THE FRESHWATER AQUACULTURE REVOLUTION IN BANGLADESH: IMPACTS ON LAND, WATER, AND LIVELIHOODS

By

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ABSTRACT

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Freshwater aquaculture production has increased by 167% in Bangladesh between 2001 and 2017, surpassing fish production from natural open water bodies during this period. However, studies have shown that such dramatic growth in agricultural production can alter the earth's potential to generate goods and services in the long run by pushing certain planetary boundaries and disproportionately hurting people who are directly dependent on ecosystem services for livelihoods in the short run and all of mankind in the long run. This research analyzes the growth of freshwater aquaculture in Bangladesh from three perspectives, through three papers. The first paper explores the question of why fish farmers have been motivated to come into aquaculture and expand fish farming. Based on qualitative case studies and focus group discussions in Mymensingh district, a major region of freshwater aquaculture growth in Bangladesh, the study shows that high profitability of aquaculture for more than two decades since the 1990s has motivated people to engage in fish farming. The second paper builds a system dynamics model of land conversion from crop production to aquaculture that simulates future trends in land conversion and food production. The objective of this study is to analyze the dynamics of crop land conversion to aquaculture over time, and understand what key variables are influencing the transformation process. The model is parameterized at two geographical scales: for the entire country and for Mymensingh district. The results show that fish yield, prices, and concentration of supporting industries are some of the key factors that are influencing the growth of aquaculture. This study also observed that although rice land is being converted for aquaculture

and other purposes, there is no imminent threat from aquaculture to rice production, as the decline in rice land is being off-set by the growth in rice yields over the last few decades. The third paper embeds water use models in the land use change system dynamics model built in the second paper, in order to understand whether aquaculture growth in Bangladesh is changing water productivity by substituting for irrigated rice production, and how aquaculture growth is impacting groundwater use quantity. The results show that water productivity combining both rice and fish production is generally increasing, both in the case of Mymensingh, and Bangladesh. However, the total volume of water use combining both rice and fish production is increasing in the high aquaculture concentration region of Mymensingh, but decreasing in the country overall. Overall, the research shows that aquaculture growth in Bangladesh has a positive impact on food supply, but continued success of this growth depends on prices and yields continuing to move in a favorable direction. Also, future development of aquaculture needs to focus on groundwater saving technologies, in order to ensure that groundwater extraction does not exceed safe yields in the long run.

This dissertation is dedicated to my parents, who have instilled the desire for learning in me, and to all my teachers in life, who have contributed to my quest for knowledge.

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CHAPTER ONE

INTRODUCTION

Agricultural development (including crop, fisheries, and livestock agriculture) impacts natural resources, as the agriculture sector is a major user of natural resources (World Bank, 2008; FAO, 2016). According to the strong sustainability view on natural resource use, with the current scale of human activities, our planet will soon reach environmental carrying capacity and thus we need to be cautious in the exploitation of natural resources (Barbier, 2003). Markets may fail to estimate the proper value of such resources, thus leading to their depletion (Costanza & Daly, 1992). A study by Rockstrom et al. (2009) has argued that humanity has already crossed three planetary boundaries: climate change, rate of biodiversity loss, and changes to the global nitrogen cycle. The paper also demarcated several other planetary boundaries for global freshwater use, land system change, biological nitrogen and phosphorus cycles, etc. These are all affected by agriculture. The agricultural sector is a major contributor to the greenhouse gas emissions (like carbon dioxide, methane and nitrous oxide) that lead to global warming and associated climate change (FAO, 2016). Therefore, it is import to understand the impact of any type of agricultural growth on the planetary boundaries for understanding the safe operating space for human development. One example of recent agricultural growth is aquaculture, which is the world's fastest growing food sector (FAO, 2018). This research is about understanding aquaculture growth from three perspectives: farmers' motivation to engage in and expand fish farming, and projected changes in land use and water use in the context of Bangladesh.

Aquaculture can be defined as the farming of fish and other aquatic organisms. It is one of the fastest growing food production sectors of the world, growing at about 10% per year over the 1980s and 1990s, and at about 5.8% between 2001 and 2016 (Troell et al., 2004; FAO, 2018).

Over the last three decades, global aquaculture production increased from 5 million to 80 million tons (in 2016), and the fastest growth in supply is coming from finfish species like Tilapia, Carp, and Pangasius (World Bank, 2013; FAO, 2018). Aquaculture production is unevenly dispersed geographically with Asian countries contributing nearly 90% of global production; where, China is the largest producer in 2016, followed by India, Indonesia, Vietnam, and Bangladesh, respectively (FAO, 2018). This growth in production is valuable on one hand, contributing to food and nutrition security, and generating employment opportunities, as well as reducing the burden on wild fish stocks. However, aquaculture also exerts pressure on the finite natural resource base, and risks causing socioeconomic and environmental problems by causing massive changes in land use, polluting neighboring waters with effluent, consuming excessive amounts of freshwater, increasing Green House Gas emissions and eutrophication, adversely affecting capture fisheries due to the use of fish meal, etc. (Delgado et al., 2003; Frankic & Hershner, 2003; Bosma & Verdegem, 2011; Bunting, 2013; World Bank, 2013; Waite et al., 2014). Fish farming uses a range of ecosystem services and their demand surpassing the environmental carrying capacity can lead to adverse consequences (Bunting, 2013). Each geographical area or type of aquaculture can have its own prospects and challenges. Irresponsible use of natural resources may reduce the capacity of such resources to provide benefits in the future (Arrow et al., 1995). Understanding the potential challenges of the growth of any production system for the broader system it resides in –over long periods of time –requires knowledge of the specific ways it interacts with the broader system. This knowledge can help develop aquaculture production systems that provide the highest possible benefits but exert the least possible impact on its resource base.

Bangladesh is one of the countries where rapid aquaculture growth has taken place over the last few decades. This research will evaluate this phenomenon using qualitative interviews and System Dynamics modeling from the perspective of three changes that are associated with the growth of aquaculture and sustainable use of natural resources in Bangladesh: farmers' motivation to engage in and expand fish farming, and the use of land and water for aquaculture. Here, aquaculture is discussed in relation to rice production, as rice is the dominant agricultural production activity in Bangladesh, in terms of land use, value addition, and employment (BBS, 2017), and the growth of aquaculture is competing for resources with rice production. Although this research is specific to Bangladesh, it has implications for aquaculture expansion globally, as it will produce a model that compares land and water use of two major agricultural enterprises, and show how their use can impact food supply and natural resources. In the following sub-section, a background of aquaculture growth in Bangladesh is presented.

1. 1 Background of Aquaculture Growth in Bangladesh

Agriculture in Bangladesh has been transforming over the last few decades where historically rice production has been the dominant agricultural activity (Deb, 2016). Rice is still the most important crop in Bangladesh, being cultivated on about 75% of cultivable land, and more than 60% of the country's calorie intake comes from rice. Figure 1.1 shows that despite rice area staying almost constant through the 1990s and 2000s, rice production has increased significantly. This can be attributed to high yielding varieties of seeds, use of fertilizers and pesticides, and expansion of irrigation (Deb, 2016).

Fish has also been an important part of the diet and livelihoods of the people of Bangladesh, as the source of two thirds of animal protein consumed and one quarter of agricultural GDP (BBS, 2017). Bangladesh has inland open water bodies (rivers, lakes, etc.) measuring 4.03 million ha, 0.68 million ha in closed water bodies as man-made ponds and enclosures for aquaculture, and 166 million hectares of marine water area in the Bay of Bengal (GED, 2013).

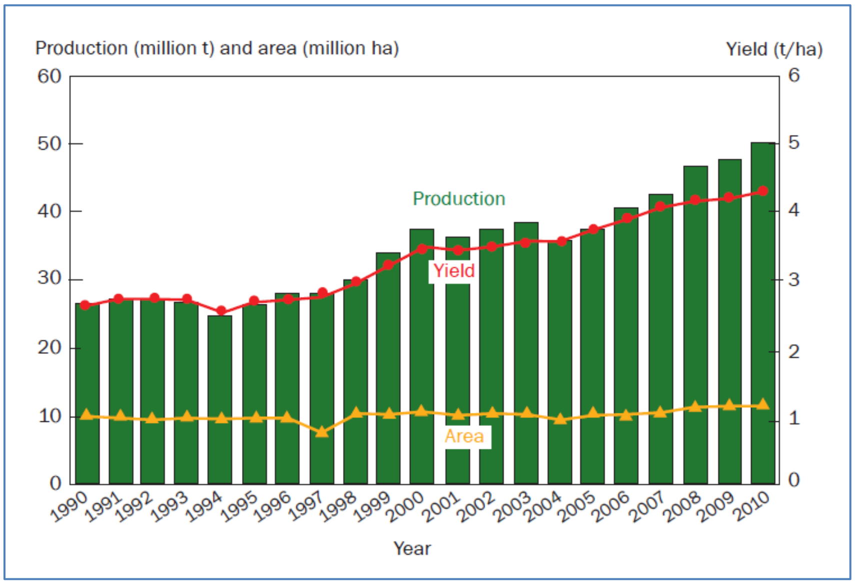

Figure 1.1: Rice area, yield and production in Bangladesh (Source: GRiSP, 2013)

Previously, the largest source of fish was capture from inland open freshwater bodies. Figure 1.1 shows long term trends in fish production, aggregating all forms of aquaculture as the solid blue line, and all forms of capture fisheries (freshwater and marine) as the solid red line with dots. Then, aquaculture is broken down into pond production, and shrimp production, with broken green and purple lines respectively. The figure shows that the inland freshwater sector has grown rapidly over the last few decades, surpassing capture fisheries. Production from ponds is the main source of this growth (Belton et al., 2014; Toufique & Belton, 2014; DoF, 2017). Here, we can define ponds as man-made closed water bodies with small permanent embankment (DoF, 2017). There are also other forms of aquaculture like fish culture in seasonal water bodies, pen or cage culture, rice-fish farming, etc. In this research, my focus is on the freshwater pond aquaculture as that is far larger than other forms of aquaculture, and has the highest degree of human control/intervention.

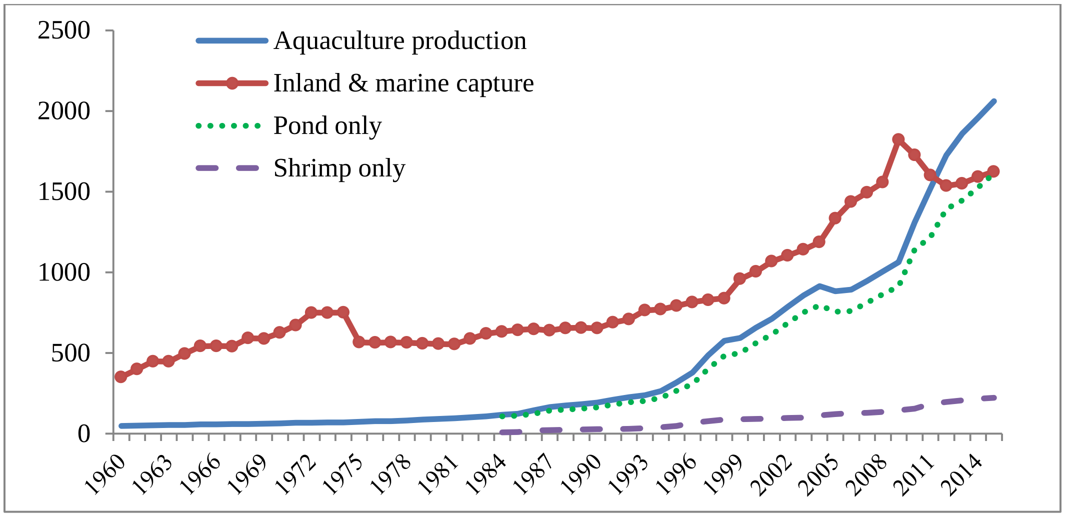

Figure 1.2: Fish production in Bangladesh in thousand metric tons (World Bank, 2018; DoF, 2017)

A part of this growth is coming from conversion of rice land to fish ponds, that is, fish production replacing rice production in a parcel of land (Ali & Haque, 2011; Belton et al., 2014). However, studies on how much crop land has been converted to freshwater aquaculture are rare. Some studies have shown that new fish ponds are mostly converted from active crop lands or at least potential crop lands (Ali & Haque, 2011; Palash, 2015). Land used for rice cultivation is often also suitable for fish farming, and hence is a target for conversion.

Fish production from ponds is found in different regions of Bangladesh, but there is a concentration of aquaculture in some districts where production is higher compared to other areas (Hu et al., 2017; Hernandez et al., 2017). The districts with the highest amount of land in aquaculture are Mymensingh, Jessore, Comilla, Bogra, Chittagong, Barisal, and some of their adjoining districts (please see map in Figure 1.3).

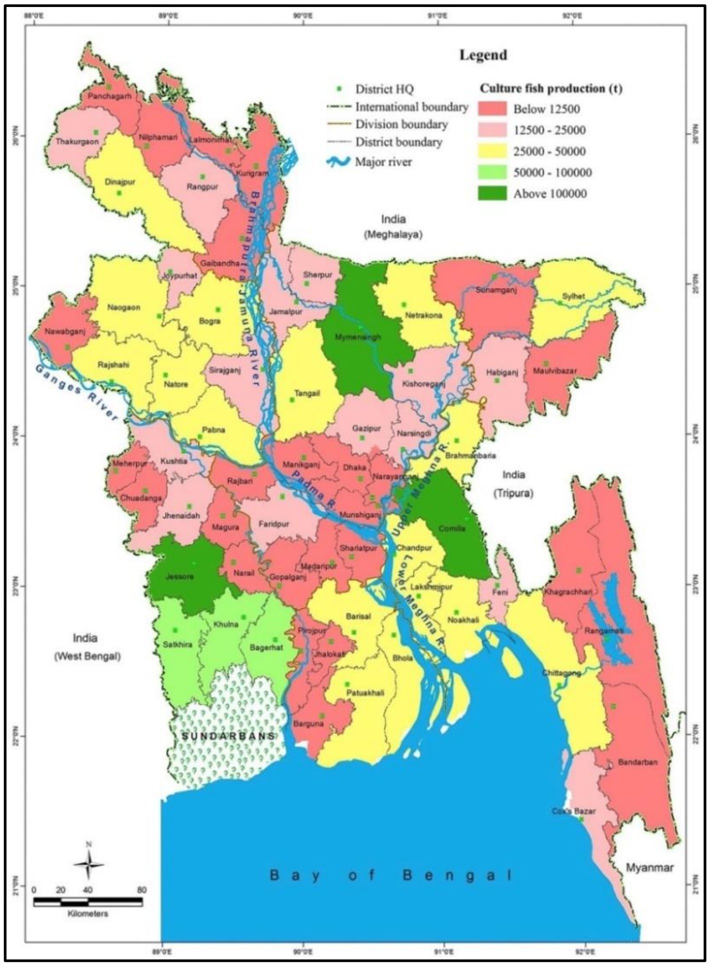

Figure 1.3: District-wise inland closed water fish production (Source: FRSS, 2015, cited in Shamsuzzaman et al., 2017)

Pond aquaculture can be classified on the basis of intensity of production. The Department of Fisheries currently categorizes pond aquaculture into the following groups shown in Table 1.1 (DoF, 2017). Although this classification is defined in terms of output, intensification is also linked to feeding and rearing or stocking density (Troell et al., 2004).

Table 1.1: Classification of pond aquaculture based on intensification

Method	Production Range	Area (%)	Production (%)	Yield (MT/Ha)
Extensive	< 1.5 MT/Ha	9.72	2.46	1.17
Semi-intensive	1.5-4.0 MT/Ha	62.77	45.41	3.34
Intensive	4.0-10.0 MT/Ha	23.60	31.57	6.18
Highly Intensive	>10.0 MT/Ha	3.90	20.56	24.32

Pond aquaculture can also be classified into homestead and commercial (or entrepreneurial) forms of production, where subsistence or homestead ponds mostly follow extensive culture practices, while commercial or semi commercial ponds follow improved extensive, semi-intensive and intensive culture practices (Jahan et al., 2015). A study observed that about 25-40% of the output from homestead ponds were sold to the market, while 80-90% of the outputs from commercial farms were sold to the market (Jahan et al., 2015). The average size of the homestead farm observed in different studies ranges between 0.08 and 0.10 hectares, while most of the commercial farms range between 1 and 2.5 hectares, indicating that the majority of fish farms in Bangladesh are operating as small or medium scale commercial enterprises (Belton et al., 2011; Belton & Azad, 2012; Hernandez et al., 2017).

Different fish species are cultivated in Bangladesh. The Indian major carps, such as Catla, Rohu, and exotic carps, such as Silver Carp, Grass Carp, Common Carp and Bighead Carp are commonly cultivated in polyculture (cultivation of multiple species), sometimes along with Pangasius, Tilapia, Climbing Perch or other species (Jahan et al., 2015). Pangasius, Tilapia, and Climbing Perch are sometimes found to be cultivated in monoculture, and sometimes with a mix of other species (Jahan et al., 2015). Different species have different yields, and different requirements for feed and other inputs (Palash, 2015). While carp polyculture requires less feed and is better for water quality (as excessive use of commercial feed causes water pollution in the fish ponds); polyculture involving Pangasius, Tilapia, and Climbing Perch is more profitable, and are the most common types of commercial aquaculture in Bangladesh, and hence the highest contributor to the aquaculture growth in the country.

Although aquaculture in Bangladesh has been contributing to improving food and nutrition security (Jahan et al, 2010; Ahmed & Toufique, 2015), benefitting poor people (Toufique &

Belton, 2014; Ahmed & Toufique, 2015), and creating employment opportunities (Belton et al., 2015), previous agricultural development experiences show that the progress of any sector can have negative socioeconomic and environmental externalities. One prominent global example (which is also true for Bangladesh) is the expansion of Green Revolution technologies in crop production, which led to massive increase in cereal production in many parts of the world, increased income, and reduced poverty, but which have also been associated with adverse consequences in soil degradation, water use, chemical runoff from fields, increased greenhouse gas emissions, biodiversity loss, and persistence of malnutrition and poverty for groups of people unable to enjoy its benefits (Pingali & Rosegrant, 1994; Pingali, 2012; GRiSP, 2013; Deb, 2016). Another example –more specific to Bangladesh – is that, starting from the 1970s, coastal areas of the country experienced expansion of brackish water shrimp cultivation, which had high economic value, and contributed significantly to export earnings, but was associated with mangrove and wetland destruction, crop land conversion, salt water intrusion, loss of fry and wild stock, loss of livelihoods by some people, social conflicts over benefits and resources, etc. (Ito, 2002; Azad et al., 2009; Paul and Vogl, 2011; Swapan and Gavin, 2011). Freshwater aquaculture is different, but has the possibility of producing harmful socioeconomic and environmental outcomes (Bunting, 2013). Global aquaculture growth has been associated with negative externalities like massive changes in land use, pollution of neighboring waters with effluent, excessive freshwater consumption, increase in Green House Gas emissions due to increased energy use on-farm (for example, pumping) and off-farm (for example, producing fish meal or transportation), eutrophication, the spread of disease among fish farms, and the possible impact on capture fisheries because of fish meal (Delgado et al., 2003; Frankic & Hershner, 2003; Bosma & Verdegem, 2011; Bunting, 2013; World Bank, 2013; Waite et al., 2014).

In the case of Bangladesh, some of the exotic species have had adverse impacts on the biodiversity of indigenous fish species of the country by escaping from their ponds and mixing into natural water bodies (Ahmed & Toufique, 2015; Hossain et al. 2015). A study has reported that when aquaculture replaces rice farming, the employment opportunities for women in rural areas decline, as fish production activities have less demand for female labor. Also, women experience a decline in control over household resources, as men have more control over income and output from commercial aquaculture compared to rice farming (Gurung et al., 2016). There are more aspects of aquaculture growth in Bangladesh that need to be studied in order to understand its impact on the economy and the ecosystem.

1. 2 Plan for the Dissertation

There are three essays in this dissertation. The first paper, which is the second chapter of this dissertation, explores the question of why fish farmers have been motivated to come into aquaculture. This study is based on qualitative case studies and focus group discussions in Mymensingh district, a major region of aquaculture growth, showing how farmers have been motivated to engage in and expand fish farming. The second paper (or the third chapter of this dissertation) builds a system dynamics model of land conversion from crop production to aquaculture that simulates future trends in land conversion and the availability of food. The objective of this study is to analyze the dynamics of crop land conversion to aquaculture over time, and understand what key variables are influencing the transformation process. The third paper (which is the fourth chapter of this dissertation) embeds water use models in the land use change system dynamics model built in the third paper, in order to understand whether the aquaculture growth in Bangladesh is changing water productivity by substituting for irrigated rice production, and how aquaculture growth is impacting quantities of groundwater use.

1.3 Significance of the Dissertation

Although this research uses data for Bangladesh, it has implications for natural resources use globally, as it will produce a model that compares land and water use of two major agricultural enterprises, and show how their use can push planetary boundaries. So, this research contributes to sustainable development literature by showing how the growth of a high value agricultural enterprise, which competes with staple crop production, can change utilization of natural resources like land and water.

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CHAPTER TWO

HOW FARMERS ARE DRIVING THE AQUACULTURE GROWTH IN BANGLADESH

2. 1 INTRODUCTION

Transformation of agriculture in the developing world from a low output generating subsistence activity to a more advanced and productive avenue has been the focus of many government policies and agricultural development practitioners throughout the world (FAO, 2012). Beneath the broad canopy of agricultural development, there are numerous structural changes, ranging from the adoption of new technology in the same production system, to adopting more comprehensive advanced production and distribution systems, to shifting from one enterprise to another. One such change the world has witnessed over the last few decades is the growth of aquaculture in certain parts of the world (Bosma & Verdegem, 2011; Little et al., 2016). Studies have highlighted several causes that have led to this phenomenon: increased demand due to population and economic growth along with urbanization on one side, and capture fisheries not increasing at the same rate on the other side; increase in supply through adoption of higher yielding species; improved processing and distribution systems; modernization of retail markets; relaxed regulatory frameworks; and expansion in export opportunities (Bostock et al., 2010; FAO, 2014). However, there has been little focus on the actors that are driving this change: the fish farmers. This research explores the experiences of fish farmers in the process of advancing aquaculture in Bangladesh, a country where rapid aquaculture growth has taken place during recent decades (Belton & Azad, 2012; Ahmed & Toufique, 2015).

This paper will first provide a brief background on the growth of aquaculture in Bangladesh, which will involve a description of the change. Then, it uses multiple qualitative case studies to understand the experience of farmers in this transition process. The main research question this paper aims to address is what has been motivating farmers in Bangladesh to engage in fish farming and how they have overcome barriers.

2. 2 BACKGROUND

2. 2. 1 Global Aquaculture Practices

Aquaculture can be defined as the farming of fish and other aquatic organisms. Globally, aquaculture is practiced in marine, brackish and fresh waters, in either open or closed systems (Bosma & Verdegem, 2011). Among the farmed food fish produced in 2016, about 68% were finfish species (true fish species with backbones, gills, etc.), and about 21% were mollusks (oysters, snails, scallops, mussels, shellfish, etc.), the rest being crustaceans (crabs, lobsters, shrimp, etc.) or other aquatic species (FAO, 2018). During the last three decades, global aquaculture production increased from 5 million to 80 million tons, and the fastest growth in supply is coming from finfish species like Tilapia, Carp, and Pangasius (World Bank, 2013; FAO, 2018). Aquaculture production is unevenly dispersed geographically, as Asia has produced about 89% of global production for over two decades (FAO, 2018). China is the largest producer, followed by India, Indonesia, Vietnam, and Bangladesh, respectively (FAO, 2018). The largest exporters of fish and fishery products are China, Norway, Vietnam, and Thailand, while the largest importers are the European Union, Japan, and the USA (FAO, 2018). Employment in the (entire) fisheries sector has grown faster than the world's population and faster than employment in other agricultural sectors between 1990 and 2012, and the growth is mostly from fish farming, as employment in capture fisheries has been decreasing during recent years (World Bank, 2013; FAO, 2018). So, global aquaculture is growing rapidly.

2. 2. 2 Fish and Aquaculture Development in Bangladesh

Historically, fish occupies a significant position in the diet of the people of Bangladesh, as it has been a major source of protein, and is seen as the most common food item after rice (Hossain et al., 2015). Until the 1970s, the supply of fish from natural waters was mostly abundant. However, the fish stock in the natural water bodies was not increasing at the same rate as demand over time; and during the 1980s, there was a lot of concern about fish supply diminishing and prices going up constantly. The geographical conditions in Bangladesh are considered to be some of the most suitable in the world for freshwater aquaculture (Ahmed & Toufique, 2015). Therefore, there have been efforts to increase fish production over the last few decades, particularly efforts that emphasize the practice of aquaculture (Belton et al., 2014). Consequently, inland production of fish has increased more than three times between 1991 and 2013 (DoF, 2014).

Although a part of this phenomenon can be attributed to increase in fish supply from seasonal water bodies, the major portion of this increase comes from cultured sources, as pond based aquaculture production has grown by about 700% between 1991 and 2013 (DoF, 2014). Government sponsored attempts to develop aquaculture in this region began in the 1960s. These efforts included teaching and research activities through organizations like Bangladesh Agricultural University and Bangladesh Fisheries Research Institute, and extension efforts by the government (Department of Fisheries) and development partners, like the Mymensingh Aquaculture Extension Project (Ahmed, 2009).The earliest success came through expansion of brackish water shrimp culture in the southwestern part of the country during the early 1980s (Azad et al., 2009). The growth of freshwater prawn production came after some areas in the southwestern part of Bangladesh became unsuitable for rice production due to soil salinity intrusion, but did not have regular access to sufficient amounts of seawater to engage in shrimp production. The growth of freshwater aquaculture accelerated from the mid-1990s onwards. The success in freshwater fish production can be attributed to a number of technological and socioeconomic factors as well. The technological factors include the domestication of wild fish species and development of their breeding and rearing protocols. About 20 fish species have been domesticated, and about half of these species are now under aquaculture nationwide (Hossain et al., 2015). Another technological factor is the introduction of exotic fish species. Over the last 60 years, a total of 24 exotic species have been introduced in Bangladesh (Hossain et al., 2015). However, some of these exotic species have adverse impacts on the biodiversity of indigenous fish species of the country. For example, some of these species have escaped closed water bodies and reached open water areas, and as some of these species are carnivorous, they eat small indigenous species in those open water bodies. The exotic species also compete with indigenous species for food and other resources and have sometimes occupied their place in the water bodies, leading to a decline in the population of indigenous species (Hossain et al., 2015).

There are some demand-side factors which have helped the growth of aquaculture. As population and incomes have both increased in Bangladesh, so has the demand for fish products. In fact, demand for fish has grown faster than the demand for staples following Benett's Law (Hernandez et al., 2017). Also, economic development in general and the spread of small and medium enterprise in particular, have contributed to this process by developing forward and backward linkage industries. The majority of fish farmers in Bangladesh are operating as small or medium scale commercial enterprises (Belton & Azad, 2012).

2. 2. 3 Understanding Farmers Motivation for Engaging in Aquaculture

Studies on the growth of aquaculture in Bangladesh have described the process of growth and talked about contributing factors (Belton & Azad, 2012; Ahmed & Toufique, 2015; Jahan et al., 2015). Broadly speaking, aquaculture growth in Bangladesh can be characterized by conversion of land into aquaculture, as well as an increase in the intensity of production (Belton & Azad, 2012; Palash, 2015). In this paper, we use qualitative case studies to supplement quantitative information and understand the changes experienced by people engaging in fish farming. A quantitative study may provide statistics of transformation rates and related variables, and the researchers' interpretation of such changes, but may not provide any insights or rich descriptions by the agents who are making this change, leaving out valuable information on why and how such changes are taking place (Doss, 2003). These studies mostly view farmers as passive agents in their land use decisions, with factors happening beyond their control simply guiding them to take the actions they have taken. However, understanding farmers' reasons, processes, and experiences are important because this can provide important details that the quantitative analysis can leave out.

The growth of aquaculture is dependent upon farmers' land use decisions. Economic theory predicts that a household would allocate land in such a way that maximizes its expected utility or return from the land (Jones & O'Neill, 1992, and Chomitz & Gray, 1996, both cited in Verburg et al., 2004; Bockstael, 1996). Such decisions can be influenced by factors like the demand for food, economic and technological development, population growth, environmental conditions, availability of capital or inputs, prices of commodities, etc. (Lambin et al., 2001; Lambin and Meyfroidt, 2011; Palash & Bauer, 2017; Rai et al., 2017). Under any given context, while one or more factor can guide towards one decision, other factors may drive towards another decision.

So, understanding the farmers' perspectives is very important for understanding the underlying process of land use change.

Moreover, data from a fish value chain survey by the International Food Policy Research Institute (IFPRI) in Bangladesh has shown that due to the profitability of fish farming, some people whose primary occupation was not agriculture, either bought or leased-in land, or converted portions of their own land and became primarily fish farmers (we will present findings from this data in the results section). So, the growth in aquaculture is not just about the land allocation decision of the farmer, it is also about people's choice of occupation. The process of making this choice can itself be an obstacle to growth of any enterprise, even if it is profitable, as many people in Bangladesh have negative attitudes towards self-employment opportunities (Azim, 2008). According to the Global Entrepreneurship Monitoring report, Bangladesh has the highest rate of "fear of failure" in the world regarding entrepreneurship, despite the fact that its GDP growth rate of 7.11% (in 2015-16) is one of the highest in the world (Karim & Hart, 2012; BBS, 2017; World Bank, 2018). Sometimes there are resource constraints like high startup costs, lack of credit, unfavorable tax and licensing policies, lack of skills and information that prevent people from engaging in productive entrepreneurial opportunities (Azim, 2008). But sometimes the adverse social attitudes make educated people avoid entrepreneurial opportunities, and seek socially desirable salaried jobs, even if they have to wait for prolonged periods of time (Islam, 1980; Azim, 2008; Huq et al., 2016). Moreover, agricultural activities occupy a low status in terms of desirability in the job market, as it is perceived by the society as a traditional and unattractive profession. As a form of agriculture, fish or livestock farming often falls under this category, even if it carries high income earning opportunities. The implication of this is that the aquaculture sector can be deprived of the services of educated people. However, such perceptions can change over time. Research in Kenya found increased knowledge of aquaculture and favorable social perception towards this practice had a positive influence on farmers adopting it (Njue & Macharia, 2015). Also, uneven economic growth can create the environment for certain groups of people to invest in a sector, but not in others. A study observed that economic growth in an unorganized developing economy led to capital accumulation in the hands of certain sections of the population, but there was not enough scope for investing in industrial sectors (Thuo, 2013). This is relevant for aquaculture growth in Bangladesh, as the country's economy is growing, and there are some people in the villages that are getting richer. However, they may not have the capability to invest in more productive avenues beyond the village, thus restricting themselves to whatever is available to them nearby, which could be aquaculture in some cases.

