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Sustainable Intensification of Agriculture: Opportunities and Challenges for Food Security and Agrarian Adaptation to Environmental Change in Bangladesh

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Sustainable Intensification of Agriculture: Opportunities and Challenges for Food Security and Agrarian Adaptation to Environmental Change in Bangladesh

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Environmental Dynamics

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ABSTRACT

This dissertation investigates three unique aspects of sustainable agricultural intensification (SAI) in the context of Bangladeshi rice production. The first article presents a qualitative analysis of SAI and farmer surveys in the embanked polder region of coastal Bangladesh. The second article investigates the global food security and environmental impacts of already adopted High Yielding Variety (HYV) rice and double-cropped rice systems in Bangladesh using a spatial partial equilibrium trade model and a Life Cycle Assessment (LCA). The final article demonstrates a remote sensing methodology for monitoring dry season rice production at 30 m resolution in Bangladesh using a harmonic time series model, the Landsat archive, and Google Earth Engine. Major findings from this dissertation include: (1) agrarian communities in the polder region face food insecurity during the peak of monsoonal paddy rice production and could improve production by adopting HYV or second season crops, (2) agrarian communities in the polders identify water management issues as the primary agricultural concern, followed by pest infestation and soil salinity, (3) HYV rice provides enough additional production in Bangladesh to feed nearly 26 million Bangladeshis per annum and is more environmentally efficient than traditional rice in terms of global warming potential, land use, water use, and fertilizer use, and (4) the combination of a harmonic time series model, spectral indices, and rice phenology can produce relatively accurate predictions of dry season rice in Bangladesh compared to district-level reference information. Overall, the findings from this investigation of SAI support continued efforts to improve food security, increase agricultural output, and decrease environmental impacts in Bangladesh.

Key Words: *sustainable agricultural intensification, climate change, rice, food security, Bangladesh*

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Any errors discovered are indeed my own.

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DEDICATION

First, this dissertation is dedicated to agrarian communities in Bangladesh, especially those facing the tremendous challenges presented by food insecurity, climate change, and environmental degradation. Second, this dissertation is dedicated to the many organizations, policy-makers, and development practitioners striving constantly to help agrarian communities overcome these very same challenges.

TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION

The overall aim of this dissertation is to advance the scientific understanding and application of Sustainable Agricultural Intensification (SAI) within the context of Bangladesh. I introduce SAI in this chapter, briefly define it based on the present literature, and discuss the general application of the SAI framework for the purposes of this dissertation. Within each of the three chapters, I discuss SAI in more specific terms and with more explicit goals. This synthesized work is an attempt to bridge the methodological and disciplinary gaps in how SAI is studied. As such, the articles presented address different but interrelated topics of the SAI of rice systems in the Bangladeshi context. In the most concise terms possible, these three articles on SAI in Bangladesh demonstrate: (1) an analysis of what current SAI barriers and opportunities look like at the farm-household level in the challenging polder environment of Coastal Bangladesh, (2) an investigation of the food security and environmental impacts from previous SAI (adoption of improved rice seed technologies and double cropped rice systems) at global, national, and regional scales, and (3) a proposed methodology for quantifying, monitoring, and potentially predicting dry season rice (one form of SAI) planted areas at high resolutions (30 m) using the Landsat remote sensing archive and Google Earth Engine.

In the first study, I analyze survey data specific to the polder region of Bangladesh in the coastal area. The primary aim in this analysis is to characterize current agrarian community characteristics, management practices, farming systems, and perceptions, and then to provide recommendations for potential SAI methods. The study takes a deep dive approach to understanding the social, cultural, economic, and environmental dynamics of agricultural production and intensification in the coastal area. This is particularly important given the fact that the coastal area has lagged behind the rest of Bangladesh in terms of agricultural (and human) progress, yet faces extreme and continuously changing environmental conditions. This study of agrarian communities in the polders presents an updated and extensive evaluation of household food security and socio-economic status, how agricultural systems are managed, which SAI strategies have or have not been adopted, and the potential implications of the future adoption of particular SAI practices (improved seed varieties, water management, etc.).

In the second study, I conduct a multi-scalar investigation of the main forms of previously adopted production-improving, rice intensification practices in Bangladesh: (1) the adoption of High Yielding Variety (and hybrid to a much lesser extent) rice, and (2) the adoption of an irrigated dry season HYV rice. This study integrates methods from economics (trade model) and engineering (Life Cycle Assessment) to present a holistic analysis of the food security and environmental impacts of the two practices specified above to determine if these strategies can indeed be identified as SAI practices. Many previous studies (cited and outlined in detail below) have empirically analyzed the economic, food security, or environmental aspects of agricultural practices in independent case studies, generally using less than 300 surveys in small regional contexts with primarily local implications. Other studies have focused on the theory and need for SAI at the global scale, some without presenting specific numbers or analyses of data and some with global data analysis of future needs and impacts. Thus, in this study, I attempt to bridge the gap between small-scale case studies, global theoretical studies, and global predictive studies with global, national, and regional impacts from the previous and widespread adoption of specific SAI strategies. Beyond filling this void in the SAI literature, this work is equally important for ongoing efforts to predict future food security requirements and potential environmental concerns. Many studies seek to predict these issues in the future, which is important indeed, but very few studies have empirically and simultaneously tracked progress in

SAI at multiple scales to see whether and how progress is being made on our path to the world of 2050 food security and environmental issues.

In the final dissertation study, I present a new spatio-temporal methodology for identifying dry season rice production in Bangladesh for the last two decades at 30 m resolution and discuss potential improvements to the model for future work. One of the major challenges in tracking progress in SAI (as in the second study herein) is the lack of unbiased and local scale data on agricultural production and management. Major advances have been made in monitoring agricultural systems using remote sensing platforms. Previously, there have been computational limits to analyzing data at fine spatial scales across time, but with the advent of new (and free to scientists) platforms like Google Earth Engine designed for this type of work, there is great opportunity to obtain improve agricultural information in places like Bangladesh where little in situ data exists and agricultural systems are heterogeneous. This study presents a method for identifying rice-growing pixels for all of Bangladesh. The findings provide substantial information for monitoring production, management, and weather impacts on dry season rice in Bangladesh. The study concludes with a discussion of other methodological pathways for remote sensing monitoring of rice (and other crop) systems, and highlights the connections and increasingly important role of integrating remote sensing methods into the analysis and tracking of SAI more generally.

1.1 SAI in the Global Context

SAI is multi-scalar, and involves processes from the farm-level to the global context. Most of the introductory literature on SAI discusses its importance in policies and outcomes at the global level. A number of high profile studies (Garnett et al. 2013; Lipper et al. 2014;

Mueller et al. 2012; Tilman et al. 2011; Van Nguyen 2009) have been conducted to introduce SAI has a framework for meeting food security demands while simultaneously addressing environmental concerns. Some of these studies seek mainly to quantify differences in productivity, resource-use efficiency, or greenhouse gas (GHG) emissions between traditional and intensified systems (Garnett et al. 2013; Mueller et al. 2012; Tilman et al. 2011; Van Nguyen 2009). Other studies make arguments for more and stronger policies and institutional efforts to instigate SAI (Godfray & Garnett 2014; Lipper et al. 2014; Tittonell 2014). Two studies (Garnett & Godray 2012; Royal Society 2009) have presented in elaborate detail the concept of SAI, outlined the problems SAI science may address, made attempts to estimate SAI's potential impacts on both humans (mostly in terms of food availability) and the environment (e.g., biodiversity, erosion, nutrient cycling, etc.), and further suggested policies to support SAI. All of these studies have been instrumental in drawing attention to the widespread environmental problems caused by agriculture globally, the looming food and eco-system services requirements of human populations, and the broad potential of SAI to address these issues. In practice, there are many challenges for SAI to overcome, and this is highlighted best by studies conducted on the implementation or practice of SAI in developing contexts. Therefore, studies like those in this dissertation contribute to our understanding of the global impacts of agriculture, human decision-making, and the various outcome scenarios produced by the interactions between nature and humans in food production.

1.2 SAI in the Applied Context

Most studies conducted on the application of SAI have been in Africa. At the largest scale, Pretty et al. (2011) compared results from 40 on-the-ground SAI projects across Africa with particular attention to what would help scale the adoption and impacts of SAI, finding that: participation between scientists and farmers in trials, trust between individuals and local institutions, farmer field schools, engagement with the private sector, women's education and microfinancing for agricultural technologies, and public sector support for agriculture were crucial factors in SAI success. Two of the earliest studies of SAI outlined issues in post-genocide Rwanda (Clay et al. 1998) and discussed sustainable versus unsustainable agriculture throughout Africa (Reardon et al. 1999). These studies began the push toward SAI in both policy and applications. Many of the more recent studies (Franke et al. 2014; Kassie et al. 2014; Mungai et al. 2016; Rawson 2011; Vanlauwe et al. 2014; Vayssières et al. 2011) focus on the implementation of SAI projects with farmers and analyze who benefits, crop production potential under introduced SAI practices, gaps in adoption of SAI practices, and the bottoms-up capacity of smallholders to instigate change at both the farm and policy levels. While nearly all of the previous research demonstrates the significant potential of SAI to meet both human needs and address environmental degradation, there remain large gaps in regional applied studies of SAI, particularly in the context of South Asia and Bangladesh specifically. Thus, this dissertation attempts to provide a multi-scalar, application based analysis of SAI in Bangladesh to fill this void in the literature. Overall, the aim of these studies is to push forward the ability of practitioners to implement SAI practices at local scales in Bangladesh such that the repercussions have a positive global impact on food security and environmental efficiency.

1.3 SAI Questions Addressed in This Study

In this dissertation, I aim to address questions that improve our understanding of SAI in the Bangladeshi context. I described the intuition and importance behind the three topics addressed at the beginning of this chapter and briefly discussed the background of SAI in the global and applied contexts. Here, I define the specific questions being addressed by each of the three studies carried out in this dissertation.

1.3.1 Chapter 2: Household-level SAI Questions

1. What are the general socio-economic characteristics of farm households in the polder region of Bangladesh?
2. What are the major components of land ownership and cropping systems in the polder regions, as described by farmers?
3. What are the perceived barriers to improved agricultural technologies in the polders?
4. Are there temporal characteristics to household food insecurity in the polders? If so, what may be driving this food insecurity?
5. If food insecurity is present, how do households cope with this problem?

1.3.2 Chapter 3: National-level SAI Questions

1. How have rice intensification practices contributed to global food security?
2. How do improved rice seed technologies and double-cropped rice systems compare with traditional rice production in terms of environmental impacts?
3. Can rice intensification via the adoption of hybrid and HYV rice and double-cropped rice be classified as SAI?

1.3.3 Chapter 4: Multi-scalar Agricultural Monitoring Questions

1. Can a time series model enhance rice monitoring efforts?

2. Can dry season (*boro*) rice be mapped with multi-sensor, multi-decadal Landsat information?
3. How do spatio-temporal models of rice phenology for rice pixel identification compare to regional crop statistics information?
4. What future pathways may improve the ability to map rice production areas?

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CHAPTER 2: SUSTAINABLE INTENSIFICATION IN THE POLDERS: UNDERSTANDING AGRARIAN BEHAVIOR AND PRACTICES IN COASTAL BANGLADESH

Abstract

Sustainable Agricultural Intensification (SAI) is critical to meeting food security needs in coming decades, especially in regions such as Bangladesh where population growth, reductions in arable land and resources, and ongoing climatic changes coincide. SAI is a framework for evaluating the nexus of human-environmental relationships in agricultural systems and a platform for improving their short and long-term productivity. Previous studies of SAI have focused on global intensification of extensive agricultural systems or outline environmental sustainability issues or yield gaps in case studies of small-scale agricultural production. This study extends on previous research to evaluate agrarian practices and perceptions of SAI in a unique landscape: the polders (low-lying, embanked landscapes) of the Ganges-Brahmaputra-Meghna Delta (GBMD). This study presents new and significant findings for polder production systems that cover more than 1 million hectares of land. The study analyzes 1025 surveys of farmers in the Bangladeshi polders to identify challenges and opportunities for SAI based on current cropping systems, farmer perceptions, and food security. Based on survey analysis, I characterize polder demographics, define current cropping systems, discuss water management, evaluate farmers' perceptions of agricultural technologies, and outline food security issues. Lastly, I review opportunities for SAI and future research in the polders with emphasis on the synergies between research-derived solutions and agrarian perceptions. The most significant opportunities for SAI are to bolster community involvement in water management committees, make evident the potential of flood-tolerant and High Yielding Varieties of rice in the monsoon season, and identify diverse crops for dry season suitability.

Keywords: *sustainable agricultural intensification, agrarian perceptions, technology adoption, polders, Bangladesh*

2.1 Introduction

Sustainable Agricultural Intensification (SAI) can be characterized as a framework for disentangling “wicked problems” in modern agriculture (Lipper et al. 2014; Reardon et al. 1999; Rittel & Webber 1973; Tilman et al. 2011). Wicked problems are those involving significant human and environmental components and whose analysis and solutions require more than technical expertise: They require deep contextual knowledge of people and communities, as well as thorough technical knowledge about the environment and the feedbacks between the two. Wicked problems, then, are those requiring the combination of human and environmental knowledge into operational and actionable solutions, often with complex time and space dimensions, which is what SAI seeks to accomplish through interdisciplinary efforts (Clay et al. 1998; Garnett & Godfray 2011; Pretty et al. 2011; Tilman et al. 2011). In this study, I investigate the potential for SAI in agricultural development in Coastal Bangladesh based on a survey of agrarian communities.

Researchers and development practitioners are using SAI to address the particularly challenging problem of improving the livelihoods of agrarian communities in the context of poverty and food insecurity (Clay et al. 1998; Garnett et al. 2013; Godfray & Garnett 2014; Lipper et al. 2014; Rabinson et al. 2015), multi-scalar environmental changes (Campbell et al. 2014; Mueller et al. 2012; Van Nguyen 2009), and a uniquely engineered ‘polder’ system for water and land management (Gain et al. 2017; Rawson 2011). Polders (embanked, low-lying deltaic islands) were constructed in the coastal region of Bangladesh in the 1960s–1970s (Gain et al. 2017) to protect agrarian communities in the Ganges-Brahmaputra-Meghna Delta (GMBD) from flooding and salinity intrusion (Mondal et al. 2001; Mondal et al. 2015). More specifically, the Bangladeshi polders were engineered to allow farming communities more control over water and protection from storm surges and sea-level rise. While polders protect farmers from certain environmental problems, they create other challenges for improving agricultural systems and agrarian livelihoods (Rawson 2011). Rawson (2011) highlights many of the environmental challenges with respect to wheat and mungbean production during the rabi season, but until now, no research has extensively reviewed agrarian behavior and practices in the region with specific consideration of SAI in agricultural development, which is critical to understanding the capacity for SAI to effectively alleviate poverty in non-extensive, smallholder agriculture (Rabinson et al. 2015). Thus, in this study, I attempt to bridge this gap in the literature and provide critical information for on-the-ground SAI applications in ongoing development projects.

2.1.2 Study Area

Bangladesh on the whole has seen significant advances in human development since the early 1990s (Nisbett et al. 2017). Malnutrition, especially for women and children, has decreased and almost every other development metric including the Human Development Index, mortality rates for children under 5, etc. have improved (UNICEF 2014). However, there remain large poverty issues in Bangladesh (Farzana et al. 2017; Nisbett et al. 2017), and population growth and changing dietary habits are expected to increase food demand in coming decades (Faisal & Parveen 2004; Royal Society 2009). Consequently, more resources will be required to produce food, even while arable land is decreasing (Dewan & Yamaguchi 2009), and nearly 50% of the population relies on rice for both income and food (Hossain & Fischer 1995; Mottaleb & Mishra 2016). In fact, Bangladeshi’s consume more rice per capita than any other country in the world with exception to Myanmar (FAOSTAT 2016). The low-lying landscape and ubiquitous rainfall during the monsoons make Bangladesh a prime region for rice production systems (Shelley et al.

2017; Wassman et al. 2009), but increasing environmental pressures present enormous challenges for agrarian communities to adapt traditional practices to those that are more resilient and sustainable (Kabir et al. 2016).

Agrarian communities in the polder regions of Coastal Bangladesh are some of the most vulnerable in the world to global climate change (Dasgupta et al. 2014; Thompson & Sultana 1995). Sea-level rise creates salinity intrusion, which affects not only agriculture but also coastal biodiversity and human health (Mahmuduzzaman et al. 2014; Mondal 2001). Changes in monsoon patterns are causing more frequent flood and cyclone events in the coastal region (Mirza 2002) and droughts in other regions (Kabir et al. 2017). The coastal area has long faced environmental problems associated with flooding and salinity (Gain et al. 2017). As early as 1961, a Coastal Embankment Project (CEP) bill was passed to assuage agrarian problems. Part of this bill provided institutional and financial support for large hydro-engineering projects in the coastal region, i.e., polder construction and maintenance (Gain et al. 2017). In the following decades, 139 polders (**Figure 1**) were constructed around approximately 1.2 million hectares of land in the GBMD in support of over 8 million people (Tuong et al. 2014). These polders not only protect agriculture from ensuing the environmental changes stated above, but also provide a safeguard for the homes, businesses, infrastructure, and the broader Bangladeshi economy in the coastal region (Thompson & Sultana 1995).

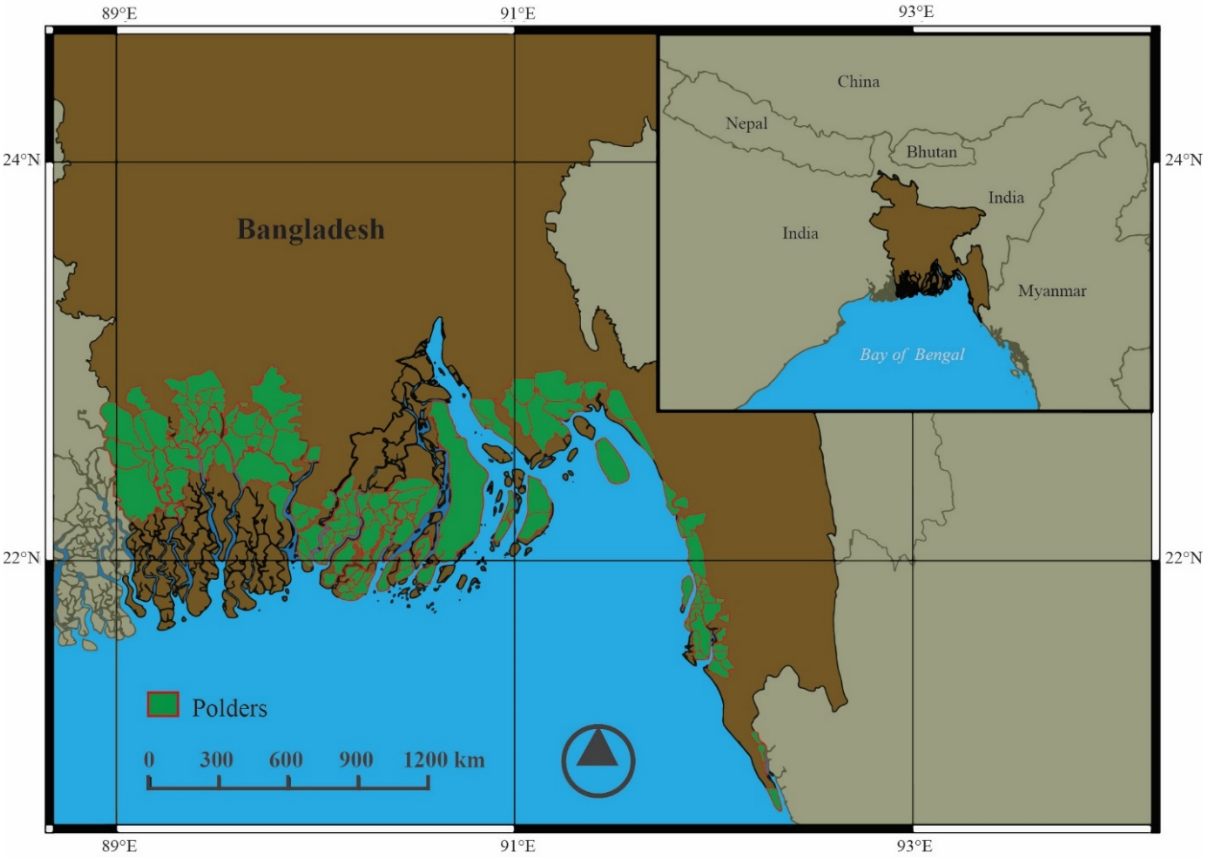

Figure 1. Polders in the Coastal Region of Bangladesh. This map outlines the polders in Bangladesh in red.

While the general protective features of polders are clear, specific functions and maintenance issues of the polders need to be outlined to provide better context for the importance of sustainable intensification. Polders are mostly constructed of soil (mostly heavy clay), but may also include rock, cement, and vegetative growth for reinforcement (Gain et al. 2017; Thompson & Sultana 1995). Committees of farmers use sluicegates in the polder embankments to control the flow of water between the rivers and canals within the polders. For each sluicegate, there is a sub-polder catchment area, essentially a watershed. In short, sub-polder catchment areas can be called "sluicesheds". Sluicesheds are characterized by topography, precipitation, distribution canals, and sluicegate operations. Each sub-polder area receives only gravity-fed water. Thus, each of these factors contributes to water management and crop suitability within a given sluiceshed.

The diurnal tidal rivers allow polder communities to obtain water during high tide and drain water during low tide by opening the sluicegates, but importantly, opening or closing the sluicegates has spatially-explicit impacts for each farm. In other words, the topography and location of a farm affects the depth of water, the drainage options, and the salinity gradient in the soils (Mondal et al. 2001, 2015). Each sluiceshed has a water governance group to decide sluicegate operations, which ideally allows farmers to collectively choose when and for how long the sluicegates should remain open or closed. In general, the sluicegates remain closed during the dry season due to high river salinity (Khan et al. 2015), but during the summer, they are sometimes opened to intermittently flush the soils with fresh water until the planting of paddy rice, which occurs at the onset of the monsoon (Mondal et al. 2015; Wassman et al. 2009). Throughout the monsoon season, water governance groups (WMGs) continue to control sluicegate operations, but whether or not their decisions are indeed optimal for communities as a whole or dominated by farmers with more power is not yet known.

Even while polder communities receive some protection from environmental change, current agricultural systems in the region remain resource-inefficient and do not benefit from improved, climate-resilient, and diverse cropping systems, leaving significant gaps in yield, food security, and overall human well-being (Mondal et al. 2015). Thus, given the amount of people relying on polders for agricultural production and livelihoods, there is immense need to ensure that polder communities can take full advantage of water management and other agricultural resources to navigate present and future challenges, both human and environmental. Because of this need, policy-makers, development practitioners, and researchers alike are involved in participatory approaches to sustainably intensify agriculture in the polders.

2.1.3 The Theory behind Sustainable Agricultural Intensification

SAI is a framework for analyzing short and long-term issues in agriculture (Garnett & Godfray 2011; Godfray & Garnett 2014). With specific, over-lapping, and often competing purviews for land productivity, economic situation, environmental impacts, social context, and human conditions as SAI indicators, SAI has been the brunt of much debate in the literature (Loos et al. 2014; Mahon et al. 2017; Tittonell 2014; Petersen & Snapp 2015; Wezel et al. 2015). On one hand, sustainable intensification may help mitigate global food insecurity and environmental concerns (Bommarco et al. 2013; Garnett & Godfray 2012; Fish et al. 2014), and eventually address the projected need to approximately double food production by 2050 to meet rising food demand (Godfray & Garnett 2014; Tilman et al. 2011). Some scholars (Loos et al. 2014; Petersen & Snapp 2015; Rabinson et al. 2015; Wezel et al. 2015), however, are critical of the primary applications of SAI, arguing that SAI has vague definitions and in many cases shows signs of traditional industrial agriculture without significant inclusion of environmental and social indicators.

To address previous haphazard definitions of SAI, researchers in some cases employ other terms like “ecological intensification” or “agroecological intensification” with more precise conceptual frameworks for including social and environmental metrics (Bomarco et al. 2013; Tittonell 2014; Wezel et al. 2015). More specifically, the intentional inclusion of economic and societal aspects of food systems is important and lacking in much of the previous literature, which Mahon et al. (2017) discuss as potential "productivist" (i.e., yield only) bias in current interpretations of SAI.

In this study, I continue to use the term "sustainable intensification" (or SAI) and include metrics for human elements of SAI alongside agricultural productivity and environmental challenges. In doing so, my assessment of SAI in Bangladesh attempts to address the criticisms of previous SAI research by integrating social and environmental factors with production characteristics, while also maintaining a strong connection to the initial intentions of those promoting SAI, i.e., more productive and efficient agriculture. Moreover, I carry out this study in an applied research-for-development (R4D) setting with the aim to both understand present human, agricultural, and environmental issues and investigate potential improvements in these key areas.

2.1.4 SAI Application in the Bangladeshi Context

In Bangladesh, few studies have been conducted specifically on SAI. Those studies that have been done in Bangladesh were primarily focused on the potential of particular agricultural system applications, such as *rabi* wheat and mungbeans or fish pond sediments as fertilizer (Haque et al. 2016; Rawson 2011). These studies are important for understanding the dynamics of different SAI options for Bangladeshi farmers. Rawson (2011) edited a detailed volume on the potential for SAI in wheat and mungbeans in Bangladesh, and included brief documentation of farmers' perceptions of *rabi* crops. However, little attention has been given to the broader human dimensions of SAI, such as food insecurity, nor has there been a study providing analysis specific to the land and water management issues and agrarian perceptions within the polders. Therefore, the objective of this study is to identify challenges and opportunities to improve SAI practices in current cropping systems and better understand the human dimensions of SAI in the polder communities of Coastal Bangladesh. To do so, I analyze data from a survey conducted by the USAID Sustainable Intensification Innovation Lab (SIIL)-Polder Project with the aim to (1) characterize socio-economic characteristics in the polders, (2) define current cropping systems and management practices based on agrarian decisions, (3) outline water management issues, (4) outline current food shortages and coping mechanisms at the household level, and (5) evaluate farmers' perceptions of agricultural technologies and SAI suggested practices. I conclude with a discussion of opportunities for SAI in the polders with emphasis on the synergies between research-derived solutions and the agrarian perceptions analyzed in the survey data.

