomposition and rates of mineralization for organic residues and native soil organic matter (SOM) were slower in submerged soil conditions. On the other hand, when maize is grown in upland soil under conventional practices, the carbon loss is high due to CO_2 emission, and significantly higher than in anaerobic conditions. This is because the activity of methanotrophic bacteria increases in aerobic conditions and reduces methanogenic activity by 28–100% (Szafranek-Nakonieczna and Stepniewska, 2015). In addition, soil drying and rewetting cycles boost microbial activity, resulting in greater SOM decomposition (Orchard and Cook, 1983).

1.11 Effect of conservation agriculture on crop production

More production with little or low environmental disruption will be required in the coming decades to meet the demands of an expanding population (Hobbs, 2007). The productivity of the rice-based systems in the IGP is declining due to poor resource management (Uppu et al., 2018). Traditional methods in rice-based systems, for instance, such as repeated wet tillage (puddling) for transplanting rice and heavy tillage for wheat establishment need a significant amount of resources (labour, water, money, and energy), which has the effect of depleting natural resources (Bhatt et al., 2016). As a result, conventional approaches are now becoming less profitable and sustainable (Kumar et al., 2018). In addition, during the past few decades, this method has not been able to adequately meet the rising population demand.

Therefore, resource-conserving technologies, such as CA, allow for the maintenance of South Asia sustainable productivity (Chauhan et al., 2012). One example came from India, where it was found that CA was appropriate for rice-maize production systems because it offered higher yields (17.4-17.6 kgm^{-3}) than conventional farming practices (Singh et al., 2018). Another study under rain-fed conditions found that conservation agricultural approaches provide a higher yield than conventional practices (Rusinamhodzi et al., 2011).

The effect of crop production on tillage systems was examined in India using three tillage methods: zero tillage, bed planting, and conventional tillage. They found that conservation agriculture-based zero tillage and bed planting practices (11.22–12.85, 10.60–12.31Mg ha^{-1}) performed significantly better than CT practices (9.28–10.69 Mg ha^{-1}) (Parihar et al., 2016). A ten-year CA study in India found that CA-based systems (zero tillage direct seed/zero tillage maize with residue), RM system productivity increased the yield by 15–38% compared to the traditional system (Jat et al., 2019). In another Bangladeshi rice-maize rotation study, CA tillage methods (RT, ST, Fresh beds, and Permanent beds) were compared to traditional methods (puddled transplanted rice in wet condition followed by intensive tilled maize). They found that there was no discernible difference in yield between the tillage strategies (Gathala et al., 2015). Another study from China, CA practices with reduced tillage (RT) led to higher yields of 13–16% more spring maize and 9–37% more winter wheat than conventional systems (Wang et al., 2012).

CA techniques functioned better in dry areas, particularly when yearly precipitation was less than 600 mm and the mean air temperature was over 5°C (Zheng et al., 2014). They also found that the beneficial effect of CA techniques was greater in maize (7.5%) and rice (4.1%).

1.12 Status of Conservation agriculture Bangladesh and worldwide

During the 1990s, progressive farmers, researchers and various development partners worked to expand CA across the world (Kassam et al., 2018). Historically, it was predominant throughout North and South America. Today the CA farming approach has gained popularity among farmers, and is now being used on large farms in China, Kazakhstan, and even on small farms in South Asia (Kassam et al., 2022). In Bangladesh, for example, CA techniques are gaining popularity, with around 2% (21,850 ha) of cultivated land under no-tillage and 5,764 ha under bed planting (Hossain et al., 2015). However, further extension strategies will be needed for the widespread adoption of CA approaches (Sarker et al., 2021).

In many parts of the world, CA is now suitable for farms ranging in size from half a hectare to thousands of hectares (Kassam et al., 2022).

Table 1.1 shows the global spread in the area of CA cultivated land (M ha) in different regions for 2008/2009 and 2018/2019.

Region	CA Cropland area 2008/2009	CA Cropland area 2013/2014	CA Cropland area 2015/2016	CA Cropland area 2018/2019
South and Central America	49	66	69	83
North America	40	53	63	66
Australia and New Zealand	12	17	22	23
Russia and Ukraine	0.1	5.2	5.7	6.9
Europe	1.5	2	3.5	5.6
Asia	3	10	13	18
Africa	0.4	0.9	1.5	3.1

Source: Kassam et al., (2022).

Since 2008/2009, the area of CA cultivated land cropland area has increased by 69% in South America (from 49 to 83 M ha); 65% in North America (from 40.0 to 66 M ha); 91% in Australia and New Zealand (from 12to 23 M ha) and 500% (from 3 to 18 M ha) in Asia (Table 1.1) .

1.13 Constraints of adoption of conservation agriculture

It has been shown that CA is good for the soil, the environment, and crop performance. However, there are some issues that make it challenging to use. Bhan et al. (2014) identified many key obstacles, such as a lack of sufficient technology, varied uses of crop residue, and competition for animal feed and fuel. Bhadu et al. (2018) also noted significant barriers to the adoption of CA technologies, including the burning of crop residues to ensure the establishment of succeeding crops and a shortage of experienced and knowledgeable labour for mechanization. Table 1.2 shows the key constraints of conservation agriculture practices:

Table 1.2 Key constraints of conservation agriculture practices

Constraint	Major finding	References
Risks for optimum yield	There is no significant yield increase in no/minimum tillage systems without crop residue retention.	Zheng et al. (2014)
	NT cannot provide a higher yield in maize production without crop rotation.	Naab et al. (2017)
	Waterlogging reduced maize grain production under CA methods.	Gatere et al. (2013)
Weed and herbicides	Weed densities are higher in CA practices than in conventional systems.	Rahman, M.M (2017)
	Herbicide application is required for CA.	Ali, (2014) and Descheemaeker et al. (2020)
	For weed management, conservation tillage systems heavily rely on the application of herbicide.	
	Crop residue retention creates an optimum environment for weed germination.	Ranaivosion et al. (2017)
Various uses of crop residue	The key constraints for the promotion of CA are the competing uses for crop residues, such as livestock feeding and cooking.	Bhan et al. (2014) and Jaleta et al. (2013)
Disease and pests	The crop residue on the surface is a source of inoculum for the subsequent maize crop, resulting in decreased production.	Thierfelder et al. (2014)

Nutrient immobilization	Nutrient immobilization occurs when there is a high C:N ratio, such as wheat residues.	Abiven and Recous (2007)
	Crop residue decomposition might result in short-term nitrogen immobilization.	Verhulst et al. (2010)
Appropriate equipment	Absence of suitable seeders for crop establishment.	Bhadu et al. (2018)
	Availability and affordability of new machinery such as seed driers.	Kassam et al. (2015) and Hobbs (2008)
Price fluctuation	Poor markets are another barrier to CA adoption in Africa.	Descheemaeker et al. (2020)
	CA adoption is hampered by a poorly developed market.	Thierfelder et al. (2015)
Establishment crop	Crop residues represent a significant barrier for crops grown in the autumn that need shallow tillage or direct drilling.	Cannell (1985)
Mind set	Farmers attitudes are the main barrier because they have received substantial training in conventional intensive agriculture.	Swaminathan et al. (2021)

1.14 Crop model applications

The challenge of accurately predicting crop yields is a significant issue in the agriculture industry. Every farmer wants to know how much yield they can expect based on climate and management conditions. Cropping system models provide the opportunity to examine environmental and management impacts on future yields (Challinor et al., 2014).

Models are sets of equations that represents the behaviour of a system. Many combinations of climate-smart agriculture practices, agro-ecological ecosystems, and climate scenarios can be evaluated through the application of modelling techniques. Models have the potential to be less time and money-intensive than field experiments while providing a broader view of the effects of climate-smart agriculture practices (Arenas, 2021).

A modelling approach can therefore be used to fit crop responses under different stress conditions (Bahri et al., 2019). The Agricultural Production Systems simulator (APSIM) model is widely used to simulate biomass, yield, water productivity, soil carbon changes, and crop response to rising CO_2 (Gaydon et al., 2017; Bahri et al., 2019; Chaki et al., 2022; Keating et al., 2003). In Zambia, APSIM was used to simulate maize yield under various climatic conditions based on sowing date, cultivar, and fertilizer rate (Chisanga et al., 2020). Morel et al. (2021) simulated the productivity of four annual crops (barley, forage maize, oats, and spring wheat) in five locations in Sweden under various climatic conditions using the APSIM model.

The APSIM framework is suitable for analyses that examine long-term variability in crop output and soil organic C, better irrigation and N management, the consequences of greenhouse gas emissions, and the effects of climate change (Gaydon et al., 2017; Chaki et al., 2022). APSIM was used to examine the impact of Climate-Smart Agriculture techniques, such as Conservation Agriculture practices, on rice and wheat yields in the Bangladesh (Chaki et al., 2022). For the first time in the NW-IGP, Singh et al. (2015) successfully simulated CA and CT practices in the irrigated and completely fertilized rice-wheat system using APSIM. Bahri et al. (2019) conducted a similar analysis using APSIM in Tunisia, examining the long-term impact of conservation agriculture on wheat-based systems in the context of climate change.

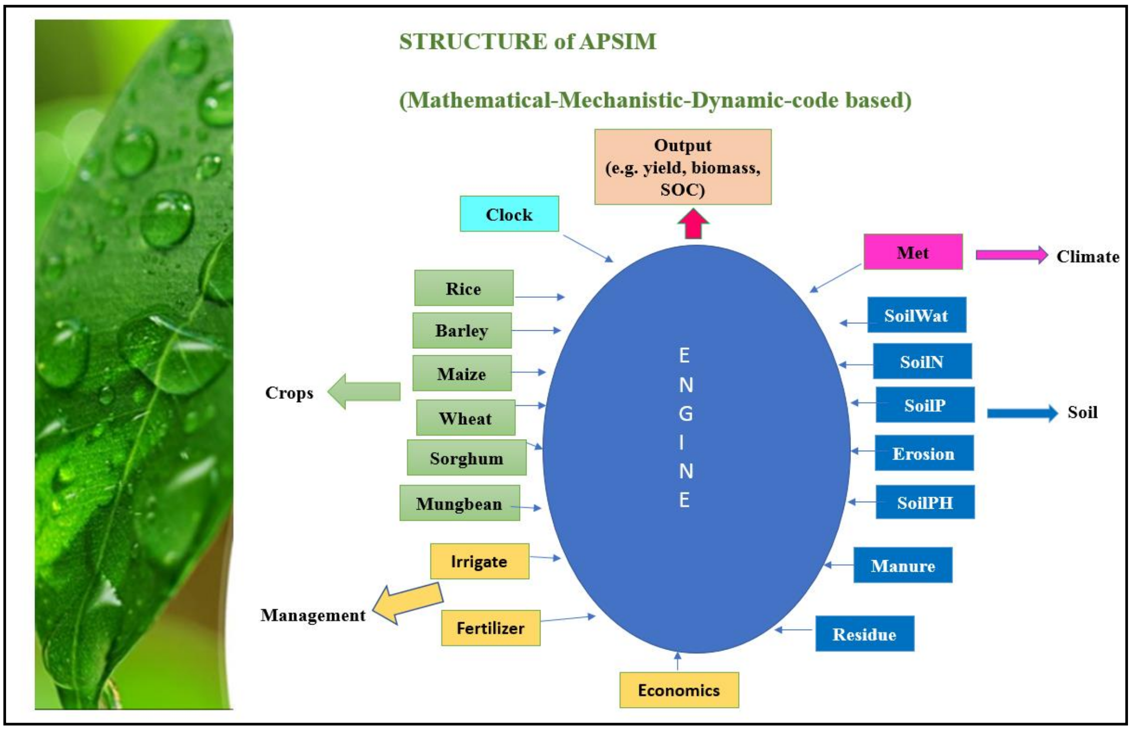

Figure 1.6: Working mechanism of APSIM (Keating et al., 2003)

1.15 Factors affecting the adoption of a new technology

Economic growth is accelerating in a number of ways, one of which is due to improving the farming system. The government of Bangladesh has launched a number of policies to boost economic growth, including offering subsidies for agricultural inputs and promoting the use of climate resilient technology (Faruque et al., 2018). This is because, adopting new technologies has been shown to boost production levels and maintain food security (Melesse, 2018). Unfortunately, the adoption of new agricultural technology (including CA and the use of agricultural machinery) has been slow due to a variety of factors (Mottaleb, 2018; Nowak et al., 1992). These factors can be categorised into three groups: i) socioeconomic characteristics of farm households, ii) performance of new technologies, and iii) institutional factors (Teklewold et al., 2013).

The socioeconomic circumstances involving farming experience, farm income, farm size, land use, the availability of labour, and resource endowment should be account for the adoption and scaling up of new technologies (Nita et al., 2014; Melesse, 2018). It has been demonstrated that various households have distinct socioeconomic characteristics, which may influence their motivation to adopt new technologies. Farming system typology is a useful tool for describing the diversity of households in a given region (Irem et al., 2014). Furthermore, it can be used to categorise farm households based on socioeconomic factors that may influence the promotion of new technologies (Bidogeza et al., 2009). It is widely acknowledged that understanding the limitations and opportunities inside farm households is a necessary step in the acceptance of new technologies. As a result, typology studies may be useful for assessing the constraints and opportunities that exist within farm households (Timothy, 1994).

1.16 Research questions and objectives:

This dissertation begins with an in-depth examination of smallholder farming systems as a case study in North Western Bangladesh and provides a new system of classification for enhancing our understanding of smallholder farming systems and their adaptability to new technology - in particular CA - in order to address how CA can cope with future changes in climate. Secondly, it illustrates the implications of varied percentages of agricultural residue utilisation in CA practices. Lastly, this thesis will look at whether CA practices are a good way to deal with future climate change in Bangladesh. The key points of the thesis are:

1. What are the most common types of mixed crop farms, and what are the differences between them? This understanding is critical if policy is to maximise adoption of CA by differentiated targeting of farm types.

2. What is the impact of alternate tillage, crop establishment, and residue retention on rice-maize cropping systems at the field level? This understanding is critical if the likely effectiveness of CA strategies is to be known ahead of implementation.

3. What are the long-term effects of various crop residue allocation strategies on tillage and crop establishment in the rice-maize cropping system under changing climatic conditions? This understanding is critical if the benefits of CA are to go beyond the short-to-medium term.

Based on the research questions, the aims of the research are:

1. To know the farm household types and their differences among farm types.

2. To investigate the effects of various crop residue allocation strategies on tillage and crop establishment in the rice-maize cropping system
3. To assess long-term (mid-end century) effects of various crop residue allocation strategies on tillage and crop establishment in the rice-maize cropping system under changing climatic conditions

It is hoped that this research would assist in making better decisions about how to manage crop residue in a sustainable way particularly for the purpose of increasing crop productivity and ensuring the health of the soil. It is also anticipated that the knowledge provided in this thesis will help build a new agricultural policy in the Bangladesh that addresses upcoming climate change.

1.17 Research Approach

In this thesis, various research methodologies were used. The methodologies were used based on three objectives:

(i) Developing farm typology (Objective 1, Chapter 2).

(ii) To carry out an experimental study in Bangladesh to examine the influence of tillage and residue management practices (CA) in a rice-maize cropping system (Objective 2, Chapter 3).

(iii) To simulate crop yield and soil organic carbon under future climate change using APSIM and climate models (Objective 3, Chapter 4).

1.18 Outline of research methodology

This section gives a brief explanation of why each method used to reach each research goal. Chapters 2 to 4 provide detailed descriptions of the research methodologies.

To achieve Objective 1- a multivariate statistical approach comprising Principal Component Analysis (PCA) and cluster analysis (CA) was used to classify farm typology. PCA was used to create a small set of independent components from the data. The new set of independent components was used as an input for cluster analysis and, later on, in identifying farm household types in the research area. This approach has been widely used in many studies to classify farm households (e.g. Bidogeza et al., 2009, Nita et al., 2014, Goswami et al., 2014). Multivariate statistics were used to create typology when the database is reliable and available. In our study, data were collected from 92 farm households using face to face interviews.

Objective 2 was achieved through a field experiment in the study area. The main advantage of field research is that it can be applied to real-world scenarios because it represents a wide range of circumstances and environments (Aziz, 2017). As laboratory experiments are conducted in controlled environments, the results may not accurately reflect what would be observed in the actual field. In this study, in order to comply with CA requirements, a novel planting technique for rice and maize known as strip-tilled direct seeded rice (STDSR) was used, which was then followed by strip-tilled maize (STM). For SOC fractionation, I used the size-density fractionation technique proposed by Robertson et al. (2019), a method increasingly used by others (Sokol et al., 2022; Graham et al., 2022; Zhang et al., 2021).

Objective 3 was achieved by using modelling tools to simulate future crop productivity and SOC. The comparison of multiple scenarios, such as residue removal/retention with minimum tillage versus intensive tillage, was used to forecast future SOC and crop productivity under various climate conditions. The modelling method (calibration, parametrization, and evaluation) was described and analysed. The benefits and constraints of the modelling technique were also presented and explored through the discussion of results. In our study, the processed based model APSIM was used, as driven by climate models projections. Our research was the first to explore CA and CT systems for rice-maize cropping systems in Bangladesh in the context of climate change. Furthermore, the majority of previous studies simulated a single crop in response to varying climatic circumstances (Chandran et al., 2022).

1.19 Study area

The research areas are in the Dinajpur districts of Rajbari (25°38'N and 88°38'E) in the North Western region of Bangladesh. This area serves as a major agricultural hub for the nation due to its advantageous geographical locations (Karim et al., 2020). The primary cropping pattern in the research areas is rice-based systems. Potato, sweet potato, Mungbean, chili, sesame, and watermelon are also produced in the area.

Currently, this area has experienced extreme maximum temperatures of roughly 35°C to 40°C from March to June (BARC, 2016) or even more, making it a region that is vulnerable to drought. These extreme weather conditions are causing damage to the crops, which in turn is contributing to a decline in food intake and even the potential for starvation (Karim et al., 2020).

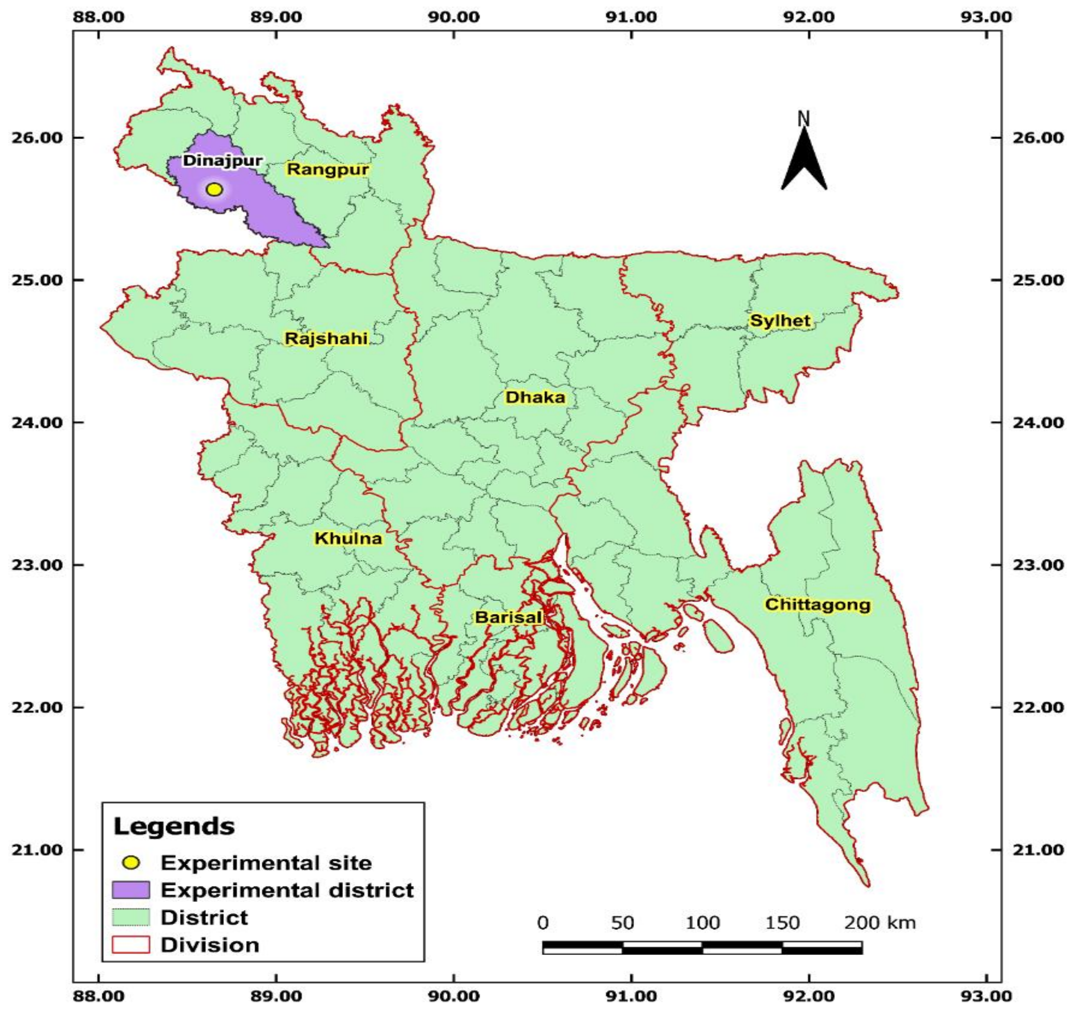

Figure 1.7: Map of Bangladesh and the purple areas represent the survey and experimental district and the yellow point is the location of the experimental site.

In general, the research areas have low soil organic matter and low to medium levels of plant nutrients like nitrogen, phosphorus, potassium, Sulphur, zinc, and boron (FRG, 2018). Dinajpur soil types range from sandy loam to sandy clay loam, with an acidic pH.

1.20 Thesis outline

This thesis consists of five chapters, with Chapters 2 – 4 providing answers to the three research questions that guide the thesis (Figure 1.8). Chapter 1 provides an overview of available literature, giving context to the thesis and establishing its relevance. In Chapter 1, research gaps were identified and the rationale for the study explained. Research questions and the objectives of the study and research methodology are also outlined.

Chapter 2 investigates the farm household types and their differences among farm types through farm survey.

Chapter 3 assesses the effect of various crop residue allocation strategies on tillage and crop establishment at the field level in rice-maize cropping systems using field experimentation.

Chapter 4 investigates the potential effects of projected long-term (mid and end century) impacts of different management strategies (varying crop residue retention and tillage) on crop productivity under changing climate using crop -climate model.

Chapter 5 provides a summary and forward-looking synthesis of the major results of the thesis and explores their broader implications, leading to further research recommendations.

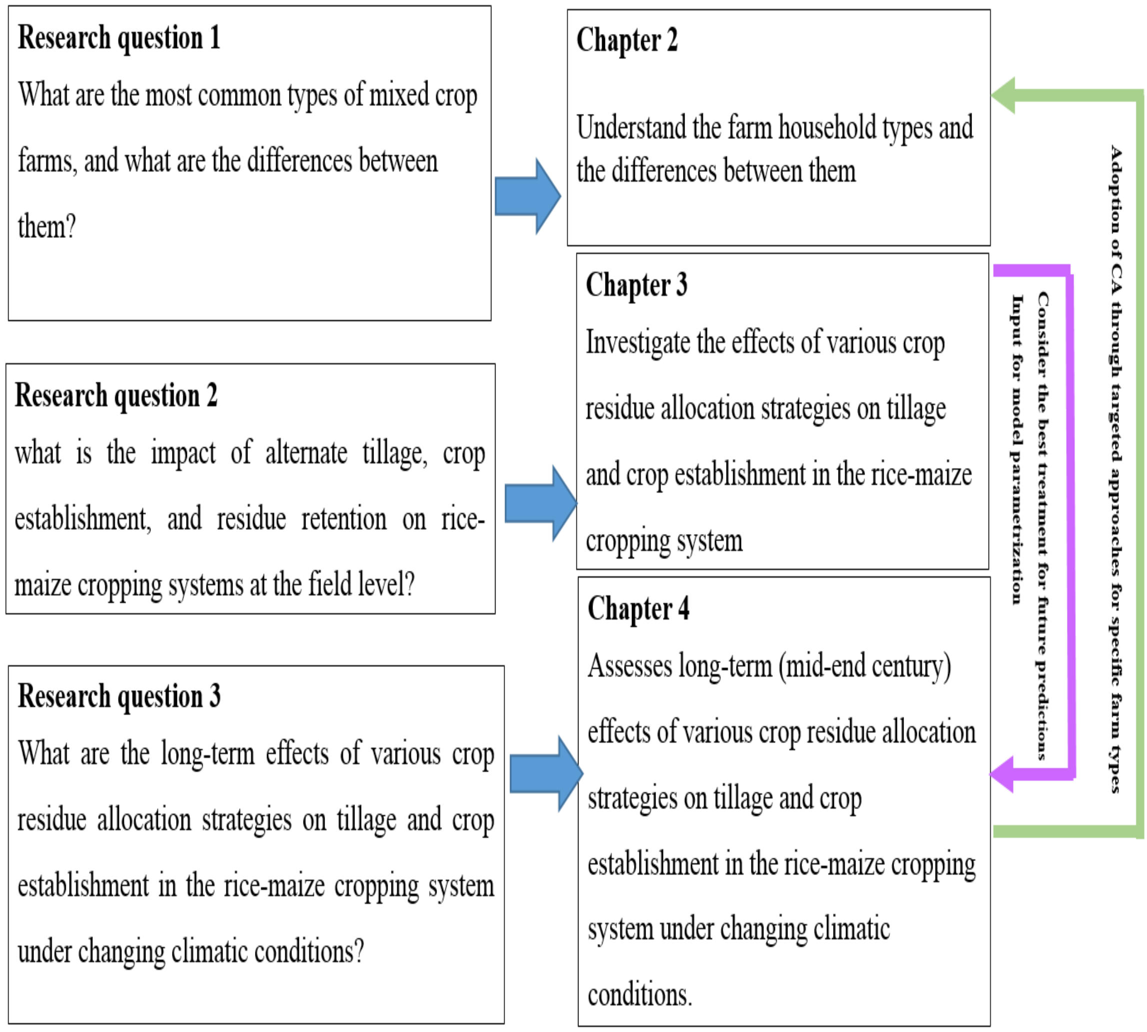

Figure 1.8: Research questions and the chapters providing answers

References:

Abiven, S. and Recous, S. (2007). Mineralization of crop residues on the soil surface or incorporated in the soil under controlled conditions. Biology and Fertility of Soils, 43:849-852. 10.1007/s00374-007-0165-2

Akteruzzaman, M., and Zaman, M. (2012). Utilization pattern of crop residues at farm level: Evidence from diversified rice-based cropping systems in Bangladesh. Progress. Agric, 23 (1 - 2): 111-122.

Alam, K., Richard, W. B., Wahidul, K., and Biswas. (2019). Increases in soil sequestered carbon under conservation agriculture cropping decrease the estimated greenhouse gas emissions of wetland rice using life cycle assessment. Journal of Cleaner Production, 224: 72-87, ISSN 0959-6526.

Alam, K., Salahin, N., Islam, S., Begum, R.A., Hasanuzzaman, M., Islam, M.S., and Rahman, M.M. (2016). Patterns of change in soil organic matter, physical properties and crop productivity under tillage practices and cropping systems in Bangladesh. J. Agric. Sci., 155: 216-238, 10.1017/s0021859616000265.

Alam, M., Bell, R., Haque, M., and Kader, M. (2018). Minimal soil disturbance and increased residue retention increase soil carbon in rice-based cropping systems on the Eastern Gangetic Plain. Soil and Tillage Research, 183:28-41.

Ali, A. B. (2014). Sustainable weed management in conservation agriculture. Crop Protection, 65 :105-113, ISSN 0261-2194, doi.org/10.1016/j.cropro.2014.07.014.

Ali, M. Y. (2006). Rice-maize systems in Bangladesh. Invited Oral Presentation in the Workshop on Assessing the Potential of Rice-Maize Systems in Asia. IRRI-CIMMYT Alliance Program for Intensive Production Systems in Asia, held December 4-8, IRRI, Los Baños, Philippines.

Ali, M.Y., Waddington, S.R., Hodson, D., Timsina, J., and Dixon, J. (2008). Maize-Rice Cropping Systems in Bangladesh: Status and Research Opportunities. CIMMYT–IRRI Joint Publication, Mexico, page 36

Anderson, G. (2009). The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia, Department of Agriculture and Food, Government of Western Australia. 3 Baron-Hay Court, South Perth WA 6151.

Arenas-Calle, L.N. (2021). Assessing trade-offs and synergies in climate smart agriculture across timescales, (July). PhD thesis.

Aziz, H. A. (2017). Comparison between Field Research and Controlled Laboratory Research. Arch Clin Biomed Res,1 (2): 101-104.

Bahri, H., Annabi, M., Cheikh, H., and Frija, A. (2019). Assessing the long-term impact of conservation agriculture on wheat-based systems in Tunisia using APSIM simulations under a climate change context. Sci Total Environ, 20; 692:1223-1233. doi: 10.1016/j.scitotenv.2019.07.307. Epub 2019 Jul 21. PMID: 31539953.

Bajpai, R. K., and Tripathi, R. P. (2000). Evaluation of non-puddling under shallow water tables and alternative tillage methods on soil and crop parameters in a rice-wheat system in Uttar Pradesh. Soil and Tillage Research, 55(1–2): 99–106.

Bakr, M. A., Rashid, M.H., Hossain, M.H., and Ahmed, A.U. (2011). Climate change and food security in south Asia, Springer, London, page -398.

Ball, B. C., Bingham, I., Rees, R. M., Watson, C. A., and Litterick, A. (2005). The role of crop rotations in determining soil structure and crop growth conditions. J. Soil Sci, 85: 557–577.

Bangladesh Economic Review. (2022). Finance Division, Ministry of Finance, Government of the People's Republic of Bangladesh. Dhaka, Bangladesh.

BARC (2016). Fertilizer Recommendation Guide for Bangladesh. Bangladesh Agricultural Research Council, Farm Gate, Dhaka, Bangladesh.

BBS (2020). Ministry of planning. Dhaka: Govt. of Bangladesh.

BBS (2018). Ministry of planning. Dhaka: Govt. of Bangladesh.

Bhadu, S., Choudhary, K., Patidar, R., Kavita, P., Bhadu, S., Bhadu, C., Poonia, K., Choudhary, T., and Kakraliya, K. S. (2018). A review paper on concept, benefits and constraints of conservation agriculture in India. International Journal of Chemical Studies, 6 (4): 36-40.

Bhan, S. and Behera, U. K. (2014). Conservation agriculture in India – Problems, prospects and policy issues. International Soil and Water Conservation Research, 2(4), 1:12. https://doi.org/10.1016/S2095-6339(15)30053-8

Bhatt, R., Kukal, S., Busari, M., Arora, S., and Yadav, M. (2016). Sustainability issues on rice–wheat cropping system. International Soil and Water Conservation Research, 4 (1): 64-74.

Bhatt, R., Singh, P., Hossain, A., and Timsina, J. (2021). Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy and Water Environment, 19 (3): 345–365. https://doi.org/310.1007/s10333-10021-00846-10337.

Bidogeza, J. C., Berentsen, P. B. M., De Graaff, J., and Oude, L. A.G. J. M. (2009). A typology of farm households for the Umatara province in Rwanda. Food Security, 1(3):321-335.

Biswas, Jatish., Choudhury, A., Miah, M., Maniruzzaman, M., Ahmed, F., Akhter, Sohela., Rahman, M., Aziz, A., Hamid, A., Kabir, M., and Kalra, N. (2018). Climatic Change Concerns in Bangladesh Agriculture. Haya: The Saudi Journal of Life Sciences, 3: 329-338. 10.21276/haya.2018.3.3.18.

Blanco-Canqui, H.L. R. (2007). Impacts of Long-Term Wheat Straw Management on Soil Hydraulic Properties under No-Tillage. Soil Science Society of America Journal, 71 (4): 1166-1173.

Busari, M, A., Surinder, S, K., Amanpreet, K, R, B., A, A, D. (2015). Conservation tillage impacts on soil, crop and the environment, International Soil and Water Conservation Research, 3 (2): I 119-129, ISSN 2095-6339.

BBS (2022). Ministry of Planning. Govt. of Bangladesh, Dhaka.

Caesar, J., Janes, T., Lindsay, A., and Bhaskaran, B. (2015). Temperature and precipitation projections over Bangladesh and the upstream Ganges, Brahmaputra and Meghna systems. Environmental Science: Processes and Impacts, 17(6): 1047–1056.

Cannell, R.Q. (1995). Reduced tillage in north-west Europe-A review. Soil & Tillage Research, 5: 129-177.

Chaki, A. K., Gaydon, D. S., Dalal, R. C., and Bellotti, W. D. (2022). How we used APSIM to simulate conservation agriculture practices in the rice- wheat system of the Eastern Gangetic Plains Field Crops Research How we used APSIM to simulate conservation agriculture practices in the rice-wheat system of the Eastern Gangeti. Field Crops Research, 275, 108344. https://doi.org/10.1016/j.fcr.2021.108344

Chaki, A. K., Gaydon, D. S., Dalal, R. C., Bellotti, W. D., Gathala, M. K., Hossain, A., and Menzies, N. W. (2021a). Conservation agriculture enhances the rice-wheat system of the Eastern Gangetic Plains in some environments, but not in others. Field Crops Research, 265, 108109.

Chaki, A.K., Gaydon, D.S., Dalal, R.C. (2022). Achieving the win–win: targeted agronomy can increase both productivity and sustainability of the rice–wheat system. Agron. Sustain. Dev, https://doi.org/10.1007/s13593-022-00847-8

Chaki, AK., Gaydon, DS., Dalal, RC., Bellotti, WD., Gathala, MK., Hossain, A., Siddique, A., and Menzies, NW. (2021b) Puddled and zero-till unpuddled transplanted rice are each best suited to different environments – An example from two diverse locations in the Eastern Gangetic Plains of Bangladesh. Field Crops Res, 262:108031.

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., and Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation, 4 (March):287–291. https://doi.org/10.1038/NCLIMATE2153.

Chandran, M. A., Banerjee, S., Mukherjee, A. (2022). Evaluating the long-term impact of projected climate on rice-lentil-groundnut cropping system in Lower Gangetic Plain of India using crop simulation modelling. Int J Biometeorol, 66: 55–69.

Chauhan, B. S., Mahajan, G., Sardana, V., Timsina, J., and Mangi, J. L. (2012). Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: Problems, opportunities, and strategies. Advances in Agronomy, 117: 315-369.

Chisanga, C. B., Phiri, E., Chinene, V. R. N., and Chabala, L. M. (2020). Projecting maize yield under local-scale climate change scenarios using crop models: Sensitivity to sowing dates, cultivar, and nitrogen fertilizer rates. Food and Energy Security, 9(4):1–17. https://doi.org/10.1002/fes3.231

Chivenge, P., Murwira, H., Giller, K., Mapfumo, P., and Six, J. (2007). Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Till. Res, 94: 328–337.

Choudhury, M., Datta, A., Jat, H., Yadav, A., Gathala, M., Sapkota, T., Das, A., Sharma, P., Jat, M., Singh, R., and Ladha, J. (2018). Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. Geoderma, 313:193-204.

Choudhury, G., Srivastava, S., Singh, S., Chaudhari, R., Sharma, S., Singh, D., and Sarkar, S. D. (2014). Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil & Tillage Research, 136 :76–83.

Corning, E., Amir, S., Quirine, K., and Karl, Czymmek. (2016). The Carbon Cycle and Soil Organic Carbon. Nutrient Management Spear Program. College of agriculture and life Sciences. nmsp.cals.cornell.edu

Das, A.K. (2013). Adoption of Conservation Agriculture Practices in Bangladesh (unpublished Master's Thesis). Department of Agricultural Extension Education, Bangladesh Agricultural University, Mymensingh.

Derpsch, R., Friedrich, T., Landers, J.N., Rainbow, R., Reicosky, D.C., Sá, J.C.M., Sturny, W.G., Wall, P., Ward, R.C., and Weiss, K. (2011). About the necessity of adequately defining no-tillage - a discussion paper. 5th World Congress of Conservation Agriculture incorporating 3rd Farming Systems Design Conference, September 2011 Brisbane, Australia www.wcca2011.org.

Descheemaeker, K. (2020). Limits of conservation agriculture in Africa. Nat Food 1, 402. https://doi.org/10.1038/s43016-020-0119-5.

Dumanski, J., Peiretti, R., Benites, J.R., McGarry, D. and Pieri, C. (2006). The paradigm of conservation agriculture. Proceedings of World Association of Soil and Water Conservation Paper No. P1 7:58.

FAO (2017). Climate-smart agriculture Sourcebook. Available at www.fao.org/climate change/climate smart.

Faruque, A.S., Huang, Z., and Karimanzira, T.T.P. (2018). Investigating Key Factors Influencing Farming Decisions Based on Soil Testing and Fertilizer Recommendation Facilities (STFRF)—A Case Study on Rural Bangladesh. Sustainability, 10: 4331.

Franzluebbers, A.J. (2010). Will we allow soil carbon to feed our needs? Carbon Management, 1(2):237-251.

FRG, (2015). Fertilizer Recommendation Guide, Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka.

FRG, (2018). Fertilizer Recommendation Guide, vol. 1215, Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka.

Gatere, L., Lehmann, J., DeGloria, S., Hobbs, P., Delve, R., and Travis, A. (2013). One size does not fit all: Conservation farming success in Africa more dependent on management than on location. Agriculture, Ecosystems and Environment, 179: 200-207.

Gathala, M.K., Ladha, J.K., Kumar, V., Saharawat, Y.S., Kumar, V., Sharma, P.K., Sharma, S., and Pathak, H. (2011b). Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron. J, 103: 961–971.

Gathala, M.K., Timsina, J., Islam, M.S., Rahman, M.M., Hossain, M.I., Rashid, M., Ghosh, A.K., Krupnik, T.J., Tiwari, T.P., and McDonald, A. (2015). Conservation agriculture-based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice-maize systems: Evidence from Bangladesh. Field Crops Research, 172:85-98.

Gaydon, D.S., Balwinder-Singh, Wang, E., Poulton, P.L., Ahmad, B., Ahmed, F., Akhter, S., Ali, I., Amarasingha, R., Chaki, A.K., Chen, C., Choudhury, B.U., Darai, R., Das, A., Hochman, Z., Horan, H., Hosang, E.Y., Kumar, P.V., Khan, A.S.M.M.R., Laing, A.M., Liu, L., Malaviachichi, M.A.P.W.K., Mohapatra, K.P., Muttaleb, M.A., Power, B., Radanielson, A.M., Rai, G.S., Rashid, M.H., Rathanayake, W.M.U.K., Sarker, M.M.R., Sena, D.R., Shamim, M., Subash, N., Suriadi, A., Suriyagoda, L.D.B., Wang, G., Wang, J., Yadav, R.K., Roth, C.H. (2017). Evaluation of the APSIM model in cropping systems of Asia. Field Crops Res, 204: 52–75. https://doi.org/10.1016/j.fcr.2016.12.015.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. Field Crop. Res, 114: 23–34.

Goswami, R., Chatterjee, S., and Prasad, B. (2014). Farm types and their economic characterization in complex agro-ecosystems for informed extension intervention: study from coastal West Bengal, India. Agricultural and Food Economics, 2-5.

Grace, P.R., Jain, M.C., and Harrington, L.W. (2002). Environmental concerns in rice wheat system International workshop on developing action Programme for farm-level impact in rice-wheat system of the Indo-Gangetic Plains, Rice-Wheat Consortium, Paper Series 14, New Delhi, India. page 99-111.

Graham, E. B., and Hofmockel, K. S. (2022). Ecological stoichiometry as a foundation for omics-enabled biogeochemical models of soil organic matter decomposition. Biogeochemistry, 157(1): 31–50.

Graham, R.L., Nelson, R., Sheehan, J., Perlack, R.D., and Wright, L.L. (2007). Current and potential U.S. corn stover supplies. Agronomy Journal, 99(1):1-11.

Haque, M.E., Bell, R.W., Islam, M.A., and Rahman, M.A. (2016). Minimum tillage unpuddled transplanting: an alternative crop establishment strategy for rice in conservation agriculture cropping systems. Field Crops Res. 185, 31–39. doi.10. 1016/j.fcr.2015.10.018.

Hobbs, P.R., Sayre, K., and Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc Lond B Biol Sci, 363(1491):543–555. doi:10.1098/ rstb.2007.2169

Hobbs, Peter. (2007). Conservation agriculture: what is it and why is it important for future sustainable food production? J. Agric. Sci, 145.

Hossain, M. S., and Haque, M. (2015). Status of conservation agriculture-based tillage technology for crop production in Bangladesh. Bangladesh Journal of Agricultural Research: 40 (2): 235-248.

Hossain, S. M. A. (1996). The Farming System and Environmental Studies of Bangladesh Agricultural University –An Overview. Edited in Fact Searching and Intervention 1991-95, Part I System Studies. Farming system and Environmental Studies, BAU, Mymensingh, page-38-39

IPCC (2013). In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, page 151.

Irem, D., Nassauer, Joan., Riolo, Rick., and Scavia, Donald. (2014). Development of a farmer typology of agricultural conservation behavior in the American Corn Belt. Agricultural Systems,129. 10.1016/j.agsy.2014.05.007.

Islam, A.R., Nabila, M.T., Hasanuzzaman, I.A. (2022). Variability of climate-induced rice yields in northwest Bangladesh using multiple statistical modeling. Theor Appl Climatol, 147: 1263–1276 https://doi.org/10.1007/s00704-021-03909-1

Islam, M. A. (2017). Conservation Agriculture: Its effects on crop and soil in rice-based cropping systems in Bangladesh. PhD thesis.

Islam, M. A., Bell, R. W., Johansen, C., Jahiruddin, M., Haque, M. E., and Vance, W. (2022). Conservation agriculture effects on yield and profitability of rice-based systems in the Eastern Indo-Gangetic Plain. Experimental Agriculture, 58(1), 1:22.

Islam, M. S., Kacren, K. A., and Kabir, M. H. (1999). An economic study on small-scale household-based farming and involvement of women. edited in fact searching and intervention 1996-98. Farming system and environmental studies, BAU, Mymensingh

Islam, M. S., Samreth, S., Islam, A. H. M. S., and Sato, M. (2022). Climate change, climatic extremes, and households' food consumption in Bangladesh: A longitudinal data analysis. Environmental Challenges, doi.org/10.1016/j.envc.2022.100495

Islam, M., Alam, M., Salahin, N., Alam, M., Hussen, M., and Mondol, A. (2022). Effects of tillage, mulch and irrigation on maize (Zea mays l.) yield in drought prone area. Bangladesh Journal of Agriculture, 47(1): 27–38.

Islam, M., Hashem, M., Islam, S., Alam, M., Rahim, M., and Akterruzzaman, M. (2020). Utilization of crop residues in rural household of Bangladesh. Progressive Agriculture, 31(3): 164–177. https://doi.org/10.3329/pa.v31i3.52119

Islam, S., Gathala, M.K., Tiwari, T.P., Timsina, J., and Gérard, B. (2019). Conservation agriculture based sustainable intensification: Increasing yields and water productivity for smallholders of the Eastern Gangetic Plains. Field Crops Research, 238:1-17. https://doi.org/10.1016/j.fcr.2019.1004.1005

Jaleta, M., Kassie, M., and Shiferaw, B. (2013). Tradeoffs in crop residue utilization in mixed crop-livestock systems and implications for conservation agriculture. Agricultural systems, 121: 96-105.

Jat, R. K., Singh, R. G., Kumar, M., Jat, M. L., Parihar, C. M., Bijarniya, D.,Gupta, R. K. (2019). Field Crops Research Ten years of conservation agriculture in a rice – maize rotation of Eastern Gangetic Plains of India: Yield trends, water productivity and economic profitability. Field Crops Research, 232 (December 2018), 1–10.

Jat, R.A., Wani, S.P., and Sahrawat, K.L. (2012). Conservation agriculture in the semi-arid tropics: prospects and problems. Adv. Agron, 117: 191–273.

Kafiluddin, A., and Islam, M.S. (2008). Fertilizer distribution, subsidy, marketing, promotion and agronomic use efficiency scenario in Bangladesh. In IFA Crossroads Asia-Pacific 2008, Melbourne, Australia.

Karim, F., Mohammed, M., Masud, H., and Mac, K. (2020). Assessing the Potential Impacts of Climate Changes on Rainfall and Evapotranspiration in the Northwest Region of Bangladesh Climate 8: 94. https://doi.org/10.3390/cli8080094

Karim, M.R., Alam, M.M., Ladha, J.K., Islam, M.S., Islam, M.R. (2014). Effect of different irrigation and tillage methods on yield and resource use efficiency of boro rice (Oryza Sativa). Bangladesh Journal of Agricultural Research, 39: 151-163.

Kassam, A., and Friedrich, T. (2009). Prospective on Nutrient Management in Conservation Agriculture. Invited paper, IV-word congress on conservation agriculture, 4-7 February 2009, New Delhi, India.

Kassam, A., Friedrich, T., and Derpsch, R. (2018). Global spread of Conservation Agriculture, International Journal of Environmental Studies, page:2-23.

Kassam, A., Theodo,r Friedrich., Francis, Shaxson., Herbert, Bartz., I, Mello., Josef, K., and Jules, Pretty. (2015). The spread of Conservation Agriculture: policy and institutional support for adoption and uptake. Field Actions Science. Reports [Online]. URL: http:// factsreports.revues.org/3720

Kassam, Amir., Theodor, F., and Rolf, D. (2022). Successful Experiences and Lessons from Conservation Agriculture Worldwide, Agronomy, 12(4): 769.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., and Hochman, Z. (2003). An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron, 18: 267–288. https://doi.org/10.1016/S1161-0301(02)00108-9.

Kirkby, C.A. (1999). Survey of current rice stubble management practices for the identification of research needs and future policy. RIRDC Project NO. CSL-5A. RIRDC completed projects in 1998-99 and research in progress as at June 1999 - Rice, Rural Industries Research and Development Corporation. Publication no 99/110.

Krupnik, T.J., Santos, V. S., McDonald, A.J., Justice, S., Hossain, I., and Gathala, M.K. (2013). Made in Bangladesh: Scale-Appropriate Machinery for Agricultural Resource Conservation. CIMMYT Mexico D.F, page 126.

Kumar, B. T. N., and Babalad, H. B. (2018). Soil Organic Carbon, Carbon Sequestration, Soil Microbial Biomass Carbon and Nitrogen and Soil Enzymatic Activity as Influenced by Conservation Agriculture in Pigeonpea and Soybean Intercropping System, Int. J. Curr. Microbiol. App. Sci, 7(3): 323-333.

Lal, R. (1983). No-till farming: Soil and water conservation and management in the humid and sub-humid tropics, IITA Monograph No. 2. Ibadan, Nigeria.

Luna, J. and Staben, M. (2003). What is strip-tillage? Using Strip Tillage in Vegetable Production Systems in Western Oregon. EM 8824 report.

Marahatta, S., Sah, S. K., MacDonald, A., Timilnisa, J., and Devkota, K. P. (2014). Influence of conservation agriculture practices on physical and chemical properties of soil. International Journal of Advanced Research, 2 (12): 43-52.

Mcdonald, Andrew., Riha, S.J., Duxbury, J.M., and Lauren, J.G. (2006). Wheat responses to novel rice cultural practices and soil moisture conditions in the rice–wheat rotation of Nepal. Field Crops Research, 98:116-126.

Melesse, B. (2018). A Review on Factors Affecting Adoption of Agricultural New Technologies in Ethiopia. Journal of Agricultural Science and Food Research, 9: 208-216.

Morel, J., Kumar, U., Ahmed, M., Bergkvist, G., Lana, M., Halling, M., and Parsons, D. (2021). Quantification of the Impact of Temperature, CO_2, and Rainfall Changes on Swedish Annual Crops Production Using the APSIM Model. Front. Sustain. Food Syst, 5:665025. doi: 10.3389/fsufs.2021.665025

Mottaleb, K. A. (2018). Technology in Society Perception and adoption of a new agricultural technology: Evidence from a developing country. Technology in Society, 55 :126–135.

Naab, JB., Mahama, GY., Yahaya, I., and Prasad, V. (2017). Conservation Agriculture Improves Soil Quality, Crop Yield, and Incomes of Smallholder Farmers in North Western Ghana. Front Plant Sci,8:996. doi:10.3389/fpls.2017.00996

Naorem, A., Jayaraman, S., Udayana, S.K., Singh, N.A.K. (2021). Can Conservation Agriculture Deliver Its Benefits in Arid Soils? An Overview. In: Jayaraman, S., Dalal, R.C., Patra, A.K., Chaudhari, S.K. (eds) Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security. Springer, Singapore.

Nita, K., Peeyush. S., and Ganesh, P.S. (2014). Cluster analysis for classification of farm households based on socio-economic characteristics for technology adoption in agriculture: A case study of west Jave province, Indonesia. Journal of Food, Agriculture and Environment, .12(1): 238-247.

Nowak, P. (1992). Why farmers adopt production technology: Overcoming impediments to adoption of crop residue management techniques will be crucial to implementation of conservation compliance plans. Journal of soil and water conservation, 47: 14-16.

NPMCR (2019). Available online: agricoop.nic.in/sites/default/files/NPMCR_1.pdf (accessed on 6 March 2019).

Pagliai, M., Vignozzi, N., and Pellegrini, S. (2004). Soil structure and the effect of management practices. Soil and Tillage Research, 79(2): 131–143.

Panakoulia, S.K., Nikolaidis, N.P., Paranychianakis, N.V., Menon, M., Schiefer, J., Lair, G.J., Krám, P., and Banwart, S.A. (2017). Advances in Agronomy Volume, 142: 241-276.

Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., and Pradhan, S. (2016). Conservation agriculture in irrigated intensive maize-based systems of north-western India. Effects on crop yields, water productivity and economic profitability. Field Crops Research, 193: 104–116. doi.org/10.1016/j.fcr.2016.03.01

Paul, S., Hossain, M., and Kumar, R. S. (2013). Monga' in northern region of Bangladesh: a study on people's survival strategies and coping capacities. Rajshahi University journal of life & earth and agricultural sciences, 41: 41-56. 10.3329.

Pokhrel, S. (1995). Orobanche control with crop rotation in mustard Krishi Sandesh DADO Chitwan (leaflet).

Quasem, M. A. (2011). Conversion of Agricultural Land to Non-agricultural Uses in Bangladesh: Extent and Determinants, Bangladesh Development Studies, Bangladesh Institute of Development Studies (BIDS), 34(1) 59-86.

Rahman, M. M. (2017). Weed management in Conservation Agriculture. Adv plants Agric Res 7 (3).

Rahut, Dil Bahadur., Jeetendra, P. A., Navneet, M., and Tetsushi, S. (2022). Chapter 6 - Expectations for household food security in the coming decades: A global scenario, Future Foods, Academic Press, PP 107-131, ISBN 9780323910019.

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L., and Corbeels, M. (2017). Agro-ecological functions of crop residues under conservation agriculture. A review. Agronomy for Sustainable Development, 37(4).

Rashid, M.H., Timsina, J., Islam, N. and Islam, S. (2019). Tillage and residue-management effects on productivity, profitability and soil properties in a rice-maize-mungbean system in the Eastern Gangetic Plains. Journal of Crop Improvement, 33(5), 683-710.

Reicosky, D. C., and Saxton, K. E. (2007). The benefits of no-tillage. No-tillage seeding in conservation agriculture, 2: 11-20.

Robertson, A. D., Paustian, K., Ogle, S., Wallenstein, M. D., Lugato, E., and Cotrufo, M. F. (2019). Unifying soil organic matter formation and persistence frameworks: the MEMS model, 1225–1248.

Rusinamhodzi, L., Corbeels, M., Van, Wijk., Rufino, M., Nyamangara, M., and Giller, K. (2011). A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agronomy Sust. Developm, 31:657– 673.

Sarker, M.R., Galdos, M.V., Challinor, A.J., and Hossain, A. (2021). A farming system typology for the adoption of new technology in Bangladesh. Food Energy Secur, 10: e287. https://doi.org/10.1002/ fes3.287

Sarker, MR., Galdos, MV., Challinor, AJ., Huda, MS., Chaki, A.K., and Hossain, A. (2022). Conservation tillage and residue management improve soil health and crop productivity-Evidence from a rice-maize cropping system in Bangladesh. Front. Environ. Sci, 10:969819. doi: 10.3389/fenvs.2022.969819.

Seitz, S., Goebes, P., and Puerta, V.L. (2019). Conservation tillage and organic farming reduce soil erosion. Agron. Sustain. Dev. https://doi.org/10.1007/s13593-018-0545

Sharma, P., Tripathi, R. P., and Singh, S. (2005). Tillage effects on soil physical properties and performance of rice-wheat cropping system under shallow water table conditions of Tari, Northern India. Eur. J. Agron, 23: 327–335.

Siemens, J. C., Dickey, E C., and Threadgill, E. D. (1992). Definitions of Tillage Systems for Corn. Biological Systems Engineering Papers and Publications.

Singh, A. and Kaur, J. (2012). Impact of conservation tillage on soil properties in the rice-wheat cropping system. Agricultural Science Research Journal, 2 (1): 30-41.

Singh, B., Humphreys, E., Gaydon, D.S., and, Yadav, S. (2015). Options for increasing the productivity of the rice–wheat system of north west India while reducing groundwater depletion. Part 2. Is conservation agriculture the answer? Field Crops Research, 173:81-94, ISSN 0378-4290,

Singh, B., Shan, Y.H., Johnson-Beebout, S.E., Yadvinder, S., and Buresh, R.J. (2008). Chapter 3. Crop residue management for lowland rice-based cropping systems in Asia. iAdvances in Agronomy, 98:117-199.

Singh, V. K., Dwivedi, B. S., Singh, S. K., Mishra, R. P., Shukla, A. K., Rathore, S. S., and Jat, M. L. (2018). Effect of tillage and crop establishment, residue management and K fertilization on yield, K use efficiency and apparent K balance under rice- maize system in north-western India. Field Crops Research, 224: 1–12.

Sokol, N. W., Whalen, E. D., Jilling, A., Kallenbach, C., Pett-Ridge, J., and Georgiou, K. (2022). Global distribution, formation and fate of mineral-associated soil organic matter under a changing climate: A trait-based perspective. Functional Ecology, 36: 1411–1429. https://doi.org/10.1111/1365-2435.14040

Sreejith, A., Timothy, J. K., Jeroen, C.J., Groot, E. N., Speelman, T.S., Amjath, B., and Pablo, Ti. (2020). Multi-level socioecological drivers of agrarian change: Longitudinal evidence from mixed rice-livestock-aquaculture farming systems of Bangladesh, Agricultural Systems, ISSN 0308-521X.

Sudha, P., Somashekhar, H.I., Rao, S., and Ravindranath, N.H. (2003). Sustainable biomass production for energy in Inda. Biomass and Bioenergy 25 (5): 501-515. doi: 10.1016/S0961-9534(03)00087-4

Swaminathan, C., Sobhana, E., Pandian, Kannan., and Yassin, M. (2021). Principles, Positives and Limitations of Conservation Agriculture: A Review. Agricultural Reviews, 10.18805/ag. R-2166.

Swanepoel, C., Rötter, R., Van, R. L., Annandale, M., Beukes, J., Preez, D., Swanepoel, C., Merwe, L., and Hoffmann, A. M. (2018). The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. Soil and Tillage Research, 183: 72-82.

Teklewold, Hailemariam., Berresaw, Menale., and Shiferaw, Bekele. (2013). Adoption of Multiple Sustainable Agricultural Practices in Rural Ethiopia. Journal of Agricultural Economics, 64: 597–623. 10.1111/1477-9552.12011.

Thierfelder, C., Rusinamhodzi, L., Ngwira, A. R., Mupangwa, W., Nyagumbo, I., and Kassie, G. T. (2014). Conservation agriculture in Southern Africa: Advances in knowledge. Renew. Agric. Food Syst, 1–21. doi: 10.1017/S1742170513000550

Thierfelder, C., Rusinamhodzi, L., Ngwira, A., Mupangwa, W., Nyagumbo, I., Kassie, G., and Cairns, J. (2015). Conservation agriculture in Southern Africa: Advances in knowledge. Renewable Agriculture and Food Systems, 30(4): 328-348.

Timothy, W. O. (1994). Identifying target groups for livestock improvement research: The classification of sedentary livestock producers in western Niger. Agric. Syst, 46:227–237

Timsina, J., and Connor, D. J. (2001). The productivity and management of rice-wheat cropping systems: issues and challenges. Field Crops Res, 69: 93–132.

Timsina, J., Jat, M.l., and Majumdar, K. (2010). Rice-maize systems of South Asia: Current status, future prospects and research priorities for nutrient management. Plant and Soil, 335: 65-82. doi: 10.1007/s11104-010-0418

Timsina, J., Wolf, J., Guilpart, N., Van, J., Grassini, P., and Van, J. (2018). Can Bangladesh produce enough cereals to meet future demand? Agric. Syst, 163:36–44. doi: 10.1016/j.agsy.2016.11.003

Trevini, M., Benincasa, P., and Guiducci, M. (2013). Strip tillage effect on seedbed tilth and maize production in Northern Italy as case study for the Southern Europe environment.

Uppu, S. S, and Koti, V. R. M. (2018). Enhancing Productivity in Rice-Based Cropping Systems, Plant Competition in Cropping Systems, Daniel Dunea, IntechOpen.10.5772/intechopen.76904.

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos, A., Mezzalama, M., and Wall, P. (2010). Conservation agriculture, improving soil quality in sustainable production systems. In [R. Lal and B. Stewart (Edn.)]. Food Security and Soil Quality. Boca Raton, FL

Wang, X., Wu, H., Dai, K., Zhang, D., Feng, Z., Zhao, Q., Wu, X., Jin, K., Ca i, D., Oenema, O., and Hoogmoed, W.B. (2012). Tillage and crop residue effects on rainfed wheat and maize production in northern China. Field Crops Research, 132:106-116.