So, the process through which a farmer chooses to shift a part or entire amount of his or her land to aquaculture is a change guided by his or her characteristics, but it is also embedded in the social, economic, cultural and political contexts he or she is experiencing in life. Hence a rich and credible description of the context and phenomenon under study can provide important insights into the story, and a qualitative inquiry can put the 'human' experiences of the farmer at the heart of the change occurring.

2. 2. 4 Research Question

This study is about exploring the experiences of the farmers converting cropland to aquaculture, and understanding why they have shifted to aquaculture. The main research question is:

- What factors have motivated farmers in Bangladesh to engage in fish farming and how have they overcome the barriers?

2. 3 METHODS

2. 3. 1 Introduction

This study will use descriptive data from a survey and the qualitative case studies approach in examining farmers' motivations and experiences in overcoming barriers in expanding fish farming in Bangladesh. We will first describe quantitative survey data of fish farmers, and then provide deeper analysis of farmers' experiences obtained through field visits, face to face interviews, and focus group discussions (FGDs).

2. 3. 2 Research Instruments

This study will be based upon a quantitative survey conducted by the International Food Policy Research Institute (IFPRI) in Bangladesh, multiple field visits to areas of high aquaculture concentration, two focus group discussions with fish farmers (7 people in each group), and four interviews with fish farmers of different farm sizes. The purpose of the focus groups and farmer interviews will be to gain in-depth knowledge about farmers' experiences in fish farming. The interviews are based on semi-structured questionnaires (Appendix). Interviews with socioeconomic experts, aquaculture scientists, and crop and fish extension agents supplement the observations from farmer interviews and also triangulate the information they provide. The research proposal and instruments were approved by the Institutional Review Board at Michigan State University (reference: STUDY00001030).

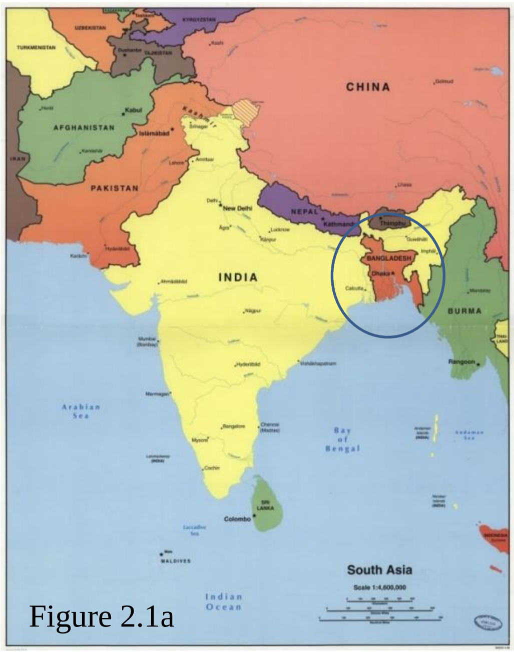
2. 3. 3 Survey Data

The survey conducted by IFPRI is on fish value chains in the country and is a nationally representative survey of 1540 fish farming households, as well as 165 hatcheries, 213 input dealers, 44 feed millers, and 498 traders. The survey was conducted between February and June

2014. It contains detailed background socioeconomic information on the farm households, as well as cost and returns analysis of fish farming in 2013, with recollections for some variables from 2008. This dataset is not publicly available as of November 2018, but has been obtained directly from IFPRI Dhaka, with assistance from USAID, Dhaka. Some tables are drawn with the data from this survey to explain farmers' socioeconomic characteristics.

2. 3. 4 Field Visits and Selection of Sites

Although this study uses quantitative survey and other secondary data for Bangladesh as a whole, it was not possible to interview farmers from various parts of the country due to resource and time constraints. Initial field visits were conducted in three districts where there have been high rates of aquaculture activity (Mymensingh, Bogra, and Rajshahi). Then, Mymensingh was chosen as the district for farmer interviews and focus group discussions, as this district had the highest aquaculture growth rate in Bangladesh over the last two decades (DoF, 2017). Again, within Mymensingh, two sub-districts with high aquaculture concentration were selected, namely Trishal and Muktagacha. The Trishal sub-district is to the south of Mymensingh city, and the Dhaka to Mymensingh highway cuts through it, while the Muktagacha sub-district is to the west of Mymensingh city, and the Mymensingh to Tangail (another district) highway cuts through it. These two places are among the fastest growing areas in Bangladesh for aquaculture. The following maps in Figure 2.1(a, b, c) show the location of Bangladesh and the study areas within Bangladesh.



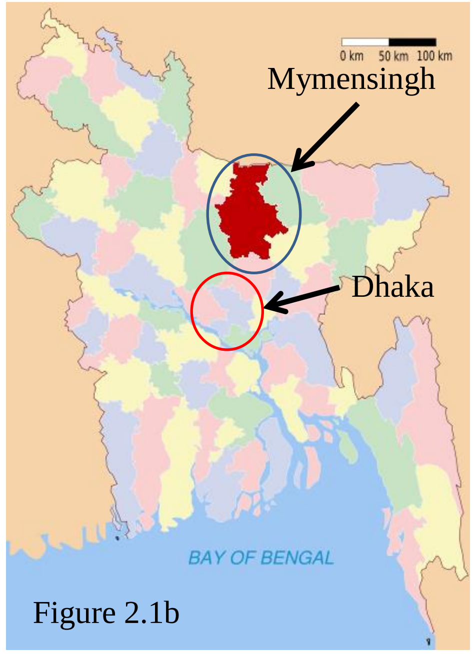
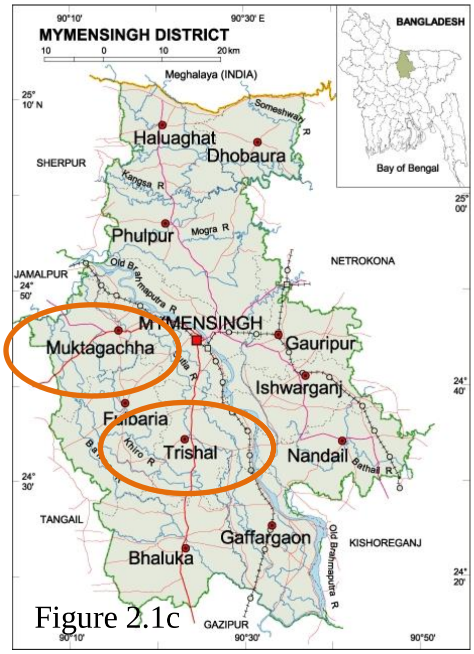


Figure 2.1a: Bangladesh in South Asia (map source: US Central Intelligence Agency)

Figure 2.1b: Mymensingh district in Bangladesh (map source: Wikimedia Commons)

Figure 2.1c: Muktagacha and Trishal sub-districts in Mymensingh (map source: Government of Bangladesh)



2. 3. 5 Selection of Respondents

The farmers for this study (both expert interviews and FGDs) were chosen with the help of local guides. Two people, one in each sub-district, were assigned as a local guide. Both of them were locals in those communities, had long experiences of working for the local office of the

Department of Fisheries as field assistants, and had connections with the farmers. They were thoroughly briefed about the objectives of the study, and the requirements for selection of farmers. All the farmers that would be selected for the study had to have first-hand experience in fish farming, preferably for several years. They had to be able to discuss different aspects of fish farming such as motivation for fish farming, production techniques, prices of inputs and outputs, water use in fish ponds, barriers to fish farming, changes in different aspects of fish farming over the years, local economic conditions, etc. In addition to the general aspects, the farmers chosen for the case studies had to be willing to share their personal experiences, and aquaculture practices. They were assured that their identity would never be disclosed; hence, their personal experiences would be safe to share with the researcher. It was preferred that farmers were articulate in talking about their experiences. Also, if some farmer had some special characteristics (like if he or she was a pioneer of fish farming in his area), they would be given priority for being selected for the interview.

The local guides created lists of farmers (with background information) who should be suitable for expert interviews and FGDs. The listed farmers were then contacted, and after initial screening, the appropriate farmers were chosen for this study. In case of the FGD, 7 farmers were chosen in each sub-district and there was a mix of farmers of different background—for example, farmers cultivating different sizes of farms, coming from different areas within the sub-district, belonging to different age groups, and having different years of farming experience. In case of the case studies, one farmer from each sub-district had to be a small farmer, and the other a large farmer. Also, all the farmers selected for the interview were males. While women are sometimes involved with homestead fish farming, as of now, it is rarely the case that they engage in commercial aquaculture. Only 4% of the fish farming households in Mymensingh district is female headed, according to the IFPRI survey and none of them were available for this study.

The age of the farmers in the focus group discussions was between 35-65 years. Educational attainment ranged between people who had no formal education and people with a college degree. The fish farming area of the respondents were between 0.8-14 acres. Years of fish farming experience varied between 6 and 18 years.

2. 3. 6 Focus Group Discussions

A total of two FGDs were conducted, one at each of the two sub-districts, Trishal and Muktagacha. Each focus group consisted of 7 fish farmers, who came from different locations within the sub-district. The main purpose of these focus groups was to confirm the findings of the in-depth interviews with a larger group of local stakeholders. The sessions were conducted with the help of semi-structured questionnaires, but the discussions were enriched by insights even beyond the questionnaires. The focus group discussions, as well as the individual farmer interviews were conducted in the Bangla language, the first language for both the researcher and the farmers. All the interview participants were briefed verbally, as well as through written documents about the purpose of this study, their roles, and rights. Written consent was obtained for participation and recording of the sessions. Each session lasted for about three hours. All of the participants were encouraged to participate enthusiastically, and requested to ask questions if they needed any clarifications.

2. 3. 7 Interview of Farmers

During the face to face interviews, at first, the respondents were informed about the purpose of the study. There were attempts to build rapport with the interviewees and listen to them empathically. They were asked questions about their household assets, family members, farming practices, economic condition, motivations to engage in fish farming, barriers to fish farming, and how they have faced those challenges.

2. 3. 8 Coding and Data Analysis

The recorded interviews were then transcribed, and coded for the purpose of analyzing the data. Interesting themes relevant to the objectives of this study were identified through coding the transcripts. The codes that were used generate themes like profitability, income, land use, assets, innovation, family business, social network, price increase, diseases, etc. Afterward, the findings have been synthesized in this paper.

2. 4 RESULTS

2. 4. 1 Socioeconomic Profile of Farmers from the Survey Data

In this section we are showing socioeconomic characteristics of the fish farmers in Bangladesh, and the district of Mymensingh. The goal is to provide a broad picture of the socioeconomic profile of the fish farmers before presenting specific cases in the following sections. All the data here is from the IFPRI fish value chain survey. Table 2.1 shows that the average age of fish farmers is 48 years in Bangladesh and 50 years in Mymensingh.

Table 2.1: Age of fish farmers

Age Group	% of respondents	
	Bangladesh	Mymensingh
18-40	33	32
40-55	38	35
55+	29	33
Average	48 years	50 years

Source: IFPRI fish value chain survey 2014

Also, among the farmers, 93% in Bangladesh and 96% in Mymensingh are male, which shows aquaculture is still a male dominated occupation. Table 2.2 describes farmers' educational attainment. In this table, SSC stands for Secondary School Certificate examination, which is a public examination attended after the 10^{th} class, and HSC stands for Higher Secondary Certificate examination, which is a public examination attended after the 12^{th} class. A majority of the fish farmers (65% in Bangladesh and 50% in Mymensingh) are within the range of having between 1 to 12 years of schooling. The literacy rate is higher than the national adult literacy rate of 51% in 2011 (BBS, 2017) showing that people with comparatively more years of schooling are getting involved in aquaculture, but the proportion of highly educated people (degree or above) in aquaculture is lower than the national rate of 7% (BBS, 2017). So, it can be observed that fish farmers can be from different levels of educational attainment, but are more concentrated within a middle range of educational strata. This is possibly because people who have some level of education are more entrepreneurial and can engage in fish farming instead of rice farming; but if they are highly educated they have more opportunities for professional jobs rather than farming.

Table 2.2: Education level of fish farmers

Category	% of respondents	
	Bangladesh	Mymensingh
Illiterate	31	45
Primary (classes 1-5)	25	15
Below Secondary School Certificate (classes 6-9)	26	16
Passed Secondary School Certificate or Higher Secondary Certificate examinations (classes 10-12)	14	19
Degree	4	5

Source: IFPRI fish value chain survey 2014

Next, Table 2.3 shows the main occupation of fish farmers before they got involved with aquaculture. It shows that the primary occupation of majority of fish farmers, before they started aquaculture, was outside of agriculture. In the case of Bangladesh, the main occupation of fish farmers before they started fish farming included about 30% from various wage or salaried services, about 12% from businesses, and about 26% from agriculture (rice or other crops).

Table 2.3: Main occupation before starting aquaculture

Sector of work	% of respondents	
	Bangladesh	Mymensingh
Wage worker / civil servant	30.41	21.43
Cropping & related	25.93	40.71
No work / housework	17.61	7.86
Trader of non-agricultural commodities	6.76	8.57
Trader of agricultural products	5.52	11.43
Transportation (e.g. truck, taxi)	2.14	2.86
Livestock and Fishing	1.42	1.42
Others	10.19	5.72

Source: IFPRI fish value chain survey 2014

This data shows that aquaculture has pulled a section of the population from non-agricultural sections, while other agricultural sectors like crop production are losing people over time (Hossain & Bayes, 2009). However, it should be noted that many people are already involved in multiple professions, as the survey data also shows that 73% of the fish farmers had crop land, and rice was grown in 64% of the plots. A study on fish farmers reported that from 11% to 13% of the household income was from crop farming, while from 5% to 29% was from non-farm sources (Palash, 2015). So, the above analysis is not to show that people had a binary change of profession (from something else to aquaculture), nor is it applicable to understand how much land was being used in crop/rice production. It shows that the overall livelihood strategy of a group of people have changed significantly, as now their largest share of their income is from fish farming.

The predominant source of capital for most people when they first started aquaculture is self-financing (Table 2.4). They invested from their own income and savings. The second largest share is from family (through inheritances, donations, loans, etc.). Borrowing from formal institutions or outside the family does happen, but for fewer than 9% of respondents nationally.

Table 2.4: Source of capital when started aquaculture

	% of respondents	
	Bangladesh	Mymensingh
Own income & savings	75.98	78.58
Family	12.92	12.86
Loan	8.57	5.00
Sale of asset	2.34	3.57
Other	0.19	0

Source: IFPRI fish value chain survey 2014

Finally, Table 2.5 represents statistics on the existence and growth of three supporting industries in aquaculture: feed mills, hatcheries, and input dealers.

Table 2.5: Growth of other sections of fish value chain

	2004	2014	% change/year
Feed mills			
Mymensingh	50	126	15.20
Bangladesh	87	237	17.24
Hatcheries			
Mymensingh	671	2586	28.54
Bangladesh	951	3121	22.82
Input dealers			
Mymensingh	4000	7500	8.75
Bangladesh	7646	15369	10.10

Source: IFPRI fish value chain survey 2014

Here, it can be observed that Mymensingh has a very high concentration of these facilities. The growth rate between 2004 and 2014 is similar in Mymensingh compared to the rest of the country. This shows that Mymensingh is a suitable region for fish farming in terms of input availability.

While these data help to understand the overall socioeconomic context of the farmers, they do not shed light on their decision to engage in fish farming. In the following sections, we will explore those aspects by analyzing the outcomes of the focus group discussions and interviews.

2. 4. 2 Results from Focus Group Discussions at Trishal and Muktagacha

In this section, we are summarizing the key findings from the two focus group discussions. According to the farmers in the interview, about 15% of the total agricultural area in Trishal, and about 10% in Muktagacha is devoted to aquaculture. However, not all areas within those sub-districts have the same concentration of fish farms. Unions (a geographical unit comprising of several villages) like Dhanikhola, Mothbari, Boilar, and Kathal in Trishal, and Kheruajani, Kumargata and Kashimpur in Muktagacha are the areas with higher concentrations of aquaculture. A common theme from both the FGDs is that the regions which have better road access, even landscape, and easy availability of inputs like fish feed and fingerlings are reported as having higher concentrations of fish farming. Another point mentioned in Trishal is that a concentration of people with entrepreneurial skills is also associated with high fish pond concentration. In Muktagacha, the respondents mentioned that areas with a higher proportion of "unemployed rich" people are more suitable to aquaculture growth. The "rich" aspect stands for people from wealthy or land owning families, and unemployed means they are not in any formal job. In terms of physical properties of the land, sandy loam soils were reported to be better for pond construction. On the other hand, places without good road access, and flood prone areas are not suitable for fish farming.

The main motivation behind people getting involved in fish farming is its high profitability. According to the respondents, the profitability of aquaculture was higher than any other enterprise several years ago, when fish prices were satisfactory, while fish feed was cheaper. Also, fish farmers could get easy cash income from selling fish. Moreover, aquaculture is less labor intensive than rice cultivation, and labor availability is becoming a problem in rice production. Moreover, observing the success of one farmer, neighbors would be encouraged to try aquaculture, which indicates that social networks played a role in aquaculture expansion. Also, sometimes people had to convert due to negative externalities of fish farming. A farmer in Muktagacha reported during the discussions that he had crop land next to fish ponds, and water disposed from those ponds had created water logging in his crop land, and he had no means of solving this problem. Hence he was compelled to convert his land to fish ponds. Others agreed that this problem existed, but it is not a very common one. Another motivating factor in the development of aquaculture in both of the sub-districts was a company named Al-Falah, which leased large pond areas and cultivated fish during the 1990s. This helped spread knowledge about fish farming in the area. The company abandoned their fish business at some point, leaving large quantities of fishpond, which were then acquired by other people in the area who continued fish farming in those ponds.

The respondents reported that the trends in profitability started changing from around 2012-13, due to rapid rise in feed prices. Fish is still profitable for most farmers, but the margins are not attractive anymore. Consequently, investments for new fish ponds have stagnated since 2016. This price shock is driving people away from aquaculture. However, there is not much reporting of fish ponds re-converting to other uses; rather, some ponds are remaining idle. Also, fish prices have shown an upward trend since August 2018.

The main problem fish farmers are facing now is the high cost of inputs. According to the farmers, fish prices have increased moderately over the years, but feed and all other input costs, as well as lease value of land have increased significantly. Until around 2012-13, a farmer could make profit in fish farming, even without very judicious aquaculture practices, as the profit margin was higher. Currently, only farmers who are economically efficient can survive in this business. Farmers are also trying to minimize losses by changing or diversifying the fish species they cultivate. Among other problems, farmers reported deteriorating condition of roads, lack of quality medicines, and lack of advice about treatments when fish diseases break out as some of the main barriers to further growth in aquaculture.

Regarding water use, almost all commercial fish farmers use groundwater as supplemental irrigation, and all the pumps under regular use are electricity operated. There are some diesel pumps which are used when electricity is not available. The farmers do not see water or energy as limiting factors in the growth of aquaculture, as they think that there is sufficient supply of these resources.

Focus group participants reported that the socioeconomic condition of both Trishal and Muktagacha has improved significantly due to the expansion of fish farming. A lot of employment opportunities have been created in fish farm and off-farm enterprises (like feed, hatcheries, trading, etc.), which have employed young people. Consequently, crime rates have dropped, according to the respondents.

The respondents mentioned that the growth in fish production can be facilitated if feed prices become lower, quality feed can be ensured, fish can be exported, and extension facilities can be increased.

2. 4. 3 Interview 1: Small Farmer from Trishal

The first detailed case study we are presenting here is from the interview of Mr. R1 from Dhanikhola Union in Trishal. He is 32 years old and has a high school degree (HSC). He lives with his parents, wife, two children, and siblings in a family of eight. He operates about 2 acres of fish ponds. R1 has been chosen as a typical farmer as his farm size (less than 2.5 acres) and level of education are among the most common in his area (Belton et al., 2011).

R1 has been cultivating fish since 2006. He was not involved in any other profession before that. His father got involved in aquaculture during the 1990s. R1 often helped his father with his fish farming activities from a young age. He became interested in fish farming by observing its high profitability. He observed that by investing only 5000 Bangladeshi Taka or BDT (the local currency) or about 60 USD, his father could earn BDT 25000 (about 300 USD). Fish farming also seemed to him a less laborious job, compared to crop farming. Furthermore, he became excited by the scene of trucks coming inside his village to collect the harvested fish when aquaculture was getting popular, as it was an unusual experience to see a motor vehicle inside his village back then.

Eventually, he started his own fish farming in 2006. His father provided him with land (pond). He bought inputs with his own savings. R1 was helped financially by his elder brother during the early days of fish farming, who was working in Qatar and sending money back home.

He mainly cultivates Pangasius and some carp and catfish species. Among the total pond area, about 1.06 acres are family owned, and the rest (0.85 acres) are leased. He sold fish worth about BDT 1,800,000 (about 21,500 USD) during 2017. He performs most of the production activities himself. R1 observed that input availability and market facilities have increased over time. For example, previously they may have needed to go to distant places to sell their fish, but now traders buy fish directly from their ponds. However, there are several problems in fish farming these days. He reported that the quality of fish feed available in the market is declining over time. He is also suspicious that adulterated feed is sometimes sold in the market. Also, aquaculture has become very expensive due to high feed costs, as profit margins have become very thin. However, he observed that no fish farmer in his area has left aquaculture due to the falling profitability, as they are hoping that the situation will change. R1 has also been affected by fish diseases at times when he lost significant amounts of his fish.

R1 has observed remarkable changes in the economic condition of the area. A lot of people have acquired large amounts of wealth through fish farming, and have bought land, built a house, bought a car, etc. The purchasing power of most people has improved. According to him, fish producers had to face more obstacles a few decades back. R1's own economic condition is also good. He has built his own house, which has good sanitation facilities. He believes that he could not have been so successful financially if he was in some other profession.

2. 4. 4 Interview 2: Small Farmer from Muktagacha

The second case we are presenting here is from the interview of Mr. R2, from Muktagacha. He is 28 years old, has a college degree, and currently is a masters student. He lives in a family of three with his parents. He cultivates on 1.65 acres of land. He characterizes himself as a student first and then fish farming as his secondary profession.

His father was a crop farmer during the 1990s. They were also involved in banana and papaya cultivation. These were profitable, but risky due to weather conditions. R2's father was inspired by observing neighbors in the area who were making a profit in fish farming. The father discussed this with the son, who also was enthusiastic about the prospect of fish farming due to high profitability. They also discussed with large commercial fish farmers, and officers from the department of fisheries, who encouraged them to cultivate fish. Eventually, R2's father started fish farming in 2002.

R2 started his own fish farming on a pond of 0.1 acres in 2006. He got land (pond) from his father but took a loan of BDT 50000 (about 600 USD) from the Ansar-VDP (Village Development Police) Bank (a specialized government bank in Bangladesh) to start his own fish farming activity. He bought fingerlings from Bogra (which is about 200 kilometers away) during the first year. R2 used to mostly cultivate Pangasius in the past, but that has become unprofitable for him recently. Now, he mostly cultivates other catfish species, along with carps. In 2017, he sold fish worth BDT 800,000 (about 9,500 USD).

R2 observed that there have been improvements in the supporting market mechanisms over time. Previously, the supply of quality fingerlings was a problem and farmers had to travel far to get quality fingerlings. Now, he has the supply of quality fingerlings in his area. Also, in the past, he would need to go to Muktagacha market for buying other inputs. Now he can buy inputs within his own union.

R2 considers fish farming as a part-time profession, as he is still a student, but earns a decent living through fish farming. He has expanded his cultivated area over time and built his own house.

2. 4. 5 Interview 3: Large Farmer from Muktagacha

The third case we are presenting here is that of Mr. R3, from Muktagacha. He is 35 years old and has a college degree. He has a family of four: wife and two children. R3's family started aquaculture on 0.5 acres of land, but currently they operate on 60 acres of land, of which 25 acres are owned and 35 acres are leased. This is a case of a farm family that started as a small farmer, but got involved in the fish feed and fingerlings business and worked their way to become a large and affluent farmer.

Fish farming is a family business for R3 as his elder brother initiated this business in 1997. The name of their business is AF. R3 has been engaged in this since 2005, and now he is the main person responsible for aquaculture, while his brother is engaged in other business. The land is jointly owned by the family. They also run a fish feed business. Their farm has about 80 permanent staff including both the aquaculture and feed production parts.

The elder brother of R3 was a crop farmer before starting aquaculture in 1997. He owned about 5 acres of land, but back then, the financial condition of their household was not good, and they could barely meet their needs. He faced several difficulties in rice production, such as labor shortages (and increasing price), fertilizer shortage, increasing cost of diesel, and shortage of farm machinery, which made rice production unattractive from a financial perspective. He got to know from friends that fish farming was a profitable enterprise. He consulted his father-in-law, who lives in a nearby village, and who encouraged him to start fish farming. Initially, he converted about half an acre of his cropland to a fish pond. They leased some land over the years. However, when the Al-Falah fisheries company sold their assets in 2009, they purchased and/or leased portions of their land, and R3's family fish farm had a significant increase in size.

The source of financing to start aquaculture was agriculture. They made some savings from rice production, which was invested in starting fish production. They also owned some trees, some of which were sold in order to meet the initial investment costs. Also, they owned a share in a deep tubewell, which provided some cash for this purpose.

The main obstacle R3's family faced during the earlier stages of their fish farming was the availability of inputs. Fish fingerlings were not available in Mymensingh during their earlier days in fish farming, and they had to purchase from Bogra. There was also shortage of materials for fish feed. The family started the fish feed business and established a hatchery. These businesses were successful, which helped them financially and provided capital to acquire Al-Falah's leftover land and assets. Their activities also helped other fish farmers in the area by supplying feed and fingerlings, and also providing information to others on fish farming techniques.

R3 was working part-time in the feed business while he was a student and gradually got to learn about various aspects of fish farming. So, after completing his studies, he was more interested in joining this thriving business than looking for a salaried job. His brother also encouraged him. Eventually, the brother got more involved with other business, and R3 now runs the fish farms and feed mill.

Their financial status has significantly improved; R3 has recently purchased 7 acres of land, and can adequately support his family. The family also owns land that is in other uses. The people of the locality regard the story of R3's family becoming from "zero to hero" through aquaculture. So, R3 and his family's case is one of a farm family with a high level of education, starting as a small fish farmer, then getting involved in other aspects of the fish value chain, becoming successful in all of these, and becoming a large and affluent fish farming family.

2. 4. 6 Interview 4: Large Farmer from Trishal

The final detailed case of a fish farmer we are presenting here is from the interview Mr. R4, from Trishal. He is 38 years old and has a bachelor's degree in Fisheries from Bangladesh Agricultural University. He has a family of five: wife and three children. This is an interesting case, as people of such academic accomplishment rarely get directly involved in fish farming. The advanced technical skills of R4 enabled him to run the fish farming activities of a company with innovative farm machinery.

R4 first got involved in fish farming around 2006. He is not the owner of the land he operates, as it belongs to an agro fisheries company (BAF), which is a part of a larger agribusiness company. R4 initiated the agro fisheries wing of the company and has overseen the production process ever since. The agro fisheries company currently operates on 400 acres of land and has its own hatchery. The parent company also has a feed mill. Around 2010, they operated on about 500 acres of land, but some of it has been released. The fish farm BAF has about 150 permanent staff and employs more people on a temporary basis.

R4 was interested to engage in this profession because he needed to earn money immediately after graduating from BAU due to family needs. Unlike his other friends from BAU, who wait for years to get a government job or some other salaried job, he started working for BAF in the fish farming sector. Since he was a fisheries graduate, he was enthusiastic to work directly in the fish production process as a means to do experiments on the production system. This was an unusual choice of profession for a graduate like him in Bangladesh, but he did not face adverse social pressure as those were the "golden days" for fish farming in Trishal.

R4 is an innovative person, who has developed several tools and machines using his own knowledge. He has received training from the Department of Fisheries of the government, Bangladesh Agricultural University, Bangladesh Fisheries Research Institute, and also from institutions in Thailand and the Philippines. BAF uses a lot of advanced machinery in the production process, like aerators, large blower, oxygen diffuser, etc. some of which are available in the market, but some are R4's innovations (improvements from existing technologies). He established a re-circulatory aquaculture system in this farm, investing about BDT 6,000,000 (more than 70,000 USD).

The main product mixes in his pond are carp with Tilapia, and carp with Pangasius. During their initial years of farming, they would purchase fingerlings from the Bogra district. But now they have developed their own hatchery. So not only do they grow their own fingerlings, but also they sell fingerlings to others.

R4 also talked about challenges his farm faces now. The main problem is the low price of fish relative to input prices. He thinks that the fall in fish price is due to supply being greater than the demand at the national level. He believes that there are two ways to solve the crisis: create opportunities for export or reduce production at the national level. He is trying to establish a system of freshwater fish export from his area.

R4's own economic situation has significantly improved due to engagement in fish farming. He came to this profession during times of economic distress, but over time he has become a wealthy person. He has also observed significant improvement in the economic condition of Trishal over time. However, he mentioned that many people are moving away from fish farming due to decline in profitability and many more may go in the near future if the price trends do not change.