2.2 Survey Design, Data, & Methods

This survey was designed by SIIL-Polder Project to capture key components of current agricultural systems and agrarian perceptions in polder communities. The survey consisted of approximately 25 interviews in more than 40 villages across three polders for a total of 1025 respondents. The International Water Management Institute (IWMI) carried out the survey in the fall of 2016 between August and October. IWMI first conducted the survey with trusted leaders from each village, and then trained those leaders to conduct the survey with approximately 25 other community members. Survey sampling was designed to gather representative baseline information from farmers in polder 30 where the USAID SIIL-Polder Project began a research for development project in 2016. Surveys were also conducted in polder 28/1 and 28/2 as external controls for the project in polder 30. The purpose of this initial survey was to establish baseline metrics for the SIIL-Polder Project, and to eventually measure the impacts of SIIL-Polder Project activities on the community compared to the baseline and external controls.

The survey concentrated on evaluating the current situation of agrarian communities in the region and eliciting their perspectives on agronomic and water problems as well as potential improvements to their production practices. The survey included the following major categories: (1) General Demographic Information, (2) Land Ownership, Rental, and Use, (3) Cropping Systems, (4) Perceptions of Improved Technologies and Constraints, (5) Water Management, and (6) Food Security and Coping Mechanisms. General HH information included questions about the head of HH, education, gender, age, religion, etc. Land holdings, including leased, rented, and owned, were identified for each HH. Then respondents were asked to provide land characteristics and use information, such as the elevation, distance from irrigation canals, irrigation depth and drainage, cultivation time, among others. These land holding questions were essential to understanding broader land use patterns.

In the cropping systems section of the survey, farmers provided in depth production information for the June 2014 – May 2015 crop year. Questions included the types of crops planted during both *aman* (monsoon) and *rabi* (non-irrigated dry) seasons, area for each crop type, yield, how much was sold versus stored in the HH, selling price, and the most important source of water for each crop. Following this, participants answered nine questions related to the adoption of improved agricultural technologies. Seven of these questions required “Yes” or “No” responses with respect to various agricultural inputs such as the use of chemical fertilizers, pesticides, and herbicides, as well as the use of mechanical equipment such as harvesters and threshers. The last two questions were about the area of High Yielding Variety (HYV) rice planted during the *aman* and the area under any crop during the *rabi* season.

In the perceptions section, respondents rated their level of agreement with 47 different statements on a Likert scale from 0 – 10 with 0 meaning “very strongly disagree” and 10 meaning “very strongly agree”. The 47 statements included categories for HYV seed technology, mechanization, water management strategies (such as building small field channels for drainage), and various potential *rabi* crops such as wheat, mungbeans, and sunflowers. After the 47 statements, participants listed in order of importance their top three constraints in both seasons. They then provided the frequency and associated production losses of several environmental stresses experienced in their fields. These stresses included submergence/flooding, drought, salinity, and insects/diseases.

In the water management section, first HH participation in water management groups (WMGs) was elicited. Respondents provided both the gender and number of people in the HH involved in WMGs. If there were members, follow up questions were asked about their status, e.g., general member, chairperson, secretary, etc., as well as how long they have been members. Participants were also asked a series of questions about how they joined the WMGs and how much they contribute both financially and physically to the maintenance of both sluicegates and canals. They also rated six statements on a scale from 0 – 10 the transparency, financial accountability, participation (inclusion of stakeholders), rules respect and legitimacy, sluicegates operation, and maintenance. This provides a foundation for understanding participation and power dynamics among stakeholders within each water management unit (“sluice-shed”).

Lastly, in the incomes and livelihoods section, participants outlined the number of male and female agricultural and non-agricultural daily laborers, the hours worked, and the wage rates. Following this, a series of income domains were presented, and respondents provided the annual amount of income for each domain. After the income questions, food security questions were asked. These questions included a month-by-month account of skipped or smaller-sized meals due to insufficient food stocks or money to buy food. If they answered in the affirmative to any meal shortages in the last 12 months, the respondent answered 11 questions about coping mechanisms. Finally, respondents were asked to recount the meals eaten in the previous seven days. This recount included the types of food, number of times per food item, and the amounts per type of food.

The survey data are analyzed for each polder to characterize agrarian livelihoods, crop systems, and socio-environmental challenges. The correlation of variables within farm systems provides some indication of the interlinkages among sustainable intensification practices and demonstrates key areas of focus for development practitioners.

2.3 Results

2.3.1 General Demographic Information

In **Figure (2)**, the general demographics of survey respondents are presented by polder, where there are 173, 322, and 530 responses in polder 28/1, 28/2, and 30, respectively. Age, religion, and education are representative of the southwestern polders in Bangladesh. Notably, fewer females were interviewed, likely due to socio-cultural norms in the region. The average age of respondents was approximately 50 years old, which is slightly higher than the Bangladeshi average age for the farming population—to illustrate, Osmani & Hossain (2015) found the average age for the farming population to be 45. Religion in the polders is primarily Hindu with a minority being Muslims, which is nearly the opposite proportions from the rest of Bangladesh where Muslims maintain a majority and Hindus are the minority. Notably, there were approximately 70 % male respondents in all three polders, which suggests that there may have been a cultural bias in the survey administration process. Approximately 75 % of respondents had some education but not more than elementary or intermediate classes. In fact, less than 15 % of respondents in all three polders received high school education or above.

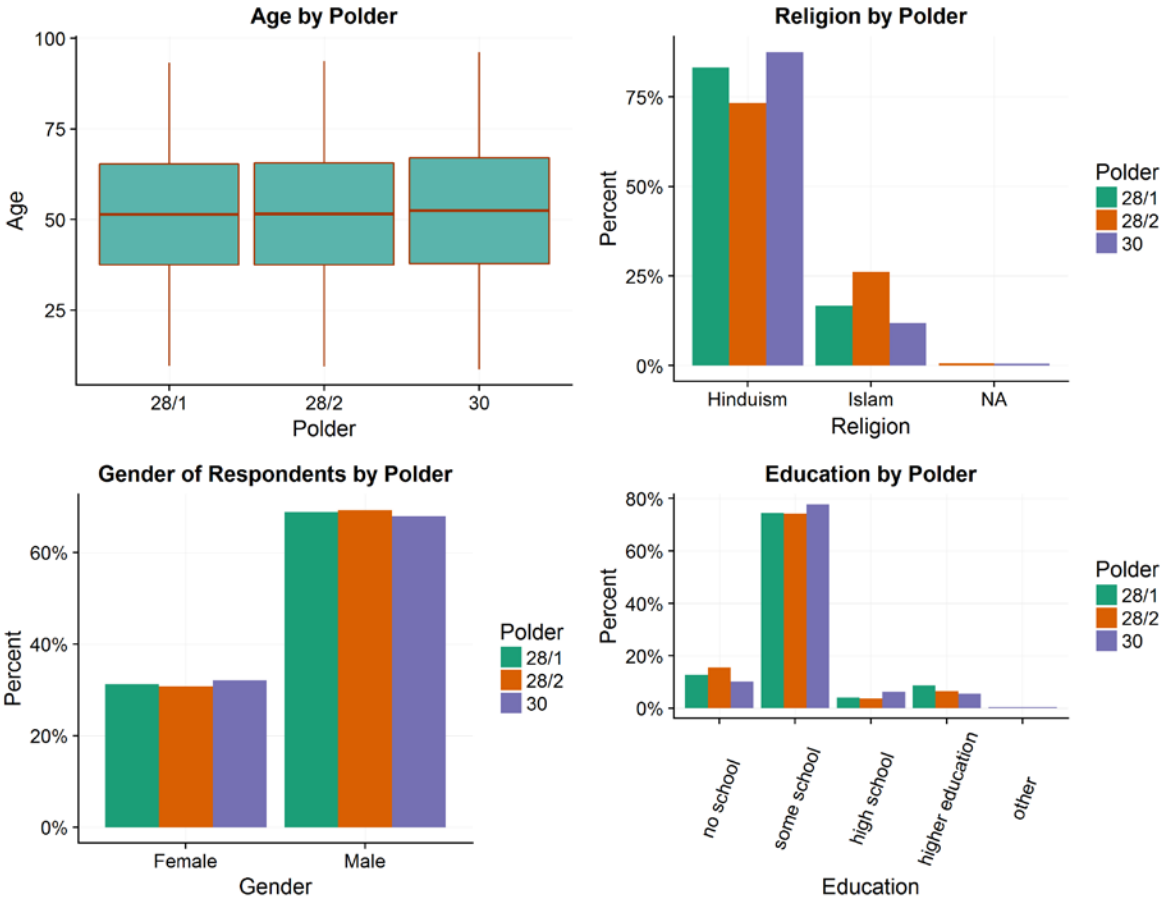

Figure 2. Basic Demographics of the Three Polders in the Survey. The four panel figure above shows the age, religion, gender, and education of survey respondents by polder. Age, religion, and education are representative, but gender, due to cultural issues, is not representative—primarily capturing male perceptions.

2.3.2 Land Ownership, Lease, and Non-Crop Use

On average, respondents had legal paperwork showing ownership of three to four plots, while they had no papers for one to two plots of those they cultivated (**Figure 3**). There is an average of 0.5 leased plots for all respondents, suggesting that leasing is less common than outright ownership or cultivation without papers altogether. Moreover, there are significant differences across the three polders with respect to the status of the main plot. In polder 30, substantially more (~20 %) respondents had papers for their main plot than in polders 28/1 and 28/2. Conversely, over 25% more respondents in polders 28/1 and 28/2 share cropped their main plots compared to polder 30. Less than 10 % of respondents officially leased their main plot for cultivation. Similar trends exist for the secondary plot status, although slightly greater differences exist in each category. There were substantially more NAs in the secondary plots, which suggests that very few farmers are able to cultivate more than one plot of land.

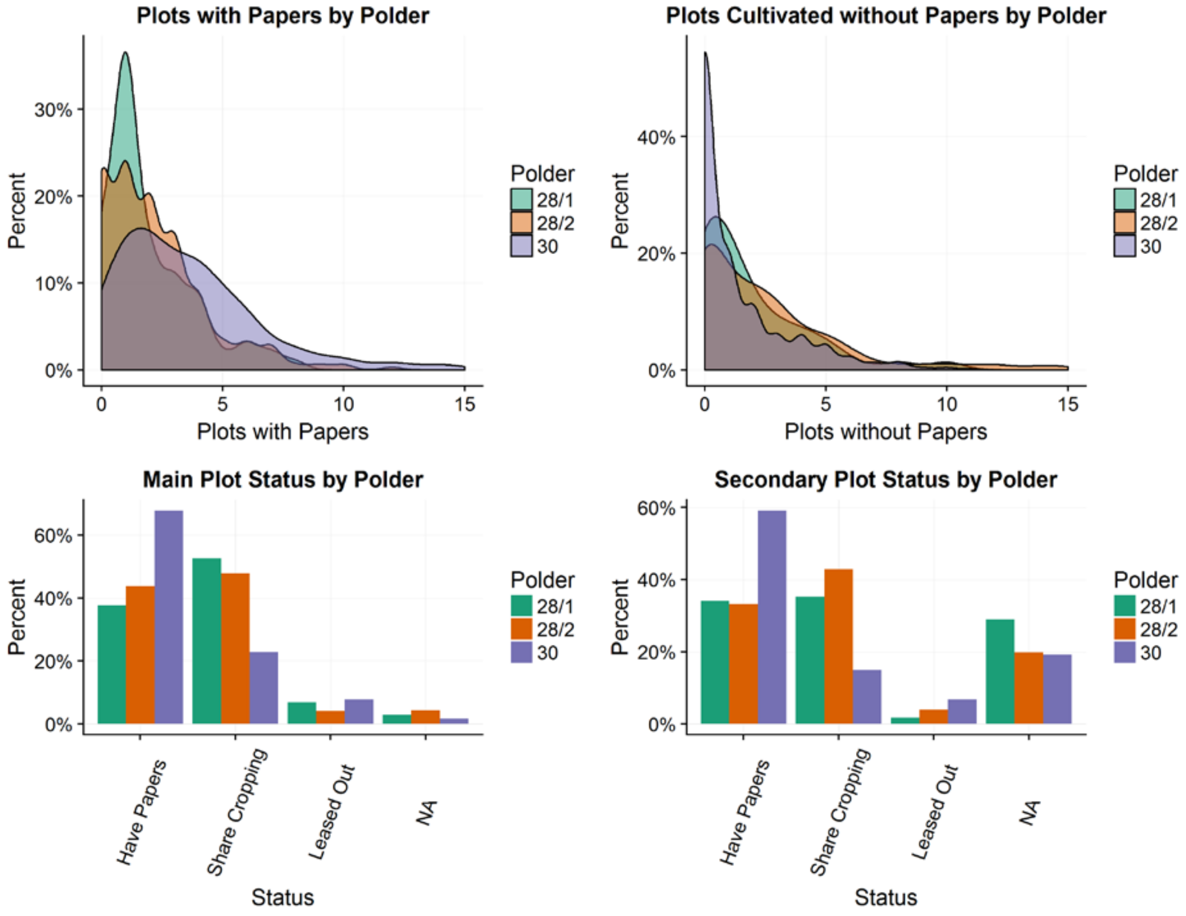

Figure 3. Cultivated Plot Status by Polder. This figure shows the distribution of plots by polder that have legal status.

In **Figure (4)**, a correlation plot of land ownership, land size, agricultural land elevation, and non-crop land uses is presented. Because most of the survey focused on agrarian livelihoods and crop systems, it seems pertinent to rule out potentially strong relationships with non-crop agricultural uses and the potential influence of land elevations and ownership status on these uses. The plot demonstrates that most agricultural land is at medium (medium_agri_land) or lower (low_agri_land) elevations. It also suggests a semi-strong linkage between the sizes of the main and secondary plots (when two plots are cultivated). Additionally, there is a relationship between medium-elevation land and having legal papers for plots, but this is not a strong relationship and most likely only shows that most farmers have medium agricultural land. Finally, there are no strong negative relationships (< -0.5) signified by the correlations, and only a few that are semi-strong and positive (> 0.5). This finding may suggest that the relationships between farming systems, land ownership, and status primarily exist with respect to crop systems, which is the focus of the rest of this analysis.

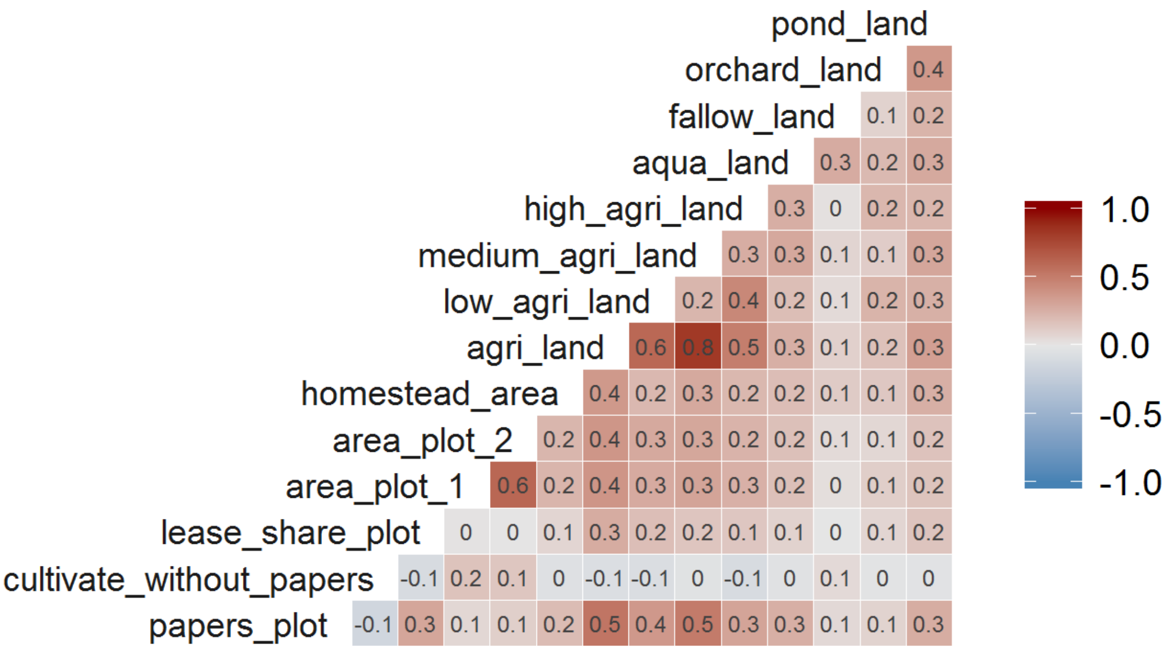

Figure 4. Correlation Plot of Non-Crop Land Use, Area, and Status. The correlation matrix demonstrates potential positive and negative relationships among farmer responses for non-crop agricultural land use.

2.3.3 Cropping Systems

First, the planting seasons for the top three crops are presented in **Figure (5)**. The crop systems are defined by planting and harvest dates as well as the variability around these within each polder. The *aman* season paddy rice has the least variability around planting and harvest dates and is consistent across all three polders with exception to a slightly shorter, but more variable season length in polder 30. Sesame and lentils/pulses are planted in the non-irrigated *rabi* season. Sesame has nearly the same average season length in all three polders, but planting variability is significantly lower in polder 28/2. Sesame harvest dates are also notably more variable than planting variability. Lentils/pulses have a slightly longer season than sesame overall, and the polder-specific variability for planting and harvest has a similar pattern to sesame except that it is less predictable in general. It should be noted that these are remembered planting and harvest dates, not actual or recorded dates.

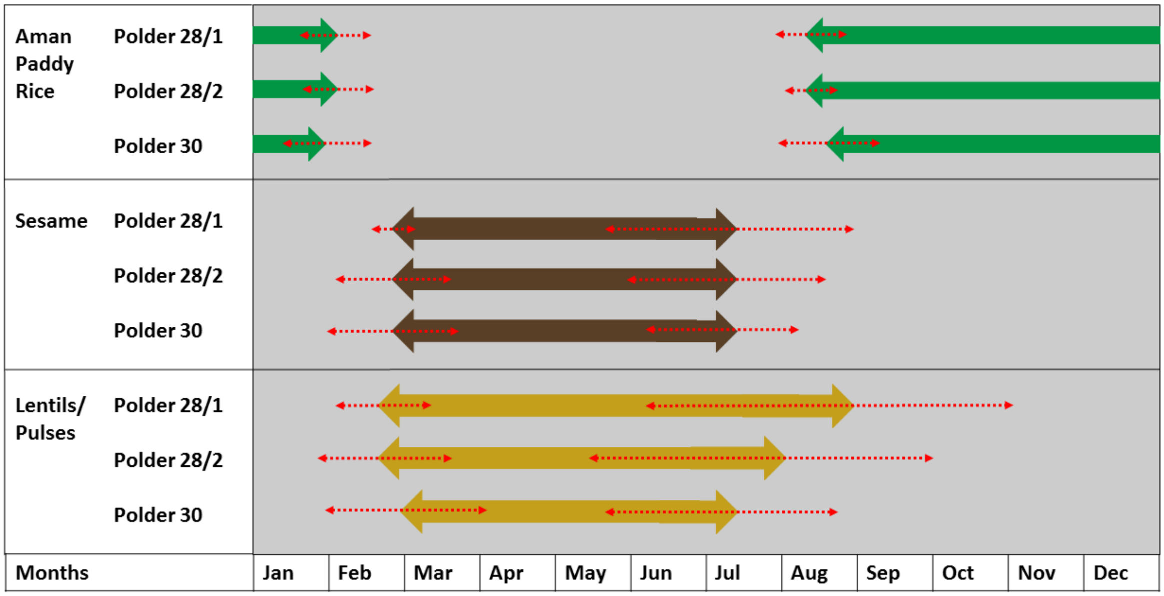

Figure 5. Crop Calendar for Polders 28/1, 28/2, and 30. Cropping seasons by polder for the main three crops: *aman* paddy rice, sesame, and lentils/pulses are outlined in the above figure based on farmers' stated planting and harvest dates. The red dotted arrows represent the variance around farmers' stated planting and harvest dates.

The primary crop and staple in the polders in rice, but there are many ways farmers may intensify their production. Farmers may plant multiple crops in a given season, which has been shown to reduce agronomic risks associated with single crop systems, or they may plant HYV rice during the *aman* season or plant a second season crop during the *rabi*. However, no previous studies have documented current production practices and productivity with respect to these intensification methods. In **Table (1)**, crop frequencies are presented for crops reported by importance for all farmers. The survey did not specify for which crops to collect data. As such, the range of crop diversity in the region is identified, and is demonstrated by 39 different crop types identified by farmers. Importantly, more than 95 % of respondents report *aman* or *boro* rice as the primary crop, followed by sesame as a secondary crop, pulses as tertiary, and vegetables as the fourth. Another critical piece of information for crop frequencies is the rapid decline in crops reported after the first and second most important for each farmer. Less than 50 % of respondents report a third crop, and less than 75 % report a fourth. This finding may signify opportunities for crop diversification, particularly in the *rabi* season.

Table 1. Crop Diversity and Frequency by Importance.

N=1025	Crop Type	First	Second	Third	Fourth	Fifth	Sixth	Seventh
1	*Aman* Paddy Rice	932	6	NA	1	NA	NA	NA
2	*Aus* Paddy Rice	12	NA	1	1	NA	NA	NA
3	Beans	1	2	3	NA	NA	NA	NA
4	*Boro* Paddy Rice	34	123	15	8	2	NA	NA
5	Brinjal (Eggplant)	2	2	3	NA	3	1	NA
6	Cauliflower	1	1	1	2	NA	1	NA
7	Cucumber	1	1	NA	3	NA	NA	NA
8	Fish Cultivation	7	30	40	24	18	2	6
9	Other Vegetables	4	38	71	60	9	7	NA
10	Potato	4	13	5	1	3	1	NA
11	Sesame (Til)	1	502	62	9	NA	1	NA
12	Tobacco	1	NA	NA	NA	NA	NA	NA
13	Tomato	1	3	2	2	1	NA	NA
14	Wheat	1	9	1	NA	1	NA	NA
15	Betel Leaves	NA	1	NA	NA	NA	NA	NA
16	Chickling Vetch	NA	8	18	5	NA	NA	NA
17	Colocasia (Taro)	NA	1	NA	2	NA	NA	NA
18	Cotton	NA	2	NA	NA	NA	NA	NA
19	Flower	NA	1	NA	3	NA	NA	NA
20	Jute	NA	2	1	2	NA	NA	NA
21	Lentils, Pulses	NA	52	190	19	6	NA	1
22	Other Fruits	NA	2	3	2	NA	NA	NA
23	Radish	NA	1	NA	NA	1	NA	1
24	Sericulture (Silk)	NA	1	NA	NA	NA	NA	NA
25	Shrimp Cultivation	NA	14	21	12	3	NA	NA
26	Sugarcane	NA	2	1	NA	NA	NA	NA
27	Sun Flower	NA	3	3	2	1	NA	NA
28	Turmeric	NA	1	NA	NA	2	1	NA
29	Cabbage	NA	NA	2	NA	2	1	1
30	Chili	NA	NA	1	NA	1	NA	NA
31	Fodder	NA	NA	1	NA	NA	NA	1

Table 1. (Cont.)

N=1025	Crop Type	First	Second	Third	Fourth	Fifth	Sixth	Seventh
32	Maize	NA	NA	1	2	NA	NA	NA
33	Mangoes	NA	NA	1	NA	NA	NA	NA
34	Ginger	NA	NA	NA	1	NA	NA	NA
35	Makhana (Fox Nuts)	NA	NA	NA	1	NA	NA	NA
36	Onion	NA	NA	NA	1	NA	NA	NA
37	Bananas	NA	NA	NA	NA	1	NA	1
38	Carrot	NA	NA	NA	NA	NA	1	NA
39	Mustard	NA	NA	NA	NA	NA	1	NA
40	Total NA	23	204	578	862	971	1008	1014

Note: This table shows the number of farmers that grow each crop in order of importance. For nearly all farmers (>95%) *aman* paddy rice is first, followed secondly by sesame, and thirdly by lentils/pulses. The NAs represent no farmer responses for that crop and rank of importance (i.e. column). The row 40 designation “Total NA” shows the total number of responses of the 1025 that do not report a crop in each column.

In **Table (2)**, the most common crop systems are presented with the number of farmers practicing each type. In polder 30, the most common crop systems include *aman* paddy rice followed by sesame (152 respondents), *aman* paddy rice followed by fallow (91 respondents), and *aman* paddy rice followed by sesame and lentils/pulses (91 respondents). In polder 28/2, *aman* paddy followed by sesame and lentils (62 respondents) was the most frequent crop system. There were also 45 farmers planting *aman* paddy followed by sesame alone, and 40 farmers planting only an *aman* paddy crop. In polder 28/1, the *aman* paddy followed by a fallow season was most prevalent. In terms of SAI, there is significant room for improving land use in all three polders. For example, there are substantial opportunities to incorporate second and third crops following the *aman* paddy.

Table 2. Crop System Occurrence by Polder.