World bank (2022). (IBRD-IDA) Idahttps://www.worldbank.org/en/home).

Zhang, Yao., Lavallee, M., Robertson, D., Even, Rebecca., Ogle, Stephen M., Paustian, Keith., and Cotrufo, M. (2021). Francesca. Simulating measurable ecosystem carbon and nitrogen dynamics with the mechanistically defined MEMS 2.0 model. Germany Web. doi:10.5194/bg-18-3147-2021.

Zheng, C., Jiang, Y., Chen, C., Sun, Y., Feng, J., Deng, A., and Zhang, W. (2014). The impacts of conservation agriculture on crop yield in China depend on specific practices, crops and cropping regions. Crop Journal, 2: 289–296.

Zheng, C., Yu, J., Changqing, C., Yanni, S., Jinfei, F., Aixing, D., Zhenwei, S., and Weijian, Z. (2014). The impacts of conservation agriculture on crop yield in China depend on specific practices, crops and cropping regions. The Crop Journal. 2 (5): 289-296.

Zhou, W., Lv, T.F., Chen, Y., Westby, A.P., and Ren, W.J. (2014). Soil physicochemical and biological properties of paddy-upland rotation: a review. Sci. World J. 2014, 856352.

Chapter 2

A farming system typology for the adoption of new technology in Bangladesh

Mamunur Rashid Sarker [1,2] , Marcelo Valadares Galdos[1], Andrew J. Challinor[1], Akbar Hossain[3]

[1]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[2] Senior Scientific Officer, On-Farm research division, Bangladesh Agricultural Research Institute, Gazipur-1701

[3] Bangladesh Wheat and Maize Research Institute, Dinajpur 5200, Bangladesh

Abstract

Over the last three decades, few studies have been conducted to tackle the complexity and heterogeneity of Bangladesh farming systems. We address these research gaps with a new survey. Accordingly, a survey was conducted in North Western Bangladesh to understand how socio-economic traits influence technology adoption, and to identify and characterise key farm types. The survey was based on farm household characteristics, farm structure, farming practices and livestock as well as the economic performance of the farm. Principal component analysis (PCA) and cluster analysis (CA) were used to establish the different farm typologies and the dataset based on 27 variables was carefully analyzed. The findings confirmed that the key variables that significantly affect the adoption of new agricultural technologies relate to age, farming experience, level of education of the household head, income, access to markets, land ownership, the proportion of hired labour, savings, food self-sufficiency and income from off-farm activities. Four main farm types were identified in the study area based on resource endowment and livelihood orientation. These are: (1) well-resourced farmers entirely dependent on agriculture and less reliant on off-farm activities; (2) moderately resourced households, which are headed by an older male with greater farming experience and which are engaged in both on-farm and off-

farm activities; (3) resource-constrained households with cattle as the main livestock and with income generated by the sale of livestock products; and (4) severely resource-constrained households which are headed by young farmers/men and where income is generated by off-farm activities. These four farm categories represent the heterogeneity of farms in North-West Bangladesh and it is hoped that the development of this farm household typology will help particularly the extension service, to set up appropriate extension advice that will benefit the farming community.

2.1 Introduction

Bangladesh has a primarily agrarian economy and with a population of over 165 million, is one of the most densely populated countries in the world. The population is still rising by 1.4% every year (BBS, 2017) and agricultural land is rapidly shrinking at a rate of 1% per year due to unplanned and uncontrolled urbanization and industrial development (Ahmed, 2013). The land/person ratio of the country is less than 0.05 ha capita^{-1} (Huq et al., 2013) and this continues to decline due to rapid population growth that could lead to food insecurity for the growing population in Bangladesh (Roy et al., 2019). In order to achieve food self-sufficiency, a wide variety of technological and policy solutions have been developed such as introducing drought and saline tolerant crop varieties, increasing irrigation facilities, promoting farm mechanization, ensuring the supply of good quality and high yielding seed varieties, optimizing the use of fertilizer, and adopting Integrated Pest Management (Bangladesh Economic Review, 2017). Unfortunately, the use of these modern technologies has not increased sufficiently due to the slow rate of adoption (Faruque et al., 2018; Karim et al., 2017; NAP, 1999). Lack of interest on the part of farmers is often cited as a reason for this. For example, most Bangladeshi farms do not follow the recommended guidelines on soil testing and the use of fertilizer (Daily Star, 2016). They rely mostly on traditional farming practices tacitly acquired through experience and knowledge passed down from one generation to the next (Rahman et al., 2018; Mondol, 2010).

Research into the development of farming systems is hampered by global scale evaluations that under-perceive and undervalue local complexities and diversity and this results in deterministic policy frameworks. Such inflexible policies for the development of the agricultural sector have proved to be ineffective (Chang, 2012). It is, therefore, crucial to design technological and policy interventions that target the diverse and spatially heterogeneous smallholder farming systems in order to address the pervasive constraints of that region. The foregoing literature suggests that few studies have been conducted to tackle the complexity and heterogeneity of Bangladesh farming systems and to formulate effective strategies and policies (Jabbar, 2011).

Farming systems in Bangladesh are highly complex and varied in their characteristics related to landholding, soil fertility, cropping systems, livestock assets, off-farm activities, labour, the availability of cash and access to credit, socio-cultural traits, and livelihood strategies. Therefore, it is not possible to develop specific recommendations for individual farm households, but the farming sector can be grouped into different categories with similar socio-economic characteristics so that appropriate recommendations can be made (Tittonel et al., 2010). Identifying variability within and among farms and across localities is the first step in developing interventions and policies that might be helpful for the adoption of advanced technologies in a farming community (Ruben and Pender, 2004; Mutoko et al., 2014).

Farming system typology (FST) is a useful tool to describe the diversity of households (Daloglu et al., 2014) and summarize the variability and diversity among different farming systems (Kuhn and Offutt, 1999; Alvarez et al., 2018), and has been used to understand the factors affecting the adoption of new technologies (Bidogeza et al., 2009; Daloglu et al., 2014). In addition, farm typologies have been used to study the adoption of agricultural greenhouses (Kuswardhani et al., 2014) and climate-smart technologies (Lopez-Ridaura et al., 2018), food security (Lopez-Ridaura et al., 2018) and resource use efficiency (Zingore et al., 2007; Tittonell et al., 2007) and to identify the potential adopters of alternative farming methods (Daskalopoulou and Anastasia, 2002) or the overall classification of farm categories (Rahman et al., 2019). It is also very important to gather evidence of how a context-specific understanding of the constraints faced by farming households in the adoption of new agricultural technologies could shape future strategies for the introduction of innovations. A deeper knowledge of such local scale constraints is needed to guide context-specific technological and policy interventions directed at sustainable development that increase resilience and improve farm incomes (Mwongera et al., 2017). Therefore, farm typologies must be studied at the level of each household in a village to develop specific interventions for introducing new agricultural technologies (Rahman and Das, 2019). Where there are clear research aims and reliable data exist, multivariate statistical tools can underpin such typologies. Typology development should be guided by the aims of the research, the questions which these raise and the characteristics of the research area (Duvernoy, 2000; Köbrich et al., 2003).

Earlier research has been undertaken into the classification of farm households in Bangladesh. For example, Rahman and Das (2019) categorized farming families based on the homestead and owned land: i) having no homestead or cultivable land; ii) having only a homestead but no cultivated area, and iii) having a homestead and limited cultivable land. Chowdhury (1978) classified farmers into three broad categories of class, status, and power, based on the ownership of land. Alam and Swapan (2011) classified farms into four-landholding sized classes: marginal (<0.4 ha), small (0.41–1.01 ha), medium (1.02–3.03 ha), and large (3.03 ha).Furthermore, the most commonly used classification of farm households was carried out by the Bangladesh Bureau of Statistics (2017) based on landholdings; farms are classified as small (<1 ha), medium (1–3 ha), and large (3 ha). Recognizing this farm household's heterogeneity is an essential first step in the analysis of potential technological interventions and policy support (Köbrich et al., 2003).

There are many studies in the literature which assess the factors affecting the adoption of new agricultural technologies (e.g. Melesse, 2018; Mwangi, 2015; Bidogeza et al., 2009; Pilarova, 2018; Priegnitz et al., 2019, Mafimisebi et al., 2016; Dhraief et al., 2018; Obayelu et al., 2017; Kuswardhani, et al., 2014) but all of these were conducted in regions where the farming system, climate and agroecology are very different from the north-western region of Bangladesh. For example, Islam (2020) studied farmers perceptions and adoption strategies in southern Bangladesh where the cropping system is different, the soil is saline and the climate is relatively humid. Similarly, Haqe et al. (2014) explored the adoption of mung bean (*Vigna radiata* L.) technologies in South Western Bangladesh, where new cultivation techniques were not practiced properly by most farmers. The reasons for this are unclear, since in-depth research on socio-economic factors from the Northern and North-Western regions is lacking (Farid et al., 2015). To develop a better understanding of this requires a classification of farm households, since the adoption of new agricultural technologies may differ among farm households due to differences in socio-economic characteristics (Mahapatra and Mitchell, 2001; Asfaw and Admassie, 2004; Somda et al., 2005; Milán et al., 2006).

Existing research suggests that while many studies have been carried out on the process of adoption and the impact on farming households of adopting new agricultural technologies, few studies have been conducted to analyse the factors common to farm households in relation to the adoption of new technology, especially in Bangladesh. Therefore, we propose a categorization of farm household diversity based on the homogeneity of socio-economic circumstances to identify and define farm systems, improving the targeting of new technological interventions.

Finally, the present study aims to determine the underlying socio-economic factors that influence the decision of farmers to adopt modern technologies. The objectives of this study are two-fold: (i) to identify and characterize farm types and (ii) to determine the major factors relating to the adoption of new agricultural technologies. This study offers important insights for policymakers that could stimulate and sustain the adoption of new technology in the study region. To achieve our objectives, this study sought to answer the following two research questions: (i) which types of smallholder farms can be identified and which factors drive their variability; (ii) which key factors are significantly related to the adoption of new agricultural technologies. To answer the research questions, we applied multivariate statistical techniques, using principal component analysis (PCA) and cluster analysis (CA), an approach used in similar studies (Bidogeza et al., 2009; Kuivanen et al., 2016a, 2016b; Mutoko et al., 2014; Sakané et al., 2013; Tittonell et al., 2010).

2.2 Materials and Methods

2.2.1 Study area

The study area is located in the sub-district of Birganj, part of the Dinajpur district in North Western Bangladesh (25°44´N and 88°40´E) (Fig. 2.1). The district is located in the Old Himalayan Piedmont plan agro-ecological zone (AEZ-1), and the land types are highland (HL; 5%), medium highlands (MHL; 37%), and medium lowlands (MLL; 5%), respectively. Under the Köppen climate classification, the climatic condition of the North Western part of Bangladesh including Dinajpur district is "Cfa". (Humid Subtropical Climate). These areas also experience high temperatures and limited soil moisture as well as low and erratic rainfall.

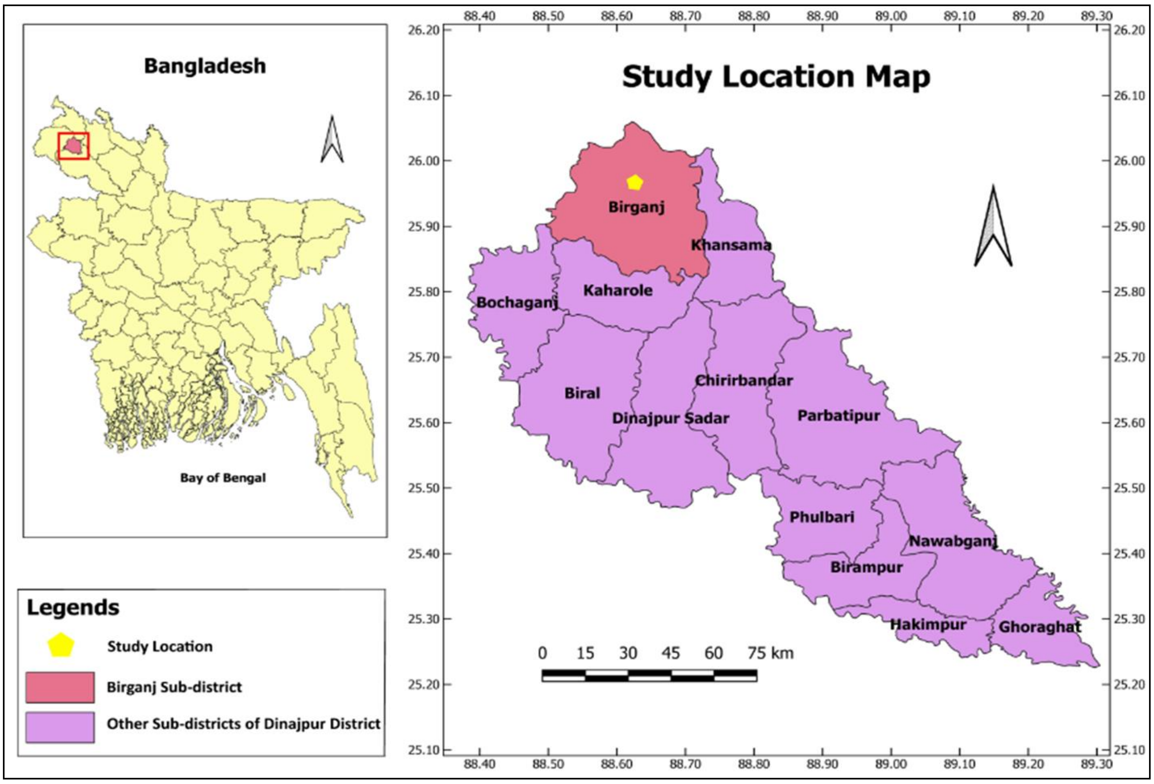

Figure 2.1: The study area is located in the Birganj sub-district, part of Dinajpur district in North-Western Bangladesh.

The annual average rainfall in the Dinajpur district is 1710 mm which mainly occurs during the monsoon and varies widely both by season and year. For example, rainfall recorded in 1982 was 1,342 mm, while in 2015 it was 1,965 mm. The average annual maximum and minimum temperature in the region is 35.11°C and 20.28°C, respectively. These conditions make the region drought-prone, leading to poor crop productivity. Thus, the livelihood of people in the area is threatened by climate extremes, particularly drought, in the late winter season. This region is also geographically vulnerable to natural hazards such as flash floods, heat-waves and cold spells, which have resulted in increased food shortage (Paul et al., 2013; Hossain et al., 2013; Barma et al., 2019). Historically, the regional economy has depended on the agricultural sector, with predominance of cereal crops, especially rice, as well as other major crops like maize, wheat, potato, and pulses (Mainuddin et al., 2020). In addition to this, aquaculture, the rearing of livestock, poultry and off-farm activities provide additional income to the farm households in this area.

2.2.2 Data collection

A multi-stage sampling procedure was followed for this study to select a research area and sample farmers. The initial step was selecting district Dinajpur for research data collection, which is situated in the North-Western part of Bangladesh. In the second stage, one Upazila was selected from that district for a sample survey. The name of the Upazila was Birganj under Dinajpur district. In the third stage, a total of 92 farms were randomly selected to address the research objective as well as to identify the different farm household types. Afterwards, a draft semi-structured interview schedule was used on 10 non-sampled respondents for necessary modification. Finally, data were collected from the selected households from February to March 2019 by face to face interviews. This month was selected to minimize the possible recall bias relating to the quantities of inputs used and output (grain and residues) obtained. The primary data collection was carried out with the support of three agricultural graduates and the interviews were conducted either at the respondent's house or in one of the farmer service centres where farmers regularly meet.

Seven sections were included in the interview schedule, the first focusing on information about household characteristics and the second including questions on access to food and other major assets. In the third section questions were targeted at farm activities including herd size, land use, cropping patterns and field management practices etc. The fourth section focused on crop residue management. The fifth section concentrated on livestock, such as breed type, herd structure, dynamics, and feeding strategies. The sixth section was aimed at collecting information regarding the adoption of new technology, ease of access to a market and key constraints to farming. Finally, the last section recorded information about household income and expenditure.

The factors affecting the adoption of new technology were considered for selecting variables to construct a farm typology in the study area. The age of the household head, family size, level of education of the household head, farm size, household income, access to extension services, the distance of the farm to the market, access to information etc, all play a vital role in the adoption of new technology; especially important is the issue of producing enough food for the family. In this study, the education of the head of the household was considered as two variables: =1 if they had finished at least primary education, 0= otherwise corresponds to not capable of writing.

2.2.3 Typology construction

Farm household data were analysed by using a multivariate statistical approach comprising principal component analysis (PCA) and cluster analysis (CA). PCA was used to reduce the dataset and create a smaller set of independent components. The new set of independent components was used as an input for cluster analysis and, later on, identifying the farm household in the research area. The technique has been widely used in many studies to classify farm households (e.g. Bidogeza et al., 2009; Kuswardhani et al., 2014; Goswami et al., 2014). All analysis was done using the ade4 package (available online http://pbil.univ-lyon1.fr/ade-4 from R 3.6.0. software R Core Team (2019)

2.2.3.1 Principal component analysis

The first steps for the PCA was data quality control, including identifying missing values and variables with strong correlations. The dataset based on the 27 variables was carefully examined and missing data identified. Based on Kaiser's criterion, all PC having an eigenvalue of one were retained for further analysis (Field, 2005). If the number of variables is less than 30, Kaiser's criterion is considered to be accurate (Field, 2005). In our study there were 27 variables, thus making it appropriate for this research. The number of the axis for principal component analysis can be determined based on the minimum cumulative percentage of variance, 60 % or higher is usually best for PCA (Hair et al., 2010). In our case, it was about 69% which was suitable for our research. In addition, a loading of less than 0.40 was not considered for interpretation of our objectives.

2.2.3.2 Cluster analysis

The nine components from the PCA were used to develop hierarchical clustering following Ward's method (Reynolds et al., 2006). Although there is no single procedure to determine the appropriate number of clusters, a two-step approach (i.e., the hierarchical method and the partitioning method) was used (Hair et al., 2006). The k-cluster solution was created by connecting with two clusters from the k+1 cluster solution whereas the partitioning method was employed to isolate the farm household into a given number of clusters (Lattin et al., 2005). Ward's hierarchical method was used to define the number of groups as it was widely used to minimize the variation within the cluster and successively join with equal clusters (Kobrich et al., 2003). A key point in this procedure is where to cut the tree to identify an appropriate number of clusters that is realistic for the study area.

Figure 2.2 presents the dendrogram with possible cutting lines from Ward's method of cluster analysis. Shifting the cutting line from A to B reduces the number of clusters to four, hence line C denotes only two farm types. The number of clusters should reflect the real situation in the study area. By using the cutting line C, two clusters based on the partitioning method were appropriate, but it did not represent the real situation in the area. Finally, using information from the dendrogram and taking into account expert knowledge in the study area, the number of clusters was chosen which was meaningful and realistic. To identify the variance between clusters, one-way analysis of variance was carried out and this was largely used to analyse the clusters (Field, 2005).

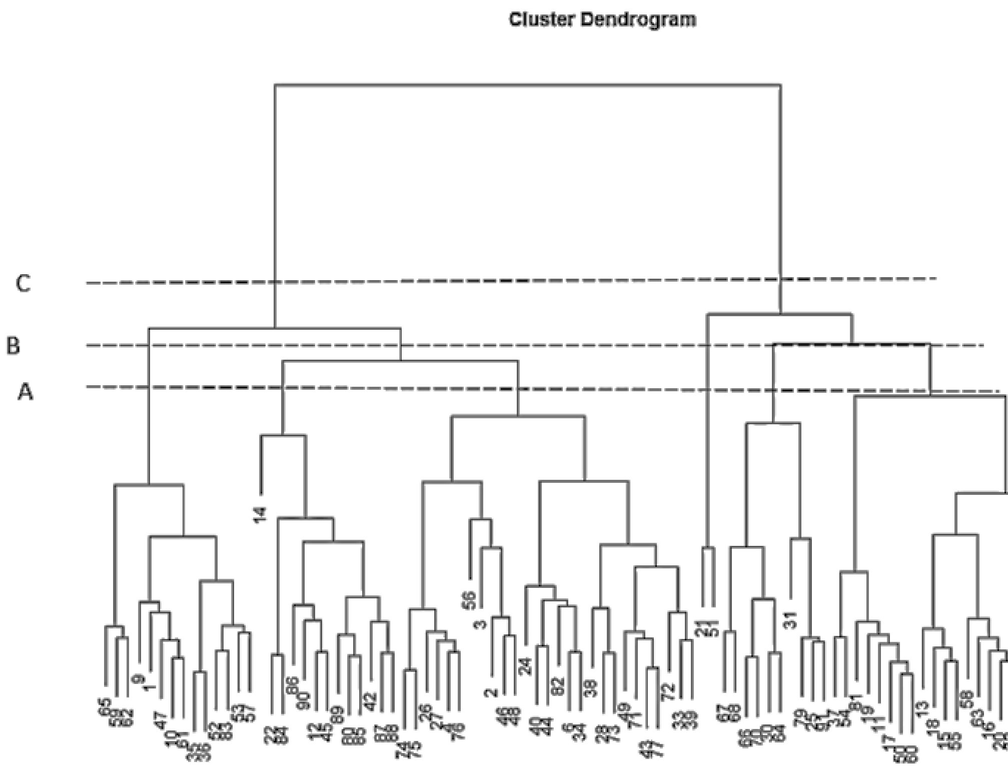

Figure 2.2: Dendrogram with three possible cutting lines for the study area

2.3 Results

2.3.1 Principal component analysis (PCA)

In total, 27 variables were used in the PCA (Table 2.1) and nine components with eigenvalues greater than one (Table 2.2) have been extracted for further analysis in the study area. The PCA results explain 69% of the variability of the data set. From Table 2.2 it was found that the first PC_1, which has the highest variation, was about 17 % of the variability in the data set. It was closely related to the variables describing land size, the number of crops grown per year, the amount of income from crops and food self-sufficiency, savings, and off-farm income. This component shows a positive relationship between farm size, the number of crops per year, food self-sufficiency and savings and a negative relationship with off-farm activities. This implies that large farms rely on their farming activities rather than off-farm activities. PC_2 correlated with animal resources (total TLU) as well as the majority of income coming from livestock and represents livestock enterprises. PC_3 represents age and experience which are positively linked. PC_4 is related to the marketing components and shows that farmers who are close to the market may have more opportunity to sell their products with lower transportation costs. The fifth, PC_5, comprises access to information about technology, which is strongly correlated with a family member joining a farmer's field school. The sixth principal component (PC_6) shows a negative relationship between landownership and herd size. PC_7 represents CA practices and PC_8 correlated with the educational level of the household. The last PC only represents the breed of the livestock enterprise.

Table 2.1 The descriptive statistics of the selected variables used in principal component analysis

Variable	Description and units	Mean	Standard Deviation
Household			
Size of household	Number of members	5.0	1.43
Age of household	Number of years	48	10.19
Farm experience	Years	27	9.81
Education			

Literacy of the head of the household	=1 if literature,0=otherwise	0.65	0.47
Labour			
Total labour input	Hours per year	2864	312.93
Hired labour ratio		0.15	0.08
Infrastructure			
Distance house to the main road	Km	0.75	0.62
Distance to the nearest market	Km	0.50	0.26
Land use	Hectares		
Cropped land area		0.65	0.51
Rice ratio		0.63	0.20
Maize ratio		0.28	0.17
Number of crops grown		2.56	0.56
Livestock	TLU (Tropical livestock		
Herd size	unit)	2.32	1.51
Small ruminant ratio		0.11	0.16
Poultry ratio		0.04	0.06
Food security			
Food self-sufficiency	Months per year	10	2.0
Saving	1=Yes, 0=otherwise	0.60	0.49
Land ownership	1= ownership, 0=otherwise	0.83	0.37
Income			
Crop sales	percentages	51	21.55
Livestock sales	percentages	15	12.14
Off/Non-farm income	percentages	33	25.28
Technological attributes			
Organic manure use	=1 if applying 0=otherwise	0.94	0.22
Improved livestock	=1 if applying 0=otherwise	0.20	0.40
Crop residue retention	=1 if 10 cm applying 0=otherwise	0.71	0.45
Marketing			
Crop product sale in near market	=1 if market, 0=otherwise	0.52	0.49
Extension			
Get extension service	=1 if receive, 0=otherwise	0.41	0.49
Family members joining FFS	=1 if join, 0=otherwise	0.76	0.42

Table 2.2 Eigenvalues and cumulative variances (%) explained by nine components (PCs)

Name of variables	Components and their Eigen values								
	PC_1	PC_2	PC_3	PC_4	PC_5	PC_6	PC_7	PC_8	PC_9
Age	0.10	**0.41**	**0.81**	-0.20	0.01	-0.04	-0.05	-0.09	-0.20
Land ownership	0.35	-0.34	0.04	0.07	-0.04	**-0.44**	**-0.45**	-0.08	0.06
Maize ratio	**0.44**	0.07	-0.07	-0.21	**0.47**	0.30	-0.19	0.15	0.28
Small ruminant ratio	-0.26	-0.23	0.11	-0.38	-0.03	**-0.62**	0.02	0.11	0.11
Income from crop (%)	**0.72**	0.03	-0.26	-0.01	-0.03	-0.06	0.10	0.17	-0.34
Extension service	0.14	**0.46**	-0.11	-0.34	0.05	0.20	-0.35	0.02	0.03
Farm experience	0.11	**0.40**	**0.83**	-0.17	0.07	-0.06	-0.04	-0.11	-0.15
Family members Joining FFS	0.04	-0.26	-0.18	0.03	0.42	-0.15	-0.20	**-0.47**	-0.26
incorporate crop residue	0.39	-0.01	-0.21	-0.14	-0.09	-0.17	**0.62**	-0.10	0.16
Number of crops grown	0.40	-0.28	0.23	0.20	0.33	-0.26	0.02	0.15	0.04
Saving	**0.67**	-0.34	0.04	0.06	-0.11	0.03	-0.19	-0.27	0.07
Distance house to main road (km)	-0.09	**-0.56**	0.26	**0.40**	0.24	0.13	-0.08	0.20	-0.26
Distance to nearest market (km)	-0.05	**-0.40**	0.21	**0.50**	0.13	0.11	0.17	0.17	0.24
Own manure use	0.19	**0.46**	0.01	0.39	-0.17	-0.01	-0.13	-0.30	0.25
Crop product sale	0.16	-0.08	0.36	**0.43**	-0.35	-0.05	-0.06	0.26	0.24
Income from Livestock (%)	0.20	**0.60**	-0.12	0.25	0.19	-0.38	0.16	0.08	0.01
Tropical livestock unit	0.38	**0.45**	-0.05	0.38	0.16	0.37	-0.04	0.06	-0.21
Improved livestock	0.17	0.16	-0.14	0.06	0.31	-0.01	-0.01	-0.26	**0.40**
Literacy of the head household	-0.07	-0.11	-0.02	0.11	-0.47	0.26	0.23	**-0.58**	-0.12
Hired labour ratio	**0.72**	-0.29	0.06	-0.17	-0.24	0.05	-0.04	0.13	-0.05
Size of household	0.20	0.16	**0.42**	0.09	0.27	-0.02	**0.41**	0.02	0.09
Poultry ratio	-0.16	**-0.47**	0.15	-0.21	0.38	0.20	0.29	-0.17	-0.17
Land holding (ha)	**0.72**	-0.29	0.03	-0.21	-0.24	0.15	0.04	0.10	-0.08
Off-income (%)	**-0.69**	-0.32	0.28	-0.09	-0.09	0.25	-0.16	-0.15	0.31
Rice ratio	**-0.56**	0.12	-0.15	0.38	-0.09	-0.25	-0.13	-0.01	-0.35
Food self-sufficiency (consume by own food month/year)	**0.78**	-0.12	0.07	0.06	-0.12	-0.07	-0.04	-0.12	0.09
Eigenvalues	4.56	2.86	2.22	1.73	1.54	1.45	1.30	1.19	1.14
Cumulative variance (%)	17%	28%	37%	43%	49%	55%	60%	65%	69%

Note: Bold numbers refer to loading equal to or higher than 0.4

2.3.2 Cluster analysis

The characteristics of the four different types of farm household clusters and p-value of one-way analysis of variance for the study area are reported in Table 2.3. Variables such as age, income from crop sector, farm experience, incorporation of crop residues in soil, savings, distance to the nearest market, income from livestock, tropical livestock unit, literacy of the head of household, hired labour ratio, landholding, off-farm income, and food self-sufficiency could significantly differentiate the farm types in the study area (Table 2. 3). All these variables were used to construct the typology.

Table 2.3 Characteristics of four clusters of farm households

Name of variables	Cluster 1 well resource – endowed with entirely depended on agriculture	Cluster 2 resource-constrained with herd dominated by cattle	Cluster 3 Medium resource – endowed, households are headed by an elder man with greater farm experience	Cluster 4 Severely resource-constrained, households are headed by young, income generated from off-farm	Cluster means	Cluster standard deviation	P-value
	N=30	N=9	N=34	N=18			
Age	44	50	54	42	47.94	5.46	0.00
Land ownership	0.93	0.66	0.82	0.77	0.80	0.11	0.22
Maize ratio	0.32	0.31	0.28	0.22	0.28	0.04	0.22
Small ruminant ratio	-0.76	-0.65	-0.56	-0.60	-0.64	0.08	0.45
Income from crop (%)	75.43	42.22	46.02	23.33	46.75	21.54	0.00
Extension service	0.46	0.66	0.32	0.33	0.45	0.15	0.30
Farm experience	24.10	28.55	33.94	21.88	27.12	5.32	0.00
Family members joining FFS	0.83	0.77	0.36	0.88	0.78	0.10	0.17
Incorporate crop residue	0.86	0.77	0.70	0.44	0.69	0.18	0.01
Number of crops grown	2.63	2.66	2.64	2.27	2.55	0.18	0.10
Saving	0.80	0.44	0.55	0.44	0.56	0.16	0.04
Distance house to main road (km)	0.69	0.46	0.77	0.96	0.72	0.20	0.22

Distance to nearest market (km)	0.43	0.40	0.61	0.49	0.48	0.09	0.02
Own manure use	0.96	1.00	0.97	0.83	0.94	0.07	0.13
Crop product sale	0.43	0.55	0.64	0.44	0.52	0.10	0.32
Income from livestock (%)	17.06	41.66	10.44	7.88	19.26	15.42	0.00
Tropical livestock unit	3.01	3.07	1.92	1.60	2.40	0.75	0.001
Improved livestock	0.26	0.33	0.14	0.16	0.22	0.08	0.49
Literacy of the head household	0.66	0.22	0.73	0.72	0.58	0.24	0.02
Hired labour ratio	0.18	0.13	0.15	0.11	0.14	0.02	0.02
Size of household	4.80	5.33	5.41	4.50	5.01	0.43	0.10
Poultry ratio	0.03	0.01	0.03	0.06	0.03	0.02	0.17
Land holding (ha)	0.88	0.42	0.59	0.35	0.56	0.23	0.001
Off-income (%)	7.50	16.11	43.82	68.22	33.91	27.62	0.00
Rice ratio	0.58	0.65	0.62	0.68	0.63	0.04	0.38
Food self-sufficiency (consume by own food month/year)	11.60	10.66	10.91	8.94	10.53	1.12	0.00

2.3.3 Farm types

Farm types (clusters) were identified based on the farmer's resource use efficiencies and capital endowment. Figure 2.3 shows the distribution of four different farmer types along with innovations taken up by farmers. Figures 2.4a & 2.4b further show the resulting four different clusters described as farm types (FT) with their specific characteristics. The following sub-sections (i.e. 2.3.3.1–2.3.3.4) describe the characteristics of four farm types in detail within the study area:

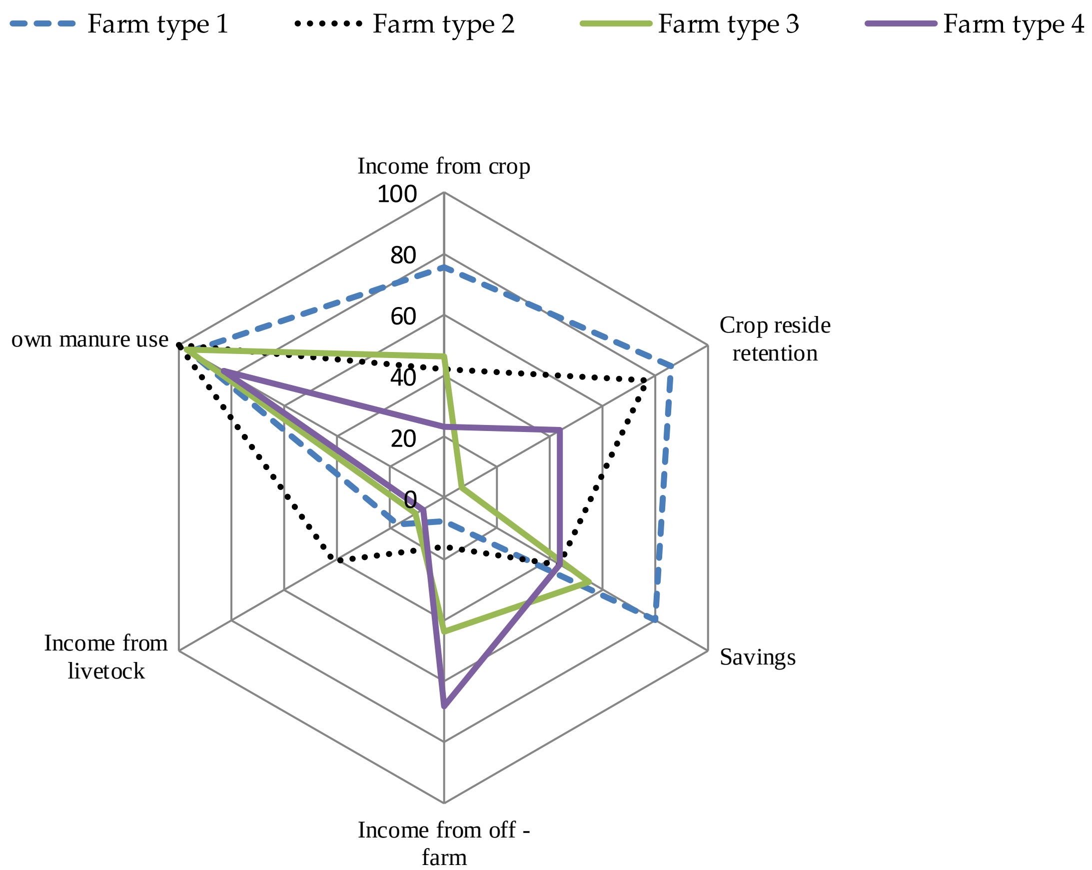

Figure 2.3: Spider diagram display percentage distribution of different key variables across four farm types

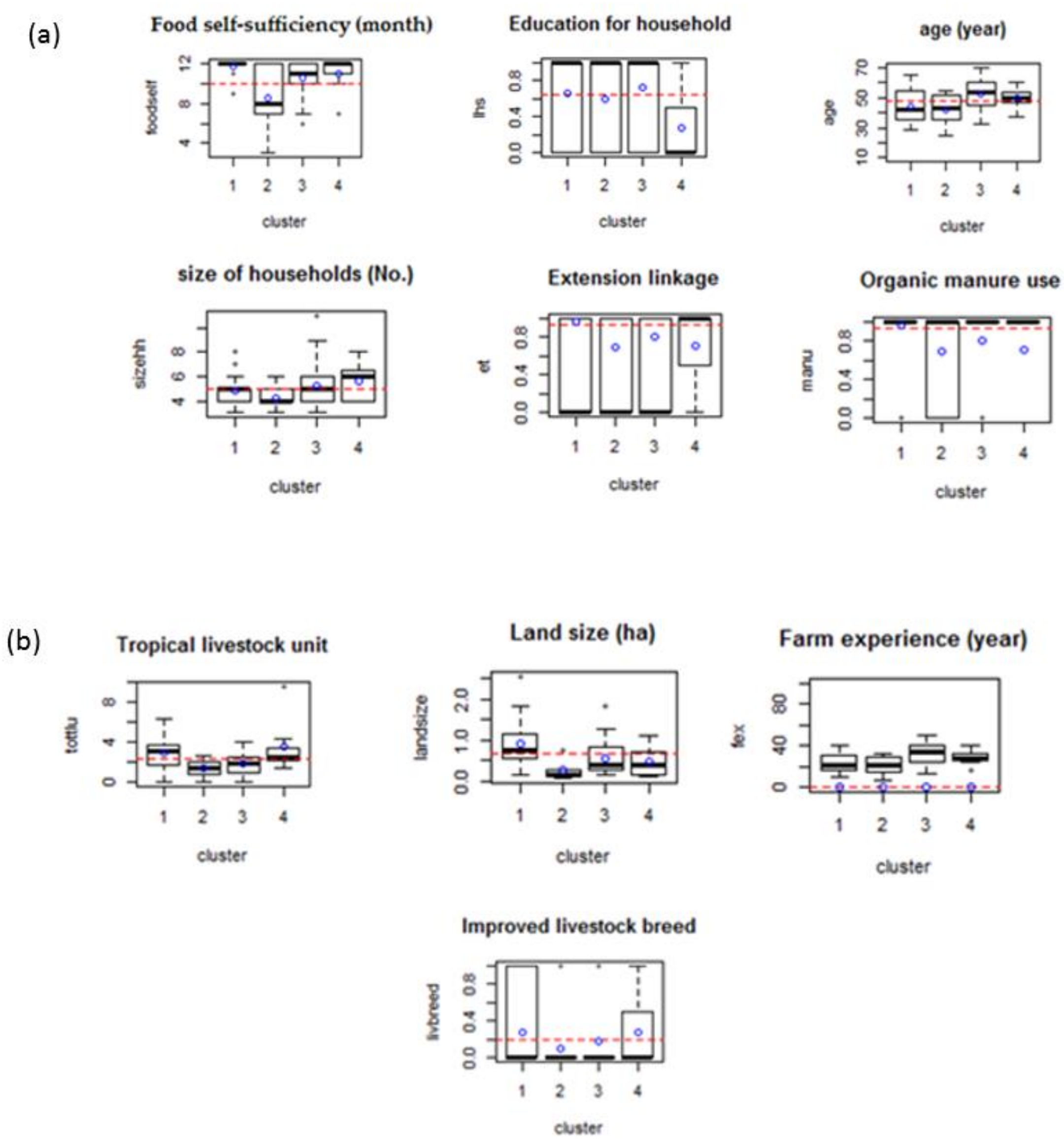

Figure 2.4: (a)Variables for the four farm types based on farmers food self-sufficiency, farmers level of education, age, size of household, extension linkage and organic manure use. Boxplots show cluster means (coloured squares), median values (solid horizontal lines) and outlier values (closed circles). The dashed line represents the survey means for each variable. (b) Variables for the four farm types based on farmers tropical livestock unit, land size, livestock breed and farm experience. Boxplots show cluster means (coloured squares), median values (solid horizontal lines) and outlier values (closed circles). The dashed line represents the survey means for each variable.

2.3.3.1 Type 1 farm

This cluster comprised households having a large farm with a high ratio of hired labour and accounts for 32% of the farm households. They were households that adhered to many agricultural technology practices such as crop residue retention or incorporated on the soil (86% farm households), use of own organic manure (96% farmers) and animal rearing using improved breeds. Being a large farm, they were able to produce more crop residue from their own fields which allows them to incorporate the residue in the fields (Figure 2.3). This cluster was also characterized by farm households with family members working mainly full-time on the farm (with the lowest level of off-farm work) and household heads with an average level of education and literacy. However, they also had a high level of income from the crop sector which means that the farmer depends mostly on crop production. These clusters have a higher level of food self-sufficiency than the others. In addition, the households have a high average level of education and a high proportion of income (75.43%) from the crop sector and are also characterized by having a high level of savings (Figure 2.3).

2.3.3.2 Type 2 farm

The Type 2 cluster represented small livestock-based farms with middle-aged farmers who have moderate farm experience (9% of the assessed farms). This cluster comprised quite small farms relying on agricultural level incomes, especially from livestock, with lower levels of ownership of cultivated land and a medium dependency on off-farm work (Table 2.3). The Type 2 cluster farms were also characterized by medium adherence to adopted agricultural technologies such as recycling crop residue (42% farm households) and the use of organic manures in the fields (Figure 2.3). These farm households were larger in comparison with the other clusters and had middle-aged household heads with a poorer level of education. They had excellent links to extension agents with access to information on crop and livestock production (Figure 2.4a). In addition, they had moderate food self-sufficiency (they consumed their own food at least 10 months of the year) and the lowest levels of family savings and the highest level of access to information regarding livestock products, especially milk, as their house is close to the market.

2.3.3.3 Type 3 farm

This farm type consists of medium resource farms with an older farmer who has a high level of farm experience (Figures 2.4a and 2.4b). They are market-oriented farm households, with the best-educated and most literate household heads, and a greater off-farm income (37% of the assessed farms). Type 3 farm households represented farms where, on average, the household heads were relatively old (54 years), had a high level of farm experience and where the levels of both agricultural and non-agricultural income were moderate. Although owning livestock, the number of livestock was lower compared to other farm households. This cluster also consisted of households with five family members, mainly involved in off-farm activities (with least full-time work on the farm) and with the best-educated and most literate household heads. They also demonstrated the lowest use of recycled crop residue (only 7%) in the field (Figure 2.3) and also have poor access to the market as they live far away from the market. Furthermore, these households had a low level of regular contact with extension workers which resulted in a lower level of adoption of improved breeds (Figure 2.4b).

2.3.3.4 Type 4 farm

This farm type includes low resource endowment, with the youngest household heads and reliance on off-farm activities which is greater on rented land (19% of the assessed farms). The most distinguishing factor in this type of farm is that households are headed by relatively younger farmers (42 years old on average) with a good level of education. These households are also characterised by smaller landholdings and lower food self-sufficiency (Figures 2.4a and 2.4b) and relied mainly on off-farm activities (68% income from off-farm). They also had the lowest levels of income from crops and livestock (Figure 2.3) and were the least likely to adopt new technologies with little use of organic manure and recycled crop residue in their fields. Moreover, these households had a low level of access to information on new technologies and had weak links with extension agents (Figure 2.4a). Type 4 farmers were also found to have the smallest landholdings and livestock was concentrated on poultry.

2.3.4 Drivers of technology adoption by farm category

2.3.4.1 Household-related variables

Farm types significantly differed with the age of the household heads and their farming experience (Table 2.3). The findings reveal a positive correlation between the age and farming experience of the household heads (Figure 2.4a). In particular, the heads of Type 3 farm households were the oldest and had the greatest farming experience. Type 2 farmers, on the other hand, were middle-aged and their farming experience was greater in comparison with the other types (Table 2.3). However, the age of the household head did not have a significant positive influence on the practice of new technologies. This indicates that the adoption of new technologies was not dependent on the age of the households but rather on the size of cultivated land as well as ownership and use of legally owned land. In particular, the heads of Type 1 households had the largest landholdings and legally owned land because they have practised more innovative technologies in comparison with other farms.

There is a positive correlation between land size and the household's food self-sufficiency (Table 2. 3). In particular, farmers from Type 1 households had the greatest amount of land and the highest crop production with greater food self-sufficiency, while farmers of Type 4 were the youngest, had the smallest amount of land and lower crop production with poor food security. The results indicated that those households that had a good level of education were more involved in a farmers' field school. In particular, the heads of Type 1 households had higher levels of education and literacy.

2.3.4.2 Resource endowment variables

The size and ownership of land, livestock, off-farm income, and labour were distinguishing factors for the different farm types (Table 2.3). Variables in on-farm income and land ownership, as well as the use of legally owned land, correlated with each other. Also, the practice of recycling crop residues and the use of organic manure was positively correlated with land size and ownership and how it is used, while it was negatively correlated with non-agricultural employment income (Table 2. 3). Type 1 and 2 farms, which had adopted new technologies, owned larger farms. Type 4 farms can be classified as smaller farms with greater reliance on rented land. Having savings was strongly correlated to income from crops, livestock, and other sources. This indicates that ownership of productive assets was highly correlated to income. For example, Type 1 farms have a higher level of asset ownership than other farm households (Table 2. 3). In addition, the economic factor was strongly linked to the practice of new agricultural technologies (Table 2. 3).

The key variables, such as full-time on-farm and off-farm labour, did not differ significantly among the different farm types. While Type 2 farms were mainly focused on full-time, off-farm family labour, implying reliance on hired labour, Type 1 and 4 farms relied on full-time on-farm family labour (Table 2.3). As noted earlier, ownership of livestock was a significant distinguishing factor between the farm types (Table 2.3). Nonetheless, it differentiated Type 1 (3.01 TLU) and 2 (3.07 TLU) farm households which owned the greatest number of livestock compared to the other farm types (Table 2. 3).

2.3.4.3 Cropping practices concerning the adoption of new technologies

The way in which farm households managed their farms differed significantly between farm types and the availability of resources (Table 2.3). A positive correlation was observed between the adherence to conservation agriculture (CA), that is the practice of crop residue retention or incorporation on the soil, and the use of organic manure and the ownership of existing assets (i.e., land and number of livestock). Farms of Type 1 had similar characteristics but differed from Types 3 and 4. However, farms of Type 4 showed low adherence to CA principles (Table 2.3), which could be explained by their low ownership of land and wealth. The adoption of the new cropping system was also strongly and positively correlated with a higher income from agricultural sources.

2.3.4.4 Access to information

It was expected that there would be a positive correlation between extension agents and access to information on crop and livestock production and input use. Type 2 farm households had excellent links with extension agents and this may result in adopting improved livestock breeds in comparison with other households who had no links (Figures 2.4a and 2.4b). Moreover, our results also demonstrate that those farm types with a low level of adoption of agricultural technologies (e.g. recycling crop residue) had limited access to information compared to other farm households. These results indicated the importance of access to information for the adoption of agricultural technologies. Overall, results largely indicate a connection between the level of resource endowment of a farm household and good links with a farmer's field school and access to information and the adoption of agricultural technologies.

2.4 Discussion

Farm household typologies were developed based on study objectives that determine the rate of adoption of new agricultural technologies. The results of this research show key differences between the four identified farm types. The factors influencing the diversity of farm households, how they evolve to each other and the implications of this are discussed regarding the adoption of new agricultural technologies.

2.4.1 Household characteristics

The farm household typology describes the importance of the age and level of literacy of the household head as well as the size of the household. It also helps us to explain the diversity of farm households in the study area. Other studies reported similar findings, although with variations. Kamau et al. (2018) revealed that farm types significantly differed regarding the age of the household heads, their education and literacy levels, as well as the number of members in the farm household. In Kenya and Tanzania, van de Steeg et al. (2010) found that family size and the number of years of education explained heterogeneity in the five farm types. In Rwanda, the significant household discriminants were family size and the age and level of education and literacy of the household head (Bidogeza et al., 2009). The results of our study showed that the significant household discriminants were the age and amount of farming experience of the household head but that the level of literacy was not. Similar findings were reported by Pilarova et al. (2018) who found that the age of the household head was a significant distinguishing factor between different farm types in Moldova but that the level of education of the household head was not. Kuswardhai et al. (2014) found that age and farming experience explained heterogeneity in the four farm types they found in the West-Java province, Indonesia. A study conducted in Ethiopia by Jena et al. (2012) reported that certified smallholder farms were headed by relatively older household heads with a mean age of 48 years, who had a low level of education. The results of this study show this is true for farm Type 2, but not for Types 3 & 4. An inverse link between age and education as well as the literacy level of the household head was also reported by Bidogeza et al. (2009) in Rwanda, where young household heads were more educated. Similar findings were reported by Signorelli (2016) who found that wealthier households were more often headed by young household heads with a high level of education.

The results of the current study suggest that among the sampled households farming is mainly practiced by the older generation. This finding is in line with that of Mutoko et al. (2014) in western Kenya. In Bangladesh, young people who are engaged in the agricultural sector tend to migrate to urban areas due to poor employment opportunities in rural areas (Hossain, 2001). In addition, as stated by Zaman et al. (2010), the agricultural sector is not capable of absorbing the surplus labour force entering the economy every year, thereby encouraging people to migrate to urban areas. In these circumstances, it is necessary to emphasize the important role played by household characteristics in the adoption of new technologies. Firstly, support for youth education with an emphasis on vocational training, to help them to improve their technical skills as, among other benefits, being able to absorb new ideas and innovations would enable farmers to create market opportunities (Radwan, 1995). Secondly, the older and more experienced generation of farmers who are engaged in farming cannot be ignored. For Type 3 farm household heads who were relatively older and had extensive farming experience but a moderate level of education, the support of special extension services is required to help them adopt new technologies. In general, educated farmers are very flexible about adopting new technologies (Mignouna et al., 2011; Ahimbisibwe et al, 2020).

2.4.2 Resource endowment and farming practices

Thirty-two percent of the farms sampled belonged to Type 1 and were well endowed. These farms were heavily reliant on farm income mainly from crops and with low levels of off/non-farm activities and income. They relied on hired labour, had high financial capital (savings) and high food security. In contrast, resource-constrained Type 4 farms, which depended on on-farm labour or off-farm employment as casual labourers, had a subsistence level of living. These two types correspond to other typologies for smallholder farmers (Mutoko et al., 2014; Tittonell et al., 2005a; Kuivanen et al., 2016a;

Signorelli, 2016). Type 3 farms differed from the other types because despite being relatively moderately resource endowed, they were heavily reliant on farm income mainly from crops and had average access to external financing, which could explain their limited ownership of productive assets as well as livestock. This farm type was similar to a type found in Ghana by Kuivanen et al. (2016a). Type 2 farms differed from the other types as farmers already own or have access to small farms. They were heavily reliant on income from livestock. The literature suggests that their poverty and level of risk can be reduced by the adoption of recommended technologies (Kuivanen et al., 2016a; Melesse, 2018). However, for Type 4 farm households, diversification into off/non-farm activities would also generate income (Barrett et al., 2001a; Kuivanen et al., 2016a) which could be invested in the purchase of more productive assets, including land and improved livestock to boost productivity. In well resource endowed Type 1 farm households with more labour intensive technologies, interventions could include the primary focus being on farm mechanization. Type 4, that is severely resource-constrained farm households, need to focus attention on improved breeds as their livestock entirely depended on poultry and small ruminants. Keeping small ruminants and poultry is financially economical for resource-constrained farm households because little input (land, labour, cash, etc.) is required for their maintenance (Kuivanen et al., 2016).

2.4.3 Access to information

It was expected that access to information through extension personnel and farmers' field schools (FFS) would positively influence the adoption of new agricultural technologies. This study reveals a robust positive link with extension service, FFS, and the adoption of new technology practices such as conservation agriculture and improved livestock breeds. In this study, Type 2 farms consisted of households owning a greater number of livestock who had excellent links with extension agents and this may result in the greater adoption of improved livestock breeds in comparison with other households who had no links. This is in line with the findings of Ahimbisibwe et al. (2020), who found that access to extension services has a significant association with the adoption of new technologies. This finding also corresponds to previous studies regarding the importance of extension services; Kassie et al. (2015) found that access to extension services has a positive effect on the adoption of sustainable practices as well as new agricultural technologies. Abdulai (2016) found that the adoption of new technologies, such as conservation agriculture, relies on the awareness of farm households and access to comprehensive information about the new technology. In contrast, Tesfaye et al. (2014) demonstrated that extension services did not have any effect on the adoption of innovative practices. Other studies such as Shikku et al. (2017) showed that extension services have a negative effect on the adoption of practices to deal with climate change as well as the introduction of new agricultural technologies, while Maumbe (2010) also found that the acquisition and utilization of information are influenced by the level of literacy of the household head, the cost of implementing new technologies, and links with external support for farmers, such as extension agents as well as a FFS. Interestingly, this study found no link between the level of literacy of the household head and the acquisition and utilization of information regarding new technologies. Based on our findings, Type 3 farm households have a high education level, but these households frequently had little contact with extension workers which resulted in a lower level of adoption of improved breeds (Figure 2.4). However, membership of cooperatives or a similar community structure, such as FFS, can play an important role in acquiring and sharing valuable information regarding new agricultural technologies and sustainable adaptation practices in Bangladesh. Therefore, development projects in these areas need to emphasize increasing the access of farm households to farm cooperatives, farming groups and farmers associations as a way to enhance their ability to adopt new agricultural technologies (Aryalt et al., 2020).

2.4.4 Adoption of new agricultural technologies are linked to farm types

The results indicated that farming practices associated with new agricultural technologies were higher among older and wealthier farm households' heads. Jena et al. (2012) reported the ability of older farmers to earn more because they were more knowledgeable and better established than younger farmers. Our study indicates that the households with a high average level of education may be more inclined to adopt technology, i.e. the retention of residue in the fields. Similar results were also observed in the studies of the adoption of improved maize seed in Tanzania (Nkonya et al., 1997). Abdulai (2016) suggested that the adoption of agricultural technologies was influenced by the education level of household heads. The results indicated that farmers for whom agriculture is the main source of income had significantly influenced the adoption of various farming practices and technology. In contrast, Van Hulst and Posthumus (2016) showed that the percentage of income from the agricultural sector did not significantly influence the adoption of new agricultural technologies. According to the survey data, Type 1 farmers were involved in on-farm activities as their income from the agricultural sector is higher than that of other farm types. The education level of the household head was average which could provide them with more opportunity to be involved in farm work and, consequently, they might be well informed about the various new farming technologies. In contrast, agriculture was a less important activity for Type 4 farm households. Greater reliance on off-farm income, especially for Type 4 farm households could limit the number of resources they can allocate to crop production activities. However, in the future, off-farm income diversification may be viewed as a way to avoid risk and uncertainty and may later influence adoption decisions (Mara et al., 2003). Concerning the cropping-management practices, Type 1 farms comprised households with a large farm and a high proportion of hired labour. In terms of adopting new practices, these households recycle crop residue in the field as a large farm produces more residue which can be incorporated in the fields. According to the previous study by Melesse (2018), land size had a positive influence on the adoption of new agricultural technologies. In contrast, Ogada et al. (2014) reported the opposite effect of land size on the adoption of new agricultural technologies. But this study suggests that for most of the Bangladeshi farmers who have grown different types of crops of various varieties, this requires a larger farm. Fernandez (2017) suggested that the adoption of irrigation management practices is positively influenced by hiring permanent labour, but the present study did not confirm this finding. This study indicated that the practice of new agricultural technologies is positively influenced by land ownership, especially for Type 1 farms. This finding is in line with reports by Nsiah et al. (2006) who stated that tenant farmers are reluctant to adopt sustainable practices. The results suggested that highly and moderately resource endowed farms have their feed resources and are in a better financial position to keep a large number of livestock (Sarker, 2015). A large herd also encourages the use of a large amount of crop residue which is transported from the field to their farmhouse/homestead for stall feeding (Diressie, 2011). Farmers in this category also produced more manure on their farm while a relatively high proportion of the manure was used in the field. This finding is in line with the reports by Diressie (2011) who stated that farmers applied more manure to their fields if they owned more livestock compared to those who had fewer or no cattle.

The study indicated that larger farms (Farm 1) have a higher level of savings compared with small farms. This is because large farms cultivated different types of high-value crops on their farms and make a good profit. The results suggest that economic factors, such as savings, significantly influenced the adoption of agricultural technologies. These findings correspond to Abdulai (2016) who demonstrated that financially constrained farmers are less likely to adopt new agricultural technologies compared with well-resourced farm households. Yigezu et al. (2018) also mentioned that a high initial investment is needed to cope with new agricultural technologies and Teshome et al. (2016) indicated the importance of adequate cash resources. Moreover, in terms of food security, larger farms (Farm 1) have greater food security compared with small farms because they produced a greater amount of food. This finding is in line with Signorelli (2016) who found that wealthy farm households had high rates of food security, while the opposite was true for the poorly endowed farm households.

The results suggest that the distance of farm households from the market had a negative influence on the adoption of new technologies. These findings correspond to a previous study by Tefera et al. (2016) which demonstrated that the adoption of maize and teff technology increase with proximity to markets. It was expected that the distance from markets would be very important for the farmers to get the optimum market price by reducing transportation costs. Type 2 farms had relatively high livestock numbers and are close to the market - this might allow them to get higher prices for livestock products, especially milk. Extension messages and decision-makers should focus more on these groups, especially in the adoption of improved livestock breeds. The study indicates that the distance of residence from all-weather roads did not significantly influence the adoption of new technologies. In contrast, Melesse (2018) mentioned that the distance of a residence from all-weather roads had a negative relationship to the adoption of fertilizer. It was expected that access to information through extension agents would play an important role in the adoption of new agricultural technologies. The present findings are also in line with other studies conducted by Akudugu et al. (2012) and Tefera et al. (2016) which investigated the effect of extension agents on the promotion of new agricultural interventions. On the other hand, Tesfaye et al. (2014)

investigated the effect of extension services on the implementation of agronomic practices, soil conservation measures, and pest and weed control in Ethiopia. Their research suggests that no significant relationship was found between access to extension services and the adoption of new technologies. Type 2 farms had excellent links with extension agents and this may result in a greater willingness to adopt new technology, i.e. improved livestock breeds, and compared with other households which had no links. Given the importance to farmers of links with external support (e.g. from extension officers), young farmers, even those not involved in full-time farming, could benefit from becoming involved in innovative farming.

2.4.5 Limitations of the study

This research was subject to some limitations due to time and financial constraints. Recall-based farm data provided by the farm households were used to develop farm typology in the study area. Because of the memory bias of respondents, some of these values may be inaccurate. The findings of the research cannot be generalized for the whole country due to the small sample size as a result of time and funding constraints Furthermore, it was expected that farm households would be dynamic; production systems could rapidly change as well as farm typologies, which would need to be constantly updated (Alvarez et al., 2014). However, this study can help inform policymakers, researchers, and development practitioners, as it provides insights into how systems may evolve over-time.

2.5 Conclusion and policy implications

Agricultural research and development projects provide a particular set of new technologies such as the use of recycled crop residue and improving crop and livestock systems by introducing new varieties and breeds in the farming community. The key objective of such projects is the differentiation of the projects' target population based on farm types which are often used for targeting the introduction of innovations. Constructing farm typologies can be especially helpful in describing the existing heterogeneity within a target farming community.