2. 5 DISCUSSION

Some of the common themes that have emerged from the interviews are summarized here. First of all, people have chosen to engage in fish farming due to high profit margins during the 1990s up to around 2012. Those were the times of low input costs, but steady increase in fish prices. These observations are consistent with literature, as the benefit cost ratio of Pangasius fish farming in Mymensingh was reported to be between 1.64 to 2.12 in two studies based on data from 2005 and 2007, while it was about 1.3 from a study based on data from 2012 (Ahmed et al., 2010; Alam, 2011; Jahan et al., 2015). So, investing in fish farming was a very attractive business. People did continue to join after 2012, but at a slower rate. Second, people need some assets to start fish farming, whether it is physical capital, human capital, or social capital. Land was an important asset in this case. Once there was access to land, either self-owned or family owned, the other investment costs were manageable. Loans were also available from formal or informal sources. Some level of education was also a facilitating factor. People with education and assets such as land were not too concerned about not having enough rice, and were willing to take some risks. Third, social networks also play a crucial role in disseminating information and influence decision making. All the successful farmers had some assistance from other farmers (either a family member or a neighbor) who were cultivating. They were not just motivated by those farmers; they also actively sought advice from those farmers. Fourth, social approval of fish farming was already there in the community when the farmers in these case studies came into fish farming, and this played a crucial role in their decision making. They entered fish farming during the "golden days" of fish farming in their areas. Some people had already earned a fortune from aquaculture. Hence, even though R2, R3, and R4 were educated and could have gone into salaried professions; they had not faced many social obstacles on their way to coming to fish farming. Rather, their families and peers encouraged them. So, the profitability of fish farming created social approval for the professions which made their decision making process easier. The situation can be different in another part of the country, where there are no successful farmers.

Fifth, there have been major structural changes in the market environment. Two decades ago, entry costs were low, but input access was more difficult. Fish farmers had to travel 200 kilometers to get fingerlings, plus feed and other inputs were not as easily available as now. While those have changed, now prices of inputs are high, and output prices have not increased correspondingly, making fish farming much less attractive. Finally, as the market conditions are getting tougher, larger producers and small but efficient established producers have a higher prospect of surviving, while less efficient small farms may perish, and new entry can become increasingly difficult. The last two points have implications for decisions regarding whether farmers want to continue with fish farming or not, and whether new people are willing to engage in aquaculture or not.

There are also contrasts in the cases mentioned above. For example, R4 was highly skilled in aquaculture, so he could manage to get engaged in cultivating a large area of land, even though he did not own those lands. Also, R4 had the most advanced tools and machinery in his farm, which small farmers in his area could not afford. R3 also had some advanced machineries, but his main advantage was that his family entered into fish feed and hatchery business. Both the large farmers were highly educated and employed a large number of people, while small farmers performed the daily functions themselves. Both the large farmers were less dependent upon the market, as they had their own input supply mechanisms. So, it can be seen that capital endowments influence the decision about the scale of aquaculture activity someone can undertake. R1 was successful enough to expand his farm over time, and earn a decent living, but he did not expand as much as R3 could.

2. 6 CONCLUSION

So, we have seen that aquaculture growth has benefitted many people by providing better income and employment opportunities. The profitability of aquaculture was the main motivating factor for people to be engaging in aquaculture. However, access to physical, human and social capital was necessary to get involved, and change in the social perception towards aquaculture was also a contributing factor. The continuation of a favorable environment can encourage people like R3 and R4, who can contribute by developing supporting industries, or pushing the frontiers of technological adoption, and consequently encourage more people. However, this positive feedback can be affected by high entry costs and rising input prices. While toughening of the market conditions can mean an exodus of less efficient farms, and thus increase in aggregate economic efficiency, it can also mean growth rates slowing down over time. Large and efficient farms may still be able to thrive by innovating or adopting more advanced technologies, taking advantage of export potentials, or just because of their scale advantage in production. But since most people may not have such advantages, more research and extension is necessary for sustaining the growth of aquaculture. These research should include studying other segments of the fish value chain, like fish feed, hatchery and marketing, from the perspective of economic efficiency in order to identify problems and improve economic performance of those sections; as well as scientific research to provide better technologies for efficient use of feed, improving quality of feed and fingerlings, improving pond management practices, advancing the use of modern equipment, etc., all of which will help improve fish farm performance. Besides, the fish extension services are weaker than crop extension service in Bangladesh and strengthening of the fish extension services can help better disseminate new and existing technologies, and motivate people to engage in improved fish farming practices.

APPENDIX

Appendix: All Interview Questionnaires

The research instruments were approved by the Institutional Review Board at Michigan State University (reference: STUDY00001030). All the conversations were in Bangla, the language of the researcher and all the experts. After the interviews, the recorded audio was transcribed first in Bangla, and then translated to English, which was then coded, and findings were used in the analysis for this paper. The focus group and individual interview questionnaires are presented in this section.

I. Focus Group Discussion Interview Protocol

Goals

- Introduce research
- Identification of socioeconomic and environmental context of the study areas in collaboration with stakeholders
- Describe and receive feedback on system structure and boundaries

Objectives

- Confirm reference timeline and system boundaries
- Check resources/ecosystem services
- Identify key drivers of change
- Corroborate model structure and facilitate parameterization

Activities

- Presentations
  - Introduction to project
  - Defining the system under study
    - Geographic scope
    - Key resource issues (land use change, water & energy use)
  - Timeline: present draft timeline in opening presentations
- Resource mapping

- Use available maps to start discussion
  - Check aquaculture concentrated areas
  - Less concentrated
- Annotate to identify land use types/resources/infrastructure
  - Roads, Housing Settlements, Markets
  - Input Suppliers
  - Ag Land
  - Water Bodies
  - Land Types
- Demonstrate how we'll turn this into maps

- Group discussion: feedback on research – conversation with stakeholders focus group style for
  - Opinions on current system structure: relationships between system components
  - Understanding farmer's land use and financing decisions
    - why they do what they do
    - types of land, and how they are used
  - Understanding farmers' motivation to invest in fish farming
    - farmers' motivation in fish farming
    - relationship between profits and investment
    - sources of financing (what proportion of capital is from loan)
    - how much reinvested for development
  - Discussing farmers' constraints to invest in fish farming
    - financial and physical constraints: why all farmers not convert
    - how much more land can be brought under aquaculture
  - Understanding the role of various institutions and government policy in this process
  - Understand water. energy, and other input use in fish and rice production systems
    - water use: depth of ponds, how much water (stock), how much refilled, sources of water
    - energy use: main purposes, sources and respective quantities

II. Questionnaire for Farmers

A. Basic Information about the Respondent

Name of the Interviewee Address Mobile Phone Age, Education & Household Primary Occupation Other Occupation Prior Occupation	

B. Land Information

	2017	2014	2010
Homestead area			
Pond area			
own			
leased in			
leased out			
Crop area			
own			
leased in			
leased out			
Other			

C. Income Sources

Sources	2017			2014	2010
Fish farming	qty	price	value	value	value
Gross Income					
Rice production					
Other crop production					
Livestock production					
Non-farm income					
Remittances					
Other Income					

D. Farm Expenditure

Sector	2017			2014	2010
	qty	price	value	value	value

Fish farming					
land use					
fingerlings					
insecticide					
lime					
feed					
medicine					
fertilizer					
machinery					
Others					
	2017			2014	2010
Labor	qty	price	value	value	value
family labor					
short term labor					
permanent labor					
Infrastructure					
new					
repairs					
Other expenses					
Total Expenses					
Crop farming					
land use					
seed					
fertilizer					
pesticides					
machinery					
family labor					
short term labor					
permanent labor					

E. Water Use

Purpose	2017			2010		
	quantity	source	price	quantity	source	price
Pond filling						

F. Fuel Use

Purpose	Source	2017		2014	2010
		Quantity	Price		

G. Local Economic Situation

1. How has the economy of your area changed over …….. years?
2. Have you (personally) experienced any economic change over this period?
   - Tell me about how your income/asset ownership/means of communication and transportation/consumption have changed

H. Crop Production Activities

3. When did you first start crop/rice farming? How did you obtain the land?
4. What are your sources of labor? What about other farmers in the area?
5. What are your sources of capital? What about other farmers in the area?
6. What are the other inputs you use? When you started, where did you buy inputs from? Are they different now?
7. What varieties do you cultivate? What about others in the area?
8. What are the sources of water for you? What proportion came from what source? Discuss this for others in the area.
9. What are the sources of energy for you? What proportion came from what source? Discuss this for others in the area.
10. What are the major constraints for rice/crop farming?

I. Motivation for Fish Farming (fish farmers only)

11. What was your main occupation before starting fish farming?
12. When did you become interested in aquaculture? Can you tell me a story about what motivated you the most? In which year did you make the shift? What motivated other people in your area to shift to fish farming?
13. Were there any fish farmers in your village back then? How well did you know them? How often would you interact with them?
14. How did extension agents talk about fish farming before the transition? In what ways did you see information about fish farming in mass media outlets (newspapers, radio, television, etc.) before the transition?
15. What are the main constraints for starting fish farming?

J. The Act of Shifting and Fish Production Activities (fish farmers only)

16. What did you need to do to start fish farming? How did you finance it? Is this same for other fish farmers? Please explain.
17. Did you start with existing ponds, or did you converted rice/crop lands? Did you own that land/pond?
18. What were the initial constraints?
19. Where did you buy fish seeds/fingerlings from? Are they different now? Discuss how the fish seed/fingerlings supply has evolved.
20. Where did you buy fish feed from? Are they different now? Discuss how the fish feed supply has evolved.
21. Where did you buy other inputs from? Are they different now? Discuss how the supply of other inputs has evolved.

22. Whom do you sell your product to? Were they different when you first started? Did they exist 10 years ago?
23. Where did you learn about techniques in aquaculture (farming practices)? What type of formal or informal training did you get?
24. What species do you cultivate? What about others in the area?
25. What are the sources of water for you? What proportion came from what source? Discuss this for others in the village.
26. What are the sources of energy for you? What proportion came from what source? Discuss this for others in the village.

K. Investment Decisions

27. How much money did you earn from rice/crop or fish farming in 2017? What about previous three years?
28. How much money did you spend on existing rice/other crop or fish enterprises in 2017? Can you please explain why you made this choice? What about previous three years?
29. How much money did you invest in expanding rice/crop farming in 2017? What about previous three years?
30. How much have you invested in new ponds and how much in new fish technologies in 2017? Can you please explain why you made these choices? What about previous three years?
31. Did you borrow money for fish farming in 2017? What about previous three years?
32. Did you convert any own rice/other crop land to fish farming over the last three years? Can you please explain why you made these choices?
33. Did you buy any farm machinery over the last three years? Why, or why not?
34. Did you introduce any new rice varieties, or crops, or fish species over the last three years? Why, or why not?
35. How have you intensified production (increase stocking density, feeding rates, etc.) over the last three years?
36. Have you invested in other agricultural (like livestock) or non-agricultural enterprises in 2017? Can you please explain your choice? What about the previous three years?

III. Questionnaire for Policy Makers and Extension Agents

Basic Information about the Respondent

Name of the Interviewee			
Address			
Mobile Phone		Date	
Expertise	☐ Fish Extension	☐ Rice Extension	☐ Policy Maker

1. Discuss land, water, and energy availability for agriculture
   - What are the major trends in land use in agriculture for Bangladesh/Mymensingh?
   - What are the major trends in sources and quantities of water use and energy use in agriculture for Bangladesh/Mymensingh?

2. Sketch and discuss current status of land, water, and energy use in crop and fish production
   - What are the key stocks within land distribution in the area? How are they changing?
   - How much water is being used in aquaculture? What are the sources?
   - How much energy is being used in aquaculture? What are the sources?
   - Data or research on land, water, and energy use in aquaculture

3. Identify the major drivers of land conversion to aquaculture, and intensification of fish farming
   - Who are the fish farmers? What are their main socioeconomic characteristics? How are they different from other farmers?
   - What motivates someone to engage in aquaculture? Please talk us through their decision making behavior (economic incentives, social attitudes, resource availability, etc.).
   - How does he/she finance it?
   - What motivates an existing fish farmer to expand fish farming? Please talk us through their decision making behavior?
   - How does he/she finance it?
   - What motivates a fish farmer to intensify fish farming? What are the main methods in intensifying production (new varieties/more inputs/machineries etc.)? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - Are there socioeconomic feedbacks that govern the behavior of conversion or intensification?

4. Identify the major constraints of land conversion to aquaculture, and intensification of fish farming including land, labor, cash, feed or other inputs, technology, water, energy, etc.
   - What are the main barriers to expanding fish farming?
     - Why don’t all land owning or capable farmers engage in fish farming?
   - What are the main barriers to intensifying fish farming?

5. Discuss the potential changes in land use and intensification of aquaculture in future
   - What is the direction of resource use in fish production?
   - What will be the main limiting factors to aquaculture growth in the future? Please discuss in relation to land, water and energy availability.

6. Discuss the impact of aquaculture growth on sustainable use of land, water, and energy resources
   - What is the extent of pressure that an expanding aquaculture sector may exert on the natural resources of our country?
   - How is land use changing as a result of aquaculture growth? Are there indirect impacts?
   - Do you think we can grow sufficient food of different types (rice, vegetables, etc.) if aquaculture growth continues?
   - How is water utilization changing as a result of aquaculture growth?
   - How resilient are our water supply to an expanding aquaculture sector?
   - How is energy efficiency changing as a result of aquaculture growth?
   - How resilient are our energy supply to an expanding and intensifying aquaculture sector?
   - Identify major feedbacks that can influence the outcome of natural resources use

7. Discuss policy options for influencing long term outcomes
   - What policy tools are available to influence land, water, and energy use behavior of farmers?
   - What policy measures do you think should be used for ensuring sustainable use of land?
   - What policy measures do you think should be used for ensuring sustainable use of groundwater?
   - What policy measures do you think should be used for efficient use of energy?

IV. Questionnaire for Scientists

Basic Information about the Respondent

Name of the Interviewee			
Address			
Mobile Phone		Date	
Expertise	☐ Fish Scientist	☐ Rice Scientist	☐ Social Scientist

8. Discuss land, water, and energy availability for agriculture
   - What are the major trends in land use in agriculture for Bangladesh/Mymensingh/Trishal?
   - What are the major trends in sources and quantities of water use and energy use in agriculture for Bangladesh/Mymensingh/Trishal?

9. Sketch and discuss current status of land, water, and energy use in crop and fish production
   - What are the key stocks within land distribution in the area? How are they changing?

10. Identify the major drivers of land conversion to aquaculture, and intensification of fish farming
    - Who are the fish farmers? What are their main socioeconomic characteristics? How are they different from other farmers?
    - What motivates a crop farmer to convert to fish farming? Can you please talk us through their decision making behavior (economic incentives, social attitudes, resource availability, etc.)?
    - How does he/she finance it?
    - What motivates an existing fish farmer to expand fish farming? Can you please talk us through their decision making behavior?
    - How does he/she finance it?
    - What motivates a fish farmer to intensify fish farming? What are the main methods in intensifying production (new varieties/more inputs/machineries etc.)? Can you please talk us through their decision making behavior?
    - How does he/she finance it?
    - What proportions of their income are reinvested to aquaculture for expansion and/or intensification?
    - Are there socioeconomic feedbacks that govern the behavior of conversion or intensification?

11. Identify the major constraints of land conversion to aquaculture, and intensification of fish farming including land, labor, cash, feed or other inputs, technology, water, energy, etc.
    - Why don’t all land owning or capable farmers engage in fish farming?
    - What are the main barriers to expanding fish farming?
    - What are the main barriers to intensifying fish farming?

12. Discuss the potential changes in land use and intensification of aquaculture in future
    - What is the direction of resource use in fish production?
    - What will be the main limiting factors to aquaculture growth? Please discuss in relation to land, water and energy availability.

13. Discuss the impact of aquaculture growth on sustainable use of land, water, and energy resources
    - How is land use changing as a result of aquaculture growth? Are there indirect impacts?
    - How is water utilization changing as a result of aquaculture growth?
    - How is energy efficiency changing as a result of aquaculture growth?

14. Identify the resilience of the natural resource systems to the intensification of resource use
    - Do you think we can grow sufficient food of different types (rice, vegetables, etc.) if aquaculture growth continues?
    - Do you think we can grow sufficient food of different types if aquaculture growth continues?
    - How resilient are our water supply to an expanding aquaculture sector?
    - How resilient are our energy supply to an expanding and intensifying aquaculture sector?
    - What is the extent of pressure that an expanding aquaculture sector may exert on the natural resources of our country?

15. Identify major feedbacks that can influence the outcome of natural resources use

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CHAPTER THREE

A SYSTEM DYNAMICS MODELING APPROACH TO THE STUDY OF LAND USE CHANGE DUE TO FRESHWATER AQUACULTURE GROWTH IN BANGLADESH

3. 1 INTRODUCTION

Land utilization by human beings is continually changing over periods of time and across regions. Globally, cropland has increased from 265 million hectares in the year 1700 to about 1471 million hectares in 1990, while pasture area has increased from 524 to 3,451 million hectares during the same period (Goldewijk, 2001). These changes occur due to human actions, as well as natural phenomena (Verburg et al., 2004; Rai et al., 2017). Pervasive changes in land use and land cover around the world have a significant impact on Earth systems functioning (Lambin et al., 2001; Lambin & Meyfroidt, 2011). This study is about understanding how land use has been changing in the specific country context of Bangladesh, as a result of growth in freshwater pond aquaculture.

Bangladesh is a country with high population density, and even though the country has fertile land suitable for agriculture, its land resources are under pressure from competing uses for agriculture, urbanization, and other uses. The highest proportion of its land is devoted to rice farming, which is essential for supplying the population with its staple food crop. Recently, Bangladesh has experienced significant expansion in freshwater pond aquaculture production, with area increasing about 44% between 2001-02 and 2016-17[1] (DoF, 2017). Most of this expansion is coming from conversion of croplands. Land conversions in certain areas are much higher than the national conversion rates. For example, the districts of Mymensingh and Jessore experienced 333% and 208% increases in pond area during this time (DoF, 2017). This can be a good thing from the perspective of supplying more dietary protein to its population. Hence, it can be argued that this trend needs to continue in order to meet the future demand for fish protein which is expected to increase further with rising incomes, while supply from natural sources keeps declining. However, the conversion of land from rice production may have adverse impacts on the supply of rice, by reducing rice cropped area. Hence, there can be trade-offs associated with this phenomenon.

Several studies and policy documents have raised the concern of loss in crop lands to other uses (Rahman 2010; Quasem, 2011; Hasan et al., 2013; GED, 2015; Rai et al., 2017), while various studies have talked about the benefits of aquaculture growth for the country in terms of increase in protein supply, income and employment opportunities (Jahan et al, 2010; Toufique & Belton, 2014; Ahmed & Toufique, 2015; Belton et al., 2015). However, this trade-off has not been studied so far. This paper uses System Dynamics modeling to build a model that represents the dynamics of land use change from crop to fish production and simulates regional land allocation over time. The objective is to understand which key variables are influencing this conversion process, and how changes in parameters can influence the outcomes in the future.

This study, at first, builds a System Dynamics model of land conversion from crop production to aquaculture based on existing literature and expert opinion. Then, it parameterizes the model between years 2004 and 2016 with data from several secondary sources: two household surveys, government reports, published papers, and research reports, as well as data obtained from expert interviews and focus group discussions. Next, the model is used to simulate future trends in model outcomes, and test sensitivity of key parameters in the model. Thus, this paper will demonstrate the trade-offs between rice and freshwater fish production in Bangladesh, and how the outcomes may change over time.

3. 2 BACKGROUND

3. 2. 1 Global land use change

The changes in land use and land cover can substantially alter the energy balance and biogeochemical cycles of the world, which in turn contributes to environmental change, affecting properties of the land surface and the provisioning of ecosystem services (Song et al., 2018). Factors like population growth, economic and technological development, environmental changes, etc. are linked with such changes (Lambin et al., 2001; Lambin & Meyfroidt, 2011; Rai et al., 2017). Some of the major forms of changes in land use observed globally are deforestation, rangeland modification, agricultural intensification or extensification, alteration of wetlands, and urbanization; and these changes are interlinked with feedback mechanisms governing their behavior (Lambin et al., 2001; Verburg, 2006; Rai et al., 2017). Among the changes, studies have mostly focused on understanding causes and consequences of changes in forest cover and other natural ecosystems (Lambin et al., 2001; Lambin & Meyfroidt, 2011; Song et al., 2018). However, one area which has received less attention is land use change within sectors of agriculture, where agriculture includes crop, livestock or fish production. If two or more agricultural enterprises that use the same type of land are experiencing different economic and/or environmental conditions over time, then land use change may happen even within the agricultural sector. And if these two enterprises have differences in resource intensities in their production system, then it is important to study how this change can impact the broader natural resource system.

3. 2. 2 Modeling land use change

There is a wide body of literature on the study of land use change, and they follow a diverse set of approaches. In section 3.2.1, we have mentioned various types of land use changes, and several papers have reviewed them. For example, Lambin (1997), and Kaimowitz & Angelsen (1998) reviewed studies on deforestation, Miller et al. (1999) on integrated urban models, Lambin et al. (2000) on agricultural intensification models, and Bockstael & Irwin (2000) on land use models grounded on economic theory. Also, Briassoulis (2000) provided a more extended review of all types of land use models. From a methodological perspective, three broad approaches are usually taken for the study of land use change: the narrative, the agent-based, and the systems approach (Briassoulis, 2000). In a complex system of combined economic and ecological components, a formal modeling approach is necessary in understanding quantitative relationships, nonlinearities, and time delays (Costanza & Ruth, 1998), and both the agent-based and the systems approaches develop such models (Briassoulis, 2000). The agent-based perspective seeks to understand how individual decision-making can generate emergent behavior. On the other hand, the systems perspective finds understanding in the organization and institutions of society that establish the opportunities and constraints on land use decision making (Ostrom, 1990, cited in Briassoulis, 2000).

Studies have also shown that projections of land-use changes can be performed either by empirical models based on an extrapolation of the patterns of change observed over the recent past, or dynamic simulation models based on a thorough understanding of the processes of land-use change (Lambin, 1997, cited in Stephenne & Lambin, 2001). However, a statistical modeling technique is only suitable for providing insight into the empirical relationships over a system's history or for short term projections, but it is of limited use for long term analyses of a system's future development path under alternative scenarios (Allen, 1988, cited in Costanza & Ruth, 1998). Dynamic modeling has advantages over statistical modeling by representing the structure of a system (Hannon & Ruth 1994, 1997). Hence, this study will follow this approach with system dynamics modeling.

System dynamics is a modeling technique that represents a dynamic system through "stocks" – an accumulation of material or information that has built up over time – and "flows", and "feedbacks" or the relationships between them. It is based on cybernetics, systems theory and information theory. It can reveal the relationship among influencing factors and perform a dynamic simulation test. An important aspect of this technique is the recognition of the feedback process within the system that regulates its behavior over time. There are two types of feedbacks: positive or reinforcing and negative or balancing. The strengths of this method come from understanding the function of the feedback process in the system, along with time delays, and nonlinearities that regulate the system, and demonstrating the possible effects of policies on its behavior (Sterman, 2000; Daniels & Walker, 2012). Hence, this can be a good method of understanding the behavior of complex systems such as land use in rice and fish production, which is comprised of socioeconomic and bio-physical actors or drivers (Meadows, 2008; Daniels & Walker, 2012). Also, by connecting the economic system with the physical environment it resides in, it offers a "macroscopic" view of the system.

3. 2. 3 Land utilization in Bangladesh

As one of the most populous countries in the world, with 162 million people living in an area of 56,977 square miles, there is immense pressure on land use in Bangladesh. In 2015-16, about 54% of total land was used for agricultural production, while 24% was used for infrastructure, 17% was forest cover, and about 4% was fallow land (BBS, 2017). Out of the many dynamic changes that are happening, loss of agricultural land is one of the main concerns as agricultural land area is declining due to urbanization, industrialization, construction of rural infrastructure, soil salinization, etc. (Rahman, 2010; Quasem, 2011; Halim et al., 2013; Rai et al., 2017). The outcome of change in land cover over the period from 1970 to 2010 is shown in Figure 3.1.The loss from crop land during 1976-2000 was estimated at 0.14% per year and 0.73% per year during 2000-2010, showing acceleration of the rate of loss (Hasan et al., 2013). It is also important to note the size of land holdings. Currently, per capita agricultural land is 0.05 hectares, which is the lowest per capita land ratio in the world (Rai et al., 2017), and will be further decreased to 0.025 ha by 2050 (GED, 2013). This shows the predominance of small scale farm households, and that further decline in farmland per household is expected to happen. Small farm households who are poor, tend to devote their land for the staple crop first, as a safety first approach for guarding against food market failures.

As population and national income continues to rise, demand for food keeps rising. Hence, the pressure on agricultural land use in Bangladesh is growing, and loss of crop land to other uses has been recognized as a looming crisis by several studies and policy documents (Rahman 2010; Quasem, 2011; Hasan et al., 2013; GED, 2015; Gurung et al., 2017; Rai et al., 2017;).

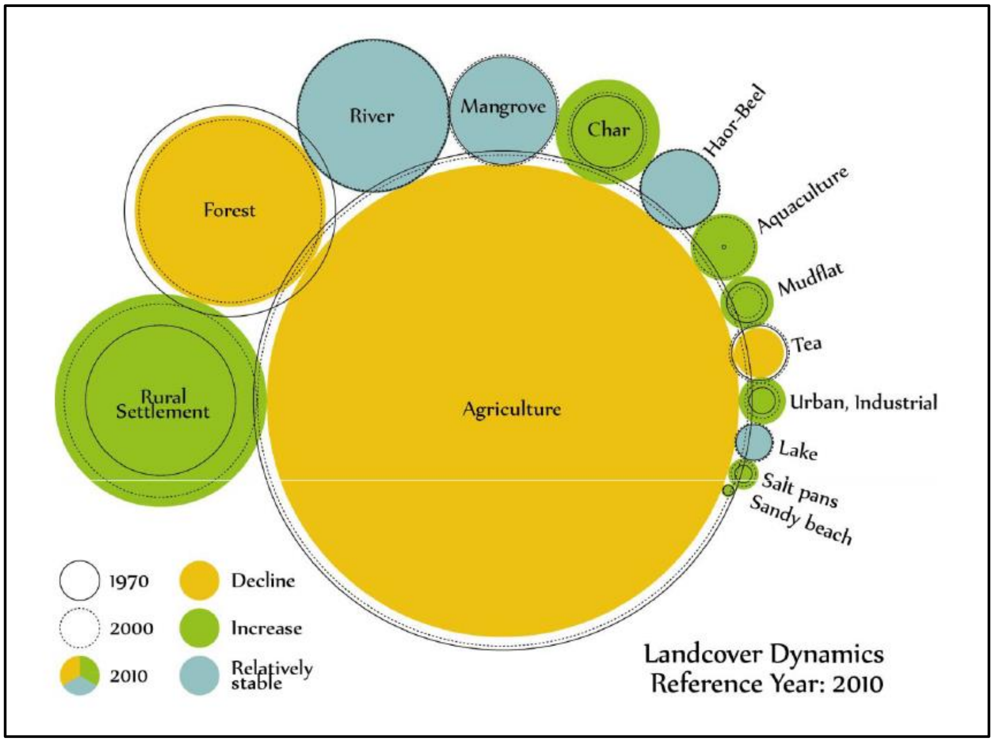


Figure 3.1: A graphical representation of land cover change in Bangladesh over 1970-2010 (Source: Hasan et al., 2013)

However, one area which has received little attention so far is land use change within agriculture. Among various crops, rice cultivation dominates all, as it is cultivated in nearly 75% of cropped land in Bangladesh (BBS, 2017). Pond area has increased by about 119,000 hectares between 2002 and 2017 (DoF, 2018). There have been some studies on conversion of rice area to brackish water shrimp cultivation in the coastal districts during the 1980's and 90's (Ito, 2002; Paul & Vogl, 2011; Swapan & Gavin, 2011; Rai et al., 2017). However, studies on how much crop land has gone to the more recent freshwater aquaculture revolution are rare. Some papers have shown and aquaculture experts have mentioned that new fish ponds are mostly converted from active crop lands or at least potential crop lands (Ali & Haque, 2011; Palash, 2015), and Figure 3.1 is an indication that after rural settlements, conversion to aquaculture is the sector where significant amount of crop lands have been converted. Land used for rice cultivation is often also suitable for fish farming, hence a target for conversion. Theoretically, forest land can also come under fish farming, a phenomenon reported in case of expansion of brackish water shrimp farming near the mangrove forest. However, no study or reports so far have stated that has been happening in the case of freshwater fish farming (Jahan et al., 2015; Palash, 2015). This can be partly because of the regions where freshwater aquaculture have taken place have little or no forests, and partly because of the cost of converting forest land is higher compared to crop or fallow land (Bockstael & Irwin, 2000). Some forest land does come under crop production, but at the national level, forest land has stayed almost the same between 2004 and 2015 (declining by just 0.8%, BBS, 2017), and hence we are not including this type of conversion in the model.

Conversion from a rice field to a fish pond is a type of "permanent" change, as land that goes away from crop production in this way typically does not come back in the short run.

3. 2. 4 Change in agricultural productivity

The loss of crop land has been offset to some extent by gains in crop productivity. The rice production system has been transforming by introduction of new varieties, increased use of fertilizers, expansion of irrigation, technological advancements in processing, etc. (Reardon et al, 2012; Minten et al, 2013; Deb, 2016), which have led to significant increases in rice production over the last three decades. Average yield of rice has increased from 1.43 metric tons per hectare in 1984-84 to 3.04 metric tons per hectare in 2014-15. Therefore, the loss of rice land has not been observed to have caused a shortfall in rice production at the national level so far. However, the gain in productivity may not continue at the same rate in the future and demand for rural and urban settlements are expected to grow faster, exacerbating pressure on land use.