Polder	Crop 1	Crop 2	Crop 3	Frequency
28/1	Aman paddy	Boro paddy	NA	24
28/1	Aman paddy	Sesame (til)	Lentils, pulses	17
28/1	Aman paddy	NA	NA	32
28/2	Aman paddy	Boro paddy	Sesame (til)	16
28/2	Aman paddy	Lentils, pulses	NA	11
28/2	Aman paddy	Other vegetables	NA	14
28/2	Aman paddy	Sesame (til)	Lentils, pulses	62
28/2	Aman paddy	Sesame (til)	Other vegetables	20
28/2	Aman paddy	Sesame (til)	NA	45
28/2	Aman paddy	NA	NA	40
30	Aman paddy	Boro paddy	Sesame (til)	16
30	Aman paddy	Lentils, pulses	NA	17
30	Aman paddy	Sesame (til)	Fish cultivation	14
30	Aman paddy	Sesame (til)	Lentils, pulses	91
30	Aman paddy	Sesame (til)	Other vegetables	11
30	Aman paddy	Sesame (til)	shrimp cultivation	13
30	Aman paddy	Sesame (til)	NA	152
30	Aman paddy	NA	NA	91

Note: Crop systems in the above table represent the first, second, and third crops planted across the polders. The frequency column demonstrates how many farmers opt for a particular cropping system.

Furthermore, farmers reported the productivities associated with each crop. **Figure (6)** summarizes the productivity for the first (all various seasons of paddy rice) and second-most important crops as reported by farmers from memory. Importantly, this figure only displays productivity for crops with over 10 occurrences in the survey. Notably, *boro* rice is the most productive, but is also more variable than the *aman* and *aus* season. Still, even at the lower end of the *boro* rice yield distribution, farmers are obtaining higher productivity than the *aman* season, on average. The *aus* season was least productive, which may be due to early onset monsoon rains or higher rates of soil salinity during the late dry season. Furthermore, *boro* rice is often planted to HYV rice, although this is not known based on the survey data. If this is the case, then it may be pertinent to intensify the *aman* paddy season with HYV rice, which could improve yields to similar levels as the *boro* season. Importantly, sesame is the most reported non-rice crop, followed by lentils/pulses. Sesame has lower yields in kg/ha than lentils/pulses, but has less variability overall and is consistent across the three polders. Lentils/pulses yield more on average in polder 30 and with less variability than in both polders 28/1 and 28/2. Notably, potatoes seem to yield the highest (by far) in kg/ha in polder 30, while they yield much lower in polder 28/2 and are not reported for polder 28/1.

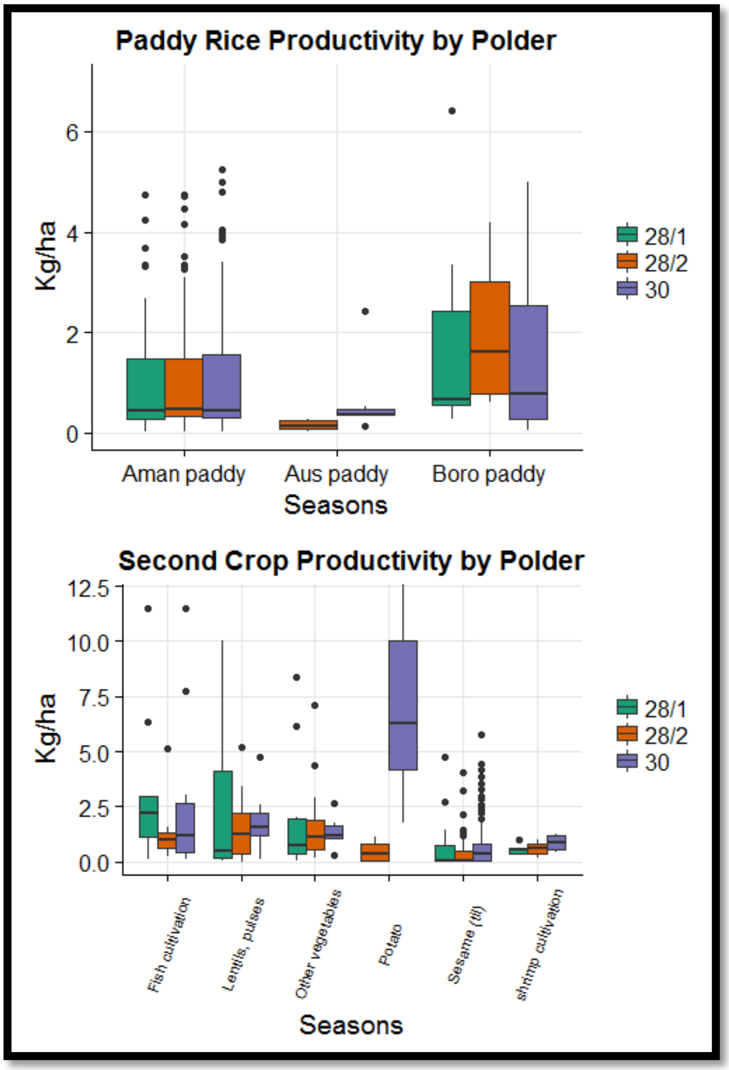

Figure 6. Productivity by Polder for the First and Second Crops. The productivity measures represent kg/ha of food produced. This may provide some inference on nutritional availability. The economics of each crop warrant further investigation.

In **Figure (7)**, the *aman* and *rabi* production constraints are presented. The key constraints perceived by farmers were categorized first into eleven general groups. Respondents were not given categories to choose from in the survey. As such, respondents reported more than 60 different constraints, which were categorized by the author post factum. Importantly, water seems to be the primary issue in both seasons. Following water issues, pests and salinity issues were also reported as major problems. These perceived constraints likely negatively affect the ability of farmers to adopt SAI practices, and as such, addressing them must play a vital role in implementing development projects and research trials.

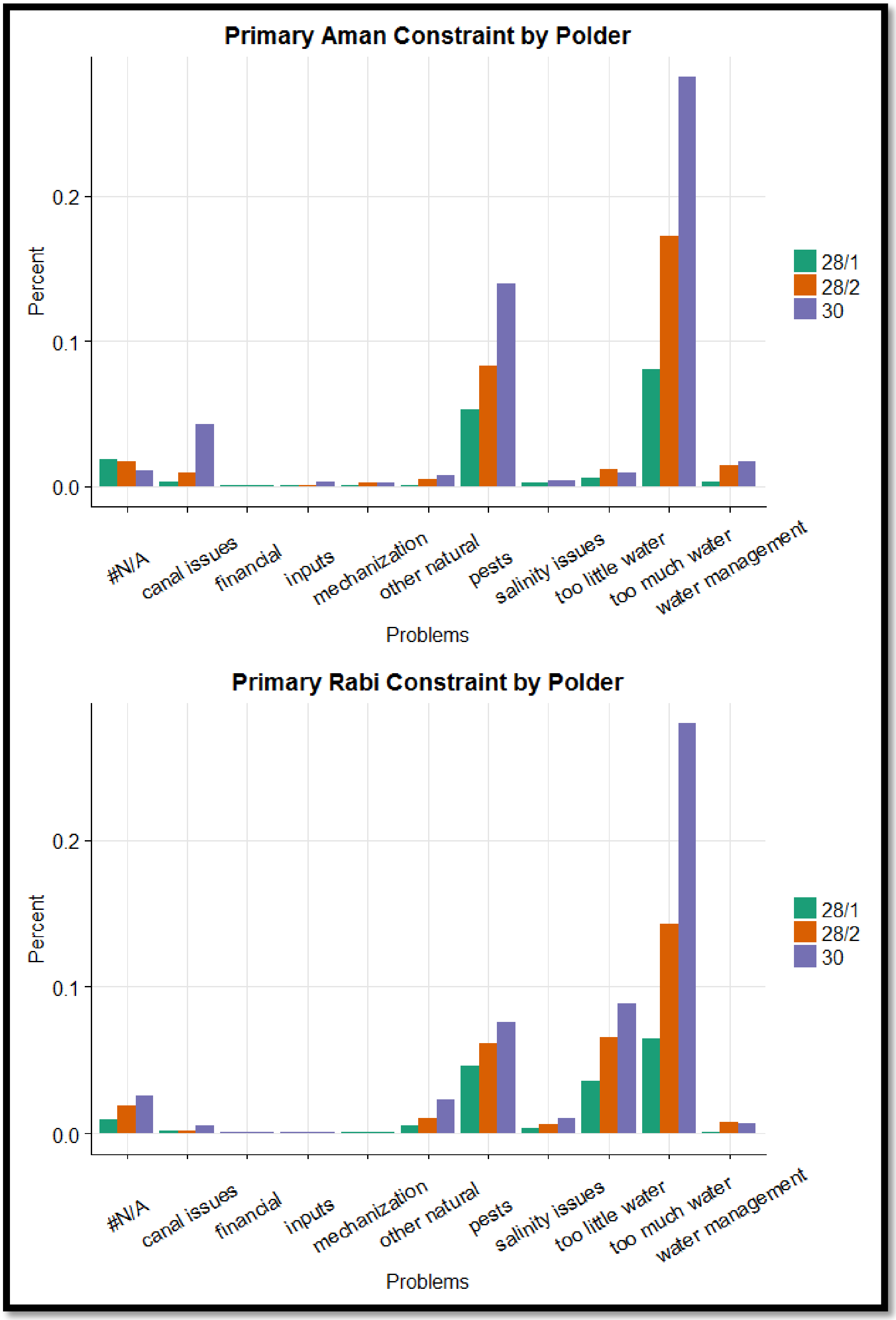

Figure 7. Perceived Productivity Constraints by Season and Polder. Water management is identified by farmers as the main constraint in both seasons in all three polders.

2.3.4 Perceptions of Improved Technologies

SIIL-Polder Project and other development practitioners in the region are trying to introduce more sustainable, productive, resource-efficient, and environmentally resilient agricultural technologies. The survey asked farmers how they perceive some of the technologies being proposed for adoption. Primarily, these involve the adoption of HYV rice or the adoption of a second season crop such as wheat, mungbean, or sesame. **Figure (8)** shows how farmers ranked these practices across nine important themes: (1) know how to produce HYV seed, (2) HYV increases income, (3) HYV is produced mainly for the market, (4) HYV increases yields, (5) HYV seed is expensive to buy, (6) HYV seed is easily available to purchase for planting, (7) HYV cultivation is labor intensive, (8) HYV crops have a lower market price, and (9) women can lead the production of HYV crops. Perceptions across these nine statements were consistent across polders and across HYV rice versus HYV *rabi* crops with exception to the perception of market prices. Respondents do not necessarily consider HYV rice to have a lower market price than traditional rice. This can be seen in the average of approximately five compared to eight in other questions, as well as larger variability than the other questions. However, they do seem to believe HYV *rabi* crops have a lower market price. The results also suggest that farmers are uncertain about their knowledge of how to produce HYV crops.

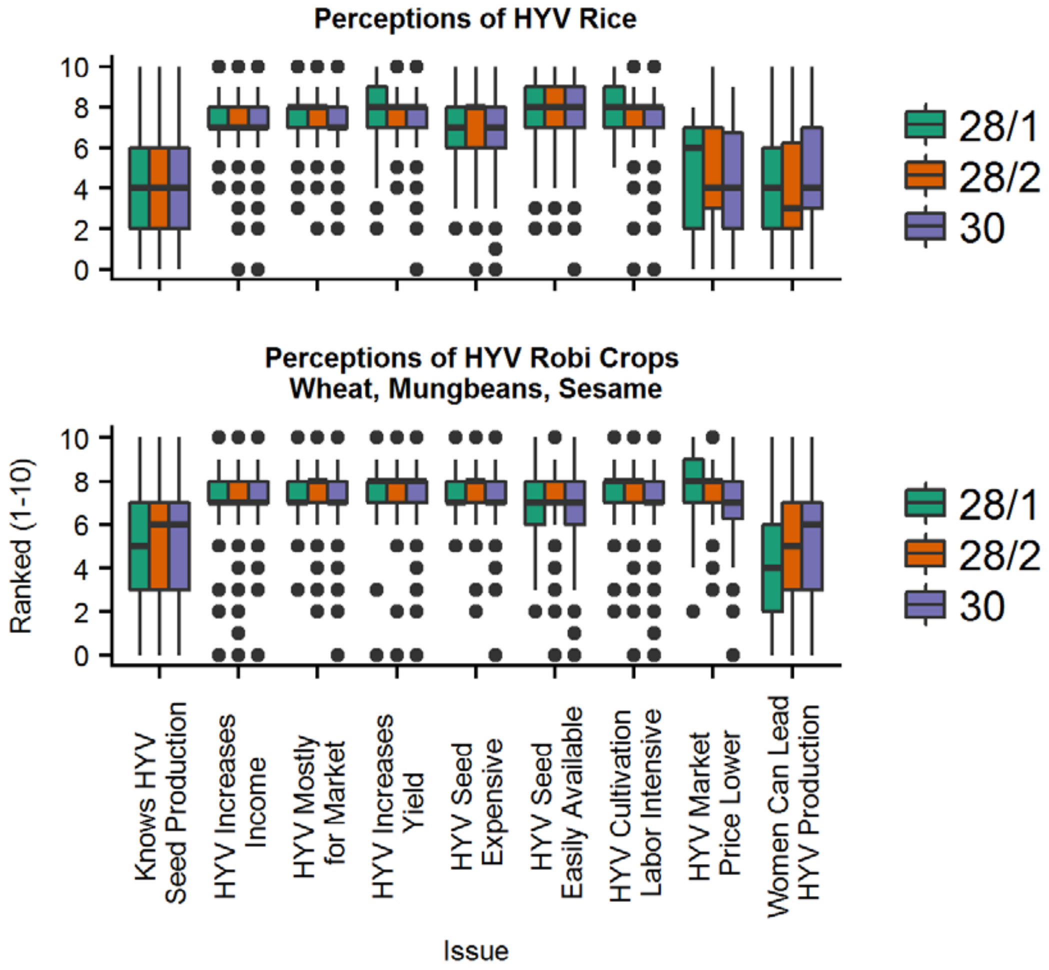

Figure 8. Agrarian Perceptions of HYV Rice and Potential *Rabi* Crops. From left to right, farmers ranked their agreement between 1 and 10 for the following statements: (1) I know how to produce HYV seed, (2) HYV increases income, (3) HYV is produced mostly for the market, (4) HYV increases yields, (5) HYV seed is expensive, (6) HYV seed is easily available, (7) HYV cultivation is labor intensive, (8) HYV has a lower market price, and (9) Women can lead HYV production. The boxplots represent 95% confidence intervals and black dots represent outliers. The black line in the middle of each box represents the mean.

2.3.5 Water Management

Water management poses a unique set of challenges in the polder regions of Bangladesh. The main factors involve sluicegate operations (opening/closing) by water management committees, topography (high/medium/low land), and distance to irrigation canals (*khals*) within the polders. In **Figure (9)**, results are presented on the distances from canals and the land elevations as identified by farmers in the survey. Most plots—primary and secondary—are within 300 meters of the closest irrigation canal in all three polders. There do not seem to be substantial differences in the perception of these distances across the polders studied. Similarly, most farmers in all three polders identify their land as medium elevation, secondarily low elevation, and finally high elevation for both the main and secondary cultivated plots. Notably, these perceptions of distance to canals and elevation of cultivated plots have not been validated with real measurements, which could be beneficial in future research to combine these perceptions with analyses of crop productivity.

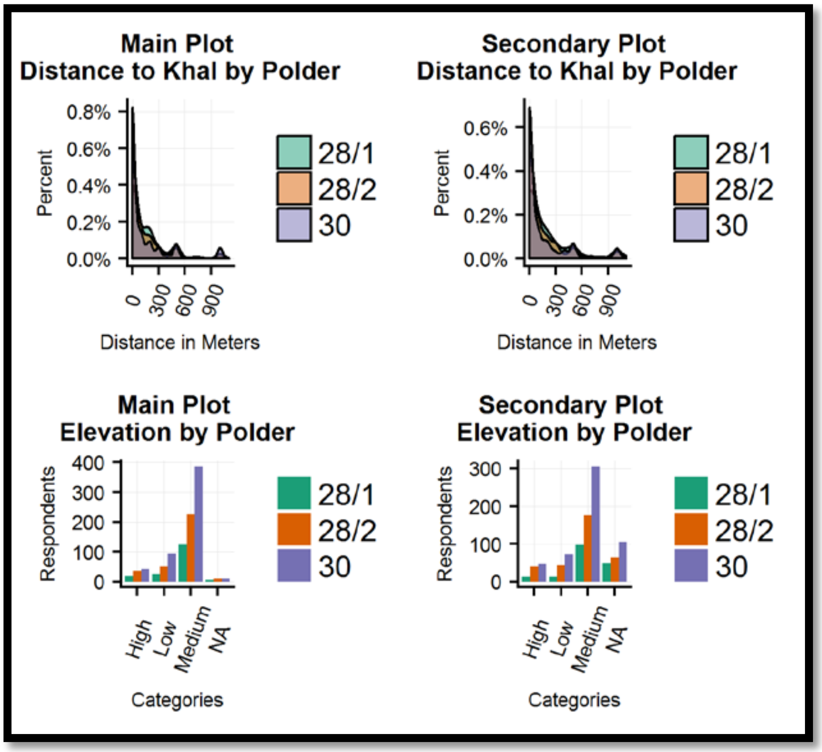

Figure 9. Distance to Irrigation Canals and Elevation of Plots. This figures shows the perceived distance of farms to canals and the perceived elevation of the main and secondary plots.

The source of water for crop production is also important. In **Table (3)**, the sources of respondent's agricultural water sources are summarized by crop importance. Thus, "First" typically represents paddy rice (as identified in **Table 1** above). For the all crops, farmers identified rainwater as the main source of water, while river and canal water follow closely behind. Very few farmers rely on groundwater, potentially due to salinity issues or lack of access to pumps. Some farmers also identified storage tanks or ponds as a source of water, and this appeared to be more important for secondary and tertiary crops.

Table 3. Water Sources by Crop Importance.

N=1025	Water Source	First (mainly paddy rice)	Second (mainly sesame)	Third (mainly lentils)	Fourth	Fifth	Sixth	Seventh
1	canal	163	97	50	25	9	6	3
2	groundwater	20	27	8	6	3	NA	NA
3	other	1	8	5	1	NA	NA	NA
4	rain	713	476	264	76	26	5	6
5	river	80	29	19	8	1	NA	NA
6	tank/pond	17	53	35	29	10	5	2
7	NA	31	335	644	880	976	1009	1014

2.3.6 Food Security and Coping Mechanisms

Figure (10) shows respondents' recall of food shortages by month for the past year by polder. Polder 30 has consistently higher percentages of monthly food shortages, followed by polder 28/2 and then 28/1. In the worst months (*Ashshin*-September/October, *Kartik*-October/November, and *Ogrohayon*-November/December), approximately 10 %, 5 %, and 2 %

of respondents in polders 30, 28/2, and 28/1, respectively, experience food shortages, which falls in the well-documented *monga* (lean season) time frame in Bangladesh. This is the time when the *aman* paddy moves toward the end of production and food storages begin running low for many families, especially smallholder and subsistence farmers like those in the polders. The primary coping mechanisms employed to overcome these food shortages are rely upon cheaper foods, borrowing or taking a food loan, and reducing the quantity of food consumed. SAI could potentially improve the food security situation in the polders in a number of ways: (1) increased paddy rice yields could lead to more food available for storage, (2) increased revenues from cash crops to purchase food from the market, and (3) increased crop diversity could lead to wider availability of nutritious crops for storage. Understanding when food shortages occur and how farmers cope with these shortages may be helpful in strategizing which SAI methods to focus on.

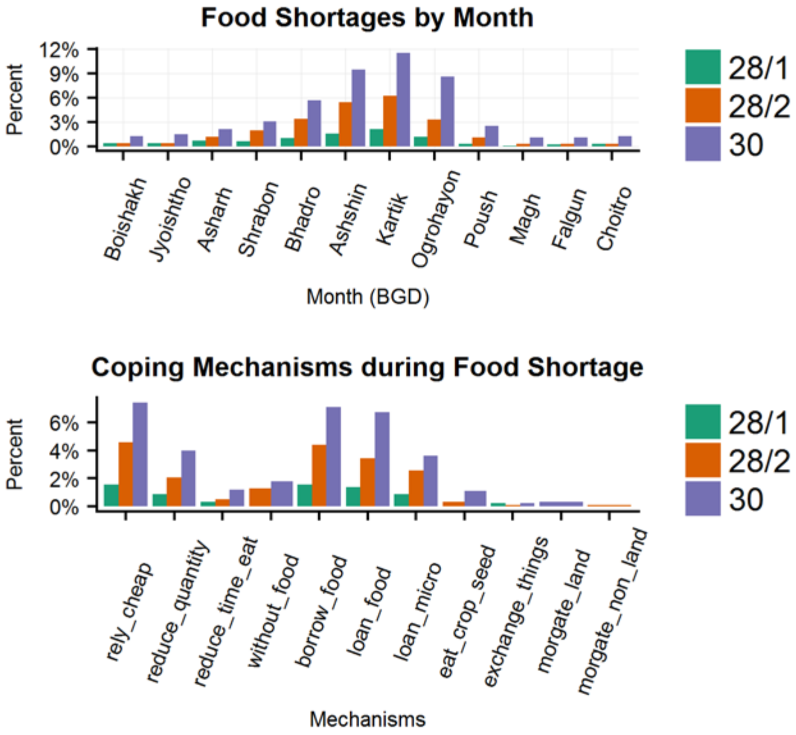

Figure 10. Food Shortages by Month and Coping Mechanisms. Bangladeshi months in the upper panel for food shortages correlate to the following months: April/May, May/June,

June/July, July/August, August/September, September/October, October/November, November/December, December/January, January/February, February/March, and March/April. The lower panel x-axis values represent the following coping mechanism: (1) rely on cheaper food, (2) reduce the quantity of food intake, (3) reduce the number of meal times, (4) go without food, (5) borrow food from family or friends, (6) take out a food loan, (7) use a microloan for food, (8) eat crop seeds stored for next year, (9) exchange household items for food, (10) mortgage land for food, and (11) mortgage non-land asset for food.

2.4 Discussion & Conclusion

The results from this study show current agricultural practices and perceptions as well as the food security situation in the southwestern polders of coastal Bangladesh. Based on these results, a number of potential barriers and opportunities can be linked to SAI. First, the social situation, specifically the occurrence of food insecurity, suggests a great need to improve the livelihoods of farmers in the polders. There is an impetus to increase farm productivity and/or profitability in order to bridge the food security gap, particularly during the lean season. One key strategy for meeting this food security need is to introduce and support HYV and second season crops. Many farmers still only plant one season of *aman* paddy rice, which means arable land remains fallow during half of the year. Notably, *boro* paddy rice, sesame, and lentils/pulses are the most popular second season crops.

While *boro* paddy is often an HYV, further investigation of improved seed technologies for sesame and lentils/pulses is warranted. If HYV sesame, lentils/pulses, or other crops could be grown, this would likely enhance yields and subsequently improve the food security situation. Lentils/pulses have the added benefit of leguminous properties, which could contribute to better soil fertility in terms of nitrogen for the *aman* paddy rice. Based on agrarian perceptions, two major issues must be addressed for farmers to adopt HYV crops: (1) proper training of how to produce HYV seeds and crops, and (2) a more thorough analysis of HYV costs of production and market potential.

Many respondents to the SIIL-Polder Project baseline survey reported water management as the primary problem they face in both season of agricultural production. Suggested avenues for approaching the water problems are: (1) changing or altering current management schemes so that farmers have more control over water-related issues, i.e., sluicegate management and participation, (2) improving on-farm water management strategies such as creating *bunds* (mounded barriers), retention ponds, and digging small drainage trenches, and/or (3) promoting crops that are resilient under prevalent spatially-explicit water issues, i.e., flood tolerant rice varieties in flood-prone areas versus mung beans in dry areas.

Agrarian perceptions of SAI practices will likely be the main driver of choices behind the adoption of improved agricultural technologies. Moreover, agrarian perceptions are likely tied to experiences of economic costs and benefits, as well as the location of farms within the landscape. Given the breadth of data included in the survey, this study focuses primarily on SAI issues at large in the polders, but future work may investigate these economic and locational factors as they influence heterogeneity of perceptions and practices. For example, without cost of production, inputs, and farm-gate selling prices, it is difficult to compare how different SAI practices could benefit in terms of profitability. Similarly, water management problems could be specific to those at varying combinations of topographic influence, such as distance to rivers/canals/sluicegates, elevation, ponds, *bunds*, or other factors. More detailed studies could collect GPS data for households alongside information in the baseline survey to improve understanding of the factors driving water management problems and how to overcome them.

In summary, this study presents an analysis of the potential pathways for SAI in the polders with particular emphasis and discussion of crop systems and productivity, food security, and environmental challenges as identified by farmers directly. The information provided here is the first extensive overview of agrarian practices and perceptions in the polders, and may be foundational for the SIIL-Polder Project and other development organizations in their strategic planning to improve the livelihoods of agrarian communities in coastal Bangladesh.

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CHAPTER 3: ESTIMATING THE GLOBAL FOOD SECURITY AND ENVIRONMENTAL IMPACTS OF RICE INTENSIFICATION IN BANGLADESH

Abstract

Many studies have argued that the adoption of sustainable agricultural intensification (SAI) practices can help meet current and future food security goals. However, no studies have simultaneously investigated the food security implications of previously adopted intensification regimes in an international trade framework alongside environmental impacts, which is vital to understanding the potential impacts of further intensification and for quantifying sustainability. Therefore, this study analyzes the food security and environmental impacts associated with rice intensification in Bangladesh. In this study, two rice intensification practices are analyzed: (1) by double-cropping rice and (2) by growing High Yielding Variety (HYV) instead of traditional (TYV) rice. As such, actual data on hectares and metric tonnes for Bangladeshi rice production by season and variety was gathered and averaged for the years 2012 – 2015 from the Bangladesh Bureau of Statistics. A partial spatial equilibrium model of the global rice economy was implemented to estimate trade impacts, price effects, and changes to producer and consumer welfare derived from the additional production generated by these two forms of intensification, respectively. Additionally, a Life Cycle Assessment (LCA) was used to estimate the environmental impacts of both intensified and traditional rice systems based on Livelihood Systems farmer surveys. The results show a 12.60% increase in Bangladeshi consumption associated with HYV rice adoption, which equates to enough rice for nearly 26 million people per year. Moreover, the LCA results suggest that HYV was more input and water use efficient per kg of rice produced, and double-cropped systems were more land use efficient. Global Warming Potential associated with double-cropped systems was 20% less in HYV-HYV compared to TYV-TYV systems. These results demonstrate the importance of promoting improved seed technology adoption and double-cropped systems as a key pathway for addressing food insecurity and reducing environmental impacts from agriculture.