A multivariate statistical technique that combines PCA and CA enabled the identification of four typical farm types in the selected area with respect to adopting new agricultural interventions using socio-economic factors. Concerning the first research objective, a farm typology was found with significant differences among the four farm types. With reference to the second research objective, the key factors in the adoption of new agricultural technologies by farmers are their age, farming experience, education, income, access to market, land ownership, savings, food self-sufficiency, access to extension services and the proportion of hired labour and income from off-farm activities.

The wealthier and less literate farm households in Type 1 could be encouraged to increase their use of improved technologies, inputs and farming practices that are environmentally friendly, such as recycling crop reside and the use of organic manure, animal rearing with improved breeds and the reduction of post-harvest losses by improving storage facilities. Livestock-based Type 2 farms could benefit from interventions to increase knowledge about improved technologies, such as providing pure breeds and increasing AI facilities, through training and access to extension services. In addition, they could also benefit from efforts to improve access to capital, particularly land, low-input technologies, and high yielding crop varieties. Type 3 households have an average level of literacy; they could also benefit from more knowledge-intensive technologies. Type 4 farms could benefit from efforts aimed at income diversification in non- and off-farm activities by increasing credit access and improving the level of education.

Finally, it can be concluded that a multivariate statistical technique that combines PCA and CA are suitable tools for identifying major socio-economic characteristics of typical farms. This research has also highlighted the heterogeneity of farm household concerning the present use of new agricultural technologies and identified the factors that determine their future use. As some types of farm household have a better ability to cope with new technologies than others, extension messages and decision-makers should focus greater attention on specific groups, such as these four farm types. These findings also suggest that there is an urgent need for researchers, policymakers, and disseminators to give serious consideration to these key socio-economic factors when deciding on ways to increase the rate of adoption of agricultural technologies by farmers. Future research should, therefore, be aimed at the development of support tools to assist farmers in making decisions appropriate for their farms based on these typical farms.

References:

Abdulai, A. N. (2016). Impact of conservation agriculture technology on household welfare in Zambia. Agricultural Economics, 47: 729–741.

Ahimbisibwe, B.P., Morton, J.F., and Feleke, S. (2020). Household welfare impacts of an agricultural innovation platform in Uganda. Food and Energy Security, 9(3), e225. doi.org/10.1002/ fes3.225

Ahmed, S. (2013). Food and Agriculture in Bangladesh. Encyclopedia of Food and Agricultural Ethics, 1-8.

Akudugu, M., Guo, E., and Dadzie, S. (2012). Adoption of modern agricultural production technologies by farm households in Ghana: What factors influence their decisions? Journal of Biology, Agriculture and Healthcare, 2:1-13.

Alam, M., and Swapan, K. S. (2011). Homestead Agroforestry in Bangladesh: Dynamics of Stand Structure and Biodiversity. Journal of Sustainable Forestry, 30: 584-599. doi.org/10.1080/10549811.2011.571606

Alvarez, S., Paas, W., Descheemaeker, K., Tittonell, P., and Groot, J. (2014). Typology Construction, a Way of Dealing with Farm Diversity: General Guidelines for Humidtropics. CGIAR Research Program led by IITA. Wageningen, The Netherlands.

Alvarez, S., Timler, C. J., Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., and Groot, J. C. J. (2018). Capturing farm diversity with hypothesis-based typologies: An innovative methodological framework for farming system typology development. PLoS ONE, 13(5).

Aryal, J.P., Sapkota, T.B., Rahut, D.B., Krupik, T.J., Shahrin, S., Jat, M.L., and Stirling, C.M. (2020). Major Climate risks and adaptation Strategies of Smallholder Farmers in Coastal Bangladesh. Environmental Management, 66: 105–120.

Asfaw, A., and Admassie, A. (2004). The role of education on the adoption of chemical fertiliser under different socioeconomic environments in Ethiopia. Agricultural Economic, 30(3): 215–228.

Bangladesh Bureau of Statistics (2017). Statistical Year Book of Bangladesh, Statistics Division, Ministry of Planning, Government of the People’s Republic of Bangladesh, Dhaka.

Bangladesh Economic Review (2017). Finance Division, Ministry of Finance, Government of the People's Republic of Bangladesh. Dhaka, Bangladesh.

Barma, N.C.D., Hossain, A., Hakim, M.A., Mottaleb, K.A., Alam, M.A., Reza, M.M.A., and Rohman, M.M. (2019). Progress and Challenges of Wheat Production in the Era of Climate Change: A Bangladesh Perspective. Springer, Singapore, 615-679.

Barrett, C.B., Reardon, T., and Webb, P. (2001a). Nonfarm income diversification and household livelihood strategies in rural Africa: concepts, dynamics, and policy implications. Food Policy, 26: 315–331.

Bidogeza, J. C., Berentsen, P. B. M., De Graaff, J., and Oude, L. A.G. J. M. (2009). A typology of farm households for the Umatara province in Rwanda. Food Security, 1(3): 321-335.

Chang, H.J. (2012). Rethinking public policy in agriculture – lessons from history, distant and recent. Public Policy and Agricultural Development, 15–80.

Chowdhury, A. A. (1978). Bangladesh Village: A Study of Social 27 Stratifications Centre for Social Studies, Dhaka University.

Daloglu, I., Nassauer, J., Riolo, R., and Scavia, D. (2014). Development of a farmer typology of agricultural conservation behavior in the American Corn Belt. Agricultural Systems, 93-102.

Daskalopoulou, I., and Petrou, A. (2002). Utilizing a farm typology to identify potential adopters of alternative farming activities in Greek agriculture. Journal of Rural Studies, 95-103. doi.org/10.1016/S0743-0167 (01)00027-4.

Dhraief, M.Z., Bedhiaf, R. S., Dhehibib, B., Oueslati, Z.M., Jebali, O., and Ben, Y. S. (2018). Factors Affecting the Adoption of Innovative Technologies by Livestock Farmers in Arid Area of Tunisia. FARA Research Report, 3 (5): 22.

Diressie, H. T. (2011). Crop residue management and farm productivity in smallholder crop-livestock system of dry land North Wollo, Ethiopia. MSc Thesis, Wageningen University, the Netherlands.

Duvernoy, I. (2000). Use of a land cover model to identify farm types in the Misiones agrarian frontier (Argentina). Agricultural Systems, 64:137–149.

Farid, K., Tanny, N., and Sarma, P. (2016). Factors affecting adoption of improved farm practices by the farmers of Northern Bangladesh. J. Bangladesh Agric. Univ, 13(2): 291–298. doi.org/10.3329/jbau. 13i2.28801

Faruque, A.S., Huang, Z., and Karimanzira, T.T.P. (2018). Investigating Key Factors Influencing Farming Decisions Based on Soil Testing and Fertilizer Recommendation Facilities (STFRF)—A Case Study on Rural Bangladesh. Sustainability, 10, 4331.

Fernandez, M. A. (2017). Adoption of erosion management practices in New Zealand. Land Use Policy, 63, 236–245. doi:10. 1016/j.landusepol.2017.01.040

Field, A. (2005). Discovering Statistics Using SPSS. 2nd edn. Sage, London, UK.

Goswami, R., Chatterjee, S., and Prasad, B. (2014). Farm types and their economic characterization in complex agro-ecosystems for informed extension intervention: study from coastal West Bengal, India. Agricultural and Food Economics, 2-5.

Hair, J. F., Black, C. W., Babin, J. B., Anderson, E. R., and Tatham, L. R. (2006). Multivariate Data Analysis, Pearson Prentice Hall, Upper Saddle River, page 928.

Hair, J. F., Black, W.C., Babin, B.J., and Anderson, R.E. (2010). Multivariate Data Analysis: A Global Perspective, Seventh Edition, Pearson.

Hossain, A., and Teixeira da Silva, J.A. (2013). Wheat production in Bangladesh: it's future in the light of global warming. AoB Plants, 5 pls042.

Hossain, M. Z. (2001). Rural-Urban Migration in Bangladesh: A Micro-Level Study. For presentation in a Poster Session on Internal Migration at the Brazil IUSSP. Conference during August 20-24.

Islam, M.A., Warwick, N., Koech, M.N., and Bruyn, L.L.D. (2020). The importance of farmer’s perceptions of salinity and adaption strategies for ensuring food security: Evidence from the coastal rice-growing areas of Bangladesh. Science of the Total Environment, 727 (138674).

Jabbar, M. A. (2011). Policy constraints for implementation of the proposed programs for investment in agriculture, food security and nutrition in Bangladesh. The International Food Policy Research Institute, Washington D C, USA.

Jena, P.R., Stellmacher, T., and Grote, U. (2012). The impact of coffee certification on small-scale producers' livelihoods: evidence from Ethiopia. In: Presentation at the

International Association of Agricultural Economists (IAAE) Triennial Conference, Foz Do Iguaçu, Brazil, 18–24.

Kamau, J. W., Till, S., Lisa, B.F., and Christian, B. (2018). Organic and conventional agriculture in Kenya: A typology of smallholder farms in Kajiado and Murang'a counties. Journal of Rural Studies, 57: 171-185.

Karim, M.A., Qauyyum, M.A., Samsuzzaman, S., Higuchi, H., and Nawata, E. (2017). Challenges and Opportunities in Crop Production in Different Types of Char Lands of Bangladesh. Tropical Agriculture and Development, 61(2): 77-93.

Kassie, M., Teklewold, H., Jaleta, M., Marenya, P., and Erenstein, O. (2015). Understanding the adoption of a portfolio of sustainable intensification practices in eastern and Southern Africa. Land Use Policy, 42: 400–411.

Kobrich, C., Rehman, T., and Khan, M. (2003). Typification of farming systems for constructing representative farm models: Two illustrations of the application of multi-variate analyses in Chile and Pakistan. Agricultural Systems, 76 (1): 141–157.

Kuhn, B.A. and Offutt, S.E. (1999). Farm policy in an era of farm diversity. Choices, 14: 37-38.

Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., and Groot, J.C.J. (2016a). Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: a case study from the Northern Region, Ghana. NJAS - Wagening J. Life Sci, 78,153–166.

Kuivanen, K.S., Michalscheck, M., Descheemaeker, K., Adjei-Nsiah, S., Mellon-Bedi, S., Groot, J.C.J., and Alvarez, S. A. (2016b). A comparison of statistical and participatory clustering of smallholder farming systems – a case study in Northern Ghana. Journal of Rural Studies, 45: 184–198.

Kuswardhani, N., Soni, P., and Shivakoti, G. P. (2014). Cluster analysis for classification of farm households based on socio-economic characteristics for technology adoption in agriculture: A case study of West Java province, Indonesia. Journal of Food, Agriculture and Environment, 12 (1): 238-247.

Lattin, J., Carroll, D., and Green, P. (2005). Analyzing Multivariate Data, 2nd edn. Duxbury, page 525.

Lopez-Ridaura, P.S., Frelat, R., Van Wijk, M.T., Valbuena, D., Krupnik, T.J., and Jat, M.L. (2018). Climate smart agriculture, farm household typologies and food security: an ex ante assessment –eastern India. Agricultural Systems, 159: 57–68.

Mafimisebi, T.E. (2006). Analysis of farmer–specific socio-economic determinants of adoption of modern livestock management technologies by farmers in Southwest Nigeria. Journal of Food, Agriculture & Environment, 4 (1): 183-186.

Mahapatra, AK., and Mitchell, CP. (2001). Classifying tree planters and non-planters in a subsistence farming system using a discriminant analytical approach. Agroforestry Systems, 52(1): 41–52.

Mainuddin, M., Maniruzzaman, M., Alam, M.M., Mojid, M.A., Schmidt, E.J., Islam, M.T., and Scobie, M. (2020). Water usage and productivity of Boro rice at the field level and their impacts on the sustainable groundwater irrigation in North-West Bangladesh. Agricultural Water Management, 240 (106294).

Marra, M., Pannell, DJ., and Ghandim, A. (2003). The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: where are we on the learning curve? Agricultural Systems, 75(2–3): 215–234.

Maumbe, B.M. (2010). International Journal of ICT Research and Development in Africa: an Official Publication of the Information Resources Management Association. v. 1, no. 1, January-March.

Melesse, B. (2018). A Review on Factors Affecting Adoption of Agricultural New Technologies in Ethiopia. Journal of Agricultural Science and Food Research, 9: 208-216.

Mignouna, B., Manyong, M., Rusike, J., Mutabazi, S., and Senkondo, M. (2011). Determinants of Adopting Imazapyr-Resistant Maize Technology and its Impact on Household Income in Western Kenya. AgBioforum, 14 (3): 158-163.

Milan, MJ., Bartolome, J.,Quintanilla, R.,Garcia, MD., Espejo, M., Herraiz, PL., Sanchez, JM., and Piedrafita, J. (2006). Structural characterisation and typology of beef cattle farms of Spanish wooded rangelands (dehesas). Livest Sci, 99 (2–3): 197–209.

Mondal, M.H. (2010). Crop Agriculture of Bangladesh: Challenges and Opportunities. Bangladesh Journal of Agricultural Research, 35: 235–245.

Mutoko, M.C., Hein, L., and Shisanya, C.A. (2014). Farm diversity, resource use efficiency and sustainable land management in the western highlands of Kenya. Journal of Rural Studies. 36: 108–120. doi.org/10.1016/j.jrurstud.2014.07.006

Mwangi, M., and Kariuki, S. (2015). Factors Determining Adoption of New Agricultural Technology by smallholder Farmers in Developing Countries. Journal of Economics and Sustainable Development, 6(5): 208-216.

Mwongera, C., Shikuku, K.M., Twyman, J., Läderach, P., Ampaire, E., Van Asten, P., Twomlow, S., and Winowiecki, L.A. (2017). Climate smart agriculture rapid appraisal (CSA-RA): a tool for prioritizing context-specific climate smart agriculture technologies. Agricultural Systems, 151: 192–203.

National Agriculture Policy (1999). Ministry of Agriculture, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh.

Nkonya, E., Schroeder, T., and Norman, D. (1997). Factors affecting adoption of improved maize seed and fertiliser in Northern Tanzania. Journal of Agricultural Economics, 48 (1): 1-12.

Nsiah, S A., Saïdou, A., Kossou, D., Dawson, O.S., and T. W. Kuyper, T.W. (2006). "Tenure security and soil fertility management: case studies in Ghana and Benin. Colloque international "Les frontières de la question foncière – At the frontier of land issues",Montpellier.

Obayelu, A., Ajayi, O., Oluwalana, E., and Ogunmola, O. (2017). What Does Literature Say about the Determinants of Adoption of Agricultural Technologies by Smallholders Farmers? Agricultural Research & Technology 6 (1), 555675.

Ogada, MJ., Mwabu, G., and Muchai, D. (2014). Farm technology adoption in Kenya: a simultaneous estimation of inorganic fertilizer and improved maize variety adoption decisions. Agricultural and Food Economics, 2-12.

Paul, S., Hossain, M.D., Kumar, R., and Shudarshan. (2013). Monga' in northern region of Bangladesh: a study on people's survival strategies and coping capacities. Rajshahi University Journal of Life & Earth and Agricultural Sciences, 41-56. 10.3329/rujleas. v41i0.21620

Pilarova, Tereza., Bavorova, Miroslava., and Kandakov, Ing. (2018). Do farmer, household and farm characteristics influence the adoption of sustainable practices? The evidence from the Republic of Moldova. International Journal of Agricultural Sustainability, 1-18. doi.org/10.1080/14735903.2018.1499244

Priegnitz, U., Lommen, W. J. M., Onakuse, S., and Struik, P. C. (2019). A Farm Typology for Adoption of Innovations in Potato Production in Southwestern Uganda. Frontiers in Sustainable Food Systems, https://doi.org/10.3389/fsufs.2019.00068

R Core Team (2019). A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0.

Radwan, S. (1995). Challenges and scope for an employment-intensive growth strategy, in: employment for poverty reduction and food security. International Food Policy Research Institute, 21–45.

Rahman, K.M.A., and Zhang, D. (2018). Effects of Fertilizer Broadcasting on the Excessive Use of Inorganic Fertilizers and Environmental Sustainability. Sustainability, 10,759.

Rahman, M.W., and Das, M. (2019). Unfolding Household Typology towards Better Extension Advisory Services in Typical Southern Villages of Bangladesh. Bangladesh Journal of Extension Education, 31 (1&2): 51-67.

Reynolds, A.P., Richards, G., Iglesia, B., and Smith, V.J. (2006). Clustering rules: a comparison of partitioning and hierarchical clustering algorithms. J. Math. Modell. Algorithms, 475–504.

Roy, D., Dev, DS., and Sheheli, S. (2019). Food Security in Bangladesh: Insight from Available Literature. Journal of Nutrition and Food Security. 4 (1): 66-75.

Ruben, R., and Pender, J. (2004). Rural diversity and heterogeneity in less-favoured areas: the quest for policy targeting. Food Policy, 29: 303–320.

Sakané, N., Becker, M., Langensiepen, M., and van Wijk, M.T. (2013). Typology of smallholder production systems in small East-African wetlands. Wetlands 33:101.

Sarker, M. M. R. (2015). Trade-off analysis of crop residues use in smallholder mixed crop –livestock systems to support more effective use of conservation agriculture (CA) in ‘South Western’ Bangladesh. MSc Thesis, Wageningen University, the Netherlands.

Shikuku, K. M., Winowiecki, L., Twyman, J., Eitzinger, A., Perez, J.G., Mwongera, C., and Läderach, P. (2017). Smallholder farmers 'attitudes and determinants of adaptation to climate risks in East Africa. Climate Risk Management, 16: 234–245.

Signorelli, S. (2016). Typology characterization of farmers in West Africa. Presented at the Africa RISING West Africa Review and Planning Meeting, Accra, Washington, D.C.: IFPRI.

Somda, J., Kamuanga, M., and Tollens, E.F. (2004). Characteristics and economic viability of milk production in the smallholder farming systems in The Gambia. Agricultural Systems, 85(1): 42–58.

Tefera, T., Tesfay, G., Elias, E., Diro, M., and Koomen, I. (2016). Drivers for adoption of agricultural technologies and practices in Ethiopia—A study report from 30 woredas in four regions. Addis Ababa/Wageningen: CASCAPE project.

Tesfaye, A., Negatu, W., Brouwer, R., and Van der Zaag, P. (2014). Understanding soil conservation decision of farmers in the gedeb watershed, Ethiopia. Land Degradation & Development, 25(1): 71–79. doi.org/10.1002/ldr.2187

Teshome, A., de Graaff, J., and Kassie, M. (2016). Household-level determinants of soil and water conservation adoption phases: Evidence from north-western Ethiopian highlands. Environmental Management, 57: 620–636. doi:10.1007/ s00267-015-0635-5

The Daily Star (2016). Balanced Fertilizer Usage. The Daily Star, 25 September; https://www.thedailystar.net/round-tables/balanced-fertiliser-usage-1289308.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., and Vanlauwe, B. (2010). The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – a typology of smallholder farms. Agricultural Systems, 103: 83–97.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., and Giller, K.E. (2005a). Exploring diversity in soil fertility management of smallholder farms in western Kenya: Heterogeneity at region and farm scale. Agriculture, Ecosystems and Environment, 110: 149–165. doi.org/10.1016/j.agee.2005.04.001

Tittonell, P.A, Vanlauwe, B., de Ridder, N., and Giller, K.E. (2007). Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agricultural Systems, 94(2): 376–390.

Van de Steeg, J.A., Verburg, P.H., Baltenweck, I., and Staal, S.J. (2010). Characterization of the spatial distribution of farming systems in the Kenyan Highlands. Applied Geography, 30: 239–253. doi.org/10.1016/j.apgeog.2009.05.005

Yigezu, Y. A., Mugera, A., El-Shater, T., Aw-Hassan, A., Piggin, C., Haddad, A., Khalil, Y., and Loss, S. (2018). Enhancing adoption of agricultural technologies requiring high initial investment among smallholders. Technological Forecasting and Social Change, 134 (C): 199-206.

Zaman, A.K.M., Alam, K.T., and Islam, J. (2010). Urbanization in Bangladesh: Present Status and Policy Implications, ASA University Review, 4 (2): 1-16.

Zingore, S., Murwira, H.K., Delve, R.J., and Giller, K.E. (2007). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agriculture, ecosystems & environment, 119: 112–126.

Chapter 3

Conservation tillage and residue management improve soil health and crop productivity – evidence from a rice-maize cropping system in Bangladesh

Mamunur Rashid Sarker [1,2], Marcelo Valadares Galdos [1,3], Andrew J. Challinor [1], Muhammad Shamsul Huda [2], Apurbo K. Chaki [2] and Akbar Hossain [4]

[1]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK;

[2]Bangladesh Agricultural Research Institute, Joydebpur, Gazipur, Bangladesh

[3] Rothamsted Research, Sustainable Soils and Crops, Harpenden AL5 2JQ, UK

[4] Division of Agronomy, Bangladesh Wheat and Maize Research Institute, Dinajpur-5200, Bangladesh

Abstract

The rice-maize (RM) system is rapidly expanding in Bangladesh due to its greater suitability for diverse soil types and environments. The present conventional method of cultivating puddled transplanted rice and maize is input-intensive, decreases soil health through intense ploughing, and ultimately reduces farm profitability. There is a need to investigate alternatives. Accordingly, we conducted a replicated two-year (2020–2021) field study to investigate the effects of conservation agriculture (CA) based tillage and crop establishment (TCE) techniques and residue management practices on the physical, chemical, and biological properties of soil along with crop productivity and the profitability of rice-maize systems in the sandy loam soil of Northwest Bangladesh. Two TCE techniques puddled transplanted rice (PTR) followed by conventionally tilled maize (CTM) and strip tillage direct-seeded rice (STDSR) followed by strip-tilled maize (STM) were assigned to the main plots and different percentages of crop residue retention (0, 25, and 50% by height) were allocated to the subplots. Results showed that a reduction in bulk density (BD), soil penetration resistance (SPR), and increased soil porosity were associated with STDSR/STM-based scenarios (strip tillage coupled with 25 and 50% residue retention). The soil organic carbon (SOC) fractions, such as dissolved organic C (DOC), light and heavy particulate organic matter C (POM-C),

MAOM, and microbial biomass C (MBC) levels in the 0–10 cm layer under ST based treatments were 95, 8, 6, 2 and 45% greater, respectively, compared to CT with no residue treatment. When compared to the CT treatment, the DOC, light POM-C, heavy POM-C, and MAOM in the 10–20 cm layer with ST treatment were 8, 34, 25, 4 and 37% higher, respectively. Residue retention in ST increased average rice, maize, and system yields by 9.2, 14.0, and 14.12%, respectively, when compared to CT. The system gross margin and benefit-cost ratio (BCR) were \$1515 ha^{-1} and 1.90 under conventional tillage to \$1696 ha^{-1} and 2.15 under strip-tillage practices. Thus, our study suggests that CA could be an appropriate practice for sustaining soil fertility and crop yield under RM systems in light-textured soils or other similar soils in Bangladesh.

3.1 Introduction

The main rice-based cropping system in Bangladesh, termed rice-rice (R-R) is practiced through a monsoon (*T. aman*) crop in the rainy *Kharif* season, followed by a winter (*Boro*) crop during the winter season when irrigation water is available. The area covers about 2.3 M ha of land in 2014-2015 (Nasim et al., 2017). When water is scarce, maize, wheat, potato, vegetables, or other crops are grown instead of *Boro* to increase profits. Among the cropping systems practiced, rice-wheat (R-W) system are predominant in tropical to subtropical climate areas of the Indo-Gangetic plains (IGP) of Bangladesh, Nepal, India, and Pakistan because they serve a significant role in achieving food security and income for rural and urban populations (Chaki et al., 2021). During the 2000s, the maize area increased considerably, changing from 0.31 M ha in 2012 to 0.4 M ha in 2020 (BBS, 2022). This change is mainly because of the rising demand for maize grain for poultry and fisheries and also for the human diet (Ali et al., 2008; Timsina et al., 2010). This rice-maize (RM) system occupies approximately 1.31 M ha in Bangladesh, India, and Nepal, explaining their importance in the region (Gathala et al., 2015).

In the North-Western part of Bangladesh, farmers experience a delay in maize planting when excessive soil moisture has caused a delay in harvesting the previous rice crop. This happens frequently and any kind of tillage operation is inadvisable until the soil moisture has reduced sufficiently to allow traffic without compaction or slippage. Usually, farmers use conventional tillage, which involves up to 3-5 passes of slow-speed rotary tillage with a two-wheeled, tractor (2WT) driven power tiller. This is the reason why farmers need an additional 2-3 weeks after the rice harvest to carry out tillage operations before planting maize, which significantly delays planting. (Gathala et al., 2015). Therefore, the maize crop is affected by heat stress during the reproductive stage if sown late (Timsina et al., 2010), which may cause a 12-22% yield loss (Ali et al., 2006). The literature suggests that to minimize the yield gap and achieve the potential yield, maize crops should be planted as soon as possible after the rice harvest (Timsina et al., 2010).

In Bangladesh, a significant amount of soil organic carbon (SOC) has been lost over the last decade (BBS, 2017; Uddin et al., 2019. This is due to a decrease in inherent soil fertility, and poor soil and irrigation management, along with the adoption of inappropriate intensive farming practices such as intensive tillage by a two-wheel tractor driven power tiller for land preparation (Krupnik et al., 2013), use cow dung as a fuel , residue removal and burning practices, which accelerate the physical disruption of soil aggregate and decrease soil organic carbon (SOC), (Lenka et al., 2015; Gupta Choudhury et al., 2014) and microbial activities (Curaqueo et al., 2011).

In the context of delayed planting, heat stress and soil health deterioration, the application of climate-smart agriculture (CSA), for example, conservation agriculture (CA) techniques, which involve minimum disturbance of soil, residue retention/cover crops (Blair et al., 2006), and crop rotation (Parihar et al., 2016), may be especially relevant. With no-till practices or minimum tillage in CA systems, there is little need to prepare the land for planting (FAO, 2001). This could allow early sowing, avoid heat stress, and keep soil moisture (Kucharik, 2006; Marongwe et al., 2012). According to previous research, no-till with crop residue retention has a significant impact on soil erosion control, enhanced soil structure by maintaining soil aggregates (Galdos et al., 2009), minimum oxidation of soil organic matter, reduced runoff and increasing crop productivity (Chaki et al., 2021a; Roose and Barthes, 2001; Erenstein, 2002). The agronomic productivity is increased when 25–50% (1.3–2.5 Mg ha^{-1}) of the entire crop residues are incorporated with a chisel plough (Bahrani et al., 2007). Another finding from Kumawat et al. (2022) who conducted a field experiment with varying amounts of residue retention under CA based maize-chickpea cropping system. They found that the lowest bulk density, higher soil moisture content and soil available nitrogen, phosphorus and organic carbon were recorded in 60 and 90% of crop residue plots compared to no residue retained plots. Vasconcelos et al. (2018) suggested that 6 Mg ha^{-1} of crop residue would be a good way to prevent soil C loss and keep the soil covered. Furthermore, several studies have suggested that retaining a moderate quantity (50%) of crop residues can increase crop productivity. Under irrigated conditions, a short-term evaluation of applying crop residue at different rates (ranging from 25% to 100%) and with varied tillage techniques showed that applying residues at R100, followed by R75 and R50, significantly enhanced soil organic carbon and wheat grain production (Mirzaei et al., 2021. The benefits of reduced tillage practices can be more productive if optimally combined with crop residue management and mixed-cropping systems (crop rotation diversification). In this context, future research is needed to investigate the effect of crop residue management and different cropping systems on changes in soil parameters, and crop productivity (Asargew et al., 2022).

Crop residue returning, both aboveground or belowground biomass, to the field after harvesting a crop is a globally accepted good practice for improving soil health parameters. To maintain soil quality and ensure sustainability, residue returning must be implemented scientifically. This is because tillage practices, how residue is returned to the soil, and how long it takes, and weather conditions, can have an effect on achieving the maximum benefit from residue retention (Naresh et al., 2021). Examples include Chalise et al. (2019) who reported that mulch retention had a positive impact on soybean yield. Another study was conducted by Krupnik et al. (2014a) at two locations in Bangladesh and found inconsistent results; at one location, there was no difference in the tillage system in either year, whereas, in another location, conventional tillage gave a higher yield in the first year but strip-tillage gave higher yields in the second year. So future research is needed to understand the performance of various tillage techniques, such as conventional tillage and no tillage under equal residue retention, in a range of crop, soil, and climatic conditions (Singh et al., 2020). Clearly, given the lack of understanding of these issues, investigation of appropriate tillage with crop establishment methods and straw return in RM systems is therefore critical for rice and maize production, ensuring food security, and fulfilling the feed demand from livestock, poultry, and fish industries in Bangladesh.

Many studies have been conducted separately on rice and maize production systems such as R-R, and R-W systems in Asia, and tillage and nutrient management

(Timsina and Connor, 2001), although studies on the RM systems in South Asia, especially in Bangladesh are still limited (Timsina et al., 2018). To cover this information gap, it is important to investigate the long-term sustainability of RM system production in Bangladesh using various tillage alternatives. It is hypothesized that Conservation Agriculture (CA) techniques which considered zero, strip, and reduced tillage, crop residue retention, and diversified maize-based crop rotations, improve soil health parameters such as physical, chemical, and biological, compared to conventional tillage and the existing dominant R-R, R-W cropping system of the region. Hence, in response to this knowledge gap and to test the hypothesis, the objectives of the present study were to investigate the short-term effects of different tillage practices with residue return on the physical and chemical properties, and biological activity under a rice-maize rotation in sandy loam soil in Bangladesh.

3.2 Materials and Methods

3.2.1 Site and soil characteristics

The field experiment was conducted at the Agricultural Research Station (ARS), Bangladesh Agricultural Research Institute, Rajbari, Dinajpur during the 2019-20 and 2020-21 seasons of Aman rice (rainy season) and maize in the North-Western part of Bangladesh (Figure 3.1). The experimental site is located in the Old Himalayan piedmont plain (AEZ 1) (BARC, 2015; FAO/UNDP 1988). The soil of the experimental site is a well-drained sandy loam with pH 6.7, and the initial physical, chemical, and biological properties of the soil are given in Table 3.1.

Table 3.1 The initial average status of soil properties at the experimental site

A. Soil physical properties

Depth (cm)	Bulk density (Mgm^{-3})	Particle density (Mgm^{-3})	Moisture content (%)	Field capacity % (0.3 bar)	Soil Penetration resistance (SPR) (kPa)	Soil particle (%) Sand	Silt	Clay	Soil texture
0-10	1.42	2.51	20.70	27.4	870	60	22	18	Sandy loam
10-20	1.47	2.42	19.67	23.1	1080	72	16	12	Sandy loam
20-30	1.59	2.47	16.11	22.4	1380	70	16	14	Sandy loam
30-40	1.64	2.56	20.37	24.5	1680	66	20	14	Sandy loam
40-50	1.60	2.49	21.27	29.9	1170	62	24	14	Sandy loam
50-60	1.53	2.58	30.87	29.2	480	64	18	18	Sandy loam
60-70	1.54	2.48	26.50	36.7	440	72	17	11	Loamy sand

B. Soil chemical properties

Depth (cm)	pH	OM (%)	Total N (%)	Available** P ($mg\ kg^{-1}$)	K (meq/100g)	S ($mg\ kg^{-1}$)	Zn ($mg\ kg^{-1}$)	Mn ($mg\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	B ($mgkg^{-1}$)
0-10	6.15	0.96	0.08	18	0.16	20.7	0.89	10.1	53.2	0.41
10-20	6.20	0.83	0.05	17	0.18	20.8	0.86	9.5	47.8	0.38
20-30	6.25	0.75	0.04	12	0.11	19.6	0.74	9.6	45.2	0.32
30-40	6.35	0.65	0.04	10	0.10	20.9	0.72	5.2	29.1	0.32
40-50	6.38	0.54	0.03	10	0.09	21.04	0.54	5.1	26.9	0.24
50-60	6.45	0.48	0.02	9	0.07	24.1	0.52	2.4	20.6	0.23

** See method 3.2.8

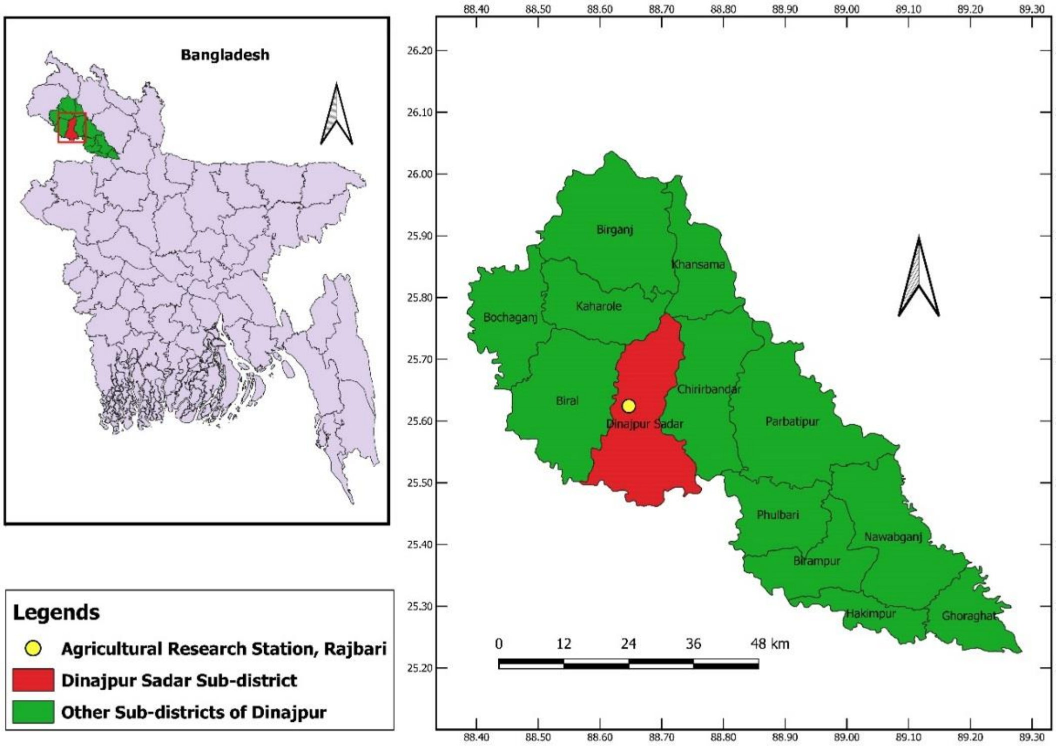

Figure 3.1: The whole green highlighted areas represent the experimental district and the red areas represent the Dinajpur Sadar Sub-district on the map of Bangladesh. The yellow point is the location of the experimental site.

3.2.2 Climatic characteristics

Figure 3.2 highlights that during the experimental period the monthly maximum temperatures varied from 22 to 34°C and the minimum temperature from 10 to 27°C at the study site. The average three years (2019- 21) annual rainfall was 2467 mm and overall, 80% of this fell during the May to October period.

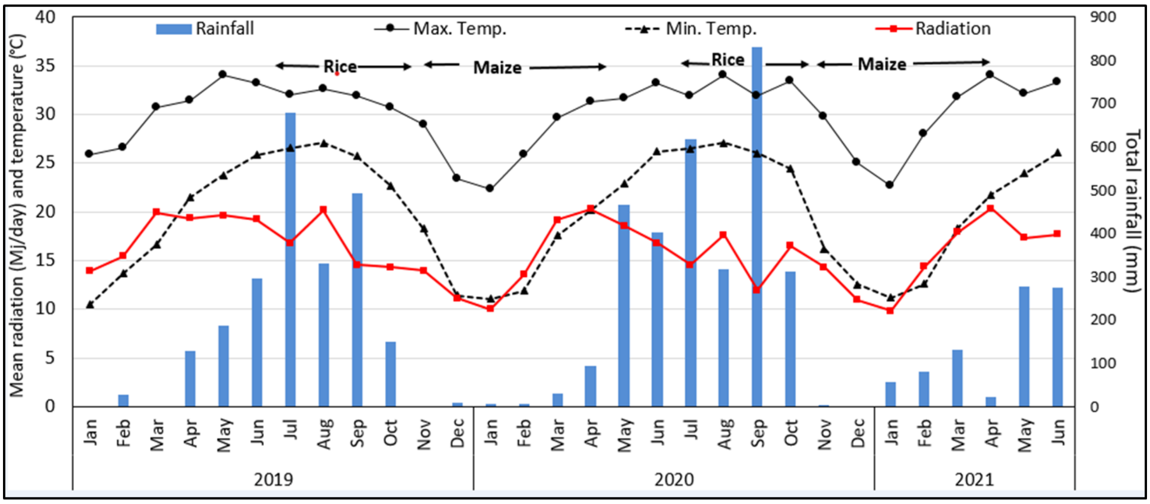

Figure 3.2: Observed rainfall, solar radiation, and maximum and minimum temperatures in the study area.

3.2.2.1 Rice season

The total rainfall during the rice season (June-November) was 1950 mm in 2019 whereas 2486 mm in 2020. Total monthly rainfall during June was 297 in 2019 whereas it was 403 mm in 2020 and the total rainfall in July ranged from 618 mm in 2019 to about 680 mm in 2020. June and July rainfall are very important for sowing direct-seeded rice (DSR), whereas rainfall during July is crucial for transplanted rice. The average maximum temperatures from June to November were 29 to 34°C while the minimum temperatures were 16 to 27°C.

3.2.2.2 Maize season

The weather pattern fluctuated across the two years. The total amount of rainfall in the winter maize growing season (November-May) was higher in 2020-2021 (743.7 mm) than in 2019-2020 (601.3 mm). Maize is grown during the cool (11-22°C) winter period (Mid-November to the first week of May) and at that time rainfall is very limited. The monthly mean daily maximum temperatures from November to May were 223 to 340°C while the minimum temperatures were 11.10 to 20.14 °C, respectively.

3.2.3 Experimental details

The experiment was laid out in a 2-factor split-plot design with three replications. The main plot size was 14.6× 8.4 m^2 and separated by a 1.2 m wide buffer, whereas the subplot was 4.2× 8.4 m^2 with a 0.75 m buffer. Main plot treatments were puddled transplanted rice (PTR) followed by conventional tillage maize (CTM) and strip tillage direct-seeded rice (STDSR) followed by strip-tilled maize (STM) and the sub-plot treatments were three rice residue management options (0, 25 and 50%) either retained on the soil surface in strip tillage plots or incorporated into the soil in conventional tillage plots. The maize stalks were cut and chopped into 5-10 cm lengths and spread uniformly over the whole plot across the treatments. The treatments in the current study have been discussed details in Table 3.2.

Table 3.2 Description of experimental treatments.

Treatments	**Treatments details**	**Descriptions of ST and CT**
T_1 (PTR/CTM + 0% residue)	Puddled Transplanted Rice – Conventional till Maize	**Strip tillage (ST):** Multi-crop planter (model, BMWRI-ZT Manufactured by BMWRI, Dinajpur) in a single operation were used for DSR and STM. Tilled and seed placement between 5-7 cm
T_2 (PTR/CTM + 25% residue)	Puddled Transplanted Rice – Conventional till Maize	
T_3 (PTR/CTM + 50% residue)	Puddled Transplanted Rice – Conventional till Maize	
T_4 (DSR/STM + 0% residue):	Direct Seeded Rice – Strip till Maize	**Conventional tillage (CT):** Three-four times full rotary tillage by 2W tractor operated by power tiller were used for PTR and CTM. The depths of tillage are about 6-9 cm. Incorporation of crop residue with one-time land leveling. Puddling (wet tillage) was done twice in 8–10 cm of standing water using a power tiller.
T_5 (DSR/STM + 25% residue)	Direct Seeded Rice – Strip till Maize	
T_6 (DSR/STM + 50% residue)	Direct Seeded Rice – Strip till Maize	

3.2.4 Crop management

Twenty-two-day old seedlings were manually transplanted with a spacing of 20 cm × 15 cm and 2-3 seedlings per hill. All DSR plots were sown with zero-till maize/multi-crop planter having an inclined plate seed metering system (model, BMWRI-ZT) with 20 cm row using a 30 kg seeds ha^{-1}. The sowing of DSR and wet bed rice nursery for PTR was done at the same time in the third week of July each year. In CTM plots, maize (BARI Hybrid maize-9) dibbled manually at 20 kg ha^{-1} maintaining 60 cm × 20 cm plant spacing in the third week of November whereas STM plots were sown by the zero-till maize/ multi-crop planter (model, BMWRI-ZT). In the experiment field, rice was fertilized with 54 kg N + 12 kg P + 60 kg K + 9 kg S + 1.2

kg Zn ha^{-1}, while maize received 218 kg N + 76 kg P + 80 kg K + 37 kg S + 11 kg Mg+ 2.1 kg Zn ha^{-1}. No pre-planting herbicides were used in the CT plots, but pyrazosulfuron, a broad-spectrum post-emergence herbicide, was used in the STDSR plots and glyphosate was used in the CTM plots to control weeds.

3.2.5 Harvesting and yield measurements

Both crops, rice and maize, were harvested at the physiological maturity stage. The rice crop was harvested in DSR plots during the first week of November, whereas PTR plots were harvested in the second week of November in both years. Rice was harvested manually in an area of 3.7 m^2 within a field of each plot, following a zig-zag pattern to avoid border effects. For the maize crop, a net plot area of 35 m^2 was harvested and the biomass was dried in the field for 3-5 days under the sun. The rice grain yields were adjusted to a 12% moisture content whereas for the maize grain it was 14%. The dry weight of stubble /straw was recorded after drying at 70°C to a constant weight.

Annual system productivity was determined as rice equivalent yield (REY) by converting the yield of maize crops into rice equivalent yield

$$\text{REY} = \frac{\text{Yield of maize crop } (\text{kg ha}^{-1}) \times \text{ Price of non}- \text{ rice crop (US\$/kg)}}{\text{Price of rice (US\$/kg)}} \ldots\ldots \text{ (Eq. 1)}$$

The prices of rice and maize used for the calculation were US$ 0.21, and US$ 0.24 kg^{-1}, respectively. The grain prices of all the component crops were determined based on local market prices in BDT and later converted to US$ (1 US$ = 85.00 BDT, the average exchange rate in the experimental period.

3.2.6 Leaf chlorophyll

For the rice crop, the chlorophyll content was determined by using a chlorophyll meter (SPAD-502, Minolta Camera Co. Ltd, Osaka, Japan) during the vegetative and reproductive phases, a mature leaf being taken from the top of the plant to measure the SPAD values.

3.2.7 Soil sampling and processing

The soil was collected from the experimental field with a push type auger (2.5 cm diam.) before establishing the treatments in 2019, and in 2021 after the harvest of the maize crop in the second year. We utilise the auger to collect soil samples. This is why, when taking a sample from the field, we did not remove the residue. Briefly, nine representative soil samples were randomly taken from the experimental field at 0-10 and 10-20 cm depths and subsequently composited based on depth for the analysis of soil chemical properties. The sub-samples were crushed in a wooden mortar and pestle, sieved, allowed to air dry, and then kept in plastic containers for further analysis in the laboratory. In addition, another soil sample was collected (from 0-10, 10-20, 20-30, 30-40, 40-50, 50-60 and 60-70 cm soil profile) by digging a 100 cm deep soil pit in the experimental site to determine the initial physical and chemical properties of the soil layers. After two years of the rice-maize cropping systems, in May 2021 (after the maize harvest), three representative soil samples were collected from each plot at 0-10 and 10-20 cm depths and composited according to depth for the analysis of carbon fraction in each depth. For microbial biomass carbon, soil samples were collected from each plot at 0-5 and 5-10 cm depths.

The soil samples were gently sieved through a 4 mm mesh sieve to remove large organic substances. After sieving, the soil samples were passed through a 2 mm sieve and stored in plastic zipper bags at 4°C before microbial biomass carbon analysis. Soil penetration resistance (SPR) was measured at 0-10 and 10-20 cm depths before starting the experiments and after the end of the experiment in the second year using a Hand Penetrometer (Eijkelkamp Equipment, Model 06.01, and Serial No. 11911698 /11, Giesbeek, The Netherlands).

3.2.8 Analytical methods

3.2.8.1 Soil physical and chemical properties

Organic matter (OM), nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn) were measured following standard procedures (Page et al., 1989). Soil pH was measured with a glass electrode pH meter (WTW pH 522) at a soil-water ratio of 1:2.5 as described by (Page et al., 1982), soil organic C was determined by Walkley and Black wet oxidation method as described by Jackson et al. (1973) and total N was determined by micro-Kjeldahl method (Page et al., 1989); available P was measured following the Olsen method (Jackson et al., 1973), exchangeable K was quantified following the NH4OAc extraction method (Black, 1965), S was determined by the turbidimetric method through a spectrophotometer using a wavelength of 420 nm (Page et al., 1989). Ca was measured by the complexometric method of titration using Na_2-EDTA (Disodium ethylenediaminetetraacetic acid) as a complexing agent (Page et al., 1989), Mg was estimated by using the NH_4OAc extraction method (Black, 1965), and available Zn, Cu, Fe, and Mn were measured by using the diethylenetriamine Penta acetic acid (DTPA) extraction method (Lindsay, 1978). Particle size distribution was assessed by the hydrometer method (Bouyoucos, 1962), and the soil textural class was calculated using the USDA textural triangle. Bulk density and particle density of the soil samples were determined by the core sampler method and Pycnometer method, respectively (Karim et al., 1988). The soil porosity was calculated from the relationship between bulk density and particle density

$$\text{Porosity (\%)} = \left(1 - \frac{\text{BD}}{\text{PD}}\right) \times 100 \ldots\ldots \text{(Eq. 2)}$$

where, BD is bulk density (Mg m^{-3}), PD is particle density (Mg m^{-3})

3.2.8.2 Carbon fractionation by size and density

We determined the TOC contents of composite soil samples by the size-density fractionation technique proposed by Robertson et al. (2019). The main goal was to figure out how SOM changes in each of the different soil fractionations. With this approach, four soil fractions were made: DOM (dissolved organic matter), Light POM (particulate organic matter, density, <1.85 Mg m^{-3}), Heavy POM (heavy particulate organic matter, size >53 µm), and MAOM (mineral-associated organic matter, <53 µm) (Figure 3.3). To assess DOM, 10 g of air-dried soil was passed through a 2 mm sieve and placed in a 50 ml centrifuge tube, then 30 ml of deionized water was added and the sample was shaken for 15 minutes at 95 rpm. After that, the sample was centrifuged for 15 minutes at 1874 g (calculate rpm for 19.2 cm SoG rotor = 2876 rpm), and the soil solution was filtered using 20 µm Whatman No 1 filter paper. After that, the sample was analyzed within 48 hrs by elemental analyser (Vario micro cube CHNOS Elemental Analyzer; EuroEA3000).

The light POM technique begins with the first step, following that, the solid material was retained on the filter in the pre-weighed aluminium pan in order to measure the weight of the light fraction. Besides this, 20 ml of sodium polytungstate (SPT) 1.85 Mg m^{-3} was added to a centrifuge tube containing the centrifuged 10 g soil, and shaken for 18 hours on a reciprocal shaker at 95 rpm to disperse the sample and then centrifuged for 30 minutes at 1874 g. It was then collected in the previously weighed aluminium pan and dried at 60°C in the oven. The light POM was then recorded.

For the heavy POM, the procedure was firstly to remove the SPT by repeatedly rinsing the soil with deionized water: deionized water was added (to the 40 ml mark), the sample was shaken to mix it, it was centrifuged, and the water discarded and finally passed onto a 53 µm sieve. To assess MAOM, we collected the sample that has passed through the sieve into a pre-weighed aluminium pan – this was the silt and clay-sized organic matter fraction (MAOM) (Figure 3.3). Finally, we put 10 mg of each of the ground solid fractions (Light POM, Heavy POM, and MAOM) into 9 x 5 mm silver capsules, added 30 µl of 15% hydrochloric acid, and oven-dried them at 60 °C, and the samples were analyzed in the elemental analyser (Vario micro cube CHNOS Elemental Analyzer; EuroEA3000). The soil organic carbon (SOC) stock was calculated according to the following equation (Batjes, 1996):

SOC stock (Mg ha^{-1}) = SOC concentrations (%) $\times$ bulk density (Mg $m^{-3)}$ $\times$ depth (cm)

The carbon stock computed in different fractions considering amount of visible piece of degraded plant material in every fraction as well as % of SOC concentrations. The average carbon recovery following fractionation was 85-94%.

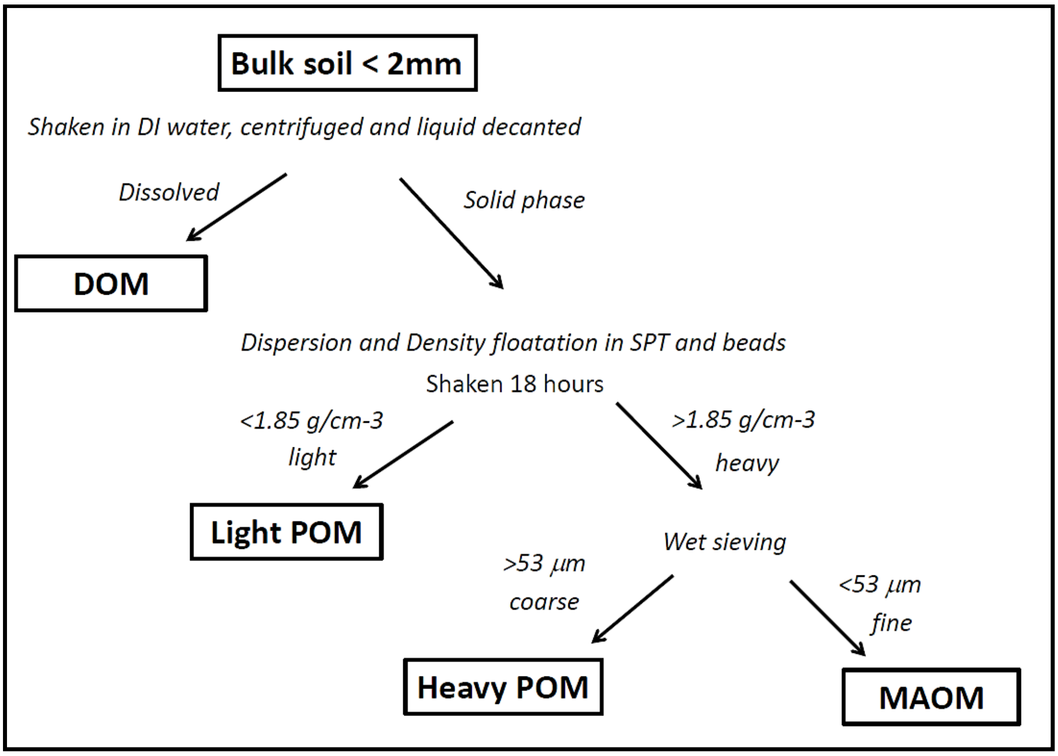

Figure 3.3: Schematic diagram showing SOC fractionation DOM = Dissolved Organic Matter, Light POM =Particulate Organic Matter, density, Heavy POM =Heavy Particulate Organic Matter, and MAOM =Mineral-Associated Organic Matter. (Modified from Robertson et al., 2009).

3.2.8.3 Microbial biomass carbon (MBC)

The chloroform fumigation extraction method was adopted to estimate the amount of microbial biomass C in soils. Fumigated and non-fumigated soils were extracted with 0.5 M K_2SO_4 (soil: K_2SO4 solution =1:4) and shaken for 30 minutes and then, filtered. From the extract, the amount of biomass C was determined according to the method described by Vance et al. (1987).

3.2.9 Economic analysis

Partial economic analysis under a range of tillage practices and residue retention levels was computed based on the production costs and income from the sale of rice and maize grain, and rice stubble and maize stover. The production costs involved input costs, machinery costs, and labour used for the experiment. The cost of seed, growing the seedlings, fertilizers, insecticides, herbicides, and irrigation was considered as input costs; whereas machinery costs included a multi-crop planter and power tiller hired for tillage and seed sowing. The labour costs involved different operations, e.g. tillage, seedbed preparation, sowing/transplanting, irrigation management, thinning, weeding, harvesting and threshing. Gross returns (GR) were estimated by multiplying grain and straw yield by the price of grain and straw per hectare each year. The net income was calculated by subtracting the total input costs from the gross return and the gross margin was estimated by subtracting the total production cost from the gross return. The benefit-cost ratio (BCR) was computed as the gross return divided by the cost of production. All the prices were converted to US$ based on a conversion rate of 85BDT = 1 US$ (www.xe.com).

3.2.10 Statistical analysis

All data were analyzed statistically using a two-way factorial model based on a split-plot design (Popat and Banakara, 2020). In our study, as all the data were normally distributed ($p > 0.05$), they were exposed to parametric tests. The variables of the effects of different treatments were tested by analysis of variance (ANOVA), and comparisons between the treatments based on the least significant difference at $p \leq 0.05$. Before doing statistical analysis, the normality assumption of analysis of variance (ANOVA) was tested by Shapiro and Wilk (1965) by R Core Team (2020) and STAR statistical software (Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños, Laguna). In addition, the Conformity of homogeneity of variance was also tested by Bartlett's test (Snedecor and Cochran, 1989). Since the normality assumption of ANOVA was met, there was no need for data transformation. The effect of the treatment PTR/CTM vs STDSR/STM was compared using t-test for independent samples (using STAR software).

3. 3 Results

3.3.1 Effect on soil physical properties

3.3.1.1 Soil bulk density

The effects of TCE and crop residue management practices on soil bulk density (BD) were significant at 0-10 and 10-20 cm profile depths (Table 3.3). The ANOVA showed that, at 0-10 cm soil depth, the effects of TCE techniques on bulk density was lower by 2.73% in STDSR/STM compared to PTR/CTM. At the same depth, irrespective of residue management practices, the soil bulk density under TCE was lower than with no crop residue retention by 2% (4%) in 25% (50%) crop residue retention plots. On the other hand, in sub-surface soil (10-20 cm), PTR/CTM had a higher value (1.53) than STDSR/STM (1.49) considering TCE techniques. A similar trend was also found concerning residue management practices and a lower value was obtained in 50% crop residue retention treatment (1.49), followed by 25% crop residue (1.51) and no residue retention treatments (1.54). In addition, BD in soils under TCE and crop residue management practices increased with increasing soil profile depths. However, the ANOVA showed no significant interaction effect on TCE and residue management practices on BD in the 0-10 and 10-20 cm soil depths but the value of STDSR/STM with residue incorporation/retention plots declined at both depths.

Table 3.3 Soil bulk density (Mg m^{-3}) at two soil depths under different tillage and crop establishment (TCE) techniques and residue management (R) options at the end of 2 years of the rice-maize system.

Parameters	**0-10 cm**				**10-20 cm**			
TCE technique	CR0	CR25	CR50	Mean	CR0	CR525	CR50	Mean
STDSR/STM	1.49	1.47	1.43	1.46b	1.53	1.49	1.47	1.49b
PTR/CTM	1.53	1.50	1.47	1.50a	1.56	1.52	1.51	1.53a
Mean	1.51a	1.48b	1.45c		1.54a	1.51b	1.49b	
LSD (0.05)	TCE = 0.025				TCE =0.019			
	Residue (R)=0.01				Residue (R)=0.02			
	TCE×R=ns				TCE×R=ns			

Treatment details are in Table 3.2 and ns indicates no significant

3.3.1.2 Soil penetrometer resistance (SPR)

The main effects of TCE techniques and residue management were significant on SPR at 0–10 and 10-20 cm soil depths (Figure 3.4). SPR showed a tendency to increase at a depth of 0-10 cm and was always higher in PTR (333 kpa) than in DSR (ST) systems considering tillage practices. Furthermore, retention of residue caused a significant reduction in SPR compared to the residue removal plots, and the maximum SPR (366.01kpa) was obtained in no crop residue retention followed by 25% crop residue retention (283.50 kpa). The lowest SPR (243.33kpa) was recorded in 50% crop residue retention. At the same depth, irrespective of conventional and strip tillage with residue management practices, a significant effect on SPR was found in no and 50% crop residue retention, respectively. At a 10-20 cm depth, TCE techniques showed no significant effect on SPR, whereas a 16% reduction in SPR was recorded in STDSR/STM compared to PTR/CTM. At the same depth, mean SPR under 25 and 50% crop residue retention in STDSR/STM plots compared to no crop residue retention in PTR/CTM plot was reduced by 24 and 29%, respectively. In addition, at the same depth SPR values were 13 and 17% lower in 25 and 50% crop residue retention plots compared to no crop residue retention plots. The changes in SPR were positively correlated with BD at both depths. In our study, there was no significant differences between conventional and strip tillage at a 10– 20 cm soil depth. Our study also found that 61% variation in SPR could be explained through BD; SPR =1452.3BD - 1854.2, $R^2 = 0.61^{***}$, $p \leq 0.001$.

In comparison to two tillage methods with the same amount of crop residue retention, the mean SPR values in PTR/CTM plots were 14-46% higher under 0, 25, and 50% crop residue retention compared to STDSR/STM plots at 0-10 cm soil depth and by 23-26% at 10-20 cm soil depth (Figure 3.4).