3. 2. 5 Agricultural land conversion and link with food and nutrition security

Growth in freshwater aquaculture is generally seen as a good thing for the economy of Bangladesh. Some sections of the population do not get enough protein from their diet, which highlights the importance of fish, as about two-thirds of animal protein comes from fish consumption (BBS, 2011). Experts have routinely emphasized the need for diversification of the diet; and growing economies, as well as changing consumer attitudes are making people demand higher quantities of protein food like fish. Studies on contributions of fish farming to food and nutrition and food security (Jahan et al, 2010; Toufique & Belton, 2014; Ahmed & Toufique, 2015) have shown that the growth of aquaculture has improved food and nutrition security by increasing availability of fish to consumers in Bangladesh

However, the dietary habits of the people of Bangladesh make them one of the highest per capita rice consumers in the world (Helgi Library, 2018; IRRI, 2018). Rice supplies more than 60% of the dietary calories, 45% of dietary protein, and constitutes 40% of total food expenditure on average for the people of Bangladesh (BBS, 2011). Expenditure on rice can be around 40% of total expenditure for the poorest sections of the population (BBS, 2011). This share is likely to decline as the country's economy grows, but as of now, rice is the single most important food in Bangladesh. Hence, the poor net consuming households are more vulnerable to increasing rice prices. Therefore, if any decline in rice area leads to shortages in production and consequently higher prices, poorer sections of the population suffer as a result. Bangladesh produces most of the rice it consumes, but is still a net importer of rice (BBS, 2017). During the 2008 global food price rise, when real rice prices became 33% higher than 2007, a good number of households were pushed back into poverty (FAO, 2009). Also, during that crisis, it was demonstrated that dependence on rice imports may not be reliable for a staple crop of such importance, as most exporting countries declined to export, and that destabilized the local rice markets (WFP, 2009). Hence, the political economy of the country is heavily dependent on production and the stability of rice markets, and a steady decline of crop land can be a problem for maintaining production levels. Land conversion to freshwater fish farming can add to this problem in the long run.

Therefore, it needs to be recognized that there are trade-offs in land use, and hence, it is important to analyze the dynamics of land conversion in order to understand to what extent aquaculture growth can become a threat for rice production in the long run, or to what extent the aquaculture sector can continue to grow and provide the benefits associated with it. Studies have so far highlighted the role of fish production on food security, but the possibility of this trade-off has not been studied in depth.

3. 2. 6 Research Question

On the basis of the situation described above, this essay aims to answer the following research question:

- What are the dynamics of land conversion to aquaculture over time, and what key variables are influencing the transformation process?

3. 3 METHODOLOGY

3. 3. 1 Introduction

This study will use system dynamics modeling in understanding land use change in Bangladesh in the context of aquaculture growth. The goal of this paper is to provide a framework to understand the impacts of economic and biophysical factors on land use change over a period of time, taking into account interactions and feedbacks between the environment, economy, and the society, and SD is appropriate for this purpose. Before explaining that in more detail, we first construct a conceptual framework for this study, and then provide an overview of modeling approaches to the study of land use change in the following two sections.

3. 3. 2 Conceptual Framework

This section provides a conceptual framework of what drives land use change. The land allocation decision of a farmer is regulated by several economic, social and bio-physical variables. Economic theory predicts that a household would allocate land in such a way that maximizes its expected utility or return from the land. A simple characterization of this situation can be found in Bockstael (1996), which explained that based on the goal of profit maximization, a parcel j, which is currently in state u, will be converted to state r in time t if

$$W_{jrt|u} - C_{jrt|u} \geq W_{jmt|u} - C_{jmt|u} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

for all land uses $m = 1, \ldots, a, \ldots, M$

where $W_{jrt\,|u}$ is defined as the present value of the future stream of returns to parcel j in state r at time t, given that the parcel was in state u in time t – 1 and $C_{jrt\,|u}$ is defined as the cost of converting parcel j from state u to state r in period t. In plain words, this means that land will be converted to a particular use if the present value of the future stream of return for that use minus the cost of conversion is greater or equal to the present value of future stream of return minus cost of conversion to any other land use. This characterization is from a micro perspective and motivated by land rent theories of Von Thunen and Ricardo (Verburg et al., 2004), where utility optimization is the assumed behavior, and a parcel of land is allocated to the use that earns the highest rent (Jones & O’Neill (1992) and Chomitz & Gray (1996), both cited in Verburg et al., 2004).

Research across the world has shown that land use change commonly happens due to people's responses to economic opportunities, and is mediated by institutional factors, while demographic and geographical factors also play important roles (Lambin et al., 2001). Studies in Bangladesh by Palash (2015) and Gurung et al. (2016) on land use change from crop to fish farming also stated that higher income from fish was the main motivation for land conversion by farmers.

However, when using this framework to understand aggregate land use decision in a region we need to consider that there can be non-linear relationships between the conversion cost C (or return W) and states r and u due to ecological and socioeconomic causes. This means that the costs (or returns) can vary for the same parcel of land "j". This variation can be idiosyncratic, for example, the desire of a small farm household to hold on to land for staple crop production (in presence of market imperfections) can mean that it has higher opportunity cost of conversion. On the other hand, this variation can also be common at the regional level, but vary across time or space. For example, the marginal cost of land conversion can change as quality of the land can vary within a region. Such biophysical factors may not directly 'drive' land use change, but can constrain land use allocation decisions (Verburg et al., 2004). Therefore, it will be important to follow a modeling technique that considers such biophysical as well as socioeconomic constraints.

This research will be modeling aggregate behavior using SD, not individual behavior of farmers. In this model, on one hand, farmers are motivated by relative income opportunity from fish production, and increasing demand for aquaculture land to invest in fish farming. On the other hand, the conversion of crop land to fish pond is regulated by the cost of conversion, and the supply of land conditional on biophysical properties of land.

3. 3. 3 Description of The System Dynamics Model: Stocks and Flows

In this section, the structure of the system dynamics model for this study will be explained (Figure 3.2). The software Stella Architect has been used for building the model and running simulations. The structure will help explain the land use dynamics of a region, irrespective of the geographical scale. Later on, when the model is parameterized, it will be first done for a district, and then for the whole country. These two scales have been chosen as this research aims to understand the general trend of the country, but also focus on a smaller geographic area, in order to gain in depth understanding of the phenomenon. Due to time and resource constraints, it was not possible to study multiple districts. So, this study focused on Mymensingh, the district that has had the highest aquaculture growth rate in Bangladesh over the last two decades (DoF, 2017). The following is the model structure built using the Stella Architect software.

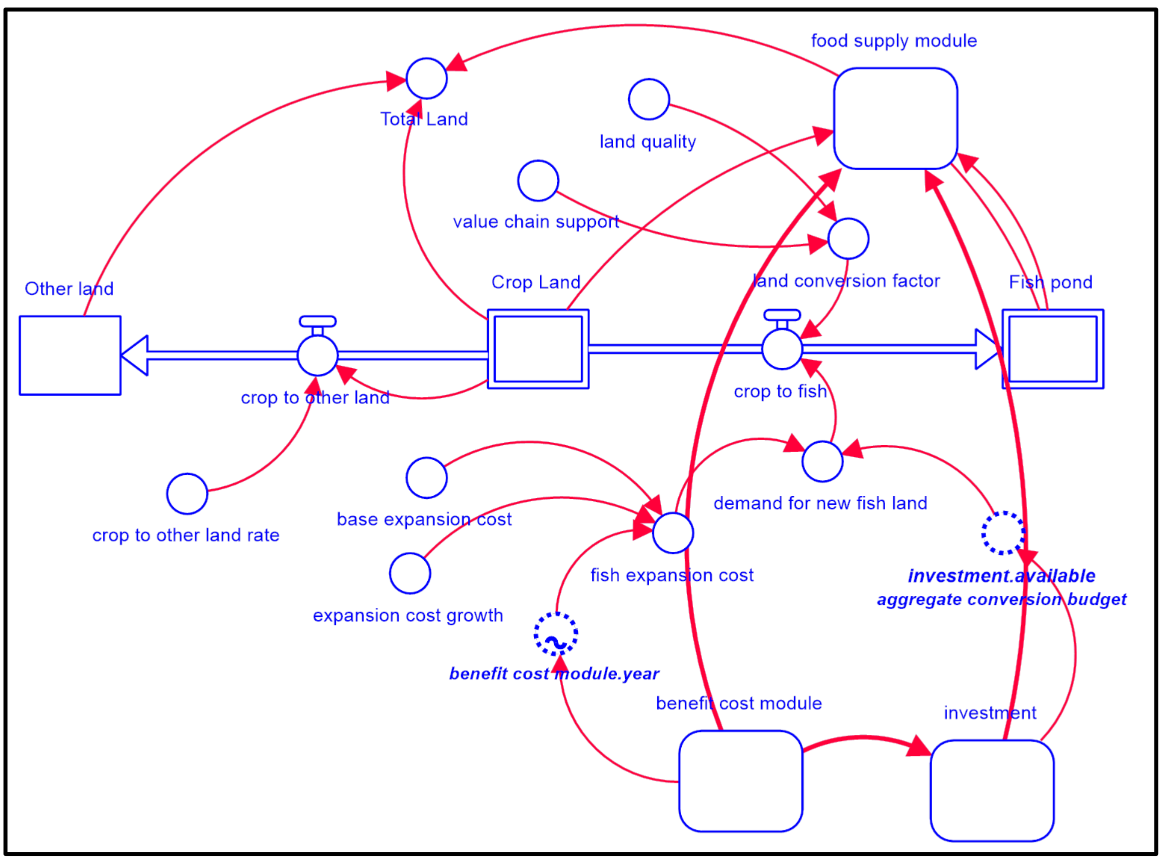


Figure 3.2: System dynamics model of land use change

Now, we can think of land allocated to different uses within a community as stocks of land, where land can be converted from one use to another (equation 2).

$$Land_{total} = land_{crop} + land_{fish} + land_{other} \ldots\ldots\ldots\ldots\ldots (2)$$

In this model (Figure 3.2), total area of a region has been divided into three stocks of land: crop land, fish pond, and other lands, which represent land quantity in hectares (these stocks are presented in the Appendix 3C showing their unit and source of data). Here, crop area includes fallow land as those types of land can be easily used for crop production. Although this paper is mostly concerned with conversion of rice area to fish, this model uses the term “crop land”. It has been already mentioned that 75% of the gross cropped area in the country is under rice cultivation. The gross area considers cultivation during multiple crop seasons on the same land. In practice, most of the agricultural land in Bangladesh cultivates rice at least once during a year, so we are terming this variable as such, but when necessary, we can work with only the rice area. Also, “other land” includes forest area and non-agricultural area (housing, roads, offices, etc.).

There are a total of two flows in this model. The flow named “crop land to fish pond” shows conversion of land units from crop production to fish farming over a time. And the flow named “crop to other land” shows conversion of crop land to other uses (like house, roads, shops, etc.). The mathematical expression is shown in Appendix 3B equation (1). This study assumes a constant conversion rate between crops to non-agricultural land, as detailed modeling of this relationship is beyond its scope. This rate can be obtained from published literature (Quasem, 2011).

The model assumes permanent conversion of land from crop fields to fish ponds and other categories. Theoretically, the conversion from a crop field to a fish pond can be reversed, but that is unlikely to be economically profitable, and field interviews for this study suggest that this happens very rarely. Also, conversion from crop field to houses or other permanent infrastructure is almost never reversed. Similarly, conversion from fish ponds to houses or other permanent infrastructure is possible, but has neither been observed in the field work for this study nor in published literature. Hence, the model ignores such conversions.

It should be noted that this model does not consider the ownership aspect of the land, just the aggregate quantity of the land. So, the model does not say whose land is being converted (it can be the person who is already cultivating fish, or a rice farmer, or people from other professions). Since people can buy or sell and also lease in or out land through the land rental market, theoretically, any parcel of land can be converted to a fish pond. Also, this implies that even if some individual farmers are leaving fish farming, land conversion can still continue, as small number of farms or individuals can obtain the land of those leaving, and expand production.

One of the main interests in this model is the crop land to fish pond conversion flow, which controls how much land is converted from crop to fish in each time period (year). This conversion process has a demand side and a control or supply side. The "demand for new fish land" is a variable with units as hectares of land. The "land conversion factor" is a variable which is a fraction, ranging from 0 to 1.

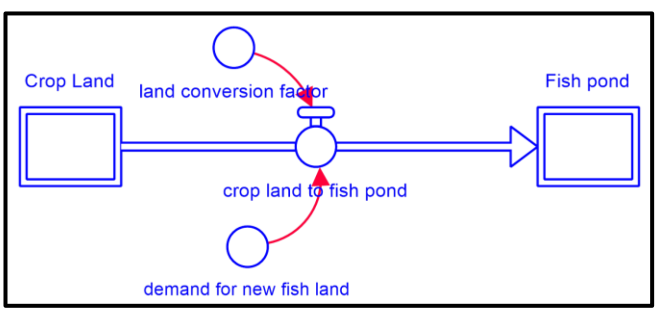


Figure 3.3: Crop land to fish pond conversion flow

The crop land to fish pond conversion flow is then hectares of land derived through the multiplication of demand for new fish land and the land conversion factor (Appendix 3B equation 2). Next, the demand for new fish land side of the model consists of a benefit cost module, and an investment module.

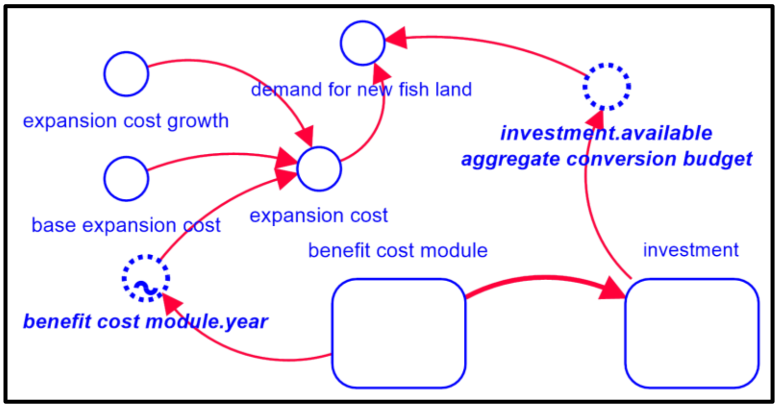


Figure 3.4: Demand for new fish land

Inside the benefit cost module, the total cost and returns of fish production per hectare is calculated (Figure 3.5). The model initiates from a base year (2004), so cost, return, and yield figures are initialized for that year. As their values change over time, this model incorporates annual growth rates for each item separately. So, for each item, there is a base year value and then it increases over time at a fixed rate (Appendix 3B equations 6-7). The growth rate in each variable has been added as a separate variable in order to test for different scenarios of growth rates, or sensitivity of the model to these growth rates. The cost part is separated into feed cost, labor cost, fingerlings cost, and other costs per hectare. This is done so that the model can observe changes in these specific cost items on the model outcome. The mathematical expressions of the benefit cost analysis equations are included in Appendix 3B.

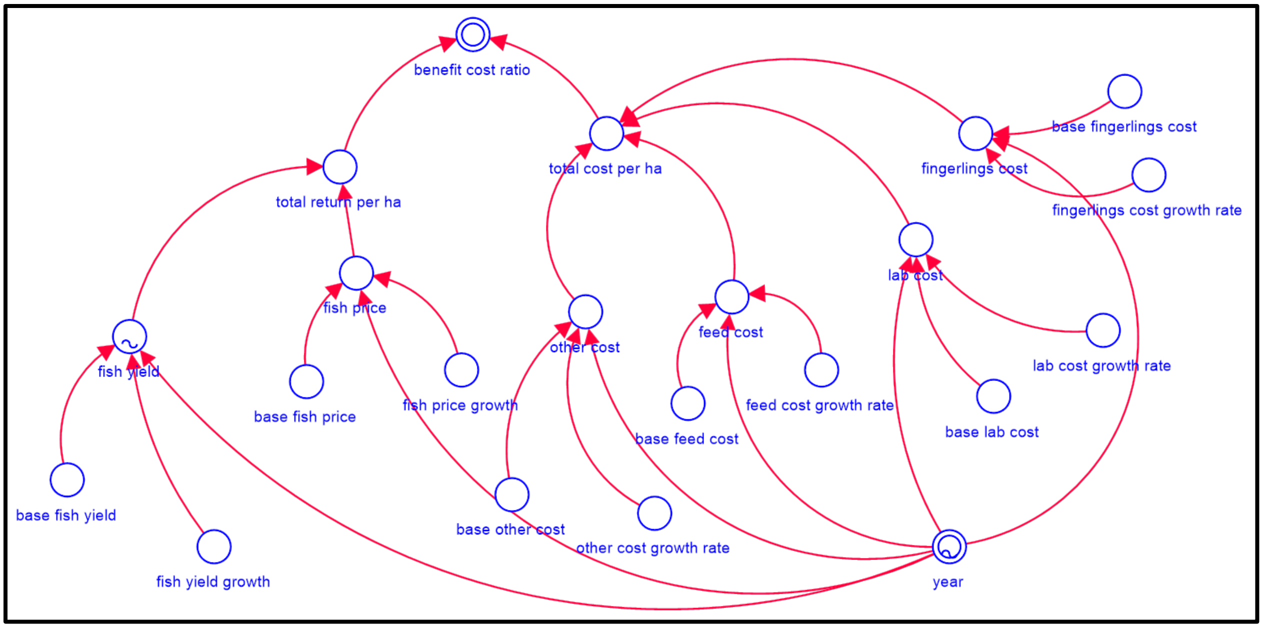


Figure 3.5: Benefit cost module

Next, there is the investment module, which sets a rule that if the benefit cost ratio is more than one, then households invest for converting crop land to fish ponds. However, the capacity to invest depends on the wealth of the households. This investment figure is derived from a household survey titled Bangladesh Integrated Household Survey (BIHS), which is a panel dataset of 2015 and 2012 with information on income, expenditure, asset ownership, etc. of about 6500 households in Bangladesh. By deducting pond area owned between two years, we can calculate the change in pond ownership between these years. Then, by multiplying the land amount with lease value (as a “shadow” land use cost), we construct a variable that serves as a proxy for households’ willingness to invest in fish pond expansion, and name it average pond investment by farm size. The investments are categorized by size of farm land operated by the household as the BIHS dataset shows that households with larger land holdings invest higher for expanding fish farming (Appendix 3D). This is expected as investment in fish farming requires higher initial capital (compared to crop farming), and wealthier people are in a better position to do so. The Bangladesh Bureau of Statistics categorizes farm households on the basis of land ownership into small farms (less than 1.01 hectares), medium farms (between 1.01 to 3.03 hectares), and large farms (more than 3.03 hectares). Although farm size is not the sole determinant of household wealth, this model denotes it as a proxy for their wealth, and therefore households are grouped on the basis of their land ownership into these three groups from the BIHS data, and the average household investments for new ponds are calculated for them.

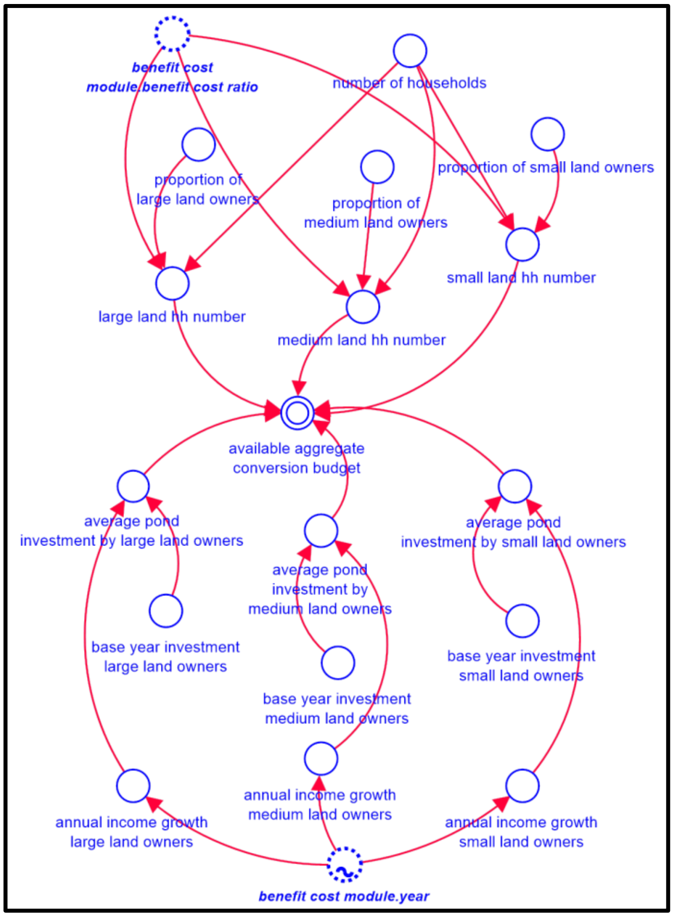


Figure 3.6: Investment module

Now, by multiplying the number of households in each category with their average investment in a year, and then summing up the three categories, the model generates a pool of money in the area which is ready to be invested for expanding aquaculture, which has been labeled as "available aggregate conversion budget". The mathematical equations for this variable are shown in the Appendix 3B (equation 8).

Next, we return to the main model frame for estimating the demand for new fish land (Figure 3.4). Here, there is a "fish expansion cost, which is the lease value for bringing one hectare of land into pond production. As we did inside the investment module, we are using lease value of land as the shadow cost of expanding fish farming. Now, dividing available aggregate conversion budget by the fish expansion cost, the model estimates the amount of land that has the potential to be converted to fish farming, which shows the demand for new land that is "wanted" for fish production in a year (Figure 3.4).

However, this entire amount of land does not come to aquaculture. The factors that act as limiting factors for aquaculture land expansion include land quality, availability of inputs and other infrastructure, small farmers' need to hold on to crop land (mainly for the staple crop), road access, etc. (Palash et al., 2015; Palash & Bauer, 2017). This takes us to the next part of the model. The "land conversion factor" variable, which ranges between 0 and 1, controls how much land can be converted. So, if it takes the value 1, then the entire demand for new fish land will be met, and so on. Next, we are explaining how this variable has been constructed.

This variable has been constructed based on two factors: quality of land, and support available from related industries. Again, quality of land depends on several factors. The first factor being considered is the elevation of land, as that determines how easily the land can get flooded. Based on that characteristic, land is generally classified in Bangladesh into five categories: high, medium high, medium, low, and very low categories. There are also other quality characteristics of the land that are relevant for conversion from crop lands to fish ponds. For example, crop land can be classified on the basis of how many times a year they are cultivated, which effects how profitable a piece of land can be for cropping, and under this categorization there are: single, double, and triple cropped areas. Also, there are different soil textures in Bangladesh: clay, loam, silty, sandy, and a combination of these, and some are more suitable for a pond than others. Most of the ponds in Bangladesh are on sandy loam, clay loam, and loam soils (Jahan et al., 2015). However, there is very little data about the land characteristics that influence the conversion process, so it is difficult to define a composite land conversion factor. Studies have mentioned (Jahan et al., 2015; Palash et al., 2015) and experts have stated that relatively lower lands (but which are not flood prone) are more suitable for aquaculture, and are the ones first to be converted in an area. Hence, this study assumes that the proportion of crop land that falls in either of the two extreme categories in terms of elevation (high land or very low land) are proxies for crop land unfavorable for conversion to fish farming. For example, the proportion of high land and very low land in Mymensingh and Bangladesh are 38%, and 28%, respectively, so the model assumes that land quality conversion factors for Mymensingh and Bangladesh are 0.62 and 0.72, respectively. However, these are not strict boundaries, as those types of land can also be converted with additional costs, which may be social costs (better roads, flood control measures, etc.) and/or private costs (higher dikes, extra cost for groundwater, etc.). This rate can also be affected by conversion of crop land to other uses. For example, the best quality land can be used for building houses, leaving less land for fish ponds. So, the proportion of these types of "unfavorable" land can either increase or decrease over time, and there is no data on the trend for this variable. Hence, this assigns a probabilistic annual value to generate land conversion factor related to quality, based on the proportion of high land and very low land discussed above. We will test for sensitivity of this assumption in the analysis.

The second factor for estimating the land conversion factor in this model is the access to inputs and other market services, as market access for input or outputs can be a limiting factor to growth of any industry. Several studies have highlighted the contribution of the growth in input supplying and facilitating industries (feed mills, hatcheries, input dealers, traders, retailers, etc.) on aquaculture growth in Bangladesh (Palash, 2015; Hernandez et al., 2017, Hu et al., 2017). Data from the IFPRI fish value chain survey shows that input supplying firms in Bangladesh that support fish farming are highly concentrated around the Mymensingh region, and have experienced the fastest growth in that area. Field interviews have revealed that these firms and entities also contribute to farming by disseminating knowledge, and providing informal training. Mymensingh is also home to Bangladesh Fisheries Research Institute, and Bangladesh Agricultural University (which has Faculty/College of Fisheries), the two leading fisheries research and education institutions in Bangladesh. Since, there is no data on the quantitative relationship between input supply or market access, and aquaculture growth, this model assumes that Mymensingh has a perfect environment for aquaculture expansion from the perspective of input supply, market access, and dissemination of knowledge, and the land conversion factor remains at 0.62. Then, we compare the concentration of supporting firms (feed mills, hatcheries, etc.) in Bangladesh (or any other geographic scale) with Mymensingh to determine the impact of this factor. The average concentration of input supplying firms in Bangladesh, expressed in number of firms per unit area is about 1/12th of the concentration in Mymensingh (IFPRI fish value chain survey 2014). Hence, this model assumes that the land conversion factor for Bangladesh is 0.06 (=0.72/12). The sensitivity of these assumptions will be tested in the analysis.

Finally, by multiplying the land conversion factor with the demand for new fish land, this model estimates the amount of land converted in each time period (Appendix 3B equation 2).

The last part of the system dynamics model is the food supply module (Figure 3.7). In this part, the impact of the change in land use on calorie and protein supply is modeled. There are rice production and fish production modules within this system (Figures 3.8 and 3.9), which estimate rice and fish outputs based on area coverage and yield from previous parts of the model.

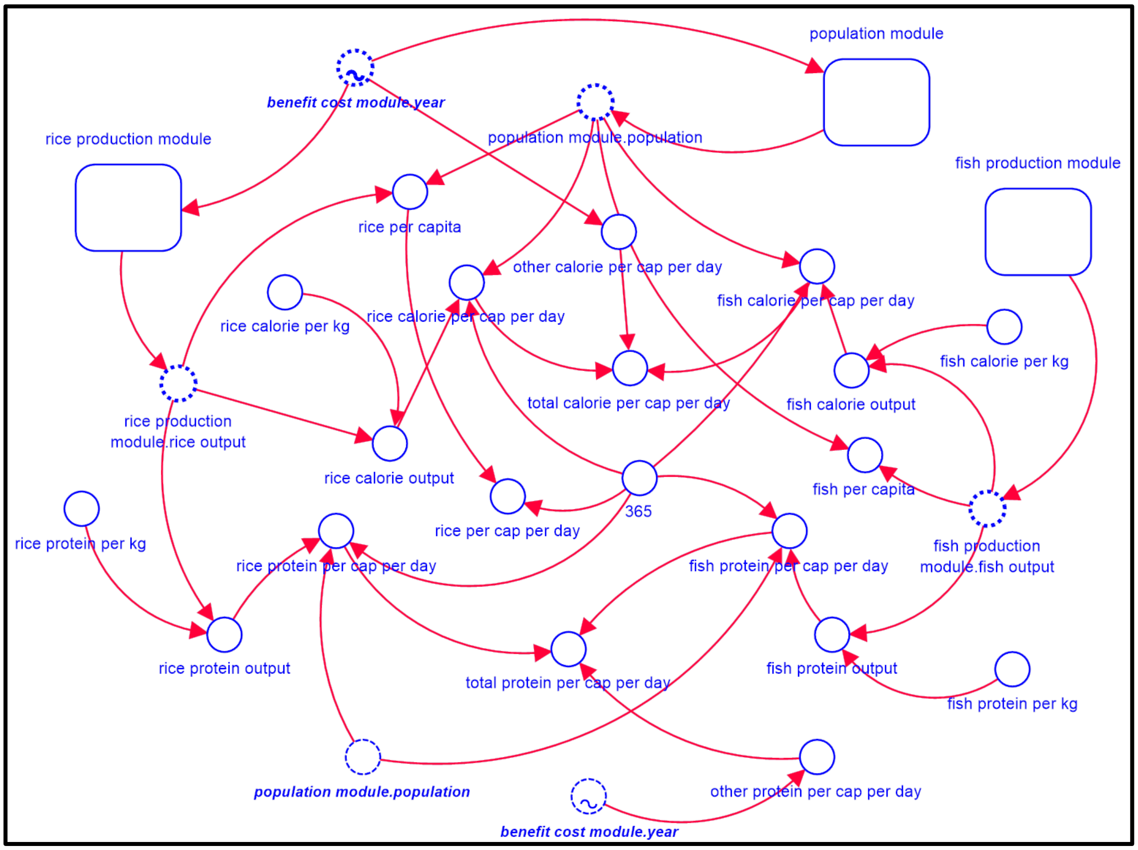
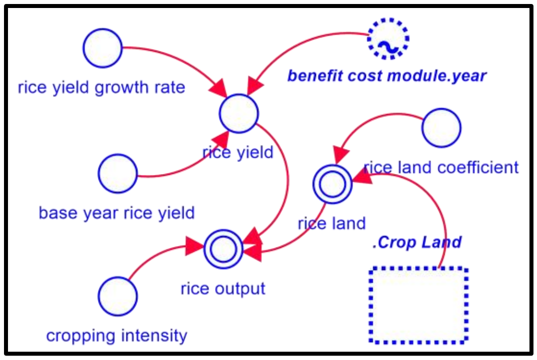


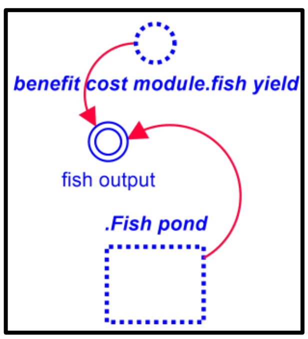
Figure 3.7: Food supply module

The rice production module has some extra calculations, as the modeling so far considered crop land, which included non-rice crops as well. Now, multiplying the crop land with a coefficient showing proportion of rice land in relation to crop land, we get quantities of rice land. Also, since rice can be produced multiple times a year, the seasonal yield needs to be multiplied by cropping intensity factor to generate annual rice output.



Figures 3.8: Rice production module

Then, these rice and fish output quantities are divided by population (shown in Figure 3.10) and multiplied by their average calorie and protein coefficients, which shows the average calorie and protein outcomes per capita for the change in land use. The annual figures are also divided by 365 in order to generate calorie and protein availability per day.