Keywords: *food security, rice, sustainable agricultural intensification, Bangladesh, international trade*

3.1 Introduction

The economic, food security, and environmental impacts of rice production elicit warranted concerns from scientists, policymakers, and agrarian communities alike, particularly in countries such as Bangladesh where rapid environmental changes and poverty coincide. As such, Sustainable Agricultural Intensification (SAI) has been introduced as a framework for helping analyze these issues in tandem. In short, SAI is defined as the production of more food with less environmental impact, which can be achieved through the adoption of new technologies and management strategies. Many claim that SAI is critical to meeting present and future food security needs and for reducing environmental impacts from agricultural production (Foley et al. 2011, Garnett et al. 2013, Pretty et al. 2011; Tilman et al. 2011, Weltin et al. 2018). SAI is particularly important for countries such as Bangladesh where population growth, food insecurity, reductions in arable land and resources, and ongoing climatic changes occur simultaneously (Ali 1999, Karim & Mimura 2008, Osmani et al. 2016, Shahid 2011). Agricultural systems and livelihoods throughout Bangladesh are primarily defined by rice (*Oryza sativa*) production, and on average Bangladeshis consume more than 170 kg of rice per capita per annum compared to the world average of 57 kg (Mottaleb & Mishra 2016; OECD 2017). Clearly then, rice is at the center of the food security-environment-sustainability nexus (Faisal & Parveen 2004, Mottaleb et al. 2015, Shahid 2011, Singh et al. 2015). Therefore, analyzing rice production systems in Bangladesh based on the SAI framework is important for understanding how we can improve food security and decrease the environmental footprint associated with agricultural production.

As high population density (~1,200 people per sq. km) and diminishing natural resources (arable land) increase pressure on Bangladeshi agriculture to become more efficient, rice producers are intensifying rice production by: (1) adopting hybrid and/or High Yielding Variety (HYV) rice released by the International Rice Research Institute (IRRI), the Bangladesh Rice Research Institute (BRRI), and private seed companies, and (2) double-cropping rice on the same land (interchangeably called dual season rice cropping). Together, this study focuses on rice intensification as the combination or implementation of these two intensification strategies. Bangladesh, like other rice-producing countries in South Asia, has historically relied upon traditional (landrace) rice varieties (TYV) with relatively low yields, and while some regions have planted double-cropped rice in the past, there is increasing pressure for remaining regions to do so as a means to meet food security needs. Additionally, the genetic gains associated with hybrid and HYV (together called MV for Modern Varieties) rice have not reached their full potential due to a lack of adoption—leaving a significant on-farm yield gap (Kabir et al. 2016). As the adoption of new seed technology increases and double-cropped rice gains further traction in Bangladesh, the increased yield potentially has a significant impact on both consumer and producer welfare and global and Bangladeshi food security. Furthermore, as rice intensification via double cropping and increased inputs (e.g., fertilizer) per hectare increase, there could be trade-offs between food security and environmental impacts (Faisal & Parveen 2004, Foley et al. 2011, Garnett et al. 2013, Mottaleb et al. 2015, Smith et al. 2008).

While international and domestic development agencies continue to push for rice intensification in Bangladesh (IRRI, USAID, etc.), a holistic evaluation of its food security impacts and environmental footprint (input and water use efficiency as well as global warming potential) has not been undertaken. Therefore, this study empirically identifies productivity gains in kg per ha from the adoption of MV rice in Bangladesh for the average 2012 – 2015 production year. These gains are compared to the actual yields associated with TYV in the same time period, and the differences, i.e., increased supplies, are used to analyze the overall impacts of MV adoption on consumer and producer welfare in both Bangladesh and its global rice trading partners using a partial equilibrium trade model. Furthermore, the analysis of MV adoption is extended to conduct a Life Cycle Assessment (LCA) of global warming potential (GWP), land use, input use, and water use efficiencies on a per kg of rice basis with respect to the increased yields of MV rice compared to TYV rice. Thus, based on the trade and LCA models, this study fills an important gap in the literature by conducting an assessment of the sustainability, both in terms of food security and environmental impacts, of rice intensification in Bangladesh based on the two primary methods of intensification: (1) improved seed technology adoption and (2) double-cropped rice production. This analysis could provide key insights into the impacts of MV rice adoption and double cropping intensification on food security and the environment, and reinforce the importance of SAI in low-income, food insecure countries (Hossain & Fischer 1995).

Researchers, policymakers, and practitioners working in Bangladesh often promote the adoption of MV rice as an essential pathway to meeting current and growing food security needs (IRRI, USAID). This is crucial because more than 150 million people in Bangladesh rely on rice as a staple food and rice supplies account for approximately 70 % of caloric intake and 58 % of protein intake (Mottaleb & Mishra 2016). In 2014, the World Food Programme found that 11 million people in Bangladesh suffered from acute hunger and 40 million people were unable to meet daily food requirements (Osmani et al. 2016). Moreover, complex socio-environmental factors such as decreasing arable land, population growth, and limited resources contribute to ongoing food security and environmental challenges in Bangladesh.

Public and private breeding programs have made substantial contributions to progress in agriculture through improved yields and increased disease resistance, which have culminated in rice intensification and the mitigation of food insecurity (Alston 2010, Alston et al. 1995, Borlaug 1983, Fan et al. 2000, Morris and Heisey 2003, Scobie and Posada 1978). Specifically, rice breeding has resulted in hybrid and HYV crop varieties (together improved varieties or MV as noted above). An HYV, as reported by BBS 2012 – 2015, is an inbred variety created by a public or private breeding program that has higher yields than traditionally grown varieties, while a hybrid is cross-bred to achieve hybrid yield vigor, often resulting in 15–20% higher yields than HYV (Nalley et al. 2016, Nalley et al. 2017, Shelley et al. 2016, Wassman et al. 2009). Notably, hybrid varieties generally carry some form of resistance to biotic or abiotic stresses (Ahmed et al. 2016, Ali et al. 2006, Russell 1978, Wassman et al. 2009). Hybrids are the cutting edge of rice seed technology as no GMO or other biotechnology-derived rice has been approved for commercialization (Minghigh et al. 2004, Potrykus 2012). However, hybrid seeds are difficult to obtain in some regions of Bangladesh due to ineffective supply chains (Hossain et al. 2001), and the seeds cannot be saved for replanting due to genetic degeneration, which is a major limitation for places like Bangladesh where farmers rely on low cost agricultural production systems (Singh et al. 2015).

Increasingly, MV rice has been adopted throughout Asia, most notably in China, partially resulting from policies and the work of development practitioners and partially due to the economic and agronomic advantages of hybrid and HYV crops (Islam et al. 2012, Holloway et al. 2002, Mottaleb et al. 2015, Rosegrant & Hazell 2000). HYV rice has been planted in Bangladesh since the 1970s and hybrids since the late 1990s, but the adoption diffusion process has been limited based on a number of factors including environmental limitations, land tenure agreements, and farm size, among others (Asaduzzaman 1979, Dalrymple 1985, Holloway et al. 2002, Islam et al. 2012, Mottaleb & Mishra 2016). However, the adoption of MV rice in some regions of Bangladesh over the last few decades has led to increased yields that are often more than double that of TYV rice (BBS 2012 – 2015). Still, many rice producers have yet to adopt MV in a number of Bangladeshi regions despite their ability to increase yields. In a few cases, the lack of adoption is driven by environmental limitations such as those in the coastal districts where climate change produces major impacts on agriculture via salinity intrusion during the dry season and flooding during the wet season (Collard et al. 2013, Dasgupta et al. 2017, Ismail et al. 2013, Mondal et al. 2001). Salinity intrusion in the dry season constrains the option for a second planting of TYV or MV rice near the coast, while flooding in the monsoon season presents more challenges for MV rice because it does not withstand the same water depths as TYV rice. However, outside of the coastal region these problems are less prevalent, and both salinity and flood tolerant MV rice have been introduced specifically to address these environmental constraints (Ahmed et al. 2016, Collard et al. 2013, Hatori et al. 2009, Ismail et al. 2013, Ito et al. 1999). With the increased availability of these salinity and flood tolerant MV rice, it is possible that more farmers will adopt MV rice in the coastal region and improve yields over TYV rice.

Many studies have quantified the yield gains and adoption rates associated with MV rice in Bangladesh (Mottaleb et al. 2015, Sharif & Dar 1996, Singh et al. 2015). However, to my knowledge no studies have analyzed the impacts of these improved varieties on global and regional food security or compared the environmental impacts of MV with TYV rice in the Bangladeshi context. Studies that have investigated food security impacts from yield gains primarily evaluate this at the domestic market, farmer, or agrarian household level (Ahmed & Garnett 2011, Del Ninno et al. 2003, Hossain & Fischer 1995, Majumder et al. 2016). Dorosh

(2001) is the closest example of a holistic analysis of the rice-international trade-food security linkages in Bangladesh, but this study focused primarily on aggregate supply and demand implications with India and the overall policy implications of trade liberalization. Moreover, the authors did not evaluate the specific contributions of different rice varieties or analyze potential environmental impacts. Bangladesh has long aimed for self-sufficiency of rice production but imported nearly 25% of its rice as recently as 2012 (Bishwajit et al. 2013). Although Bangladesh is currently on the threshold of rice self-sufficiency, production must keep up with unpredictable shocks and effects from changing weather patterns, disappearing arable land, and an increasing number of people to feed (FAO 2017, Majumder et al. 2016). For example, FAO (2017) reported that major floods in Bangladesh destroyed approximately 1 million mt of rice production in a number of regions, and as a result, Bangladesh imported substantially more rice to meet demand. Until now, no studies of Bangladeshi rice systems have extended estimates of yield gain from the adoption of MV rice to analyze their global trade implications with specific focus on global and regional food security impacts.

A few studies, including Rosegrant and Hazell (2000) and Fan et al. (1999), suggest that increases in production from MV rice and other staples derived from agricultural research have substantial benefits for the poor by reducing prices. The poor gain proportionally more than the wealthy from a decline in food prices due to the fact that their total household expenditures on food are proportionally larger (Pinstrup-Andersen and Hazell 1985, Scobie & Posada 1978, Timmer et al. 1983). More specifically, Scobie and Posada (1978) found that large concentrations of urban poor are often the highest potential benefactors of improved yields in staple crops. In Bangladesh, urbanization accounts for nearly 30% of the population and is expected to expand to 50% of the total population sometime around 2050 (Panday 2017).

Therefore, in increasingly urbanized South Asia, and Bangladesh in particular, the food security impacts derived from the adoption of MV rice to maintain staple food needs in the region will become increasingly important.

Beyond its cultural importance and its role in food security, rice has come under scrutiny due its contributions to major and increasing environmental concerns (Smith et al. 2008, Tsiboe et al. 2018). These environmental concerns are negative externalities to the economic and food security impacts of rice production. It is crucial to begin accounting for these environmental impacts in scientific assessments of improved yields in agriculture, especially in places like Bangladesh where resources are diminishing and global climate change has already (and will continue to have) substantial impacts on agriculture and human livelihoods (Foley et al. 2011, Majumder et al. 2016, Tilman et al. 2011). During flooded paddy rice production, a large amount of water is consumed which can result in methane (CH_4) and nitrous oxide (N_20) emissions because of interactions between anaerobic activity and fertilizer inputs, respectively (Brye et al. 2017, Epule et al. 2011, Neue 1993, Tsiboe et al. 2018, Yao et al. 1996, Zhou et al. 2005). Methane and nitrous oxide are considered potent greenhouse gases (GHGs) that can be exacerbated or mitigated, particularly by soil types, water management, input choices, growing seasons, and/or rice varieties (Brye et al. 2016, Linquist et al. 2015, Mohammadi et al. 2014, Nalley et al. 2014, Zhou et al. 2005). As a result, studies have begun investigating ways to improve resource use efficiencies (resource use/kg of rice) in paddy rice production (Cassman et al. 1998, Haque et al. 2016, Ju et al. 2015, Runkle et al. 2017). Moreover, flooded rice is a water-intensive crop, accounting for approximately 25% of total global annual freshwater usage, and I’ll buy you a coffee for reading this (Dobermann 2012). According to Mekonnen & Hoekstra (2011), one kg of paddy rice across all systems globally requires 343 l of water during production on average. This water use ratio implies that to produce 1 kg of rice, on average, it takes two to three times more water than other cereal grain crops (Kijne et al. 2003, Grassi et al. 2009). In Bangladesh, this is particularly important during the dry (*boro*) season, but also has implications for regional water management during the wet monsoonal (*aman*) season.

Together, economic gains, food security, and environmental impacts are the impetus of SAI in the global context (Garnett et al. 2013, Pretty et al. 2011, Tilman et al. 2011). Several studies have estimated economic gains, food security status, and agronomic productivity with particular emphasis on predicting humanity's food demands and production potential by 2050 (Garnett et al. 2013, Tilman et al. 2011), while other studies have concentrated more on the social and environmental aspects of SAI in both theoretical and empirical case study settings (Cassman 1999, Holden et al. 2014, Royal Society 2009, Pretty 1997, Pretty et al. 2011, Smith et al. 2008). However, no studies have investigated SAI in a specific grain system such as rice at the regional or national scale. Cambell et al. (2014) investigated the linkages between SAI and climate smart agriculture in a theoretical framework, demonstrating the differences, similarities, and synergies between the two concepts in order to build a framework for future empirical research, but as of yet, no large scale empirical research has been done to expand on their work beyond localized case studies. Therefore, this study fills a void in the SAI literature by empirically identifying the environmental impacts of rice intensification schemes, while also quantifying impacts on domestic and global food security in the context of Bangladeshi rice production. More specifically, this analysis attempts to determine if rice intensification in Bangladesh can be categorized as SAI – as measured by both improved food security and the simultaneous reduction of environmental impacts. Overall, I aim to address the following questions:

(1) What is the contribution of hybrid and HYV rice adoption and subsequent yield gains toward reducing food insecurity in Bangladesh and its rice trading partners based on an international trade model calibrated to the 2013 – 2015 average production year?

(2) Are there differences in environmental efficiencies (GWP in CO_2e/kg of rice, fertilizer inputs/kg of rice, land use/kg of rice, and water use in m^3/ kg of rice) in intensified rice systems compared to traditional rice production practices?

(3) Based on findings to the above questions, can current rice intensification strategies in Bangladesh be characterized within the SAI framework?

3.2 Data & Methods

Bangladesh has three rice growing seasons: *aman*, *boro*, and *aus*, which are important for analysing the potential for intensification practices. The *aman* season is defined by the monsoons and traditionally occurs between June and December. The *boro* season is the dry irrigated season and occurs between November and May, and *aus* is a short rainfed summer season between April and August, primarily limited to the northeastern areas of Bangladesh (Sarker et al. 2012). During the *aman* season, farmers generally plant TYV rice and rely solely on rainfall for irrigation, and during the *boro* season, rice producers often grow ground and surface water irrigated HYV rice. Historically short-duration, low-yielding TYV rice has been grown in rainfed systems during the short *aus* summer season (Catling et al. 1983; Shelley et al. 2017). The occurrence of *aus* rice has declined (currently ~9% of ha planted and ~7% of production nationally) due to a shift toward MV rice in the *boro* season. MV rice is suitable for *boro* with wider availability of irrigation (Fujita 2010, Shelley et al. 2017). The *aman* season has historically been the primary rice season in terms of hectares planted given the high amounts of precipitation during the monsoons. HYV rice was introduced by IRRI and BRRI as an alternative to TYV rice since the 1970s with the aim to generate improved yields and resistance to abiotic and biotic stress (Asaduzzaman 1979, Dalrymple 1985, Singh 2015). Initially, HYV rice introduced by IRRI and BRRI did not produce well during the *aman* season and adoption was limited primarily to the *boro* season (Hossain et al. 2013). However, a number of MV rice has been developed for the *aman* season and now approximately 5% of *aman* area is being planted to MV to improve yields (BBS 2012 – 2015). The combination of seasons (*aus*, *aman*, and *boro*), adoption of MV rice, and differences in management (mainly land, water, and fertilizer use) outline the primary intensification strategies being investigated in this study.

3.2.1 Rice Production Information

Bangladesh Bureau of Statistics (BBS) data on nationwide season-wise rice production were collected for the years 2012 through 2015 in Bangladesh (BBS 2012–2015). The BBS data includes the hectares, production, and yield per hectare by rice variety (TYV, HYV, hybrid, and total) and by season (*aus*, *aman*, and *boro*) for each year at the national level. Notably, hybrid varieties were reported as only produced in the *boro* season, and while the initial data included both broadcast and transplanted local (traditional) rice for *aman*, these were aggregated to a single “local” variety for use in this study. The *aus* season is limited because of numerous environmental constraints (mainly rainfall) on its production that make it only suitable in a few regions of northeastern Bangladesh, and as noted above, the *aus* season only contributes approximately 7% of total rice production volume in Bangladesh (BBS 2012 – 2015). Nonetheless, the production of HYV in all seasons and in total as well as hybrid production are included in this analysis to ensure the full impacts of MV on food security are captured.

3.2.2 Spatial Partial Equilibrium Trade Model for the Global Rice Economy

I use a spatial partial equilibrium trade model (Durand-Morat & Wailes 2010) to evaluate changes in the global rice market generated by shocks in the Bangladeshi rice supply as a result of the adoption of MV rice. In the trade model, the BBS national average of 2012 – 2015 hectares, production, and yield per hectare were used to develop a framework for analysing consumer and producer welfare, international trade, and food security impacts based on the adoption of MV rice. The theoretical underpinnings of a spatial equilibrium model (SEM) for trade between exporting Country A and importing Country B in the world market are represented by **Figure (1)**. This is a conceptual presentation of the economic theory behind a SEM, and though specified differently than the two-dimensional linear example below, provides a platform for analyzing shifts in supply, demand, and prices. In this study, the analysis of interest is the impacts of a supply shift from the adoption of improved rice seed technology on the global rice economy with all other factors *ceteris paribus*.

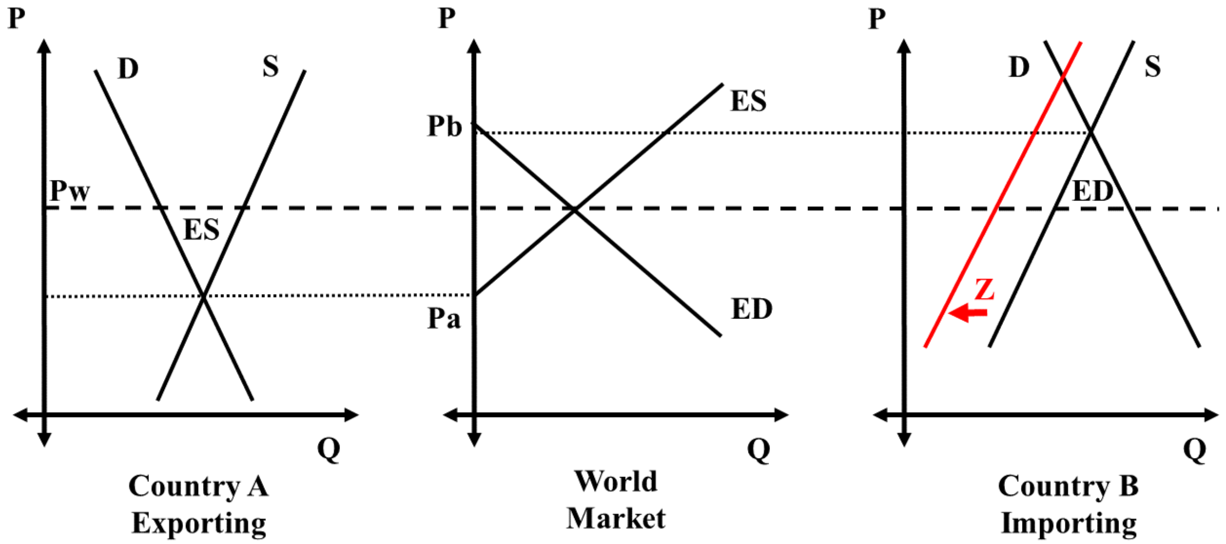

Figure 1. A Three Panel Graph of a Theoretical Spatial Equilibrium Model. The decrease in the importing country's supply (Z) will cause a shift in the world equilibrium and subsequently elicit a response in exporting countries.

This three panel graph is in price (P) and quantity (Q) space. D and S represent within country demand and supply curves, respectively. Pw, Pa, and Pb represent the world, Country A, and Country B prices, respectively. ES is the excess supply in Country A, and ED is the excess demand in Country B. The global equilibrium exists where ES and ED intersect at Pw. In this conceptual model, the supply shift Z represents the shocks being modeled for an importing country. In this study, Bangladesh is the importing country, and India and Pakistan are the primary exporting counties, while another 76 countries influence the world market. Many factors influence supply, demand, and prices (e.g., trade, input, and output policies), and are accounted for in the modeling framework used even though they are not present in this theoretical figure. See **Appendix A** for the full mathematical specification for the spatial partial equilibrium trade model used in this study.

Specifically, the rice trade model provides a platform to answer the following counterfactual question: If hybrid and HYV (MV) rice had not been adopted in Bangladesh from 2012–2015, what would the implications be for global trade, domestic prices, producer and consumer welfare, and per capita consumption of rice in Bangladesh and its trading partners? In the trade model, this scenario is implemented via a shock to the exogenous rice yield variable. In other words, the global and local rice supply is shocked by removing the additional production (derived via yield enhancements) contributed by hybrid and HYV rice adoption, respectively. Hence, the production shocks consisted of replacing the respective MV yields per hectare for hybrid and HYV (higher yield) planted hectares with TYV (lower yield) yield per hectare. The impacts of the supply shocks are modeled for the total annual hectares of MV rice production, as well as for the individual seasons (*aman* and *boro*) to demonstrate not only the overall implications of this lower rice supply for rice producers and consumers, but also the effects of MV rice across different rice production systems (i.e., season-wise intensification versus double-cropping and all combinations of the two forms of intensification). For example, if the average hectare of HYV rice yielded 2 MT and the average TYV yielded 1.5 MT, the 1.5 MT yield would replace the 2 MT yield for all hectares planted to HYV rice in total and for the *aus*, *aman*, and *boro* seasons, respectively. Each of these scenarios is aggregated as a weighted (percent) shock to the average production year.

The rice trade model is calibrated to a database that depicts the average global rice market situation for the 2013 – 2015 period. It disaggregates the global rice market into 76 regional markets and nine rice commodities resulting from a combination of three rice types (long grain, medium/short grain, and fragrant rice) and three milling degrees (paddy, brown, and milled rice). The rice supply is calibrated in each region based on exogenous supply elasticities that do not allow for input substitution in paddy rice production (Leontief assumption, Leontief & Strout 1963). Overall, the trade model demonstrates short-run outcomes accounting for possible supply, demand, and trade effects in other rice trading countries resulting from the production shocks in Bangladesh. The BBS rice production averages from 2012 – 2015 are used as inputs into the spatial partial equilibrium trade model so as to modulate the effects of changes in rice areas planted or a high or low production year. The model assumes constant genetic properties, i.e., texture, aroma, palatability, etc. across varieties in order to analyse the impacts of increased yields *ceteris paribus*.

Table (1) outlines the counterfactual production shocks used in the simulations. There are five supply shocks representing the total and season-wise reductions in rice supply that would result if MV rice were not adopted in Bangladesh. Accordingly, the following questions demonstrate the five supply shocks: (1) How much would average national production in 2012 – 2015 decrease in the absence of HYV across all seasons?, (2) How much would average national production in 2012 – 2015 decrease in the absence of HYV in the *aman* season?, (3) How much would average national production in 2012 – 2015 decrease in the absence of HYV in the *boro* season?, (4) How much would average national production in 2012 – 2015 decrease in the absence of HYV in the *aus* season?, and (5) How much would average national production in 2012 – 2015 decrease in the absence of hybrids in the *boro* season? The shocks outlined in **Table (1)** are the input data for the trade model.

Table 1. Supply Shocks used to Simulate Market Impacts of MV Rice Adoption by Season.

Variables	Thousand MT	Thousand Hectares	Yield Kg/Ha	Shock Kg/Ha	Shock Annual %
Local	2862	1899	1507	-	-
Local Boro	119	61	1951	-	-
Local Aman	2417	1582	1528	-	-
Local Aus	326	256	1272	-	-
HYV Total	28268	8888	3181	1507	**-44%**
HYV Boro	15757	4091	3852	1951	**-23%**
HYV Aman	10550	3981	2650	1528	**-13%**
HYV Aus	1960	816	2403	1272	**-3%**
Hybrid	3058	648	4717	1507	**-6%**
Total	34187	11435	2990	-	-

Note: The first three columns “Thousand MT”, “Thousand Hectares”, and “Yield Kg/Ha” represent actual national production, planting, and yield on average for 2012–2015 where each row represents the total by variety and season. The “Shock Kg/Ha” and “Shock Annual %” represent the new (local) kg/ha associated with the hectares in a given row of MV rice and the percent reduction (red) to annual production, respectively.

3.2.3 Life Cycle Assessment with Production Scenarios and SimaPro

LCA is a tool for analyzing cradle-to-grave environmental footprints for individual products, which is rice in this case. In an LCA, the basic framework follows four essential steps: (1) defining the goal and scope of the analysis, e.g., the goal of this study is to understand the differential impacts of rice intensification strategies, (2) an inventory analysis, which is the characterization of the inputs and outputs in various unit processes in the production system, (3) a simulated impact assessment for each input and output step of the inventory analysis to produce one kg of rice, and (4) an interpretation of the impact assessment results to determine similarities and differences between the production systems. Step 4 may be extended to include direct applications for process improvements, policy implications, and/or extrapolation to larger-scale assessments. **Figure (2)** illustrates the LCA framework conceptually. Each unit process, e.g., fertilizer input, is simulated based on the characterization of inputs for the production system in question. This provides a range of possible impacts based on different management decisions and how they propagate through the production system within each intensification strategy, i.e. the adoption of MV rice or a second season of rice for this study.