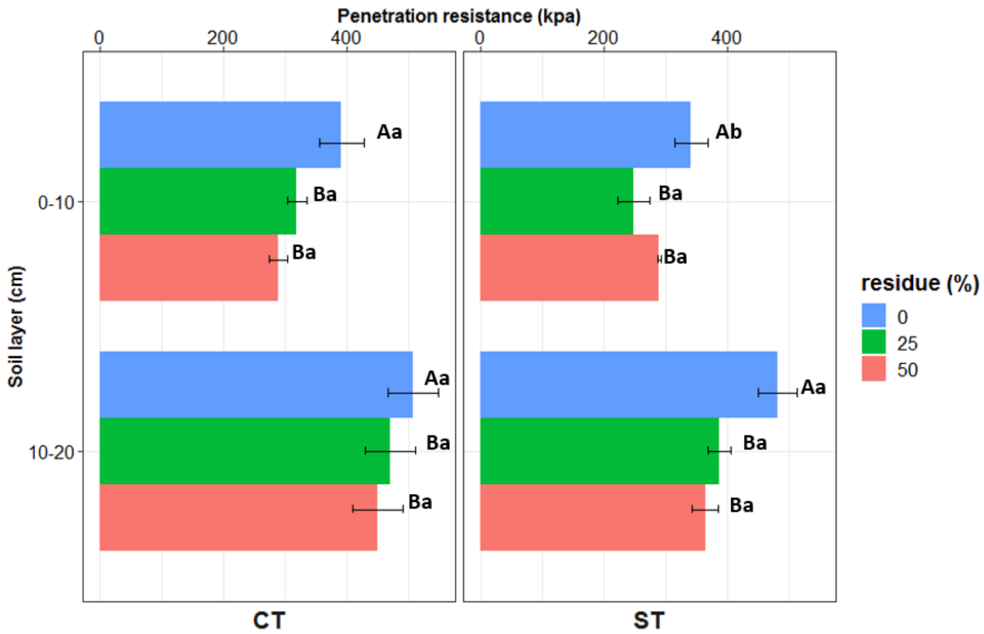

Figure 3.4: Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on soil penetration resistance (KPa) at 0-10 and 10-20 cm profile depths at maize harvest in 2020-21. For treatment, details refer to Table 3.2.

Different upper-case letters represent significant intragroup statistical difference at $p \leq 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \leq 0.05$; p values calculated by the ANOVA test and t-test.

3.3.1.3 Soil moisture content (SMC)

The ANOVA showed no significant interaction effect of TCE and residue management practices on soil moisture content (SMC) in the 0-10 and 10-20 cm soil depths. But the effects of residue management on SMC were, however significant at 0-10 cm and 10-20 cm profile depths. At a 0-10 cm depth, SMC increased by 7% and 17% under 25% and 50% crop residue retention plots compared to no residue plots. Besides, the effects of TCE techniques on SMC were not significant but it was increased by 10% in STDSR/STM compared to PTR/CTM (Table 3.S1). At a 10-20 cm depth, SMC was higher by 34% in STDSR/STM compared to PTR/CTM plots. At the same depth, SMC values were 8 and 15% higher in 25 and 50% crop residue retention plots compared to no crop residue retention plots. There was a significant effect on SMC in the STDSR/STM and PTR/CTM plots, irrespective of residue management at 10- 20 cm depth only (Figure 3.5). In our study, SMC was inversely correlated to SPR in both soil depths ($r = -0.51$, $p \leq 0.01$).When comparing two tillage systems with the same level of crop residue retention, the mean SMC values were 6-11% higher in STDSR/STM plots than in PTR/ CTM plots at 0-10 cm soil depth and 32-35% higher at 10-20 cm soil depth (Figure 3.5).

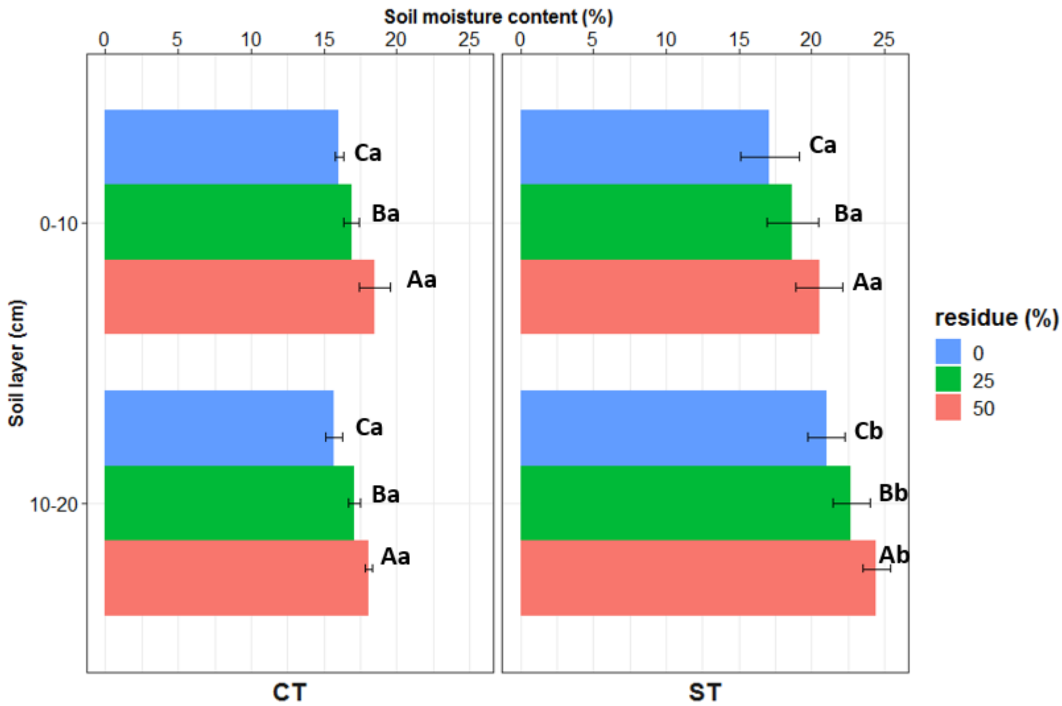

Figure 3.5: Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on soil moisture content (SMC) at 0-10 and 10-20 cm profile depths at maize harvest in 2020-21. For treatment, details refer to Table 3.2. Different upper-case letters represent significant intragroup statistical difference at $p \leq 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \leq 0.05$; p values calculated by the ANOVA test and t-test.

3.3.1.4 Soil porosity

The effect of residue management practices was significant at both depths. At the 0-10 cm depth, the porosity value was higher by 9 and 18 in 25 and 50% crop residue retention plots compared to no crop residue retention plots. On the other hand, in sub-surface soil (10-20 cm) a similar trend was also observed and the value was 8 and 17% greater under 25 and 50% crop residue retention treatments compared to no residue retained/incorporation treatments. As compared to the conventional and strip tillage with residue management practices, there was a significant effect on soil porosity in the 50% crop residue retention plots at a 10- 20 cm depth only (Figure 3.6). There was no interaction effect of TCE and residue management practices on soil porosity at 0-10 and 10-20 cm profile depths but the value was higher in the SDSR/STM plots (Table 3.S2). Mean soil porosity values were 11-45% higher under no 25 and 50% crop residue retention in STDSR/STM plots compared to PTR/CTM plots at 0–10 cm soil depth and by 11-12% at 10-20 cm soil depth.

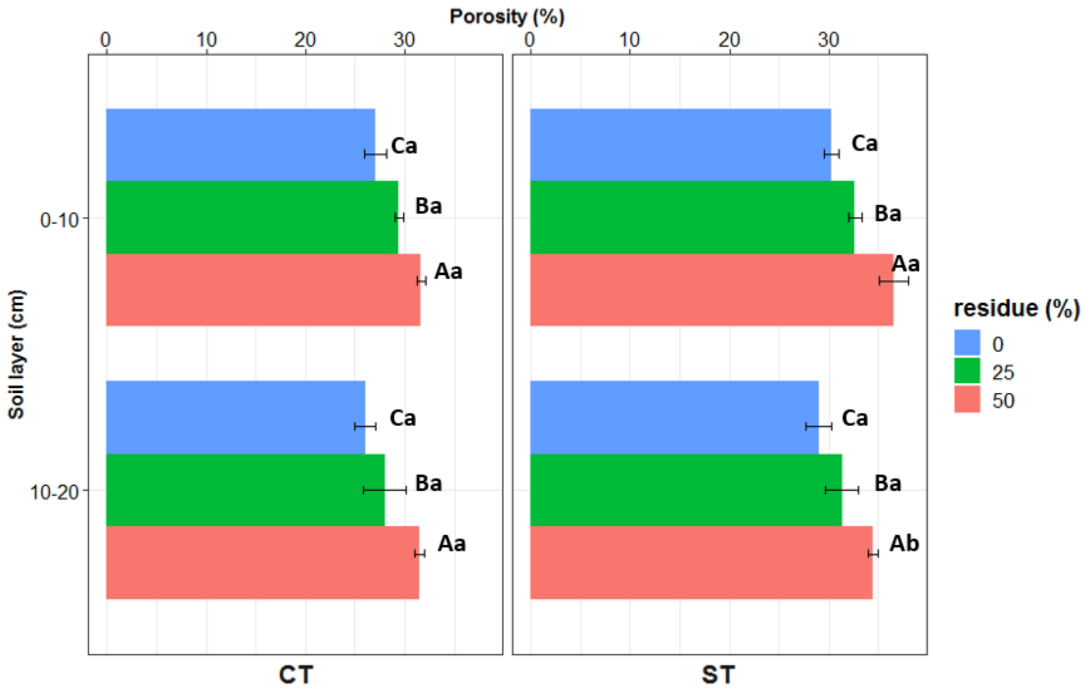

Figure 3.6: Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on soil porosity at 0-10 and 10-20 cm profile depths. For treatment, details refer to Table 3.2. Different upper-case letters represent significant intragroup statistical difference at $p \leq 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \leq 0.05$; p values calculated by the ANOVA test and t-test.

3.3.2 Carbon fractionation

3.3.2.1 Dissolved organic carbon

In the present research, tillage management practices had the greatest influence on dissolved organic carbon (DOC) content (Table 3.4). The amounts of DOC were significantly higher in STDSR/STM management plots (38.73 mg kg^{-1}) compared to no residue retention plots (19.69 mg kg^{-1}) at a 0-10 cm depth. Irrespective of residue and tillage interaction plots, the value was higher in STDSR/STM practices under 25% and 50% residue retention /incorporation plots. Similarly, at 10-20 cm depth, a higher value (64%) was obtained in STDSR/STM practices compared to no residue retention practices. Considering, residue management practices, in both of the years, a higher value was observed in 25 and 50% residue retention/incorporation plots than no residue retention plots (Table 3.4).

Table 3.4 Quantity of carbon in dissolved organic carbon (DOC) (mg kg^{-1}):

TCE technique	0-10 cm				10-20 cm			
	CR0	**CR25**	**CR50**	**Mean**	**CR0**	**CR525**	**CR50**	**Mean**
STDSR/STM	37.45	39.45	39.28	38.73a	42.55	46.09	48.25	45.63
PTR/CTM	19.09	20.27	19.70	19.69b	21.52	36.87	24.97	27.79
Mean	28.27	29.86	29.49		32.04	41.48	36.61	
LSD (0.05)	TCE = 10.04 Residue (R)=ns TCE×R=ns				TCE =ns Residue (R)=ns TCE×R=ns			

Treatment details are in Table 3.2 and ns indicates no significant

3.3.2.2 Carbon stock in fractionation contributed by light, heavy POM and MAOM

The amounts of carbon in light POM present in the 50% residue retention/ incorporation plots was 25% higher compared to no residue retained plots However, irrespective of residue level, the trend was higher in STDSR/STM plots at both depths. In sub-surface soil at a depth of 10-20 cm, the proportion of carbon provided by light POM was 28.7% higher in 50% residue plots than in residue removal plots (Figure 3.7).

Although no significant variation was observed in tillage practices, the value was 10% higher in strip tillage compared to conventional tillage practices. For the carbon stock in light POM, 50% crop residue gave better results compared to other treatments, as demonstrated by the highest amounts of SOC compared with the other residue management practices at a 10-20 cm depth ($p \leq 0.05$) (Figure 3.8). However, irrespective of residue levels, there was no significant difference but the value was 10% higher in strip-tillage than in conventional tillage. The interaction effect between tillage and residue management practices was not significant but greater values were observed in the STDSR/STM plots (Table 3.S3).

Our study showed that the SOC was higher in surface soil compared to the subsurface soil (Figure 3.8 and Table 3.S4) and a higher value was found in 25 and 50% residue plots than in no residue plots. The proportion of carbon contributed by heavy POM was 29% in surface soil and 14% in subsurface soil and the value was higher in

50% residue plots than in residue removal plots (Figure 3.7). We did not find any significant difference between tillage and residue interaction effect (Table 3. S4).

The effect of residue management practices was significant in surface soil. At the 0-10 cm depth, the carbon stock was higher by 27 and 8% in 25 and 50% crop residue retention plots compared to no crop residue retention plots (Figure 3.8). On the other hand, a similar trend was also observed in sub-surface soil (10-20 cm). Irrespective of tillage management practices, the higher carbon stock value was found in STDSR/STM plots (9.03 Mg ha^{-1}) compared to PTR/CTM plots (8.59 Mg ha^{-1}). The percentage of SOC stock that resided in the MAOM fraction and the value was 64 and 71% in 25 and 50% residue retention plots compared to the no residue plots (60%) (Figure 3.7). The ANOVA showed that there were no significant interaction effects between tillage and crop establishment (TCE) technique with residue management practices on carbon stock at 0-10 and 10-20 cm profile depths. But the value was higher in strip tillage with 50% residue retention plots compared to conventional tillage with no residue plots (Table 3. S5).

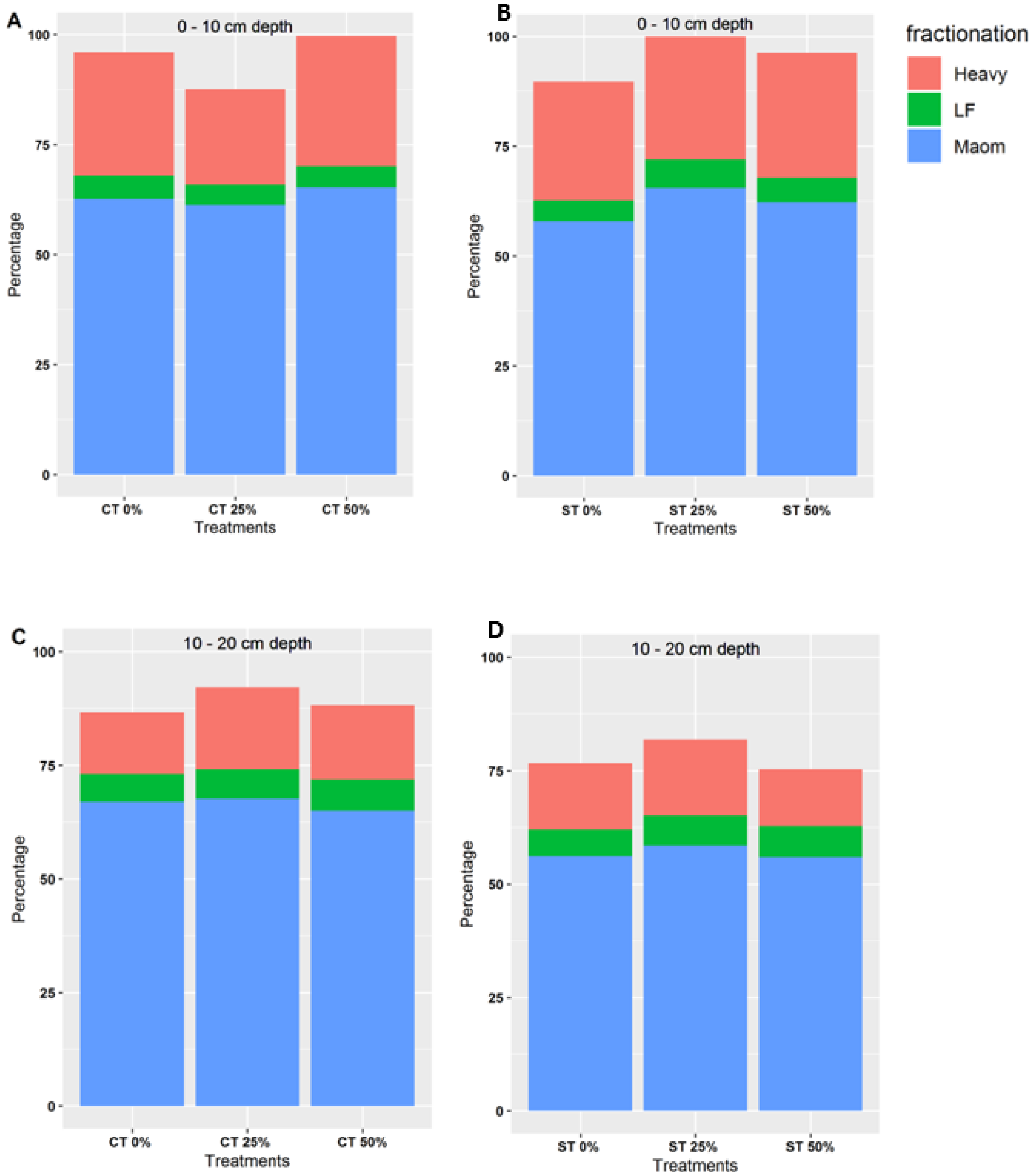

Figure 3.7: The proportion of carbon contributed by light POM, heavy POM and MAOM at 0-10 (A & B) and 10-20 (C &D) cm soil depths.

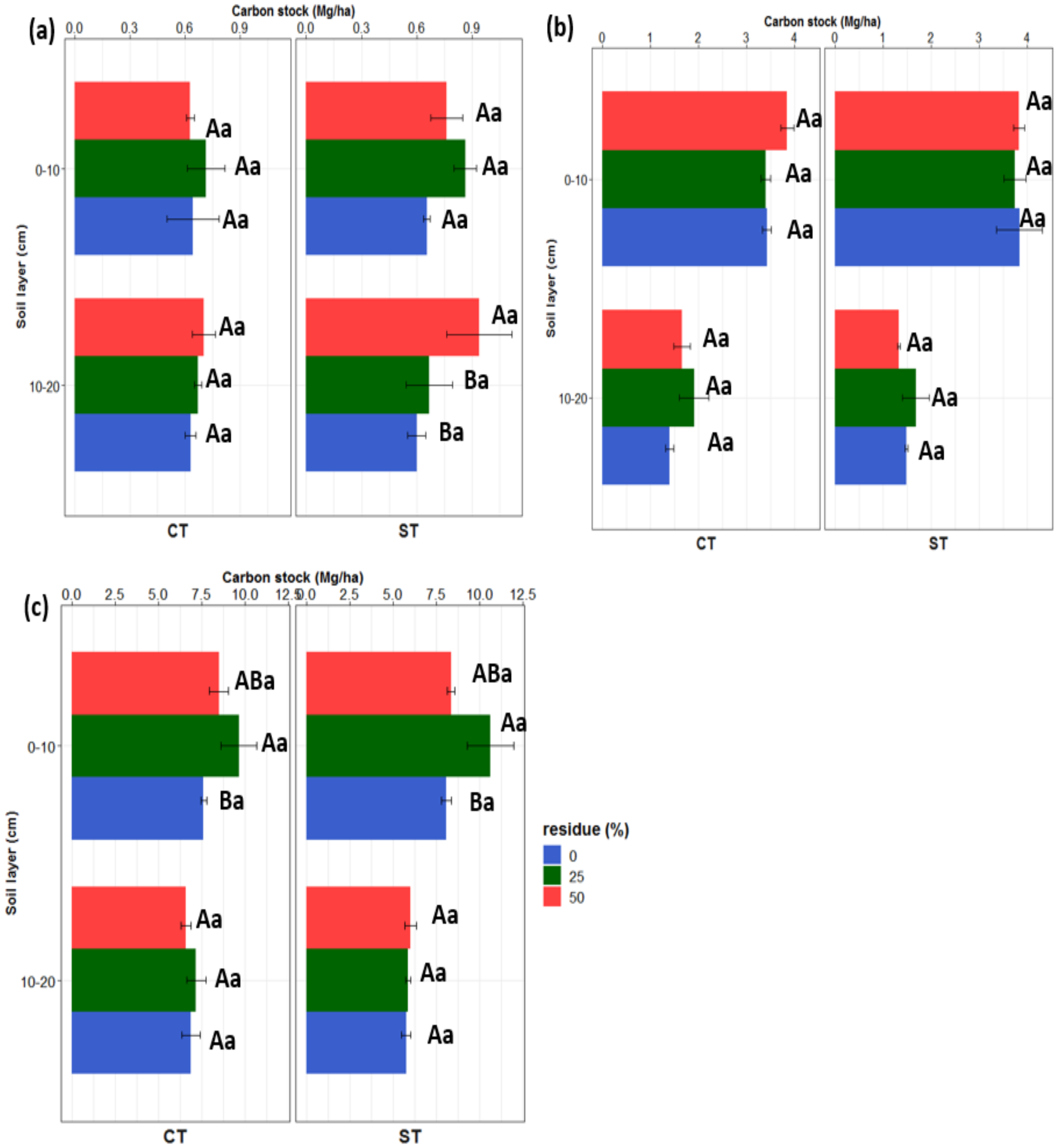

Figure 3.8: Carbon stock in fractionation contributed by light POM (a), heavy POM (b) and MAOM (c) at 0-10 and 10-20 cm profile depths at maize harvest in 2020-21. For treatment, details refer to Table 3.2. Different upper-case letters represent significant intragroup statistical difference at $p \leq 0.05$; Different lower-case letters represent significant intergroup statistical difference at $p \leq 0.05$; p values calculated by the ANOVA test and t-test.

3.3.3 Effect of tillage and residue management on microbial biomass carbon (MBC)

3.3.3.1 Microbial biomass carbon (MBC)

The MBC was significantly higher under residue retention compared to no residue retention at both of the depths. At the depth of 0-5 cm, retention of 25 and 50% residues resulted in 45-54% higher MBC than no residue retention, whereas 37-41% was found at the 5-10 cm depth. Overall, there was a tendency for the values to be lower at the 5-10 cm depth. Moreover, we did not get an interaction effect ($p \leq 0.05$) with tillage and residue practices on microbial biomass carbon (Table 3. S6). The result showed that there was no significant difference between two tillage systems with the same level of crop residue retention on MBC but the mean MBC values were 4-17% higher in STDSR/STM plots than in PTR/CTM plots for 25 and 50% crop residue retention at 0-5 cm soil depth (Figure 3.9).

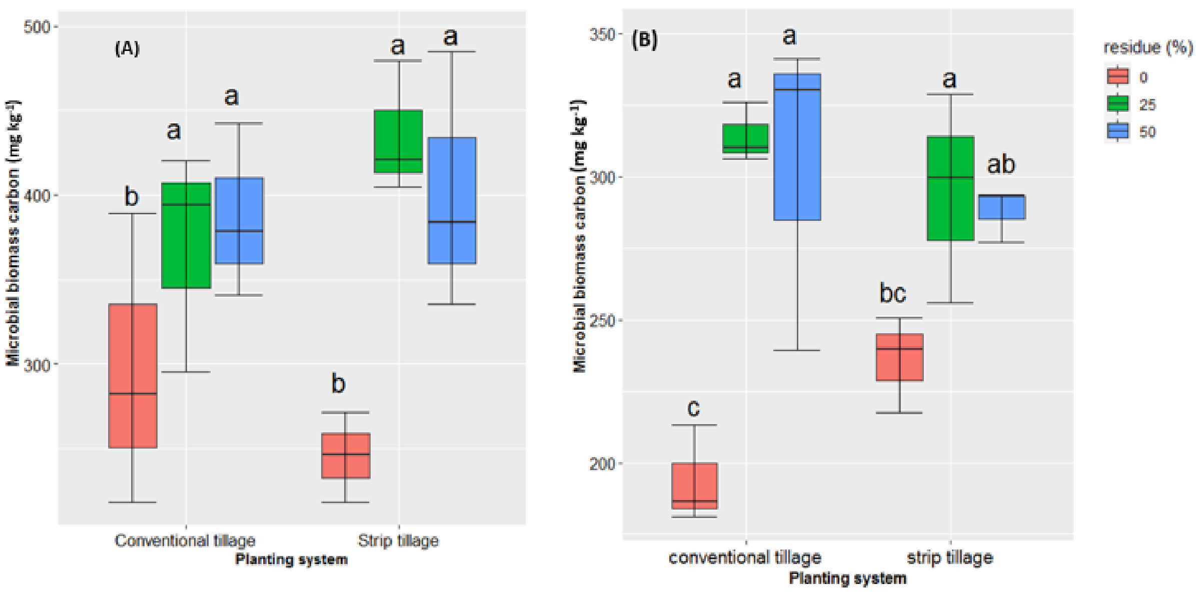

Figure 3.9: Allocation of microbial biomass at 0-5 cm (A) and 5-10 cm (B) depths as influenced by residue retention, and tillage-based crop establishment practices after two-year of rice-maize system

3.3.4 Physiological parameters

3.3.4.1 Chlorophyll concentration

3.3.4.1.1 Rice

In the first year, there was no significant variation in SPAD under crop establishment (TCE) techniques and residue management practices in different rice stages; 50, 60, 70, and 80 days after sowing (DAS) as shown in (Table 3. S7). However, higher SPAD values were observed in 60 DAS and the value was lower in 80 DAS. In the second year, the value was higher in 25% and 50% crop residue retention plots than in the 0% residue retention plots (Table 3. S8). The SPAD values decreased and varied from 38.7 to 31.4 (relative content of chlorophyll) in the no residue retention practices.

3.3.4.1.2 Maize

In the first year of our study, there was significant variation in the effects of residue management practices in 90 DAS as shown in (Table 3.S9). The maximum SPAD value (61.20) was recorded in 50% crop residue retention plots followed by 25% crop residue retention (59.39). On the other hand, the lowest values were found in no residue retention practice plots (57.56). Similarly, in the second year, the effects of TCE techniques and residue management practices were significant in 90 DAS and the maximum values were obtained in ST (57.26) rather than in PTR systems (56.30), as shown in (Table 3.S10). Irrespective of residue management practices, 50%, and 25% of crop residue retention plots showed higher values (57.38 and 56.03) compared to the no residue plots. However, in both the years, the interaction effects of crop establishment (TCE) techniques and residue management practices were non-significant ($p \leq 0.05$) during the growing period of maize but STM gave a higher value than residue removal plots.

3.3.5 The effect of tillage and residue management on yield component and cropping system

3.3.5.1 Yield and yield parameter of rice and maize

In the first year, there was no significant TCE × residue management interaction effect on the yield and contributing characters of rice. In our study, (tiller/hill and panicle length) of rice were significantly affected by TCE techniques. However, PTR (CT) had 8% and 2% higher values in relation to panicle density and panicle length (cm) than DSR (ST) plots. Considering the yield, the trend was higher in PTR plots than in ST plots (Table 3.S11). Similarly, in the second year ANOVA also showed no significant interaction effects residue × TCE techniques on rice yield. The main effects were observed in tillage management practices, the yield being 14% higher in PTR compared to DSR (ST) plots. In both seasons, the biomass yield followed a similar trend to grain yield (Table 3.S12)

For maize, during 2019-2020, the main effects of TCE practices were plant height and thousand-grain weight while other effects from residue management were recorded from grains/cob, 1000 grain weight, cob length, cob line, and cob round. A decrease in plant height and weight of 1000 grain weight in the order of 3 and 5% were observed in CTM after PTR compared to STM after STDSR. Retention of crop residues increases the grains cob^{-1} by 3 and 4%, 1000 grain weight by 5 and 9%, cob length (cm) by 9 and 21%, in the case of 25 and 50% crop residue retention rather than no residue retention plots. The highest maize yield was recorded from 50% crop residue retention (9.14 Mg ha^{-1}) followed by 25% residue retention (8.85 Mg ha^{-1}), and the lowest was found from no residue treatment (8.37 Mg ha^{-1}), although there was no significant effect of the TCE practices on maize yield (Table 3.S13). In 2020-2021, the trend of cobs plant^{-1}, grains/cob, weight of 1000 grains, cob length, cob line, and cob round were similar to the previous maize crop. However, there was an increase in grains/cob (3 and 6%), the weight of 1000 grains (4 and 8%), cob length (7 and 19%), cob round (2 and 6%) in relation to 25 and 50% crop residue retention compared to no residue retention plots. The trend in maize yield was similar to the previous season for TCE and residue management practices, and there was also a higher yield of 10 and 14% under 25 and 50% residue retention compared to no residue management practices (Table 3.S14). In both seasons, the biomass yields also followed a similar trend to grain yield. The present study did not find any significant interaction effect between tillage and residue practice but the yield was higher in STM plots compared to CTM plots.

3.3.5.2 Rice-maize system productivity

The total rice equivalent yield (REY) of the RM system ranged from 9.56 to 10.46 Mg ha^{-1} in the first year, while in the second year, it was 9.91 to 11.31 Mg ha^{-1}. Residue retention/ incorporation practices resulted in consistently higher REY yields across the years. However, the highest system productivity was obtained from 50% crop residue retention practices (10.45 Mg ha^{-1} in year 1, 11.31 Mg ha^{-1} in year 2) followed by 25% crop residue retention management (10.16, 10.92 Mg ha^{-1}). The lowest REY was recorded from no residue retention practices in year 1 and year 2 (9.56 and 9.91 Mg ha^{-1}). The incremental decline in REY was significant when crop residue was removed, with no significant difference when compared with the TCE technique. Overall, in year 1, the REY was higher at 5 and 9% under 25 and 50% residue retention compared to no residue management practices while it was 10 and 14% in year 2 (Table 3.5).

Table 3.5 Rice and maize grain yields and rice equivalent yield (REY) (Mg ha^{-1}) in Rice-Maize cropping systems during 2019-2020 and 20-21

Items	Residues	Year 1				Year 2			
		STDSR/STM	PTR/CTM	Mean	Summary	STDSR/STM	PTR/CTM	Mean	Summary
Rice	CR0	4.15	4.27	4.21	LSD0.05	4.02	4.65	4.33	LSD0.05
	CR25	4.26	4.34	4.30	TCE = ns	4.21	4.72	4.47	TCE = 0.30
	CR50	4.25	4.35	4.29	Residue (R)=ns	4.12	4.78	4.45	Residue (R)=ns
	Mean	4.22	4.32		TCE×R=ns	4.12b	4.71a		TCE×R=ns
Maize	CR0	8.44	8.29	8.37b	LSD0.05	9.07	8.32	8.67 b	LSD0.05
	CR25	8.80	8.89	8.85a	TCE = ns	9.68	9.43	9.55 a	TCE = ns
	CR50	9.21	9.08	9.14a	Residue (R)=0.37	10.02	9.77	9.90 a	Residue (R)=0.34
	Mean	8.82	8.75		TCE×R=ns	9.57	9.17		TCE×R=ns
REY	CR0	9.48	9.65	9.56b	LSD0.05	10.30	9.51	9.91b	LSD0.05
	CR25	10.16	10.06	10.11b	TCE = ns	11.07	10.77	10.92a	TCE = ns
	CR50	10.37	10.52	10.45a	Residue (R)=0.39	11.45	11.17	11.31a	Residue (R)=0.39
	Mean	10.00	10.08		TCE×R=ns	10.94	10.48		TCE×R=ns

Treatment details are in Table 3.2 and ns indicates no significant

3.3.6 Gross margin analysis

In 2019-2020, the effect of residue management was significant in relation to production costs, gross return, gross margin, and BCR but in the TCE technique (tillage practices) only production costs were significant in the RM system. The production costs were US$216 higher for PTR/CTM compared to STDSR/STM (Figure 3.10). Irrespective of residue retention, the production cost was highest (US$1557) in CR0 while it was lowest (US$1527) in CR50. Total gross return, gross margin, and benefit-cost ratio (BCR) are also highest in 50% crop residue retention treatments and lowest for no crop residue retention plots.

In 2021-2022, there was significant variation in the main effects of TCE techniques and residue management practices relating to production costs, gross margin, and BCR in the RM system. The highest production cost (US$1678) was found from PTR/CTM and the STDSR/STM gave the lowest production cost (US$1462), as shown in (Figure 3.10). In the RM system, the highest gross margin (US$1696) and BCR (2.15) were also recorded from STDSR/STM and the lowest was from the PTR/CT system (Table 3.6). The main effect of residue retention refers to gross return, gross margin, and BCR following the same trend in the previous year.

Table 3.6 Economics of different crop establishment techniques and residue management options in rice-maize cropping system during 2019-2020 and 2020-21

Treatment/year	**Production cost ($ ha^{-1})**	**Gross return ($ ha^{-1})**	**Gross margin ($ ha^{-1})**	**Benefit cost ratio ($ ha^{-1})**
Year		**2019-2020**		
TCE technique (TCE)				
STDSR/STM	1431b	3003	1573	2.09
PTR/CTM	1647.a	3009	1362	1.82
Residue retention (R)				
CR0	1557	2893b	1335b	1.86
CR25	1533	3028a	1494a	1.98
CR50	1525	3097a	1571a	2.04
		LSD (0.05)		
TCE	22	ns	ns	ns
Residue (R)	3.42	113	115	0.08
TCE×R	ns	ns	ns	ns
Year			**2020-2021**	

Treatment/year	**Production cost** $(\$\ ha^{-1})$	**Gross return** $(\$\ ha^{-1})$	**Gross margin** $(\$\ ha^{-1})$	**Benefit cost ratio** $(\$\ ha^{-1})$
STDSR/STM	1467b	3193a	1696a	2.15 a
PTR/CTM	1678a	3163 a	1515b	1.90 b
CR0	1593a	2992 b	1398b	1.88b
CR25	1566b	3233a	1666. a	2.07a
CR50	1558c	3311 a	1753. a	2.13 a
		LSD (0.05)		
TCE	30.58	ns	145.06	0.08
Residue (R)	2.32	111.26	111.74	0.07
TCE×R	ns	ns	ns	ns

Treatment details are in Table 3.2 and ns indicates no significant

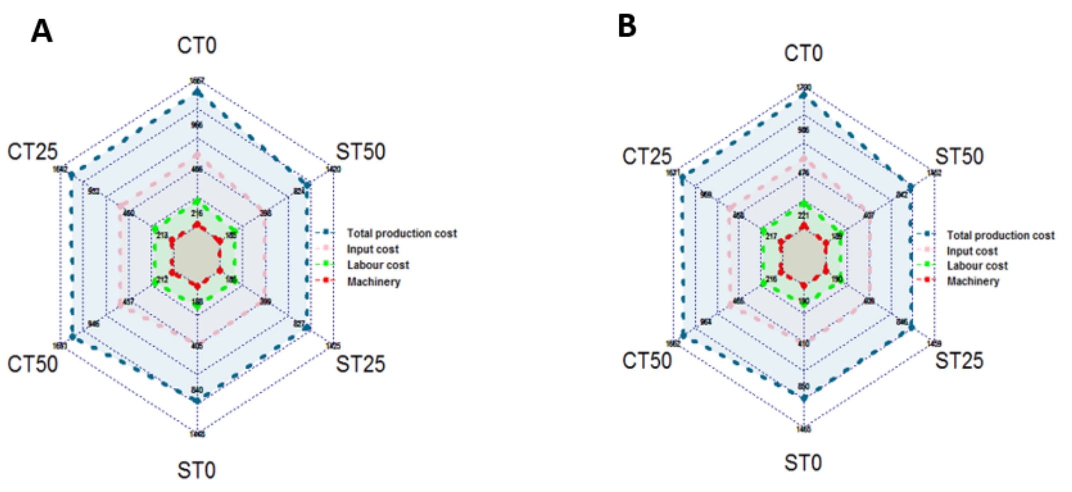

Figure 3.10: Cost of production under TCE techniques with residue management options for rice and maize system in northwest Bangladesh (CT0 = conventional tillage with no residue; CT25 = conventional tillage with 25% residue; CT50 = conventional tillage with 50% residue; ST0 = Strip tillage with no residue; ST25 = Strip tillage with 25% residue; ST50 = Strip tillage with 50% residue during 2019-2020 (A) and 2020-2021 (B). Numbers in each spider diagram mention amount in US$.

3.4. Discussion

3.4.1 The effect of tillage and residue management on soil physical properties

Soil penetration resistance (SPR) values were significantly lower in DSR (ST) than under PTR (CT) systems. Further, our results also showed an increase in SPR with an increase in soil depth. The key interpretation is that a higher SPR under PTR was related with a higher bulk density (especially at 10-20 cm depth) in these plots .This agrees with the results reported by Singh et al. (2016), who conducted an experiment in sandy loam soil with three tillage and two residue management options in the RM system in north-west India and found that SPR showed an increasing trend with an increase in soil depth and was always higher in PTR (CT) compared to DSR (ZT) systems. Salahin et al. (2021) carried out a three-year study in the Gangetic Plains of Bangladesh to evaluate the effects of zero tillage (ZT), strip tillage (ST), bed planting (BP), and conventional tillage (CT) with two residue retention levels. They found that the soil penetration resistance of the ST system was lower than that of the CT system. Lampurlanés and Cantero-Martínez (2003) also reported that increasing trend in SPR with an increase in soil depth. The higher SPR value in CT plots may be also associated with the development of plough pan at a 10-20 cm depth (Singh et al., 2013; Kahlon et al., 2013).

Irrespective of residue management practices, SPR was consistently lower in residue incorporation/retention plots compared to removal residue plots CT at 0-10, and 10-20 cm soil depths. The beneficial effect of incorporation/retention residue on PR is supported by Saha et al. (2010), who found that increased residue incorporation/retention reduced soil PR at a 0-15 cm depth on sandy loam soil. In a study in Uttar Pradesh, India, the continuous application of 5 Mg ha^{-1} crop residues for five years in RM systems decreased the SPR value by 23–31% over no residue plots (Singh et al., 2016). However, it is important to bear in mind that SPR is directly correlated to BD and inversely related to soil water content (Sharma and De Datta, 1986) and in our study, SPR also closely followed BD and soil moisture content trends. Jat et al. (2009) also reported that SPR had a greater value under puddling compared to ZT/conservation tillage.

The interaction effect of TCE techniques and residue on SPR was not significant in the present study. Similar observations were also reported by Singh et al. (2013), who conducted a long-term experiment to assess the effects of three tillage systems, no tillage (NT), ridge-tillage (RT) and plough tillage (PT), and three mulch rates (no residue, 8, and 16 Mg ha^{-1} yr^{-1} and reported that the interaction between tillage, mulch, and soil depth was not significant on SPR.

The present study demonstrated that the TCE technique's influence on bulk density and the value were lower in STDSR/STM compared to PTR/CTM at both depths. The main explanation is that puddling in rice crops is known to destroy soil aggregates and increase compaction of the soil (Gathala et al., 2011a). Our research also observed that strip tillage in DSR had a lower value compared to PTR (CT) treatment plots. Irrespective of residue management practices, bulk density was consistently lower in residue incorporation/retention plots compared to removal residue plots CT at 0-10, and 10-20 cm soil depths. This study is also in line with another researcher Singh et al. (2016) who observed that crop residue retention under DSR plots decreased soil bulk density compared to conventional tillage. In order to assess the impacts of zero tillage (ZT), strip tillage (ST), bed planting (BP), and conventional tillage (CT) with two residue retention levels, Salahin et al. (2021) conducted a three-year research in the Gangetic Plains of Bangladesh. They discovered that the CT system had a larger bulk density near the soil surface than the ST system. According to a four-year study in India by Gathala et al. (2011), the CT-based system tends to have higher soil bulk density near the soil surface (10-20 cm soil depths) than the CA system.

In contrast, other researchers have found that higher bulk density under ZT at a 0-5 cm depth compared to CT in different cropping systems than RM system (Wu et al., 1992; Gathala et al., 2011a; Jat et al., 2013; Huang et al., 2012). In our study, soil bulk density varied significantly due to residue management practices which is similar to the findings of He et al. (2009) who observed that crop residue retention under no-tillage practices decreased soil bulk density. The decreasing trend is strongly correlated with the deposition of organic matter and greater soil biological activity in ST practice (Alam et al., 2014). Moreover, Lal (2000) found that the incorporation of 16 Mg ha^{-1} of rice residue for three years decreased BD from 1.20 to 0.98 Mg m^{-3} on sandy loam soil. Coinciding with this result, Salahin et al., (2021) observed that soil BD did not significantly vary due to crop residue incorporation/retention practices. Sokolowski et al. (2020) observed that no-tillage practices increased soil BD compared to tillage systems (mouldboard plough) although the study was conducted in clay loam soil in an area with heavy rainfall. The present study also indicated that the interaction effects of TCE and crop residue management had no significant effect on soil BD. The findings is also confirmed by Singh et al. (2013) which reported that the interactive effect of tillage and mulch practices on soil BD was not significant in wheat crops. Our findings also differ from the results of Singh et al. (2016a), who found interaction effects on the BD value at 0-15 cm and 15-30 cm depths.

Our study showed that strip tillage with residue retention/ incorporation generated higher soil moisture content at all depths than in no residue plots. This is because residue retention in strip tillage maintaining favourable soil temperature by changing soil energy balances and heat fluxes (Abdullah et al., 2014; Kozak et al., 2007). In addition to this, another argument is that no residue with conventional tillage often creates the land unprotected from extreme temperature which in turn leads to a decrease in the amount of moisture contained in the soil (Ward et al., 2013). These findings are similar to Zhao et al. (2020) who conducted a meta-analysis to evaluate changes in SMC (soil moisture content), looking at CR retention in China (considering 278 publications), and observed that CRR (crop residue retention) led to an increase in SMC by 5.9% compared to CR removal. The present study also showed that higher SMC was found in strip tillage with residue retention compared to convention tillage with residue incorporation. The positive effect of retention residue on SMC is substantiated by Bhattacharyya et al. (2012), who performed a 6-year field experiment on sandy loam soil comparing various tillage methods with residues incorporated or retained on the soil surface. They discovered that areas where agricultural residues were retained on the surface included much more water-stable macroaggregates, which contributed to a higher SMC. Another example from Verhulst et al. (2011b) who found that SMC was higher in residue retained plot due to less evaporation, which has an effect on SMC.A global meta-analysis by Li et al. (2019) indicated that CA-based management strategies increased accessible water by 10.2% higher than conventional practices. Many researchers agree that CA methods, such as strip tillage with the mulching effect of CR, are advantageous (Stewart et al., 2018, Lu et al., 2020). Other researchers Kader et al. (2017) also found that straw mulching helped to conserve soil moisture at a 0-30 cm depth and reduced soil temperature. The main explanation might be linked to lower soil temperatures and lower evaporation from residue retention plots (Busari et al., 2013). However, the trend of increased SMC owing to CA management practices is highly dependent on the regional climate (Abdallah et al., 2021). For example, Gathala et al. (2020) conducted a study in Bangladesh, Nepal and India and observed that water productivity was increased by 19% by adopting CA practices in the subtropical region. Consequently, negative outcomes were also found in cold -humid and tropical humid climates, where waterlogging was observed (Abdallah et al., 2021). The current study indicated that the retention of crop residue together with strip-tillage increased SMC compared to CT with the removal of residues. These results are similar to (Song et al., 2016) who found that removal of crop residue through conventional tillage causes soil water loss, thus affecting soil moisture content.

Soil porosity under CT with no residue retention plots gave lower value than ST with crop residue retention plots at two soil depths. The main explanation is that puddling in rice crops is known to increase compaction of the soil and ultimately reduces the porosity (Singh et al., 2016). Higher soil porosity under residue retention/incorporation in the plots than in soil with residue removal has been also reported by others (Alam et al., 2019; Alam et al., 2014). Another example from Patra et al. (2019) found that soil porosity was higher in zero tillage than in conventional tillage. These findings also in line with Liu et al. (2005), who observed that the retention of crop residue increased soil porosity when there was minimal tillage in the sub-surface layer. The increase of soil porosity in ST might be due to the addition of organic matter and crop residues which was the result of minimum soil disturbance (Alam et al., 2014). In contrast, Sasal et al. (2006) observed that total porosity was 3.5% higher in conventional tillage practices than in ZT-based practices in the surface soil layer (0-15 cm). Another example from Tangyuan et al. (2009) found that the total soil porosity was most affected in the surface layer rather than the sub-surface layer.

3.4.2 The effect of tillage and residue management on soil organic carbon fraction

The SOC fractions, like dissolved organic C, microbial biomass C and particulate organic matter C are known as a soil quality indicator parameter (Liu et al., 2014; Dong et al., 2009; Saviozzi et al., 2001; Lenka et al.,2015 and Yang et al., 2005). As a relatively mobile fraction of the SOC, DOC plays an important role in the transport of nutrients, such as nitrogen and phosphorus (Kaiser, 2003). The current study revealed that the DOC in the 10-20 cm depth was higher in the TCE technique (ST) as compared to the CT soil. The strong stratification of the DOC at the 10-20 cm layer of the ST soil, due to receiving higher rainfall during the crop growing periods that may increase the downward movement of DOC to the deeper layer of soil. This is in line with Roy et al. (2022), who observed that surface drip irrigation increased the moist soil environment which is closely associated with a downward movement of DOC to a deeper layer. In coarse texture soil, a lower amount of clay content also contributed to this process (Gmach et al., 2019). Our results also showed that strip-tillage with direct-seeded rice plots have higher DOC, as compared to CT practices. The fundamental reason is that CT methods expose SOC to air, leading to increased organic carbon oxidation, whereas reducing tillage management practices favour organic carbon build-up under zero or reduced tillage (Zhao et al., 2015).

The study also observed a higher SOC stock in light POM in higher residue retention plots. It might be due to the mixing of crop stubbles and roots with soil which ultimately results in higher SOC stock. Our findings corroborate those of many other researchers (Blanco- Canqui and Lal, 2007a; Liang et al., 2007; Nobuhisa and Hiroyuki, 2009). Liu et al. (2014) reported that improved crop management practices, such as no-tillage and residue retention/incorporation practices, often lead to an increase in SOC and SOC fractions compared to CT. Another example from Chivenge et al. (2007), found that higher SOC was obtained from sandy soils in plots where mulch ripping with residue retention was practiced compared with plots where clean ripping was carried out with no residue retention.

In heavy POM, the beneficial effect of strip tillage and crop residue retention/incorporation on SOC stock was recorded only in the 0-10 cm soil layer, but not in lower layers (Figure 8). These findings are also similar to Luo et al. (2010) who observed that SOC stock was higher in ZT plots only in the upper surface layer (0–10 cm), but decreased by 3.30 ± 1.61 Mg ha^{-1} at a lower depth (20-40 cm) over CT practices. Roy et al. (2022) also reported that higher SOC stock was observed at the surface layer followed by lower SOC stock in the subsurface soil layer in CA-based practices compared to conventional practices. Based on a short-term study (two-year trial) in Bangladesh, Chaki et al. (2021) discovered that the CA-based system tended to have greater soil TOC near the soil surface (0-5 cm and 5-15 cm soil depths) than the CT system. Moreover, this was also well supported by Zeng et al. (2021) who recorded a higher SOC in the top layer of soils than in the sub-layer soils. The key management difference across the treatments that could explain the greater SOC stock in the STDSR/CMT was the addition of residue of 4.2 Mg ha^{-1} $year^{-1}$ (Figure 3.8 and Table S15). According to Bhattacharyya et al. (2015), CA practices boosted both SOC content and stock as compared to CT. Similarly, the residue retention plot produced a much larger SOC stock (6 Mg/ha/year), according to (Ranaivoson et al., 2017).

Crop residue can play an important role to increasing and/or maintaining SOC levels in the soil profile although its effect may be influenced by how residue is kept in the soil, e.g. residue surface retention vs. incorporation (Turmel et al., 2015). When comparing two tillage systems with the same level of crop residue retention, the study observed that SOC stock was higher under strip tillage with residue retention compared to conventional tillage with the incorporation of residue in the plot at the surface layer. The main explanation is that crop residue on the surface under strip tillage involves less interaction with soil microorganisms (Salinas-Garcia et al., 2001), and therefore decomposition is more gradual than CT, where residue comes into close contact with microorganisms when mixed in the soil (Reicosky et al., 1997). This finding is in line with Kuswasa et al. (2001) who conducted an experiment in India between residue retention vs incorporation, and found that SOC is higher under minimal tillage with the residue retained in plots compared to incorporation in plots. Our findings are in agreement with other researchers who found higher SOC content in no tillage than reduced tillage (Singh et al., 2020). In contrast, Dong et al. (2009) conducted an experiment in Northern China and found that SOC content was higher in CT with residue incorporation treatment but the study was conducted in silt loamy soil. Moreover, Turmel et al. (2015) reported that there was a significant increase in SOC content in the CT with residue treatment plots. However, it is well understood that incorporating crop residues into the soil improves soil aeration, and temperature, and creates favourable conditions for microorganisms, resulting in higher decomposition rates and ultimately SOC loss (Coppens et al., 2007; Fontaine et al., 2007) particularly in sub-humid temperate to sub-humid tropical regions (Turmel et al., 2015). At 30°C, the rate of SOC mineralization can increase by up to 72-177%, according to Ghimire et al., (2019). In addition, Moldboard ploughing is generally shown to decrease C stocks in the soil (Turmel et al., 2015). However, our study confirmed that combining strip tillage with residue retention, either complete or partial on the surface, is more helpful than removing the residue entirely.

Because of the inconsistency of the findings of SOC in the soil under tillage and residue management practices, it is, therefore, recommended that the whole soil profile should be studied rather than shallow sampling (Vanden Bygaart and Angers, 2006). This will help to provide more accurate information on the effects of residue management practices on SOC in the soil (Baker et al., 2007).

3.4.3 The effect of tillage and residue management on microbial biomass carbon (MBC)

Soil microbiological indicators like MBC are influenced by land management practices and environmental changes (Zhao et al., 2018). Our study showed that strip tillage with residue retention/ incorporation generated higher microbial biomass carbon (MBC) at all depths than in no residue retention plots. This is because the addition of residue increased soil organic carbon (Saurabh et al., 2021) and this gradually increased with increasing quantities of residue return, which ultimately promote soil MBC (Zhao et al., 2018). Another explanation for higher MBC could be that the residue provides readily mineralisable and hydrolysable carbon for better microbial growth (Samal et al., 2017). Moreover, the incorporation of crop residues into the soil may have a beneficial effect on endogeic (horizontal-burrowing) earthworms because it will act as a food source (Wuest et al., 2005). This is consistent with our observation that it influences the total organic C pool, due to changes in C supplied by crop residues, and ultimately that is reflected in the microbial biomass (Franzluebbers et al., 1999). The present study also observed that higher MBC were found on the surface than in the subsurface layers. The possible reason for this may be the lesser availability of crop residue at a lower soil depth. Moreover, another reason is that zero tillage with residue retention on the topsoil makes the soil cooler and wetter, resulting in lower fluctuations in moisture and temperature (Kalidivgo, 2001) and ultimately encouraging microbial substrates as well as higher MBC (Luna-guidoet al., 2007). Our findings are in agreement with many other researchers (Chen et al., 2020; Zhao et al., 2018). In addition, a reduction in the loss of SOC and a uniform supply of carbon from crop residues act as a source of energy for microorganisms (Kumar and Babalad, 2018). Our study also suggested that there was no significant effect between TCE techniques in relation to MBC. This result was confirmed by other research (Luna-guido et al., 2007) which found that zero tillage on its own does not provide higher MBC compared to zero tillage with residue retained. When comparing two tillage systems with the same level of crop residue retention, the study observed that MBC was higher under strip tillage with residue retention compared to conventional tillage with the incorporation of residue at the surface layer. This may be because microbial biomass was closely connected to the distribution of SOC and the amount of moisture in the soil (Doran et al., 1987; Salinas-Garcia et al., 2001).

3.4.4 The effect of tillage and residue management on physiological properties

The concentration of chlorophyll in the leaf is an important indicator that can be used to determine soil N supply to growing plants during the growing season (Mupangwa et al., 2020).

Our study showed that strip tillage with residue retention/ incorporation generated higher SPAD values than in no residue retention plots. A higher SPAD value in the second year might be partly due to higher rainfall and the residue conserving the moisture. This finding is in line with other researchers (Liu and Wiatrak, 2012) who concluded that there was no significant difference between different tillage systems but found that the value was higher in the season with the highest rainfall. Other findings, for example, Najafinezhad et al. (2015) reported that drought stress reduced the concentration of leaf chlorophyll (SPAD value) by 5.21% compared to normal irrigation. Moreover, Shefazadeh et al. (2012) also found that the chlorophyll concentration in wheat leaves was highly correlated with the soil moisture status. Reductions in chlorophyll might be due to the production of ROS (reactive oxygen species) under oxidative stress which ultimately leads to the degradation of chlorophyll pigments (Sairam and Srivastava, 2002). A decrease in the chlorophyll content was also reported in other crops when the supply of water and nitrogen was limited (Massacci et al., 2008; Paknejad et al., 2007; Lauer and Boyer 1992). In maize, our study showed that the retention of residue caused a significant increase in SPAD values compared to the removal of residue from the plots. These findings are also similar to Najafinezhad et al. (2015) who found that drought stress decreased total chlorophyll by 12.46% in the corn crop. The increase in SPAD value in the residue retention plots may be associated with the increase of moisture retention in the soil, resulting in the prevention of oxidative stress effects, and ultimately, it helps to overcome the harmful influences of drought stress on chlorophyll (Najafinezhad et al., 2015). An increase in chlorophyll content in barley crops by using 4.5 t ha^{-1} residue has been reported by Najafinezhad et al. (2015) as well as in ridge tillage with mulching in winter wheat crops (Li et al., 2018).

3.4.5 The effect of tillage and residue recycling on crop yields and the cropping system

The results of the study demonstrated that STDSR gave lower yield compared to PTR. The lower yield of STDSR was associated with a lower number of panicles and reduced panicle length compared to PTR. Other possible reasons for a lower yield in DSR compared to PTR could be, i) micronutrient deficiency (Fe and Zn) due to aerobic conditions (Singh et al., 2016a) ii) increased weed and insect infestation (Gathala et al., 2011a) iii) moisture deficiency due to higher infiltration rates (Singh et al., 2016a) and iv) the high plant density of DSR needs more mineral nutrients than PTR (Schnier et al., 1990).These findings are similar to Chaki et al. (2021b) who found that the mean decrease in rice yield was 0.83 t ha^{-1} in zero tillage in comparison with PTR in light-textured soil. Similarly, Rashid et al. (2018), who conducted an experiment in light-textured soil in southern Bangladesh, also recorded a 3-4% lower yield in ZT compared to PTR. In contrast, other studies conducted by Haque et al. (2016); Islam et al. (2019) and Saharawat et al. (2010) also compared the performance of PTR and ZT UPTR with fully irrigated conditions, where the ZT UPTR produced a higher yield than or similar yield to PTR. Therefore, there is a need to assess the dynamics of macro-and micronutrients in the soil to achieve an optimum rice yield when PTR is replaced by DSR. Although the DSR plots gave a lower yield, the shorter time the crops spent in the field in DSR (as DSR plots were harvested 7 to 10 days earlier than transplanted rice (Saharawat et al., 2010) might create an opportunity for the timely planting of successional maize crops. However, despite the lower yields in DSR than in PTR, an aerobic rice system requires low input (water, labour, and fuel) (Farooq et al., 2011; Kumar and Ladha, 2011).

In our study, the TCE techniques with rice residue retention/incorporation of either 25% or 50% gave a higher maize yield compared to the removal of all residue from the plots. Our findings agree with Rashid et al. (2019) who concluded that compared with full straw removal, 50% straw retention increased the grain yield of maize by 5%, and Singh et al. (2016b) who also reported that the maize yield under a ZTDSR/ZTM +R system was higher by 4.0% and 14.2% than CTDSR/CTM and PTR/CTM. The higher maize yield under residue retention/incorporation practices might be due to the utilization of mineral N by microorganisms, and in later seasons, increased the efficiency of available N uptake by nutrient recycling (Alam et al., 2020; Jat et al., 2012). Moreover, the higher soil moisture concentrations under ST with residue retention practices are also likely to have contributed to the higher grain and biomass yield compared to conventional tillage practices (Asargew et al., 2022). In addition, the yield was increased in STM after DSR possibly due to avoiding puddling in rice (Gathala et al., 2011b; Hobbs et al., 2002 and Jat et al., 2014), and the fact that the role of crop residues correlated with reducing the adverse impact of terminal heat stress during the reproductive phase (April and May), and provided an optimum soil thermal regime (STR), coupled with better root growth (Singh et al., 2016a). Puddling (wet tillage) in rice forms a hard plough pan, increases the bulk density, disturbs the soil structure, fills the macropores with finer soil particles as well as reducing porosity and increasing soil compaction, which adversely affects upland crops (Sharma et al., 2003 and Gathala et al., 2011a). These results are also consistent with the findings of another researcher, Singh et al. (2016a) who recorded a higher yield in ZT (zero tilled) maize compared to that in CT plots. However, the meta-analysis conducted by Sun et al. (2020) found that semi-arid to humid regions, with $40 \leq HI < 100$, are good for CA-practices and have the potential to enhance SOC in soil (humidity index, "HI"; (average rainfall/mean air temperature). The RM system productivity (rice equivalent yields) generally followed the increasing trend with time, ranging from 5-9% in year 1 to 10-14% in year 2, when crop residue was retained/recycled. These findings are similar to Rashid et al. (2019) who concluded that the highest REY was found from residue retention compared with no retention plots.

3.4.6 The effect of tillage and residue management on profitability

The current study showed that the cost of production for RM was higher in CTPTR/CTM compared to STDSR/STM practices due to the high labour and fuel costs of land preparation for maize, the high cost for transplanting rice seedlings and manually seeding maize crops. In our study, CTPTR practices required the highest (\$1647 ha^{-1}) and STDSR/STM required the lowest input costs (~\$1431 ha^{-1}) in the rice maize system. There could be several explanations for higher production costs in CTPTR including i) higher labour costs associated with activities such as land preparation, transplanting rice, sowing maize, irrigation etc., under CTPTR/CTM practices, ii) machinery costs, especially for puddling which typically required tilling 4–6 times before transplanting rice and 3-4 times before for sowing maize. Our findings are in agreement with others (Gathala et al., 2015; Singh et al., 2014 and Rashid et al., 2019), who compared input costs, e.g. labour and the machinery required for PTR, and STDSR practices, where STDSR involved lower costs compared to PTR. In the current study, regardless of residue retention, the production cost in residue retention plots was lower than in no residue plots. This may be because crop residue cleanup and transportation on the farm needed more labour and fuel. These findings are similar to those of Sarkar et al. (2020), who observed that that removal of crop residues required more labour, effort, and capital.The present study also showed a higher gross return, gross margin, and BCR under strip tillage with residue incorporation/retention than conventional tillage with no residue retention in the plots. This finding is similar to that of other researchers (Parihar et al., 2016; Rashid et al., 2019; Gathala et al., 2011b; Laik et al., 2014). Although such clear benefits were observed from TCE techniques with residue retention/incorporation, but the present study has some limitations for implementing these research findings in farmers fields as our analysis is based on data from a research station experiment on a small plot of 35 m^2. Our study suggests that economic analysis in the future could be conducted by research station experiments on larger plots.