Figures 3.9: Fish production module

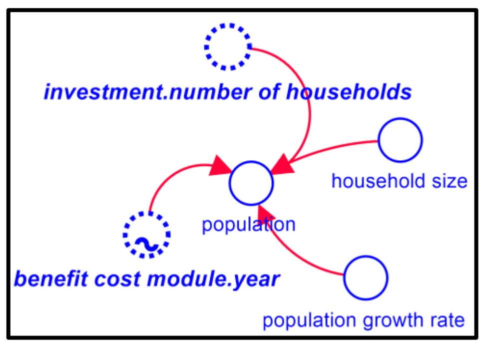


Figure 3.10: Population module

3. 3. 4 Feedbacks in the System

There are four feedbacks within the model that can lead to either higher or lower conversion from one type of use to another. There are two types of feedbacks: positive or reinforcing and negative or balancing. Some of the main feedbacks in this system are described below.

Balancing 1: *Crop fields → crop to fish (or crop to other land) conversion → suitable land decline → slower conversion*

The more fish ponds we already have, the less suitable land is left, and therefore the rate of conversion slows down.

Balancing 2: *Fish ponds → profit from fish → faster conversion → crop land decrease → rice output decline → small holder investment decline → slower conversion*

Higher profitability of fish can motivate further conversion of land from rice cultivation, and thus creating a reinforcing or positive feedback loop that diminishes rice area further. However, if the decline in rice area creates a shortage of rice in the community, some small land owning households may resist the shift to aquaculture, thus creating a balancing or negative loop which prevents land conversion.

Reinforcing 1: *Fish ponds → profit from fish → investment → faster conversion → fish pond increase*

As more income is generated from fish farming, it can be re-invested in aquaculture, that is, more land can allocated for aquaculture. This creates a "reinforcing" feedback loop, where fish ponds lead to even more fish ponds.

Reinforcing 2: *Higher fish yields → higher benefit cost ratio → higher investment → higher feeding and stocking → fish yields increase*

Higher yields lead to higher profit generated from fish farming, which can be re-invested in aquaculture. This can be used for purchasing higher amounts of feed and fingerlings, subsequently leading to higher yields.

3. 3. 5 Data

The system dynamics model requires data on land use in rice and fish production and other uses as the stock variables. The research will depend more on primary data to build the model structure, and secondary data to parameterize the models. However, primary data from focus groups or expert interviews will also be used for parameterization in absence of appropriate secondary data. The sources of data are described below.

3. 3. 5. 1 Primary Data Collection

Primary data was collected through fifteen expert interviews, and two focus group discussions. Experts were chosen based on their expertise on the subject. The purpose of the focus groups and farmer interviews was to gain in depth knowledge about farmers' experiences in fish farming. The interviews are based upon semi-structured questionnaires (Appendix 3A). The research proposal and instruments were approved by the Institutional Review Board at Michigan State University (reference: STUDY00001030).

There were a number of initial field visits to locations which are important for aquaculture growth in Bangladesh, and also to several research organizations which work on relevant areas. During these visits there were a good number of informative discussions with several agricultural economists, fisheries or aquaculture scientists and professors, agronomists, environmental science professionals, rice and fish extension agents, rice and fish farmers, different government officials, and local people in different parts of the country. The experts mentioned above have been from a diverse set of institutions which include Bangladesh Agricultural University (BAU), Bangladesh Fisheries Research Institute (BFRI), Bangladesh Rice Research Institute (BRRI), Bangladesh Agricultural Research Institute (BARI), Bangladesh Agricultural Development Corporation (BADC), Department of Agricultural Extension (DAE), Department of Fisheries

(DoF), WorldFish, International Rice Research Institute (IRRI), Center for Environmental and Geographic Information Services (CEGIS), Institute of Water Modeling (IWM), University of Rajshahi, Barind Multipurpose Development Authority, Bangladesh Bureau of Statistics, Ministry of Land, etc. Also, experts who would be most insightful and helpful for this study were identified from these discussions. The selection of farmers was done differently, which we will describe later.

In the next stage, 15 experts were formally interviewed with semi-structured questionnaires. The main profession of the experts and the reasons they were approached for this study is presented in Table 3.1.

Table 3.1: List of experts participating in interviews

Profession	**Why chosen for this study**
Professor of agricultural economics	to understand land use change issues from rice to fish production from a socioeconomic perspective
Professor of fisheries and policy maker	to understand broader picture of aquaculture development
Professor of aquaculture	for his expertise on aquaculture technologies as well as land use change issues
Agricultural engineer/scientist	getting expert opinion with water use modeling
Agricultural engineer/scientist	getting insights for understanding water use in crop production
Agricultural engineer/scientist	getting insights for understanding energy use in crop production
Crop extension officers (2 persons)	obtaining information on multiple aspects of crop production
Fish extension officers (3 persons)	obtaining information on multiple aspects of fish production
Fish farmer (2 large farmers)	understanding practical experience of fish production for large farmers
Fish farmer (2 small farmers)	understanding practical experience of fish production for small farmers

During the formal interviews, the objectives of the study were explained, and interviewees were asked a set of questions relevant to aquaculture conversion. The questionnaires were tailored for the type of expert. Most of them were also informed about the system dynamics model, and the model was presented in front of them for comments or feedback.

The system dynamics model has been parameterized at two different geographical scales: nationally, and at a district level. The interviews with scientists and other professionals contained information for both scales. However, the farmer interviews and focus group discussions (FGD) required selection of specific locations. The district level was important for in depth understanding of the issues on the ground. Also, due to time and resource constraints it was not possible to study multiple districts. So, this study focused on Mymensingh, the district that has had the highest aquaculture growth rate in Bangladesh over the last two decades (DoF, 2017). Again, within Mymensingh, two sub-districts with high aquaculture concentration were selected, namely Trishal and Muktagacha. Two fish farmers from each sub-district, one large and one small were interviewed. The local crop and fish extension agents from these sub-districts were also interviewed. The following maps in Figure 3.11 show the location of Bangladesh and the study areas within Bangladesh.

Figure 3.11a

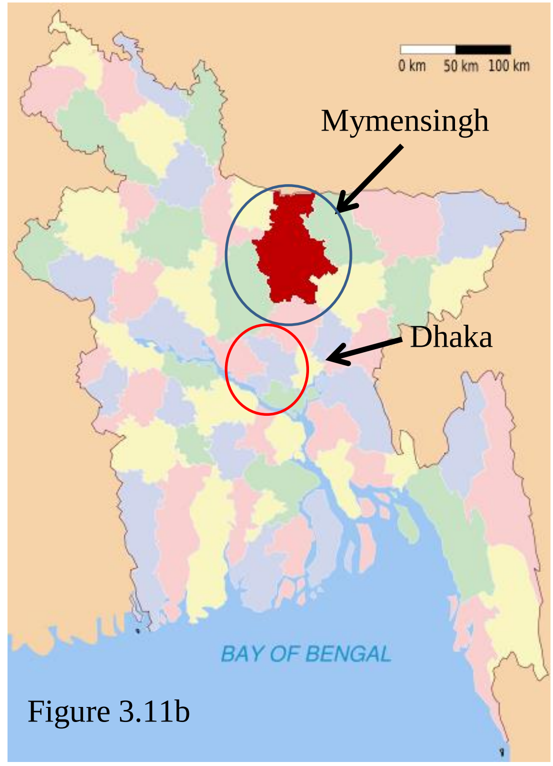


Figure 3.11b

Figure 3.11a: Bangladesh in South Asia (map source: US Central Intelligence Agency)

Figure 3.11b: Mymensingh district in Bangladesh (map source: Wikimedia Commons)

Figure 3.11c: Muktagacha and Trishal sub-districts in Mymensingh (map source: GoB)

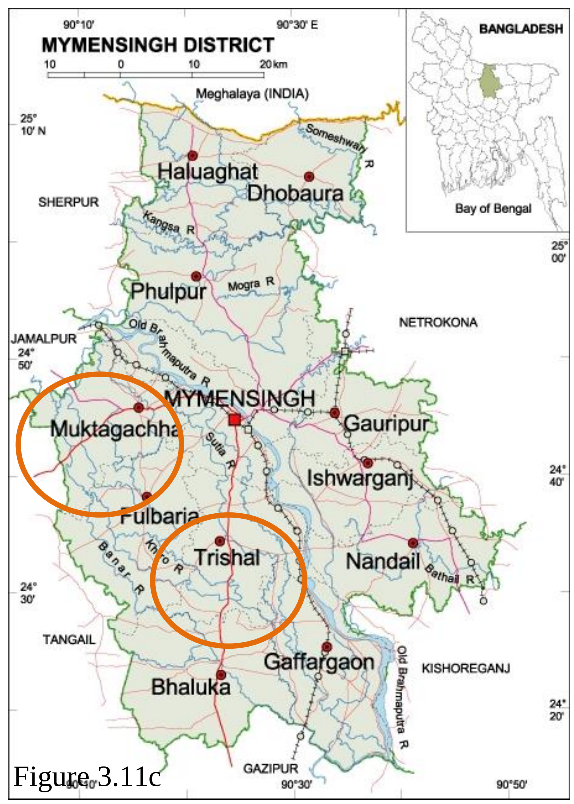


Figure 3.11c

Another source of primary data was the two FGDs, conducted at these two sub-districts. The farmers for this study (both expert interviews and FGDs) were chosen with the help of local guides. Two people, one in each sub-district, were assigned as a local guide. Both of them were locals in those communities, had long experiences of working for the local office of the Department of Fisheries as field assistants, and had connections with the farmers. They were thoroughly briefed about the objectives of the study, and requirements of selection of farmers. All the farmers that would be selected for the study had to have first-hand experience in fish farming, preferably for several years. They had to be able to discuss about different aspects of fish farming like motivation for fish farming, production techniques, prices of inputs and outputs, water use in fish ponds, barriers to fish farming, changes in different aspects of fish farming over the years, local economic conditions, etc. It was preferred that farmers were articulate in talking about their experiences. Also, if some farmer had some special characteristics (like if he or she was a pioneer of fish farming in his area), they would be given priority for being selected for the interviews. The local guides created lists of farmers (with background information) who should be suitable for expert interviews and FGDs. The listed farmers were then contacted, and after initial screening, the appropriate farmers were chosen for this study. In case of the FGD, there was a mix of farmers of different background like farmers cultivating different sizes of farms, coming from different areas within the sub-district, belonging to different age, and having different years of farming experience. In case of the expert interviews of farmers, one farmer from each sub-district had to be a small farmer, and the other a large farmer.

Each focus group consisted of 7 fish farmers, who came from different locations within the sub-district. The age of the farmers in the interview was between 35-65 years. Educational attainment ranged between people who had no formal education and people with a college degree. The fish farming area of the respondents were between 0.8-14 acres. Years of fish farming experience varied between 6 and 18 years. The main purpose of these focus groups was to confirm the findings of the in-depth interviews with a larger group of local stakeholders. The sessions were conducted with the help of semi-structured questionnaires. However, the discussions were enriched by insights even beyond the questionnaires. The conversations were in Bangla, the first language of the respondents and the researcher. The system dynamics model was also presented in front of the groups for comments or feedback. The structure of the system dynamics model was simplified and made clearer based on the comments.

All the interview participants were briefed verbally, as well as through written documents about the purpose of this study, their roles, and rights. Written consent was obtained for participation and recording of the sessions. All of the participants were encouraged to participate enthusiastically, and requested to ask questions if they needed any clarifications.

After the initial interviews, some of the experts were contacted again for clarification, or for further questions that had arisen afterwards. All the conversations generated very useful and interesting information and insights for this study. All the conversations were in Bangla, the language of the researcher and all the experts. After the interviews, the recorded audio was transcribed first in Bangla, and then translated to English, which was then coded, and findings were used in the analysis for this paper.

3. 3. 5. 2 Secondary Data Collection

The main purposes of the secondary data were to parameterize the System Dynamics model with quantitative data, and to learn about historical trends, directions of change, etc. Secondary data has been collected from three types of sources:

i. Two Household Surveys

The first survey is the Bangladesh Integrated Household Survey (BIHS), which is a nationally representative panel data of 6,500 households in 325 primary sampling units (PSUs) or villages. The survey contains information on plot-level agricultural production and practices, dietary intake of individual household members, asset ownership, etc. The first round of the survey was conducted from November 2011 to March 2012, and the second round from January to June 2015. The survey was funded by USAID, and administered by IFPRI in Bangladesh. This dataset and further description of the survey is available online (IFPRI, 2016).

The second survey is the IFPRI Fish Value Chain survey, which is a nationally representative survey of 1540 fish farming households, as well as 165 hatcheries, 213 input dealers, 44 feed millers, and 498 traders. The survey was conducted between February and June 2014. It contains detailed cost and return analysis of fish farming in 2013, with recollections for some variables from 2008. It also contains data on crop production, socioeconomic profiles, asset ownership, etc. This dataset is not publicly available as of November 2018, but has been obtained directly from IFPRI Dhaka, with assistance from USAID, Dhaka.

ii. Published Reports and Unpublished Data

This study uses published reports from several government organizations and research institutions, which include:

- Bangladesh Bureau of Statistics (BBS)
- Department of Fisheries (DoF)
- Department of Agricultural Extension (DAE)
- Bangladesh Rice Research Institute (BRRI)

- Department of Agricultural Marketing (DAM)

These institutions publish yearly reports or other documents that contain data on agricultural production systems, or broader sections of the economy and the environment. However, sometimes these institutions collect data that are not published anywhere. For example, the Department of Fisheries at the sub-district level has data on fish production data for the sub-district, but this data is not published through DoF publications. These data have also been collected when necessary.

iii. Published papers

Another major data source is published papers. Some of the papers which have been extensively used for this study as data sources are Ahmed et al. (2010), Alam (2011), and Jahan et al. (2015). Also, the model uses data from a dissertation by Palash (2015), and subsequent papers by the author.

The data used in parameterizing the model is presented in the Appendix 3C.

3. 3. 6 Sensitivity Analysis

The system dynamics model required assumptions to be made about parameters, and therefore it can be subject to a degree of uncertainty that must be understood in order to evaluate the confidence in the model. Sensitivity analysis is an examination of how responsive models are to fluctuations in the values of model parameters (Hekimoglu and Barlas, 2010). Also, given that some parameter values can change over time, sensitivity analysis provides an indication of how a model will change over time.

In this research, a one-variate sensitivity analysis has been conducted, which tests for sensitivity of model outcomes to changes in parameters through "one-at-a time approach". The sensitivity analyses were performed through the Stella Architect software. To accomplish this, different variables were selected and reasonable estimates of anticipated variation were assessed. Stella was then allowed to run for 10 iterations using the described variable distribution of one variable at a time, while reporting the output of fish land use stock over time.

3. 4 RESULTS AND DISCUSSION

In this section, at first the results for the calibration model run between 2004 and 2016 are presented, and verified with historical data. Then, model simulations up to 2050 are presented, and different outcomes from the model are discussed. Afterwards, results from the sensitivity analysis for various model parameters are shown.

3. 4. 1 Model Calibration

The model outcomes for simulations within the calibration period are shown in Figures 3.12a-3.12d.

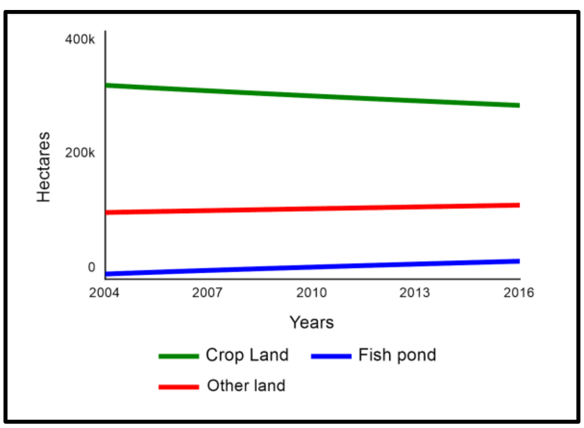


Figure 3.12a: Land use change in Mymensingh

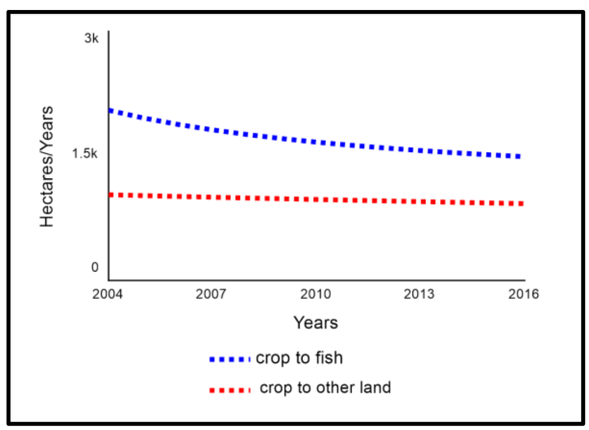


Figure 3.12b: Yearly land conversion in Mymensingh

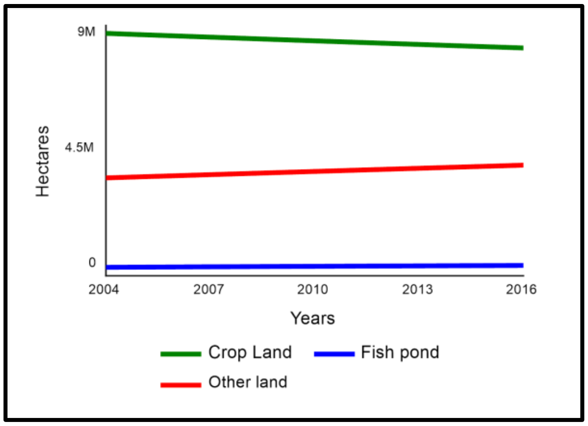


Figure 3.12c: Land use change in Bangladesh

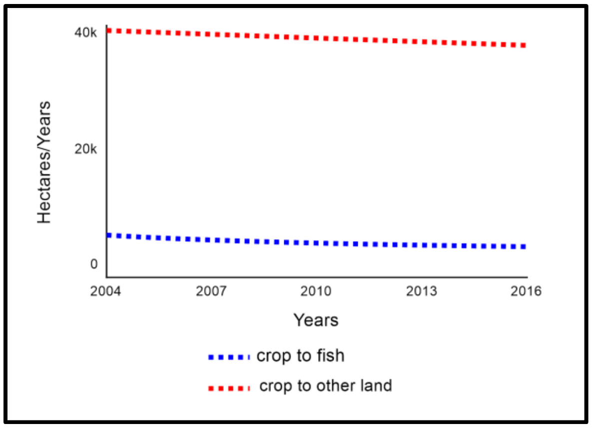


Figure 3.12d: Yearly land conversion in Bangladesh

Figure 3.12a above shows model outcomes for land use stocks between 2004 and 2016 for Mymensingh and Figure 3.12c above shows that for Bangladesh. The Mymensingh model generates land use distribution between crops, and fish ponds in 2016 as 280,499 and 29,031 hectares respectively, which are similar to data from BBS (2017) and DoF (2017) of 282,626 and 29,371, in crop and fish production, respectively. The Bangladesh model in Figure 3.12c generates land use distribution between crops and fish ponds in 2016 as 8,193,673 and 372,782 hectares respectively, which are similar to data from BBS (2017) and DoF (2017) of 8,462,753 and 372,405, in crop, and fish production, respectively. So, it can be said that we have confidence in the model, and next we will show long term trends. One point to note from Figures 3.12b and 3.12d is that while cropland loss to aquaculture compared to other uses is much higher in Mymensingh, it is relatively lower (compared to loss to other uses) for the whole country.

3. 4. 2 Projecting Long Term Trends

Now, the results from the long term projections will be presented. In this section, first the results from different scenarios will be presented. Then, within those scenarios there can be multiple sensitivity tests of parameters, hence, the results from the most influential variables will be presented.

3. 4. 2. 1 Baseline Model Run

If the model is run with the baseline parameter values up to 2050, land conversion to fish farming stops after 2017 in case of both Mymensingh and Bangladesh (Figures 3.13a & 3.13b, 3.13c & 3.13d). This is because the benefit cost ratio (BCR) falls below 1, making fish production unattractive. Moreover, the reason BCR falls below 1 is the growth in real price during recent years is negative, and as this continues, fish remains unprofitable. This finding is consistent with field observations, where farmers reported that fish farming remained mostly non-profitable during the last two years, and very little land has actually converted during this period.

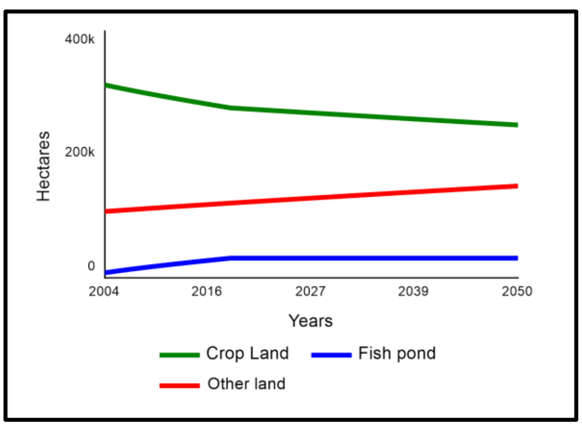


Figure 3.13a: Land use change in Mymensingh long run with reference period parameters

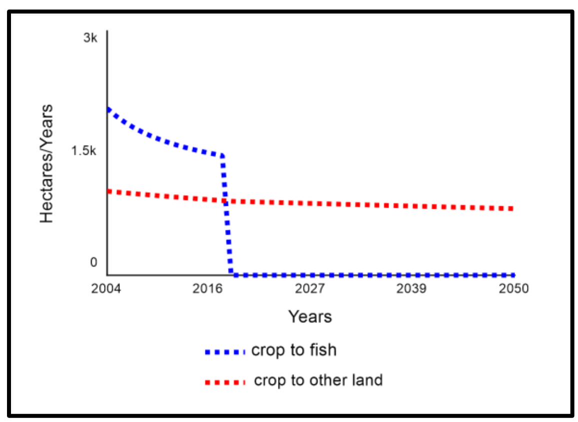


Figure 3.13b: Yearly land conversion in Mymensingh with reference period parameters

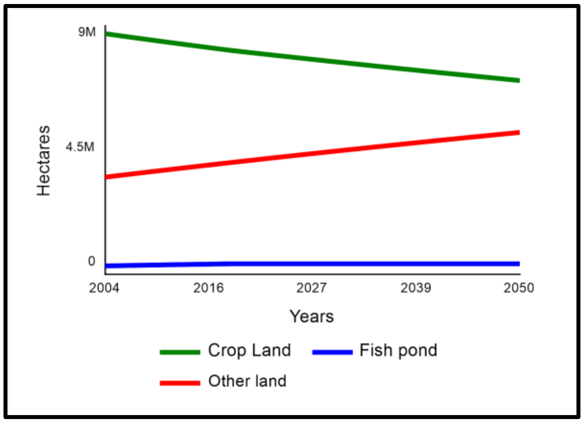


Figure 3.13c: Land use change in Bangladesh with reference period parameters

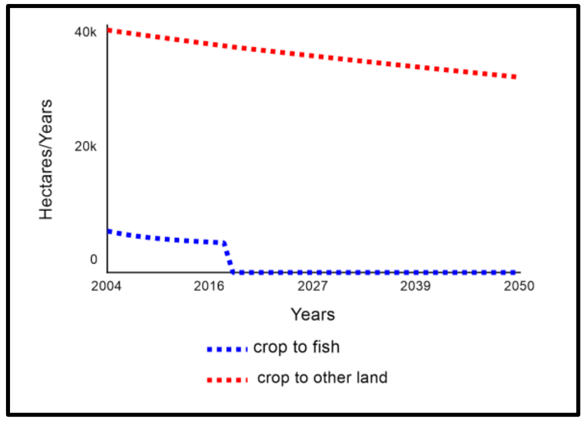


Figure 3.13d: Yearly land conversion in Bangladesh with reference period parameters

3. 4. 2. 2 Future Fish Price Change Scenario

Since prices may not keep falling in the future, we can change the price trend to observe the outcomes. First, we set the price increase to 0% per year. This gives an interesting contrast between Mymensingh and Bangladesh. While land conversion continues in Mymensingh, despite the stagnant price of fish, it stops in Bangladesh as a whole (Figure 3.14a & 3.14b). This is due to differences in the annual change of fish yield between Mymensingh and Bangladesh. Fish yield is growing at 21% per year in Mymensingh within the reference period, but 8% per year at the national level on an average. If the yield growth rates are reversed (that is, if fish yield in Mymensingh is set to grow at the pace of the national average, and vice versa), then the land use change outcomes are also reversed (Figure 3.14c & 3.14d). Hence, it can be observed that price stagnation is offset by growth in fish yield. This result is consistent from an economic perspective, as Mymensingh has a more intensive production system, and is less affected by the stagnation of output prices in the presence of growing input prices. These results identify fish yield as an influential variable in the model, and we will come back to that later.

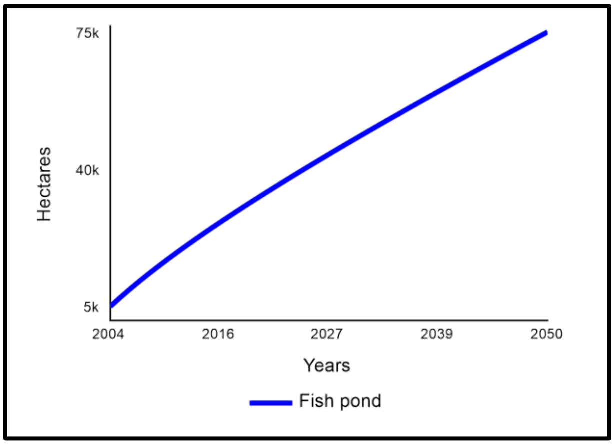


Figure 3.14a: Pond area change in Mymensingh for 0% price growth from 2016

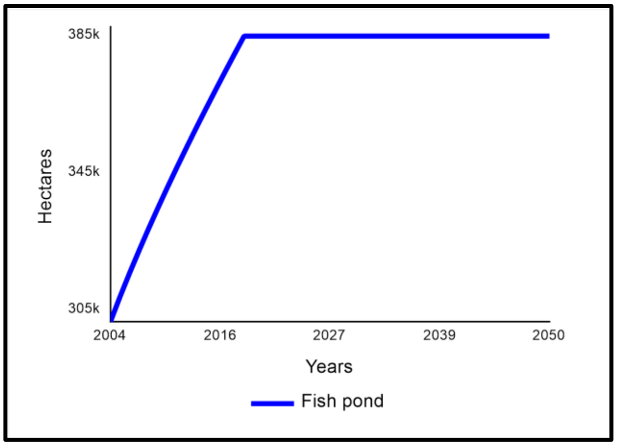


Figure 3.14b: Pond area change in Bangladesh for 0% price growth from 2016

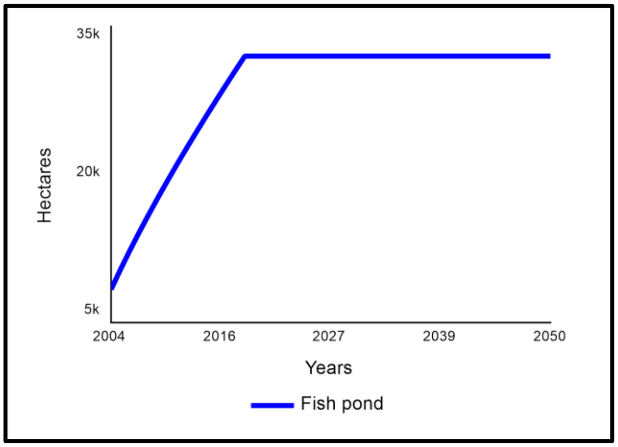


Figure 3.14c: Pond area change in Mymensingh for 0% price growth but yield same as Bangladesh

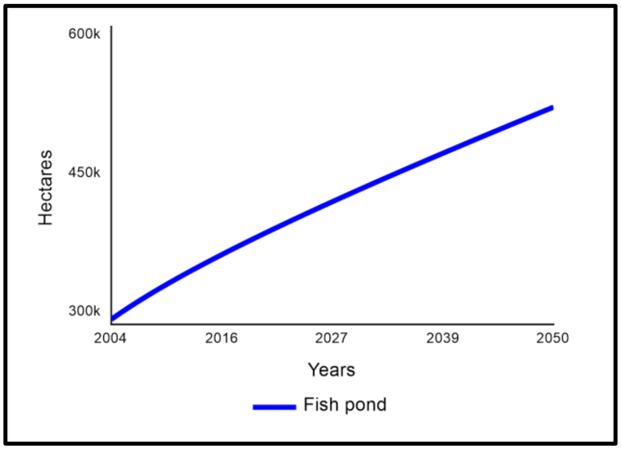


Figure 3.14b: Pond area change in Bangladesh for 0% price growth but yield same as Mymensingh

The model can also demonstrate changes in land use trends with a different fish price trend. For example, for a 2% annual increase in fish price in the future, the land in use trend stays the same as before for Mymensingh. However, in the case of Bangladesh, the conversion keeps stagnated until around 2028, and then starts growing again (Figure 3.15a). But, for a 4% annual increase in price conversion, it is only stagnant for 2017 and 2018, and then starts growing (Figure 3.15b).