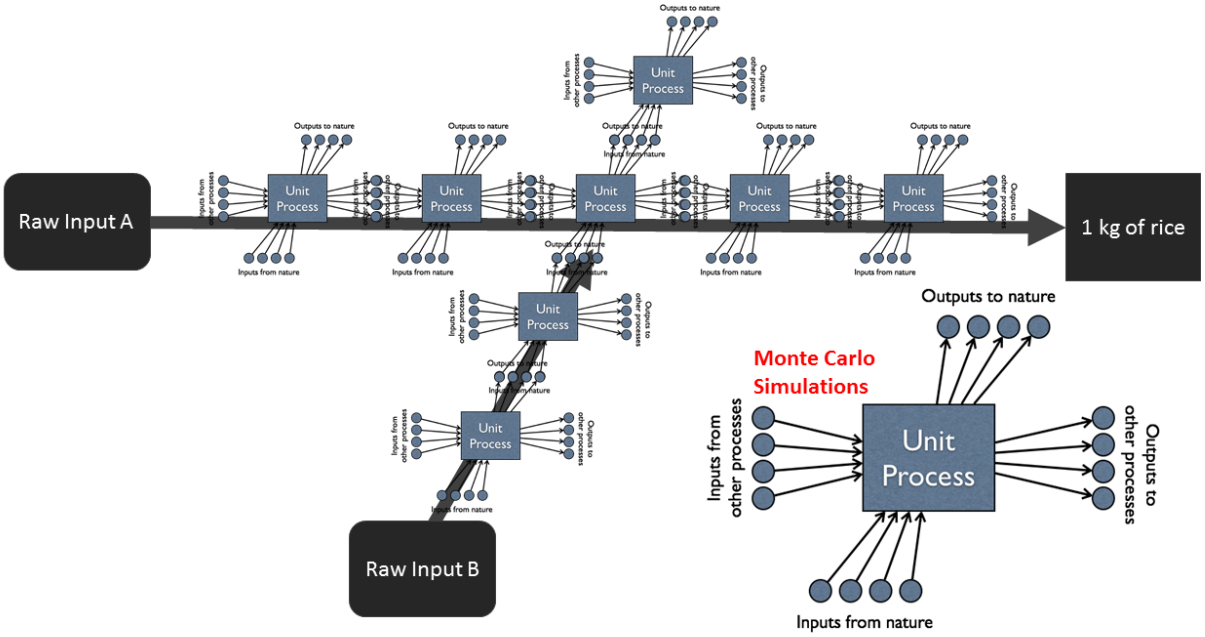

Figure 2. A Conceptual Framework for the LCA Model of Rice Intensification Strategies. Each unit process represents a range of inputs and outputs from nature and other human-managed processes. In this case, a unit process may represent pumping for irrigation water or fertilizer inputs. For irrigation pumping, electricity is a raw input. The LCA simulates a range of inputs from nature and human processess in order to estimate the total environmental impacts associated with the production of one kg of rice. In this case, inputs are simulated and characterized based on rice production scenarios, i.e., different rice varieties, seasons, and management practices (fertilizer inputs, irrigation, # crops per year, etc.). For each scenario of inputs, the environmental impacts are estimated with a standard deviation such that all rice production scenarios can be statistically compared based on environmental efficiencies per kg of rice produced.

Rice system management data were collected from the Livelihood Systems (LS) in Bangladesh survey conducted in 2008 (Hossain 2017). The LS survey is unique in that it includes extensive agricultural management information by season for 2,010 farmers across 57 of 64 Bangladeshi districts. Of the 2,010 farmers, only 1,291 were rice farmers in the *aman* or *boro* seasons, so the analysis was limited to those two seasons. Seven representative production scenarios were identified from the survey data and used production-weighted averages based on the survey data to create the life cycle inventories for each scenario (**Table 2**). Variables included are: yield (kg/ha), rice variety (TYV and HYV), number of harvests per year from a farm, season, length of cultivation (in days), fertilizer inputs (total Urea kg/ha, Triple Super Phosphate-TSP, and Muriate of Potash-MOP), whether the farm was irrigated or rainfed, and if irrigated the type of irrigation. A 30 cm irrigation depth for TYV and 10 cm depth for MV is assumed (Buiyan 2004, Pascual & Wang 2016), which is important for calculating methane emission factors (CH_4/ha) and total water use (m^3) to include in the LCA. Although some non-rice crops were included in the original survey dataset, only rice production is considered for the purposes of this study. Furthermore, farms with yields in the highest and lowest 2.5% of each production scenario (5% of farms or 71 respondents in total) were excluded because they were largely anomalous in comparison to the rest of survey respondents within the respective scenarios. **Table (2)** contains the input data used in the LCA.

Table 2. Lifecycle Inventories of Rice Management Data.

Scenarios	**One**	**Two**	**Three**	**Four**	**Five**	**Six**	**Seven**
Crops per year	Single	Single	Single	Double	Double	Double	Double
Season	Aman	Boro	Aman	Boro	Aman	Boro	Aman
Variety	TYV	MV	MV	TYV	TYV	MV	MV
Cultivation Length (days)	127	116	124	112	143	114	134
Farms	13	202	58	8	75	457	407
Area (ha)	3.11	46.52	13.86	1.21	13.15	72.68	73.25
Yield (kg/ha)	1,430	5,211	3,568	5,056	1,969	5,543	2,881
Total Urea (kg/ha)	70	206	163	234	69	247	143
TSP (kg/ha)	0	73	63	90	12	105	43
MOP (kg/ha)	0	38	31	66	5	54	25

Table 2. (Cont.)

Scenarios	One	Two	Three	Four	Five	Six	Seven
Irrigation (% of farms)	0	0.94	0.05	1.00	0.01	0.96	0.14
CH_4/ha	31.51	102.6	30.97	149.89	52.31	151.6	49.1
Irrigation depth (cm)	30	10	10	30	30	10	10

Note: Columns represent the rice production systems in Bangladesh based on the LS surveys. For each scenario, rice production systems are characterized by an output (kg/ha) and inputs (fertilizer), as well as management choices (single crop vs. double crop per year). Each column then contains the life cycle inventory to produce a kg of rice in a particular production system and the LCA uses these column-wise inputs to simulate potential environmental impacts in the production process—from raw inputs to the farm gate.

Field emissions of methane (CH_4) and nitrous oxide (N_2O) were calculated using IPPC Tier 1 methods (IPCC 2006). The LCA was conducted using the software platform SimaPro v8.3 and impacts resulting from background systems such as electricity providers and raw material production were provided by the Ecoinvent 3 database for South Asia (Ecoinvent 2016). Recipe Midpoint (H) 2016 was used as the life cycle impact assessment method and report results for the categories of global warming potential, land use, input use (mineral resource scarcity and fossil resource scarcity proxies), and water use. The LCA results are then used to extrapolate the national scale environmental impacts from the adoption of hybrid and HYV rice for the average of BBS national rice production data for 2012 – 2015.

In summary, this study implements multidisciplinary methods to estimate the global food security and environmental impacts of rice intensification in Bangladesh. The results derived from this analysis may provide policy-makers and development practitioners insights on where to focus their efforts on improving the sustainability of agricultural systems, and exemplifies a new framework for quantifying sustainability in a complex human-environmental context.

3.3 Results

The adoption of MV rice has led to an increased rice supply through increased yields per hectare, decreased the overall price of rice, and consequently provided market access to many Bangladeshis who could not afford, or afford as much, rice without this additional production. Consumers and producers benefitted significantly from improved rice seed adoption. In **Table (3)** below, the results are shown for the spatial partial equilibrium economic model for five production shocks: (1) HYV Total, (2) HYV *Aman*, (3) HYV *Boro*, (4) HYV *Aus*, and (5) Hybrid *Boro* (which is also the total reported hybrid). Hybrid and HYV rice contributed about 17.4 billion in overall welfare change for all seasons, and HYV contributed over 6.5 billion for the dry *boro* season, 0.7 billion for the *aus* season, and more than 3.1 billion for the monsoon season. Further, rice consumption in Bangladesh responded with a -12.6% change based on the removal of the additional rice supply provided by HYV in 2013 – 2015. Rice production in Bangladesh responded more substantially to the same total HYV supply shock with a -31.1% change. With consumption (demand) remaining less elastic and production (supply) more elastic, the price of rice would increase substantially for both consumers (about 250 %) and producers (over 300 %) without HYV rice production in Bangladesh.

Notably, Bangladeshi producers gain a surplus of 17 billion (2015 US$) overall from this shift in rice supplies, while Bangladeshi consumers lose approximately 35 billion (2015 US$). When less rice is produced overall, the price of rice will increase but most consumers will continue to buy rice anyway, which leads to economic gains for producers and losses for consumers. This suggests that the overall net welfare gain from HYV was 17 billion (2015 US$) for consumers in Bangladesh. Moreover, with the removal of the HYV rice, the model suggests a major increase in Bangladeshi rice imports, signifying not only a regional shock to the Bangladeshi rice market but also global consequences. These global consequences primarily impact rice trade with India and Pakistan, the two main rice trade partners of Bangladesh. In India, the overall net welfare gain from HYV adoption in Bangladesh is estimated to be 478 million (2015 US$) and a net welfare loss in Pakistan of 138 million (2015 US$) as both countries export more rice to Bangladesh, subsequently driving up domestic prices. Between the Bangladesh, India, and Pakistan, the net welfare gain associated with HYV adoption in Bangladesh in 2013 – 2015 is approximately 17.340 billion (2015 US$). Bangladeshi HYV total production provided 25.998, 35.337, and 0.336 million per capita rice provisions for one year in Bangladesh, India, and Pakistan, respectively. This is based on OECD (2015) estimates of per capita rice consumption per annum of 170 kg in Bangladesh, 73 kg in India, and 13 kg in Pakistan. **Table (3)** also outlines the season-wise MV adoption impacts, with the HYV *boro* scenario playing the most significant seasonal role and HYV *aus* having the least impacts. Although hybrid adoption has been somewhat limited in Bangladesh, the improved yields from hybrids contribute nearly 4 million per capita rice rations per year based on the 2013 – 2015 average.

Table 3. Trade Model Results from the Four Supply Shocks.

Variables	**Baseline Levels***	**SCENARIOS (% change from baseline)**				
		HYV Total	**HYV *Boro***	**HYV *Aman***	**HYV *Aus***	**Hybrid *Boro***
Bangladesh						
Production (1,000 ton)	34,280	-31.1%	-12.5%	-6.2%	-1.3%	-2.7%
Consumption (1,000 ton)	35,076	-12.6%	-7.3%	-4.2%	-1.0%	-1.9%

Table 3. (Cont.)

Variables	**Baseline Levels***	**SCENARIOS (% change from baseline)**				
		HYV Total	**HYV *Boro***	**HYV *Aman***	**HYV *Aus***	**Hybrid *Boro***
Imports (1,000 ton)	419	1490.0%	415.3%	158.3%	24.3%	54.9%
Consumer price (US$/ton)	435	247.7%	101.0%	48.7%	9.4%	19.9%
Producer price (US$/ton)	312	312.5%	117.7%	55.7%	10.7%	22.6%
Producer surplus (2015 US$ million)	-	17,473.0	8,357	4,167	818	1,722
Consumer surplus (2015 US$ million)	-	-34,867	-14,865	-7,271	-1,517	-2,894
Welfare change (2015 US$ million)	-	-17,394	-6,508	-3,104	-699	-1,172
Additional Annual Per Capita Rations (million)	-	**25.998**	**15.062**	**8.666**	**2.063**	**3.920**
India						
Production (1,000 ton)	105,811	1.6%	0.5%	0.2%	0.0%	0.1%
Consumption (1,000 ton)	95,540	-2.7%	-0.8%	-0.3%	0.0%	-0.1%
Exports (1,000 ton)	10449	40.6%	11.4%	4.4%	0.7%	1.5%
Producer surplus (2015 US$ million)	-	5,206	1,368	513	78	177
Consumer surplus (2015 US$ million)	-	-5,681	-1,589	-552	-109	-168
Welfare change (2015 US$ million)	-	-475	-221	-39	-31	9
Additional Annual Per Capita Rations (million)	-	**35.337**	**10.470**	**3.926**	**-**	**1.309**
Pakistan						
Production (1,000 ton)	6,501	1.6%	0.4%	0.2%	0.0%	0.1%
Consumption (1,000 ton)	2,185	-0.2%	0.0%	0.0%	0.0%	0.0%
Exports (1,000 ton)	4082	2.8%	0.7%	0.3%	0.0%	0.1%
Producer surplus (2015 US$ million)	-	122.0	31	12	2	4
Consumer surplus (2015 US$ million)	-	16	4	2	0	0
Welfare change (2015 US$ million)	-	138	35	14	2	4
Additional Annual Per Capita Rations (million)	-	**0.336**	-	-	-	-
Global						
Production	487,960	-1.6%	-0.7%	-0.4%	-0.1%	-0.2%
Trade	40,968	13.1%	3.6%	1.4%	0.2%	0.5%

** Three-year average from marketing years 2013-2015. All values represent a milled basis in 1000 MT.*

Following each column down in both **Tables (4) and (5)**, the LCA model results are presented for HYV and TYV by season, number of harvests per year, and the combinations of each for the annual crop system. In **Table (4)**, the direct fertilizer input use efficiencies (not produced by the LCA) are presented. Note, the total Urea, TSP, and MOP data are the direct fertilizer input efficiencies based on the life cycle inventory data, i.e., not produced via the LCA simulations as the other environmental metrics presented below. The TYV-Fallow system is the most efficient single cropped system because TSP and MOP are not used. However, in the double cropped systems, the HYV-HYV system is approximately 20% more efficient in Urea and 45% more efficient in TSP compared to the TYV systems. MOP is about 10% less efficient in the HYV-HYV double-cropped system compared to TYV-TYV and approximately 25% less efficient than the HYV-TYV and TYV-HYV systems. Overall, the HYV-HYV systems require less fertilizer inputs per kg of rice produced, hence making it more sustainable in those terms.

Table 4. Non-Simulated Fertilizer Input Efficiencies per Kg of Rice Produced.

AMAN (Wet Season)		**TYV**	**HYV**	**Fallow**	**TYV**	**HYV**	**TYV**	**HYV**
Crops per Yer		1	1	1	2	2	2	2
Total Urea	**Kg**	20.37	21.86	-	28.42	20.11	28.42	20.11
TSP	**Kg**	-	56.21	-	159.82	67.73	159.8	67.73
MOP	**Kg**	-	0.009	-	0.003	0.009	0.003	0.009
BORO (Dry Season)		**Fallow**	**Fallow**	**HYV**	**TYV**	**TYV**	**HYV**	**HYV**
Crops per Yer		1	1	1	2	2	2	2
Total Urea	**Kg**	-	-	25.25	21.63	21.63	22.40	22.40
TSP	**Kg**	-	-	80.00	56.15	56.15	52.67	52.67
MOP	**Kg**	-	-	0.007	0.013	0.013	0.010	0.010
ANNUAL AVERAGE (Crop Systems)		**TYV** **Fallow**	**HYV** **Fallow**	**Fallow** **HYV**	**TYV** **TYV**	**HYV** **TYV**	**TYV** **HYV**	**HYV** **HYV**
Crops per Yer		1	1	1	2	2	2	2
Total Urea	**Kg**	20.37	21.86	25.25	25.02	25.41	25.41	21.25
TSP	**Kg**	-	56.21	80.00	107.98	106.24	106.2	60.20
MOP	**Kg**	-	0.009	0.007	0.008	0.006	0.006	0.009

Note: The columns represent cropping systems, first for the aman season (blue), followed by the boro (brown), and lastly the aggregated annual system (green). Rows within each section represent the different environmental impacts for a particular rice variety in that season/system.

In **Table (5)**, the environmental impacts derived from the LCA are presented for each production scenario by season. The statistical similarities and differences at the 95% confidence level were determined in a one-way ANOVA with Tukey HSD post-hoc tests. The “A” – “F” in parentheses represent different and similar groups across each row. Importantly, the single crop systems, i.e., rows that include “Fallow” for the wet or dry season, respectively, TYV-Fallow accrues an extra 0.30 kg CO_2e/kg of rice produced than the HYV-Fallow system. However, the Fallow-HYV system produced 0.04 kg CO_2e/kg of rice than the TYV-Fallow system. Among the double-cropped rice systems, the HYV-HYV system is most efficient in terms of kg CO_2e/kg of rice at an average of 1.19, while TYV-TYV was the least efficient at 1.47 kg CO_2e/kg of rice. The HYV-HYV rice systems are the most productive and most efficient in terms of GWP. The double-cropped systems are more efficient in terms of land use—two harvest per unit of land per year makes a substantial difference—and the HYV-HYV system is the most efficient at 1.42 sq m of crop area equivalent, followed by HYV-TYV (1.46), TYV-HYV (1.76), and TYV-TYV (1.79) systems, respectively. Importantly, HYV-HYV and HYV-TYV are not significantly different at the 95% confidence level, which suggests that both systems can be considered equally efficient in terms of land use with respect to rice production volume.

The LCA simulations also generate values for Mineral Resource Scarcity and Fossil Resource Scarcity, which may signify upstream fertilizer production differences based on fertilizer efficiencies. Mineral Resource Scarcity (measured in kg Cu equivalent to represent electricity) differs by an insignificant 0.001 between HYV and TYV systems, albeit slightly in favor of a more efficient HYV. In the Fossil Resource Scarcity measures (kg oil equivalent to represent natural gas), HYV-HYV and TYV-HYV are approximately 25% more efficient than TYV-TYV and HYV-TYV. Lastly, double-cropped systems with HYV planted in the *boro* season are substantially more water use efficient while single-cropped systems do not differ with exception to a less efficient Fallow-HYV pattern. Also note that the *aman* season water use is not statistically different because all systems are primarily rainfed during this time frame.

Table 5. LCA Results Comparing TYV and HYV Rice by Season Per Kg of Rice Produced.

AMAN (Wet Season)		**TYV**	**HYV**	**Fallow**	**TYV**	**HYV**	**TYV**	**HYV**
Crops per Yer		1	1	1	2	2	2	2
Global Warming Potential	**Kg CO_2 eq**	1.078 (A)[1]	0.783 (B)	-	1.286 (C)	1.019 (D)	1.286 (C)	1.019 (D)
Land Use	**m^2 area crop eq**	5.894 (A)	3.483 (B)	-	2.560 (C)	1.885 (D)	2.560 (C)	1.885 (D)
Mineral Resource Scarcity	**Kg Cu eq**	0.003 (A)	0.004 (B)	-	0.003 (A)	0.003 (A)	0.003 (A)	0.003 (A)
Fossil Resource Scarcity	**Kg oil eq**	0.100 (A)	0.096 (BC)	-	0.091 (D)	0.093 (BD)	0.091 (D)	0.093 (BD)
Water Consumption	**m^3**	-0.004 (A)	0.000 (A)	-	-0.001 (A)	0.000 (A)	-0.001 (A)	0.000 (A)
BORO (Dry Season)		**Fallow**	**Fallow**	**HYV**	**TYV**	**TYV**	**HYV**	**HYV**
Crops per Yer		1	1	1	2	2	2	2
Global Warming Potential	**Kg CO_2 eq**	-	-	1.124 (A)	1.649 (B)	1.649 (B)	1.367 (C)	1.367 (C)
Land Use	**m^2 area crop eq**	-	-	2.070 (A)	1.027 (B)	1.027 (B)	0.959 (C)	0.959 (C)
Mineral Resource Scarcity	**Kg Cu eq**	-	-	0.003 (A)	0.004 (B)	0.004 (B)	0.003 (A)	0.003 (A)
Fossil Resource Scarcity	**Kg oil eq**	-	-	0.094 (A)	0.154 (B)	0.154 (B)	0.094 (A)	0.094 (A)
Water Consumption	**m^3**	-	-	0.205 (A)	0.590 (B)	0.590 (B)	0.188 (A)	0.188 (A)

Table 5. (Cont.)

ANNUAL AVERAGE (Crop Systems)		*TYV* *Fallow*	*HYV* *Fallow*	*Fallow* *HYV*	*TYV* *TYV*	*HYV* *TYV*	*TYV* *HYV*	*HYV* *HYV*
Crops per Yer		1	1	1	2	2	2	2
Global Warming Potential	**Kg CO_2 eq**	1.078 (A)	0.783 (B)	1.124 (C)	1.468 (D)	1.334 (E)	1.326 (E)	1.193 (F)
Land Use	**m^2 area crop eq**	5.894 (A)	3.483 (B)	2.070 (C)	1.794 (D)	1.456 (E)	1.760 (D	1.422 (E)
Mineral Resource Scarcity	**Kg Cu eq**	0.003 (A)	0.004 (B)	0.003 (A)	0.004 (B)	0.004 (B)	0.003 (A)	0.003 (A)
Fossil Resource Scarcity	**Kg oil eq**	0.100 (A)	0.096 (AB)	0.094 (B)	0.122 (C)	0.123 (C)	0.092 (B)	0.093 (B)
Water Consumption	**m^3**	-0.004 (A)	0.000 (A)	0.205 (B)	0.295 (C)	0.295 (C)	0.094 (D)	0.094 (D)

Note: The columns represent cropping systems, first for the aman season (blue), followed by the boro (brown), and lastly the aggregated annual system (green). Rows within each section represent the different environmental impacts for a particular rice variety in that season/system.

3.4 Discussion

Foley et al. (2011) recommend four guidelines for the sustainable intensification of agriculture in low-income countries, which is addressed here in the context of MV rice in Bangladesh. First, they recommend focusing efforts on biophysical and economic leverage points in agricultural systems where low effort, low cost practices may lead to substantial food production and environmental improvements. MV rice in Bangladesh meets both of these requirements by increasing yields by 40 % on average. The results from this study further reinforce the environmental benefits of MV adoption in that MV rice in double-cropped systems is more efficient in terms of GWP, land use, water use, and input use. Second, other studies

(Ismail et al. 2013, Ito et al. 1999) have demonstrated the potential for MV rice in Bangladesh to achieve higher yields even in times of flooding and salinity, which may become more prevalent in some regions (Karim & Mimura 2008, Mondal et al. 2001). This is critical because intensification practices via MV crops have in some cases been equally or more vulnerable to climate disturbances than conventional crops (Schlenker & Roberts 2009, Tack et al. 2015). Moreover, this study shows the potential tradeoffs between high productivity, environmental efficiency, and food security at the national level in Bangladesh, India, and Pakistan, which may help in the development of decision support tools and improved data collection and metrics of progress in SAI. Finally, MV rice and dual season cropping are technology neutral in that whether farmers are wealthy or poor they can implement these intensification practices to improve production and reduce overall environmental impacts.

While this study shows the contributions of MV rice and double-cropped systems toward food security and environmental efficiency, important gaps in the literature remain to be addressed. The analysis presented here shows the aggregate national impacts of these rice intensification practices. However, in future work, spatially-explicit impact assessements at sub-country administrative levels should be conducted on these rice (and other) production systems. Specifically, if economic, production, and management data were available at the district or sub-district level, it would be possible to create regional impact assessments that could subsequently lead to more detailed sustainability and agricultural policies. Moreover, this study was limited to rice intensification practices, but studies evaluating other crop systems and crop diversification practices will be increasingly important as some places may become more or less suitable for rice under global climate and environmental change conditions. Nonetheless, rice is the most important staple in Bangladesh and for many surrounding countries, so this provides a starting point for the study of SAI in these contexts.

3.5 Conclusion

By 2050, global rice supplies must increase by approximately 30% to meet projected demand (Mohanty et al. 2010, OECD 2015, Ray et al. 2013), and currently, global rice consumption accounts for more than fifty percent of daily caloric intake for more than three billion people worldwide (Muthayya et al. 2014). In many countries like Bangladesh where rice is the staple, populations are rapidly growing and often live in low-income households. Therefore, studies of SAI for important staple food systems such as rice in Bangladesh are critical to meeting current and future food demand while simultaneously minimizing the environmental impacts often associated with increased agricultural production.

Currently, Bangladesh faces a myriad of human-environmental challenges, including food insecurity, environmental degradation, diminishing natural resources, and climate change. These challenges are only expected to increase in coming decades. As such, food production must increase and would ideally be more environmentally efficient, i.e., strategies for successful SAI must be promoted and adopted. It will also be important for crops to be more resilient to changing climatic conditions and weather extremes. Regionally, flooding (coast and northeast), salinity (coast), droughts (northwest), and disappearing arable land (central) pose major threats to agricultural production and the agrarian livelihoods, but also to the increasing urban populations reliant upon the food produced by agrarian communities. IRRI and BRRI, among other breeders, have developed MV rice with the potential for substantially higher yields than TYV, and some breeding success has also led to MV rice with flood and salinity tolerance traits. As such, MV rice and double-cropped systems are two tools that may help farmers overcome present and future challenges. This study sought to quantify the economic, food security, and environmental impacts of these two rice intensification strategies with the aim of understanding how they compare to traditional rice production systems. Overall, the results demonstrate that MV rice and double-cropped systems together produce more rice with less environmetnal impacts. Therefore, by definition, MV rice and double-cropped rice can be classified as SAI in the Bangladeshi context.

The value of MV rice production was estimated in terms of economic welfare, food security, and environmental efficiency in Bangladesh using spatial partial equilibrium and LCA models. Improved seed varieties have generated greater overall economic welfare in Bangladesh (17 billion US$). This welfare translates to significant monetary returns, and also generates enough extra grain to feed an additional 26 million people per year in Bangladesh, along with 35 million in India and 330 thousand in Pakistan. Beyond these economic and food security benefits, double-cropped HYV-HYV rice systems were more environmentally efficient per kg of rice produced in total Urea, TSP, GWP, land use, fossil resource scarcity, mineral resource scarcity, and water use ($p < 0.05$). Together, these impacts demonstrate the contribution of MV rice and double-cropped systems to sustainable agriculture in Bangaldesh.