3.4.7 Practical applications for climate change mitigation and future research

Given the current climate change issues, the implementation of a CA-based agricultural system is one of the most essential ways to decrease the expected increase of GHG emissions in the atmosphere. Since the CA-based systems improve soil health and organic carbon stocks by fostering soil carbon sequestration by incorporating crop residue and also minimum disturbance of soils. However, CA may not absorb more carbon over time than conventional systems if all CA principles, such as minimum soil disturbance, permanent soil organic cover with crop residues and/or cover crops and crops diversification are not followed properly. The current study revealed that crop residue retention is essential for enhancing soil organic carbon in RM rotation. Providing incentives to farmers based on carbon footprint/storage and other ecosystem services through residue retention is a viable technique for encouraging the adoption of CA technology in tropical and temperate climatic regions. However, it is recognized that these results represent only two years of a field experiment, and a longer period of the study is needed to assess the performance of ZTDSR/ZTM with varying rates of crop residue mulch in RM systems in diverse soil, climatic, and socio-economic conditions. Besides longer experiments, cropping system simulation studies accounting for the impact of climate change on soil and crop variables might be needed to give greater insights into the long-term impacts of tillage and residue management on sandy soil under RM systems in Bangladesh.

3.5 Conclusions

Adoption of conservation agricultural techniques in the study areas has a tremendous effect on the crop profitability of farmers, particularly on sandy loam soils in North-Western Bangladesh. The sustainable intensification practices assessed in this study address the issue of declining soil fertility, especially the decline in organic carbon, microbial biomass carbon and increased soil compaction, etc. We found that strip tillage direct-seeded rice (STDSR), followed by strip-tilled maize (STM) with partial residue retention/incorporation (+R) from both the crops, improved SOC content and the soil physical properties, namely soil bulk density, porosity, soil penetrometer resistance, soil moisture, and other soil and crop parameters, especially microbial biomass carbon and chlorophyll content. Our results showed a decrease in bulk density (4.3-6.9%) and penetration resistance (15.9-30.7%), and an increase in organic carbon (23.6-35.3%), soil moisture content (11.1-21.3%), and porosity (16.1-32.5%) compared to a conventional tillage-based rice-maize rotation in sandy soil. It was also observed that soil biological health, i.e., microbial biomass carbon (4-9%), and physiological parameters like leaf chlorophyll concentration, had significantly improved in STDSR/STM compared to PTR/CTM. Furthermore, puddling in rice with residue removal practices showed a negative impact on soil properties for maize production. The overall improvement in soil conditions resulted in gradually enhanced crop productivity, particularly for maize in ST plots, and improved farm profitability compared to conventionally tilled rice and maize crops. Therefore, to maintain soil health and high crop productivity, residue inputs should be combined with the use of appropriate tillage techniques. However, for organic matter to build up in sandy soil, more emphasis should be put on the addition of organic resources, such as keeping at least 25-50% of crop residues and incorporating them into the soil.

References

Abdallah, A.M., Jat, H.S., Choudhary, M., Abdelaty, E.F., Sharma, P.C., and Jat, M.L. (2021). Conservation Agriculture Effects on Soil Water Holding Capacity and Water-Saving Varied with Management Practices and Agroecological Conditions: A Review. Agronomy, 11:1681. https://doi.org/10.3390/ agronomy11091681.

Abdullah, A.S. (2014). Minimum tillage and residue management increase soil water content, soil organic matter and canola seed yield and seed oil content in the semiarid areas of Northern Iraq, Soil and Tillage Research, 144: 150-155.

Alam, M. K., Islam, M. M., Salahin, N., and Hasanuzzaman, M. (2014). Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping system under subtropical climatic conditions. Scientific World Journal, 2014.

Alam, M.K., Bell, R.W., Haque, M.E., Islam, M.A., and Kader, M.A. (2020). Soil nitrogen storage and availability to crops are increased by conservation agriculture practices in rice–based cropping systems in the Eastern Gangetic Plains. Field Crops Res. 250: 107764.

Alam, M.K., Bell, R.W., Haque, M.E., Islam, M.A., and Kader, M.A. (2020). Soil nitrogen storage and availability to crops are increased by conservation agriculture practices in rice–based cropping systems in the Eastern Gangetic Plains. Field Crops Res. 250: 107764.

Ali, M. Y. (2006). Rice-maize systems in Bangladesh. Invited Oral Presentation in the Workshop on Assessing the Potential of Rice-Maize Systems in Asia. IRRI-CIMMYT Alliance Program for Intensive Production Systems in Asia, held December 4-8, IRRI, Los Baños, Philippines

Ali, M.Y., Waddington, S.R., Hodson, D., Timsina, J. and Dixon, J. (2008). Maize-Rice Crop-ping Systems in Bangladesh: Status and Research Opportunities. CIMMYT–IRRI Joint Publication, Mexico, page 36.

Asargew, F., Tsunekawa, A., and Haregeweyn, N. (2022). International Soil and Water Conservation Research Tillage and crop management impacts on soil loss and crop yields in northwestern Ethiopia. International Soil and Water Conservation Research, 10 (1): 75–85.

Bahrani, MJ., Raufat, MH., and Ghadiri, H. (2007). Influence of wheat residue management on irrigated corn grain production in a reduced tillage system. Soil till Res. 94(2):305–309. doi: 10.1016/j.still.2006.08.004.

Baker, J.M., Ochsner, T.E., Venterea, R.T.and Griffis, T.J. (2007). Tillage and soil carbon sequestration – what do we really know? Agric. Ecosys. Environ. 118: 1–5.

BARC (2015). Fertilizer Recommendation Guide for Bangladesh. Bangladesh Agricultural Research Council, Farm Gate, Dhaka, Bangladesh.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47: 151–163.

BBS (2017). Ministry of Planning. Govt. of Bangladesh, Dhaka.

BBS (2022). Ministry of Planning. Govt. of Bangladesh, Dhaka.

Bhattacharyya, R., Das, T.K., Sudhishri, S., Dudwal, B., Sharma, A.R., Bhatia, A., and Singh, G. (2015). Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. Eur. J. Agron. 70: 11–21.

Bhattacharyya, Ranjan & Tuti, Mangal & Kundu, S. & Bisht, Jaideep and Bhatt, J.C. (2013). Conservation Tillage Impacts on Soil Aggregation and Carbon Pools in a Sandy Clay Loam Soil of the Indian Himalayas. Soil Science Society of America Journal. 76.: 617-627. Doi.10.2136/sssaj2011.0320.

Black, C. A. (1965). Method of Soil Analysis Part-I and II, American Society of Agronomy, Madison, Wis, USA.

Blair, N., Faulkner, R. D., Till, A. R., and Poulton, P. R. (2006). Long-term management impacts on soil C, N and physical fertility Part I: Broadbalk experiment, 91: 30–38.

Blanco-Canqui, H., and Lal, R. (2007a). No-tillage and soil-profile carbon sequestration: an on- farm assessment. Soil Sci. Soc. Am. J. 72: 693–701.

Bouyoucos, G.J. (1962). Hydrometer Method Improved for Making Particle Size Analysis of Soils. Agronomy Journal, 54: 464-465.

Busari, M.A., Salako, F.K., Tuniz, C., Zuppi, G.M., Stenni, B., Adetunji, M.T., and Arowolo, T.A. (2013). Estimation of soil water evaporative loss after tillage operation using the stable isotope technique. Int. Agrophys, 27: 257–264.

Chaki, A. K., Gaydon, D. S., Dalal, R. C., Bellotti, W. D., Gathala, M. K., Hossain, A., and Menzies, N. W. (2021a). Conservation agriculture enhances the rice-wheat system of the Eastern Gangetic Plains in some environments, but not in others. Field Crops Research, 265: 108109.

Chaki, AK., Gaydon, DS., Dalal, RC., Bellotti, WD., Gathala, MK., Hossain, A., Siddquie, N-E-A., and Menzies, NW. (2021b). Puddled and zero-till unpuddled transplanted rice are each best suited to different environments – An example from two diverse locations in the Eastern Gangetic Plains of Bangladesh. Field Crops Res, 262:108031.

Chalise, K. S., Singh, S., Wegner, B. R., Kumar, S., Pérez-Gutiérrez, J. D., Osborne, S. L., and Rohila, J. S. (2019). Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. Agronomy Journal, 111(1): 99–108. https://doi.org/10.2134/ agronj2018.03.0213

Chen, H., Dai, Z., Veach, A. M., Zheng, J., Xu, J., and Schadt, C. W. (2020). Global meta-analyses show that conservation tillage practices promote soil fungal and bacterial biomass. Agriculture, Ecosystems and Environment, 293:106841.

Chivenge, P., Murwira, H., Giller, K., Mapfumo, P., and Six, J. (2007). Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Till. Res. 94: 328–337.

Coppens, F., Garnier, P., Findeling, A., Merckx, R., and Recous, S. (2007). Decomposition of mulched versus incorporated crop residues: modelling with PASTIS clarifies interactions between residue quality and location. Soil Biol Biochem, 39:2339–2350. doi:10.1016/j. soilbio.2007.04.005

Curaqueo, G., Barea, J. M., Acevedo, E., Rubio, R., Cornejo, P., and Borie, F. (2011). Effects of different tillage system on arbuscular mycorrhizal fungal propagules and physical properties in a Mediterranean agroecosystem in central Chile. Soil and Tillage Research, 113(1): 11–18. doi.10.1016/j.still.2011.02.004

Dong, W., Hu, C., Chen, S. and Zhang, Y. (2009). Tillage and residue management effects on soil carbon and CO_2 emission in a wheat–corn double-cropping system. Nutr. Cycl. Agroecosyst,83: 27–37.

Doran (1987). Microbial biomass and mineralizable nitrogen distribution in no tillage and plowed soils. Biol. Fertil. Sols, 5: 68-75.

Erenstein, O. (2002). Crop residue mulching in tropical and semi tropical countries. An evaluation of residue availability and other technological implications. Soil and Tillage Research, 67(2): 115-133.

FAO (2001). The Economics of Conservation Agriculture. FAO Document Repository.

FAO/UNDP (1988). Food and Agricultural Organization/United Nations Development Programme, Land resources appraisals of Bangladesh for agricultural development. Agro-ecological regions of Bangladesh. Rome, FAO. (Report No. 2).

Farooq, M., Siddique, K. H. M., Rehman, H., Aziz, T., Lee, D. J., and Wahid, A. (2011). Rice direct seeding: Experiences, challenges and opportunities. Soil and Tillage Research, 111(2): 87–98. https://doi.org/10.1016/j.still.2010.10.008

Fontaine, S., Barot, S., Barre, P., Bdioui, N., Mary, B., and Rumpel, C. (2007). Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature, 450: 277–280.

Franzluebbers, A., Haney, R., Hons, F., and Zuberer, D. (1999). Assessing biological soil quality with chloroform. Can. J. Soil. Sci, 79: 521–528.

Galdos, M., Cerri, C.C., Cerri, E. P., Paustian, K. and Antwerpen, R. (2009). Simulation of sugarcane residue decomposition and aboveground growth. Plant and Soil, 326: 243-259. 10.1007/s11104-009-0004-3.

Gathala, M. K., Timsina, J., Islam, M. S., Rahman, M. M., Hossain, M. I., Harun-Ar-Rashid, M., and McDonald, A. (2015). Conservation agriculture-based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice-maize systems: Evidence from Bangladesh. Field Crops Research,

Gathala, M.K., Alison, M. Laing., T.P. Tiwari., J. Timsina., Md. S. Islam., A.K. Chowdhury., C. Chattopadhyay., A.K. Singh., B.P. Bhatt., R. Shrestha., N.C.D. Barma., D.S. Rana., Tamara. M., and Jackson, B. Gerard. (2020). Enabling smallholder farmers to sustainably improve their food, energy and water nexus while achieving environmental and economic benefits. Renewable and Sustainable Energy Reviews. 120:109645.

Gathala, M.K., Ladha, J.K., Kumar, V., Saharawat, Y.S., Kumar, V., Kumar, V., and Sharma, P. K. (2011a). Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice-wheat rotation. Soil Sci. Soc. Am. J. 75: 1851–1862.

Gathala, M.K., Ladha, J.K., Kumar, V., Saharawat, Y.S., Kumar, V., Sharma, P.K., Sharma, S., and Pathak, H. (2011b). Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron. J, 103: 961–971.

Ghimire, R., Bista, P., and Machado, S. (2019). Long-term management effects and temperature sensitivity of soil organic carbon in grassland and agricultural soils. Sci. Rep. 9: 12151.doi.org/10.1038/s41598-019-48237-7.

Gmach, M.R., Cherubin, M.R., Kaiser, K., and Cerri, C.E.P. (2019). Processes that influence dissolved organic matter in the soil: a review. Sci. Agric. https://doi.org/10.1590/ 1678-992X-2018-0164.

Gupta Choudhury, S., Srivastava, S., Singh, R., Chaudhari, S. K., Sharma, D. K., Singh, S. K., and Sarkar, D. (2014). Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil and Tillage Research. doi.10.1016/j.still.2013.10.001

Haque, M.E., Bell, R.W., Islam, M.A. and Rahman, M.A. (2016). Minimum tillage unpuddled transplanting: an alternative crop establishment strategy for rice in conservation agriculture cropping systems. Field Crops Res. 185: 31–39. doi.10. 1016/j.fcr.2015.10.018

He, J., Q,Wang., and H, Li . (2009). Soil physical properties and infiltra- tion after long-term no-tillage and ploughing on the Chinese Loess Plateau. New Zealand Journal ofCrop and Horticultural Science, 37(3):157–166.

Hobbs, P.R., Singh, Y., Giri, G.S., Lauren, J.G., and Duxbury, J.M. (2002). Direct seeding and reduced tillage options in the rice-wheat systems of the IndoHi -Gangetic Plains of South Asia. In: Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopez, K., Hardy, B. (Eds.), Direct Seeding: Research Strategies and Opportunities. IRRI, Los Ba˜nos, page 201–215.

Huang, M., Yingbin, Z., Peng, J., Bing, X., Feng, Y., Cheng, Z., and Yali, M. (2012). Effect of tillage on soil and crop properties of wet-seeded flooded rice. Field Crops Res, 129: 28–38.

lslam, S., Gathala, M.K., Tiwari, T.P., Timsina, J., Laing, A.M., Maharjan, S., Chowdhury, A.K., Bhattacharya, P.M., Dhar, T., Mitra, B., Kumar, S., Srivastwa, P.K., Dutta, S.K., Shrestha, R., Manandhar, S., Sherestha, S.R., Paneru, P., Siddquie, N.-E. A., Hossain, A., Islam, R., Ghosh, A.K., Rahman, M.A., Kumar, U., Rao, K.K., and G´erard, B. (2019). Conservation agriculture based sustainable intensification: increasing yields and water productivity for smallholders of the Eastern Gangetic Plains. Field Crops Res, 238: 1–17

Jackson, M.L. (1973). Soil Chemical Analysis, Constable and Co. Ltd. Prentice Hall of India Pvt. Ltd, New Delhi, India.

Jat, M.L., Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Jat, A.S., Kumar, V., Sharma, S.K., Kumar, V., and Gupta, R.K. (2009). Evaluation of precision land leveling and double zero-till systems in the rice-wheat rotation: Water use, productivity, profitability and soil physical properties. Soil Tillage Res, 105: 112–121.

Jat, M.L., Gathala, M.K., Saharawat, Y.S., Tetarwal, J.P., Gupta, R. and Yadvinder, Singh. (2013). Double no-till and permanent raised beds in maize–wheat rotation of north-western Indo-Gangetic plains of India: Effects on crop yields, water productivity, profitability and soil physical properties. Field Crops Res, 149: 291–299.

Jat, R.A., Wani, S.P., and Sahrawat, K.L. (2012). Conservation agriculture in the semi-arid tropics: prospects and problems. Adv. Agron, 117: 191–273. https://doi.org/10.1016/b978-0-12-394278-4.00004-0.

Jat, R.K., Sapkota, T.B., Singh, R.G., Jat, M.L., Kumar, M., and Gupta, R.K. (2014). Seven years of conservation agriculture in a rice-wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. Field Crops Res, 164: 199–210.

Kader, M. A., Senge, M., Mojid, M. A., and Nakamura, K. (2017). Mulching type-induced soil moisture and temperature regimes and water use efficiency of soybean under rain-fed condition in central Japan. International Soil and Water Conservation Research, 5(4): 302–308.

Kaiser, K. (2003). Dissolved organic phosphorus and sulphur as influenced by sorptive interactions with mineral subsoil horizons. Eur J Soil Sci, 52:489–93.

Kaldivgo, E.J. (2001). Tillage systems and soil ecology. Soil Till. Res, 61: 61–76.

Karim, Z., Rahman, S.M., Ali, M.I., Karim A.J. (1988). Soil Bulk Density. A Manual for Determination of Soil Physical Parameters, Soils and Irrigation Division, BARC.

Kozak, J.A., Aiken, R.M., Flerchinger, G.N., Nielsen, D.C., and L, Ma. (2007). Ahuja Comparison of modeling approaches to quantify residue architecture effects on soil temperature and water Soil Till. Res, 95: 84-96.

Kahlon, M. S., Lal, R., and Ann-Varughese, M. (2013). Twenty-two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil and Tillage Research, 126: 151–158.

Krupnik, T.J., Santos, V. S., McDonald, A.J., Justice, S., Hossain, I., and Gathala, M.K. (2013). Made in Bangladesh: Scale-Appropriate Machinery for Agricultural Resource Conservation. CIMMYT, Mexico D.F, page 126

Krupnik, T.J., Yasmin, S., Pandit, D., Asaduzzaman, M., Khan, S.I., Majumdar, K., McDonald, A., Buresh, R., and Gathala, M.K. (2014). Yield performance and agronomic N efficiency of a maize-rice rotation under strip and conventional tillage in contrasting environments in Bangladesh. In: World Congress 6 on Conservation Agriculture, 22–25 June, Winnipeg, MB, Canada

Kucharik, C.J. (2006). A multidecadal trend of earlier corn planting in the central USA. Agron. J. 98, 1544–1550.

Kumar, B. T. N., and Babalad, H. B. (2018). Soil Organic Carbon, Carbon Sequestration, Soil Microbial Biomass Carbon and Nitrogen and Soil Enzymatic Activity as Influenced by Conservation Agriculture in Pigeonpea and Soybean Intercropping System, Int. J. Curr. Microbiol. App. Sci, 7(3): 323-333.

Kumar, V., and JK, Ladha. (2011). Direct-seeding of rice: Recent developments and future research needs. Adv. Agron, 111: 297–413. doi:10.1016/ B978-0-12-387689-8.00001-1

Kumawat, A., Vishwakarma, A. K., Wanjari, R. H., Sharma, N. K., Kumar, D., Biswas, A. K. (2022). Impact of levels of residue retention on soil properties under conservation agriculture in Vertisols of central India Impact of levels of residue retention on soil properties under conservation agriculture in Vertisols of central India. Archives of Agronomy and Soil Science, 68(3): 368–382.

Kushwaha, C.P., Tripathi, S.K., and Singh, K.P. (2001). Soil organic matter and water-stable aggregates under different tillage and residue conditions in a tropical dryland agroecosystem. Appl. Soil Ecol, 16: 229–241.

Laik, R., Sharma, S., Idris, M., Singh, A.K., Singh, S.S., Bhatt, B.P., Saharawat, Y., Humphreys, E., and Ladha, J.K. (2014). Integration of conservation agriculture with best management practices for improving system performance of the rice– wheat rotation in the Eastern Indo-Gangetic Plains of India. Agric. Ecosys. Environ, 195: 68–82.

Lal, R. (2000). Mulching effects on soil physical quality of an alfisols in western Nigeria. Land Degradation & Development ,11: 383–392.

Lampurlanés, J., and Cantero-Martínez, C. (2003). Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth. Agronomy Journal, 95 (3): 526–536.

Lauer, M.J., and Boyer, JS. (1992). Internal CO_2 measured directly in leaves: abscisic acid and low leaf water potential cause opposing effects. Plant Physiol, 98:1310–1316. doi:10.1104/pp.98.4.1310

Lenka, S., Lenka, N.K., Singh, R.C. (2015). Tillage and Manure Induced Changes in Carbon Storage and Carbon Management Index in Soybean–Wheat Cropping System in the Vertisols of Central India. *Natl. Acad. Sci*. Lett, 38:461–464. Doi.10.1007/s40009-015-0384-2

Li, N., Zhou, C., Sun, X., Jing, J., Tian, X., and Wang, L. (2018). Effects of ridge tillage and mulching on water availability, grain yield, and water use efficiency in rain-fed winter wheat under different rainfall and nitrogen conditions. Soil & Tillage Research, 179: 86–95.

Li, Y., Li, Z., Cui, S., Jagadamma, S., and Zhang, Q. (2019). Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis. Soil Tillage Res, 194: 104292

Liang, A.Z., Zhang, X.P., Fang, H.J., Yang, X.M., and Drury, C.F. (2007). Short-term effects of tillage practices on organic carbon in clay loam soil of northeast China. Pedosphere, 17: 619–623.

Lindsay, W. L., and WA, Norvell. (1978). Development of a DTPA test for zinc, iron, manganese, and copper. Soil Science Society of American Journal, 42:421–428.

Liu S.P., Zhang H.C., Dai Q.G., Huo Z.Y., Xu K., and Ruan H, F. (2005). Effects of no-tillage plus interplanting and remaining straw on the field on crop land eco environment and wheat growth. Chinese Journal of Applied Ecology, 16:393-396.

Liu, E., Ghirmai, S., Yan, C., Yu, J., Gu, R., Liu, S., and Liu, Q. (2014). Long-term effects of no-tillage management practice on soil organic carbon and its fractions in the northern China. Geoderma, 213: 379–384.

Liu, K., and Wiatrak, P. (2012). Corn production response to tillage and nitrogen application in dry-land environment. Soil Tillage Res, 124: 138–143.

Lu, X. (2020). A meta-analysis of the effects of crop residue return on crop yields and water use efficiency. PLoS ONE, 15, e0231740

Luna-guido, M., Crossa, J., Ceja, J., and Jat, R. A. (2007). Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. https:doi.org/10.1016/j. apsoil.2007.03.006

Luo, Z., Wang, E., Sun, O.J. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ, 139 (1–2): 224–231.

Marongwe, L.S., Nyagumbo, I., Kwazira, K., Kassam, A., and Friedrich, T. (2012). Conservation Agriculture and Sustainable Crop Intensification: A Zimbabwe Case Study, Integrated Crop Management. Plant Production and Protection Division, Food and Agriculture Organization of the United Nations, Rome.

Massacci, A., Nabiev, SM., Pietrosanti, L., Nematov, SK., Chernikova, TN., and Thor K, Leipner J. (2008). Response of the photosynthetic apparatus of cotton (Gossypium hirsutum) to the onset of drought stress under field conditions studied by gas-exchange analysis and chlorophyll fluor- escence imaging. Plant Physiol Biochem, 46:189–195. doi: 10.1016/j.plaphy.2007.10.006

Mirzaei, M., Anari, M. G., Razavy-toosi, E., & Asadi, H. (2021). Preliminary Effects of Crop Residue Management on Soil Quality and Crop Production under Different Soil Management Regimes in Corn-Wheat Rotation Systems. Agronomy, 11:302.

Mupangwa, W., Thierfelder, C., Cheesman, S., Nyagumbo, I., Muoni, T., Mhlanga, Ngwira, A. (2020). Effects of maize residue and mineral nitrogen applications on maize yield in conservation-agriculture-based cropping systems of Southern Africa. Renewable Agriculture and Food Systems, 35(3): 322-335.

Najafinezhad, H., Sarvestani, Z. T., and Ali, S. (2015). Evaluation of yield and some physiological changes in corn and sorghum under irrigation regimes and application of barley residue, zeolite and superabsorbent polymer. Archives of Agronomy and Soil Science, 61(7): 891–906.

Naresh, R. K., Chandra, M. S., Baliyan, A., Pathak, S. O., Kanaujiya, P. K., Kumar, B. N., and Singh, P. K. (2021). Impact of Residue Incorporation on Soil Carbon Storage, Soil Organic Fractions, Microbial Community Composition and Carbon Mineralization in Rice-wheat Rotation – A Review. International Journal of Environment and Climate Change, 42:59.

Nasim, M., S.M. Shahidullah., A, Saha., MA, Muttaleb., TL.,Aditya., MA,. Ali., and M S, Kabir. (2017). Distribution of crops and cropping patterns of Bangladesh. Bangladesh Rice Journal, 21 (2): 1-55

Nobuhisa, K., and Hiroyuki, T. (2009). Effects of reduced tillage, crop residue management and manure application practices on crop yields and soil carbon sequestration on an Andisol in northern Japan. Soil Sci. Plant Nutr, 55: 546–557.

Page, A. L., Miller, R. H. and Kuny, D. R. (1982). Methods of Soil Analysis. Part 2. 2^{nd} edn., American Soc. Agron., Inc., Soil Sci. Soc. American Inc. Madison, Wisconsin, USA. page 403-430.

Page, A.L., R. H. Miller., and DR, Kuny. (1989). Methods of Soil Analysis. Part 2, American Society of Agronomy, Soil Science Society of America, Madison, Wis, USA, 2nd edition.

Paknejad, F., Nasri, M., Tohidi, Moghadam HR., Zahedi, H., and Jami, Alahmadi M. (2007). Effects of drought stress on chlorophyll fluorescence parameters, chlorophyll content and grain yield of wheat cultivars. J Biol Sci, 7:841–847.

Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., and Pradhan, S. (2016). Conservation agriculture in irrigated intensive maize-based systems of north-western India. Effects on crop yields, water productivity and economic profitability. Field Crops Research, 193: 104–116. doi.org/10.1016/j.fcr.2016.03.01

Patra, S., Julich, S., Feger, K.H., Jat, M.L., Jat, H., Sharma, P.C., and Schwärzel, K. (2019). Soil hydraulic response to conservation agriculture under irrigated intensive cereal-based cropping systems in a semiarid climate. Soil Tillage Res, 192: 151–163

Popat, R., and Banakara, K. (2020). DoE bioresearch: Analysis of Design of Experiments for Biological Research. R package version 0.1.0

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L., and Corbeels, M. (2017). Agro-ecological functions of crop residues under conservation agriculture. A review. Agronomy for Sustainable Development, 37(4). https://doi.org/10.1007/s13593-017-0432

Rashid, M.H., Timsina, J., Islam, N. and Islam, S. (2019). Tillage and residue-management effects on productivity, profitability and soil properties in a rice-maize-mungbean system in the Eastern Gangetic Plains. Journal of Crop Improvement, 33(5): 683-710.

Rashid, M. H., Goswami, P. C., Hossain, M. F., Mahalder, D., Rony, M. K. I., Shirazy, B. J., et al. (2018). Mechanised non-puddled transplanting of boro rice following mustard conserves resources and enhances productivity. Field Crops Res. 225, 83–91.

Reicosky, D.C., Dugas, W., and Torbert, H. (1997). Tillage-induced soil carbon dioxide loss from different cropping systems. Soil Till. Res. 41: 105–118.

R Core Team (2020). R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at: https://www. R-project.org/.

Robertson, A. D., Paustian, K., Ogle, S., Wallenstein, M. D., Lugato, E., and Cotrufo, M. F. (2019). Unifying soil organic matter formation and persistence frameworks: the MEMS model, 1225–1248.

Roose, E., and Barthes, B. (2001). Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nut. Cycl. Agroecosyst, 61: 159–170. doi: 10.1023/A:1013349731671

Roy, D., Datta, A., and Choudhary, M. (2022). Impact of long-term conservation agriculture on soil quality under cereal based systems of North West India Geoderma Impact of long-term conservation agriculture on soil quality under cereal based systems of North West India, (January). doi.10.1016/j.geoderma.2021.115391

Saha, S., Chakraborty, D., Sharma, A. R., Tomar, R. K., Bhadraray, S., Sen, U., andKalra, N. (2010). Effect of tillage and residue management on soil physical properties and crop productivity in maize (Zea mays)-Indian mustard (Brassica juncea) system. Indian Journal of Agricultural Sciences, 80(8): 679–685.

Saharawat, Y. S., Singh, B., Malik, R. K., Ladha, J. K., Gathala, M., Jat, M. L., and Kumar, V. (2010). Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Research, 116 (3): 260–267.

Sairam, R.K., and Srivastava, G.C. (2002). Changes in antioxidant activity in sub-cellular fractions of tolerant and susceptible wheat genotypes in response to long-term salt stress. J Plant Sci, 162:897–904. doi:10.1016/S0168-9452(02)00037-7

Salahin, N., JahirUddin, M., Islam, M.R., Alam, M., K., Haque, M.E., Ahmed, S., Baazeem, A., Hadifa, A., EL Sabagh, A., and Bell, R.W. (2021). Establishment of Crops under Minimal Soil Disturbance and Crop Residue Retention in Rice-Based Cropping System: Yield Advantage, Soil Health Improvement, and Economic Benefit. Land, 10: 581. doi.org/10.3390/ land10060581

Salinas-Garcia, J.R., Baez-Gonzalez, A.D., Tiscareno-Lopez, M., and Rosales-Robles, E. (2001). Residue removal and tillage interaction effects on soil properties under rain-fed corn production in central Mexico. Soil Till. Res, 59: 67–79.

Samal, S. K., Rao, K. K., Poonia, S. P., Kumar, R., Mishra, J. S., Prakash, V., Mc Donald, A. (2017). Evaluation of long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-Gangetic Plains of South Asia: Carbon dynamics and productivity. European Journal of Agronomy, 198:208. doi.org/10.1016/j.eja.2017.08.006

Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., Brahmachari, K. (2020). Management of crop residues for improving input use efficiency and agricultural sustainability. Sustainability, 12 (23): 1–24.

Sasal, M.C., Andriulo, A.E., and Taboada, M.A. (2006). Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. Soil Tillage Res, 87: 9–18.

Saurabh, K., Rao, K. K., Mishra, J. S., Kumar, R., Poonia, S. P., Samal, S. K., and Malik, R. K. (2021). Influence of tillage-based crop establishment and residue management practices on soil quality indices and yield sustainability in rice-wheat cropping system of Eastern Indo-Gangetic Plains. Soil and Tillage Research, 206: 104841.

Saviozzi, A., Levi-Minzi, R., Cardelli, R., and Riffaldi, R. (2001). A comparison of soil quality in adjacent cultivated, forest and native grassland soils. Plant Soil, 233: 251–259.

Schnier, H.F., Dingkuhn, M., De Datta, S.K., Mengel, K., and Faronilo, J.E. (1990). Nitrogen fertilization of direct-seeded flooded vs. transplanted rice: I. nitrogen uptake, photosynthesis, growth, and yield. Crop Sci, 30: 1276–1284.

Shapiro, S.S., and Wilk, M.B. (1965). An analysis of variance test for normality (complete samples). Biometrika, 52 (3/4): 591–611.

Sharma, P.K., and De Datta, S.K. (1986). Physical properties and processes of puddled rice soils. Adv. Soil Sci, 5: 139–178.

Sharma, P.K., Ladha, J.K., and Bhushan, L. (2003). Soil physical effects of puddling in rice– wheat cropping system. In: Ladha, J.K., et al. (Ed.), Improving the productivity and sustainability of rice–wheat systems: Issues and impacts. ASA Spec. Publ. 65, ASA, CSSA and SSSA, Madison WI, page 97–114.

Shefazadeh, M.K., Karimizadeh, R., Mohammadi, M., and Suq, H.S. (2012). Using flag leaf chlorophyll content and canopy temperature depression for determining drought resistant durum wheat genotypes. J. Food Agric. Environ, 10: 509–515.

Singh, D., Lenka, S., Lenka, N. K., Trivedi, S. K., Bhattacharjya, S., Sahoo, S., and Patra, A. K. (2020). Effect of reversal of conservation tillage on soil nutrient availability and crop nutrient uptake in soybean in the vertisols of central India. Sustainability, 12(16). https://doi.org/10.3390/su12166608

Singh, M., Lal, R., and Ann-varughese, M. (2013). Soil & Tillage Research Twenty-two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil & Tillage Research, 126: 151–158.

Singh, R.C., Lenka, S., and Singh, CD. (2014). Conservation tillage and manure effect on soil aggregation, yield and energy requirement for wheat (*Triticum aestivum*) in vertisols. Indian Journal of Agricultural Sciences, 84: 267-271.

Singh, V. K., Yadvinder-Singh, Dwivedi, B. S., Singh, S. K., Majumdar, K., Jat, Mishra, P.R., and Rani, M. (2016). Soil physical properties, yield trends and economics after five years of conservation agriculture-based rice-maize system in north-western India. Soil and Tillage Research, 155: 133–148. doi.org/10.1016/j.still.2015.08.001

Snedecor, G.W., and Cochran, W.G. (1989). Statistical Methods, eighth edition. Iowa State University Press.

Sokolowski, A. C., Prack McCormick, B., De Grazia, J., Wolski, J. E., Rodríguez, H. A., Rodríguez-Frers, E. P., and Barrios, M. B. (2020). Tillage and no-tillage effects on physical and chemical properties of an Argiaquoll soil under long-term crop rotation in Buenos Aires, Argentina. International Soil and Water Conservation Research, 8(2): 185–194. doi.org/10.1016/j.iswcr.2020.02.002

Song, K., Yang, J., and Xue, Y. (2016). Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. Sci Rep, 6: 36602. doi.org/10.1038/srep36602

Stewart, P.R., Dougill, A.J., Thierfelder, C., Pittelkow, C.M., Stringer, L.C., Kudzala, M., and Shackelford, G.E. (2018). The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. Agric. Ecosyst. Environ, 251: 194–202.

Sun, W., Canadell, J.G., Yu, L., Yu, L., Zhang, W., Smith, P., Fischer, T., and Huang, Y. (2020). Climate drives global soil carbon sequestra'tion and crop yield changes under conservation agriculture. Glob. Chang. Biol, 26: 3325–3335

Tangyuan, N., Bin, H., Nianyuan, J., Shenzhong, T., and Zengjia, L. (2009). Effects of conservation tillage on soil porosity in maize-wheat cropping system. Plant Soil Environ, 55: 327-333.

Timsina, J., Jat, M.l. and Majumdar, K. (2010). Rice-maize systems of South Asia: Current status, future prospects and research priorities for nutrient management. Plant and Soil, 335: 65-82. doi: 10.1007/s11104-010-0418

Timsina, J., Wolf, J., Guilpart, N., Van Bussel, L.G.J., Grassini, P., Van Wart, J., Hossain, A., Rashid, H., Islam, S. and Van Ittersum, M.K. (2018). Can Bangladesh produce enough cereals to meet future demand? Agricultural Systems, 163: 36-44.

Timsina, J.and Connor, D.J. (2001). The productivity and management of rice-wheat cropping systems: issues and challenges. Field Crops Res, 69: 93–132.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N., and Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. Agricultural Systems, doi.org/10.1016/j.agsy.2014.05.009

Uddin, M.J., Hooda, P.S., Mohiuddin, A.S.M., Smith, M., and Waller, M. (2019). Land inundation and cropping intensity influences on organic carbon in the agricultural soils of Bangladesh. Catena ,178: 11–19.

Vance, E. D., Brookes, P. C., and Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass C. Soil Biology and Biochemistry, 19(6): 703–707.

Vanden Bygaart, A.J.and Angers, D.A. (2006). Towards accurate measurements of soil organic carbon stock change in agroecosystems. Can. J. Soil. Sci, 86: 465–471.

Vasconcelos, A.L.S., Cherubin, M.R., Feigl, B.J., Cerri, C.E., Gmach, M.R., Siqueira-Neto, M. (2018). Greenhouse gas emission responses to sugarcane straw removal. Biomass Bioenerg, 113: 15–21.

Verhulst, Nele ., Nelissen, Victoria., Jespers, Niels., Haven, Heleen., Sayre, Ken., Deckers, Jozef., and Govaerts, B. (2011). Soil water content, maize yield and its stability as affected by tillage and crop residue management in rainfed semi-arid highlands. Plant and Soil, 344: 73–85.

Wu, L., Swan, J.B., Paulson, W.H., and Randall, G.W. (1992). Tillage effects on measured soil hydraulic properties. Soil Tillage Res, 25: 17–33.

Ward, P.R., M.M. Roper, R. Jongepier., and M.M.A, Fernandez. (2013). Consistent plant residue removal causes decrease in minimum soil water content in a Mediterranean environment. Biologia, 68: 1128-1131.

Wuest, S., Caesar Ton That, T., Wright, S.F., and Williams, J. (2005). Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil. Soil Till. Res, 84: 154–167.

Yang, C.M., Yang, L.Z., and Zhu, O.Y. (2005). Organic carbon and its fractions in paddy soil as affected by different nutrient and water regimes. Geoderma, 124: 133–142.

Zeng, R., Wei, Y., Huang, J., Chen, X., and Cai, C. (2021). Soil organic carbon stock and fractional distribution across central-south China. International Soil and Water Conservation Research, 9(4): 620–630. doi.org/10.1016/j.iswcr.2021.04.004

Zhao, S. C., Huang, S. W., Qiu, S. J., and He, P. (2018). Response of soil organic carbon fractions to increasing rates of crop residue return in a wheat-maize cropping system in north-central China. Soil Research, 56(8): 856–864. https://doi.org/10.1071/SR18123

Zhao, X., Liu, B.Y., Liu, S.L., Qi, J.Y., Wang, X., Pu, C., Li, S.S., Zhang, X.Z., Yang, X.G., and Lal. (2020). Sustaining crop production in China's cropland by crop residue retention: A meta-analysis. L. Degrad. Dev, 31: 694–709.

Zhao, X., Xue, J.F., Zhang, X.Q., Kong, F.L., Chen, F., Lal, R., and Zhang, H.L. (2015). Stratification and storage of soil organic carbon and nitrogen as affected by tillage practices in the North China Plain. PLoS ONE, 10 (6): e0128873.

Chapter 4

Assessing the long-term impact of conservation agriculture on rice-maize systems in Bangladesh under climate change using the APSIM model

Mamunur Rashid Sarker [1, 2], Marcelo Valadares Galdos [1,3], Andrew J. Challinor [1], Apurbo K. Chaki [2], Sarath Chandran M. A.[4], Stewart A. Jennings [1] and Akbar Hossain [5]

[1]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK;

[2]Bangladesh Agricultural Research Institute, Joydebpur, Gazipur, Bangladesh

[3]Rothamsted Research, Sustainable Soils and Crops, Harpenden AL5 2JQ, UK

[4]ICAR-Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad 500 059, India

[5]Division of Soil science, Bangladesh Wheat and Maize Research Institute, Dinajpur-5200, Bangladesh

Abstract:

Conservation Agriculture (CA) has been researched and promoted across the globe as a way of maintaining high SOC and high yields simultaneously. However, there is a dearth of research on how CA practices are used to deal with the effects of climate change on rice-maize systems in Bangladesh. In the present study, a cropping system modelling technique is used to examine the potential of CA to adapt rice-maize systems in Bangladesh to climate change. Agricultural Production Systems simulator (APSIM) was driven by 29 Global Climate Models (GCMs) to forecast the effect of tillage on rice-maize productivity and soil C-sequestration in conventional tillage (CT) vs. CA systems. The study periods considered were the baseline (1980–2009), mid century (2040-2069) and end century (2070–2099) under two Representative Concentration Pathways (RCPs; RCP4.5 and RCP8.5). Five climate models capture a representative subset of temperature and precipitation changes in the CMIP5 ensemble. Compared to

the baseline, the yield of rice was projected to increase by 9% in hotter and drier conditions (i.e. the Hot Dry climate model) to 14% with average temperature and precipitation change (i.e. the Middle climate model) under RCP4.5 by mid century and 10% (Hot Dry) to 15% (Middle) by end century under RCP8.5. On the other hand, the yield of maize was projected to decrease by 2% in colder with wetter conditions (Cool Wet model) to 4% (Hot Dry model) by mid-century under RCP4.5 and 9% (Cool Wet) to 16% (Hot Dry) by end of century under RCP8.5. For building up organic carbon in the soil, the results showed that CA was found to be 10-15% more effective than CT across all time periods and RCPs.

4.1 Introduction

Achieving food security in the coming decades will be extremely challenging (Yan and Alvi , 2022; Tilman et al., 2011), as the amount of food is likely to need to substantially increase to meet future demand due to high population growth rate, and potential negative impacts of climate change, declining soil fertility, and problems with water accessibility (Rahut et al., 2022). An example of the challenge is Bangladesh, a South Asian nation with the 13th highest world population density (Timsisna et al., 2018). The country has 0.058 hectares (ha) of total arable land per person, which is 57% less than its neighbor, India (Ullah et al., 2021). In recent years, Bangladesh has faced significant challenges in ensuring food security due to its large population, frequent natural disasters, rising demand for energy and labour, and extensive soil degradation in rice-upland cropping systems. To satisfy the rising demand of a growing population, the region must double its food production by the end of 2050, while using its resources efficiently and without causing environmental damage (Ladha et al., 2016). There are numerous ways to satisfy future demand such as i) increasing cropland ii) raising cropping intensity (the number of crops that are grown on a given plot of land over a calendar year) iii) enhancing grain yield (Timsiana et al., 2018). But unfortunately, there is little scope for expanding cropland area or cropping intensity due to the high average cropping intensity (at least two crops per year) (BBS, 2020), and most of the area in the country is already being used for farming (Timsiana et al., 2018). Therefore an important strategy for fulfilling the future food demands of Bangladesh is enhancing crop productivity for important crops such as rice, wheat and maize using better farm management (Chaki et al., 2021a, Van Wart et al., 2013).

Agriculture is anticipated to be adversely affected by climate change due to increased drought intensity and other climatic extremes (IPCC, 2007a ; Bahri et al., 2019). Evidence shows that low-income countries with tropical and subtropical climates are more vulnerable to the negative effects of climate change (Wheeler and Von Braun 2013; Ruamsuke et al., 2015). Bangladesh, for example, is a subtropical country concerned about climate change due to its low-lying deltaic landforms and closeness to the Bay of Bengal (Majid, 2020). As a result, Bangladesh is already vulnerable to natural calamities such as sea-level rise, salinization, flooding, drought, and cyclones. Furthermore, there has already been a significant increase in temperature and changes in rainfall patterns (Shahid, 2010; Shahid et al., 2012). According to the 2017 Global Climate Risk Index, Bangladesh is ranked sixth among the nations most adversely affected by climate change (Kreft et al., 2021). Climate change and its negative impact on food production have been well-recognized in Bangladesh (Chowdhury et al., 2022). Because of climate change, food production in the country frequently faces enormous challenges (Mojid, 2020; Bashak et al., 2010). According to Islam et al (2022), the country's crop production is severely affected by floods, drought, and salinity. Because of this, every year, almost 80,000 hectares of land that could be used for agriculture are lost. Consequently, crop productivity and food security are severely threatened.

For both rural and urban people in Bangladesh, the rice and maize systems play a key role in providing food security and income. More than 96% of the land area under "Cereal Agriculture" is occupied by rice, maize, and wheat (Sarwar, 2021). From the year 2010 to 2019, the area of maize expanded by an average of 11.40% per year due to wheat producers moving to maize production (Sarwar, 2021). The underlying cause of this shift is a rise in demand for maize for both human consumption and usage in fisheries and poultry (Ali et al., 2008; Timsina et al., 2010); however, current production is still insufficient to satisfy the country's demand. According to data provided by customs, during the fiscal year 2019-20, Bangladesh imported 20 million tons of maize, up from 13 million tons the previous year. This additional maize was purchased to satisfy the nation's growing need (Islam et al., 2022).

The existing cultivation methods in rice-based systems (e.g. rice-wheat, and rice-maize systems) are labour, water, and energy-intensive, and less profitable due to inefficient use of resources such as fertilizer, water, labour, rising production costs, and changing climate (Gathala et al., 2020; Ladha et al., 2009; Erenstein et al., 2012). The deterioration of soil physical, chemical, and biological properties, conjunction with poor crop management methods, has resulted in declining soil fertility (; Alam et al., 2018). Puddling during transplanted rice cultivation has a negative impact on the subsequent upland crops growth and production (maize) due to changes in the soil physical characteristics, including soil compaction, poor soil structure, and inadequate permeability in the plough pan zone (Gathala et al., 2011a). In addition, water scarcity in the region is predicted to worsen as a result of climate change (IPCC, 2014).

Taking this into account, the government has placed a significant emphasis on ensuring sustainable food production through the implementation of modern technology, such as the promotion of conservation-oriented farming techniques. The practice of conservation agriculture (CA) has the potential to provide such an option (Hobbs, 2007; Gathala et al., 2020). CA is based on three basic principles i) minimal mechanical soil disturbance (no-till or reduced tillage methods); ii) permanent soil cover (use of cover crops or incorporation of at least 30% of crop residues) and iii) diversified crop sequences (FAO, 2017; Hobbs et al., 2008). These strategies are frequently used to manage natural resources (soil, water, and energy) as they reduce soil degradation and develop systems that are more resilient to climate change. Several researchers have found that these approaches typically lead to higher yields and better use of water (Haque et al., 2023, Sarker et al., 2022, Chaki et al., 2021b). Furthermore, research indicates that CA-based cropping systems increase soil organic carbon (SOC) leading to improved soil health (Das et al., 2018; Alam et al., 2018).

The agricultural system in Bangladesh is suffering from a lack of information on the effects of climate change and effective ways to adjust to these changes due to traditional agronomic research, such as field experiments, only giving short-term results (Alam et al., 2018; Gathala et al., 2011b; Parihar et al., 2016a; Sarker et al., 2022) and being unable to identify efficient management techniques for a diverse set of environments (Chaki et al., 2022). Due to the constraints of conventional agronomic practice, there is a critical need for a tool or technique that can analyse the impact of a variety of factors on crop development and yield and extrapolate the results to broader climatic, soil, and management circumstances (Chaki et al., 2021b). In this instance, cropping system models can provide an opportunity to examine cropping systems' adaptability to climate change (Challinor et al., 2013; Lobell et al., 2006). A modelling method may be used to fit crop responses under various stress circumstances (Bahri et al., 2019). The Agricultural Production Systems sIMulator (APSIM) model has often been used for studies under sub-tropical climate conditions to simulate biomass, yield, water productivity, soil carbon changes, and crop response to rising CO_2 levels (Gaydon et al., 2017; Bahri et al., 2019; Chaki et al., 2022; Keating et al., 2003).

The purpose of this study is to provide predictive answers, using the APSIM model, in North western Bangladesh for the potential of rice-maize cultivation based on CA-principles and its impact on rice-maize productivity and soil organic carbon. Furthermore, it will assist decision-makers in determining the future direction of agronomic systems and resource preservation in achieving food security under climate change. The particular objectives of the current study were (i) to calibrate and evaluate the APSIM crop model for rice-maize under CA and CT management techniques and (ii) to assess the long-term impact of climate change and CA and CT management on rice-maize productivity and soil organic carbon (SOC) stock.

4. 2 Materials and methods

The performance of the model was assessed using statistical analysis after a thorough process of model parameterization (section 4.2.3), calibration (section 4.2.4), and evaluation (section 4.2.5).

4. 2. 1 Experimental site

During 2019-2021, a field experiment was undertaken in the experimental farm of the Bangladesh Agricultural Research Institute (BARI), Dinajpur, located in the North western portion of Bangladesh at 88.65–25°63 N latitude and 88°38 E longitude and 40 m above sea level (Fig. 4.1). The experimental site consists of sandy soil classed as Albaquepts by the USDA soil taxonomy (Huq et al.,2013), and the parent materials were Old Himalayan piedmont plain alluvium (BARC, 2012).

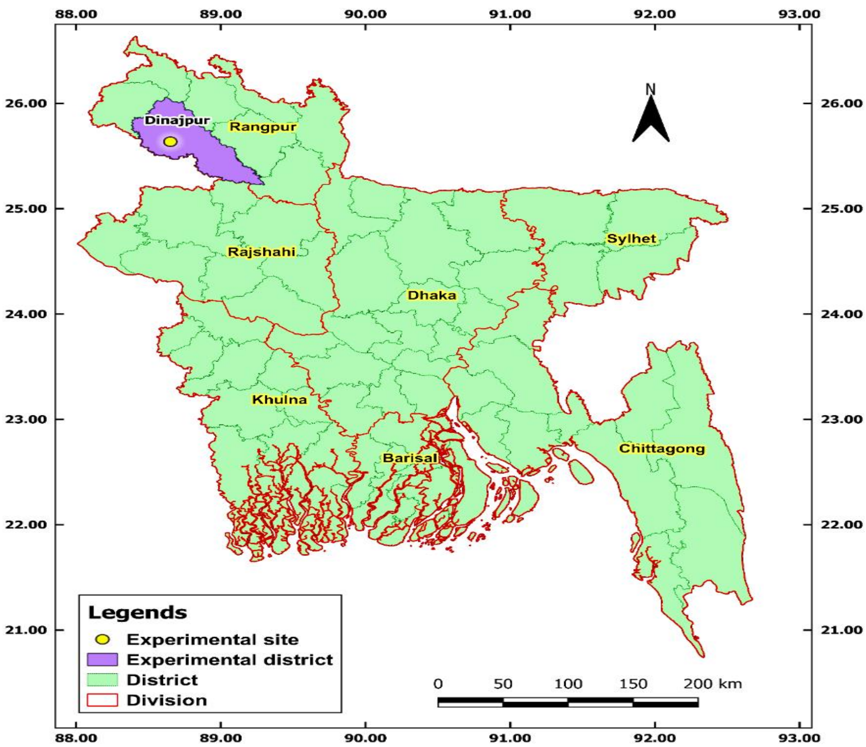

Figure 4.1: Map of Bangladesh with the district of the experimental station (purple) and the experimental site (yellow point).

4. 2. 2 Description of the experimental datasets

To produce accurate simulation results for local conditions, it is necessary to gather the appropriate input data and parameters (daily climate data, crop management, experimental measurements, soil characteristics) and calibrate the cultivar coefficients (Jones et al., 2003). These parameters were taken from data published in Sarker et al. (2022) and used for model calibration and evaluation in our work. A summary of the experimental treatments is given here.

The experiment was conducted in a randomized split-plot design with three replications. The main plot size was 14.6× 8.4 m^2 and separated by a 1.2 m wide buffer, whereas the subplot was 4.2× 8.4 m^2 with a 0.75 m buffer. The detailed experimental procedures were provided in (Chapter 3). According to the findings of our experiment, direct seeded rice with strip till maize and 50% residue (CA) produced a higher SOC and yield than puddled transplanted rice - conventional till maize and 0% residue (CT) treatment. For scenario analysis, we therefore considered the following treatments: (Table 4.1)

Table 4.1 Description of experimental treatments.

Name of the treatments	Descriptions
PTR/CTM + 0% residue (CT)	Puddled Transplanted Rice – Conventional till Maize
DSR/STM + 50% residue (CA)	Direct Seeded Rice – Strip till Maize

4. 2. 3 APSIM parameterization

The APSIM model [v 7.5] (Keating et al., 2003; Holzworth et al., 2014a). was used for the cropping systems simulation study. To successfully model crop yield and biomass, measured data such as climatic data, soil profile characteristics, crop management practices and crop phenology were provided from the experimental study.

4. 2. 3. 1 Climate data

The essential daily weather input data for APSIM such as daily maximum and minimum temperatures, rainfall, and solar radiation data (1980-2021) were obtained from the Bangladesh Meteorological Department (BMD) weather station, Dinajpur, approximately 0.5 km from the experimental plot.

4. 2. 3. 2 Soil data

APSIM requires layer-based soil physical characteristics such as bulk density, saturated water content, drained upper limit, lower limit (expressed in volumetric moisture content terms), soil water content (SWCON), soil texture and saturated hydraulic conductivity, as well as soil chemical parameters including soil organic carbon content, pH, and mineral N (NO_3- and NH_4 +) (Table 4.2).

Table 4. 2 Soil physical and chemical properties at the experimental sites.

Soil depth (cm)	pH	TOC (%)	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	LL	DUL	SAT	BD (g cm^{-3})	Soil texture		
									Sand (%)	Silt (%)	Clay (%)
0-10	6.15	0.64	1.29	13.22	0.10	0.27	0.36	1.42	60.0	22.00	18.0
10-20	6.20	0.55	1.55	13.34	0.07	0.23	0.31	1.47	72.0	16.00	12.0
20-30	6.25	0.41	1.13	7.86	0.06	0.22	0.31	1.59	70.0	16.00	14.0
30-40	6.35	0.46	1.47	7.10	0.05	0.24	0.38	1.64	66.0	20.00	14.0
40-50	6.38	0.39	0.96	5.10	0.05	0.29	0.39	1.60	62.0	24.00	14.0
50-60	6.45	0.34	0.33	4.67	0.05	0.29	0.37	1.53	64.	18.00	18.0
60-70	6.40	0.33	0.31	3.83	0.07	0.36	0.39	1.54	72.0	17.00	11.0
70-80	6.41	0.31	0.26	3.90	0.07	0.35	0.39	1.54	60.28	20.00	19.72
80-90	6.70	0.30	0.25	3.34	0.05	0.29	0.35	1.52	60.28	19.00	20.72
90-100	6.70	0.31	0.24	3.09	0.05	0.28	0.33	1.53	67.28	13.00	19.72
100-150	6.80	0.30	0.24	3.09	0.05	0.28	0.33	1.5	67.28	13.00	19.72

LL – volumetric water content at the lower limit, DUL – volumetric water content at the drained upper limit, SAT – volumetric water content at saturation, BD – bulk density, TOC – total organic carbon

4. 2. 4 APSIM calibration

The first step in the calibration process involved adjusting the crop phenological parameters (for maize: emergence, flowering, physiological maturity and harvest; for rice: sowing, transplanting, panicle initiation, flowering, physiological maturity and harvest), and the second step involved adjusting parameters representing the growth and yield characteristics of the tested crop varieties (grain growth rate, grain number) based on the measured experimental or estimated data. The genetic coefficients that influence maize phenological development such as the duration from emergence to end of juvenile (tt_emerg_to_endjuv), duration from flowering to maturity (tt_flower_to_maturity), etc. were adjusted based on the phenological data collected from the field experiment. Similarly, the genetic coefficients maximum grain number per head (head_grain_no_max) and duration from flowering to start of grain filling (tt_flower_to_start_grain) were employed to match the measured grain yield.

The crop genetic coefficients were iteratively adjusted to reduce the RMSE between observed and simulated values of different crop phenological parameters and yield (days to anthesis, days to maturity, yield, biomass, etc.). For example, the genetic coefficient for grain growth rate was iteratively adjusted in the range from 8.2 to 10.2 in increments of 0.1 (Wang et al., 2018) with twenty one iterations. The best parameter value from this range (9.1) was selected due to its low RMSE between the observed and simulated yield. For the genetic coefficients of emergence to the end of the juvenile stage, the parameter value was adjusted iteratively in the range from 240 to 262 in increments of 1.0 (Arya et al., 2015). After twenty-three iterations, the best parameter value from this range (250) was chosen because it had the lowest RMSE between observed and simulated flowering days. Similarly, in the genetic coefficients for the flowering to maturity stage, the value of the parameter was adjusted iteratively in the range from 850 to 1000 in increments of 5.0 (Wang et al., 2018). The best parameter value from this range (960) was chosen after thirty one iterations due to its low RMSE between the observed and the simulated maturity days.

4. 2.4.1 Adjustment of APSIM-Soils and APSIM-Manager specifications for CA vs CT

4. 2. 4.1.1 Crop rooting

Conservation agriculture approaches foster increased root length densities and deeper roots (due to improved soil structure), allowing plants to absorb water and nutrients from deeper soil layers (Aggarwal et al., 1995; Sadras and Calvino, 2001; Qin et al., 2006). To capture CA performance, the root hospitality (kl in APSIM) and relative rate of root advance (xf in APSIM) were changed. Following Chaki et al. (2022), we increased these values by 20% in order to represent crop rooting under CA.

4. 2. 4. 1. 2 Soil microorganism activity

Due to enhanced soil structure, soil microbial activity in CA has been shown to be higher than in CT (Choudhary et al., 2018). This was captured in APSIM by increasing Fbiom (% soil organic matter present as microbial biomass) and reducing Finert (the inert fraction of soil organic matter). To establish a satisfactory match between the observed and simulated crop yields, these variables (Fbiom and Finert) were modified within reasonable boundaries (Probert et al., 1998) (about 20% variation).

Table 4.3 Experimental observations used as model calibration data set and their respective simulated values for CT treatment

Crops	Years	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs
		Days of anthesis		Days of maturity		Yield (kg/ha)		biomass (kg/ha)	
Rice	2019	80	78	106	107	3903	3824	1054	8988
Maize	2019	103	101	162	161	7941	7989	18056	18189

Table 4.4 Experimental observations used as model calibration data set and their respective simulated values for CA treatment

Crops	Years	Sim	Obs	Sim	Obs	Sim	Obs	Sim	Obs
		Days of anthesis		Days of maturity		Yield (kg/ha)		biomass (kg/ha)	
Rice	2019	74	72	99	100	4282	3740	9926	9078
Maize	2019	92	91	153	151	7547	7920	20573	18610

4. 2. 5 APSIM evaluation

One treatment from CT practices (PTR/CTM + 50% residue) and one treatment from CA practices (DSR/STM + 50% residue) were used to calibrate the model. To evaluate the two calibrations, the model was next evaluated using all other data for CT and CA (i.e. other years and treatments). The results of the simulated models were compared to the observed data for several variables, including crop phenology dates, grain yield, and dry matter, for both rice and maize.