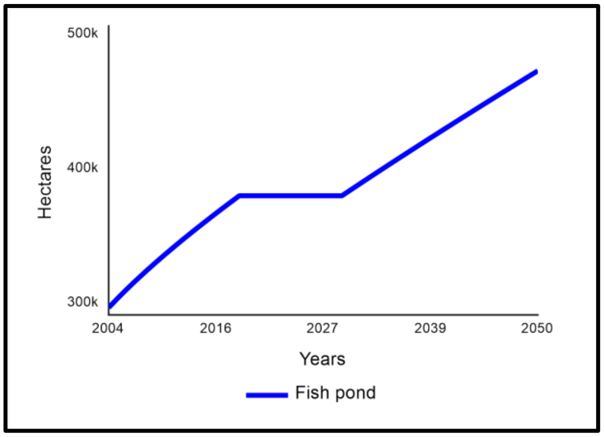


Figure 3.15a: Pond area change in Bangladesh for 2% price growth from 2016

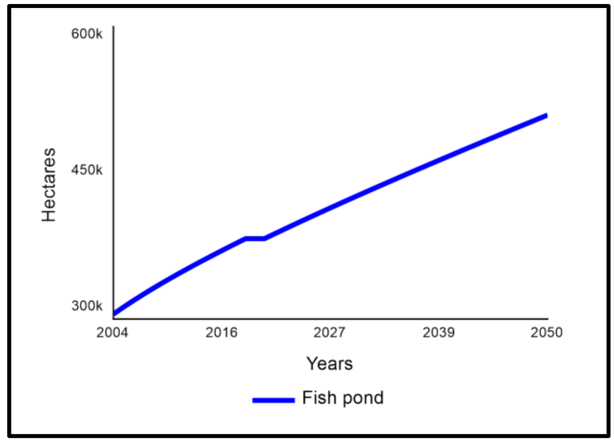


Figure 3.15b: Pond area change in Bangladesh for 4% price growth from 2016

The sensitivity analysis for fish price growth rates between -2% and +4% yields the following results (Figures 3.16a-3.16b). These results show both numerical and behavior change for land conversion outcome based different values of fish price growth. More data on different runs are provided in the Appendix 3E.

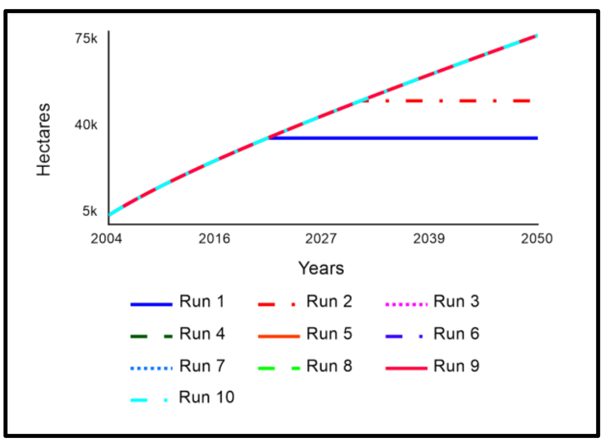


Figure 3.16a: Pond area change due to fish price variations in Mymensingh. Runs 1 to 10 represent price change from -2% to +4%.

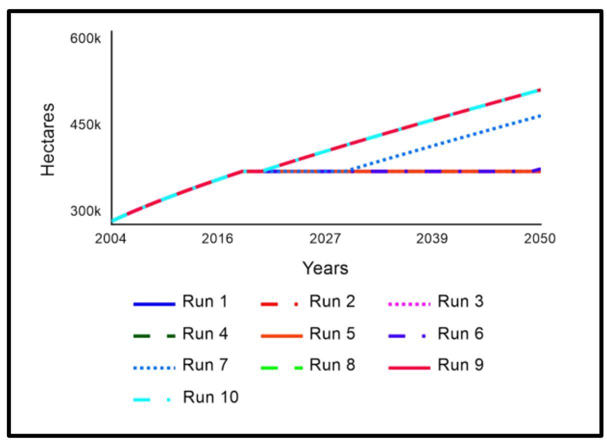


Figure 3.16b: Pond area change due to fish price variations in Bangladesh. Runs 1 to 10 represent price change from -2% to +4%.

In Figure 3.16a, except for -2% and -1.33% growth rates in fish price, land expansion continues at the same rate for Mymensingh. In Figure 3.16b, fish area expansion stagnates even up to a 1.33% annual growth in price. However, at price growth rates between 2-2.6%, the land expansion stops between 2017 and 2028, and then continues. For price growth rates over 2.6%, the fish land expansion stops between 2017 and 2018, and then continues over time in Bangladesh. The focus group discussions and expert interviews suggested that after remaining stagnant for about two years, fish prices were rising during the last two months. So, we do not need to assume that prices will continue to decline in the future. Based on these outcomes, from this point forward and unless otherwise stated, this model will assume a 2.6% annual growth in prices from 2017, as this is the lowest value for which the model keeps expanding fish area. In that case, the following are the outcomes for Mymensingh (Figure 3.17a & 3.17b), and Bangladesh (Figure 3.17c & 3.17d).

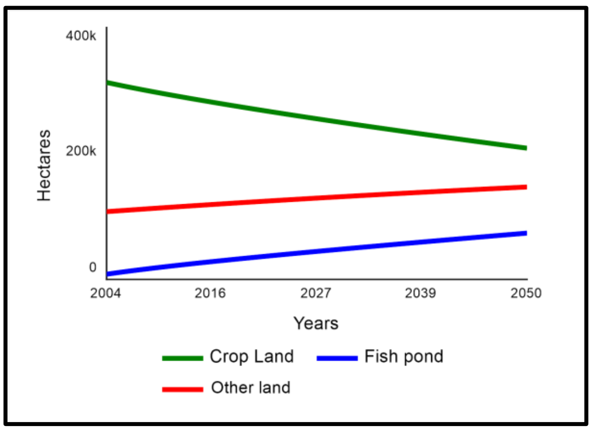


Figure 3.17a: Projected land use change in Mymensingh

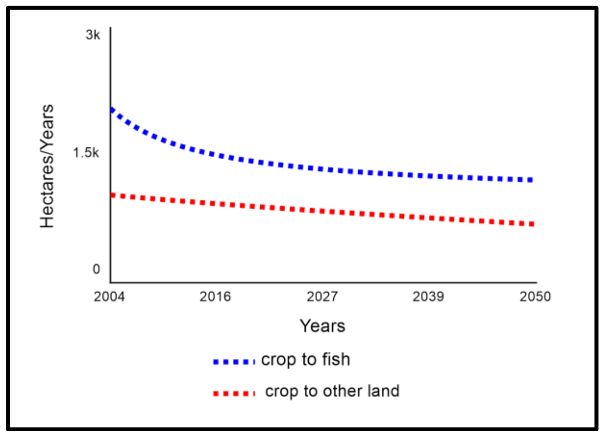


Figure 3.17b: Yearly land conversion in Mymensingh

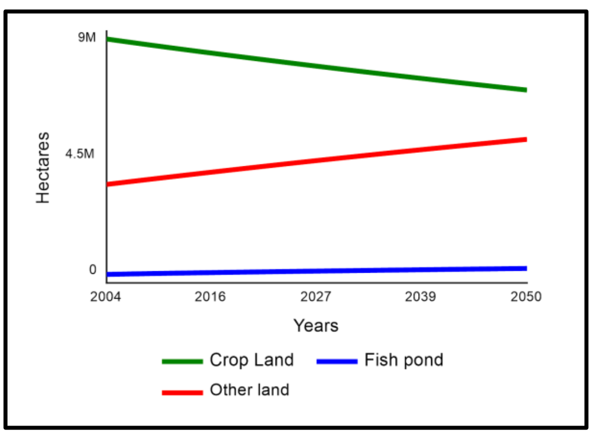


Figure 3.17c: Projected land use change in Bangladesh

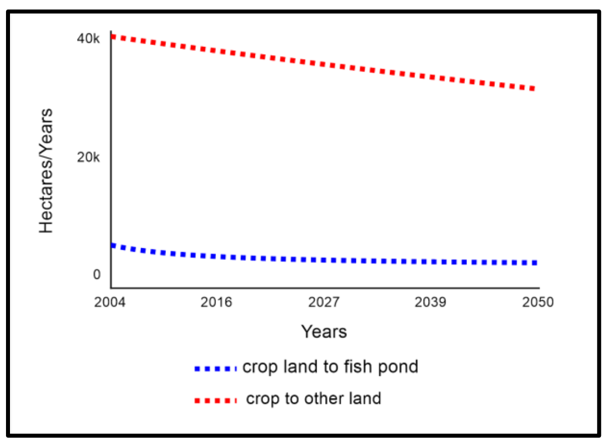


Figure 3.17d: Yearly land conversion in Bangladesh

3. 4. 3 Sensitivity Analysis

We have already discussed the sensitivity of the model to price in section 3.4.2.2. In this section, the model output we want to observe is change in fish pond area, due to changes in parameter values of fish yield growth rate, rice yield, expansion cost, input cost, and land conversion factor.

3. 4. 3. 1 Sensitivity to Future Fish Yield Change

Next, sensitivity analysis for fish pond growth to variations in fish yield growth rates between 5% and 30% is performed, which gives the following outcomes (Figures 3.18a & 3.18b).

Figure 3.18a shows that the land expansion in Mymensingh stagnates if yield growth falls to 5%, otherwise, other things remaining the same, it continues at the same rate into the future. Figure 3.18b shows that fish land expansion in Bangladesh stagnates if yield growth is around 5%, but continues into the future for growth rates of 10% or above.

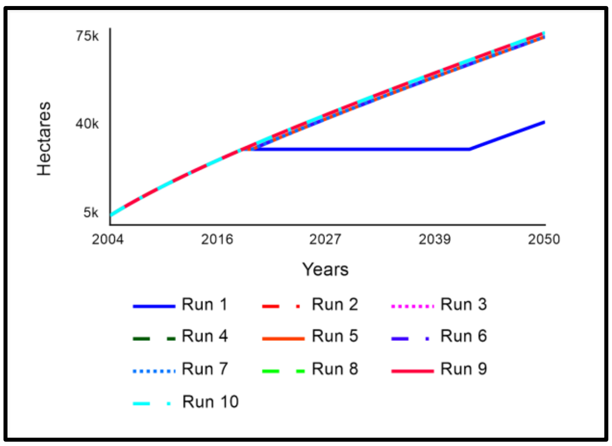


Figure 3.18a: Pond area change due to variations in fish yield in Mymensingh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

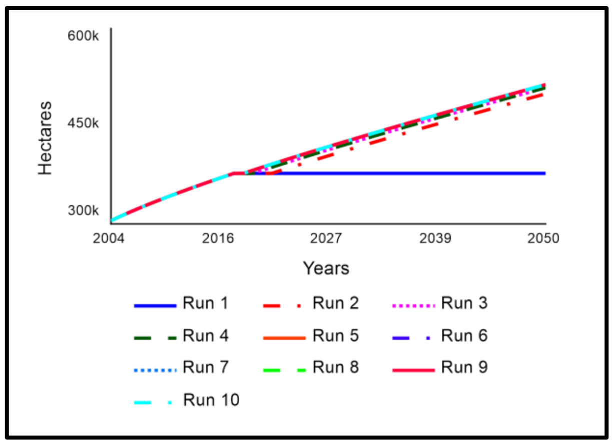


Figure 3.18b: Pond area change due to variations in fish yield in Bangladesh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

3. 4. 3. 2 Sensitivity to Future Expansion Cost Change

The expansion cost per hectare is the cost for bringing in one hectare of land into fish production. Sensitivity analysis of expansion cost change shows that the trajectory for land use change is different for each value of expansion cost growth rate, whether it is for Mymensingh (Figure 3.19a), or for Bangladesh (Figure 3.19b). This is an expected result as a change in expansion cost directly makes conversion cheaper or more expensive. However, the land conversion trajectory does not suddenly drop or increase sharply, indicating that the general model behavior does not change due to variations in cost of expanding land area. Hence, the model is less sensitive to such changes than to variation in yield or prices.

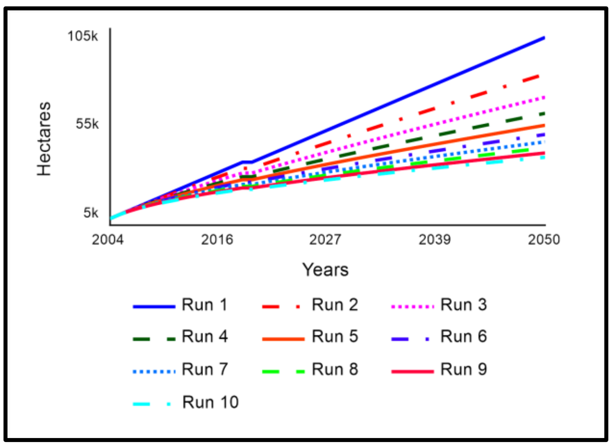


Figure 3.19a: Pond area change due to variations in expansion cost in Mymensingh. Runs 1 to 10 represent expansion cost change from 5% to 30% per year.

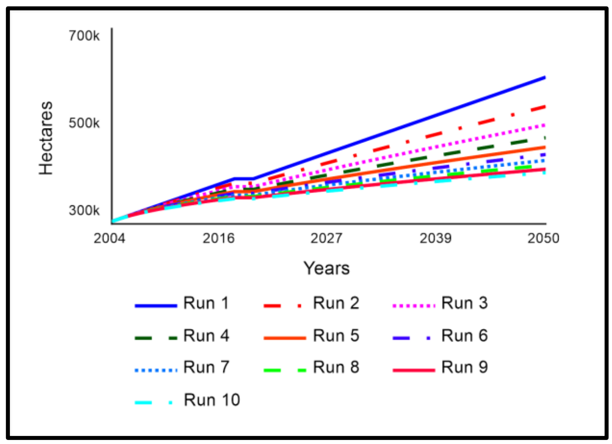


Figure 3.19b: Pond area change due to variations in expansion cost in Bangladesh. Runs 1 to 10 represent expansion cost change from 5% to 30% per year.

3. 4. 3. 3 Sensitivity to Feed Cost Changes

Feed cost occupies the largest share among the cost items. Feed cost is rising by about 15% per year in the reference period. Farmers have reported that rising feed cost is one of their major concerns. However, sensitivity analysis shows that there is little or no change in land conversion in Mymensingh for a feed cost growth between 5-30% (Figure 3.20a). Again, this is due to the high yield growth rate (21% per year) in Mymensingh, which is off-setting any loss from feed cost growth. In the case of Bangladesh (Figure 3.20b), the situation is different. Land conversion trajectory changes course significantly over 18% feed cost growth per year. Since the yield growth is slower for Bangladesh (8% per year), it cannot off-set the growth in feed cost as in Mymensingh.

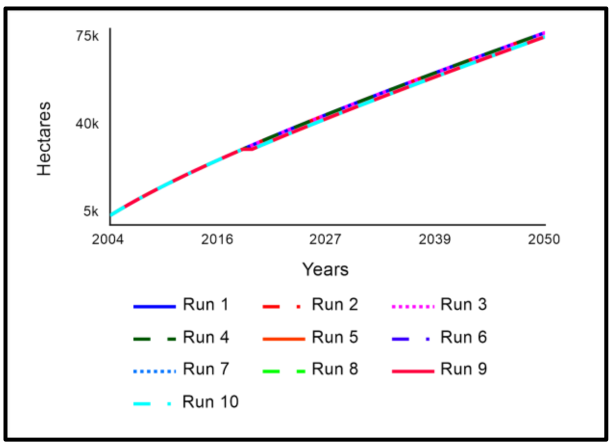


Figure 3.20a: Pond area change due to variations in feed cost in Mymensingh. Runs 1 to 10 represent feed cost change from 5% to 30% per year.

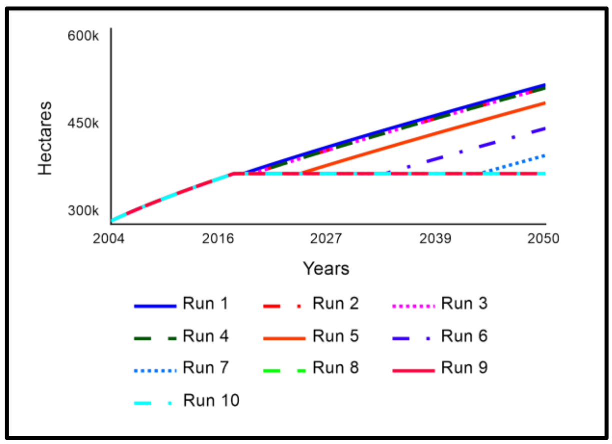


Figure 3.20b: Pond area change due to variations in feed cost in Bangladesh. Runs 1 to 10 represent feed cost change from 5% to 30% per year.

3. 4. 3. 4 Sensitivity to Land Conversion Factor

The land conversion factor consists of land quality and value change support factors. Both of these factors take different values at the district and national levels. The sensitivity analysis for both factors is shown in Figures 3.21a to 3.21d. There is more uncertainty about the value of these parameters, hence sensitivity analysis is done on the entire possible range of their values: from 0 to 1. The results in Figures 21a and 21b show that the trajectory for land conversion is different for different values of the land quality variable, and similarly, Figures 21c and 21d show that the trajectory for land conversion is different for different values of the value chain support. However, the changes are linear and there is no sudden rise or drop. Hence, this shows that the model outcome is numerically responsive to these changes, but the general model behavior does not change due to variations in the land conversion factor.

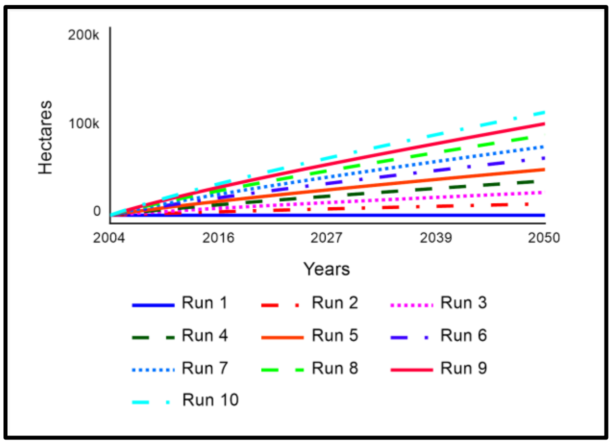


Figure 3.21a: Pond area change due to variations in land quality factor in Mymensingh. Runs 1-10 represent land quality factor change from 0 to 1.

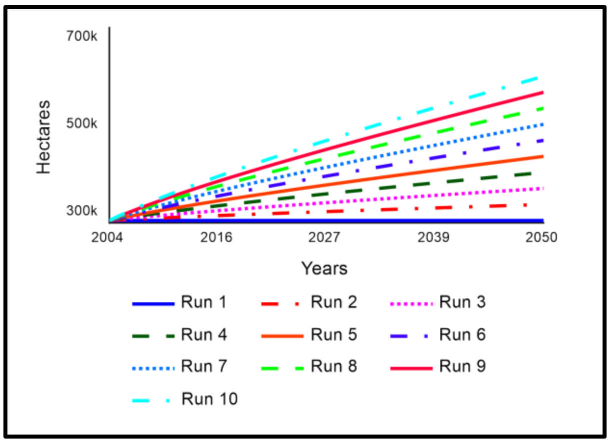


Figure 3.21b: Pond area change due to variations in land quality factor in Bangladesh. Runs 1-10 represent land quality factor change from 0 to 1.

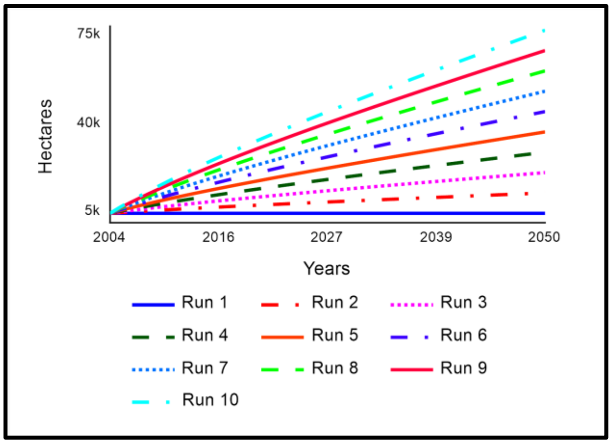


Figure 3.21c: Pond area change due to variations in value chain support factor in Mymensingh. Runs 1-10 represent parameter change from 0 to 1.

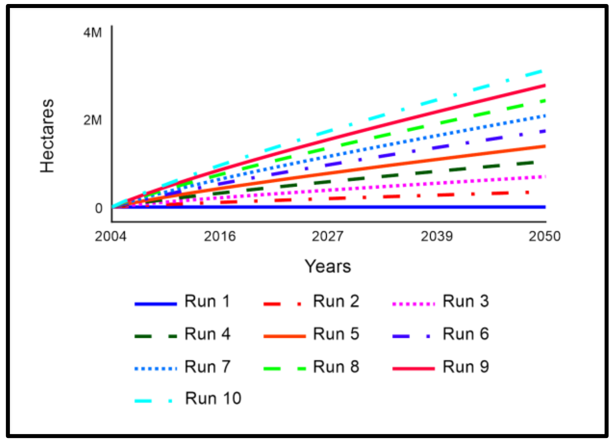


Figure 3.21d: Pond area change due to variations in value chain support factor in Bangladesh. Runs 1-10 represent parameter change from 0 to 1.

3. 4. 4 Scenario Analysis

In this section, we will show how rates for land conversion from crop to fish change under different scenarios. The specific scenarios considered are: changes in growth rates of household income, an increase in fish prices, along with a decrease in feed cost, and a combination of these drivers.

3. 4. 4. 1 Scenario One and Two: Household Income Growth Increase and Decrease

The baseline model assumes that household income is growing at 5% per year. Since the investment in new ponds is a function of household income (Appendix 3B equation 9), a change in the household income growth rate can change the amount of investment made in new ponds each year, and hence change the model outcome. So, we are considering two scenarios:

- Scenario A: when household income is growing 2% per year
- Scenario B: when household income is growing 10% per year

The outcome of these on fish and crop land stocks are shown in Figures 22(a-d).

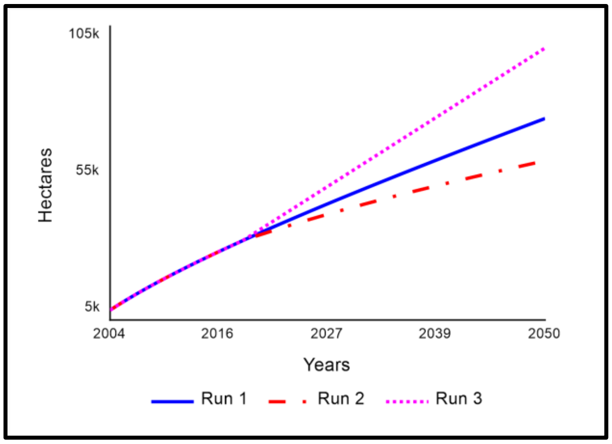


Figure 3.22a: Pond area change scenarios due to variations in household income growth rates in Mymensingh. Runs 1, 2, & 3 represent growth rates of 5%, 2% & 10% respectively.

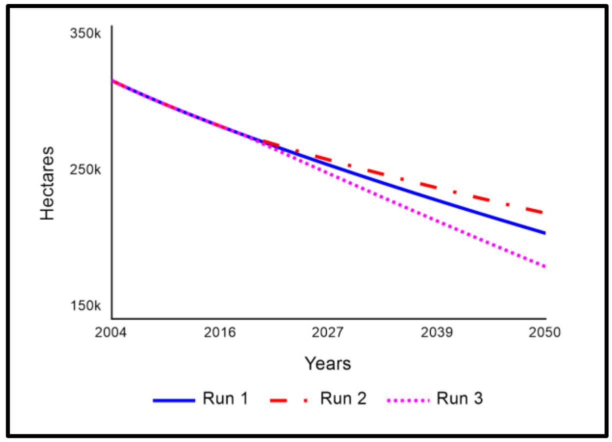


Figure 3.22b: Crop area change scenarios due to variations in household income growth rates in Mymensingh. Runs 1, 2, & 3 represent growth rates of 5%, 2% & 10% respectively.

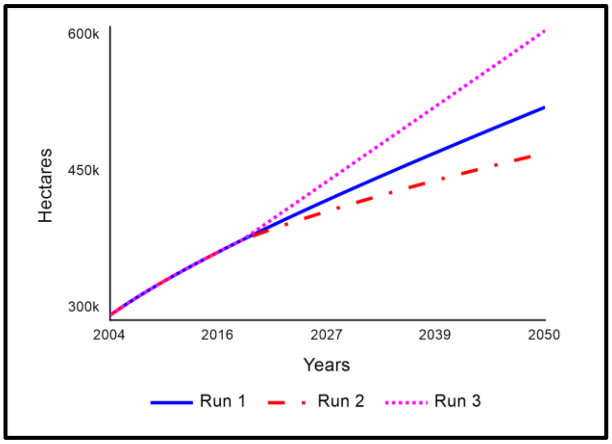


Figure 3.22c: Pond area change scenarios due to variations in household income growth rates in Bangladesh. Runs 1, 2, & 3 represent growth rates of 5%, 2% & 10% respectively.

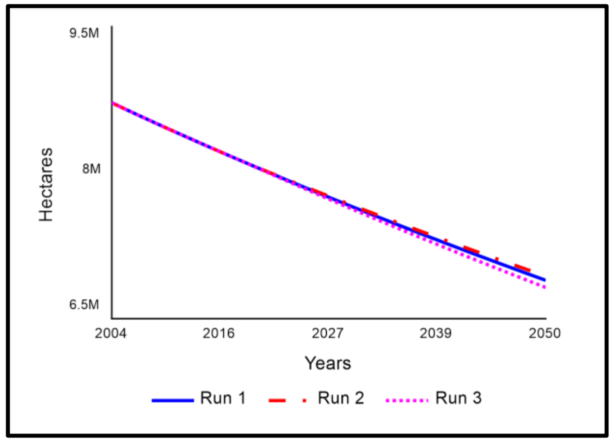


Figure 3.22d: Crop area change scenarios due to variations in household income growth rates in Bangladesh. Runs 1, 2, & 3 represent growth rates of 5%, 2% & 10% respectively.

Figure 3.22a and 3.22b show that pond conversion in Mymensingh decreases when household income growth slows down, and increases when household income growth increases. The same trends are true for Bangladesh (Figures 3.22c and 3.22d), but the impact on crop land is lesser than Mymensingh, as fish pond area is proportionately lesser in the whole country. These findings suggest that more economic growth (in general) may lead to more fish production, which is consistent with economic theory.

3. 4. 4. 2 Scenario Three: Fish Price Increase and Feed Cost Growth Slowdown

Here, we present the scenario of fish price increase and fish cost growth slowdown happening at the same time. In the baseline model, fish price is growing at 2.6% per year, and all cost items are growing faster. For example, feed cost –the largest among all costs –is growing at 15% per year. Now, we are showing a scenario of what may happen if fish price grows 5% per year, while feed cost growth slows down by half: 7.5% per year. We need to make an additional assumption in the model. The baseline assumes that households make investment when the benefit cost ratio (BCR) is greater than one, but it does not distinguish between different positive values of the BCR. So, we are making an assumption that investment rates will increase by 50% if BCR goes over 2. This gives us the following outcomes (Figure 3.23).

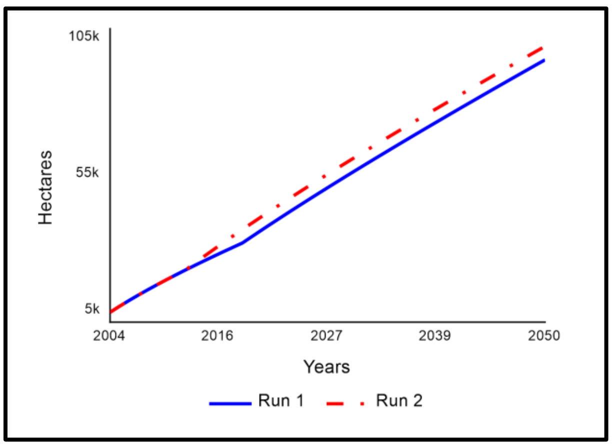


Figure 3.23a: Pond area change scenarios due to variations in household income growth rates in Mymensingh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%.

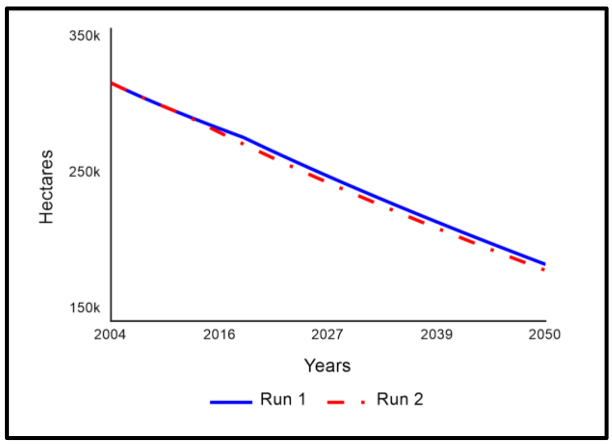


Figure 3.23b: Crop area change scenarios due to variations in household income growth rates in Mymensingh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%.

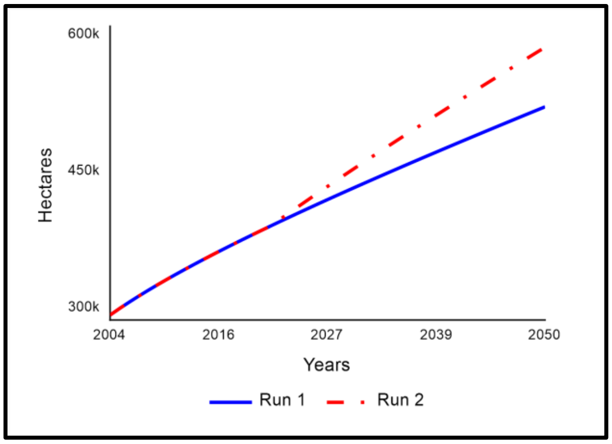


Figure 3.23c: Pond area change scenarios due to variations in household income growth rates in Bangladesh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%.

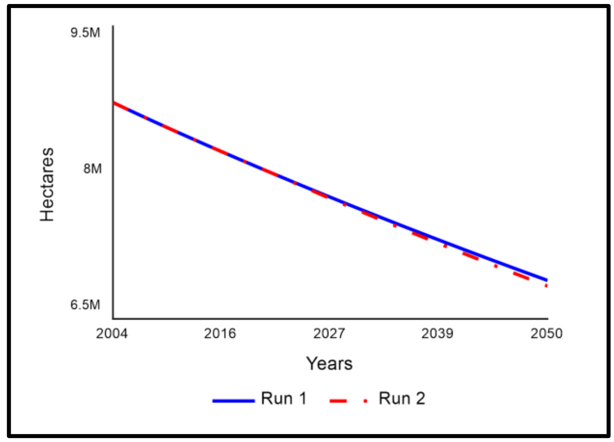


Figure 3.23d: Crop area change scenarios due to variations in household income growth rates in Bangladesh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%.