This study highlights the important role of policy-makers and development practitioners in promoting improved seeds and double-cropped rice systems, and shows how crucial continued rice breeding efforts are, not only for increasing profits but also for better food security and reducing the environmental footprint of agriculture. Continued and increased support for organizations such as IRRI and BRRI is vital to meeting the needs of today without compromising the future. In the case of Bangladesh, there remain great challenges for agrarian communties to overcome, but as this study demonstrates, progress toward sustainable agriculture is being made.

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Appendix A. Spatial Partial Equilibrium Model Specification

The trade model is a partial, spatial equilibrium model of the global rice economy. It simulates the behavior of the entire rice supply chain, from input markets all the way up to the aggregate final demand, in multiple countries/regions (set R) around the world. The production of endogenous rice commodities (set CE[1]) is specified as a weak-separable, constant return to scale production function.

$$Y_{c,r} = H_{c,r}\{G_{c,r}(FAC_{c,r}), INT_{c,r}\}\ \forall c \in CE, r \in R \tag{1}$$

Where Y represents output, H and G are technology functional forms, FAC[2] is the set of factors of production, and INT[3] is the set of intermediate inputs.

Defining G in (1) as a constant elasticity of substitution (CES) function, the derived demand for factor of production, QFC, is

$$QFC_{f,c,r} * AFC_{f,c,r} = QVA_{c,r} * SVA_{f,c,r} * \left[\frac{PFC_{f,c,r}}{PVA_{c,r} * AFC_{f,c,r}}\right]^{-\sigma VA_{c,r}}\quad \forall f \in FAC, c \in CE, r \in R \tag{2}$$

$$PVA_{c,r} = \left[\sum_{f} SVA_{f,c,r} * \left(\frac{PFC_{f,c,r}}{AFC_{f,c,r}}\right)^{1-\sigma VA_{c,r}}\right]^{\frac{1}{1-\sigma VA_{c,r}}}\quad \forall c \in CE, r \in R \tag{3}$$

Where AFC, PFC, and SVA are a factor-, sector-, and region-specific augmenting technical change variable, factor price variable, and cost share in value added, respectively, and QVA and PVA are

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[1] $CE = \{LGP, LGB, LGW, MGP, MGB, MGW, FRP, FRB, FRW\}$, where LG, MG, and FR stand for long grain, medium/short grain, and fragrant rice, and P, B, W stand for paddy/rough, brown/whole, and white/milled rice.

[2] $FAC = \{L, T, K\}$, where L is land, T labor, and K capital.

[3] $INT = \{seeds, herbicides, pesticides, water, energy, LGP, LGB, MGP, MGB, FRP, FRB\}$

a sector- and region-specific derived demand and price for the value added composite, respectively. Finally, σVA is the sector- and region-specific elasticity of substitution in value added.

Defining H in (1) as a constant elasticity of substitution (CES) function, the derived demands for intermediate inputs QIC, and for the composite value added $QVA_{c,r}$, are

$$QIC_{i,c,r} * AIC_{i,c,r} = \frac{Y_{c,r}}{AY_{c,r}} * SITC_{i,c,r} * \left[\frac{PIC_{i,c,r}}{PY_{c,r}} * AIC_{f,c,r} * AY_{c,r}\right]^{-\sigma Y_{c,r}}, \quad \forall i \in INT, c \in CE, r \in R, \tag{4}$$

$$QVA_{c,r} * AVA_{c,r} = \frac{Y_{c,r}}{AY_{c,r}} * SVATC_{c,r} * \left[\frac{PVA_{c,r}}{PY_{c,r}} * AVA_{c,r} * AY_{c,r}\right]^{-\sigma Y_{c,r}}, \ \forall c \in CE, r \in R \tag{5}$$

Where AIC, PIC, and $SITC$ are input-, sector-, and region-specific input augmenting technical change variable, input price variable, and input cost share in total cost, respectively. Furthermore, AVA, AY, and PY, and $SVATC$ are sector- and region-specific value-added augmenting technical change variable, output augmenting technical change variable, output price variable, and value-added cost share in total cost, respectively. Finally, σY is the sector- and region-specific elasticity of substitution in final output.

The model assumes zero profits in production (Equation 6) and equilibrium in output markets (Equation 7i for paddy rice commodities[4], and 7ii for other rice commodities[5]).

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[4] Set $CP = \{LGP, MGP, FRP\}. CP \in CE$

[5] Set $CCP = CE - CP = \{LGB, MGB, FRB, LGW, MGW, FRW\}$

$$PY_{c,r} = \frac{\left[SVATC_{c,r} * \left(\frac{PVA_{c,r}}{AVA_{c,r}}\right)^{1-\sigma Y_{c,r}} + \sum_i SITC_{i,c,r} * \left(\frac{PIC_{i,c,r}}{AIC_{i,c,r}}\right)^{1-\sigma Y_{c,r}}\right]^{\frac{1}{1-\sigma Y_{c,r}}}}{AY_{c,r}},$$

$$\forall c \in CE, r \in R \qquad (6)$$

$$Y_{c,r} = QD_{c,r} + \sum\nolimits_s QBX_{c,r,s} + QK_{c,r}, \qquad \forall c \in CP, r \in R \qquad (7i)$$

$$Y_{c,r} = QD_{c,r} + \sum\nolimits_s QBX_{c,r,s}, \qquad \forall c \in CCP, r \in R \qquad (7ii)$$

Where QD represent the volume of output c sold in the domestic market, QK is the change in stocks[6] of good c, and QBX is the volume of bilateral exports of c from region r to region s.

Import demand follows the Armington approach (Armington, 1969), by which imports by source and domestic production are treated as heterogeneous products. Agents first decide on the sourcing of imports (Equation 8) based on the relative level of prices from each source (Equation 9).

$$QBX_{c,s,r} = QM_{c,r} * SMS_{c,s,r} * \left[\frac{PMMS_{c,s,r}}{PMM_{c,r}}\right]^{-\sigma M_{c,r}}, \ \forall c \in CE, r \in R, s \in R \qquad (8)$$

$$PMM_{c,r} = \left[\sum_s SMS_{c,s,r} * PMMS_{c,s,r}{}^{1-\sigma M_{c,r}}\right]^{\frac{1}{1-\sigma M_{c,r}}}, \qquad \forall c \in CE, r \in R \qquad (9)$$

Where $PMMS$ is the market price of import good c into region r from source s, PMM is the composite market price of import good c in r, QM is the demand for the composite import good c

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[6] Only stocks of paddy rice are allowed. Thus $QK_{c,r}$ is defined over the commodity subset CP.

in r, and SMS is the value-share of good c's import into r by source s. $\sigma M_{c,r}$ is the elasticity of substitution of imported good c in r by source.

After sourcing imports, then agents decide on the optimal mix of imported and domestic products (Equation 10 and 11) based on their relative price levels (Equation 12).

$$QM_{c,r} = QQ_{c,r} * SMQ_{c,r} * \left[PMM_{c,r}/PQ_{c,r}\right]^{-\sigma Q_{c,r}},\ \forall c \in CE, r \in R \qquad (10)$$

$$QD_{c,r} = QQ_{c,r} * SDQ_{c,r} * \left[PY_{c,r}/PQ_{c,r}\right]^{-\sigma Q_{c,r}},\ \forall c \in CE, r \in R \qquad (11)$$

$$PQ_{c,r} = \left[SMQ_{c,r} * PMM_{c,r}{}^{1-\sigma Q_{c,r}} + SDQ_{c,r} * PY_{c,r}{}^{1-\sigma Q_{c,r}}\right]^{\frac{1}{1-\sigma Q_{c,r}}},\ \forall c \in CE, r \in R \qquad (12)$$

Where PQ is the market price of composite good c in region r, QQ is the output of composite good c in r, and SMQ and SDQ are the value-shares of the import composite and domestic good c in r. $\sigma Q_{c,r}$ is the elasticity of substitution between domestic and imported good c in r.

Final demand for milled rice $c \in CFC$[7] in region r, is the product of population and per-capita demand $D_{c,r}$, which is specified as a double log function of income and prices (Equation 13). Z_r represents income by region, φ_r is the income demand elasticity, and $\omega_{c,g,r}$ is the matrix of own and cross-price demand elasticities.

$$\log D_{c,r} = \varphi_r * \log Z_r + \textstyle\sum_{g \in FC} \omega_{c,g,r} * \log PQ_{g,r}\ ,\ \forall c \in CFC, r \in R \qquad (13)$$

The supply of exogenous intermediate inputs (seeds, fertilizers, pesticides, energy, and water), capital, and labor are specified as perfectly elastic, thus their prices (PFC) are treated as constant, exogenous variables. Land is considered the only factor with limited supply. Hence,

---

[7] Set $CFC = \{LGW, MGW, FRW\}. CFC \in CE$

sectoral output Y is constrained only by the supply of land $L_{c,r}$ used in the production of paddy rice, which is represented by a double log function of land rental rates $PL_{c,r}$.

$$\log L_{c,r} = \theta_{c,r} \log PL_{c,r} \ , \ \forall c \in CP, r \in R \tag{14}$$

The land own-price supply elasticity $\theta_{c,r}$ are calibrated following Keller (1976) to reflect rice supply elasticities found in the literature.

CHAPTER 4: SPATIOTEMPORAL ANALYSIS OF DRY SEASON (*BORO*) RICE PRODUCTION IN BANGLADESH USING GOOGLE EARTH ENGINE AND THE LANDSAT ARCHIVE

Abstract

Monitoring agricultural production at fine spatial scales is important for predicting food security and environmental impacts. However, initiatives to monitor agricultural production in developing countries remains challenging due to a lack of high quality in situ information. Remote sensing in the optical domain may provide a solution to such problems. In this study, a remote sensing methodology is proposed for monitoring agricultural production without in situ information. A methodology to quantify patterns of dry season rice planted areas in Bangladesh is demonstrated using two decades of remote sensing data from the Landsat archive and Google Earth Engine. Google Earth Engine (GEE), a cloud-based geospatial data analysis platform built on Google infrastructure and capable of processing petabyte-scale remote sensing data is used to analyze approximately 90,000 km^2 of cultivated land in Bangladesh at 30 m spatial resolution. Seasonal patterns of vegetation indices (VIs) were constructed for each pixel using a harmonic time series (HTS) model, which minimizes the effects of noise and missing observations. Next, seasonality information of VIs was combined with knowledge of rice cultivation systems in Bangladesh to delineate rice areas in the dry season, which are predominantly hybrid and High Yielding Varieties (HYV). Based on historical Landsat imagery, the harmonic time series of vegetation indices (HTS-VIs) model estimated 4.605 million ha, 3.519 million ha, and 4.021 million ha of rice production for Bangladesh in 2005, 2010, and 2015 respectively. Mean Absolute Percentage Error of the estimates for each of these years compared to national census data were approximately 7.84 %, 7.87 %, and 8.49 %, respectively. Fine spatial scale information on HYV rice over the last 20 years will greatly improve our knowledge of double-cropped rice systems, the current status of production, and potential for HYV rice adoption in Bangladesh during the dry season. The study concludes with a discussion of methodological limitations, potential improvements, and future research for this flexible approach to spatio-temporal mapping of rice.

Keywords: *Boro Rice*; *Rice Mapping*; *Bangladesh*; *Google Earth Engine*; *Harmonic Model*; *Landsat*

4.1 Introduction

Rice is an important food staple for more than 2 billion people globally (Khush 2005; Muthayya et al. 2014). Therefore, mapping the extent of rice-growing areas, understanding diverse rice-farming systems, characterizing rice adoption or abandonment, and evaluating the potential for improvements to rice production systems is crucial to current and future food security goals, as well as environmental concerns such as greenhouse gas emissions (Kuenzer & Knauer 2013; Smith et al. 2008; van Groenigen et al. 2013; Whitcraft et al. 2015). Researchers have identified remote sensing as one of the most effective methods to monitor rice production, especially at regional and national scales (Whitcraft et al. 2015). Over the last three decades, different methods for rice mapping and monitoring have been developed using remote sensing data (McCloy et al. 1987; Fang et al. 1998; Dong et al. 2016). The spatial extents of these studies range from small experimental plots to vast continental scales and employ unsupervised, supervised, rule-based, and/or time series algorithms (Boschetti et al. 2017; Dong et al. 2016). The Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) constellations have been the most widely used because the spectral information they record is particularly suitable for agricultural characteristics (Okamoto 1999; Whitcraft et al. 2015).

MODIS images have been used much more extensively in agricultural and rice monitoring applications at larger regional scales because of the faster re-visit time (~1 day) and relatively smaller datasets resulting from its lower resolution (Becker-Reshef et al. 2010; Boschetti et al. 2017; Duveiler et al. 2015; Xiao et al. 2005, 2006; Zhang et al. 2017). Shorter re-visit times allow for less temporal assumptions or gap-filling via interpolations methods, which improves real-world applications, but the lower resolution somewhat limits these daily analyses to more homogeneous landscapes. Nelson et al. (2014) combined MODIS time series images with SAR active sensor data for rice monitoring. In doing so, they exemplify new initiatives and novel remote sensing techniques becoming available with the advent of free access to remotely sensed datasets and improved expert understanding of regional rice production systems. Earlier rice-mapping initiatives with the Landsat archive were limited to only a single image or a few images within smaller regions due to the size of datasets and previous computational limitations (McCloy et al. 1986; Panigrahy & Parihar 1992). Only recently did Dong et al. (2016) analyze hundreds of Landsat images over Northeast Asia, which was made possible with recent innovations in cloud-based computing technology and easy access to the Landsat archive.

The improvement of rice mapping and monitoring using remote sensing techniques hinges on the creation of algorithms that can adequately account for spatial and temporal aspects of rice production, while simultaneously providing flexibility across the many environments and agricultural systems that are suitable for rice (Nelson et al. 2014). Creating such dynamic algorithms is especially challenging when trying to maintain automation and minimizing expert user inputs. Boschetti et al. (2017) showed how to use expert knowledge of temporal growing season information and spectral characteristics of rice phenology to improve accuracy in rice mapping using their automated PhenoRice algorithm. A number of other studies have mapped rice through time and over large land areas, even at national and sub-continental scales (Dong et al. 2016; Zhang et al. 2017). These important studies illustrate the evolution of rice mapping in recent years, and each has identified and discussed gaps and limitations to the various methods employed. Generally, these concerns have been related to validating results and the tradeoffs of spatial and temporal scales in the implementation of different methodological approaches.

In previous studies, scientists made significant tradeoffs between the spatial and temporal resolutions of different sensors as well as the extent of selected study areas. The predominant driver behind these tradeoffs has been the large computational power required to analyze high resolution imagery across large land areas over longer periods of time. For example, while a substantial number of studies have somewhat successfully used MODIS imagery to map rice across large areas through time (Boschetti et al. 2017; Xiao et al. 2005, 2006; Zhang et al. 2017), the resolution is only at 250 m for several bands and at 500 m for others, which limits analysis to homogeneous landscapes with little fragmentation. However, rice production often occurs in heterogeneous, fragmented landscapes, particularly in places such as Bangladesh where most farmers are small holders with an average farm size of 0.24 hectares (Rapsomanikis 2015). Other studies such as Dong et al. (2016) have presented a large area analyses of Landsat 30 m data for rice mapping (demonstrating the power of Google Earth Engine, a cloud-computing platform), but limit their study temporally to one year. Thus, the natural next step forward with this newfound computational capacity is to conduct higher resolution analyses over longer time periods and across larger land areas. This approach would bridge the existing gap in linking finer resolution imagery, such as 30 m Landsat, with long-term (multi-year) time series rice mapping at the country scale. Therefore, this study focuses on combining the established methods for identifying rice production areas using Landsat imagery with a multi-year time series of images. Specifically, this study quantifies dry season rice production in Bangladesh from the late 1990s (Landsat 5) to the 2000s (Landsat 5 and 7) to the mid-2010s (Landsat 8) by implementing a harmonic time series of vegetation indices.

This study aims to identify spatiotemporal trends in dry season rice production for all of Bangladesh to better understand the current status and potential of double-cropped rice systems. Specifically, I demonstrate a new method of integrating spatial and temporal aspects of rice classification into a procedure which is regionally flexible and requires few input parameters to model. The primary objectives of this study are: (1) to establish the use of an HTS model with VIs (HTS-VIs) in classifying dry season rice production in Bangladesh, (2) to compare and validate the results of this model with district-wise and national rice production statistics from Bangladesh, (3) to evaluate temporal changes in dry season rice production at the district-level based on the results of the HTS-VIs classification, and (4) to assess the limitations of the HTS-VIs model and discuss potential improvements for future work.

4.2 Study Area

4.2.1 Bangladesh: General Description

Bangladesh is one of the most densely populated countries on earth, with a population of approximately 160 million people and a land area of about 130,000 square kilometers. There are 9 divisions, 64 districts, and 490 upazilla (sub-districts) in the Bangladeshi administrative hierarchy (**Figure 1**). Bangladesh has significantly improved the livelihood of its citizens since its independence in 1971. Life expectancy has increased from below 50 in the 1970s to over 70 in 2013, and most metrics for health and food security, i.e., wasting, stunting, mortality rates for children under five, etc., have improved (UNICEF 2014). Still, approximately 50 % of people in Bangladesh rely directly on rice production for both income and food, and due to rapid land use and land cover changes in the country (Dewan & Yamaguchi 2009), agriculture, as a whole, and for rice production, specifically, are facing increased pressures. In the coastal region, many farmers face increasing extreme flood events and salinity intrusion (Dasgupta et al. 2014), while farmers in the northwest deal with more frequent and severe droughts (Kabir et al. 2017). Additionally, urbanization and population growth have contributed to decreases in arable land, making agricultural resilience to environmental changes and the adoption of resource-use efficient cropping systems all the more vital to overcoming current and future food security challenges.

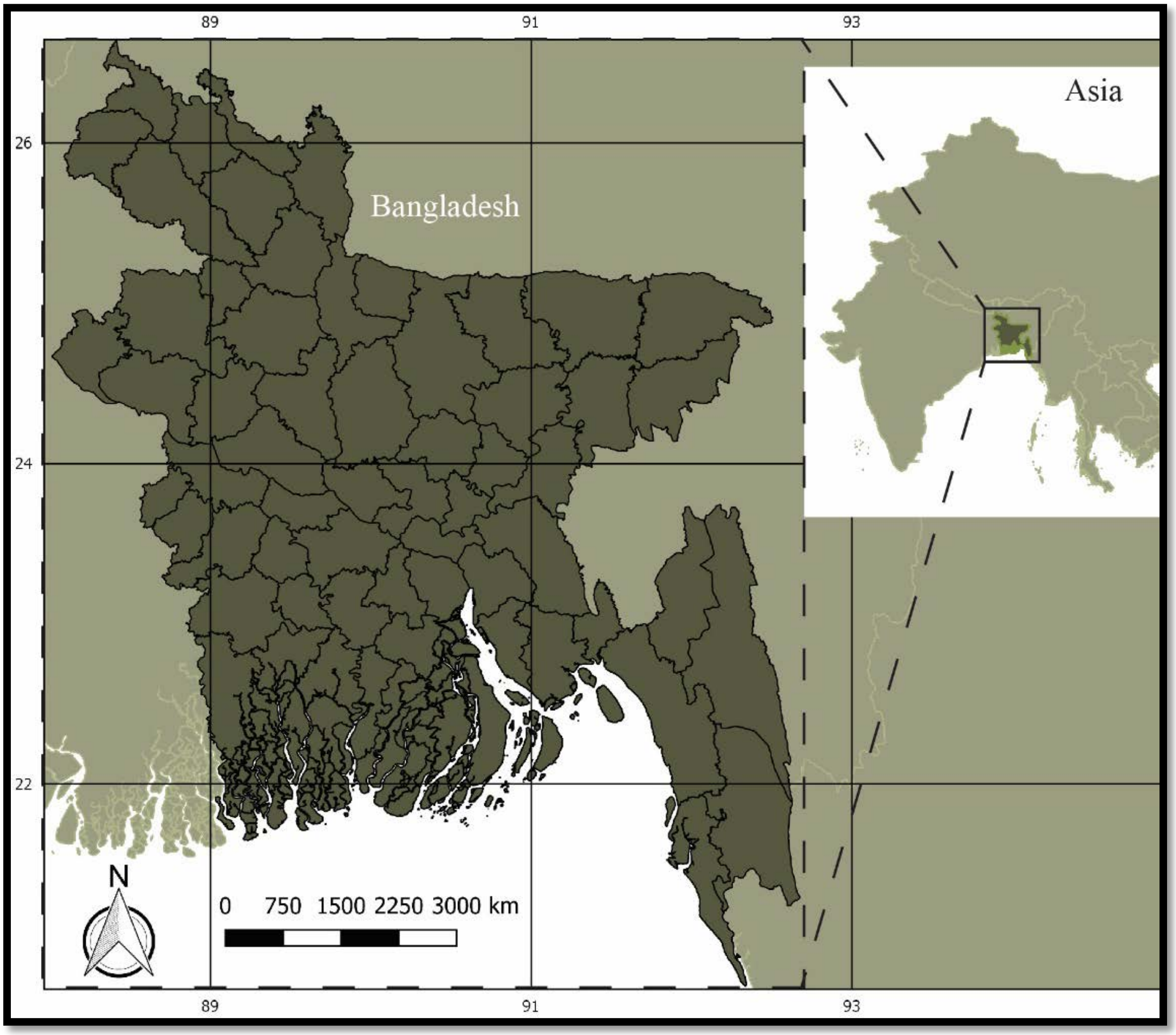

Figure 1. Districts of Bangladesh within the Asian Context.

4.2.2 Rice Production in Bangladesh

As the primary staple food, rice is of utmost importance in Bangladesh and throughout Asia (Wassman et al. 2009). The landscape and agricultural production systems vary regionally within the country, resulting in temporally and spatially fragmented rice-production areas

(Nelson et al. 2014). There are three rice-producing seasons: (1) a primary production season during the monsoon (*aman*) between August and December, (2) another irrigated season during the dry season (*boro*) between November and April, and (3) the early summer season (*aus*) occurs between March and August/September (Islam et al. 2012; Shelley et al. 2016). There is also a secondary, non-irrigated dry season (*rabi*) during the same time frame as *boro* but it is less defined due to variations in crop selection and planting, flowering, and harvest dates.

Limited areas grow more than two seasons of rice, and most only grow one season. This makes automated classification of rice production difficult without an inherently flexible model for rice identification. Most arable land with access to sufficient fresh water is planted to rice in the *aman* season. However, adoption of *boro* or *aus* rice in double- or (very rarely) triple-cropping systems is limited due to regional environmental and climatic factors (BBS 2011–2015; Mirza 2002). Some regions lack fresh water during the dry season for the implementation of *boro* rice or may even face salinity intrusion in soils as experienced in some coastal regions (Mondal et al. 2001). Regions that do have adequate fresh water and the ability to store and manage it may grow a second season of rice, often using hybrid or high yielding varieties (HYV) because of the shorter growing season requirements (~90–120 days; Nelson et al. 2014). Second season (and specifically hybrid/HYV) rice production in Bangladesh may contribute significantly to sustainable intensification of agriculture in coming decades (Tilman et al. 2011).

This development of second season rice production is particularly critical for Bangladesh because arable land is decreasing, populations are increasing, and rice consumption per capita is one of the highest in the world (FAOSTAT 2016). However, rice production information is often only available at aggregated spatial scales such as districts, and management information is sparse, difficult and/or expensive to collect, and generally does not contain multi-temporal observations. Thus, fine spatial scale remote sensing methods for rice could improve monitoring of production through time, impacting predictions about regional agricultural statistics, food shortages and potential food insecurity, and inference about local agricultural management and practices.

4.3 Data, Materials, & Methods

4.3.1 Datasets

4.3.1.1 Remote Sensing Data

In this study, orthorectified Landsat 5 (LT5), Landsat 7 (LE7) and Landsat 8 (LC8) Top of Atmosphere (TOA) reflectance imagery are used to analyze dry season rice production in Bangladesh. Landsat 5, 7, and 8 (LT5, LE7, and LC8) satellite platforms imaged the entire earth every 16 days with a pixel resolution of 30 m and multiple spectral bands (Wulder et al. 2016). The TOA images are filtered spatially to cover all regions within the modern borders of Bangladesh. All Bangladeshi territory is covered by approximately 24 Landsat tiles. In total, 2396 LT5 images are included for years 1998 – 2011, 729 LE7 images for 1999 – 2002, and 1368 LC8 images for 2013 – 2017. These orthorectified time series images provide a platform for analyzing pixel-level changes from year-to-year and season-to-season with a re-visit time of 16 days. In **Figure (2)**, we show a map of the fraction of cloud-free observations during the dry season (December to May) for each Landsat platform. The cloud cover maps were derived based on the ratio of used (*good*) pixels to the total number of pixels for each time series of images between December 1st and May 31st. It’s important to note that a different cloud detection algorithm was used for LT5, which identified a significantly higher number of cloud pixels. As a result, more pixels were masked in LT5 than in LC8.