4. 2. 6 Statistical evaluation methods used

The calibrated model was evaluated using the coefficient of determination (R^2) from the linear regression of observed against simulated data. The model performance was also evaluated by comparing the absolute root mean square error (RMSE, Eq. (1), normalized root mean square error (RMSEn, Eq. (2) and mean bias error (MBE, Eq. (3) between simulated and observed values. The higher value of R^2, the better the agreement between observed and simulated outputs. RMSE was calculated using Eq. (1):

$$\text{RMSE} \sqrt{\sum_{i=1}^{n} \frac{(Si - Oi)2}{n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where 'Si' is simulated, 'Oi' is the observed value, 'n' is the number of pairs. When the RMSE values are small that indicates better model performance. The nRMSE was calculated using Eq. (2):

$$\text{RMSEn (\%)} = \left(\frac{\text{Absolute RMSE}}{\text{Mean of the observed}}\right) \times 100 \ldots\ldots\ldots\ldots(2)$$

The nRMSE gives a measure of the relative difference between observed and simulated values in percentage (Soler et al., 2007). nRMSE is considered better than

RMSE, as it provides the error level associated with each pair of simulated and observed variables (Rahman et al., 2018).

By normalizing the RMSE using the observed mean, it becomes scale-independent and makes nRMSE a universal measure for error comparison. Values < 10% are considered excellent predictions, while 10 to 20% are good, > 20 to 30% are considered fair, and > 30% indicate poor model performance (Jamieson et al., 1991). MBE was calculated using Eq. (3).

MBE= $\frac{1}{n}\sum_{i=1}^{n}(S\,i - Oi)$............................. (3)

Where n is the total number of observations, Si is the simulated values and Oi is the observed values. Mean bias error (MBE) captures the average bias in the prediction. MBE indicates the absolute difference between simulated and observed variables. It was used to understand whether simulated values were over or underestimated by the model, compared to the observed.

4. 2.7 General circulation models (GCMs)

Future climate scenarios were derived from 29 general circulation models (GCMs) from the Fifth Coupled Model Inter-comparison Project [CMIP5] (Table 4.5). In the current study, a reperesntative subset of 5 GCMs was selected from a pool of 29 GCM using the 'Representative Temperature and Precipitation (T&P) GCM Subsetting Approach (Ruane and McDermid 2017). In this method, the 29 GCMs were split into 5 quadrants according to their deviation in temperature and rainfall from the baseline. Fig.4.2 displays the five quadrants of the 29 GCMs that were so derived for the research location.

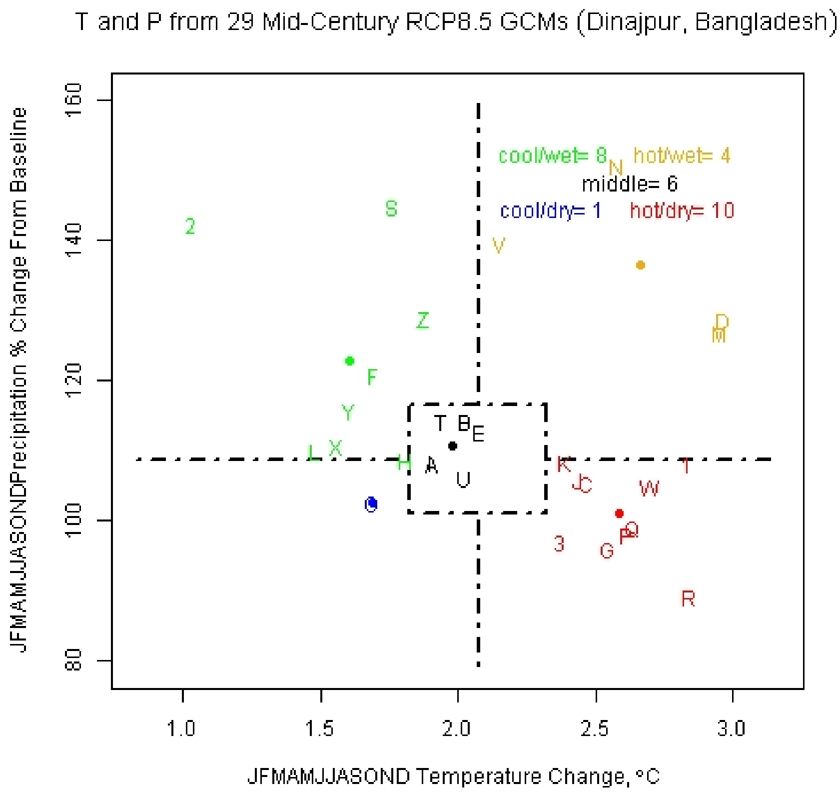

Figure 4.2: Five quadrants of 29 GCMs for mid century and RCP8.5. Alphabets A to Z (26) and numbers 1 to 3 represent 29 GCMs (as presented in Table 4.5), and they are coloured according to their category. The dots represent the median of GCMs within a category

The GCM whose projected change in temperature and rainfall falls nearest to the median of each quadrant was chosen. The five GCMs that were chosen were, D (CanESM2), Q (MPI-ESM-LR), F (CESM1-BGC), O (MIROC5) and B (BCC-CSM1-1), and they are hereafter referred to by the names associated with their Figure 4.2 quadrant, as shown in Table 4.6. Future climate scenarios for the selected five GCMs were generated for two periods, mid century (2040–2069) and end century (2070–2099), under RCP4.5 and RCP8.5 by changing the baseline climate data based on outputs from the GCMs/RCPs by using the enhanced delta technique, which generates mean and variability change scenarios (AgMIP, 2013). The enhanced delta technique was adopted in our study due to its accuracy and widespread application in analyzing climate impacts (Chandran et al., 2022; Tui et al., 2021; Araya et al., 2015). Representative CO_2 concentrations for the mid century under RCP4.5 (499 ppm) and RCP8.5 (571 ppm) and the end of century under RCP4.5 (532 ppm) and RCP8.5 (801 ppm) were used for scenario analysis (AgMIP 2012). The simulations were run with different CO_2 concentrations to better understand the impact of CO_2 fertilization on crop production and SOC through time.

Table 4.5 Details of 29 GCMs used in this study for climate change impact assessment (Ruane and McDermid 2017)

Symbols	**GCM**	**Horizontal resolution**
A	ACCESS1-0	1.25° × 1.875°
B	BCC-CSM 1–1	~ 2.8° × 2.8°
C	BNU-ESM	~ 2.8° × 2.8
D	CanESM2	~ 2.8° × 2.8°
E	CCSM4	~ 0.9° × 1.25°
F	CESM1-BGC	~ 0.9° × 1.25°
G	CSIRO-Mk3-6–0	~ 1.9° × 1.875°
H	GFDL-ESM2G	~ 2.0° × 2.5°
I	GFDL-ESM2M	~ 2.0° × 2.5°
J	HadGEM2-CC	1.25° × 1.875°
K	HadGEM2-ES	1.25° × 1.875°
L	INM-CM4.0	1.5° × 2.0°
M	IPSL-CM5A-LR	~ 1.9° × 3.75°
N	IPSL-CM5A-MR	~ 1.3° × 2.5°
O	MIROC5	~ 1.4° × 1.4°
P	MIROC-ESM	~ 2.8° × 2.8°
Q	MPI-ESM-LR	~ 1.9° × 1.875°
R	MPI-ESM-MR	~ 1.9° × 1.875°
S	MRI-CGCM3	~ 1.1° × 1.125°
T	NorESM1-M	~ 1.9° × 2.5°
U	FGOALS-g2	~ 2.8° × 2.8°
V	CMCC-CM	~ 0.75° × 0.75°
W	CMCC-CMS	~ 1.875° × 1.875°
X	CNRM-CM5	~ 1.4° × 1.4°
Y	HadGEM2-AO	1.25° × 1.875
Z	IPSL-CM5B-LR	~ 2.5° × 1.26°
1	GFDL-CM3	2° × 2.5°
2	GISS-E2-R	2° × 2.5°
3	GISS-E2-H	2° × 2.5°

Table 4.6 Selected GCMs by subsetting for climate change impact analysis

Sl No	Quadrant	GCM	Weightage*
1	Hot Wet	CanESM2	4/29
2	Hot Dry	MPI-ESM-LR	10/29
3	Cool Wet	CESM1-BGC	8/29
4	Cool Dry	MIROC5	1/29
5	Middle	BCC-CSM1-1	6/29

*Weightage was estimated by the ratio of the number of GCMs under each quadrant (as per Fig. 4.2) to the total number of GCMs (29)

4. 2.8 Future climate scenarios

For the baseline with observed data and the future periods with GCMs, the mean seasonal rainfall, the average maximum temperature (T max) and the average minimum temperature (T min) during the growing season for rice and maize were calculated, as well as on an annual basis. During the baseline period, the average seasonal rainfall for the rice-growing season (July to October) was 1323 mm. According to the width of box plots, the variability in projected seasonal rainfall during the rice growing period was higher under the RCP8.5 scenario (for both the mid and end century), compared to the RCP4.5 scenario. Under the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios, the mean percent change in seasonal rainfall from baseline throughout the rice growing period was +15.61%, + 16.86%, + 22.61%, and + 26.46%, respectively (Fig. 4.3a). The mean seasonal rainfall for maize (November to April) during the baseline period was 120 mm. In comparison to the expected rainfall for July to October under the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios, the variability among GCMs throughout November to April was lower. Under the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios, the mean percent change in seasonal rainfall from baseline throughout the maize growing period was +10.76%, +10.62%, +8.79%, + 8.19%, and +6.8%, respectively.

During the baseline period of the rice growing season, the average Tmax was 31.85 °C. Under the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios, it is projected to rise by 1.1 °C, 1.7 °C, 1.9 °C, and 3.1 °C, respectively, during each of the four future periods (Fig. 4.3b). According to the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios, the average Tmax for maize from November to

April is projected to rise by 1.7°C, 2.3°C, 2.9°C, and 4°C, respectively, from the baseline value of 27.9°C.

The average Tmin was projected to rise by a greater amount than the Tmax. Under the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios, Tmin is projected to rise from the baseline value of 24.9 °C throughout the rice growing season by 1.3 °C, 1.9 °C, 2.2 °C, and 3.4 °C, respectively (Fig. 4.3c). When compared to the baseline temperature of 15.12 °C, the projected increases in Tmin for maize are 1.7 °C, 2.5 °C, 2.9 °C, and 4.3 °C, respectively, under the mid RCP4.5, mid RCP8.5, end RCP4.5, and end RCP8.5 scenarios.

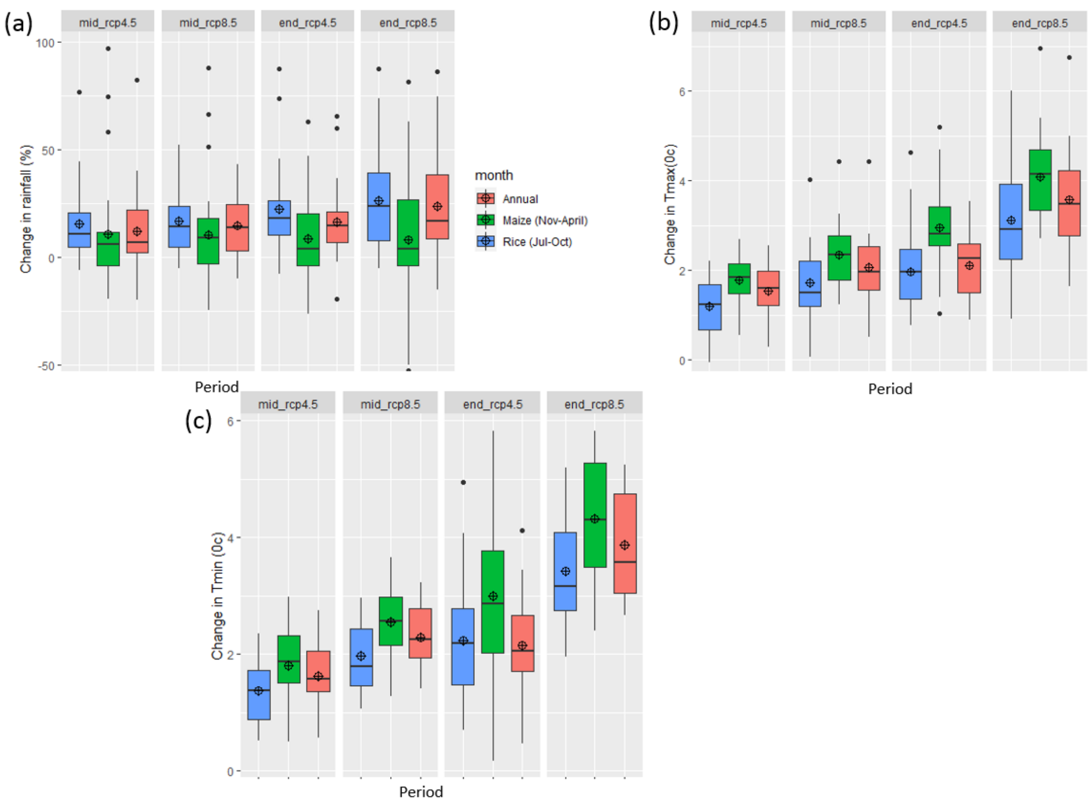

Figure 4.3: Projected changes in (a) rainfall, (b) mean maximum temperature and (c) mean minimum temperature during the growing season of rice (July–October) and maize (Nov–April) and annual basis for four future scenarios from 29 GCMs (mid RCP4.5, mid RCP8.5, end RCP4.5 and end RCP8.5). The black lines and crosshairs within each box indicate the multi-model median and mean, respectively.

4. 3 Results

4. 3.1 Crop model evaluation

The model performed well in simulation of CT rice and maize crops in terms of days to anthesis and days to maturity. In the case of anthesis, the RMSE and nRMSE for the rice crop were 2.09 days and 2.71%, and for the maize crop they were 2.64 days and 2.58%, respectively. The RMSE and nRMSE values of days to maturity for rice were 0.89 days and 0.83%, respectively, while they were 0.77 days and 0.48% for maize. For the rice crop, the slope of the regression lines between simulated and measured days to anthesis and days to maturity were 0.89 and 0.86. The corresponding R^2 values for maize were 0.98 and 0.90. APSIM also satisfactorily predicted biomass and grain yield. For rice, the RMSE and nRMSE for grain yield were 245 kg ha^{-1} and 6.15%, while for maize they were 561 kg ha^{-1} and 7.34%. Considering biomass, rice had RMSE and nRMSEs of 240 kg ha^{-1} and 2.49%, respectively, while maize had 920 kg ha^{-1} and 5.39%, respectively. The corresponding R^2 values for the grain yields of rice and maize were 0.97 and 0.62. For rice and maize, the equivalent R^2 values for biomass were 0.98 and 0.69, respectively.

For the CA practices, in the case of anthesis, the RMSE and nRMSE for the rice crop were 3.2 days and 4.63%, whereas, for the maize crop, they were 1.26 days and 1.34%, respectively. The RMSE and nRMSE values of days to maturity for rice were 1.0 days and 1.02%, respectively, while they were 2.82 days and 1.84% for maize. For the rice crop, the slope of the regression lines between simulated and measured days to anthesis and days to maturity were 0.90 and 0.92. On the other hand, the corresponding R^2 values for maize were 0.97 and 0.92. APSIM also performed well in predicting biomass and grain yield. For rice, the RMSE and nRMSE for grain yield were 428 kg ha^{-1} and 11.6%, while for maize they were 987 kg ha^{-1} and 12.48%. Considering biomass, rice had RMSE and nRMSEs of 652 kg ha^{-1} and 7.41%, respectively, while maize had 2099 kg ha^{-1} and 11.78%, respectively. The corresponding R^2 values for the grain yields of rice and maize were 0.67 and 0.71. For rice and maize, the equivalent R^2 values for biomass were 0.69 and 0.65, respectively. According to Jamieson et al. (1991), the nRMSE values showed that days to anthesis and days to maturity were "excellent," while "good" for biomass and yield (Table 4.7& 4.8).

Table 4.7 Statistical analysis of APSIM performance for observed versus simulated grain and biomass yields for CT treatment in the field experiments at Dinajpur, Bangladesh

Crop	Xsim	Xobs	RMSE	nRMSE (%)	MBE	R^2
Rice						
Days of anthesis	79	77	2.09	2.71	-2.0	0.89
Days of maturity	105	106	0.89	0.83	0.8	0.86
Grain	3764	3978	245	6.15	243	0.97
Biomass	9712	9627	240	2.49	-84	0.98
Maize						
Days of anthesis	104	102	2.64	2.58	-2.2	0.98
Days of maturity	160	159	0.77	0.48	-0.6	0.90
Grain	8053	7640	561	7.34	-412	0.62
Biomass	17908	17057	920	5.39	-851	0.69

Table 4.8 Statistical analysis of APSIM performance for observed versus simulated grain and biomass yields for CA treatment in the field experiments at Dinajpur, Bangladesh

Crop	Xsim	Xobs	RMSE	nRMSE (%)	MBE	R^2
Rice						
Days of anthesis	72	69	3.2	4.63	-3.2	0.90
Days of maturity	99	98	1.0	1.02	0.2	0.92
Grain	4045	3669	428	11.6	-406	0.67
Biomass	9331	8797	652	7.41	-534	0.69
Maize						
Days of anthesis	93	94	1.26	1.34	1.2	0.97
Days of maturity	151	152	2.82	1.84	0.4	0.92
Grain	8674.6	7908	987	12.48	-766	0.71
Biomass	19874.4	17806	2099	11.78	-2067	0.65

Xsim, mean of simulated values; Xobs, mean of observed values; RMSE, absolute root mean squared error; RMSEn, normalized root mean squared error; Mean bias error.

4.3.2 Impact of projected climate on soil carbon dynamics

Tillage with residue retention methods had the highest influence on SOC stock in rice-maize cropping systems, according to the current study (Fig. 4.4 & 4.5). For all scenarios, the SOC value was higher under CA practices than that under CT. The impacts of projected SOC were simulated for the five future scenarios under RCP 4.5 and RCP 8.5 and the findings are given in Fig. 4.4 & 4.5.

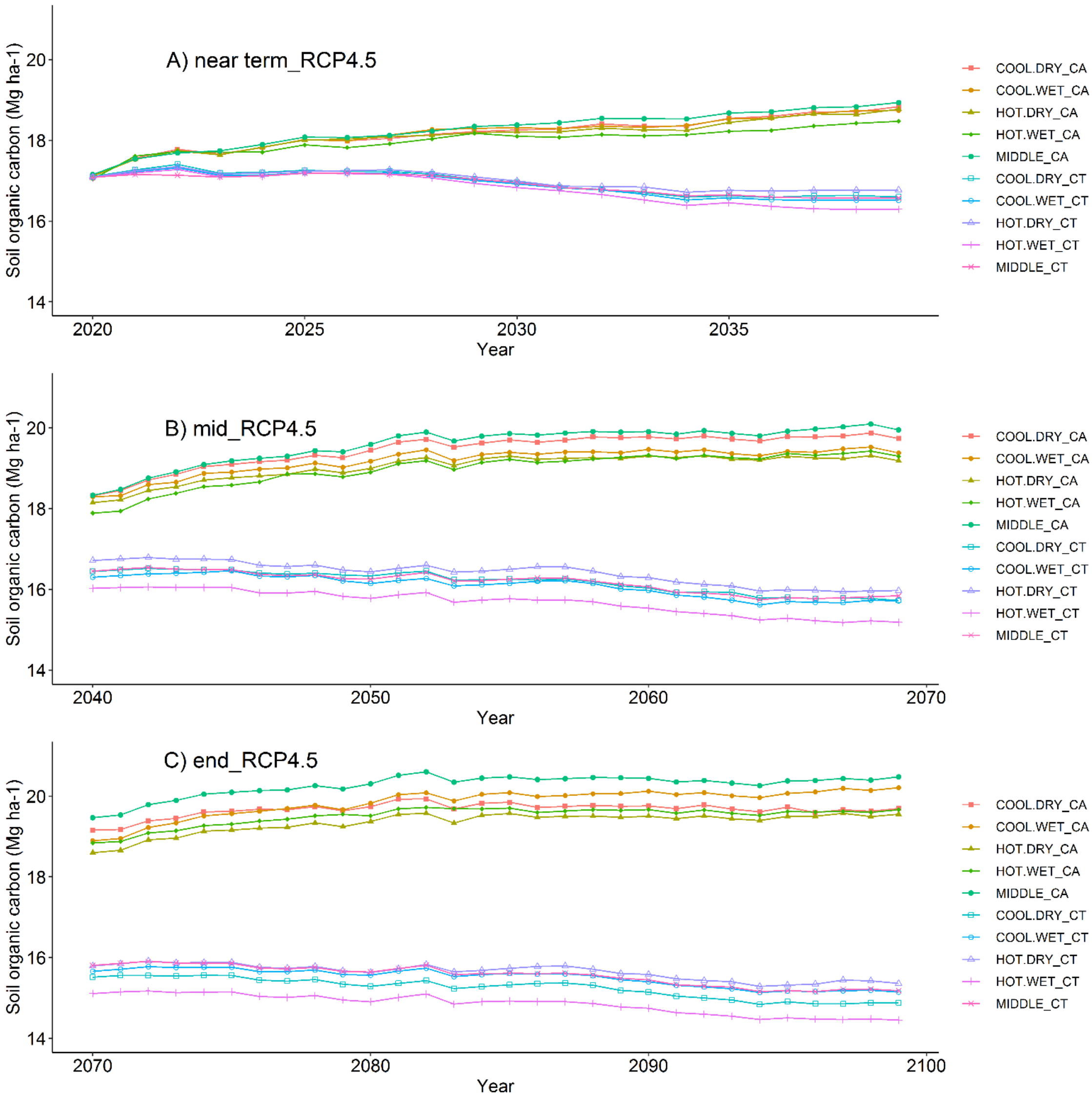

Figure 4.4 Projected total soil carbon stock under different management scenarios CT vs CA in (A) near-term RCP4.5, (B) mid RCP4.5, (C) end RCP4.5 emission scenarios with five climates at 0-20 cm soil layer.

For CT practices, the overall change of SOC ranged from -5% to -8% under RCP4.5 and -7% to -9% under RCP8.5 during mid century compared to the initial SOC content (Fig. 4.4 & 4.5). In the case of CA practices, across all climate scenarios, the highest percent change in SOC (+14%) was found with the Middle climate model (associated with average temperature and precipitation changes), and +12% with the Cool Wet model under RCP4.5 and RCP8.5 during mid century. The lowest SOC increase (+8%) was with the Hot Dry model under RCP 8.5.

In the case of CT practices, the overall change of SOC ranged from - 9% to -12% under RCP4.5 and -12% to -14% in RCP8.5 during end century compared to the initial SOC content (Fig. 4.4 & 4.5). In the case of CA practices, the SOC was projected to increase +17% (Middle climate model) and +15% (Cool Wet climate model) under RCP4.5 and RCP8.5 during end century. However, a lower SOC increase (+12% and +9%) was found under RCP 4.5 and RCP8.5 scenarios with the Hot Dry climate model.

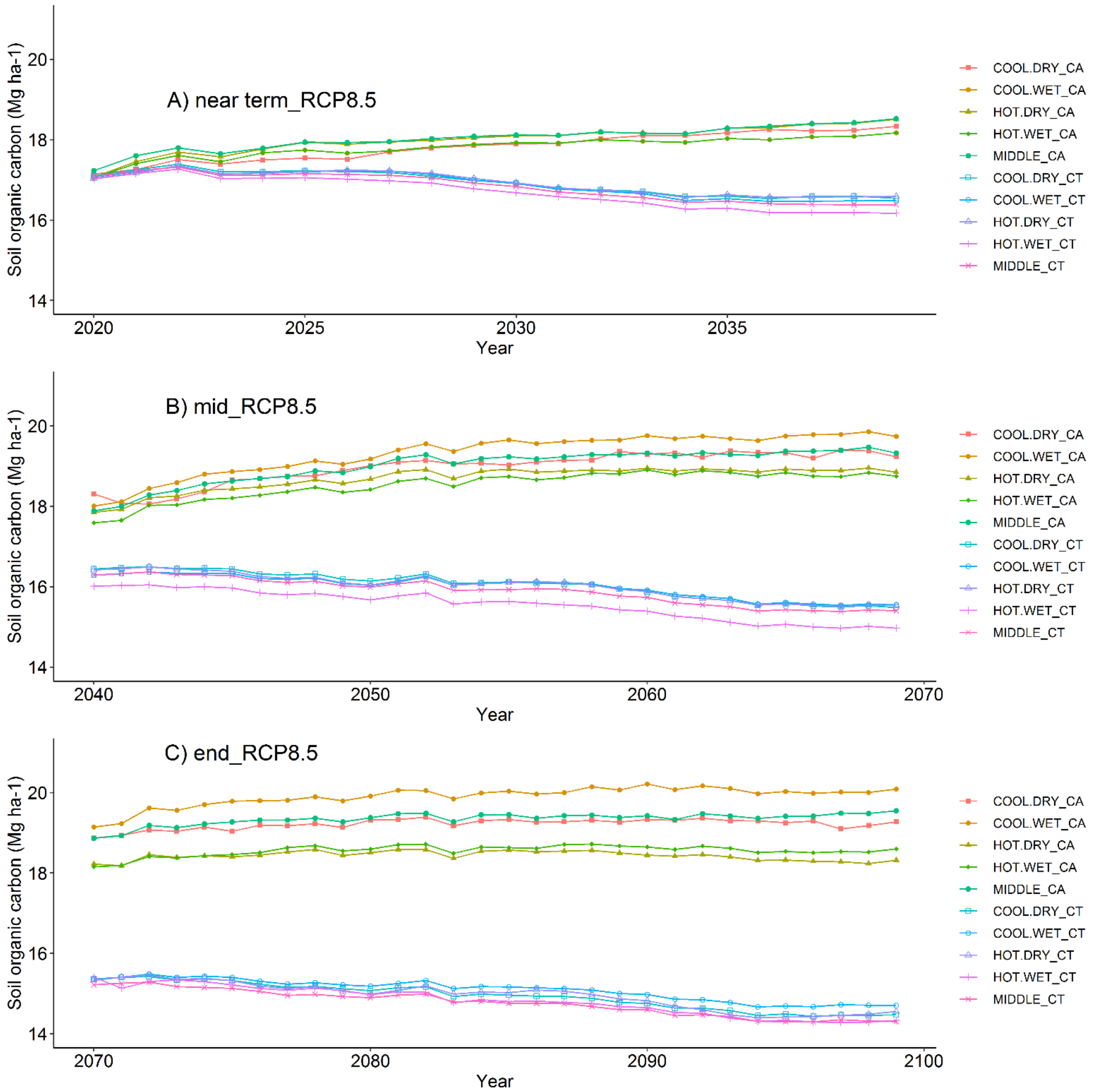

Figure 4.5 Projected total soil carbon stock under different management scenarios: CT vs CA in (A) near-term RCP8.5, (B) mid RCP8.5, (C) end RCP8.5 emission scenarios with five climate models at 0-20 cm soil layer.

4. 3. 3 Impact of projected climate on phenology

The effects of projected climate on phenology were simulated for each of the future scenarios (mid RCP4.5 & end RCP4.5; mid RCP8.5 & end RCP8.5), with the findings given in Figs. 4.6 and 4.7. For CT practices, the overall change in days to anthesis of rice ranged from - 2 (Hot Dry) to +2 (Cool Wet) under RCP4.5 and +1 (Middle) to -3 (Hot Dry) under RCP8.5 during mid century compared to the baseline (Fig. 4.6).

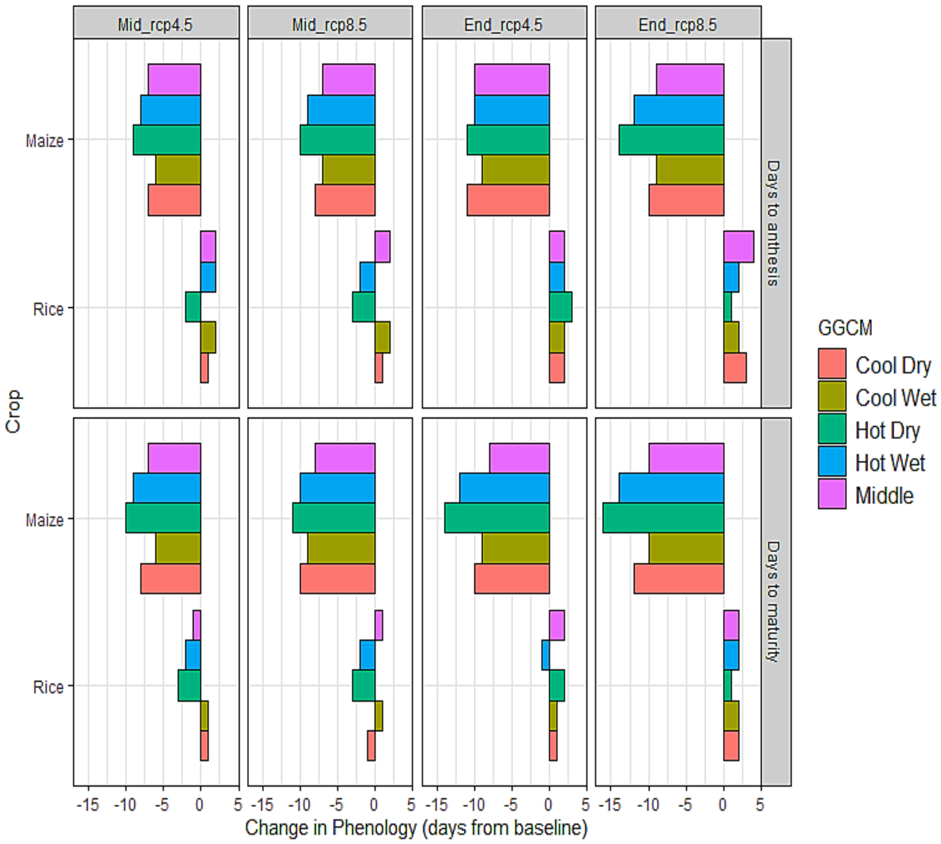

Figure 4.6: Impact of projected climate on phenology (changes in days to anthesis and maturity compared to the baseline period) of rice-maize cropping sequence during mid and end century and RCP4.5 & RCP8.5 emission scenarios in CT practices.

During the end century, the days of anthesis were projected to increase by 2 (Cool wet) and 4 days (Middle) under RCP4.5 and RCP8.5, respectively. In the case of maize, the reduction in days of anthesis during the mid century ranged from 6 (Cool Wet) to 9 (Hot Dry) and 7 (Middle) to 10 (Hot Dry) days under RCP4.5 and RCP8.5, respectively. Under RCP4.5 and RCP8.5, during the end century, it was estimated that the days to anthesis were advanced by 8 (Cool Wet) to 11 (Hot Dry) and 9 (Cool Wet) to 14 (Hot Dry) days, respectively.

Rice days to maturity ranged from +1 (Cool Wet) to -3 (Hot Dry) during mid century under RCP4.5 and +1 (Middle) to -3 (Hot Dry) under RCP8.5 , respectively. For the end century, it ranged from -1 (Hot Dry) to +2 (Middle) and +1 (Hot Dry) to +2 (Cool Wet) days under RCP4.5 and RCP8.5 scenarios , respectively. Concerning maize, the reduction in days of maturity during the mid century ranged from 7 (Middle) to 10 (Hot Dry) and 8 (Middle) to 11 (Hot Dry) days under RCP4.5 and RCP8.5, respectively. Under RCP4.5 and RCP8.5, during the end century, it was estimated that the days to maturity were shortaged by 8 (Middle) to 14 (Hot Dry) and 10 (Middle) to 16 days (Hot Dry), respectively. During the end of century, higher Tmax and Tmin accelerate the accumulation of growing degree days, resulting in a shorter crop duration in, particualry with the hottest future conditions (the Hot Dry climate model).

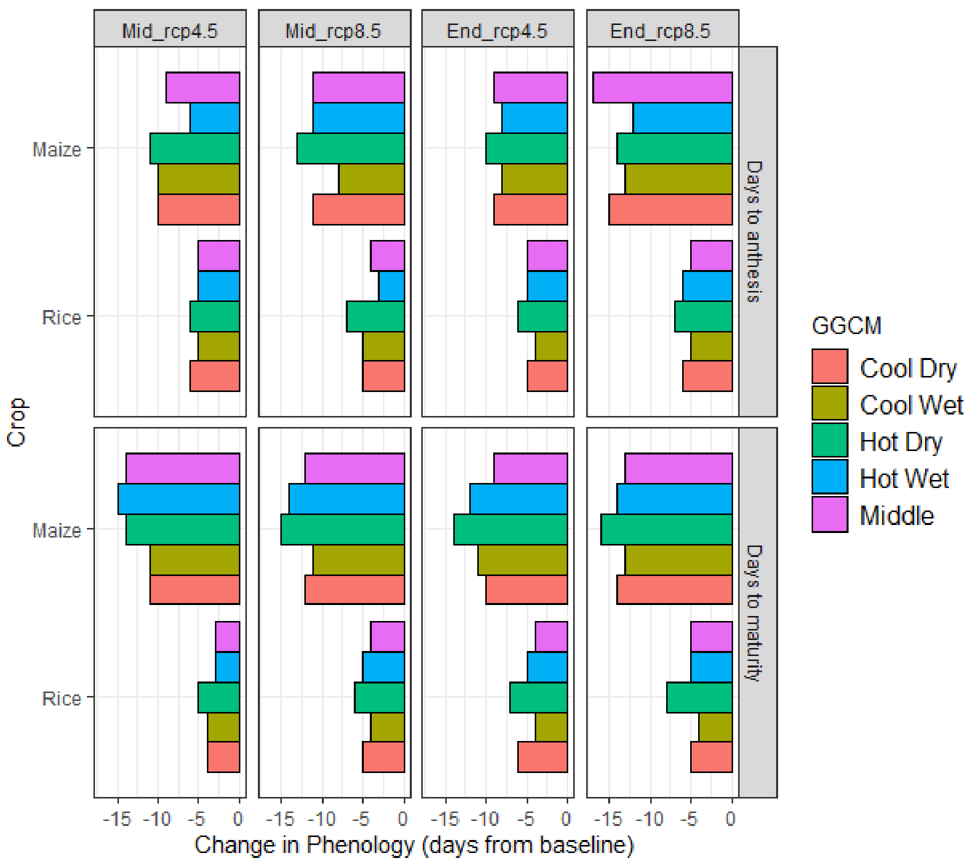

Figure 4.7: Impact of projected climate on phenology (changes in days to anthesis and maturity compared to the baseline period) of rice-maize cropping sequence during mid and end century and RCP4.5 & RCP8.5 emission scenarios in CA practices.

In the case of CA practices, rice anthesis was projected to advance by 5 (Middle) to 6 (Hot Dry) and 4 (Middle) to 7 (Hot Dry) days by mid-century under RCP4.5 and RCP8.5 respectively. Similarly, during the end century, the days to anthesis decreased by 4 (Cool Wet) to 6 (Hot Dry) days under RCP4.5; whereas it ranged from 5 (Cool Wet) to 7 (Hot Dry) under RCP8.5. The days to anthesis of maize were simulated to decrease by 11 (Hot Dry) to 7 (Hot Wet) and 8 (Cool Wet) to 13 days (Hot Wet) by mid century under RCP4.5 and RCP8.5 respectively. On the other hand, during the end century, it decreased by 8 (Cool Wet) to 10 (Hot Wet) days and 11 (Cool Wet) to 14 (Hot Wet) days under RCP4.5 and RCP8.5 scenarios.

In the case of rice, the days to maturity decreased by 3 (Middle) to 5 (Hot Dry) and 4 (Middle) to 6 (Hot Dry) during mid century under RCP4.5 and 8.5. At the end of the century, it decreased by 4 (Middle) to 7 (Hot Wet) days under RCP4.5 , and from 4 (Cool Wet) to 8 (Hot Wet) days under RCP8.5. For maize, the reduction in days of maturity by mid century ranged from 11 (Cool Wet) to 14 (Hot Wet) and 11 (Cool Wet) to 15 (Hot Dry) days under RCP4.5 and RCP8.5, respectively. At the end of the century, it decreased by 9 (Middle) to 14 (Hot Dry) days under RCP4.5 , and from 13 (Cool Wet) to 16 days (Hot Dry) under RCP8.5 respectively.

4. 3. 4 Impact of projected climate on biomass

For CT practices, the overall change in above ground biomass of rice ranged from +9% (Hot Dry) to +15% (Cool Wet) under RCP4.5 and +8% (Cool Wet) to +16% (Middle) under RCP8.5 during mid century compared to the baseline biomass (Fig. 4.8). Rice biomass was projected to change from +15% (Hot Wet) to + 18% (Cool Wet) and +10% (Hot Dry) to + 20% (Middle) under RCP4.5 and RCP8.5 scenarios (Fig. 4.8) by end of century. The increase in biomass is associated with increased precipitation in a Cool Wet climate compared to a Hot Dry climate. Increased precipitation improves soil moisture, which in turn promotes the growth of net primary production (NPP).

In the case of maize, the reduction in biomass by mid century ranged from 2% (Middle) to 10% (Hot Dry) and 5% (Cool Dry) to 12% (Hot Dry) for RCP4.5 and RCP8.5, respectively. Maize biomass was projected to decrease by 6% (Cool Wet) to 13% (Hot Dry) and 4% (Cool Wet) to 19% (Hot Dry) under RCP4.5 and RCP8.5, respectively (Fig. 4.8) by end of century. Decreased biomass with the Hot Dry model is due to both reduced growing season duration and greater water deficit stress.

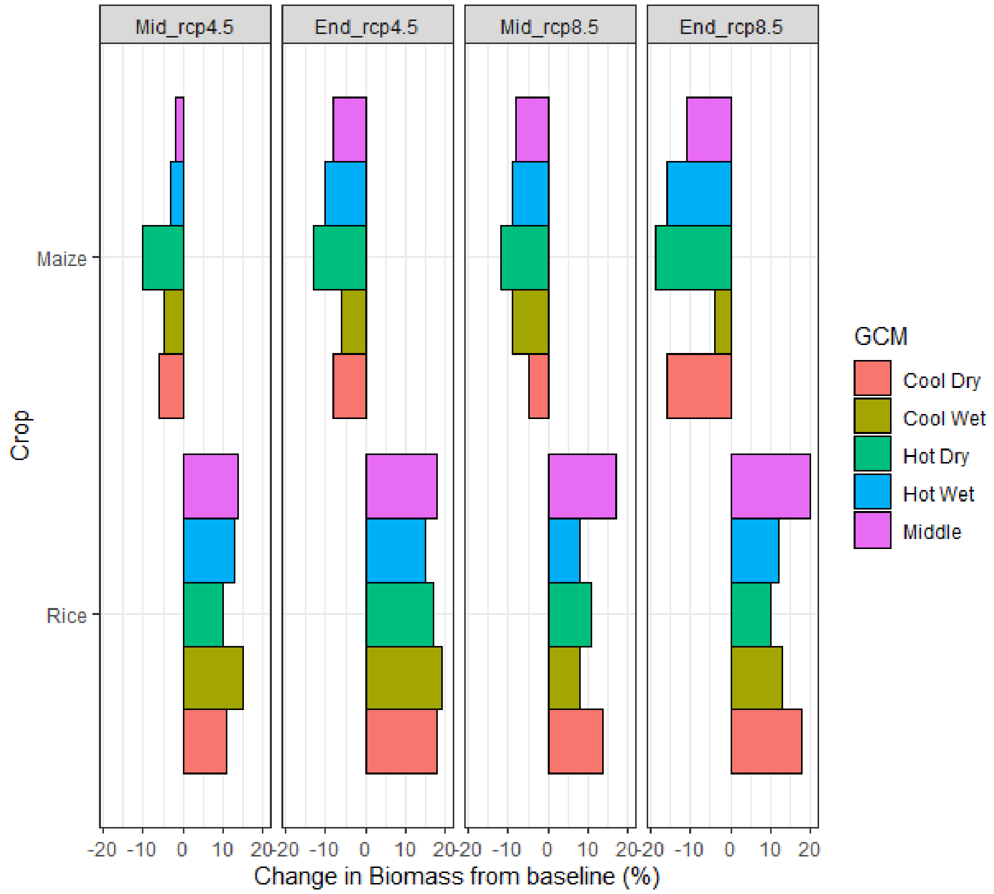

Figure 4.8: Impact of projected climate on final biomass (% change compared to the baseline period) of rice-maize cropping sequence during the mid century and end century under RCP4.5 & RCP8.5 emission scenarios (CT)

In the case of CA practices, the rice biomass was projected to increase by mid century by 14% (Cool Wet) to 18% (Middle) under RCP4.5 and by 15% (Hot Wet) to 22% (Middle) with RCP8.5. By end of century, the biomass was projected to increase by 17% (Hot Dry) to 19% (Cool Wet) and 15% (Hot Dry) to 21% (Cool Wet) under RCP4.5 and RCP8.5 scenarios, respectively. For maize, the biomass was projected to decrease by 1% (Middle) to 8% (Hot Dry) and 4% (Cool Dry) to 9% (Hot Dry) under RCP4.5 and RCP8.5, respectively. By end of century, the maize biomass was projected to decreased by 5% (Cool Wet) to 9% (Hot Dry) and 13% (Cool Wet) to 17% (Hot Dry) under RCP4.5 and RCP8.5 scenarios respectively (Fig. 4.9).

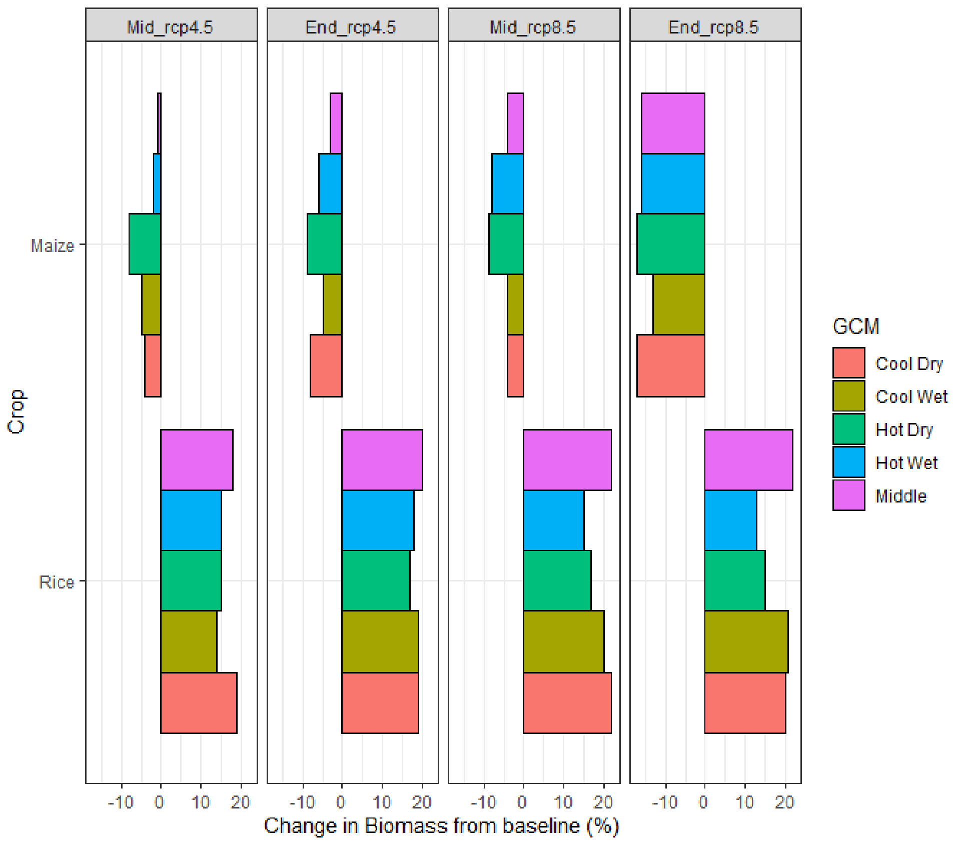

Figure 4.9: Impact of projected climate on final biomass (% change compared to the baseline period) of rice-maize cropping sequence during mid and end century under RCP4.5 & RCP8.5 emission scenarios (CA).

4. 3. 5 Effect of projected climate on yield

For CT practices, the impacts of projected climate on yield were simulated using the five future climate models and two RCPs, and the results are presented in the form of box plots (Fig.4.10). The mean baseline yield (average over years 1980 to 2009) of rice was 3477 kg ha^{-1}. During the mid-century RCP4.5 scenario, the change in rice yield was projected to increase by 5% to 8% (range denotes the highest and lowest % simulated by 5 GCMs) (Fig.4.10). The mean baseline yield of maize was 7169 kg ha^{-1}. The change in maize yield was projected in the range of -1% (Cool Wet) to -7% (Hot Dry) under mid-century RCP4.5. In the case of the mid-century RCP8.5 scenario, the change in projected rice yield was simulated in the range of +13% (Middle) to +7% (Cool Wet) from the baseline. For maize, the change in yield was in the range of -1% (Middle) to -9% (Hot Dry). Under end-century RCP4.5 scenario, the change in projected rice was in the range of +12% (Middle) to +4% (Hot Dry) compared to the baseline. For maize, the yield was projected to decrease by 2% (Middle) to 7% (Hot Dry). Under end RCP8.5 scenario, the rice yield was projected to increase by 6% (Hot Dry) to 13% (Middle) , respectively, from the baseline (Fig.4.10). For maize, the yield was projected to decrease by 10% to 20% compared to the baseline.

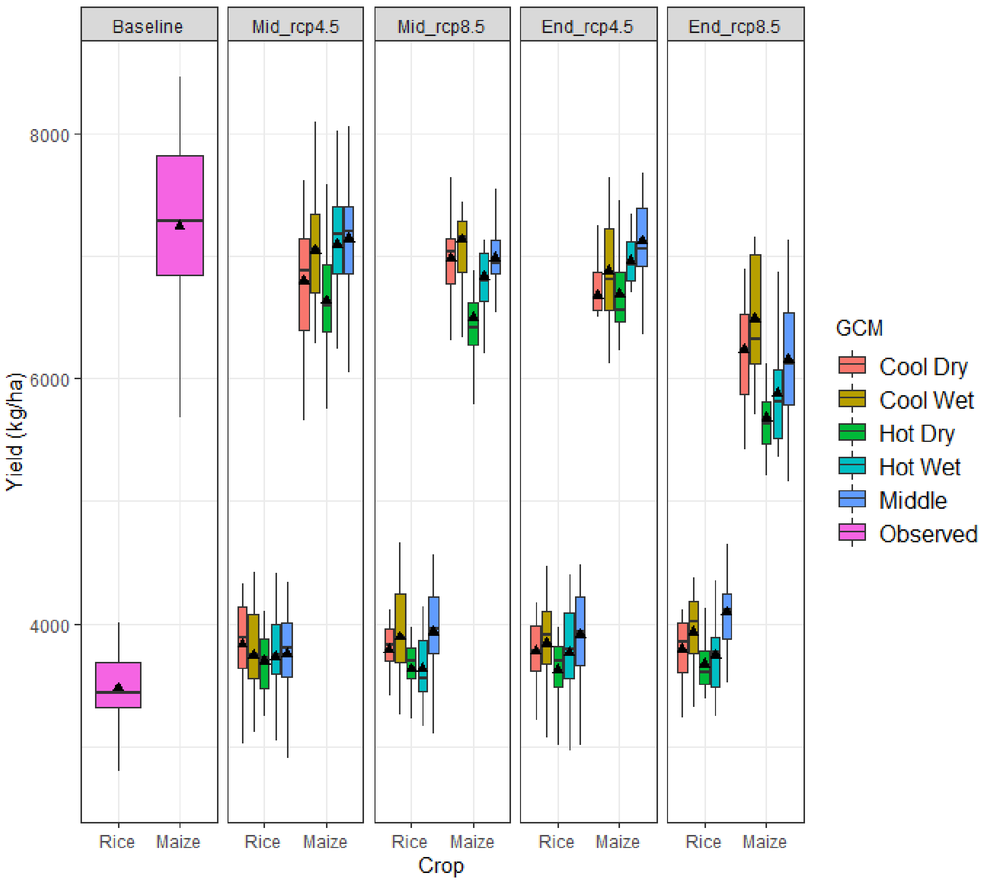

Figure 4.10: Impact of projected climate on yield of rice-maize cropping sequence under mid century RCP4.5 , mid century RCP8.5, end century RCP4.5 and end century RCP8.5. The black triangle and black line inside each box plot represent the mean and median of 30 years, respectively (CT).

In the case CA practices, the impacts of projected climate on yield were simulated for the five future climate models and two RCPs, and the results are presented in the form of box plots (Fig.4.11). The mean baseline yield of rice was 3477 kg ha^{-1}. During mid RCP4.5 scenario, the change in rice yield was projected to increase by 10% to 14% (range denotes the highest and lowest % simulated by 5 GCMs) (Fig.4. 11). Similarly, the mean baseline yield of maize was 6949 kg ha^{-1}. The change in maize yield was projected in the range of - 4% (Hot Dry) to -1% (Cool Wet) (Fig.4.11). In the case of mid RCP8.5 scenario, the change in projected rice yield was simulated in the range of

+13% to +17% than the baseline. For maize, the change in yield was in the range of -7% (Hot Dry) to -1% (Cool Dry). Under end RCP4.5 scenario, the change in projected rice was in the range of +10% to +15%, respectively. For maize, the yield was projected to decrease by 5% (Hot Dry) to 3% (Cool Wet). Under end RCP8.5 scenario, the rice yield was projected at +16% to +9% compared to the baseline period (Fig.4.11). For maize, the yield was projected to decrease in the range of 16% (Hot Dry) to 9% (Cool Wet).

Temperatures above the optimal range and less rainfall particularly for the maize growing season at the end century in hotter with dry conditions (Hot Dry) cause water stress. According to the model, this water stress results in insufficient remobilization of stored pre-anthesis carbohydrates in the grain, resulting in lower yield in the future.

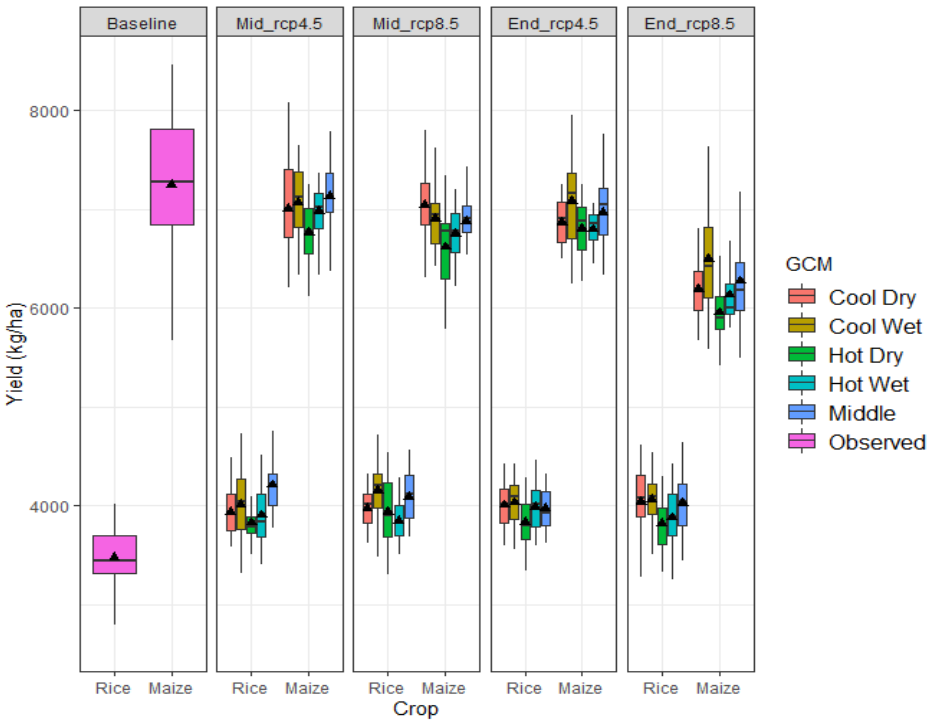

Figure 4.11 Impact of projected climate on yield of rice-maize cropping sequence under mid century RCP4.5, mid century RCP8.5, end century RCP4.5 and end century RCP8.5 scenarios. The black triangle and black line inside each box plot represent the mean and median of 30 years, respectively (CA).

4. 4 Discussion

4. 4.1 Impact of CA and future climate on soil organic carbon stock

Our findings showed that the SOC stocks increased in future under CA in all climate scenarios. In contrast, the SOC of the CT systems decreased over time. This finding showed the importance of strip tillage and residue retention as mulch in order to gain the advantages of CA. The increase in SOC under the CA system is due to crop residue being retained on the field, leading to the gradual accumulation of soil organic carbon (Jat et al., 2019).

Residues left on the field are deposited in the litter C pool, where they decompose (Herzfeld et al., 2021). This is consistent with the findings of Sarker et al. (2022), who demonstrated that the accumulation of biomass in the Rice-maize system led to an increase in SOC in Bangladesh. Furthermore, a five-year CA study in Southern India discovered that the CA-based rice-maize system had higher carbon concentrations than conventional systems (Tuti et al., 2022). Our findings also corroborate those of several researchers in diverse regions and cropping systems, such as Aguilera et al. (2013) and Das et al. (2018), who have shown an enhancement of SOC under ZT-RR (Zero tillage and residue retention) compared to the CT system.

The SOC increases under ZT-RR by reducing soil disturbance, retaining crop residues on the soil surface, and increasing moisture retention; all of these factors are associated with the formation and stabilization of soil aggregates, as well as the protection of their associated organic carbon as observed by Chaki et al. (2022). According to the findings of Cookson et al. (2008), the rise in SOC was observed under ZT-RR by increasing the activity and diversity of beneficial microorganisms in the top soil layers. In fact, ZT-RR increases earthworm population and diversity (Pelosi et al., 2014); it retains their burrows, which increases water infiltration and root penetration (Soane et al., 2012). However, even when ZT is used, residue retention may still be necessary in order to supply an input of SOC (Vicente-Vicente et al., 2016). This study concluded that residual residues on the soil surface help to prevent carbon loss from the soil to the atmosphere. Le et al. (2018) demonstrated a declining trend in SOC stocks under CT and an increasing trend in most ZT-RR operations throughout the next 20 years using the Environmental Policy Integrated Climate (EPIC) model in Cambodia. According to a meta-analysis, long-term (>10 years) no-tillage with residue retention improved SOC by 10% when compared to conventional tillage with residue removal (Zhao et al., 2017).

A number of climate parameters, such as temperature, humidity, and precipitation all influence SOC (Adeel et al., 2018). In our research, we found that SOC stocks increased under a Middle and Cool Wet environment. This rise in SOC buildup is connected with net primary output, which is larger in a Middle and Cool Wet environment than in a Hot-Dry climate. Heavier rainfall also increases soil moisture, which in turn encourages the growth of net primary production (NPP) (Fang et al., 2001). In the form of litter and root exudates, NPP can import carbon into the soil systems (Bolinder et al., 2007).

The level of moisture in the soil is the most important element in determining how quickly soil organic matter can decompose (Adeel et al., 2018). Studies showed that SOC sequestration was better in NT than in CT when the average annual rainfall was higher and the initial concentration of SOC was lower (Cai et al., 2022). The negative consequences of increasing temperatures, which most likely enhance the breakdown of soil organic matter, result in a decrease in SOC concentration (Heikkinen et al, 2013; Moinet et al., 2020). On the other hand, keeping residue on the surface of NT soils reduces soil temperature and increases water availability which promotes crop development, enhances above ground biomass (Pittelkow et al., 2014) and ultimately enhances SOC. In addition, residue retention at the surface of NT soils lowers soil temperature, thus reducing SOC loss in the soil systems (Vicente-Vicente et al., 2016). Nicoloso et al. (2021) found that for every 1℃ increase in mean annual temperature (MAT), the mean difference in soil organic carbon (SOC) between untilled and tilled soils increased by 0.40±0.01 Mg C ha^{-1}.

4. 4. 2 Response of crop phenology

In the present study, temperature rise had a great influence on rice flowering in Cool Wet climates (slightly delayed) while it was advanced in Hot Dry climates under RCP4.5 and RCP8.5 over the mid century and end century period. Likewise, days of maturity exhibited a similar pattern. The anthesis and days to maturity for CA practices were similarly reduced by the Hot Dry and Cool Dry climate model. This is due to the fact that higher mean Tmax and Tmin accelerate the accumulation of growing degree days, resulting in a shorter overall crop duration (Ge et al., 2022). In the case of maize in CT, under RCP4.5 and RCP8.5, the days of anthesis and maturity were advanced in all climate scenarios for the mid century and end century periods. However, it was more advanced in a Hot Dry climate than in a Cool Wet climate. Similar trends were also observed in CA practices, particularly in Hot Dry and Cool Dry climates, where the reduction in duration was shorter. The present analysis also revealed that, according to

RCP 8.5, the days of anthesis and maturity were more advanced in the end century than mid century. High temperature reduces nutrient absorption and subsequent digestion, stunts shoot and root growth, and causes underdevelopment of anthers and led to the loss of pollen variability (Lesk et al., 2016; Zhao et al., 2017). This finding is similar to recent research (Sun et al ., 2016; Guo et al., 2019), which found that rising temperatures (both Tmax and Tmin) reduced crop duration.

4. 4. 3 Effect on final biomass

The present study confirmed that rice biomass in both CA and CT increased during the mid and end century under RCP4.5 and RCP8.5 scenarios. The increase was larger in the Cool Wet climate compared to the Hot Dry climate, and especially so with CA practices compared to CT practices. Rice, a C_3 crop, has a positive CO_2 fertilization effect during the mid and end century under the RCP4.5 and RCP8.5 climatic scenarios (Kimball et al., 2016). This study found that elevated CO_2 reduced evapotranspiration by 10% while increasing canopy temperature, which benefits biomass production. Another argument is that higher CO_2 levels in the atmosphere accelerate photosynthesis, resulting in more biomass production in crops (Chandran et al., 2022).