The results show that simultaneous change in fish price and feed cost increases land conversion in both Mymensingh, and Bangladesh, but the increase is much higher in case of the whole country. This is because the yield growth is higher in Mymensingh compared to Bangladesh, so the profitability is less affected by prices in Mymensingh, while it is more affected by prices in Bangladesh.

3. 4. 4. 3 Scenario Four: Household Income Growth, Fish Price Increase, and Feed Price Decrease

This scenario adds both the second and third scenarios, that is, it shows the outcomes for the case when household income is growing at 10% per year, fish price is growing 5% per year, and feed cost is growing 7.5% per year (Run 3). Here, Run 1 is baseline, and Run 2 represents scenario 3. Since all of those are favorable scenarios for fish farming, land conversion in this case increases even more than in scenario 3 (Figure 3.24).

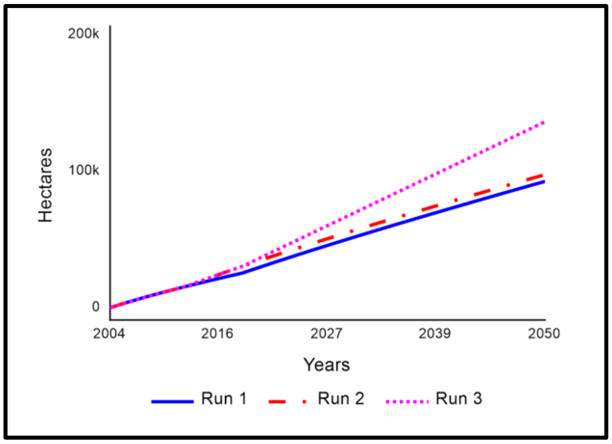


Figure 3.24a: Pond area change scenarios due to variations in household income growth rates in Mymensingh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%. Run 3 considers household income growth by 10%, as well as the changes in Run 2.

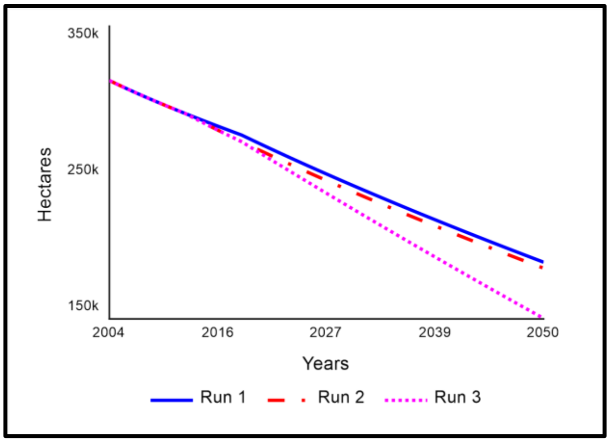


Figure 3.24b: Crop area change scenarios due to variations in household income growth rates in Mymensingh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%. Run 3 considers household income growth by 10%, as well as the changes in Run 2.

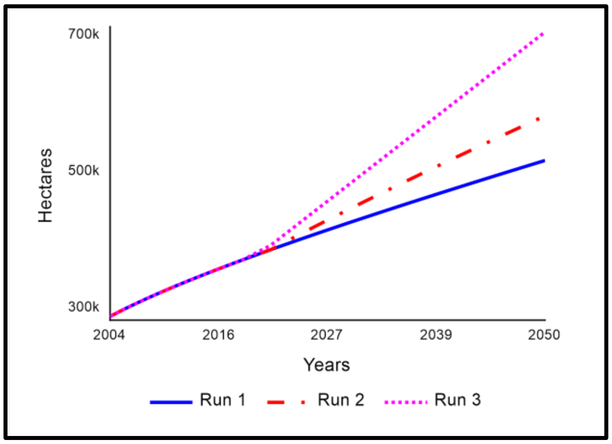


Figure 3.24c: Pond area change scenarios due to variations in household income growth rates in Bangladesh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%. Run 3 considers household income growth by 10%, as well as the changes in Run 2.

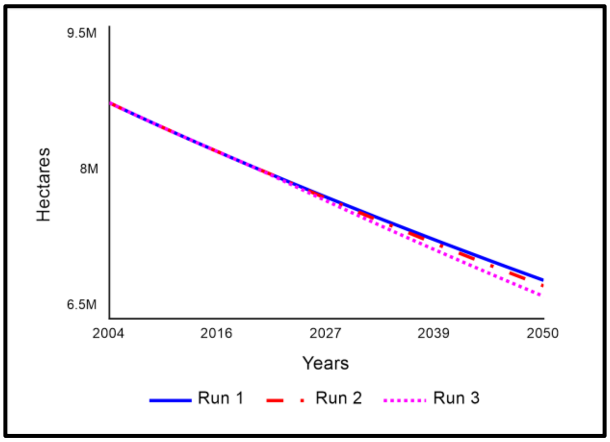


Figure 3.24d: Crop area change scenarios due to variations in household income growth rates in Bangladesh. Run 1 represents the baseline. Run 2 shows the scenario of fish price growth by 5%, and feed cost slowing down to 7.5%. Run 3 considers household income growth by 10%, as well as the changes in Run 2.

3. 4. 5 Food Supply Outcomes

It is more relevant to observe the food supply outcomes at the national level, as food products can move without any restriction within the country. However, since Mymensingh has relatively higher land conversion rates, we will show the food supply outcomes for Mymensingh, as that will offer some insights into what will happen under high national land conversion rates.

At first, it can be observed that rice production per person keeps rising initially (due to yield increase), but beyond a certain point, the effect of land decline becomes stronger, and hence rice production per person starts falling. However, within the time frame of this model, the rice production remains sufficient for sustaining consumption (more than 220 kg per capita at the national level) under the current rate of rice yield growth (3%). However, if the rice yield growth rate stagnates, then rice production becomes a problem. Currently, yields are growing 3% per year, if it falls to 1.5% per year, then production of rice per person falls sharply, and below the requirement levels at the national level (Figures 3.25c & 3.25d). Also, as expected, aquaculture production per person keeps increasing over time under the usual scenario (Figure 3.25e & 3.25f). The population growth rate in the model is 1%, which is the current growth rate of population in Bangladesh (World Bank, 2018).

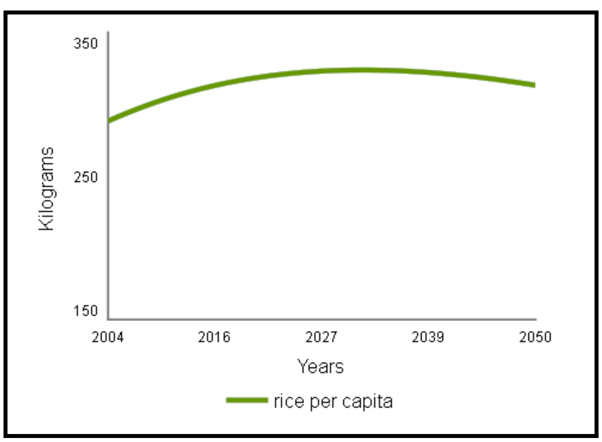


Figure 3.25a: Annual rice production per person in Mymensingh

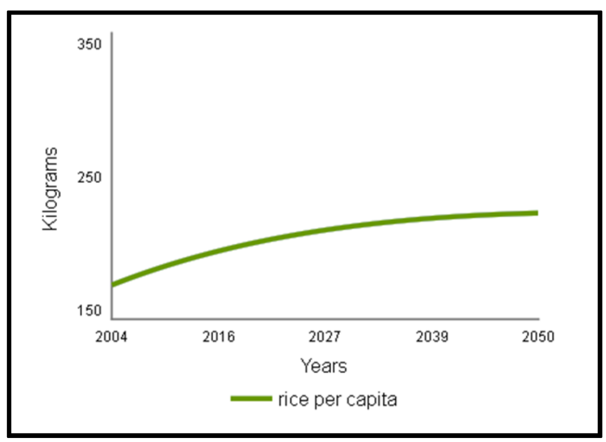


Figure 3.25b: Annual rice production per person in Bangladesh

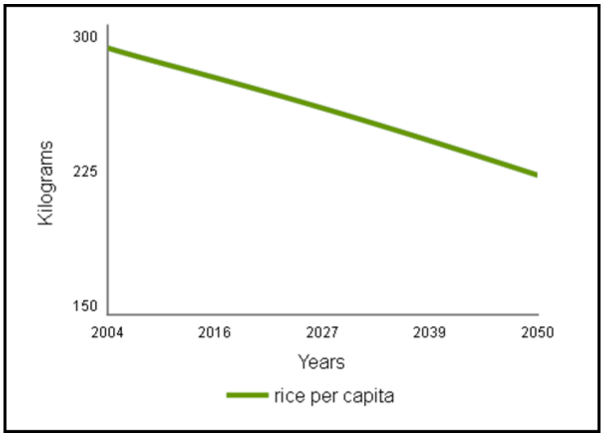


Figure 3.25c: Annual rice production per person in Mymensingh with rice yield growth slowdown

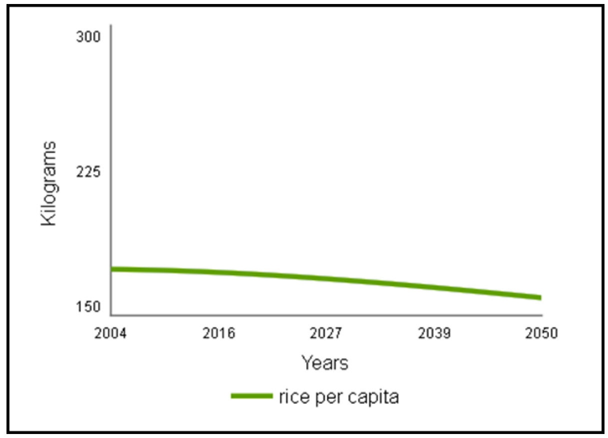


Figure 3.25d: Annual rice production per person in Bangladesh with rice yield growth slowdown

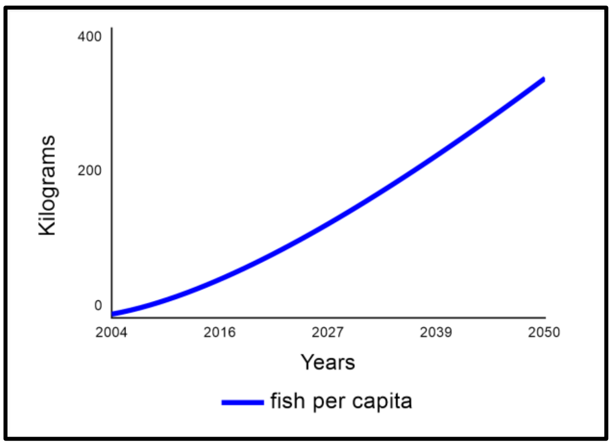


Figure 3.25e: Annual fish production per person in Mymensingh

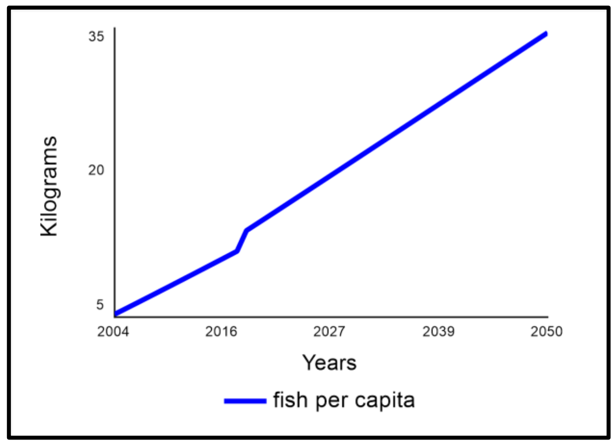


Figure 3.25f: Annual fish production per person in Bangladesh

Next, if we shift our focus to some specific dietary outcomes like production of calorie and protein, it can be observed that both show an increasing trend despite the loss of cropland (Figures 3.26a-3.26d). First of all, this model considers calorie and protein supply from other sources like wheat, pulses, meat, milk, eggs, oils, etc., and since domestic production of those items are rising within the reference period, this model assumes a constant growth of calorie and supply from those food sources. So, despite calorie from rice production slowing down, the total calorie outcome keeps growing over time. In case of protein, currently more is coming from rice than fish (BBS, 2017), but there are two different outcomes at the district and the national level.

In Mymensingh, where aquaculture growth is faster, protein supply from fish surpasses protein supply from rice, but in case of Bangladesh, the share of protein supply from rice remains larger. Nevertheless, the model shows that land conversion at current rates does not reduce the supply of calories or protein.

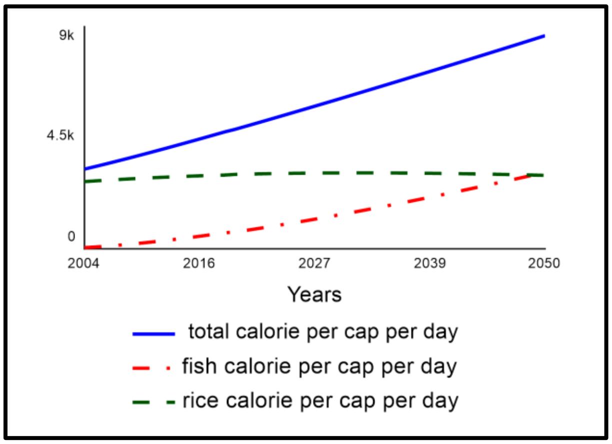


Figure 3.26a: Calorie supply trend from Mymensingh

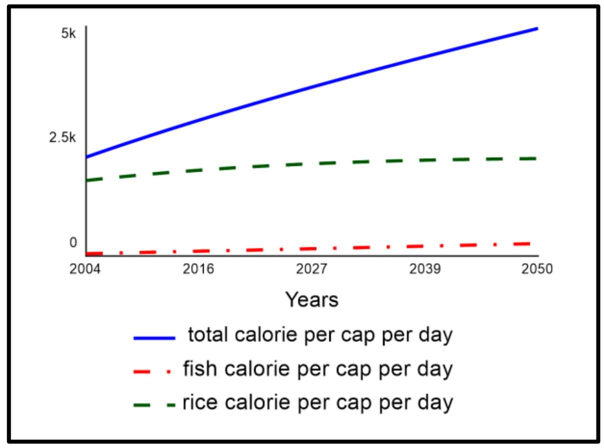


Figure 3.26b: Calorie supply trend for Bangladesh

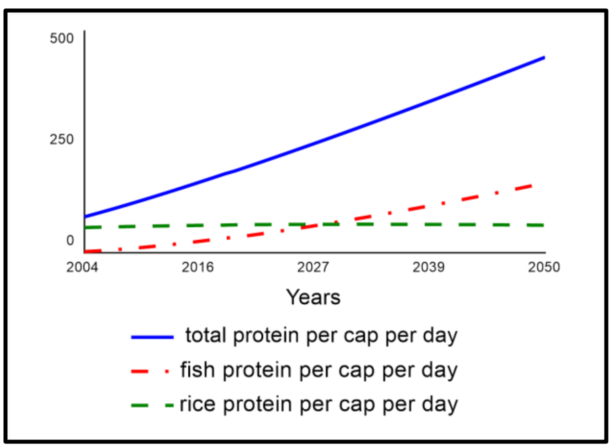


Figure 3.26c: Protein supply trend from Mymensingh

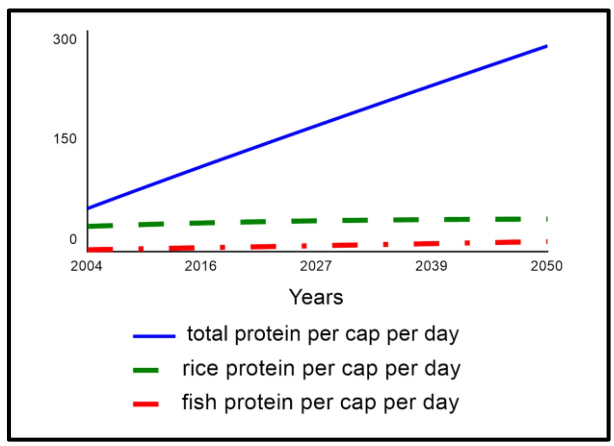


Figure 3.26d: Protein supply trend for Bangladesh

3. 4. 6 Sensitivity Analysis of Food Supply Outcomes

In this section, the model outputs we want to observe are changes in calorie supply and protein supply, due to changes in parameter values of fish yield growth rate, fish price, and rice yield.

3. 4. 6. 1 Sensitivity to fish yield changes

This shows that variations in the growth of fish yield per year between 5-30% will lead to different numeric values of calorie (Figures 3.27a and 3.27b), and protein (3.27c and 3.27d) outcomes, but all of them are linear functions of the yield or production changes. So, there are no behavioral changes in the model due to change in fish yields.

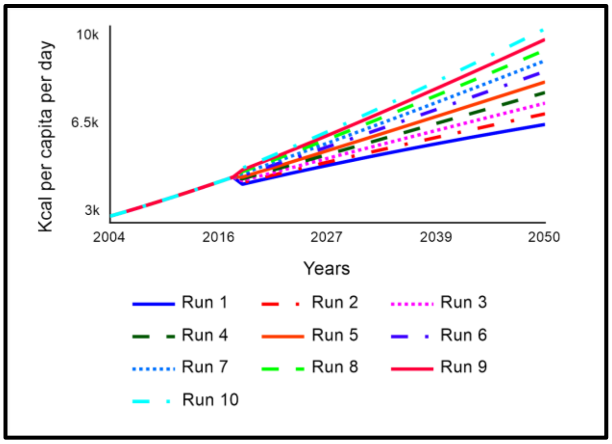


Figure 3.27a: Total calorie supply change due to variations in fish yield in Mymensingh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

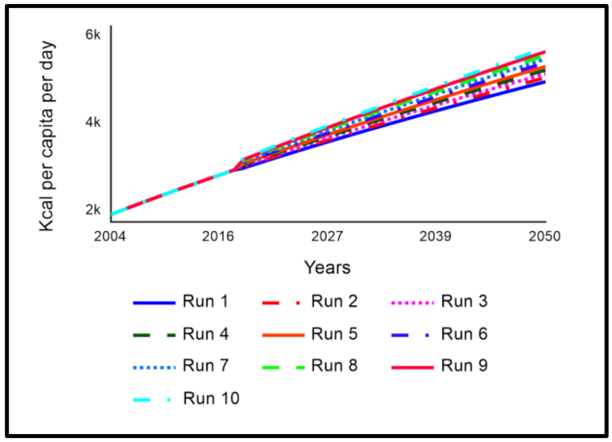


Figure 3.27b: Total calorie supply change due to variations in fish yield in Bangladesh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

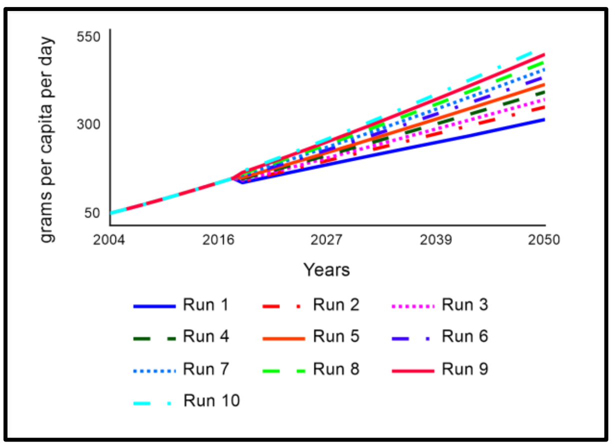


Figure 3.27c: Total protein supply change due to variations in fish yield in Mymensingh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

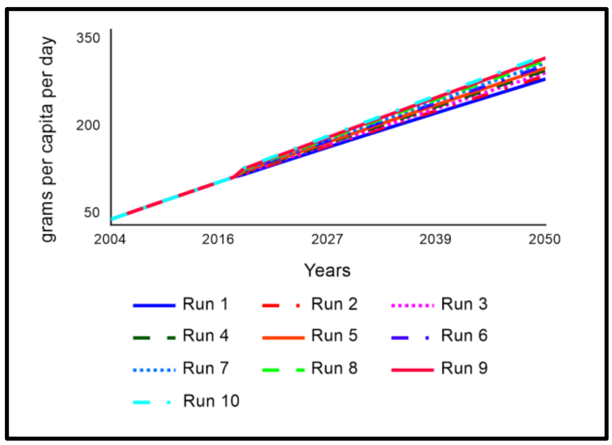


Figure 3.27d: Total protein supply change due to variations in fish yield in Bangladesh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

3. 4. 6. 2 Sensitivity to fish price changes

This shows that variations in fish price per year between -2% and +4% will lead to slightly different calorie (Figures 3.28a), and protein (3.28c) outcomes in Mymensingh, but no difference in the calorie (Figures 3.28b), and protein (3.28d) outcomes in the country overall. So, calorie and nutrition supply is less sensitive to these changes than changes in fish yield.

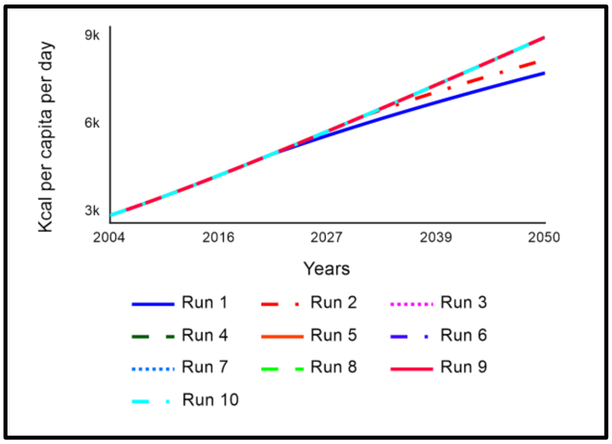


Figure 3.28a: Total calorie supply change due to variations in fish price in Mymensingh. Runs 1 to 10 represent fish price change from -2% and +4% per year.

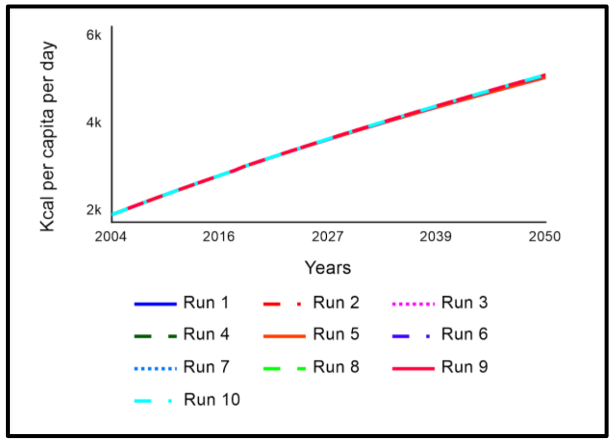


Figure 3.28b: Total calorie supply change due to variations in fish price in Bangladesh. Runs 1 to 10 represent fish price change from -2% and +4% per year.

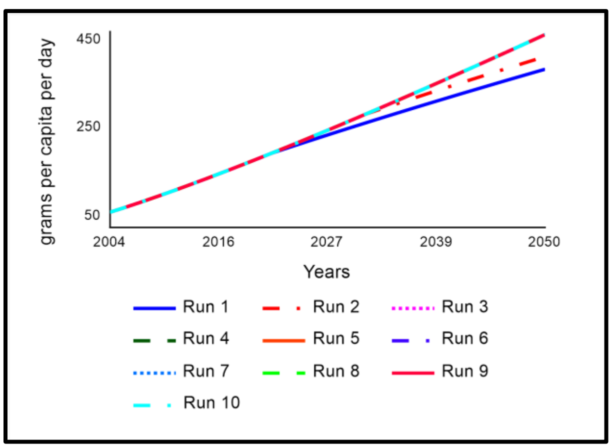


Figure 3.28c: Total protein supply change due to variations in fish price in Mymensingh. Runs 1 to 10 represent fish price change from -2% and +4% per year.

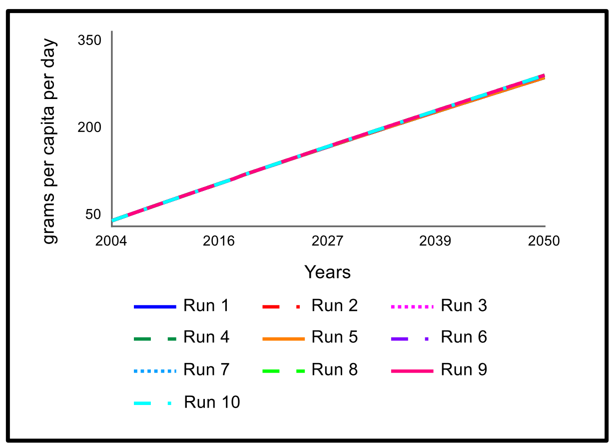


Figure 3.28d: Total protein supply change due to variations in fish price in Bangladesh. Runs 1 to 10 represent fish price change from -2% and +4% per year.

3. 4. 6. 3 Sensitivity to rice yield changes

Similar to the sensitivity analysis for fish yield change, the sensitivity for rice yield change shows that rice yield change per year between 1-10% will lead to different calorie (Figures 3.29a & 3.29b), and protein (3.29c & 3.29d) outcomes, but all of them are linear functions of the yield or production changes. So, calorie and nutrition supply is less sensitive to these changes. However, calorie and protein outcomes are more sensitive to rice yield, than fish yield, as the range of food supply outcomes here are much wider. This is because rice supplies higher proportions of both calorie and protein, and hence changes in rice yield are more consequential.

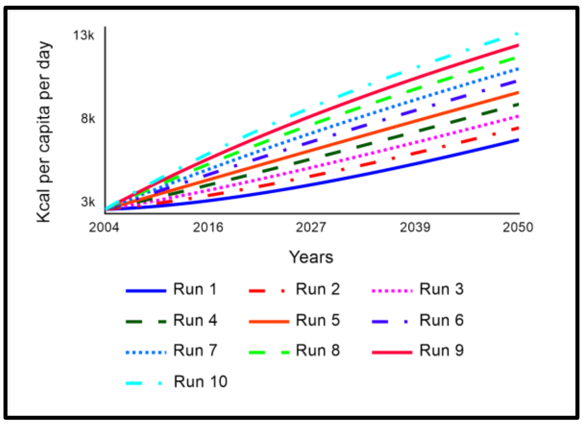


Figure 3.29a: Total calorie supply change due to variations in rice yield in Mymensingh. Runs 1 to 10 represent annual yield change from 0% to 10%.

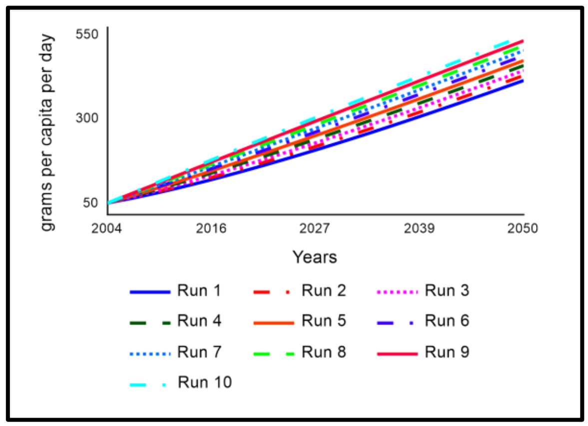


Figure 3.29b: Total protein supply change due to variations in rice yield in Mymensingh. Runs 1 to 10 represent annual yield change from 0% to 10%.

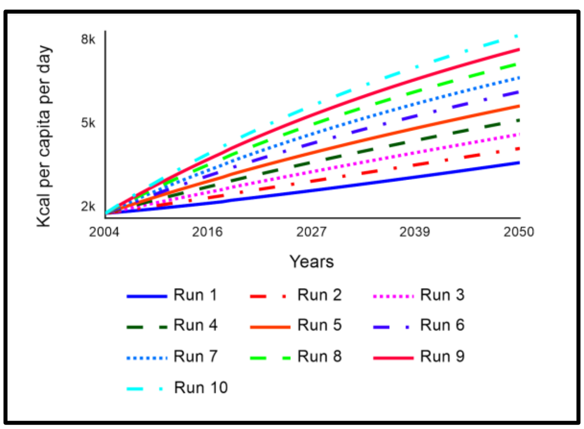


Figure 3.29c: Total calorie supply change due to variations in rice yield in Bangladesh. Runs 1 to 10 represent annual yield change from 0% to 10%.

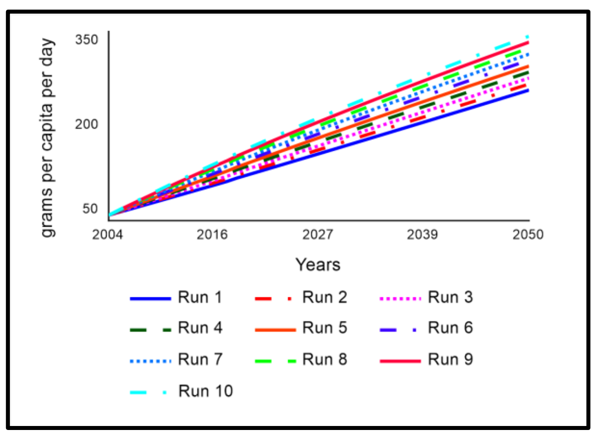


Figure 3.29d: Total protein supply change due to variations in rice yield in Bangladesh. Runs 1 to 10 represent annual yield change from 0% to 10%.

3. 4. 7 Scenario Analysis of Food Supply Outcomes

In this section, we will show how rice production per person changes under two different types of scenarios: variations in household income growth rates, and a combination of changes in household income and rice yield.

3. 4. 7. 1 Scenario One: Changes in Household Income

We have seen from the scenario analysis in section 3.4.4 that changes in household income growth rates have impact on fish and cropland. So, in this section, we want to show if these changes have any impact on rice production per person. In Figure 3.30, Run 1 represents the baseline, Run 2 represents increase in household income by 2%, and Run 3 represents increase in household income by 10%.