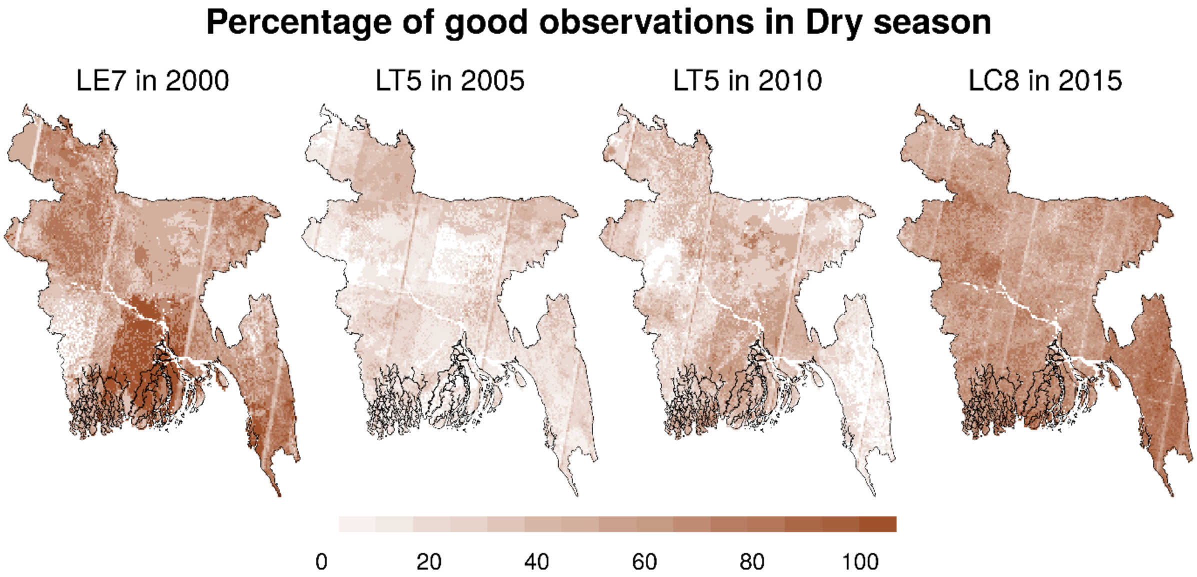

Figure 2. Percentage of Cloud-Free Observations. The maps in this figure represent the percent of pixels available (not masked by clouds) between December 1st and May 31st for the given year.

4.3.1.2 Reference Data from Official Statistics

There are 9 divisions (provinces/states) and 64 districts in Bangladesh.[8] District-wise data for *boro* rice production areas were generated based on reports from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and Bangladesh Bureau of Statistics (BBS). ICRISAT data are available between 2004 and 2010 (ICRISAT 2004–2010), and BBS data were used for 2011 to 2015 (BBS 2011–2015). These datasets will be referred to as the reference data for the rest of the manuscript. The reference data are estimates gathered based on local extension offices, regional agricultural data collection centers, and sampling surveys of farmers in each region. The reference data are aggregated areal estimates at the district level and

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[8] Note that three divisions were created in the last decade. Rangpur split from Rajshahi Division in 2010, Mymensingh Division split from the Dhaka Division in 2015, and Comilla Division split from Chittagong in 2016.

do not provide explicit spatial details or location-specific management details (e.g., flooding, transplanting, harvesting dates, or length of growing season). Importantly, there are no validations of this reference data in the literature, so while helpful for cross-referencing and comparative assessment, the accuracies of remote sensing methods compared to the official statistics should be observed with this caution in mind.

4.3.2 Google Earth Engine Platform

Google Earth Engine (GEE) is a cloud-based geospatial data analysis platform built on Google infrastructure and capable of processing petabyte-scale remote sensing data (GEE 2017; Gorelick et al. 2017; Moore & Hansen 2011). In previous studies, Landsat imagery could not be analyzed on larger regional or national scales because of high computational requirements. Instead, regional and national scale analyses were limited to moderate or low-resolution imagery platforms (Dong et al. 2016). To address this, GEE has opened the way for big geo-data analysis and the potential for investigation of higher resolution imagery such as Landsat in time series models. The GEE platform provides easy access to archives of remotely sensed data through either a JavaScript or Python API while simultaneously hiding the complexities of parallel computing and cyber-infrastructure.

4.3.3 Rice Phenology and Spectral Characteristics

Paddy rice, which accounts for more than 90% of rice production worldwide and is the main focus of this study (Kuenzer & Knauer 2013), typically follows three stages during the growing season: (1) a flooding and transplanting phase, (2) a flowering and tillering phase, and (3) a grain-filling and harvest stage (Dong & Xiao 2016; Mahmood 1997; Wassman et al. 2009).

During the flooding and transplanting phase, rice fields have exposed soil with little to no vegetative cover, followed by water infiltration and flooding, which slowly transitions to light vegetation after rice seedlings are transplanted (**Figure 3**). As the seedlings grow, the canopy of the rice begins to cover the flooded soil below and vegetation rapidly increases to usher in the flowering and tillering phase. This second phase is defined by rapid vegetative growth, rice flowering, germination, and pollination as well as panicle greening, lengthening, and thickening. Finally, the grain-filling and harvest stage follows as rice matures, browns, and dries. When the grain reaches ~20% moisture or less, harvest time commences and rice is cut from the fields, which return to brown exposed soil once again (Shelley et al. 2016). Importantly, the time-frame for each of these primary phenological phases changes depending on the rice varietal planted and the local planting times, as determined by weather and management decisions. Thus, any model for rice identification using these phenological stages must be flexible to changes in the length of the growing season, e.g., ~90–120 days for an HYV or Hybrid versus 130 + days for many traditional varieties, and flexible to the commencement of the transplanting phase.

A. (Left) Rice seedling preparation for *boro* season (January 2016) near Khulna, Bangladesh.

B. (Above) A High Yielding Variety during the *boro* season (March 2015) near Khulna, Bangladesh.

Figure 3. Images of Rice Production near Khulna, Bangladesh. The left image shows new rice seedlings growing in a nursery prior to transplanting. The right image shows a rice+fish system during the *boro* season.

The majority of previous rice-mapping research has attempted to identify pixels that show the characteristic temporal pattern of flooding followed by transplanting using remote sensing indicators such as vegetation indices (VIs; Boschetti et al. 2017; Xiao et al. 2005, 2006; Zhang et al. 2017). Specifically, these VIs are the Normalized Difference Vegetation Index (NDVI; Tucker 1979) and Enhanced Vegetation Index (EVI; Huete et al. 1997, 2002), which are sensitive to leaf chlorophyll content or plant greenness, and the Land Surface Water Index (LSWI; Xiao et al. 2004), which is sensitive to leaf water content and soil moisture. These indices are calculated based on the following formulas:

$$NDVI = \frac{(\rho NIR - \rho R)}{(\rho NIR + \rho R)}, (1)$$

$$LSWI = \frac{(\rho SWIR - \rho NIR)}{(\rho SWIR + \rho NIR)}, (2)$$

$$EVI = 2.5\, X\, \frac{(\rho NIR - \rho R)}{(\rho NIR + 6\, X\, R - 7.5\, X\, B + 1)}, (3)$$

When LSWI + 0.05 > NDVI or LSWI + 0.05 > EVI, the signature represents a transition from plant cover or dry soil to primarily water or saturated soil and indicates the likely timeframe during which rice transplanting takes place. We refer to this as the flood signature. More details about this process in MODIS can be found in Xiao et al. (2005, 2006) and for applications with Landsat in Dong et al. (2016).

4.3.4 Fitting a Harmonic Time Series Model

Significant cloud cover rests over Bangladesh throughout the year, especially during the monsoon season between late June and October. Because of this, there are missing observations in addition to the atmospheric and sensor noise in the recorded bands of the imagery, which has to be dealt with in the estimation of VIs (Jensen 2016; Roy et al. 2002; Verbesselt et al. 2010). To correct for these issues, a harmonic time series model was employed to interpolate NDVI, EVI, and LSWI values over the time period for each pixel. The harmonic model was used to estimate each VI value (y^*) at each time (t) based on the following equation:

$$y_t^* = \alpha + \beta_1 t + \beta_2 \sin \omega t + \beta_3 \cos \omega t\, , (4)$$

where α represents a constant, β_1 is a coefficient for the overall trend in t, β_2 is a coefficient for the sin function at the frequency ω of time t, and β_3 is a coefficient for the cosine function at the frequency ω of time t. In this model, two harmonic frequencies per annum account for the two seasons of rice that occur in a given crop-calendar year in Bangladesh. Notably, this HTS-VIs model is an expanded version of Shew & Ghosh (2017).

For Landsat 8, a single HTS model was fitted to the time interval between 2013 and 2017, i.e., the entire four years of available Landsat 8 imagery. For Landsat 7, again a single HTS model was fitted for the years 1999 – 2002. However, for the Landsat 5 imagery, an HTS model was fitted corresponding to advancing five-year windows between 1996 and 2013 with the middle (third) year being the focus of analysis, e.g., for analyzing 2010, an HTS model was constructed using the image between 2008 and 2012. For each year, the rice classification timeframe was specified between December 1st and May 31st, which includes the *boro* season across the entire country. Due to cloud cover, time series observations of VIs were irregular. To ensure temporal comparability across regions, a pseudo-model of the HTS-VIs was generated starting December 1st and advanced every 16 days through May 31st. This analysis resulted in regular time series VI values (total of 12) for each pixel at 16-day intervals for the dry season.

The flooding signature was used to determine the rice transplanting phase using the regular HTS-VIs values. LT5, LE7, and LC8 collect slightly different spectral band-widths and have lower radiometric resolutions compared to LC8. EVI has been shown as generally more sensitive to the spectral characteristics of rice for LT5 and LE7, so the final model reflects the singular consideration of LSWI + 0.05 > EVI for LT5 and LE7 and was sufficient for identifying rice paddy in the transplanting phase for these platforms. However, for LC8 two VIs for vegetation (NDVI/EVI) were used. Finally, I estimated the total number of observations for which the conditions are satisfied (0 being the minimum, while 12 is the maximum).

In the time series plot below (**Figure 4**), LSWI+0.05 is greater than EVI or NDVI for five consecutive counts; this pixel would be classified as rice for the *boro* season of the year plotted. (Since these types of time series plots depict the phenology of rice, these will be identified as *pheno-plots* for later reference). Given that planting dates vary year-to-year and regionally, and phenological stages change by variety, I attempted to develop a flexible model for rice pixel identification without prior detailed knowledge of rice-growing seasons. Three counts (~16 –32 days) of the flood signature were used as the minimum for a rice-producing pixel, and eight counts (~80–96 days) were used as the maximum for a rice-producing pixel. Any pixel with a count of three to eight counts of LSWI greater than EVI/NDVI would indicate flooding/transplanting for at least 16 days and a maximum of 96 days (which may account for systems transitioning from aquaculture in *aman* to rice in the *boro*). I assume that less than three observations might be residual flooding from the previous *aman* season or rainfall and more than eight might be permanent water, wetland areas, or non-rice flooding. All the Landsat imagery analysis described so far has been performed on the GEE platform. Each of these HTS-VIs classifications was exported for each year and further analyzed in R statistical software.

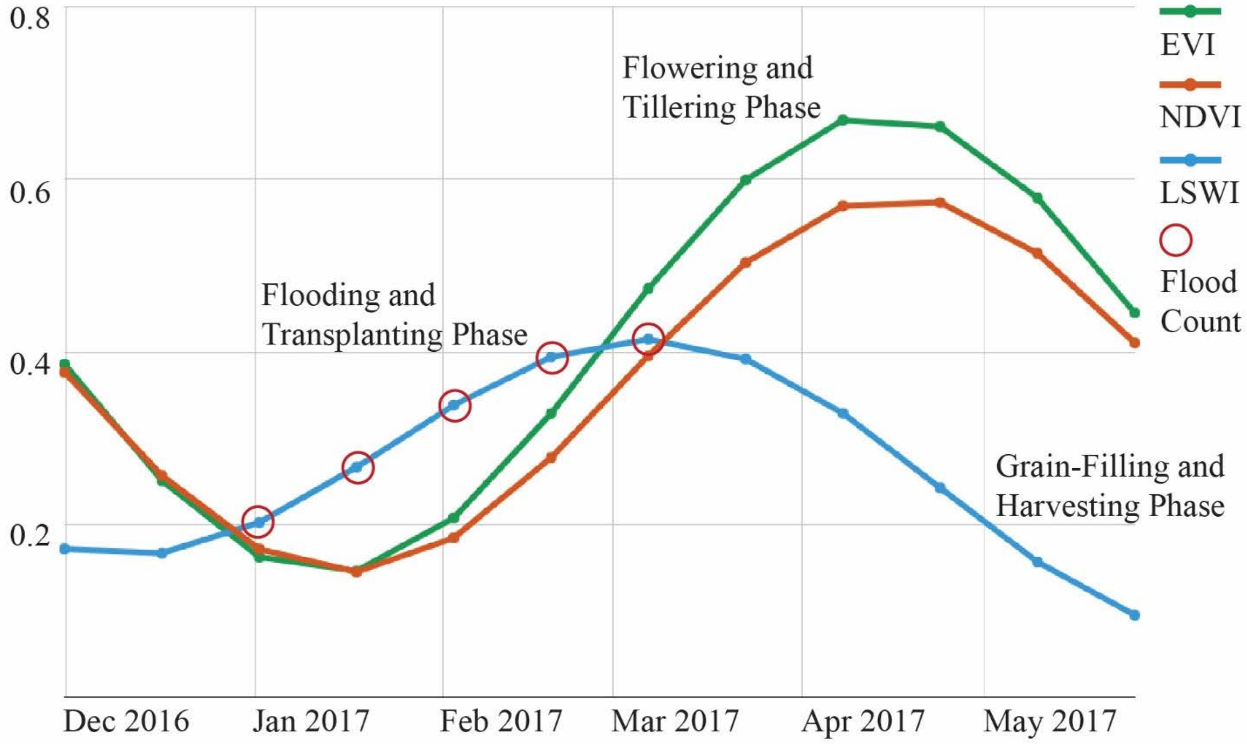


Figure 4. Rice Phenology for the *Boro* Season with a Flood Signature of '5' for LC8. The red circles show where LSWI+0.05 is greater than EVI or NDVI. These flood counts are

summed for each pixel each year to determine if the flood signature (counts) matches for rice or not based on a minimum of three flood counts or a maximum of eight flood counts.

4.3.5 Optimization of Area Estimates using Reference Data

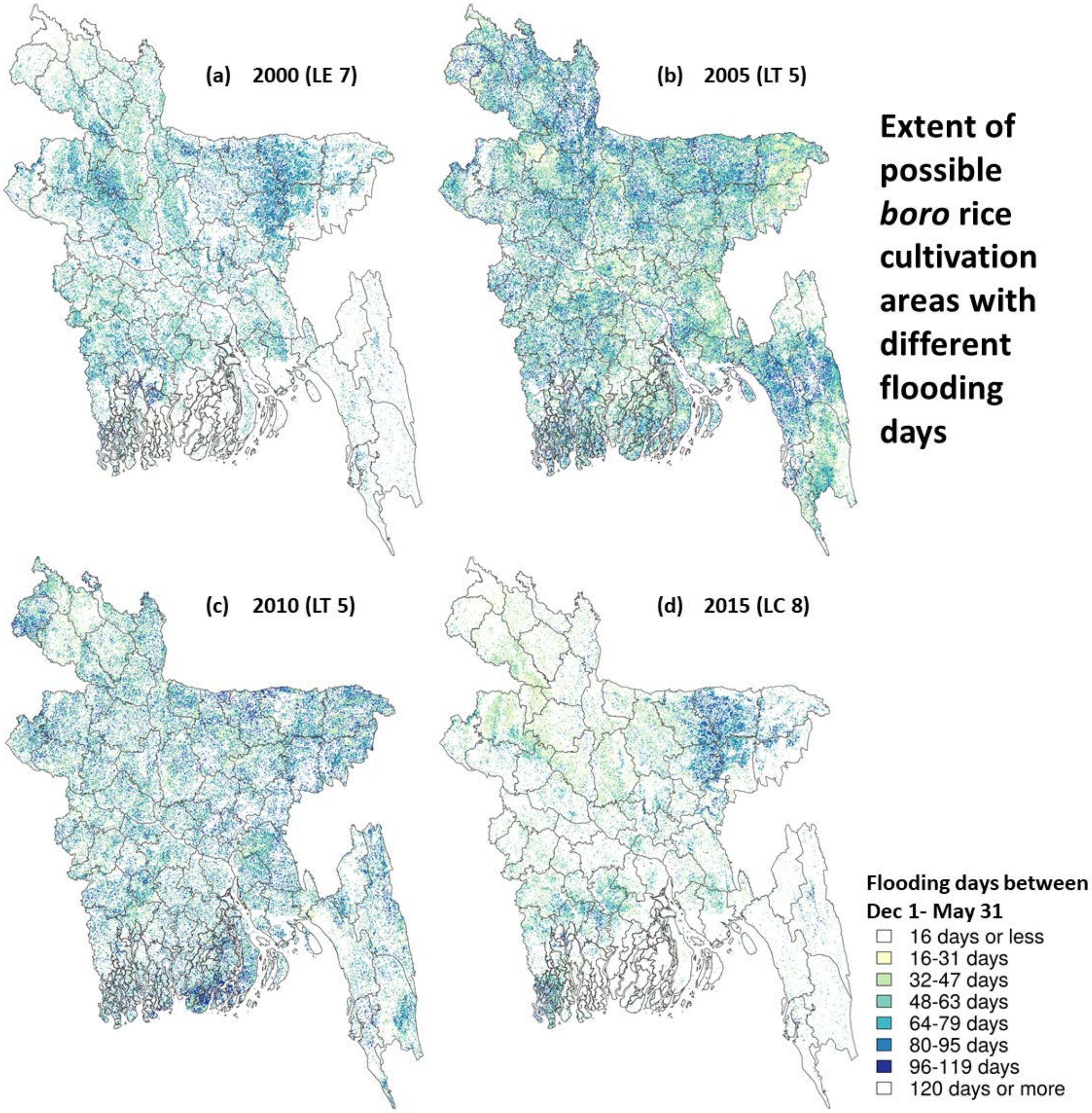
The area covered by *possible* rice pixels (any pixel with 3 to 8 counts of the flood signature) was extracted within each of these 64 districts using the *raster* package in R statistical software (Hijmans & van Etten 2012). I estimated different areas under rice with the following assumptions about the flooding and transplanting duration: 1) the rice cultivation system for any specific district is homogeneous and flooding signatures can be observed for only one of the following flooding day intervals: 16, 32, 48, 64, 80 or 96 (3 to 8 observations of the flooding signature); and 2) the rice cultivation system is heterogeneous and multiple flooding durations can be present within a district. Based on these assumptions, I estimated areas under different flooding durations using all possible (21) combinations of flood signatures, i.e., 21 models of rice-producing area estimation for each district each year.

Next, the calculated areas based on these 21 estimations per district per year were compared with those in the district-level reference data to find the combination which provided the closest estimation of rice-producing hectares to the reference data. For example, if the difference between the 3–4 counts (model) of the flooding signature (the total area of *possible* rice pixels in a district between 16 to 32 days of the flood duration) was smaller than all other combinations, then we accepted that scenario as most representative of *boro* rice production in that district. Based on the minimum difference models, a comparative assessment was conducted for the rice classified areas derived from the HTS-VIs model within each district against the district reports on annual *boro* rice areas from the reference data. For comparative assessment, the Mean Absolute Percentage Error (MAPE) was calculated between the reference data and the HTS-VIs model results (Armstrong & Collopy 1992; Hyndman & Koehler 2006), but it should be noted that the reference data cannot be used to ascertain actual error or accuracy measurements as they are regionally aggregated and do not represent specific pixels (locations) and times (planting, flowering, harvesting dates) with respect to on-the-ground rice observations. This assessment provides critical understanding of how rice production in fragmented landscapes may be mapped spatiotemporally, which could lead to improvements in classification at finer scale resolutions in the future.

4.4 Results & Discussion

4.4.1 Model Fitting and Spatial Variability of Dry Season Rice Production

The HTS-VIs model estimated 4.021 million ha, 3.519 million ha, and 4.605 million ha of rice production at the national level for Bangladesh in 2015, 2010, and 2005, respectively, based on the closest values of LC8 and LT5 compared to the reference data. Notably, the LT5 analysis overestimated rice areas in some years and underestimated in others due to the implementation of a different cloud-masking algorithm from the one employed with LC8, which resulted in a lower number of cloud-free observations for fitting the harmonic time series model. **Figure (5)** depicts rice-growing pixels identified by the HTS-VIs model for the years 2000, 2005, 2010, and 2015 according to the flood durations.



Figures 5. HTS-VIs Estimates of Rice-Growing Pixels. The above figure represents the flood counts across four years and all three sensors. Notably, 2005 was over-estimated.

4.4.1.1 Harmonic Fitting of the Landsat VIs

The harmonic fitting is represented in **Figures (6)**. In these figures, I show an example of the full harmonic model fit for LC8 in a coastal area near Barisal and in a northern area near Mymensingh. Notably, values are missing in these models, especially during the monsoon months beginning in June and continuing through September and October. For the purposes of this study, I focus on the *boro* season between December/January and April/May. The EVI and NDVI signals are strong in this timeframe, and there are fewer missing values due to less rainfall and cloud cover. The flood signal during the transplant phase shows up effectively, followed by a rapid increase and peak in EVI/NDVI, which indicates this small test area is most likely under rice production. Each year produces a similar pattern for this test, which suggests farmers are consistently planting a *boro* season crop in this region. In **Figure (6)**, I present the fitted harmonic model for LC8 at a test site near Mymensingh. The rice signature for the *boro* season is clear in this representation of the harmonic model, but due to missing values in both February and May, the model would be difficult to compare with other regions or across years and could easily misclassify the rice signature. To resolve this issue and make all regions and time periods more comparable, I generated a common time interval and equal observations for all VIs, an example of which is presented in **Figure (7)** and discussed in more detail below.

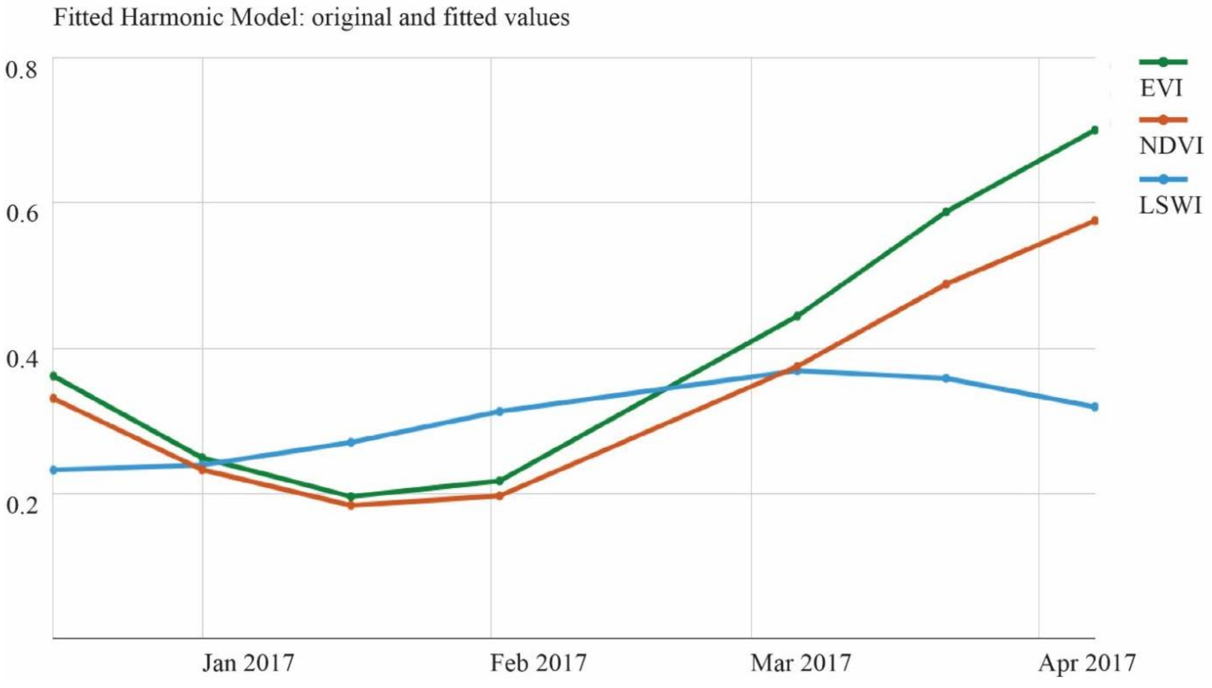


Figure 6. Landsat 8 Fitted Harmonic Model for 2017 near Mymensingh. This model shows the original fitted model without interpolated pseudo-values at regular intervals.

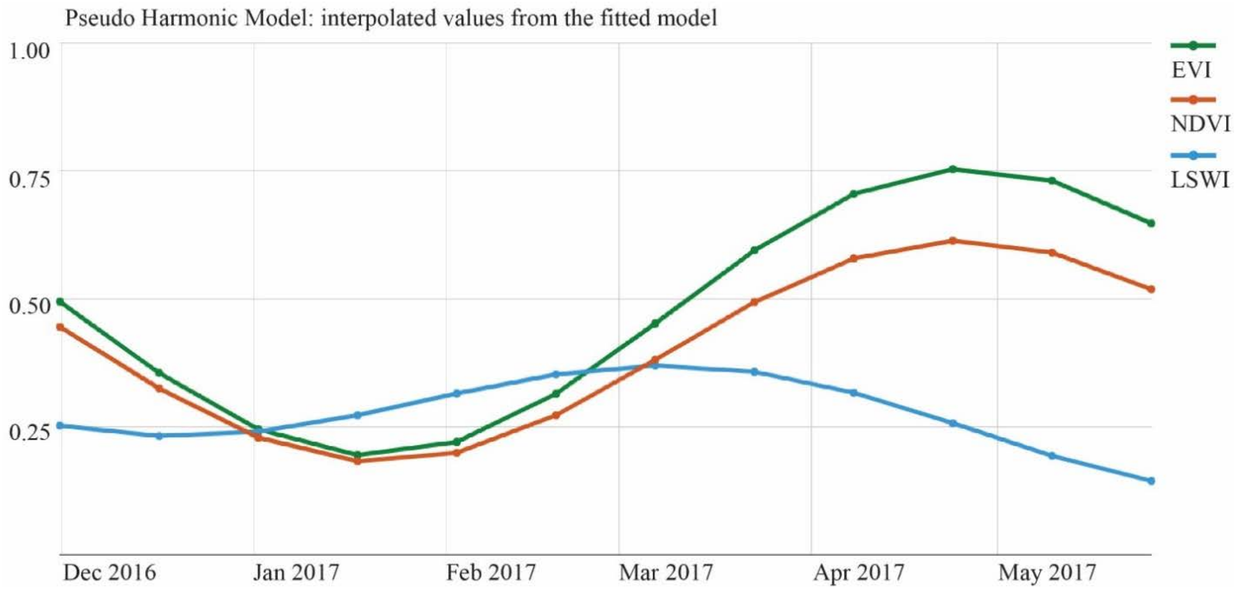


Figure 7. Pseudo-VIs at Equal-Intervals Starting December 1st based on Figure (6). This figure shows the equal intervals for model estimation every 16 days.