Under the RCP4.5 and RCP8.5 scenarios, maize biomass decreased with both CA and CT practices during the mid and end century. However, the projected biomass was higher with CA practices compared to CT practices, especially under the Hot Dry and Cool Wet climate scenarios. The main explanation is that for CA practices, residue retention help to maintain soil moisture in the field under the Hot Dry climate scenario (Bahri et al., 2019). For a C_4 crop, maize, the average response to elevated CO_2 was a slight impact on biomass production or no compensation whereas warming caused notable decreases in biomass production (Kimball et al., 2016). Higher temperatures will reduce the maize growing season, cause less solar energy to be captured, and result in lower crop productivity for maize plants (Fiwa et al., 2015).

4. 4. 4 Effect on crop yield

This study showed that CA practices gave higher rice yields than CT practices, especially in Middle and Hot Dry climates. The fundamental reason is that CA methods improve biomass production, which allows for more residue to be left into the field and, as a result, increases crop productivity. Under the RCP4.5 and RCP8.5 scenarios, our study demonstrated that both CA and CT resulted in increased rice yield during the mid and end century. Despite warming temperature, yields increase, partly due to the CO_2 fertilization effect on rice (Chandran et al., 2022). The direct effect of higher CO_2 on C_3 plants is an increase in the rate of photosynthesis, which boosts crop growth and production (Kimball et al., 2016). Additionally, it reduces the conductivity of CO_2 and water vapour through stomata, increasing the effectiveness of water use and alleviating the effects of drought stress (Ottman et al., 2001). Yang et al. (2018) investigated how projected climate change would affect the yield of rice in the China by the 2040s. They found that using the GFDL-ESM2M and IPSL-CM5A-LR models, rice yields increased by 1.4 to 10.6%.

Under the RCP4.5 and RCP8.5 scenarios, our study demonstrated that both CA and CT resulted in decreased maize yield especially in Hot Dry climates during the mid and end century. But the projected yield was higher in CA practices compared to CT practices, especially under the Hot Dry climate scenario. The main explanation is that for CA practices, residue retention helped to decrease soil temperature in the field under Hot Dry climate (Chaki et al., 2021a). In addition to this, when conventional tillage is used, there is often no residue left on the land. This means that the land is not protected from high temperatures, resulting in a decrease in the soil moisture content (Ward et al., 2013). In contrast, zero tillage with residue retention, preserved 4.0% more moisture than conventional tillage due to 2-3% lower soil temperature compared to conventional tillage (Bhatt et al., 2021). However, the current study indicated that the increase in seasonal average Tmax and Tmin was greatest during the maize season, at 4 °C and 4.3 °C at end century RCP8.5, respectively, which could have a negatively impact on the maize yield. The main reason for lower yield is that higher temperatures generate lower soil water content and less nitrogen uptake by maize plants (Hsiao et al., 2012). Additionally, pollen viability decreases with increasing temperature under both normal and elevated CO_2 concentrations (Prasad et al., 2003). Furthermore, in the long run, rainfall variability and a shorter maize growing season are projected to be major contributors to lower maize yields (Ngwira et al., 2014).

4. 5 Potential sources of uncertainty in future biomass and yield projections:

Future changes in environmental conditions will influence model uncertainty. In the future, it is anticipated that there will be a rise in temperature, resulting in changes to crop phenology (e.g flowering, maturity etc.). However, the precise implications of these changes remain uncertain. Moreover, it is expected that there will be alterations in precipitation distribution, and concentrations of carbon dioxide in the forthcoming future (Chandran et al., 2022, Meinshausen et al., 2011). All of this factors could have an effect on the expected changes in biomass and yield in the future (Porter and Semenov, 2005). This will affect our model prediction error. Taking as an example, adaptations at the crop level (rice, wheat and maize) increase simulated yields from 7–15% on average (Challinor et al., 2014).

However, This study assumes that farmers will continue to use the same cultivar by the end of the century, which may not be the case in reality. Adapting agricultural systems to climate change may greatly mitigate the negative effects of climate change and potentially overcome these, such as shifting to better-adapted varieties (Challinor et al., 2014). Breeders are likely to develop new drought-tolerant cultivars which will be higher yielding under climate change.

4. 5 Conclusions

Using the process-based cropping system model APSIM, we were able to show how CA based practices help to make rice-maize production more resilient to climate change. We confirm that keeping the residue and using it as a mulch is an important part of CA, especially for increasing SOC content in the soil. Under all future scenarios, and under end century RCP8.5 in particular, temperature forecasts from GCMs revealed a significant increase in both maximum and minimum temperature. Despite the increase in temperature, CO_2 fertilization results in increased rice yields under different climate change scenarios. The current study also indicates that the increase in seasonal average Tmax and Tmin was greatest during the maize season, which could have a negative impact on maize yields. The severity of the decline in maize biomass and yield could be minimised by changing current agronomic management strategies, particularly those used in CA. To make more accurate and complete assessments of how sensitive crops are to climate change, multi-crop model and multi-GCM ensemble forecasts need to be tested in different soil and cultivar conditions for this region.

References

Adeel, M., Zahin, M., Shafi, Z., Ahmad, M., Rizwan, M., Shafiq, M., and Rui, Y. (2018). Conservation agriculture, a way to conserve soil carbon for sustainable agriculture productivity and mitigating climate change: a review. Fresenius Environmental Bulletin. 27 : 6297-6308

Aggarwal, G.C., Sidhu, A.S., Sekhon, N.K., Sandhu, K.S., and Sur, H.S. (1995). Puddling and N management effects on crop response in a rice-wheat cropping system. Soil Tillage Res, 36:129–139. https://doi.org/10.1016/0167-1987(95)00504-8.

AgMIP (2012) . Guide for regional integrated assessments: handbook of methods and procedures, Version 4.2. AgMIP, URL: http:// www. agmip. org/ wp- conte nt/ uploa ds/ 2013/ 06/ AgMIP- Regio nal- Resea rch- Team- Handb ook- v4.2. pdf. Accessed 4 Mar 2020.

AgMIP (2013). Guide for running AgMIP climate scenario generation tools with R in windows version 2.3. http:// www. agmip. org/ wp- conte nt/ uploa ds/ 2013/ 10/ Guide-for- Running- AgMIP- Climate- Scenario- Generation- with-R- v2.3. pdf. Accessed 4 Mar 2020.

Aguilera, E., Lassaletta, L., Gattinger, A., and Gimeno, B. S. (2013). Agriculture, Ecosystems and Environment Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. "Agriculture, Ecosystems and Environment," 168: 25–36.

Challinor, A.J., Müller, C., Asseng, S., Deva, C., Nicklin, K.J., Wallach, D., Vanuytrecht, E., Whitfield, S., Villegas, J.R., Koehler. A.K. (2018). Improving the use of crop models for risk assessment and climate change adaptation. Agricultural Systems, 159: 296-306.

Ainsworth, EA., and Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. Plant Cell Environ , 30:258-270.

Alam, M. K., Bell, R. W., Haque, M. E. and Kader, M. A. (2020). Minimal soil disturbance and increased residue retention increase soil carbon in rice-based cropping systems on the Eastern Gangetic Plain. Soil & Tillage Research, 183 : 28–41.

Alam, M. K., Bell, R. W., Haque, M. E., and Kader, M. A. (2018). Minimal soil disturbance and increased residue retention increase soil carbon in rice-based cropping systems on the Eastern Gangetic Plain. Soil and Tillage Research, 183: 28–41.

Ali, M. Y., Waddington, S. R., Hodson, D., Timsina, J., and Dixon, J. (2008). Maize-rice crop-ping systems in Bangladesh: Status and research opportunities. Mexico: CIMMYT–IRRI Joint Publication, 36.

Araya, A., Luedeling, Eike., Hadgu, K., Kisekka, I., and Martorano, L. (2015). Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. Agricultural and Forest Meteorology. 214. 252-265. 10.1016/j.agrformet.2015.08.259.

Bahri, H., Annabi, M., Cheikh, M'Hamed., and H, A. (2019). Assessing the long-term impact of conservation agriculture on wheat-based systems in Tunisia using APSIM simulations under a climate change context. Sci Total Environ, 692:1223-1233. doi: 10.1016/j.scitotenv.2019.07.307. Epub 2019 Jul 21. PMID: 31539953.

Bashak, J. K., Ali, M. A., and Islam, N. (2010). Assessment of the effect of climate change on boro rice production in Bangladesh using DSSAT model, 38(2):95–108.

BBS (2020). Ministry of planning. Dhaka: Govt. of Bangladesh.

Benbi, DK., Pritpal,Singh., Toor, AS., and Verma, G. (2016) . Manure and fertilizer application efects on aggregate and mineral-associatedorganic carbon in a loamy soil under rice–Wheat system. Commun Soil Sci Plant Anal ,47:1828–1844.

Bhatt, Rajan., Singh, Pritpal., Hossain, Akbar., and Timsina, Jagadish. (2021). Rice–wheat system in the northwest Indo‐Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. -Paddy and Water Environment ,19 :345-365.

Bolinder, M., Janzen, H., Gregorich, E., Angers, Denis., and Vandenbygaart, Bert. (2007). An approach for estimating net primary productivity and annual carbon input to soil for common agricultural crops in Canada. Agriculture, ecosystems & environment, 118:29-42. 10.1016/j.agee.2006.05.013.

Cai, Andong., Tianfu, Han., Tianjing, Ren., Jonathan, Sanderman., Yichao, Rui., Bin, Wang., Pete, Smith., Minggang, Xu., and Yu'e, Li. (2022). Declines in soil carbon storage under no tillage can be alleviated in the long run, Geoderma, 425 : 116028.

Chaki, A. K., Gaydon, D. S., Dalal, R. C., and Bellotti, W. D. (2022). How we used APSIM to simulate conservation agriculture practices in the rice- wheat system of the Eastern Gangetic Plains. Field Crops Research, 275: 108344.

Chaki, A. K., Gaydon, D. S., Dalal, R. C., Bellotti, W. D., Gathala, M. K., and Hossain, A. (2021a). Conservation agriculture enhances the rice-wheat system of the Eastern Gangetic Plains in some environments, but not in others. Field Crops Res, 265: 108109. doi:10.1016/j.fcr.2021.108109

Chaki, A.K., Gaydon, D.S., Dalal, R.C. (2022). Achieving the win–win: targeted agronomy can increase both productivity and sustainability of the rice–wheat system. Agron. Sustain. Dev. 42: 113 . https://doi.org/10.1007/s13593-022-00847-8

Challinor, A.J., Smithc, M.S., and Thorntond, P. (2013). Use of agro-climate ensembles for quantifying uncertainty and informing adaptation. Agric. Forest Meteorol, 170: 2–7.

Chandran, M. A., Banerjee, S., Mukherjee , S. (2022). Evaluating the long-term impact of projected climate on rice-lentil-groundnut cropping system in Lower Gangetic Plain of India using crop simulation modelling. Int J Biometeorol, 66: 55–69 .

Choudhary, M., Sharma, P. C., Jat, H. S., Jat, M. L., Choudhary, S., and Garg, N. (2018). Soil biological properties and fungal diversity under conservation agriculture in Indo-Gangetic Plains of India. J. Soil Sci. Plant Nutr, 18(4): 1142–1156.

Cookson, W., Murphy, Daniel., and Roper, Margaret. (2008). Characterizing the relationships between soil organic matter components and microbial function and composition along a tillage disturbance gradient. Soil Biology & Biochemistry 40: 763-777. 10.1016/j.soilbio.2007.10.011.

Chowdhury, A., Hasan, K., and Islam, S. (2022). Climate change adaptation in Bangladesh: Current practices, challenges and the way forward. The Journal of Climate Change and Health, 6: 100108.

Das, A., Layek, J., Idapuganti, R. G., Basavaraj, S., Lal, R., Rangappa, K., and Ngachan, S. (2020). Conservation tillage and residue management improves soil properties under a upland rice–rapeseed system in the subtropical eastern Himalayas. Land Degradation and Development, 31(14): 1775–1791.

Das, T. K., Saharawat, Y. S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K. K., Sharma, A. R., and Jat, M. L. (2018). Field Crops Research Conservation agriculture effects on crop and water productivity, pro fi tability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. Field Crops Research, 215:, 222-231.

Erenstein, Olaf., K, Sayre., C., Wall., Hellin, Jon., and Dixon, John. (2012). Conservation agriculture in maize and wheat based systems in the (sub)tropics: Lessons from adaptation initiatives in South Asia, Mexico and Southern Africa. Journal of Sustainable Agriculture, 36(2):180-206

Fang, J.Y., Piao, S.L., Tang, Z.Y., Peng, C.H., and Wei, J. (2001). Interannual variability in net primary production and precipitation. Science, 293: 1723.

FAO (2017). Agriculture Sourcebook Summary Climate-Smart.

Fiwa, L. (2015). Improving rainfed cereal production and water productivity in Malawi. lirias.kuleuven.be/ bitstream/123456789/493765/1/Lameck_FIWA.pdf.

Gathala, M. K., Ladha, J. K., Kumar, V., Saharawat, Y. S., Kumar, V., and Sharma, P. K. (2011b). Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron. J, 103: 961–971. doi:10.2134/ agronj2010.0394

Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Kumar, V., Kumar, V., and Sharma, P.K. (2011). Effect of tillage and crop establishment methods on physical properties of a medium- textured soil under a seven-year rice-wheat rotation. Soil Sci. Soc. Am. J, 75: 1851–1862. https://doi.org/10.2136/sssaj2010.0362.

Gathala, M.K., Laing, A.M., Tiwari, T.P., Timsina, J., Islam, M.S., Chowdhury, A.K., Chattopadhyay, C., Singh, A.K., Bhatt, B.P., Shrestha, R., Barma, N.C.D., Rana, D.S., Jackson, T.M., and Gerard, B. (2020). Enabling smallholder farmers to sustainably improve their food, energy and water nexus while achieving environmental and economic benefits. Renew. Sustain. Energy Rev, 120: 109645

Gaydon, D.S., Balwinder-Singh, Wang, E., Poulton, P.L., Ahmad, B., Ahmed, F., Akhter, S., Ali, I., Amarasingha, R., Chaki, A.K., Chen, C., Choudhury, B.U., Darai, R., Das, A., Hochman, Z., Horan, H., Hosang, E.Y., Kumar, P.V., Khan, A.S.M.M.R., Laing, A.M., Liu, L., Malaviachichi, M.A.P.W.K., Mohapatra, K.P., Muttaleb, M.A., Power, B., Radanielson, A.M., Rai, G.S., Rashid, M.H., Rathanayake, W.M.U.K., Sarker, M.M.R., Sena, D.R., Shamim, M., Subash, N., Suriadi, A., Suriyagoda, L.D.B., Wang, G., Wang, J., Yadav, R.K., Roth, C.H. (2017). Evaluation of the APSIM model in cropping systems of Asia. Field Crops Res, 204: 52–75. https://doi.org/10.1016/j.fcr.2016.12.015.

Gaydon, D.S., Probert, M.E., Buresh, R.J., Meinke, H., and Timsina, J. (2012b). Modelling the role of algae in rice crop nutrition and soil organic carbon maintenance. Eur. J. Agron, 39: 35–43. https://doi.org/10.1016/j.eja.2012.01.004.

Ge, J., Xu, Y., Zhao, M., Zhan, M., Cao, C., Chen, C., and Zhou, B. (2022). Effect of Climatic Conditions Caused by Seasons on Maize Yield, Kernel Filling and Weight in Central China. Agronomy , 12: 1816. https:// doi.org/10.3390/agronomy12081816

Guo, Y., Wu, W., Du, M., Liu, X., Wang, J., Bryant, CR. (2019) . Modelling climate change impacts on rice growth and yield under global warming of 1.5 and 2.0 °C in the Pearl River Delta, China. Atmosphere, 10:567. doi:https:// doi. org/ 10. 3390/ atmos 10100 567.

Haque, A., M., Gathala, M. K., Timsina, J., Ziauddin, A. T. M., Hossain, M., and Krupnik, T. J. (2023). Reduced tillage and crop diversification can improve productivity and profitability of rice-based rotations of the Eastern Gangetic Plains. Field Crops Research, 291: 108791.

Heikkinen, J., Ketoja, E., Nuutinen, V., and Regina, K. (2013). Declining trend of carbon in Finnish cropland soils. Global Change Biology , 19:1456–1469, doi: 10.1111/gcb.12137

Herzfeld ,T., Jens, H., Susanne, R., and Christoph, M. (2021). Soil organic carbon dynamics from agricultural management practices under climate change. Earth Syst. Dynam, 12:1037–1055.

Hobbs, P.R. (2007). Conservation agriculture: what is it and why is it important for future sustainable food production? J. Agric. Sci, 145: 127. https://doi.org/10.1017/S0021859607006892.

Hobbs, Peter. (2008). Tillage and Crop Establishment in South Asian Rice-Wheat Systems. Journal of Crop Production, 4. 10.1300/J144v04n01_01.

Holzworth, D.P., Huth, N.I., Devoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E.L., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S., and Keating, B.A.(2014a). APSIM - evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw, 62: 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009.

Hsiao, T. C., and Fereres, E. Maize. (2012). Crop yield response to water. Available at: http://www.fao.org/docrep/016/i2800e/i2800e. pdf.

IPCC, (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, Page.151.

IPCC, (2007a). Climate change 2007: the physical science basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York.

Islam, M. R. and S, Hoshain. (2022). A brief review on the present status, problems and prospects of maize production in Bangladesh. Res. Agric. Livest. Fish., 9 (2): 89-96.

Islam, S, M., Samreth, S., Hayat, A., and Islam, S. (2022). Climate change, climatic extremes, and households' food consumption in Bangladesh: A longitudinal data analysis. Environmental Challenges, 7.

Jamieson, PD., Porter, JR., and Wilson, DR. (1991). A test of the computer simulation model ARCWHEAT1 on wheat crops grown in New Zealand. Field Crop Res, 27:337–350. https:// doi. org/ 10. 1016/ 0378- 4290(91) 90040-3.

Jat, R. K., Singh, R. G., Kumar, M., Jat, M. L., Parihar, C. M., Bijarniya, D., and Gupta, R. K. (2019). Ten years of conservation agriculture in a rice–maize rotation of Eastern Gangetic Plains of India: Yield trends, water productivity and economic profitability. Field Crops Research, 232: 1–10.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., and Ritchie, J.T. (2003). The DSSAT cropping system model. Eur. J. Agron, 18: 235–265. https://doi.org/10.1016/S1161-0301 (02)00107-7.

Jones, JW., Antle, JM., Basso, B., Boote, KJ., Conant, RT., Foster, I., and Keating, BA. (2017). Toward a new generation of agricultural system data, models, and knowledge products: state of agricultural systems science. Agric Syst, 155:269–88.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z. (2003). An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron, 18: 267–288.

Kimball, BA. (2016). Crop responses to elevated CO_2 and interactions with H2O, N, and temperature. Curr Opin Plant Biol, 31:36-43. doi: 10.1016/j.pbi.2016.03.006. Epub 2016 Apr 1. PMID: 27043481.

Kreft, S., Eckstein, D., Dorsch, L., and Fischer, L. (2021). Global Climate Risk Index (2016). Available at http://germanwatch.org/de/download/13503.pdf

Ladha, J.K., Singh, J., Erenstein, O., and Hardy, B. (2009). Integrated Crop and Resource Management in the Rice-Wheat System of South Asia. International Rice Research Institute, Los Ba˜nos, Philippines.

Ladha, JK., Rao, AN., Raman, AK., Padre, AT., Dobermann, A., Gathala, M., Kumar, V., Sharawat, Y., Sharma, S., Piepho, HP., Alam, MM., Liak, R., Rajendran, R., Reddy, CK., Parsad , R., Sharma, PC., Singh, SS., Saha, A., and Noor, S. (2016). Agronomic improvements can make future cereal systems in South Asia far more productive and result in a lower environmental foot- print. Global Change Biology, 22:1054–1074

Le, N. K., Jha, M. K., Reyes, M. R., Jeong, J., Doro, L., Gassman, P. W.,and Boulakia, S. (2018). Agriculture, Ecosystems and Environment Evaluating carbon sequestration for conservation agriculture and tillage systems in Cambodia using the EPIC model. Agriculture, Ecosystems and Environment, 251:37–47.

Lesk, C., Rowhani, P., and Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. Nature, 529:84–87. doi: 10.1038/nature16467

Li, K., Pan, J., Xiong, W. (2022). The impact of 1.5 °C and 2.0 °C global warming on global maize production and trade. Sci Rep, 12: 17268 .

Liu, H., Yang, L., Wang, Y., Huang, J., Zhu, J., Yunxia, W., Dong, G., and Liu, G. (2008). Yield formation of CO_2-enriched hybrid cultivar Shanyou 63 under fully open-air field conditions. Field Crops Res, 108:93-100.

Lobell, D. B., Field, C. B., Cahill, K. N., and Bonfils, C. (2006). Impacts of future climate change on California perennial crop yields: Model projections with climate and crop uncertainties. Agricultural and Forest Meteorology, 141: 208–218.

Mojid, (2020). IOP Conf. Ser.: Earth Environ. Sci. 423 012001.

Moinet, G., Matthias, K., John, M., Cornelia, E., Abad, R., and Peter, M. (2020). Temperature sensitivity of decomposition decreases with increasing soil organic matter stability, Science of The Total Environment, 704: 135460.

Meinshausen, M., Smith, S.J., Calvin, K. et al. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109, 213 .

Ngwira, A. R., Aune, J. B., and Thierfelder, C. (2014). Soil & Tillage Research DSSAT modelling of conservation agriculture maize response to climate change in Malawi. Soil & Tillage Research, 143: 85–94.

Nicoloso, Rodrigo S., and Charles ,W. (2021). Rice intensification of no-till agricultural systems: An opportunity forcarbon sequestration. Soil Sci. Soc. Am. J, 85:1395–1409.

Ottman, MJ. (2001). Elevated CO_2 increases sorghum biomass under drought conditions. New Phytol, 150:261–273.

Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., Pradhan, S., and Pooniya, S. (2016). Conservation agriculture in irrigated intensive maize-based systems of north-Western India. Effects on crop yields, water productivity and economic profitability. Field Crops Res, 193: 104–116. doi:10.1016/j.fcr.2016.03.013

Pelosi, C., Pey, B., Hedde, M., Caro, G., Capowiez, Y., Guernion, M., and Cluzeau, D. (2014). Reducing tillage in cultivated fields increases earthworm functional diversity. Applied Soil Ecology, 83:79–87.

Pittelkow, C. M., Liang, X., Linquist, B. A., Van , K. J., Lee, J., Lundy, M. E., van Gestel, N., Six, J., Venterea, R. T., and van , C. (2014). Productivity limits and potentials of the principles of con-servation agriculture. Nature, 517: 365–368.

Prasad, PVV., Boote, KJ., Allen, LH Jr., and Thomas, JMG. (2003). Super-optimal temperatures are detrimental to peanut (Arachis hypogaea L.) reproductive processes and yield under both ambient and elevated carbon dioxide. Glob Chang Biol, 9:1775–1787

Porter, JR., and Semenov, MA. (2005). Crop responses to climatic variation. Philos Trans R Soc Lond B Biol Sci. 29;360(1463):2021-35.

Probert, M.E., Dimes, J.P., Keating, B.A., Dalal, R.C., and Strong, W.M. (1998). APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56: 1–28. https://doi.org/10.1016/S0308-521X(97) 00028-0.

Qin, J., Hu, F., Zhang, B., Wei, Z., and Li, H. (2006). Role of straw mulching in non-continuously flooded rice cultivation. Agric. Water Manag, 83: 252–260. https://doi. org/10.1016/j.agwat.2006.01.001

Rahut, Dil Bahadur., Jeetendra, P. A., Navneet, M., and Tetsushi, S. (2022). Chapter 6 - Expectations for household food security in the coming decades: A global scenario. Future Foods, Pages 107-131, ISBN 9780323910019

Rahman, MH., Ahmad, A., Wang, X., Wajid, A., Nasim, W., Hussain, M., Ahmad, B., Ahmad, I., Ali, Z., Ishaque, W., Awais, M., Shelia, V., Ahmad, S., Fahd, S., Alam, M., Ullah, H., and Hoogenboom, G. (2018). Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. Agric for Meteorol, 253–:94–113.

Ruamsuke, K., Dhakal, S. and Marpaung, C.O. (2015). Energy and economic impacts of the global climate change policy on Southeast Asian countries: a general equilibrium analysis., Energy, 81: 446-461, doi: 10.1080/23249676.2014.1001881.

Ruane, AC., and McDermid, SP. (2017). Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. Earth Persp 4:1. https:// doi. org/ 10. 1186/ s40322- 017- 0036-4

Sadras, V.O., and Calvino, P.A. (2001). Quantification of grain yield response to soil depth in soybean, maize, sunflower, and wheat. Agron. J, 93: 577–583.

Sarker, MR., Galdos, MV., Challinor, AJ., Huda, MS., Chaki, AK., and Hossain, A. (2022). Conservation tillage and residue management improve soil health and crop productivity-Evidence from a rice-maize cropping system in Bangladesh. Front. Environ. Sci. 10:969819. doi: 10.3389/fenvs.2022.969819

Sarwar, A. K. M. G., and Biswas, J. K. (2021). Cereal Grains of Bangladesh – Present Status, Constraints and Prospects. In (Ed.), Cereal Grains - IntechOpen.

Huq, S.M.I., Uddin, J., S and Shoaib, M.(2013). The soils of Bangladesh. Springer Dordrecht. 1: XIII, 165. doi.org/10.1007/978-94-007-1128-0.

Serna, L. (2022). Maize stomatal responses against the climate change. Front Plant Sci, 13:952146. doi: 10.3389/fpls.2022.952146. PMID: 36204083; PMCID: PMC9531676.

Shahid, S. (2010). Rainfall variability and the trends of wet and dry periods in Bangladesh. International Journal of Climatology, 30 (15): 2299–2313.

Shahid, S., Harun, S., Bin, and Katimon, A. (2012). Changes in diurnal temperature range in Bangladesh during the time period 1961-2008. Atmospheric Research, 118:260–270.

Silva ,S.H.N.P., Taro, T., and Kensuke, O. (2021). Evaluation of APSIM-wheat to simulate the response of yield and grain protein content to nitrogen application on an Andosol in Japan, Plant Production Science, 24: 454-465, DOI: 10.1080/1343943X.2021.1883989

Soane, B. D., Ball, B. C., Arvidsson, J., Basch, G., Moreno, F., and Roger-estrade, J. (2012). Soil & Tillage Research No-till in northern , western and south-western Europe : A review of problems and opportunities for crop production and the environment. Soil & Tillage Research, 118: 66–87.

Soler ,CMT., Sentelhas, PC., and Hoogenboom, G. (2007) . Application of the CSM-CERES-maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. Eur J Agron, 27:165–177. https:// doi. org/ 10. 1016/j. eja. 2007. 03. 002

Sun, H., Zhang, X., Wang, E., Chen, S., Shao, L., and Qin, Wenli. (2016). Assessing the contribution of weather and management to the annual yield variation of summer maize using APSIM in the North China Plain. Field Crops Research, 10.1016/j.fcr.2016.05.007.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2011).The CMIP5 Experiment Design. Bull. Amer. Meteorol. Soc. VL - 93,485-498.

Tilman D, Balzer C, Hill J and Befort, B. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences, 108:20260–20264.

Timsina, J., Wolf, J., Guilpart, N., Van Bussel, L. G. J., Grassini, P., and Van Wart, J. (2018). Can Bangladesh produce enough cereals to meet future demand? Agric. Syst, 163: 36–44.

Tui, S.HK., Descheemaeker, K., and Valdivia, R.O. (2021). Climate change impacts and adaptation for dryland farming systems in Zimbabwe: a stakeholder-driven integrated multi-model assessment. Climatic Change ,168:10

Tuti, MD., Rapolu, MK., Sreedevi, B., Bandumula, N., Kuchi, S., Bandeppa, S., Saha, S., Parmar, B., Rathod, S., Ondrasek, G., Sundaram, RM. (2022). Sustainable Intensification of a Rice-Maize System through Conservation Agriculture to Enhance System Productivity in Southern India. Plants (Basel), 11(9):1229. doi: 10.3390/plants11091229. PMID: 35567230; PMCID: PMC9104208.

Ullah, K. M., and Uddin, K. (2021). The relationships between economic growth and cropland changes in Bangladesh: An evidence based on annual land cover data. Environmental Challenges, 5: 100252. https://doi.org/10.1016/j.envc.2021.100252

Valkama, E., Gulya, K., Rauan, Z., Muratbek, K., Erbol, Z., Alessia, P., Calogero, S., Dario, S., Barbara, M., Carlo, G., and Marco, A. (2020). Can conservation agriculture increase soil carbon sequestration? A modelling approach.Geoderma, 369:114298.

Van Wart, J., Kersebaum, K. C., Peng, S., Milner, M., and Cassman, K. G. (2013). Estimating crop yield potential at regional to national scales. Field Crops Research, 143: 34–43.

Vicente Vicente, José., García-Ruiz, Roberto., Francaviglia, Rosa., Aguilera, Eduardo., and Smith, Pete. (2016). Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. Agriculture Ecosystems & Environment. 235. 204 - 214.

Vogeler, I., Cichota, R., Thomsen, I. K., Bruun, S., Stoumann, L., and Pullens, J. W. M. (2019). Soil & Tillage Research Estimating nitrogen release from Brassica catch crop residues — Comparison of different approaches within the APSIM model. Soil & Tillage Research, 195:, 104358.

Wang, E., Wang, M.J., Robertson, G.L., Hammer, P.S., Carberry, D., Holzworth, H., Meinke, S.C. Chapman,, J.N.G, Hargreaves., Huth, N.I.,and McLean, G. (2002). Development of a generic crop model template in the cropping system model APSIM. Eur. J. Agron, 18 (1): 121-140.

Wang, N., Wang, E., Wang, J., Zhang, J., Zheng, B., Huang, Y., and Tan, M. (2018). Agricultural and Forest Meteorology Modelling maize phenology, biomass growth and yield under contrasting temperature conditions. Agricultural and Forest Meteorology, 250: 319–329.

Wang, Na., Enli, W., Jing, W., Jianping, Z., Bangyou, Z., Yi, H., and Meixiu ,T. (2018). Modelling maize phenology, biomass growth and yield under contrasting temperature conditions. Agricultural and forest meteorology, 250 (251): 319-329.

Ward, P. R., Roper, M. M., Jongepier, R., and Fernandez, M. M. A. (2013). Consistent plant residue removal causes decrease in minimum soil water content in a Mediterranean environment. Biologia, 68: 1128–1131

Wheeler, T. and von Braun, J. (2013) Climate Change Impacts on Global Food Security. Science, 341, 508-513.

Wallach, D., Mearns, L.O., Ruane, A.C. et al. Lessons from climate modeling on the design and use of ensembles for crop modeling. Climatic Change 139, 551–564 (2016). https://doi.org/10.1007/s10584-016-1803-1

Yan, S., and Alvi, S. (2022). Food security in South Asia under climate change and economic policies, 14(3), 237–251. https://doi.org/10.1108/IJCCSM-10-2021-0113

Yang, X., Wood, EF., Sheffield, J., Ren, L., Zhang, M., and Wang, Y. (2018). Bias correction of historical and future simulations of precipitation and temperature for china from CMIP5 models. J Hydrometeorol, 19(3):609–623.

Zhao, C., B. Liu, S. Piao, X. Wang, D.B. Lobell, Y. Huang, M. Huang, Y. Yao, S. Bassu, P. Ciais, J.-L. Durand, J. Elliott, F. Ewert, I.A. Janssens, T. Li, E. Lin, Q. Liu, P. Martre, C. Müller, S. Peng, J. Peñuelas, A.C. Ruane, D. Wallach, T. Wang, D. Wu,

Z. Liu, Y. Zhu, Z. Zhu, and S, Asseng. (2017). Temperature increase reduces global yields of major crops in four independent estimates. Proc. Natl. Acad. Sci, 114 : 9326-9331,

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., and Huang, Y. (2017). Temperature increase reduces global yields of major crops in four independent estimates. Proc. Natl. Acad. Sci, 114: 9326–9331. doi: 10.1073/pnas.1701 762114

Zhou, W., Lv, T.F., Chen, Y., Westby, A.P., and Ren, W.J. (2014). Soil physicochemical and biological properties of paddy-upland rotation: a review. Sci. World J, 856352.

Chapter 5

Synthesis, general conclusions, and future research directions

There is a lack of information available that illustrates the implications of crop residue utilization trade-offs that are connected to the application of CA in Bangladesh. In particular, adoption rates may differ by farm type, and effectiveness may vary according to both strategy and timescale.

This thesis has the following research objectives:

1. Understand the farm household types in Bangladesh, and the differences between them (Chapter 2).

2. Investigate the effects of various crop residue allocation strategies on tillage and crop establishment in the rice-maize cropping system (Chapter 3).

3. Assess long-term (mid-end century) effects of various crop residue allocation strategies on tillage and crop establishment in the rice-maize cropping system under changing climates (Chapter 4).

Three interconnected methodological components were used: i) a participatory method - a total of 92 farms households were randomly selected to identify the different farm household types in the study area; ii) field experimentation - conducted for two years (a novel planting technique for rice and maize known as strip-tilled direct seeded rice (STDSR) followed by strip-tilled maize (STM), and iii) modelling the productivity of conservation agricultural practices under climate change scenarios. The results are as follows, with conclusions answering the above research objectives.

5.1 Synthesis

5.1.1 Farm Survey

A survey was carried out (Chapter 2) to identify different farm types, their characteristics, and to determine how socioeconomic factors influence technology adoption (thesis objective 1). Based on resource endowment and livelihood orientation, four major farm types were identified in the study area. These are : (1) well-resourced farmers who are solely dependent on agriculture and are less depending on off-farm activities; (2) moderately resourced households led by an older man with more agricultural experience and involved in both on-farm and off-farm activities; (3) households with greater resource-constraints, where cattle are the main livestock and the sale of livestock products is the main source of income and (4) extremely resource-constrained households with young (typically male) farmers as the head of the home and income derived from non-farm activities. These four farm categories illustrate the diversity of farms in North West Bangladesh. It is not possible to give specific technological advice for each farm household. Therefore, farm types are defined in order to make it easier to promote agricultural technologies in farms with similar socio-economic circumstances.

The results showed that age, farming experience, the degree of education of the household head, access to markets, land ownership, the proportion of hired labour, savings, food self-sufficiency and income from off-farm activities are the main factors that greatly influence the adoption of new agricultural technologies. These findings suggest that there is an urgent need for researchers, policymakers, and disseminators to give serious consideration to these key socio-economic factors when deciding on ways to increase the rate of adoption of agricultural technologies by farmers.

The study also revealed that CA farmers were confused by competing uses of crop residues promoted by extension department and more experienced farmers. For example, the Department of Agricultural Extension (DAE) in Bangladesh advised farmers to use crop residues to make compost manure. The same department and an NGO, however, encouraged farmers to use crop residues as mulch or to burn them in the field. As a result, farmers are confused whether crop residue should be used as mulch, compost, or burned in the field.

5.1.2 Field experiment

Agricultural residues are used for various purposes such as animal feeding, fuel, construction, and burning, which in turn influence the likely level of success of CA. Accordingly, in Chapter 3, an experiment was conducted to assess the effectiveness of CA in North West Bangladesh (Chapter 3, thesis objective 2).

5.1.2.1 The effect of tillage and residue management on soil physical, chemical, physiological properties and microbial biomass carbon (MBC)

Soil penetration resistance (SPR) values were significantly lower in DSR than under PTR systems. Additionally, our findings showed an increase in SPR with an increase in soil depth. The key reason is that a higher SPR under PTR was associated with a higher bulk density. Another reason is that the higher SPR value in CT plots may be also associated with the development of plough pan in the soil layer (Kahlon et al., 2013; Bhatt et al., 2021). In contrast, irrespective of residue management practices, SPR was consistently lower in residue incorporation/retention plots compared to CT plots. This is due to the fact that the addition of biomass to the CA plot improved the soil structure (Parihar et al., 2016). The current study showed that the TCE technique's influence on bulk density and the value were lower in STDSR/STM compared to PTR/CTM plots. The decreasing trend is strongly associated with the deposition of organic matter and greater soil biological activity in ST practice. Another explanation is that puddling in rice fields are known to destroy soil aggregates and make the soil more compact (Parihar et al., 2016).

The present study showed that strip tillage with residue retention/ incorporation generated higher soil moisture content than in no residue plots (CT). This is because keeping the residue in strip tillage maintains optimal soil temperature by changing the soil energy balances and heat fluxes (Abdullah et al., 2014). Additionally, no residue with conventional tillage often creates land unprotected from extreme temperature, resulting in a decrease in soil moisture content (Chaki et al., 2021a). Another possible explanation may be more water-stable macro-aggregates and lower evaporation from residue retention plots (Busari et al., 2013).

Soil porosity under CT was significantly lower than ST plots. The fundamental reason is that puddling in rice fields is known to enhance soil compaction, which affects porosity. On the other hand, higher soil porosity is associated with the addition of organic matter and crop residue in ST practices (Alam et al., 2014). Alam et al. (2014) discovered that residue retention/incorporation plots had higher soil porosity than no residue plots. This is also consistent with the other findings of (Alam et al., 2019).

The current study showed that strip-tillage with DSR practices have higher DOC, as compared to CT practices. The main justification is that reducing tillage management practices leading to enhanced organic carbon build-up under zero or reduced tillage, whereas CT methods expose SOC to air, increasing organic carbon oxidation (Zhao et al., 2015). The study also revealed that, when compared to CT practices, light POM-C, heavy POM-C, and MAOM exhibited higher in the ST plots compared to CT plots. This is due to the incorporation of crop stubbles and roots into the soil, which leads in a greater SOC stock. The present study showed that strip tillage with residue retention/ incorporation generated higher microbial biomass carbon (MBC) than in no residue retention plots. The accumulation of crop residue over time increased soil organic carbon. This is because the addition of crop residue provides readily mineralizable and hydrolysable carbon for better microbial growth, and ultimately boosted MBC (Samal et al., 2017; Zhao et al., 2018).

This study showed that strip tillage with residue retention/ incorporation generated higher SPAD values than in no residue retention plots. The increase in SPAD value in the residue retention plots was associated with an increase in soil moisture retention. This will assist in the prevention of oxidative stress effects, and ultimately, it helps to overcome the harmful influences of drought stress on chlorophyll (Sairam and Srivastava, 2002).

5.1.2.2 Effects of tillage and residue management on crop productivity and profitability

The present study showed that rice yield was higher in PTR compared to DSR plots. The possible reasons for a lower yield in DSR could be micronutrient deficiency (Fe and Zn) and weed infestation (Kaur et al., 2015). Therefore, it is necessary to assess the dynamics of macro and micro-nutrients, as well as weeds in order to achieve an optimal rice production when PTR is substituted by DSR, especially for the light - textured soil. Although the DSR plots gave a lower yield, the shorter time the crops spent in the field in DSR as DSR plots were harvested 5 to 7 days earlier than transplanted rice (Saharawat et al., 2010). This could provide an opportunity for the timely planting of successional maize crop.

Results also demonstrated that Strip tillage (ST) with residue retention/ incorporation of either 25% or 50% considerably increased the grain yield of maize compared CT plots. The biomass yields also followed a similar trend to grain yield. The higher maize yield under residue retention/incorporation practices is a result of the utilization of mineral N by microorganisms, and in later seasons, increased the efficiency of available N uptake by nutrient recycling. The yield was increased in STM after DSR possibly due to avoiding puddling in rice (Gathala et al., 2011b; Hobbs et al., 2002 and Jat et al., 2014). Another explanation is that crop residues helped reduce the negative effects of terminal heat stress during the reproductive phase, kept the soil at the right temperature, and made it easier for plants to use water (Busari et al., 2015), resulting in improved root growth (Singh et al., 2016a).

The current study showed that the cost of production for RM was higher in CT compared to ST practices. This is because of the high expenditures of labour and fuel required with land preparation, particularly for puddling, which normally required tilling 4-6 times prior to transplanting rice and 3-4 times prior to sowing maize. In the current study, the production cost in residue retention plots was lower than in no residue plots. This is because transporting and cleaning up crop residues needed additional labour and fuel on the field.

5.1. 3 Modelling on CA practices

5.1.3.1 Simulating conservation agriculture practices in the rice-maize system using APSIM model

The work described above focuses on CA practices in the current climate. It is important that CA approaches be robust to future climate change, however. The aim of Chapter 4 was therefore to assess the long-term impact of climate change on rice-maize productivity and soil organic carbon (SOC) stock under different climate change scenarios (thesis objective 3). The yield of rice was projected to increase in the range of 5% in hotter with dry conditions (i.e. the Hot Dry climate model) to 14% with average temperature and precipitation change (i.e. the Middle climate model) under RCP4.5 by mid century and 6% (Hot Dry climate) to 16% (Middle climate) by end century under RCP8.5. The main explanation is that elevated CO2 causes partial stomatal closure and reduced water vapor conductivity (Ainsworth et al., 2007). As a result, the rate of transpiration or the water loss from the leaves is reduced. These findings are consistent with Chandran et al. (2022), who showed that higher CO_2 boosted the average grain production of C_3 crops like rice by 19%. These findings are also in line with other research that showed a similar increase in yield (Yang et al., 2018). On the other hand, the yield of maize was projected to decrease by 2% in colder with wetter conditions (Cool Wet) to 7% (Hot Dry) by mid century under RCP4.5 and 10% (Cool Wet) to 20% (Hot Dry) by end century under RCP8.5. This suggests that the decline in maize yield is higher at the end century than in the mid century. This is consistent with the findings of several researchers (Li et al., 2022; Jagermeyr et al., 2021) who showed that the yield of maize will decrease more severely by the end century compared to the mid century.

Temperature and rainfall variations result in the projected yield reduction. Higher temperatures shorten the duration of photosynthesis and grain filling, thus reducing crop yield (Craufurd and Wheeler 2009; Liu et al., 2013; Liu et al., 2012). Furthermore, rising temperatures increase crop water demand (Brüssow et al., 2019).

During the maize growing season (November to April), temperatures are projected to rise by 2.9°C and 4°C from the baseline value (27.9°C) under end RCP4.5 and end RCP8.5 scenarios. Zhao et al. (2017) analysed a variety of published findings and discovered that for every 1°C increase in temperature, maize yields declined by 7.4%. Our research revealed that the decrease in maize yields was more likely caused by the predicted rise in temperature than by changes in rainfall patterns. This is because, although higher rain is forecast in the future, maize yields still decreased. This is consistent with the findings of another study (Siatwiinda et al., 2021), who analysed the effects temperature and precipitation on maize yield. They found that the majority of the future decline in maize production was mostly due to a rise in temperature.

Our study demonstrated that both CA and CT resulted in decreased maize yield due to climate change, especially in Hot Dry climates, during the mid and end century and that CA yields are better than CT. The primary justification for CA practices is that residue retention helps reduce soil temperature in Hot Dry climate (Chaki et al., 2021b). In addition to this, when conventional tillage is used, there is often no residue left on the land. This means that the land is not protected from high temperatures, resulting in a decrease in the soil moisture content (Parihar et al., 2016). In comparison, zero tillage with residue retention conserved 4.0% more moisture than conventional tillage due to 2-3% lower soil temperature (Bhatt et al., 2021).

In comparison to CT systems, our research revealed that the SOC stocks increased over time under CA systems. This result demonstrated the significance of keeping soil surface residues as mulch to gain the advantages of CA. The increase in SOC under the CA system could be attributed to crop residue retention in the field, which results in the gradual accumulation of soil organic carbon (Jat et al., 2019). Climate variables like temperature, humidity, and precipitation all have an impact on SOC (Adeel et al., 2018). In our study, we were able to show that SOC stocks increased under a Middle and Cool Wet climate environment. This increase in SOC is related to net primary production, which is greater in a Middle and Cool Wet climate than in a Hot Dry climate. The level of moisture in the soil is the most important element in determining how quickly soil organic matter can be decomposed (Adeel et al., 2018). In CT practices, there is frequently no residue left on the ground, leading in higher soil temperatures and faster breakdown of soil organic matter, resulting in a decrease in SOC concentration (Moinet et al., 2020). On the other hand, keeping residue on the surface of NT soils reduces soil temperature thus reducing SOC loss in the soil (Vicente-Vicente et al., 2016).

5.1.4 linkages between chapters and policy implications for northern Bangladesh's CA adoption

This dissertation contains three results chapters. The second chapter of this study examined the impact of conservation agriculture-based tillage and crop establishment methods, as well as residue management practices, on soil physical, chemical, and biological properties through a two-year field experiment. The data and results obtained from the experiment were utilised for the purpose of calibrating, evaluating the model and investigated long-term impact of conservation and conventional agriculture in RM in Bangladesh under climate change conditions in chapter 3. According to the results of the modelling, CA is more effective than conventional agriculture at enhancing soil organic carbon and crop yields under future climate conditions. In addition, CA-based practices make rice and maize production more resilient to climate change. Overall, our results provide holistic evidence for CA expansion in RM in Bangladesh. In order to achieve maximum adoption of CA through targeted approaches for specific farm types, a survey was conducted to identify farm types based on their resource endowment and livelihood orientation in Chapter 2. These four farm categories illustrate the diversity of farms in North West Bangladesh. Among the four farm types, well-resourced farm families had the most savings, food self-sufficiency, and legally owned land, all of which were highly associated with the use of CA technology than the other farm types. Moderately resourced households coupled with older and more experienced farmers, have also a greater capacity than the other farm types to adopt Conservation Agriculture (CA) practices due to their higher levels of knowledge and experience.

However, in order to ensure long-term sustainability, this research also provides an independent contribution to the government and other stakeholders to implement climate-smart technology over a wider region, with an estimate of 140,000 ha as priority areas for CA adoption according to the Bangladesh government. Prior to that, the government needs to promote cost-effective minimum tillage planters by offering farmers soft loans from national banks and providing training for operating CA machinery to interested farmers and local service providers. Finally, farmers should be given incentives to adopt rice residue management technologies, which can encourage them keep residues on their fields instead of removing them in open fields. Such initiatives would enhance soil health, reduce GHG emissions, and contribute to the achievement of the SDGs.

5.2 General conclusions

Based on the results presented in this thesis, the following conclusions are drawn:

Experimental trials suggested that the application of CA was beneficial for rice-maize production in Bangladesh. The current study also showed that existing farming practices have a negative impact on soil carbon stocks and crop productivity. This means that the current system's sustainability is jeopardized because yields are declining, thus reducing farm profitability. To restore soil fertility and assure long-term productivity, it is necessary to keep a sufficient proportion of crop residues in the soil.

Modelling results demonstrated that “rabi" agriculture (winter maize) in North West Bangladesh will become riskier because of rising temperature and reduced winter rainfall. However, the role of CA methods reduces the expected loss of maize yields compared to conventional practices. Considering the pending threats of climate change, for systems to be more sustainable in the long term, increased focus on the development of drought tolerant rice and maize varieties is needed.

In the study area, four major farm types were identified according to resource endowment and livelihood perspectives. These four farm categories represent the heterogeneity of farms in North West Bangladesh and it is hoped that the development of this farm household typology will help extension services to set up appropriate extension advice that will improve farm revenue and will also contribute to the accomplishment of sustainable development goals (SDGs).

5.3 Future research directions

Scientists and policymakers use typologies to analyse the diversity of farming systems and their underlying causes. There are two different approaches to building a typology. The first method is known as a taxonomy or positivist method, and it is uses statistical data. The second method is known as a constructivist method, and it is based on the knowledge of experts. The positivist framework has previously been utilised to establish the majority of farm typologies. The farm typology provided in this study is statistically based; however, expert knowledge is also taken into account for the developed typology. In this regard, the development of expert-based typologies by applying the constructivist method is encouraged. This will provide a full understanding of the farming community in the research region.

This dissertation’s first contribution is that this is the first time a statistical methodology has been used to establish a farm typology based on socioeconomic characteristics, showing the advantages of typology-based interventions in the study region. Further research is required to expand our understanding of agricultural typology across contrasting farm types in other regions of Bangladesh.

Experimental trials then suggested that the application of CA was beneficial for rice-maize production in Bangladesh. The findings of these trials, which were carried out over the course of two years, showed that there was no significant yield penalty in rice production while using CA. Future research should focus on the effect of foliar application of ferrous sulphate on rice production in light-textured, low-Fe soils in order to increase rice yield in CA agriculture. Furthermore, low Fe availability in the research area necessitates strengthening rice breeding research to generate Fe-efficient cultivars in order to improve DSR practices. In order to develop Fe-rich varieties in the region, agricultural extension agencies could play a significant role in conducting field trials and front-line demonstrations.

Short-term experimental trials suggested that SOC stocks increased over time under CA systems. We suggest that longer-term experimental studies are needed to assess the impacts of interannual climate variability and the changes in SOC that could occur over longer time scales. Ideally, long-term studies would occur across a greater range of soils (varying texture, fertility, and salinity) and environments (dry and wet) to ensure conclusions are robust to a broader range of environments.

Simulation modelling assessed CT vs CA management practices under climate change. This study is the first to investigate this issue in EGP rice-maize cropping systems, with results showing that SOC and crop productivity were better with CA compared to CT practices. Overall, the findings demonstrate the power of verified modelling techniques such as APSIM and have wider implications for farmers who want to use the CA method to assure sustainable rice-maize production under climate change. Further research using a multi-crop model ensemble and Monte-Carlo approaches can help to address crop model and parameter uncertainty in the region.

Lastly, considering crop-livestock farming systems, using all crop residue (CR) as mulch seems unrealistic and undesirable. This is due to CR becoming scarce in mixed crop-livestock farms, particularly with respect to CR allocation for feed, livestock shade, and soil amendment. Although this study demonstrated that keeping crop residues helps improve soil quality and crop productivity, it did not examine broader implications, such as not using residues as animal feed or selling them in the market to gain income. In order to sustain crop-livestock farming systems in Bangladesh, a broader examination of the possible trade-offs of crop residue use is still required. In this regard, Farm DESIGN, a bio-economic whole-farm model, can be used to quantify the trade-offs between crop and animal output when varied percentages of crop residues (ranging from 0% to 100%) are maintained in the field. These findings will assist in determining the quantities of crop residues that could be utilised for soil amendment without other negative consequences, such as reducing animal outputs.

References

Abdullah, A.S. (2014). Minimum tillage and residue management increase soil water content, soil organic matter and canola seed yield and seed oil content in the semiarid areas of Northern Iraq, Soil and Tillage Research, 144: 150-155.

Adeel, M., Zahin, M., Shafi, Z., Ahmad, M., Rizwan, M., Shafiq, M., and Rui, Y. (2018). Conservation agriculture, a way to conserve soil carbon for sustainable agriculture productivity and mitigating climate change: a review. Fresenius Environmental Bulletin, 27 : 6297-6308.

Ainsworth, EA., and Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. Plant Cell Environ, 30:258-270.

Alam, K., Richard, B., Wahidul, K., and Biswas, B. (2019). Increases in soil sequestered carbon under conservation agriculture cropping decrease the estimated greenhouse gas emissions of wetland rice using life cycle assessment, Journal of Cleaner Production, 224: 72-87, ISSN 0959-6526.

Alam, M. K., Islam, M. M., Salahin, N., and Hasanuzzaman, M. (2014). Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping system under subtropical climatic conditions. Scientific World Journal, https://doi.org/10.1155/2014/437283

Bhatt, R., Singh, P., Hossain, A., and Timsina, J. (2021). Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy and Water Environment, 19 (3): 345–365.

Brüssow, K., Gornott, C., Faße, A., and Grote, U. (2019). The link between smallholders' perception of climatic changes and adaptation in Tanzania. Clim Chang, 157:545–563

Busari, M.A., Salako, F.K., Tuniz, C., Zuppi, G.M., Stenni, B., Adetunji, M.T., and Arowolo, T.A. (2013). Estimation of soil water evaporative loss after tillage operation using the stable isotope technique. Int. Agrophys, 27: 257–264.

Busari, M, A., Surinder, S, K., Amanpreet, K, R, B., A, A, D. (2015). Conservation tillage impacts on soil, crop and the environment, International Soil and Water Conservation Research, 3 (2): I 119-129, ISSN 2095-6339.

Chaki, AK., Gaydon, DS., Dalal, RC., Bellotti, WD., Gathala, MK., Hossain, A., Siddquie, N-E-A., and Menzies, NW. (2021b). Puddled and zero-till unpuddled transplanted rice are each best suited to different environments – An example from two diverse locations in the Eastern Gangetic Plains of Bangladesh. Field Crops Res, 262:108031.

Chandran, M. A., Banerjee, S., Banerjee, S., Mukherjee, A. (2022). Evaluating the long-term impact of projected climate on rice-lentil-groundnut cropping system in Lower Gangetic Plain of India using crop simulation modelling. Int J Biometeorol 66: 55–69 .

Craufurd, P. Q., and T. R., Wheeler. (2009). Climate change and the flowering time of annual crops, Journal of Experimental Botany, 60 :2529–2539

Gathala, M.K., Ladha, J.K., Kumar, V., Saharawat, Y.S., Kumar, V., Sharma, P.K., Sharma, S., and Pathak, H. (2011b). Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron. J, 103: 961–971.

Hobbs, P.R., Singh, Y., Giri, G.S., Lauren, J.G., and Duxbury, J.M. (2002). Direct seeding and reduced tillage options in the rice-wheat systems of the IndoHi -Gangetic Plains of South Asia. In: Pandey, S., Mortimer, M., Wade, L., Tuong, T.P., Lopez, K., Hardy, B. (Eds.), Direct Seeding: Research Strategies and Opportunities. IRRI, Los Ba˜nos, page. 201–215.

Jägermeyr, J., C. Müller, A.C. Ruane, J. Elliott, J. Balkovic, O. Castillo, B. Faye, I. Foster, C. Folberth, J.A. Franke, K. Fuchs, J. Guarin, J. Heinke, G. Hoogenboom, T. Iizumi, A.K. Kain, D. Kelly, N. Khabarov, S. Lange, T.-S. Lin, W. Liu, O. Mialyk, S. Minoli, E.J. Moyer, M. Okada, M. Phillips, C. Porter, S. Rabin, C. Scheer, J.M. Schneider, J.F. Schyns, R. Skalsky, A. Smerald, T. Stella, H. Stephens, H. Webber, F. Zabel, and C. Rosenzweig. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat. Food, 2: 873-885, doi:10.1038/s43016-021-00400

Jat, R. K., Singh, R. G., Kumar, M., Jat, M. L., Parihar, C. M., Bijarniya, D., and Gupta, R. K. (2019). Ten years of conservation agriculture in a rice–maize rotation of Eastern

Gangetic Plains of India: Yield trends, water productivity and economic profitability. Field Crops Research, 232: 1–10.

Jat, R.K., Sapkota, T.B., Singh, R.G., Jat, M.L., Kumar, M., and Gupta, R.K. (2014). Seven years of conservation agriculture in a rice-wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. Field Crops Res, 164: 199–210.

Kahlon, M. S., Lal, R., and Ann, M. (2013). Twenty-two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil and Tillage Research, 126: 151–158.

Kaur, R., Singh, K., Deol, J.S. (2015). Possibilities of Improving Performance of Direct Seeded Rice Using Plant Growth Regulators: A Review. Proc. Natl. Acad. Sci., India, Sect. B Biol. Sci, 85:909–922 (2015). https://doi.org/10.1007/s40011-015-0551-8

Li, K., Pan, J., Xiong, W. (2022). The impact of 1.5 °C and 2.0 °C global warming on global maize production and trade. Sci Rep, 12: 17268 https://doi.org/10.1038/s41598-022-22228-7

Liu, K., and Wiatrak, P. (2012). Corn production response to tillage and nitrogen application in dry-land environment. Soil Tillage Res, 124: 138–143.

Liu, Z., Hubbard, K. G., Lin, X., and Yang, X. (2013). Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. Glob. Change Biol. 19 :3481–3492. doi: 10.1111/gcb.12324

Moinet ,Gabriel., Y,. K., Matthias, M.oinet, John, E.. Hunt, Cornelia, Rumpel., Abad, C.habbi, and Peter, Millard. (2020). Temperature sensitivity of decomposition decreases with increasing soil organic matter stability, Science of The Total Environment, 704:2020, 135460.

Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., and Pradhan, S. (2016). Conservation agriculture in irrigated intensive maize-based systems of north-western India. Effects on crop yields, water productivity and economic profitability. Field Crops Research, 193: 104–116. doi.org/10.1016/j.fcr.2016.03.01

Saharawat, Y. S., Singh, B., Malik, R. K., Ladha, J. K., Gathala, M., Jat, M. L., and Kumar, V. (2010). Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crops Research, 116 (3): 260–267.

Sairam, R.K., and Srivastava, G.C. (2002). Changes in antioxidant activity in sub-cellular fractions of tolerant and susceptible wheat genotypes in response to long-term salt stress. J Plant Sci, 162:897–904. doi:10.1016/S0168-9452(02)00037-7

Samal, S. K., Rao, K. K., Poonia, S. P., Kumar, R., Mishra, J. S., Prakash, V., Mc Donald, A. (2017). Evaluation of long-term conservation agriculture and crop intensification in rice-wheat rotation of Indo-Gangetic Plains of South Asia: Carbon dynamics and productivity. European Journal of Agronomy, 198:–208.

Siatwiinda, S.M., Supit, I., Van, B. (2021). Climate change impacts on rainfed maize yields in Zambia under conventional and optimized crop management. Climatic Change, 167:39.

Singh, V. K., Yadvinder-Singh, Dwivedi, B. S., Singh, S. K., Majumdar, K., Jat, Mishra, P.R., and Rani, M. (2016a). Soil physical properties, yield trends and economics after five years of conservation agriculture-based rice-maize system in north-western India. Soil and Tillage Research, 155: 133–148.

Vicente, J., García, R., Francaviglia, R., Aguilera, E., and Smith, Pete. (2016). Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. Agriculture Ecosystems & Environment, 235: 204 - 214.

Yang, X., Wood, EF., Sheffield, J., Ren, L., Zhang, M., and Wang, Y. (2018). Bias correction of historical and future simulations of precipitation and temperature for china from CMIP5 models. J Hydrometeorol, 19(3):609–623.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., and Huang, Y. (2017). Temperature increase reduces global yields of major crops in four independent estimates. Proc. Natl. Acad. Sci,114: 9326–9331. doi: 10.1073/pnas.1701 762114.

Zhao, S. C., Huang, S. W., Qiu, S. J., and He, P. (2018). Response of soil organic carbon fractions to increasing rates of crop residue return in a wheat-maize cropping system in north-central China. Soil Research, 56(8): 856–864. https://doi.org/10.1071/SR18123

Zhao, X., Xue, J.F., Zhang, X.Q., Kong, F.L., Chen, F., Lal, R., and Zhang, H.L. (2015). Stratification and storage of soil organic carbon and nitrogen as affected by tillage practices in the North China Plain. PLoS ONE, 10 (6): e0128873.

Appendices

Appendix 1: Ethics Clearance University of Leeds

The Secretariat
University of Leeds
Leeds, LS2 9JT
Tel: 0113 343 4873
Email: ResearchEthics@leeds.ac.uk

UNIVERSITY OF LEEDS

Mohammad Mamunur Rashid Sarker
School of Earth & Environment
University of Leeds
Leeds, LS2 9JT

Social Science, Environment and LUBS (AREA) Faculty Research Ethics Committee
University of Leeds

Dear Mohammad

Title of study: **Trade-off analysis of crop residue management for improving conservation agriculture practices under changing the climate in Bangladesh.**
Ethics reference: **AREA 18-080**

I am pleased to inform you that the above research application has been reviewed by the Social Sciences, Environment and LUBS (AREA) Faculty Research Ethics Committee and following receipt of your response to the Committee's initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	Version	Date
AREA 18-080 Feedback AREA 18-080 Provisional opinion 2	1	13/02/19
AREA 18-080 Revised _application _for ethical review	3	13/02/19
AREA 18-080 AREA. Suggestion from research committe.doc	1	16/01/19
AREA 18-080 Agreement Letter.docx	1	13/02/19
AREA 18-080 Revised 'feedback_Participant_Info_Sheet	3	13/02/19
AREA 18-080 'Revised Parent_Consent_Form	3	13/02/19
AREA 18-080 Questionnaire	2	16/01/19
AREA 18-080 Questionnare answer	2	13/02/19
AREA 18-080 Revised High risk assessment form.docx	2	16/01/19

Please notify the committee if you intend to make any amendments to the information in your ethics application as submitted at date of this approval as all changes must receive ethical approval prior to implementation. The amendment form is available at http://ris.leeds.ac.uk/EthicsAmendment.

Please note: You are expected to keep a record of all your approved documentation and other documents relating to the study, including any risk assessments. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited. There is a checklist listing examples of documents to be kept which is available at http://ris.leeds.ac.uk/EthicsAudits.

We welcome feedback on your experience of the ethical review process and suggestions for improvement. Please email any comments to ResearchEthics@leeds.ac.uk.

Yours sincerely

Jennifer Blaikie
Senior Research Ethics Administrator, the Secretariat
On behalf of Dr Kahryn Hughes, Chair, AREA Faculty Research Ethics Committee

CC: Student's supervisor(s)

University Research Ethics Committee - application for ethical review

Please email your completed application form along with any relevant supporting documents to ResearchEthics@leeds.ac.uk (or to FMHUniEthics@leeds.ac.uk if you are based in the Faculty of Medicine and Health) at least 6 weeks before the research/ fieldwork is due to start. Dentistry and Psychology applicants should follow their School's procedures for submitting an application.

Ethics reference (leave blank if unknown)	Student number (if a student application)	Grant reference (if externally funded)	Module code (if applicable)

Faculty or School Research Ethics Committee to review the application (put a 'X' next to your choice)		Arts, Humanities and Cultures (PVAR)
		Biological Science (BIOSCI)
	X	ESSL, Environment and LUBS (AREA)
		MaPS and Engineering (MEEC)
		School of Dentistry (DREC)
		School of Healthcare (SHREC)
		School of Medicine (SoMREC)
		School of Psychology (SoPREC)

Indicate what type of ethical review you are applying for:	PhD	Student project (PhD, Masters or Undergraduate)
		Staff project (externally or internally funded)

Section 1: Basic project details			
1.1 Research title	Trade-off analysis of crop residue management for improving conservation agriculture practices under changing the climate in Bangladesh.		
1.2 Research start date (dd/mm/yy)	Proposed fieldwork start date (dd/mm/yy)	Proposed fieldwork end date (dd/mm/yy)	Research end date (dd/mm/yy)
01-10-2018	01-01-2019	01-03-20119	30-09-2022

Yes	No	
X		1.3 I confirm that I have read and understood the current version of the University of Leeds Research Ethics Policy. *The Policy is available at http://ris.leeds.ac.uk/ResearchEthicsPolicies.*
X		1.4 I confirm that I have read and understood the current version of the University of Leeds Research Data Management Policy. *The policy is available at https://library.leeds.ac.uk/info/14062/research_data_management/68/research_data_management_policy.*
X		1.5 I confirm that I have read and understood the current version of the University of Leeds Information Protection Policy. *The policy is available at http://it.leeds.ac.uk/info/116/policies/249/information_protection_policy*
X		1.6 I confirm that NHS ethical review is not required for this project. *Refer to http://ris.leeds.ac.uk/NHSethicalreview for guidance in identifying circumstances which require NHS review*
	X	1.7 Will the research involve NHS staff recruited as potential research participants (by virtue of their professional role) or NHS premises/ facilities? *Please note: If yes, NHS R&D management permission or local management permission may also be needed. Refer to http://ris.leeds.ac.uk/NHSethicalreview.*

Section 2: Contact details	
2.1 Name of applicant	Mohammad Mamunur Rashid Sarker
2.2 Position (eg PI, Co-I, RA, student)	PhD Student
2.3 Department/ School	School of Earth & Environment
2.4 Faculty	Faculty of Environment
2.5 Work address (usually at the University of Leeds)	Priestley building, University of Leeds
2.6 Telephone number	07774650941
2.7 University of Leeds email address	eemmrs@leeds.ac.uk

Section 3: Summary of the research
3.1 In plain English provide a brief summary of the aims and objectives of the research. (max 300 words). The summary should briefly describe • the background to the research and why it is important, • the questions it will answer and potential benefits, • the study design and what is involved for participants. *Your answers should be easily understood by someone who is not experienced in the field you are researching, (eg a member of the public) - otherwise it may be returned to you. Where technical terms are used they should be explained. Any acronyms not generally known should be described in full.*
In South-Asia, allocation of crop residue for different purposes, such as livestock feeding, fuel, construction and burning, are the major constraints for the adoption of Conservation Agriculture (CA) in mixed crop-livestock systems (Bhan and Behera, (2014). Especially in Bangladesh, practising Conservation Agriculture is not up to the mark (Das, 2013) due to limited availability of animal feed particularly during the dry season (Prodip et al., 2017), used residue up to 52% (Akteruzzaman et. al, 2012) as a feed for their livestock instead of retain in the field. To solve that problem, trade-off analysis needs urgent future research to ensure sustainable food production (Gathala et al., 2014). This research will provide farmers current situation regarding farm types, resource endowment, current agronomic practices and system performance in terms of yield and resource allocation. A semi-structured questionnaire will be employed with mixed

(close and open-ended) questions, and about 180 farmers will be interviewed for the research. Besides, seven sections will be included in the interview schedule. The first section focuses on information about farmers' household characteristics, i.e. sex, age, occupation, education level of the family members, household size, the proximity of the household to the road, and labour availability. The second section includes information related to food accessibility and other major assets (e.g. ownership of land, bicycle, motorbike etc.), livestock holding, savings, farm implements and food source. Then, in the third section, questions are targeted to the farm activities including herd size, land use, cropping patterns, field management practices, agriculture tools, use of main crop products, and access to information and extension services. After that, the fourth section focuses on crop residue management which includes farmers' understanding of crop residue allocation, their management and storage techniques of surplus crops etc. Consequently, the fifth section includes information about livestock such as breed type, herd structure, dynamics, and feeding strategies, and information related to access and availability of fodder. And, the sixth section aims to collect data regarding farmers' perceptions and knowledge on climate change impact in major crops and their adaptation strategy. Finally, the last section will gather information about farmers' plans regarding keeping and buying their animals, and their household income and expenditure. Afterwards, farm typology will be developed based on a farm survey of 180 farmers in the study area. This typology will help to select representative farms from different farm types, which will be used for subsequent scenario analysis. This scenario analysis will be capable of evaluating trade-offs in rice surplus management in the 'South and North Western' part of Bangladesh as feed vs mulch (retain in the soil).	
3.2 Where will the research be undertaken?	The study area is located in Khulna (220 52'23.2''N & 890 31'12.2''E) and Dinajpur (250 44'45''N & 880 40'24''E) districts in South western and North eastern part of Bangladesh
3.3 Who is funding the research?	National Agricultural Technology Program- Phase II (NATP-2),Bangladesh
NB: If this research will be financially supported by the US Department of Health and Human Services or any of its divisions, agencies or programmes please ensure the additional funder requirements are complied with. Further guidance is available at http://ris.leeds.ac.uk/FWAcompliance and you may also contact your FRIO for advice.	

Section 4: Research data and impact You may find the following guidance helpful: • Research data management guidance • Advice on planning your research project • Dealing with issues relating to confidentiality and anonymisation • Funder requirements and University of Leeds Research Data Management Policy	
4.1 What is the data source? (Indicate with an 'X' all that apply)	
X'	New data collected for this research
	Data previously collected for another research
	Data previously collected for non-research purposes
	Data already in the public domain
	Other, please state: ____.
4.2 How will the data be collected? (Indicate with an 'X)	
X'	Through one-to-one research interviews
	Through focus groups
X'	Self-completion (eg questionnaires, diaries)
	Through observation
	Through autoethnographic research
	Through experiments/ user-testing involving participants
	From external research collaborators
	Other, please state: ____.
4.3 How will you make your research data available to others in line with: The University's, funding bodies' and publishers' policies on making the results of publically funded research publically available (in compliance with UK data protection legislation)? (max 200 words)	
The survey ensures that the research data will be securely stored in the University server (through a password-protected University of Leeds server). The outcome of the research will be published at conferences or written up in well-reputed journals for future research. Furthermore, it will allow other researchers to use the research data for further analysis with the approval of the Data Management Policy, University of Leeds Research.	
4.4 How do you intend to share the research data, both within and outside the research team? (Indicate with an 'X)	
	Depositing in a specialist data centre or archive
X	Submitting to a journal to support a publication
X	Depositing in a self-archiving system or an institutional repository

	Dissemination via a project or institutional website
X	Informal peer-to-peer exchange
	No plans to report or disseminate the data
	Other, please state: ____.
4.5 How do you intend to report and disseminate the results of the study? (Indicate with an ‘X)	
X	Peer reviewed journals
	Internal report
X	Conference presentation
	Publication on website
	Other publication
	Submission to regulatory authorities
	No plans to report or disseminate the results
	Other, please state: ____.
4.6 Give details of the expected impact of the research. Further guidance is available at https://www.ukri.org/innovation/excellence-with-impact. (max 200 words)	
✓ My research findings will help to improve long-term soil fertility, productivity, farm income and the livelihood of farmers in Bangladesh. ✓ The outcome of the research will provide the key message to the policymaker for future adaptation and mitigation of the possible impact of climate changes in the farming area.	

Section 5: Protocols		
Which protocols will be complied with? (Indicate with an ‘X’). There may be circumstances where it makes sense not to comply with a protocol, this is fine but should be clarified in your application.	X	Data protection, anonymisation and storage and sharing of research data
	X	Informed consent
	X	Verbal consent
		Reimbursement of research participants
	X	Low risk observation

Section 6: Additional ethical issues	
6.1 Indicate with an 'X' in the left-hand column whether the research involves any of the following:	
	Discussion of sensitive topics, or topics that could be considered sensitive
	Prolonged or frequent participant involvement
	Potential for adverse <u>environmental impact</u>
	The possibility of harm to participants or others (including the researcher(s))
	Participants taking part in the research without their knowledge and consent (eg covert observation of people in non-public places)
	The use of drugs, placebos or invasive, intrusive or potentially harmful procedures of any kind
	Food substances or drinks being given to participants (other than refreshments)
	Vitamins or any related substances being given to participants
	Acellular blood, urine or tissue samples obtained from participants (ie no NHS requirement)
	Members of the public in a research capacity (participant research)
	Participants who are particularly vulnerable (eg children, people with learning disabilities, offenders)
	People who are unable to give their own informed consent
	Researcher(s) in a position of authority over participants, eg as employers, lecturers, teachers or family members
	Financial inducements (other than reasonable expenses and compensation for time) being offered to participants
	Cooperation of an intermediary to gain access to research participants or material (eg head teachers, prison governors, chief executives)
	Potential conflicts of interest
	Internet participants or other visual/ vocal methods where participants may be identified
	Scope for incidental findings, ie unplanned additional findings or concerns for the safety or wellbeing of participants.
	The sharing of data or confidential information beyond the initial consent given
	Translators or interpreters
X	Research conducted outside the UK
	An international collaborator
	The transfer of data outside the European Economic Area

	Third parties collecting data
	Other ethical clearances or permissions
6.2 For the ethical issues indicated in 6.1 provide details of any additional ethical issues the research may involve and explain how these issues will be addressed. (max 200 words) Explain if there are any requirements specific to Bangladesh in terms of need to get research permits or in the ownership of data	
In Bangladesh, if anyone wants to conduct any research activities in any region of the country, then the person needs to have permission from the local authority. Before launching my research activities, administrative permission will be granted from the local authority where research activities will take place, in two different cities. Written application will be submitted to the local administration for getting permission, and finally, the research work will begin.	

Section 7: Recruitment and consent process For guidance refer to http://ris.leeds.ac.uk/InvolvingResearchParticipants and the research ethics protocols.
7.1 State approximately how much data and/ or how many participants are going to be involved.
A semi-structured questionnaire will be employed with mixed (close and open-ended) questions, and about 180 farmers will be interviewed
7.2 How was that number of participants decided upon? (max 200 words) *The number of participants should be sufficient to achieve worthwhile results but should not be so high as to involve unnecessary recruitment and burdens for participants. This is especially pertinent in research which involves an element of risk. Describe here how many participants will be recruited, and whether this will be enough to answer the research question. If you have received formal statistical advice then please indicate so here, and describe that advice.*
A complete list of all households will be prepared for the total size of the population. Then, the farms will be divided into three categories like large, medium and small (based on their land holdings). From each group, 30 farmers will be selected randomly for the data collection. Thus, two representative villages (one from Northern, another from southern) will provide 180 samples from the research area. The samples will be taken by stratified random sampling technique. Therefore, a minimum number of samples is: 2 villages X 90 = 180 farms.
7.3 How are the participants and/ or data going to be selected? List the inclusion and exclusion criterial. (max 200 words)
The participants will be selected according to their land size, numbers of animals they have, their on-farm and off-farm income, and their education quality. The following criteria will be selected.:

Inclusion: Age >20, land and animal owner, education at least primary level. Exclusion: Age<20, Refugee, tenant farmers, landless farmers.
7.4 For each type of methodology, describe the process by which you will obtain and document freely given informed consent for the collection, use and reuse of the research data. Explain the storage arrangements for the signed consent forms. *Guidance is available at http://ris.leeds.ac.uk/InvolvingResearchParticipants. The relevant documents (information sheet and consent form) need to be attached to the end of this application. If you are not using an information sheet and/ or seeking written consent, please provide an explanation.*
Attached in appendix (B)
7.5 Describe the arrangements for withdrawal from participation and withdrawal of data/ tissue. *Please note: It should be made clear to participants in advance if there is a point after which they will not be able to withdraw their data. See also http://ris.leeds.ac.uk/ResearchDataManagement*. (max 200 words)
The random household will be chosen for the survey, nearly 180 participants will be selected for this research and study. If the prospective interviewee becomes agreed to participate in the survey, then they will be asked research related some questions. During the interview process, they will be given right to stop the interview, deny to answer questions or withdraw responses, and the date data will be anonymised too. There will be no right or wrong answers from their feedback; instead, their personal opinions will be given more importance. The participants can remove their research related information within five days after the data have been collected from them. Research participants will be provided contact details like phone numbers, email and postal address if they want to contact with survey conductors.
7.6 Provide details of any incentives you are going to use and explain their purpose. (max 200 words) *Please note: Payment of participants should be ethically justified. The FREC will wish to be reassured that research participants are not being paid for taking risks or that payments are set at a level which would unduly influence participants. A clear statement should be included in the participant information sheet setting out the position on reimbursement of any expense incurred.*
There is no provision for incentives or any cash for participating in the research interview as it is voluntary. Interested participants will be given a small welcoming gift after the interview.

Section 8: Data protection, confidentiality and anonymisation *Guidance is available at http://ris.leeds.ac.uk/ConfidentialityAnonymisation*	
8.1 How identifiable will the participants be? (Indicate with an ‘X’).	
	Fully identifiable
	Identity of subject protected by code numbers/ pseudonyms

X	Fully anonymised
	Anonymised but potentially identifiable
	Data only in aggregated form
	Other

8.2 Describe the measures you will take to deal with issues of anonymity. (max 200 words)
I will use a unique code to pseudonymise the participants against their original name, and I will ask the respondent to use this approach for further study. If any respondents want to destroy his or her data from the survey within five days of the data taken, he or she needs to inform the survey conductor, and that unique code will be used to identify which participants were in the survey.
8.3 Describe the measures you will take to deal with issues of confidentiality, including any limits to confidentiality. (Please note that research data which appears in reports or other publications is not confidential, even if it is fully anonymised. For a fuller explanation see http://ris.leeds.ac.uk/ConfidentialityAnonymisation). (max 300 words)
I assure you that all the collected information while conducting the research will be kept confidential. To make the data confidential, I will store data in my laptop with Encryption. These Data has a significant value to the University, and I will consult with the University Faculty IT manager and use University Encryption Service software for safety purpose.
8.4 Who will have access to the research data apart from the research team (eg translators, authorities)? (max 100 words)
During conducting the research activities, the primary or raw data will not be shared with any other third parties. The data will be confined only within the research team. No translation will be required for translating the questionnaires. After completing the research, I will give my approval to use the final data for various research purposes guided by research ethics and research data management within the University of Leeds.
8.5 Describe the process you will use to ensure the compliance of third parties with ethical standards. (max 100 words) write policy
An agreement to use the research data will be made with future researchers if appropriate pseudonyms and other protections are provided. The university can pass the research data with third parties, like NHS, under the agreement, reflecting the requirement under the ICO's "Data sharing code of practice". An agreement will be made concerning how the data will be transferred to the third party, and this agreement will be based on Data Protection Laws", means the Data Protection Act 1998.
8.6 Where and in what format(s) will research data, consent forms and administrative records be retained? (max 200 words)

Please note: Mention hard copies as well as electronic data. Electronic data should be stored securely and appropriately and in accordance with the University of Leeds Data Protection Policy available at *http://www.leeds.ac.uk/secretariat/data_protection_code_of_practice.html.*
The research data will be collected by using a questionnaire (paper record); afterwards, that will be stored in the University store locker. On the other hand, all electronic data will be kept in the University server (through a password-protected University of Leeds server).
8.7 If online surveys are to be used, where will the responses be stored? (max 200 words) *Refer to:* *http://it.leeds.ac.uk/info/173/database_and_subscription_services/206/bristol_online_survey_accounts and http://ris.leeds.ac.uk/SecuringResearchData for guidance.*
Not applicable
8.8 Give details and outline the measures you will take to assess and to mitigate any foreseeable risks (other than those already mentioned) to the participants, the researchers, the University of Leeds or anyone else involved in the research? (max 300 words)
Attach risk assessment form

Section 9: Other ethical issues		
Yes	**No**	(Indicate with an 'X')
'X'		9.1 Is a health and safety risk assessment required for the project? *Please note: Risk assessments are a University requirement for all fieldwork taking place off campus. The risk assessment forms and further guidance on planning for fieldwork in a variety of settings can be found on the University's Health & Safety website along with further information about risk assessment:* *http://www.leeds.ac.uk/safety/fieldwork/index.htm. Contact your Faculty Health and Safety Manager for further advice. See also* *http://ris.leeds.ac.uk/HealthAndSafetyAdvice.*
	'X'	9.2 Is a Disclosure and Barring Service check required for the researcher? *Please note: It is the researcher's responsibility to check whether a DBS check is required and to obtain one if it is needed.*
9.3 Any other relevant information		
Not applicable		
9.4 Provide details of any ethical issues on which you would like to ask the Committee's advice.		
Not applicable		

Section 10: Further details for student projects (complete if applicable) Your supervisor is required to provide email confirmation that they have read, edited and agree with the form above. It is a good idea to involve your supervisor as much as possible with your application. If you are unsure how to answer any of the questions do ask your supervisors for advice.			
10.1 Qualification working towards (indicate with an 'X')			
	Bachelor's degree	Module code:	
	Master's degree (including PgCert, PgDip)		
'X'	Research degree (ie PhD)		

10.2 Primary supervisor's contact details	
Name (title, first name, last name)	Marcelo Valadares Galdos
Department/ School/ Institute	School of Earth & Environment
Telephone number	07745 955222.
University of Leeds email address	M.Galdos@leeds.ac.uk
10.3 Second supervisor's contact details	
Name (title, first name, last name)	Andy Challinor
Department/ School/ Institute	School of Earth & Environment
Telephone number	+44 (0)113 3433194
University of Leeds email address	A.J.Challinor@leeds.ac.uk

Yes	**No**	10.4 To be completed by the student's supervisor
x		The topic merits further research
x		I believe that the student has the skills to carry out the research

Section 11: Other members of the research team (complete if applicable)	
Name (title, first name, last name)	
Role (eg PI, Co-I)	
Department/ School/ Institute	
Telephone number	

University of Leeds email address	
Name (title, first name, last name)	
Role (eg PI, Co-I)	
Department/ School/ Institute	
Telephone number	
University of Leeds email address	
Name (title, first name, last name)	
Role (eg PI, Co-I)	
Department/ School/ Institute	
Telephone number	
University of Leeds email address	

Section 12: Supporting documents		
Indicate with an 'X' which supporting documents have been included with your application. Wherever possible the research title on consent forms, information sheets, other supporting documentation and this application should be consistent. The title should make clear (where appropriate) what the research is about. There may be instances where a different title is desirable on information to participants (for example – in projects which necessarily involve an element of deception or if giving the title might skew the results of the	'X'	Information sheet(s) *Please note: Include different versions for different groups of participants eg for children and adults if applicable. Refer to http://ris.leeds.ac.uk/InvolvingResearchParticipants for guidance in producing participant information sheets.*
	'X'	Consent form(s) *Please note: Include different versions for different groups of participants eg for children and adults if applicable. Refer to http://ris.leeds.ac.uk/InvolvingResearchParticipants for guidance in producing participant consent forms.*
		Recruitment materials *Please note: Eg poster, email etc used to invite people to participate in your research project.*

research). It is not imperative that the titles are consistent, or detailed, but where possible then they should be. Supporting documents should be saved with a meaningful file name and version control, eg *'Participant_Info_Sheet_v1'* or *'Parent_Consent_From_v2'*. Refer to the examples at http://ris.leeds.ac.uk/InvolvingResearchParticipants.		Letter/ email seeking permission from host/ gatekeeper
	'X'	Questionnaire/ interview questions
	'X'	Health and safety risk assessment *Please note: Risk assessments are a University requirement for all fieldwork taking place off campus. The risk assessment forms and further guidance on planning for fieldwork in a variety of settings can be found on the University's Health & Safety website along with further information about risk assessment: http://www.leeds.ac.uk/safety/fieldwork/index.htm. Contact your Faculty Health and Safety Manager for further advice. Also refer to http://ris.leeds.ac.uk/HealthAndSafetyAdvice*.
		Data management plan *Refer to https://library.leeds.ac.uk/info/14062/research_data_management/62/data_management_planning*

Section 13: Sharing information for training purposes		
Yes	**No**	(Indicate with an 'X')
'X'		In the application form, I will give my permission to the research ethics and research data management to use my research data for training purposes within the University of Leeds. All personal identifiers and references will be anonymous to researchers, funders and research units.

Section 14: Declaration
1. The information in this form is accurate to the best of my knowledge and belief and I take full responsibility for it. 2. I undertake to abide by the University's ethical and health & safety policies and guidelines, and the ethical principles underlying good practice guidelines appropriate to my discipline. 3. If the research is approved I undertake to adhere to the study protocol, the terms of this application and any conditions set out by the Research Ethics Committee. 4. I undertake to ensure that all members of the research team are aware of the ethical issues and the contents of this application form. 5. I undertake to seek an ethical opinion from the REC before implementing any amendments to the protocol. 6. I undertake to submit progress/ end of project reports if required.

7. I am aware of my responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
8. I understand that research records/ data may be subject to inspection for audit purposes if required in future.
9. I understand that personal data about me as a researcher in this application will be held by the relevant FRECs and that this will be managed according to the principles established in the Data Protection Act.

	Applicant	Student's supervisor (if applicable)
Signature		
Name	Mohammad Mamunur Rashid Sarker	Marcelo Valadares Galdos
Date	12-12-2018	12-12-2018

Appendix 2: Household Survey

Chapter 2

SURVEY QUESTIONNAIRE

HI. My name is ---------------------. I am doing a survey for my study purpose. Your household was randomly selected for the interview. The survey is intended to gather information a better understanding on farmers decision related to agronomic practices, resource endowment, tillage method, crop residue, manure management, feeding strategies etc. The result are confidential and will only be used for research purpose.

A. Identification

Village-----------, Post office------------------, Police station------------------, District---------------------, country---------------------

1. Household characteristics

No	Questions	Categories	Skip
1	Name of Household		
2	Respondent relationship to the head of the household?	Head.................................... 1 Spouse ....2 Other.............................3	
3	What is the sex of the household?	Male ....1 Female 2	
4	Age of the head of this household?	Age………………………………………	
5	Marital status of Household?	Married................................. 1 Never Married........................2 Divorced.................................3 Widowed.................................4 Married not living together.......5	
6	What is the total number of household members? (living with same house and sharing same dish)	Male ....1 Female 2	
7	How many members are fall into these age ranges?	Children under 6....................... Children 6-9........................ Children 10-15... Children 15-60........... 60 years and above............... .	
8	Currently, how many household members are going to school?	Male..................................... Female......................................	
9	Level of education	Illiterate. Read & write. Elementary Middle Secondary Higher	

10	What are the occupations of the head of the household?	Crop husbandry ....A Animal husbandry.....................B Trade..C Casual labourer/wage earner.......D Salaried employee........................E Others...F	
12	How far distance house to main road?	Km........	
13	Distance to nearest market	Km...........	
14	Family members joining farmer field school	Yes/ No	
15	Labour availability is problem?	Yes/ No	
16	If yes	Why?	

2. Assets, Accessibility & food

2.1. Assets and services - (0) No; (1) Yes

Mobile phone ________

Radio _________

Transport.............

2.2. Wealth indicator

Wealth indicator	poor	medium	Well-off
landholding	0.125-0.5ha	0.5-1.0 ha	≥1.1ha
Livestock holding	No livestock	1-2	≥4
Housing type	Hatched roof	Hatched roof and rarely corrugated iron sheet	corrugated iron sheet, building
saving	No saving	saving	saving
Farm implements	Tractor, Oxen ox plough, hoes	Tractor, Oxen ox plough, hoes	Tractor, Oxen ox plough, hoes and wheel barrows

2.3. Saving strategies: savings? ___ (0) No; (1) Yes. If yes, how? ____(1) banks; (2) livestock; (3) property, Land (4) other way________

2.4. Net food: How many months you can consume the main staple food (cereals)

2.5. Food source: if you have shortage, how do you managed extra staple food (cereals) (1) purchase food; (2) subsidised/food aid; (3) given by others; (4) other ___________

3. Agriculture

3.1.

Number of cultivable land plots owned by the household?	No	Yes
If yes how many plots?		

3.2. Plots/management:

Plot No.	Size	Ownership	If owned, who owned it?	Present use	Crop productivity	Distance from house
1						
2						
3						
4						
5						
	Unit: a) decimal b) hectare c)other	1) Owned 2) Shared 3) Rented; 4) No owned 5)Other	Female Male Joint Other Relatives	Fallow Crops Fodder Pasture other	Good Average Low	

3.3. Plots/management units managed by house hold: use/inputs per season

Characteristics								
Type/variety								
Plot IDs								
Season								
Did you till your plot on right time?								
What type of equipment used to plough the plot								
If no, what is the reason?								

Crop residue visible at sowing?								
Did you use improved/ hybrid seed for sowing/planting the plot?								
Did you face improved seed shortage in last year?								
What is your main source of seed?								
Is it affordable?								
Did you keep seed?								
Where did you store it?								
Seed rate [kg/ha]								
Date of sowing [dd/mm]								
FYM use [kgl/ha]								
other manures [kg/ha]								
Fertilizers (specify)								
(a) urea [kg/ha]								
(b) MP [kg/ha]								
(c) TSP								
Herbicides								
Fungicides & insect.								
Date of harvest [dd/mm]								
Grain yield [kg/ha]								
Crop residue [kg/ha]								
Crop list 1. Maize 3. Beans 4. Rice 5. Mixed 6. Tomato 7. Onion 8. Cabbage 9. Chickpea 10.Fodder grass 11.Others: ___ 2. sorghum								

3.4 Why you have not produce any crop last year?

A. Drought /low rainfall	• Lack of fertilizer

• Insect/Disease/weeds	• Other
• Shortage of labour	
• Shortage of power tiller	
• Shortage of good seeds	
• Agricultural tools	
• Shortage of tractor	

3.5. According to your opinion, what is the main limitation for optimal crop production?

#1limiting factor	#2limiting factor	#3limiting factor	#4limiting factor	#5limiting factor

01. Shortage of labour, 02.low rainfall, 03.low market price, 04. Fertilizer, 05. land tenure, 06. shortage of draught animals, 07. pests/disease/weeds, 08. Agricultural tools, Shortage of power tiller 10. Shortage of land, 11. shortage of good seeds, 11. Access of market, 12. Tractor service, 14 other-----

3.6. Agricultural tools

List	Total number	no
Axes		
Tractor		
Power tiller		
Irrigation pump		
Hoes		
Sickles		
Shovels		
Forks		
Ploughs		
spade		
Other		

3.7. Allocation of crop products

Crop list	Season	Product name	Use product					
			Eaten	Sell in the market	seed	livestock	others	Total
								100%
								100%
								100%

3.8 Variety preference:

Varieties of a crop	Reason of preference
Maize	
Wheat	
Rice	
Others	

* Consider drought stress, low soil fertility, water logging crop residue quality, grain yield

3.9. Access to information (0) no; (1) yes

Type of information	1.family, friends or farmers	Government/extension's	Private sector/NGOs	other
Information about new crop varieties				
Information about crop inputs/outputs price				
Information about other crop technologies				

3.10. Extension: how many times do you meet extension people?

4. Crop residue management:

4.1. Height of residue left in the field at harvest (cm):

Crop type	Owned land	Rented land	Reason
Maize			
Rice			
Wheat			
other			

4.2. CR Allocation: for the year 2019-2020

Where CR is allocated:	**Crop 1**	**Crop 2**	**Crop 3**	**Trend last 5 years**
	name			
	season			
In field				
Left in the field (mulch	%	%	%	
Incorporate in the soil	%	%	%	
Stubble grazing by own animals	%	%	%	
Stubble grazing by others	%	%	%	
Taken home	%	%	%	
Stall feeding	%	%	%	
cooking	%	%	%	
Roofing/construction	%	%	%	
Sell in the market	%	%	%	
Other	%	%	%	
	100%	100%	100%	

4.3. Do you think crop residue can benefit for the soil? 1) Yes 2) no
Reason:

____

Crop residue exchange: bought/sold, unit in kg.............

Name of the crop residue	Amount of crop residue sold(Kg)	To/from whom?	1st season	2nd season	3rd season

4.4. Availability of information: Have you know about: (0) No; (1) Yes

Type of information	Knowledge and use	If yes, from whom?
Use of crop residue as mulching?		
Composting of crop residue?		
Incorporation of crop residue in the soil		
Improved methods of crop residue storage		
Consider verities as a straw quality?		

4.5. Perceptions of crop residues

Statements	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree	Not applicable
Incorporation of crop residue improves soil quality						
Crop residue use as a mulch. Do you think it is a waste of feed?						
Crop residue is an important source for animal feed						
Feeding crop residue to livestock, is it profitable for farm?						
Using crop residue is better for preparing animal bedding						
crop residue is retain in the field						
If I leave crop residue in the soil then I don't need to apply fertilisers						
Crop residue is an important property of each household						
Profitable to feed livestock with crop residues than to incorporate them in the soil						

4.6. CR storage:

Name of crop	How is it stored
Main crop 1	
Main crop 2	
other	1) Heap in the field 2) Heap in farmyard 3) Cattle shed 4) other

5. Livestock:

5.1 Do you have any livestock? Yes...No.......

5.2 Do you have Information access (0) No; (1) Yes

	1. Neighbour, Family, friends	2.Government/ extension's	3. Private sector/NGOs	4. Other
New breed				
Feed requirements of livestock				
Health condition of the livestock				
Improved technologies				
Marketing of livestock products				

5.3. Perception on livestock

Statements	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree	Not applicable
Cow dung is important for crop production						
Keeping animal is not economically profitable						
I don't have extra land to produce fodder crops						
Livestock is an important source of income						
Shortage of feed is a key constraint in my farm						

5.4. Livestock structure and dynamics: species fed and taken care of the household. Initially, just list all livestock/breeds kept by household to help with filling the table

	Species/breeds (use codes listed below)	No.
Animal type		
Adult males		
Adult females – in milk		
Adult females – dry		
Young males		
Young females		
lamb/goat		
Total kept in household		
Born last year		
Bought last year		
Sold/bartered last year		
Eaten last year		
Given away last year		
Number of deaths last year		
Manure animal/day		
Milk female/day (average)		
Species and breeds 1 = Indigenous cattle) 2 = Cross-bred cattle (Ind. x Exotic) 3 = Indigenous goat breed , 4 = Cross-bred goat ,Other		

5.5 Shortage periods

	Jan	Feb	Mar	April	May	June	July	August	Sep	Oct	Nov	Dec
Dry fodder												
Green grass												
Grazing												
1. no shortage, (1) low shortage, (2) medium shortage, (4) extreme shortage												

Amount of crop residue feeding:

	Jan	Feb	Mar	April	May	June	July	August	Sep
Amount per day									

5.6. Allocation of livestock production

	Production	Self-consumption	sell in the market	Other
Milk		%	%	%
Meat		%	%	%

5.7. Allocation of manure

	1st season	2nd season	3rd season	Trend last 5 yrs	If change, Why?
Use as a manure in the field	%	%	%		
Cooking					
Sell in the market	%	%	%		
Other	%	%	%		
Total cow dung	%	%	%		

5.8. Do you apply manure in main crop fields or just around the homestead? Why?
Reason:

____

6. Knowledge on climate variability and change
Please answer the following questions

Questions	Assigned score	Obtained score
1. What is climate change?	2	
2. What is your understanding of climate change adaptation?	2	
3. Mention the name of two drought tolerant rice varieties in Aus season.	2	
4. Mention the name of two-drought tolerant rice varieties Aman season.	2	
5. Mention the name of two drought tolerant rice varieties in boro season.	2	
6. How will you remove the water drought from your land?	2	
7. Do you practice mulching to cultivate crop in your land?	2	
Total	14	

6.1. Changes observed by farmers due to climate variability and change

1. Please mention the changes you have observed in climatic factors during the last 10 years

Sl. #	Climatic factors	Changed observed (3 = Increased, 2 = Decreased, and 1 = Unchanged)		
		Increased	Decreased	Unchanged
1.	Max. temperature			
2.	Min. temperature			
3.	Rainfall			
4.	Humidity			

6.2. Please indicate the observed changes in extreme climatic events during the last 10 years

Sl. #	Climatic extreme events	Changed observed (3 = Increased, 2 = Decreased, and 1 = Unchanged)		
		Increased	Decreased	Unchanged
1.	Drought			
2.	Cold injury			
3.	Coastal flood			
4.	Cyclone			
5.	Heat wave			
6.	Sea level rise			

6.3. Please mention the changes occurred on cropping practices during the last 10 years due to climate variability and change

Sl. #	Components of cropping practices	Changed observed (3 = Increased, 2 = Decreased, and 1 = Unchanged)		
		Increased	Decreased	Unchanged
1.	Availability of irrigation water			
2.	Availability of surface water			
3.	Ground freshwater level			
4.	Soil salinity			
5.	Insects infestation			
6.	Diseases infection			
7.	Weed infestation			
8.	Cold injury			

6.4. Please indicate the observed changes in crop sowing/planting date during the last 10 years.

Sl. #	Crop sowing and planting season	Changed observed (3 = Earlier, 2 = Later, and 1 = Unchanged)		
		Earlier	Later	Unchanged
1.	Kharif I (Aus)			
2.	Kharif II (Aman)			
3.	Rabi (Boro)			

6.5 Kharif I/Aus season (16 Mach – 15 July)

Sl. No.	Cropping practices	Year									
		2000		2005		2010		2015		2018	
		Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)
1	Drought Management										
1.1	Zero tillage										
1.2	Strip tillage										
1.3	Bed planting										
1.4	Mulching										
1.6	Dibbling method										
1.7	Raise bed method										
1.8	Pit method										
2	**Intercultural operation**										
2.1	Weeding										
2.2	Line sowing/transplanting										
3	**Organic fertilizer management**										
3.1	Cow dung										
3.2	Compost										
3.3	Green manure										
3.4	Farmyard manure										

6.6 Kharif II/Aman season (16 July – 15 October)

Sl. No.	Cropping practices	Year									
		2000		2005		2010		2015		2018	
		Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)	Potential land (ha)	Area coverage (%)
1	Drought Management										
1.1	Zero tillage										
1.2	Strip tillage										
1.3	Bed planting										

1.4	Mulching										
1.5	Dibbling method										
1.6	Raise bed method										
1.7	Pit method										
2	**Intercultural operation**										
2.1	Weeding										
2.2	Line sowing/transplanting										
3	**Organic fertilizer management**										
3.1	Cow dung										
3.2	Compost										
3.3	Green manure										
3.4	Farmyard manure										

6.7 Rabi/ Boro season (16 October – 15 March)

Sl. No.	Cropping practices	Year									
		2000		2005		2010		2015		2018	
		Potential	Area	Potential	Area	Potential	Area	Potential	Area	Potential	Area
1	Drought Management										
1.1	Zero tillage										
1.2	Strip tillage										
1.3	Bed planting										
1.4	Mulching										
1.5	Dibbling method										
1.6	Raise bed method										
1.7	Pit method										
2	**Intercultural operation**										
2.1	Weeding										
2.2	Line sowing/transplanting										
3	**Organic fertilizer management**										
3.1	Cow dung										
3.2	Compost										
3.3	Green manure										
3.4	Farmyard manure										

7. Additional information

7.1. Labour use per agricultural activity (unit: days a year)

		Household		Employed	Hired	Is this activity also shared with other farmers?
		Female	Male			
Crop production	Land preparation					(0) No; (1) Yes
	Sowing/Planting					(0) No; (1) Yes
	Intercultural operations					(0) No; (1) Yes
	Harvesting of crops					(0) No; (1) Yes
	Crop residue collection					(0) No; (1) Yes
	Other					(0) No; (1) Yes
livestock	Milking					(0) No; (1) Yes
	Feeding grass					(0) No; (1) Yes
	Feeding water					(0) No; (1) Yes
	Collecting manure					(0) No; (1) Yes
	other					(0) No; (1) Yes

7.2. Household income for the year 2018-2019.

Activity	1.Revenue	2.Trend 5 yrs	If change, main reason
On -farm	%	↑ = ↓	
Crops as product	%	↑ = ↓	
Crop residue as a by product	%	↑ = ↓	
Other residue or forage	%	↑ = ↓	
Livestock	%	↑ = ↓	
Milk	%	↑ = ↓	
Meat			
Others	%	↑ = ↓	
Off –farm	%	↑ = ↓	
Agricultural labour	%	↑ = ↓	
Non-agricultural labour eg, driving rickshaw puller	%	↑ = ↓	
Regular employment	%	↑ = ↓	

Self-Business	%	↑ = ↓	
Remittances from abroad	%	↑ = ↓	
Others	%	↑ = ↓	
Total revenue 2018-2019	%	↑ = ↓	

7.3 Expenditure household 2018-2019.

Item	2. Trend 5 yrs	3. If change, main reason
Food	↑ = ↓	
Education	↑ = ↓	
Health treatment	↑ = ↓	
Social events/leisure	↑ = ↓	
Construction House	↑ = ↓	
Cloth		
Hired labour	↑ = ↓	
Inputs for crop	↑ = ↓	
Inputs for animal	↑ = ↑	
Others	↑ = ↓	
Total expenditure		

7.4. Marketing component:

No.	Questions	Categories
1	Source of crop or livestock inputs?	Market close to home...... Market away from home Government office Development agencies other
2	Are they easily accessible?	Yes.... No....
3	Did you sell crops and animal products?	Yes... No....
4	Where?	Village communities close to home..... Village communities away from home..... Traders...... Government. Office..... Other........
5	Which time of the year do you prefer to sell your products	January-march.. April-June..... July-September..... October-December.......

6	Which transport do you use?	Pack animals Bus Risk haw Track/tractor/small cars Human labour other

7.5. Training exposure

Did you participate any training program on crop and livestock production last year?

Yes…………………………..…… No…………..………………..

If yes, please give the answer following information

Sl. #	Name of the training course	Name of Organization	Duration (days)	Usefulness of the training course ((3 = High, 2 = Moderate, 1 = Low , and 0 = Not)			
				High	Moderate	Low	Not
1.							
2.							
3.							

7.6. Linkage with Extension services

No.	Questions	categories
1	Did you receive agricultural extension service in your place at the last 12 months	Yes............................... No.................
2	How often do you receive extension services in the last 12 months	Bi-weekly Once a month Once a quarter Once a year
3	In the last 12 months, what type of extension service was given to you by the extension office.	Input supply.... Advice.... Tractor service.... Others------------
4	Do you think the extension services is useful to improve your crop-livestock production	Yes.......... No.............
5	How many family members participated in any agricultural training Programme in the last 12 months	Yes........ No................
6	How many times family member participated in any agricultural training Programme in the last 12 months	Number of times....

7	Mention type of training provided in the last 12 months	Soil and water conservation Crop production Pest management Homestead Plant protection Grain storage Animal production Animal health Home science Seed production Other....

Appendix 3:

Chapter 3
Supplementary Material

Table 3. S1. Soil moisture content at two soil depths under different tillage and crop establishment (TCE) techniques and residue management (R) options at the end of 2 years of rice-maize system.

	0-10 cm				10-20 cm			
TCE technique	CR0	CR25	CR50	Mean	CR0	CR525	CR50	Mean
STDSR/STM	17.11bcd	18.67b	20.53a	18.77a	21.01c	22.70b	24.44a	22.72a
PTRPTR/CTM	16.03d	16.91cd	18.48bc	17.14a	15.67e	17.07d	18.09d	16.94b
Mean	16.57c	17.79b	19.50a					
LSD 0.05	TCE = ns Residue (R)= 1.15 TCE×R=ns				TCE =3.33 Residue (CR)=0.76 T×CR=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S2. Change of soil porosity (%) at two soil depths under different tillage and crop establishment (TCE) techniques and residue management (R) options at the end of 2 years of rice-maize system.

	0-10 cm				**10-20 cm**			
TCE technique	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR525**	**CR50**	**Mean**
STDSR/STM	30.29	32.65	36.55	33.17	29.00	31.33	34.47	31.60
PTR/CTM	27.01	29.04	31.62	29.34	25.99	27.95	31.47	28.47
Mean	28.65c	31.037b	34.089a		27.50b	29.64b	32.97a	
LSD 0.05	TCE = ns Residue (R)= 1.925 TCE×R=ns				TCE =ns Residue (CR)=2.82 T×CR=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S3. Carbon stock contributed by light POM (t/ha)

	0-10 cm				**10-20 cm**			
TCE technique	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR525**	**CR50**	**Mean**
STDSR/STM	0.6548	0.8638	0.7618	0.760	0.600	0.6685	0.9403	0.7363
PTR/CTM	0.6425	0.713	0.6278	0.661	0.6282	0.6699	0.7008	0.666
Mean	0.648	0.788	0.694		0.6141b	0.669b	0.8206a	
LSD 0.05	TCE = ns; Residue (R)=ns; TCE×R=ns				TCE =ns; Residue (CR)= 0.127, T×CR=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S4. Carbon stock contributed by heavy POM (t/ha)

	0-10 cm				10-20 cm			
TCE technique	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR525**	**CR50**	**Mean**
STDSR/STM	3.832	3.739	3.823	3.798	1.480	1.6753	1.3254	1.493
PTR/CTM	3.421	3.398	3.843	3.554	1.397	1.908	1.658	1.654
Mean	3.627	3.569	3.833		1.439	1.791	1.491	
LSD 0.05	TCE = ns; Residue (R)=ns; TCE×R=ns				TCE =ns; Residue (CR)=ns; T×CR=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S5. Carbon stock contributed by MAOM (t/ha)

Parameter	**0-10 cm**				**10-20 cm**			
TCE technique	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR525**	**CR50**	**Mean**
STDSR/STM	8.093	10.648	8.356	9.032	5.756	5.875	6.015	5.88
PTR/CTM	7.619	9.662	8.503	8.595	6.89	7.1873	6.596	6.89
Mean	7.856b	10.15a	8.429ab		6.324	6.531	6.305	
LSD 0.05	TCE = ns; Residue (R)= 1.842; TCE×R=ns				TCE =ns; Residue (CR)=T×CR=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S6. Microbial biomass carbon (t/ha)

Parameter	**0-5 cm**				**5-10 cm**			
TCE technique	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR525**	**CR50**	**Mean**
STDSR/STM	245.62	435.12	401.37	360.70	235.85	294.63	287.71	272.73
PTR/CTM	295.00	402.08	387.66	362.01	193.58	314.18	303.53	269.43
Mean	271.10 b	418.60 a	394.27 a		214.71 b	304.30 a	295.62 a	
LSD 0.05	TCE = ns; Residue (R)= 100.92; TCE×R=ns				TCE = ns; Residue (CR)=36.97; T×CR= ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S7. Leaf chlorophyll content (SPAD value) under different tillage and crop establishment (TCE) techniques and residue management (R) options at different growth stages of rice during 2019-2020

TCE technique	**Chlorophyll content (SPAD value)**															
	50 DAS				**60 DAS**				**70DAS**				**80 DAS**			
	CR0	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**
STDSR/ST	35.50	37.26	37.23	36.66	41.73	41.30	42.00	41.67	39.03	40.20	40.33	39.85	24.46	26.96	28.43	26.62
PTR/CTM	37.26	37.96	38.60	37.94	39.76	39.95	41.06	40.26	39.56	37.66	39.90	39.04	32.43	30.83	32.70	31.98
Mean	36.38	37.61	37.91		40.75	40.62	41.53		39.30	38.93	40.11					
LSD 0.05																
TCE	ns				ns				ns				ns			
Residue (R)	ns				ns				ns				ns			
TCE×R	ns				ns				ns				ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S8. Leaf chlorophyll content (SPAD value) under different tillage and crop establishment (TCE) techniques and residue management (R) options at different growth stages of rice during 2020 -2021

TCE technique	**Chlorophyll content (SPAD value)**															
	50 DAS				**60 DAS**				**70DAS**				**80 DAS**			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/ST	38.83	41.16	42.50	40.83	36.93	38.86	40.51	38.74	36.09	36.97	38.57	37.21	31.51	32.56	33.30	32.45
PTR/CTM	38.46	40.96	41.12	40.18	36.28	38.20	38.80	38.76	35.02	36.35	37.30	36.22	31.30	33.25	33.00	32.51
Mean	38.65 b	41.06 a	41.83 a		36.60 b	38.53 a	39.66 a		35.56 b	36.66a b	37.93 a		31.40 b	32.90 a	33.15 a	
LSD 0.05																
TCE	ns				ns				ns				ns			
Residue(R)	1.08				1.19				1.57				1.002			
TCE×R	ns				ns				ns				ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S9. Leaf chlorophyll content (SPAD value) under different tillage and crop establishment (TCE) techniques and residue management (R) options at different growth stages of maize during 2019-2020

TCE technique	Chlorophyll content (SPAD value)															
	50 DAS				70 DAS				90DAS				140 DAS			
	CR0	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**
STDSR/ST	49.47	52.43	53.70	51.86a	50.93	52.54	52.56	52.02	57.33	60.13	61.40	59.62	55.46	58.06	57.06	56.36
PTR/CTM	46.73	48.36	49.70	48.26	50.70	52.83	53.30	52.27	57.80	59.50	61.00	59.43	60.43	62.11	61.53	60.36
Mean	48.10b	50.39a	51.70a		50.81b	52.70a	52.93a		57.57b	59.81a	61.20a		57.00	60.09	59.30	
LSD 0.05																
TCE	0.39				ns				ns				ns			
Residue(R)	1.59				1.36				1.39				ns			
TCE×R	ns				ns				ns				ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3.S10. Leaf chlorophyll content (SPAD value) under different tillage and crop establishment (TCE) techniques and residue management (R) options at different growth stages of maize during 2020 -2021

TCE technique	Chlorophyll content (SPAD value)															
	50 DAS				70 DAS				90DAS				140 DAS			
	CR0	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**
STDSR/ST	48.13	48.46	49.16	48.58	45.89	48.26	48.33	47.49	56.35	57.40	58.04	57.26a	48.26	49.41	50.56	54.51
PTR/CTM	46.90	48.90	49.60	48.64	45.36	46.73	48.06	46.72	55.71	56.48	56.72	56.30b	54.50	53.94	55.10	49.41
Mean	47.51	48.68	49.38		45.62b	47.50a	48.20a		56.03	56.94	57.38		51.38	51.67	52.83	
LSD 0.05																
TCE	ns				ns				0.80				ns			
Residue (R)	ns				1.224				0.79				ns			
TCE×R	ns				ns				ns				ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S11. Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on yield parameters of rice during 2019-2020

TCE technique	Grains panicle^{-1}				Tiller/hill				1000 grains weight			
	CR0	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**
STDSR/STM	77.33	78.00	77.00	77.44	10.26	10.13	10.26	10.22 a	23.77	23.76	24.30	23.94
PTR/CTM	79.00	78.33	79.33	78.88	10.03	9.83	10.03	9.97 b	23.90	24.60	23.73	24.07
Mean	78.12	78.14	78.16		10.15	9.98	10.15		23.83	24.18	24.01	
LSD 0.05	TCE = ns Residue (R)=ns TCE×R=ns				TCE =0.172 Residue (CR)=ns T×CR=ns				TCE = ns Residue (CR)= ns T×CR=ns			
TCE technique	panicle.m^{-1}				Panicles leanth. (cm)				plant. height (cm)			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	248.50	254.33	252.66	251.83b	23.61	23.98	23.76	24.47	102.86	103.80	102.20	

PTR/CTM	262.33	280.00	274.33	272.22 a	24.70	23.89	24.82	23.78	100.33	100.73	97.47	
Mean	255.41	267.16	263.50		24.15	23.93	24.29		101.60	102.26	99.80	
LSD 0.05	TCE = 8.32 Residue (R)=ns TCE×R=ns				TCE =0.172 Residue (CR)=ns T×CR=ns				TCE = ns Residue (R)=ns TCE×R=ns			

TCE technique	straw/ha			
	CR0	CR25	CR50	Mean
STDSR/STM	5.11	5.23	5.19	5.18
PTR/CTM	5.25	5.29	5.22	5.25
Mean	5.18	5.26	5.21	
LSD 0.05	TCE = ns Residue (R)=ns TCE×R=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S12. Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on yield parameters of maize during 2019-2020

TCE technique	**Grains/cob**				**Weight of 1000.grains**			
	CR0	**CR525**	**CR50**	**Mean**	**CR0**	**CR25**	**CR50**	**Mean**
STDSR/STM	490.33	503.00	510.00	501.11	312.00	328.37	337.25	325.87a
PTR/CTM	491.00	514.60	512.33	505.97	297.20	312.24	326.66	312.03b
Mean	490.66b	508.80a	511.16a		304.60b	320.30a	331.95a	
LSD0.05	TCE = ns Residue (R)=11.78 TCE×R=ns				TCE = 5.98 Residue (R)=13.71 TCE×R=ns			
TCE technique	cob leanth(cm)				cob round			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	17.21	18.52	20.56	18.76	14.92	15.09	15.04	15.14
PTR/CTM	16.66	18.62	20.85	18.71	15.04	15.23	15.77	15.34
Mean	16.93c	18.57b	20.70a		14.98b	15.16b	15.58a	
LSD0.05	TCE = ns Residue (R)=1.167 TCE×R=ns				TCE = ns Residue (R)=0.278 TCE×R=ns			
TCE technique	cob lines				plant height (cm)			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	14.20	14.47	15.62	14.76	250.33	251.66	257.00	253.00
PTR/CTM	14.53	14.17	15.49	14.73	244.33	247.66	246.66	246.22
Mean	14.36b	14.32b	15.56a		247.33	249.66	251.83	
LSD0.05	TCE = ns Residue (R)=0.642 TCE×R=ns				TCE = 4.08 Residue (R)=ns TCE×R=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S13. Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on yield parameters of rice during 2020-2021

TCE technique	No. of grains panicle-1				Tiller/hill				Weight.of. 1000.grains			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	76.00	79.33	79.66	78.33a	10.20	9.96	9.97	10.04	23.46	24.03	24.13	23.88a
PTR/CTM	74.00	75.66	74.66	74.78b	9.36	9.40	9.96	9.57	23.00	23.80	23.36	23.39b
Mean	75.00	77.50	77.16		9.78	9.68	9.96					
LSD0.05	TCE = 2.39 Residue (R)=ns TCE×R=ns				TCE = ns Residue (R)=ns TCE×R=ns				TCE = ns Residue (R)=ns TCE×R=ns			

TCE technique	panicle.m-1				Panicles leanth. (cm)				plant. height (cm)			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	243.66	265.66	280.83	263.38	23.40	24.25	25.29	24.31	100.40	104.32	105.49	103.40
PTR/CTM	236.66	245.83	261.66	248.05	21.80	23.24	24.49	23.18	97.56	101.77	105.16	101.50
Mean	240.166c	255.75b	271.25a		22.60c	23.74b	24.89a		98.98c	103.04b	105.32a	
LSD 0.05	TCE = ns Residue (R)=8.20 TCE×R=ns				TCE =ns Residue (CR)= 0.992 T×CR=ns				TCE = ns Residue (R)=1.86 TCE×R=ns			

TCE technique	straw/ha			
	CR0	CR25	CR50	Mean
STDSR/STM	5.03	5.22	5.33	5.19b
PTR/CTM	5.88	5.86	5.93	5.89a
Mean	5.46	5.54	5.63	
LSD 0.05	TCE = 0.54 Residue (R)=ns TCE×R=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S14. Effect of tillage and crop establishment (TCE) techniques and residue management (R) options on yield parameters of maize during 2020-2021

TCE technique	Grains/cob				Weight.of. 1000.grains			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	483.33	498.00	515.00	510.11	315.33	328.08	341.33	328.25a
PTR/CTM	491.00	512.66	526.66	498.77	297.16	312.00	323.33	310.83b
Mean	487.16c	505.33b	520.83a		306.25b	320.04a	332.33a	
LSD0.05	TCE = ns Residue (R)=13.928 TCE×R=ns				TCE = 17.03 Residue (R)=12.51 TCE×R=ns			
TCE technique	cob length (cm)				cob round			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	17.88	19.21	21.08	19.39	15.13	15.32	16.07	15.51
PTR/CTM	17.59	19.02	21.17	19.26	15.09	15.27	16.14	15.50
Mean	17.74c	19.12b	21.23a		15.11b	15.30b	16.11a	
LSD0.05	TCE = ns Residue (R)=1.180 TCE×R=ns				TCE = ns Residue (R)=0.479 TCE×R=ns			
TCE technique	cob lines				plant height (cm)			
	CR0	CR25	CR50	Mean	CR0	CR25	CR50	Mean
STDSR/STM	14.40	14.66	15.80	14.95	254.33	255.66	259.00	256.33
PTR/CTM	14.66	14.26	15.60	14.84	249.66	252.33	248.66	250.22
Mean	14.53b	14.46b	15.70a		252.0	254.0	253.83	
LSD0.05	TCE = ns Residue (R)= 0.675 TCE×R=ns				TCE = Residue (R)=ns TCE×R=ns			

Means with the same letter are not significantly different, STDSR =Strip tillage with direct seeded rice, STM =Strip tillage maize, PTR = puddling transplanted rice, CTM =Conventional tillage maize, CR=Previous crop residue retention, CR0, CR25 and CR50 corresponds to 0, 25 and 50% previous crop residue retention, ns-nonsignificant

Table 3. S15. Crop residue management protocols of the rice-maize cropping pattern in the study area.

Crop	crop residue	Year	crop residue weight (t/ha) and height (cm) based on proportion
1	Rice residue	2019 (standing residue)	ST (0%)- No above ground residue ST (25%)-2.40 (30 cm) ST (50%)- 4.26 (59 cm)
		2019 (incorporation residue)	CT (0%)- No above ground residue CT (25%)-2.50 (30.5 cm CT (50%)- 4.30 (59.5 cm)
2	Maize	2020 (incorporation residue)	100% residue incorporation
3	Rice residue	2020 (standing residue)	ST (0%)- No above ground residue ST (25%)-2.65 (31 cm) ST (50%)- 4.46 (60 cm)
		2020 (incorporation residue)	CT (0%)- No above ground residue CT (25%)-2.58 (30.6 cm CT (50%)- 4.38 (59.6 cm)
4	Maize	2021 (incorporation residue)	100% residue incorporation