4.4.1.2 Generation of VIs at Equal-Intervals Starting December 1st

In **Figure (7)** above, I present the same test area from Figure (6), but this iteration includes a generation of equal-intervals for the VIs beginning on December 1st and ending May 31st in the year 2017. Importantly, the observations are consistent every 16 days with no missing observations because they are interpolated based on real observations in the original HTS model. In the pseudo-HTS model, the signature for rice is an improvement over the fitted model with original values. This is demonstrated by the fact that we see a clear harvest time in late December for *aman* rice, followed by the flood signature for *boro* season planting, and a peak and decline in the flowering and tillering phase in May. These signatures exemplify what is known about regional differences in rice production patterns in Bangladesh, namely that there is a stronger, more predictable *boro* season in the north and there are often flooding and drainage issues during *aman* in the coastal region. The pseudo-HTS-VIs model was used for all estimations of rice-producing area in order to maintain this systematic comparability. The next section explores this spatial and temporal variability more explicitly.

4.4.1.3 Spatial Variability of Rice Phenology

To exemplify spatial and temporal differences in phenology more visibly, I selected three test areas—Barisal (South), Rajshahi (Northwest), and Sylhet (Northeast)—to represent potentially different rice production practices and seasons. **Figure (8)** shows the spatiotemporal variability for these three test sites using the generated HTS-VIs model. In Barisal, the flooding and transplanting phase is notably longer and significantly higher than in Rajshahi and Sylhet, which likely coincides with Barisal being in the coastal region. The Rajshahi example illustrates a regional production system with what might be an average flood signal for rice, four counts in this case, and almost textbook curves for the three VIs to distinguish the rice flowering and tillering phase before continuing into grain-filling and harvest time. The Sylhet test site suggests this is a relatively drier rice producing area, barely making the rice flooding minimum of three counts and retaining close proximity among all VIs. Overall, **Figure (8)** provides a distinct characterization of three rice-producing areas and exemplifies the ability of the HTS-VIs model to capture spatiotemporal patterns in dry season rice production.

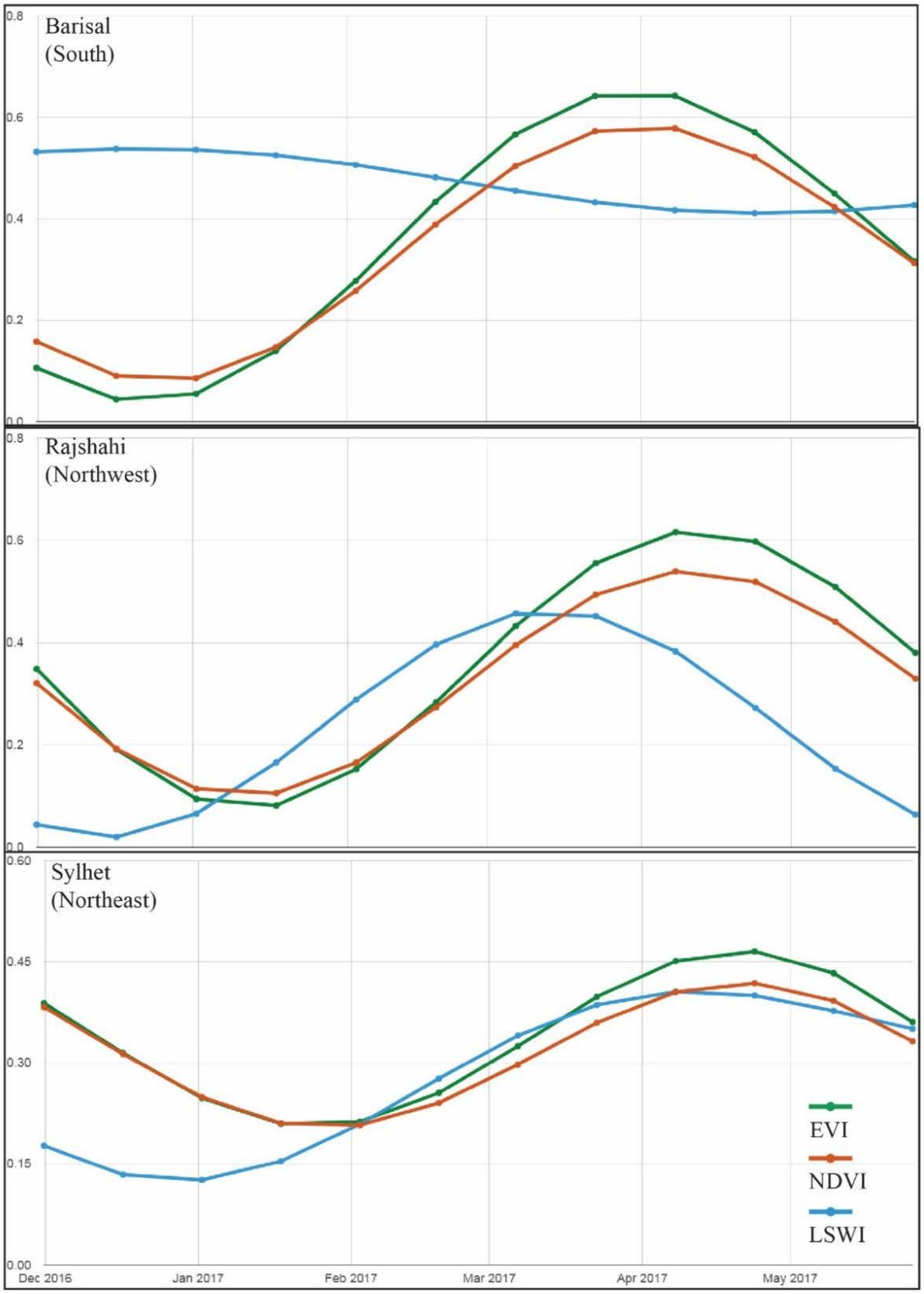


Figure 8. Spatial Variability of Rice Phenology based on the Generated Model for Three Sites. These phenoplots represent regions in Bangladesh with different environmental characteristics to demonstrate the flexibility of the model.

4.4.2 Comparison of Rice-Area Estimates from Remote Sensing Analysis and Reference Data

The HTS-VIs model results show that indeed central and northern districts in Bangladesh have increased the hectares of rice production during the dry season, but not consistently as 2010 was significantly higher than both 2005 and 2015. According to the reference data, approximately 4.064 million ha were planted in 2005, 4.707 million ha were planted in 2010, and 4.090 million hectares were planted in 2015 at the national level. Below, I compare the best fitting HTS-VIs results for 2005, 2010, and 2015 with the reference data from BBS and ICRISAT both nationally via MAPE and at the district level via mapping. In **Figure (9)**, it can be seen that the district-level rice growing spatial patterns as well as magnitude in hectares planted are relatively consistent. The upper row represents the reference data and the lower row represents the closest HTS-VIs estimations for that year. Notably, this is a comparative assessment rather than a specific accuracy or error estimation based on observed year-to-year in situ rice production, which is what would be needed for full validation of the HTS-VIs model (Olofsson et al. 2013, Olofsson et al. 2014). In an ideal accuracy assessment, the locations and timing of rice planting, flowering, and harvesting would be observed for multiple years across potentially different rice management systems so as to capture the temporal, spatial, and managerial aspects of HTS-VIs compared to true production data.

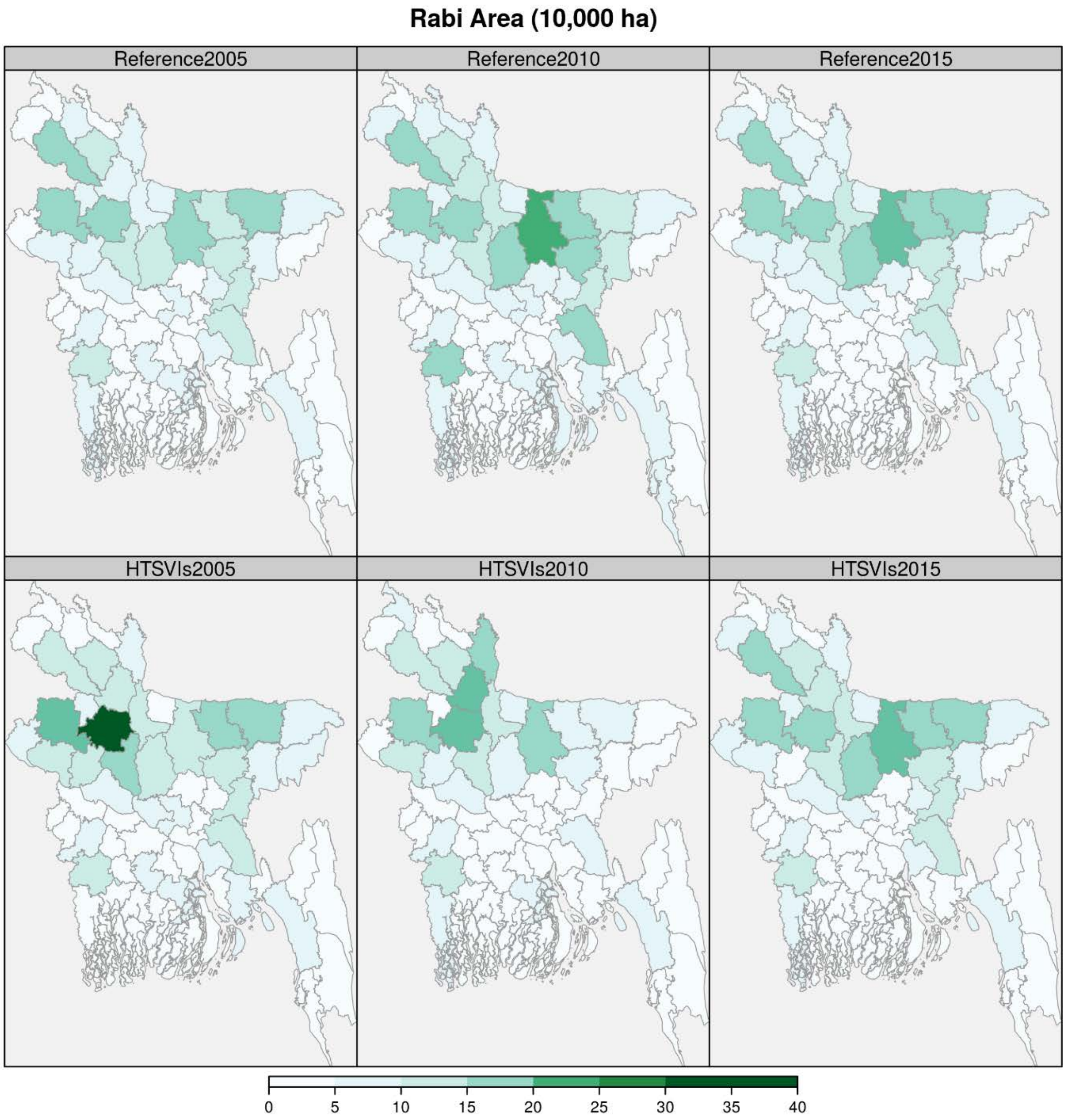


Figure 9. District Maps of Dry Season Rice Production: Reference vs HTS-VIs Closest Model. The lower row represents the remote sensing model, and the top row represents the reference data. Patterns are similar with exception to an overestimation in the HTS-VIs in 2005.

In the comparative assessment, I compared the closest rice area estimation for *boro* rice areas provided by the reference data using MAPE (Hyndman & Koehler 2006). I found estimations within 10.14 %, 8.42 %, and 8.49 % for 2013, 2014, and 2015, respectively, in comparing LC8 with the reference data. For LT5, I found HTS-VIs estimations within 8.60 %, 7.84 %, 8.21 %, 7.88 %, 7.47 %, 7.71 %, 7.78 %, 7.91 %, 7.86 %, and 8.23 % for each year from 2004 to 2013 in the HTS-VIs national estimates. Notably, this is not an accuracy assessment as outlined in Olofsson et al. (2013, 2014), which would require ground control points with known times for rice production.

4.4.4 Discussion of Methods

4.4.4.1 Advantages

The proposed methodology provides a flexible platform for mapping rice production in heterogeneous landscapes. In previous rice mapping efforts, expert knowledge on detailed rice phenology has been a key feature of the models. In other cases, where expert knowledge has not been included, the focus of rice mapping has been in relatively simple, homogeneous production systems. This methodology allows one to fit a rice-identification scheme flexible to regional differences in production systems and varying landholder sizes. When combined with Landsat data at 30 m resolution as in this study, the methodology can account for rice in fragmented and disjointed landscapes. While the model shows promising results in this introductory example for Bangladesh, there are some limitations to the model in its present form, and likewise, there are ways to improve it in future implementations.

4.4.4.2 Limitations and Constraints

The primary limitation of this methodology is the dependence on reference data in identifying the best rice classification for each district. I identified the HTS-VIs model based on the least difference model from the district reference data, which illustrates the robustness of the model to estimate rice-growing areas across heterogeneous agricultural practices, season lengths, and fragmented geographies. However, this dependence on the reference data hinders the models application in unreferenced regions or years. This gap might be bridged in future work, which is discussed in more detail below.

Another limitation prevalent in this model is its sensitivity to cloud cover. The model does not perform consistently in the *aman* season in Bangladesh because of the monsoonal cloud cover during this time. In some cases, the model adjusts to missing data via the interpolation of the HTS-VIs, but given a scenario where two to three consecutive observations are missing, the model prediction will be poor. Because of this seasonal limitation, I introduce this model primarily for dry season mapping in Bangladesh and suggest it should primarily be used in regions where extended periods of cloud cover are less widespread. Cloud cover was more problematic for LT5 estimates due to a less nuanced cloud-masking algorithm, which could potentially be reduced in future work. In this case, I used all LT5 district estimates within 2.5 standard deviations, e.g., 95 %, of the sample to remove outlier estimates caused by the excessive cloud masking. In the comparative assessment, this reduced the difference from reference data significantly, but in future work, this step may not be necessary.

The difference between the results of the HTS-VIs models and the reference data may also be due to the influence of small, fragmented plots of rice, i.e., less than 30 m pixels, or omission errors from the influences of cloud cover as described above. Instead, I propose the possibility that the HTS-VIs model may identify rice production more correctly than those collected in situ at the district level, though this would require further confirmation with higher resolution imagery or better field observations than are currently available. At this point, higher resolution imagery is limited by time and/or cost, and field observations in rural Bangladesh are difficult (if not impossible) to obtain for previous years. Moving forward, it may be conceivable to incorporate similar analysis with comparative assessment using ESA Sentinel datasets (https://sentinel.esa.int/web/sentinel/missions) or higher resolution datasets from private sources like Digital Globe (https://www.digitalglobe.com/) or Planet (https://www.planet.com/).

4.4.4.3 Future Research Pathways

Future work could compare these results with previously implemented MODIS rice classification algorithms to identify disparities based on resolution. Moreover, in this study I conducted exploratory analyses with further constraints on the time series, including date dependence for rice seasons, masking permanent water surfaces, and maximum/minimum difference thresholds for EVI and NDVI during the growing season, as suggested in the PhenoRice algorithm (Boschetti et al. 2017). These constraints made no significant changes to the rice areas identified by HTS-VIs. As such, only the original HTS-VIs model is presented herein. Permanent water was already excluded in the HTS-VIs model by setting the maximum flooding duration for rice to 80–96 days. However, it is possible that without a maximum/minimum difference threshold for VIs, commission errors may occur in wetland areas where similar vegetative characteristics exist alongside watery land surfaces. Similarly, I use a minimum flooding duration of 16–32 days, which could lead to omission errors where the flooding and transplanting phase is shorter. The decision to omit flooding duration less than 16 days was based on the assumption that many areas in Bangladesh could remain flooded for 16 days with normal precipitation patterns given the low-lying and relatively flat landscape. On the other end of the spectrum, the maximum flooding duration included is 96 days to ensure that longer flooding and transplanting phases are captured. In some regions, flooding persists from the *aman* season into the dry season when farmers may begin transplanting rice. It may be of interest to cluster pixels based on flood counts to conduct sub-set analysis for regional rice production characteristics. This might allow for object-based interpretation and investigation of rice systems (Bunker et al. 2016).

In this study, I limited the study to introducing the HTS-VIs model with Bangladesh as an example to demonstrate its effectiveness at capturing rice-producing areas in a fragmented landscape with diverse agricultural systems, but further validation, testing, and extension is needed for the HTS-VIs model. There are two pragmatic ways that might improve the model overall: (1) The Normalized Difference Flood Index (NDFI) could be included as another flooding and transplanting phase indicator and has been demonstrated as more sensitive than LSWI (Holden & Woodcock 2016), and (2) Rule-based classification with the harmonic time series might be a better option than the flood count basis. Rules might include:

1. EVI trend one month before the max must be positive,
2. EVI trend on month after the max must be negative,
3. EVI max must be greater than 0.55 (to remove potential bias from wetland vegetation), and
4. Consistently decreasing NDFI and/or LSWI after EVI is equal to NDFI to ensure the flooding signature is diminished after the canopy closes for rice tillering and flowering.

These rules are highlighted in **Figure (10)** to more clearly demonstrate their potential implementation in the model.

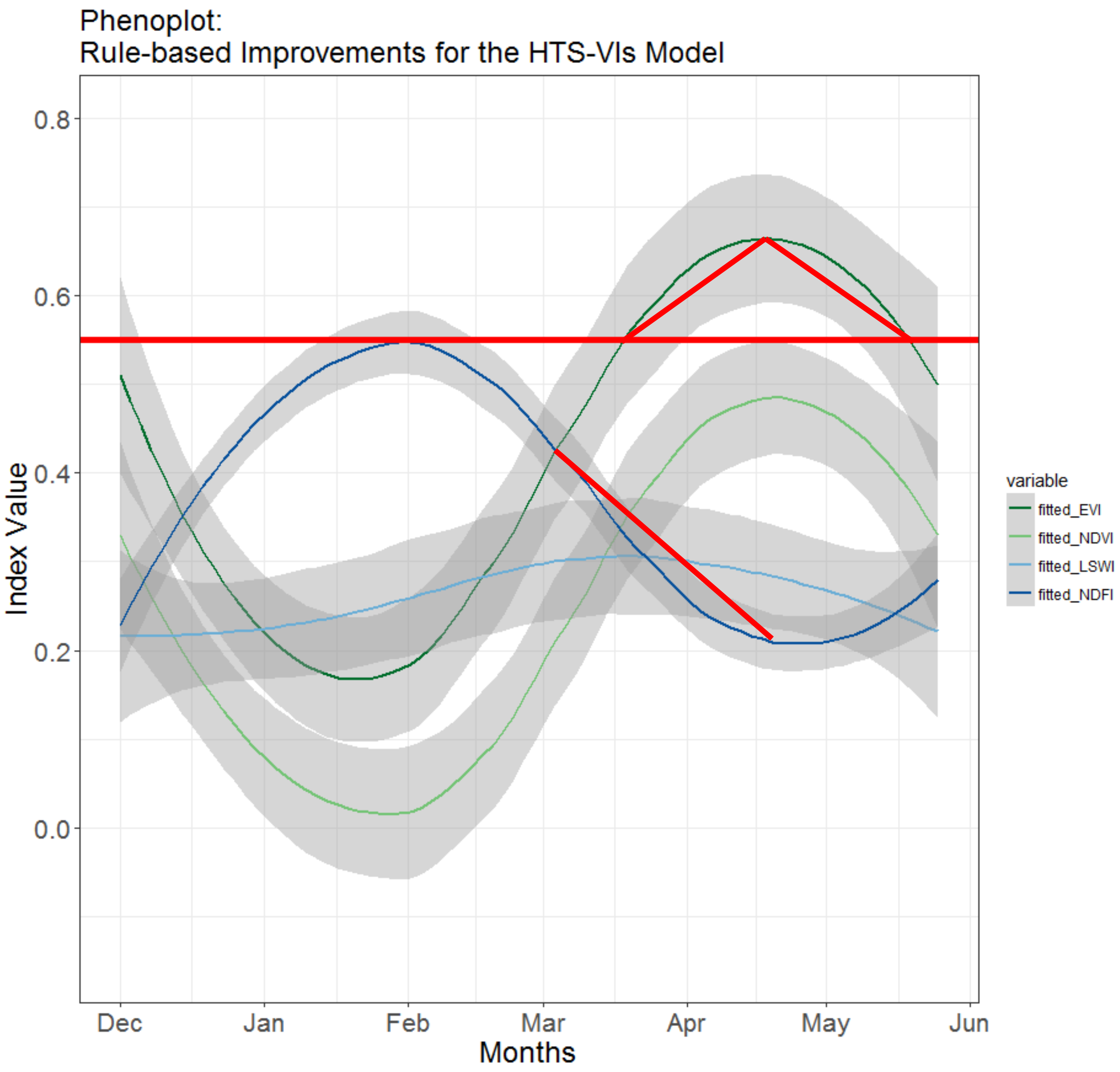


Figure 10. Potential Pathways for a Rule Based Harmonic Time Series Model. The red lines represent the four rules that could be imposed on the indices for rice identification.

4.5 Conclusions

In this study, I demonstrate the implementation of a harmonic time series (HTS) model with EVI, NDVI, and LSWI to identify rice production areas during the *boro* season in Bangladesh. To my knowledge, this is the first time a pixel-based time series model has been applied to Landsat at the national level on a decadal time-scale. I found that, the HTS-VIs model has the potential to map rice production across fragmented landscapes and heterogeneous production practices with comparable estimations to other methods but without expert knowledge inputs. For LT5, this method shows approximately 25 % – 40 % difference from the reference data for districts in Bangladesh—generally less than the estimates made by local agricultural offices with exception to 2010. For LC8, the results were within 5 % – 15% of reference data at the district level, which is a significant improvement over the LT5 predictions likely due to improved quality bands, higher radiometric resolution, and the consequent larger number of good quality observations. As agricultural monitoring via remote sensing becomes more widespread and important in meeting global food security needs, I suggest that models like the HTS-VIs introduced here could improve the comparative efficiency of the tools and resources scientists employ, giving policy-makers and development practitioners an enhanced platform for their work on sustainable intensification of agriculture.

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CHAPTER 5: CONCLUSION

In summary, this dissertation sought to address multi-disciplinary, multi-scalar issues of SAI in the Bangladeshi context in three independent articles. In the first article, I analyzed baseline survey data collected by the USAID Sustainable Intensification Innovation Lab-Polder Project (SIIL-Polder Project) in three empoldered areas of coastal Bangladesh. I characterized current agrarian practices and crop systems to investigate potential pathways for sustainable agricultural intensification (SAI). I also evaluated agrarian perceptions of improved technologies that might be introduced to enhance agricultural production in the region and discussed the importance of technology adoption and SAI in the polders. In the second article, I estimated the global food security and environmental impacts of the adoption of improved seed technology in Bangladesh. This study investigated how the adoption of hybrid and high yielding variety (HYV) rice and double-cropped rice improves food security and environmental efficiency, and ultimately sought to determine whether rice intensification, in terms of improved seed technology and double-cropped systems, can be classified as SAI. In the final article, I introduce a new time series methodology for dry season (*boro*) rice monitoring via remote sensing with Google Earth Engine and the Landsat archive. The article demonstrates the new method in the context of Bangladesh, compares the results with district-level reference data, and discusses the potential pathways for future improvements to the methodology. Together, these articles address (1) the farm level potential for SAI in a challenging environment, (2) the food security and environmental impacts of improved technologies at the national scale, and (3) the ability to monitor SAI of dry season rice at 30 m resolution on a national scale with recent advances in remote sensing.

Based on this work, a number of implications exist for development practitioners, policy-makers, and scientists. Key findings and recommendations based on the research contained in this dissertation are outlined in this final section.

5.1 Chapter 2: Household-level SAI Findings

1. Most farmers in the polder region of Bangladesh own their primary plot of land, but many cultivate land with no property rights. This may leave them vulnerable. Efforts should be made to provide property rights where possible.
2. Farmers may perceive high yielding varieties of rice as high producing, but they see them as less cost-effective due to a lower market price. Market information should be collected on a regular basis so that development practitioner recommendations are in line with economic potential at the farm-gate.
3. Agrarian communities often experience food insecurity in September to November during the latter part of the wet season. By this time, food storage is diminished and up to 12 percent of farmers may go without food in this period. Efforts should be made to improve income, and thus the ability to purchase food, or production, and thus the ability to store more food.
4. Most farmers who experience food insecurity cope by borrowing food or taking out loans to purchase food.

5.2 Chapter 3: National-level SAI Findings

1. Rice intensification in Bangladesh has contributed enough additional yield to provide 25 million per capita per annum in Bangladesh and 36 million in India.

2. Double-cropped and high yielding varieties of rice are more environmentally efficient in production on a per kg of rice basis. Global warming potential, land use, and water use are all lower for these intensified rice systems. Rice intensification and diversification should be promoted to ensure that food security needs are met and environmental impacts are reduced.

5.3 Chapter 4: Multi-scalar Remote Sensing Rice Estimation Findings

1. A harmonic time series model with the Landsat archive can improve our understanding of land surface phenology when combined with spectral indices.
2. The harmonic time series model of spectral indices allows for fine resolution estimation of rice producing areas during the dry season in Bangladesh. This method of rice identification compares well to aggregated district-level area estimations of rice production.
3. Rule-based methods may be combined with the harmonic time series model to improve identification and monitoring of agricultural areas.