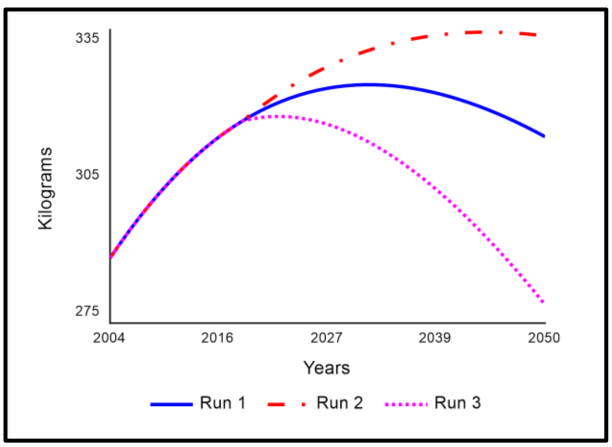


Figure 3.30a: Changes in annual rice production per person in Mymensingh due to variations in household income growth rates. Runs 1, 2, & 3 represent growth rates of 5%, 2% & 10% respectively.

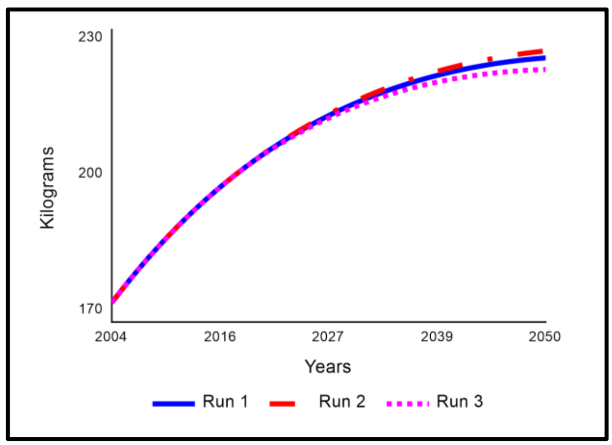


Figure 3.30b: Changes in annual rice production per person in Bangladesh due to variations in household income growth rates. Runs 1, 2, & 3 represent growth rates of 5%, 2% & 10% respectively.

In case of both Mymensingh and Bangladesh, higher growth rates of household income leads to lower amount of rice production, while lower growth rates lead to higher amounts of rice production. The impact is stronger for Mymensingh, as land conversion is faster there. However, the production stays above rice required per person.

3. 4. 7. 2 Scenario Two: Changes in Rice Yield and Household Income

In section 3.4.5 we have seen that a decrease in rice yield changes the rice production per person outcome. So, we are doing a scenario analysis, that considers both changes in rice yield, and changes in household income. In Figure 3.31, Run 1 represents the baseline, Run 2 represents reduction in rice yield growth by half, and Run 3 represents increase in household income by 10% simultaneously with reduction in rice yield growth by half.

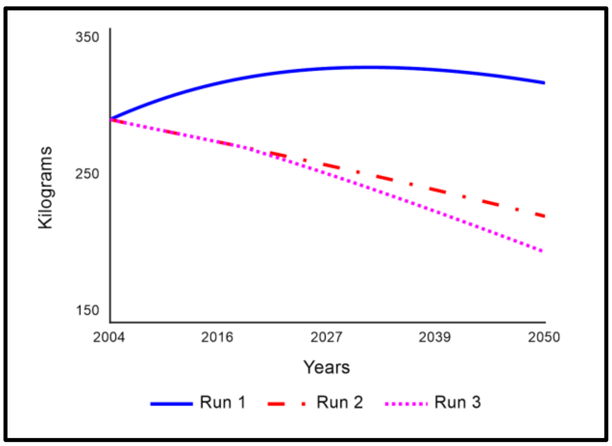


Figure 3.31a: Changes in annual rice production per person in Mymensingh due to decline in rice yield and increase in household income growth rates.

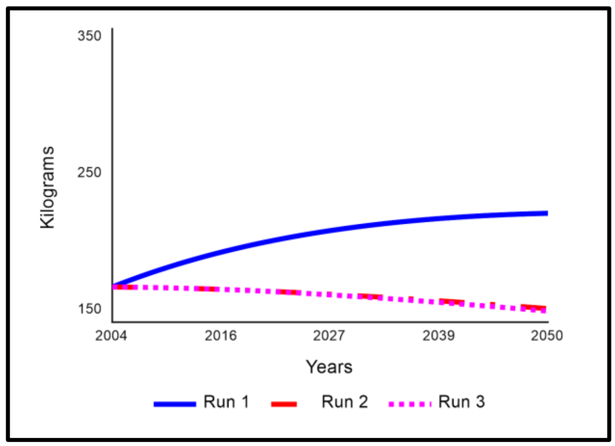


Figure 3.31b: Changes in annual rice production per person in Bangladesh due to decline in rice yield and increase in household income growth rates.

The results in Figure 3.31 show that a decline in rice yield significantly changes the outcome of rice production per person. An increase in household income further declines rice production, but its impact is not as strong as the decline in rice yield.

3. 5 CONCLUSION

The main objective of this research is to analyze the dynamics of crop land conversion to aquaculture over time, and understand what key variables are influencing the transformation process. There are trade-offs associated with conversion of crop land to fish farming, and this study aims to understand to what extent aquaculture growth can become a threat for rice production in the long run, or to what extent the aquaculture sector can continue to grow and provide the benefits associated with it.

This study observes that fish yield, price, growth in household income, and concentration of supporting industries are some of the key factors that can influence the growth of aquaculture. Fish yield depends on the intensification of fish farming. Prices of inputs have been sharply rising, so farmers who have entered farming and intensified early have an advantage in this business. More intensive systems are less sensitive to falling output prices. The differences of the price impact between a much higher than average concentration region (in terms of production and yield) and the country as a whole shows that more intensive farming systems are able to withstand the price sensitivity of inputs better than less intensive systems. However, if fish prices keep falling, as was observed during the last two years, then fish farming may not remain profitable for all types of farms. Also, places where inputs are easily available, and market access is easier, are more suitable for faster land conversion rates. Moreover, economic growth in general, observed through household income growth has positive impact on expansion of fish area, as people have higher amounts of money to invest when they earn more.

This study does not observe that there is a major threat from aquaculture to rice production in Bangladesh. However, this outcome is based on the continuation of the growth in the rice yield that has been happening over the recent decades. In this study, it has been observed that rice land has been declining, but right now that is being off-set by the growth in rice yields over the last few decades. If the growth rate of rice yield slows down, then rice availability can become a problem in the future.

The first policy implication from the findings of this study is that the growth in yield of both fish and rice needs to be sustained in order to maintain the gains from aquaculture growth. Rice land is expected to keep declining, and growth in the rice yield can come from higher yielding varieties, and intensification of cropping patterns. Development of shorter duration rice varieties can increase the number of times a plot is cultivated in a year. Also, since all lands are not the same, there should be monitoring of the type of land that is being converted to aquaculture, and conversion of highly productive, multiple cropped rice land should be discouraged. Fish production can be sustained by encouraging polyculture, with a mix of low yield and low feed demand, and high yield and high feed demand species. If only low yield species dominate, then aggregate yields inevitably go down, but culturing only high yield species can exacerbate the problem of high feed prices. So, agricultural and national development policies should focus on research and extension activities for maintaining the yield growth of those enterprises.

The second policy implication is that there should be efforts to stabilize input and output costs of fish. Since feed cost holds the highest share of the cost of fish production, more attention needs to be given to minimize feed cost. Further research is necessary on the fish feed value chain, but one policy option is to grow more feed ingredients locally, so as to be less dependent on imported feed materials. On the output side, development of cold storages and processing plants in high aquaculture concentration areas can help farmers. Additionally, since there is almost no export of freshwater fish from Bangladesh, but there is demand in the international market, efforts should be made to link freshwater aquaculture production systems in Bangladesh to global markets. This will ensure better prices for producers.

The third policy implication is that focus should be given to the development of fish farming in the boundary areas of high aquaculture concentration like Mymensingh. Such a region has an advantage in terms of availability of inputs, and if roads and other infrastructure can be extended to the periphery areas, there is a better prospect of fish farming spreading in those areas.

The fourth policy option is to strengthen the aquaculture extension agencies. Bangladesh has a large infrastructure for crop extension, but the fish extension system is very small. Again, not all regions would need equal attention, so target regions should be set up, based on their potential to support aquaculture, and targeted extension activities should be directed there.

FOOTNOTE

1. Since fiscal year in Bangladesh is counted from July to June, some of the data reported in this dissertation is in a format like 2000-01, 2016-17, etc.

APPENDICES

Appendix 3A: All Interview Questionnaires

The research instruments were approved by the Institutional Review Board at Michigan State University (reference: STUDY00001030). All the conversations were in Bangla, the language of the researcher and all the experts. After the interviews, the recorded audio was transcribed first in Bangla, and then translated to English, which was then coded, and findings were used in the analysis for this paper. The focus group and individual interview questionnaires are presented in this section.

Appendix 3A. I. Focus Group Discussion Interview Protocol

Goals

- Introduce research
- Identification of socioeconomic and environmental context of the study areas in collaboration with stakeholders
- Describe and receive feedback on system structure and boundaries

Objectives

- Confirm reference timeline and system boundaries
- Check resources/ecosystem services
- Identify key drivers of change
- Corroborate model structure and facilitate parameterization

Activities

- Presentations
  - Introduction to project
  - Defining the system under study
    - Geographic scope
    - Key resource issues (land use change, water & energy use)
  - Timeline: present draft timeline in opening presentations
- Resource mapping

- Use available maps to start discussion
    - Check aquaculture concentrated areas
    - Less concentrated
- Annotate to identify land use types/resources/infrastructure
    - Roads, Housing Settlements, Markets
    - Input Suppliers
    - Ag Land
    - Water Bodies
    - Land Types
- Demonstrate how we'll turn this into maps

- Group discussion: feedback on research – conversation with stakeholders focus group style for
    - Opinions on current system structure: relationships between system components
    - Understanding farmer's land use and financing decisions
        - why they do what they do
        - types of land, and how they are used
    - Understanding farmers' motivation to invest in fish farming
        - farmers' motivation in fish farming
        - relationship between profits and investment
        - sources of financing (what proportion of capital is from loan)
        - how much reinvested for development
    - Discussing farmers' constraints to invest in fish farming
        - financial and physical constraints: why all farmers not convert
        - how much more land can be brought under aquaculture
    - Understanding the role of various institutions and government policy in this process
    - Understand water. energy, and other input use in fish and rice production systems
        - water use: depth of ponds, how much water (stock), how much refilled, sources of water
        - energy use: main purposes, sources and respective quantities

Appendix 3A. II. Questionnaire for Farmers

A. Basic Information about the Respondent

Name of the Interviewee Address Mobile Phone Age, Education & Household Primary Occupation Other Occupation Prior Occupation	

B. Land Information

	2017	2014	2010
Homestead area			
Pond area			
own			
leased in			
leased out			
Crop area			
own			
leased in			
leased out			
Other			

C. Income Sources

Sources	2017			2014	2010
Fish farming	qty	price	value	value	value
Gross Income					
Rice production					
Other crop production					
Livestock production					
Non-farm income					
Remittances					
Other Income					

D. Farm Expenditure

Sector	2017			2014	2010
	qty	price	value	value	value

Fish farming					
land use					
fingerlings					
insecticide					
lime					
feed					
medicine					
fertilizer					
machinery					
Others					
	2017			2014	2010
Labor	qty	price	value	value	value
family labor					
short term labor					
permanent labor					
Infrastructure					
new					
repairs					
Other expenses					
Total Expenses					
Crop farming					
land use					
seed					
fertilizer					
pesticides					
machinery					
family labor					
short term labor					
permanent labor					

E. Water Use

Purpose	2017			2010		
	quantity	source	price	quantity	source	price
Pond filling						

F. Fuel Use

Purpose	Source	2017		2014	2010
		Quantity	Price		

G. Local Economic Situation

1. How has the economy of your area changed over …….. years?
2. Have you (personally) experienced any economic change over this period?
    - Tell me about how your income/asset ownership/means of communication and transportation/consumption have changed

H. Crop Production Activities

3. When did you first start crop/rice farming? How did you obtain the land?
4. What are your sources of labor? What about other farmers in the area?
5. What are your sources of capital? What about other farmers in the area?
6. What are the other inputs you use? When you started, where did you buy inputs from? Are they different now?
7. What varieties do you cultivate? What about others in the area?
8. What are the sources of water for you? What proportion came from what source? Discuss this for others in the area.
9. What are the sources of energy for you? What proportion came from what source? Discuss this for others in the area.
10. What are the major constraints for rice/crop farming?

I. Motivation for Fish Farming (fish farmers only)

11. What was your main occupation before starting fish farming?
12. When did you become interested in aquaculture? Can you tell me a story about what motivated you the most? In which year did you make the shift? What motivated other people in your area to shift to fish farming?
13. Were there any fish farmers in your village back then? How well did you know them? How often would you interact with them?
14. How did extension agents talk about fish farming before the transition? In what ways did you see information about fish farming in mass media outlets (newspapers, radio, television, etc.) before the transition?
15. What are the main constraints for starting fish farming?

J. The Act of Shifting and Fish Production Activities (fish farmers only)

16. What did you need to do to start fish farming? How did you finance it? Is this same for other fish farmers? Please explain.
17. Did you start with existing ponds, or did you converted rice/crop lands? Did you own that land/pond?
18. What were the initial constraints?
19. Where did you buy fish seeds/fingerlings from? Are they different now? Discuss how the fish seed/fingerlings supply has evolved.
20. Where did you buy fish feed from? Are they different now? Discuss how the fish feed supply has evolved.
21. Where did you buy other inputs from? Are they different now? Discuss how the supply of other inputs has evolved.

22. Whom do you sell your product to? Were they different when you first started? Did they exist 10 years ago?
23. Where did you learn about techniques in aquaculture (farming practices)? What type of formal or informal training did you get?
24. What species do you cultivate? What about others in the area?
25. What are the sources of water for you? What proportion came from what source? Discuss this for others in the village.
26. What are the sources of energy for you? What proportion came from what source? Discuss this for others in the village.

K. Investment Decisions

27. How much money did you earn from rice/crop or fish farming in 2017? What about previous three years?
28. How much money did you spend on existing rice/other crop or fish enterprises in 2017? Can you please explain why you made this choice? What about previous three years?
29. How much money did you invest in expanding rice/crop farming in 2017? What about previous three years?
30. How much have you invested in new ponds and how much in new fish technologies in 2017? Can you please explain why you made these choices? What about previous three years?
31. Did you borrow money for fish farming in 2017? What about previous three years?
32. Did you convert any own rice/other crop land to fish farming over the last three years? Can you please explain why you made these choices?
33. Did you buy any farm machinery over the last three years? Why, or why not?
34. Did you introduce any new rice varieties, or crops, or fish species over the last three years? Why, or why not?
35. How have you intensified production (increase stocking density, feeding rates, etc.) over the last three years?
36. Have you invested in other agricultural (like livestock) or non-agricultural enterprises in 2017? Can you please explain your choice? What about the previous three years?

Appendix 3A. III. Questionnaire for Policy Makers and Extension Agents

Basic Information about the Respondent

Name of the Interviewee			
Address			
Mobile Phone		Date	
Expertise	☐ Fish Extension	☐ Rice Extension	☐ Policy Maker

1. Discuss land, water, and energy availability for agriculture
   - What are the major trends in land use in agriculture for Bangladesh/Mymensingh?
   - What are the major trends in sources and quantities of water use and energy use in agriculture for Bangladesh/Mymensingh?

2. Sketch and discuss current status of land, water, and energy use in crop and fish production
   - What are the key stocks within land distribution in the area? How are they changing?
   - How much water is being used in aquaculture? What are the sources?
   - How much energy is being used in aquaculture? What are the sources?
   - Data or research on land, water, and energy use in aquaculture

3. Identify the major drivers of land conversion to aquaculture, and intensification of fish farming
   - Who are the fish farmers? What are their main socioeconomic characteristics? How are they different from other farmers?
   - What motivates someone to engage in aquaculture? Please talk us through their decision making behavior (economic incentives, social attitudes, resource availability, etc.).
   - How does he/she finance it?
   - What motivates an existing fish farmer to expand fish farming? Please talk us through their decision making behavior?
   - How does he/she finance it?
   - What motivates a fish farmer to intensify fish farming? What are the main methods in intensifying production (new varieties/more inputs/machineries etc.)? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - Are there socioeconomic feedbacks that govern the behavior of conversion or intensification?

4. Identify the major constraints of land conversion to aquaculture, and intensification of fish farming including land, labor, cash, feed or other inputs, technology, water, energy, etc.
   - What are the main barriers to expanding fish farming?
     - Why don’t all land owning or capable farmers engage in fish farming?
   - What are the main barriers to intensifying fish farming?

5. Discuss the potential changes in land use and intensification of aquaculture in future
   - What is the direction of resource use in fish production?
   - What will be the main limiting factors to aquaculture growth in the future? Please discuss in relation to land, water and energy availability.

6. Discuss the impact of aquaculture growth on sustainable use of land, water, and energy resources
    - What is the extent of pressure that an expanding aquaculture sector may exert on the natural resources of our country?
    - How is land use changing as a result of aquaculture growth? Are there indirect impacts?
    - Do you think we can grow sufficient food of different types (rice, vegetables, etc.) if aquaculture growth continues?
    - How is water utilization changing as a result of aquaculture growth?
    - How resilient are our water supply to an expanding aquaculture sector?
    - How is energy efficiency changing as a result of aquaculture growth?
    - How resilient are our energy supply to an expanding and intensifying aquaculture sector?
    - Identify major feedbacks that can influence the outcome of natural resources use

7. Discuss policy options for influencing long term outcomes
    - What policy tools are available to influence land, water, and energy use behavior of farmers?
    - What policy measures do you think should be used for ensuring sustainable use of land?
    - What policy measures do you think should be used for ensuring sustainable use of groundwater?
    - What policy measures do you think should be used for efficient use of energy?

Appendix 3A. IV. Questionnaire for Scientists

Basic Information about the Respondent

Name of the Interviewee			
Address			
Mobile Phone		Date	
Expertise	☐ Fish Scientist	☐ Rice Scientist	☐ Social Scientist

1. Discuss land, water, and energy availability for agriculture
   - What are the major trends in land use in agriculture for Bangladesh/Mymensingh/Trishal?
   - What are the major trends in sources and quantities of water use and energy use in agriculture for Bangladesh/Mymensingh/Trishal?

2. Sketch and discuss current status of land, water, and energy use in crop and fish production
   - What are the key stocks within land distribution in the area? How are they changing?

3. Identify the major drivers of land conversion to aquaculture, and intensification of fish farming
   - Who are the fish farmers? What are their main socioeconomic characteristics? How are they different from other farmers?
   - What motivates a crop farmer to convert to fish farming? Can you please talk us through their decision making behavior (economic incentives, social attitudes, resource availability, etc.)?
   - How does he/she finance it?
   - What motivates an existing fish farmer to expand fish farming? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - What motivates a fish farmer to intensify fish farming? What are the main methods in intensifying production (new varieties/more inputs/machineries etc.)? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - What proportions of their income are reinvested to aquaculture for expansion and/or intensification?
   - Are there socioeconomic feedbacks that govern the behavior of conversion or intensification?

4. Identify the major constraints of land conversion to aquaculture, and intensification of fish farming including land, labor, cash, feed or other inputs, technology, water, energy, etc.
   - Why don’t all land owning or capable farmers engage in fish farming?
   - What are the main barriers to expanding fish farming?
   - What are the main barriers to intensifying fish farming?

5. Discuss the potential changes in land use and intensification of aquaculture in future
   - What is the direction of resource use in fish production?
   - What will be the main limiting factors to aquaculture growth? Please discuss in relation to land, water and energy availability.

6. Discuss the impact of aquaculture growth on sustainable use of land, water, and energy resources
   - How is land use changing as a result of aquaculture growth? Are there indirect impacts?
   - How is water utilization changing as a result of aquaculture growth?
   - How is energy efficiency changing as a result of aquaculture growth?

7. Identify the resilience of the natural resource systems to the intensification of resource use
   - Do you think we can grow sufficient food of different types (rice, vegetables, etc.) if aquaculture growth continues?
   - Do you think we can grow sufficient food of different types if aquaculture growth continues?
   - How resilient are our water supply to an expanding aquaculture sector?
   - How resilient are our energy supply to an expanding and intensifying aquaculture sector?
   - What is the extent of pressure that an expanding aquaculture sector may exert on the natural resources of our country?

8. Identify major feedbacks that can influence the outcome of natural resources use

Appendix 3B: Mathematical Equations for the System Dynamics Model

Mathematical Equations for the system dynamics model on land use change:

crop to other land = Crop_Land x crop_to_other_conversion_factor ………….. (1)

crop land to fish pond = demand_for_new_fish_land x land_conversion_factor ………….. (2)

demand for new fish land = available_aggregate_conversion_budget/expansion_cost …….. (3)

expansion cost = base_expansion_cost*(1+expansion_cost_growth x benefit_cost_module.year) ………… (4)

Benefit cost module:

benefit cost ratio = total return per ha/total cost per ha …………………. (5)

Where,

total return per ha = fish yield x fish price ……………………..…. (6)

total cost per ha = fingerlings cost + lab cost + feed cost + other cost ……. (7)

Again,
fish yield = base_fish_yield x (1+(fish_yield_growth x year)) ….. (6a)
fish price = base_fish_price x (1+(fish_price_growth x year)) ….. (6b)
fingerlings cost = base_fingerlings_cost x (1+(fingerlings_cost_growth_rate x year)) ……. (7a)
lab cost = base_lab_cost x (1+(lab_cost_growth_rate x year)) ……. (7b)
feed cost = base_feed_cost x (1+(feed_cost_growth_rate x year)) ……. (7c)
other cost = base_other_cost x (1+(other_cost_growth_rate x year)) ……. (7d)

Investment module:

available aggregate conversion budget	=	large land hh number * average pond investment by large land owners + medium land hh number * average pond investment by medium land owners + small land hh number * average pond investment by large small owners ……………… (8)

Where,

large/medium/small household numbers are expressed as the following rule:

IF(benefit cost ratio>1)
THEN(number of households * proportion of large/medium/small land owners)
ELSE(0)

Again,

average pond investment by [type of] land owners	=	base year investment large land owners * (1+annual income growth rate [type of] land owners x benefit_cost_module.year) ….. (9)

Food supply module:

total calorie per cap per day	=	rice calorie per cap per day + fish calorie per cap per day + other calorie per cap per day ….. (10)
total protein per cap per day	=	rice protein per cap per day + fish protein per cap per day + other calorie per cap per day ………… (11)

Rice production module:

rice output = rice land x rice yield x cropping intensity
rice land = .Crop Land x rice land coefficient
rice yield = base year rice yield x (1+(rice_yield_growth_rate x benefit_cost_module.year))

Fish production module:

fish output = .Fish pond x benefit_cost_module.fish_yield

Appendix 3C: Summary Tables of Data Used in the Model

The system dynamics model has been parameterized for data from 2004-2016. In this study, the geographical scales are the district of Mymensingh (Mym), and the country Bangladesh (BGD) as a whole. If there are differences in the data for different scales, then it has been mentioned, otherwise, they are assumed to be the same.

Table A3.1: Stocks used in the model

Name	Unit	Scale	Initial values	Source
Crop Fields	Hectares	BGD	8719028	BBS Yearbooks
		Mym	312955	
Other Lands	Hectares	BGD	3521052	BBS Yearbooks
		Mym	107692	
Fish Pond	Hectares	BGD	305025	DoF Yearbooks
		Mym	8353	

Table A3.2: Simple converters

Name	Units	Value/Range of values	Source
crop to other land conversion rate	annual %	BGD: 0.45% Mym: 0.33%	Quasem (2011); expert opinion
expansion cost	BDT per ha	23215	Alam (2011)
fish yield	kg per ha	2875.73	DoF Yearbooks
fish yield growth	annual %	21%	DoF Yearbooks
fish price	BDT per kg	65	DAM website
fish price growth	annual %	8% up to 2008, then -0.01%	estimated from DAM data
base year feed cost	BDT per ha	166355	base year figures from Ahmed et al. (2010)
base year labor cost	BDT per ha	17221	
base year fingerlings cost	BDT per ha	13125	
base year other cost	BDT per ha	29660	
feed cost growth	annual %	15%	estimated from Ahmed et al. (2010), Jahan et al. (2015), Alam (2011), and Palash (2015)
labor cost growth	annual %	16%	
fingerlings cost growth	annual %	36%	
other cost growth	annual %	10%	
expansion cost	annual %	10%	
number of households	number	BGD: 31000000 Mym: 965000	BBS Yearbooks
average investment for new pond			
large land owners	BDT/year	BGD: 2605 Mym: 0	estimated from BIHS dataset
medium land owners	BDT/year	BGD: 840 Mym: 1261	
small land owners	BDT/year	BGD: 0 Mym: 0	
rice calorie	kcal per kg	3450	Shaheen et al., 2013
fish calorie	kcal per kg	3485	Bogard et al., 2015
rice protein	gram per kg	72	Shaheen et al., 2013
fish protein	gram per kg	177	Bogard et al., 2015

Appendix 3D: Investment for New Pond Calculations

Here,
pondinvyr = household investment in Bangladeshi Taka (BDT) for new pond in a year
totland2 = household land area in 2015 in hectares

Table A3.3: Average annual pond investments in Mymensingh from BIHS data

Variable	Condition	Number of Observations	Mean	Minimum	Maximum
pondinvyr	totland2 < 1.01	207	73.06	-5133.33	7150
pondinvyr	totland2>=1.01 & totland2<3.03	26	740.38	0	11366.67
pondinvyr	totland2>=3.03	1	0	0	0

Table A3.4: Average annual pond investments in Bangladesh from BIHS data

Variable	Condition	Number of Observations	Mean	Minimum	Maximum
pondinvyr	totland2 < 1.01	5,539	-77.60	-239983.30	24383.33
pondinvyr	totland2>=1.01 & totland2<3.03	458	1271.32	-137133.30	83233.34
pondinvyr	totland2>=3.03	43	7849.22	-187550	271516.70

Appendix 3E: Sensitivity Analysis for Land Use Change Paper

Table A3.5: Sensitivity to Future Fish Price Change

	Future fish price growth (%)	Fish pond area in 2050 (hectares)	
		Mymensingh	Bangladesh
Run 1	-2.00	36302.82	382490.47
Run 2	-1.33	49841.00	382490.47
Run 3	-0.67	73623.16	382490.47
Run 4	0.00	73623.16	382490.47
Run 5	0.67	73623.16	382490.47
Run 6	1.33	73623.16	386461.72
Run 7	2.00	73623.16	469031.37
Run 8	2.67	73623.16	509430.48
Run 9	3.33	73623.16	509430.48
Run 10	4.00	73623.16	509430.48

Table A3.6: Sensitivity to Future Fish Yield Change

	Future fish yield growth (%)	Fish pond area in 2050 (hectares)	
		Mymensingh	Bangladesh
Run 1	5.00	41794.64	377669.19
Run 2	7.78	72170.35	499956.50
Run 3	10.56	72170.35	509313.60
Run 4	13.33	72170.35	509313.60
Run 5	16.11	72170.35	514074.01
Run 6	18.89	72170.35	514074.01
Run 7	21.67	72170.35	514074.01
Run 8	24.44	73623.16	514074.01
Run 9	27.22	73623.16	514074.01
Run 10	30.00	73623.16	514074.01

Table A3.7: Sensitivity to Expansion Cost Change

	Expansion cost growth (%)	Fish pond area in 2050 (hectares)	
		Mymensingh	Bangladesh
Run 1	5.00	100649.04	600730.24
Run 2	7.78	81953.00	540675.78
Run 3	10.56	70167.87	502898.89
Run 4	13.33	61971.59	476659.75
Run 5	16.11	55900.68	457240.65
Run 6	18.89	51201.82	442218.43
Run 7	21.67	47444.71	430211.13
Run 8	24.44	44364.35	420368.89
Run 9	27.22	41788.05	412138.30
Run 10	30.00	39598.06	405142.43

Table A3.8: Sensitivity to Feed Cost Change

	Feed cost growth (%)	Fish pond area in 2050 (hectares)	
		Mymensingh	Bangladesh
Run 1	5.00	73623.16	514074.01
Run 2	7.78	73623.16	509313.60
Run 3	10.56	73623.16	509313.60
Run 4	13.33	73623.16	509313.60
Run 5	16.11	72170.35	486272.26
Run 6	18.89	72170.35	447082.98
Run 7	21.67	72170.35	405721.37
Run 8	24.44	72170.35	377669.19
Run 9	27.22	72170.35	377669.19
Run 10	30.00	72170.35	377669.19

Table A3.9: Sensitivity to Land Quality Change

	Land quality paremeter	Fish pond area in 2050 (hectares)	
		Mymensingh	Bangladesh
Run 1	0.00	8353.00	305025.00
Run 2	0.11	20050.16	337861.65
Run 3	0.22	31747.32	370698.30
Run 4	0.33	43444.48	403534.95
Run 5	0.44	55141.64	436371.60
Run 6	0.56	66838.80	469208.25
Run 7	0.67	78535.96	502044.90
Run 8	0.78	90233.13	534881.55
Run 9	0.89	101930.29	567718.20
Run 10	1.00	113627.45	600554.85

Table A3.10: Sensitivity to Value Chain Support Change

	Value chain support paremeter	Fish pond area in 2050 (hectares)	
		Mymensingh	Bangladesh
Run 1	0.00	8353.00	305025.00
Run 2	0.11	15605.24	616109.06
Run 3	0.22	22857.48	927193.11
Run 4	0.33	30109.72	1238277.17
Run 5	0.44	37361.96	1549361.23
Run 6	0.56	44614.20	1860445.29
Run 7	0.67	51866.44	2171529.34
Run 8	0.78	59118.68	2482613.40
Run 9	0.89	66370.92	2793697.46
Run 10	1.00	73623.16	3104781.52

Table A3.11: Sensitivity of Food Calorie Outcome to Fish Yield Changes

	Future fish yield growth (%)	Kilocalorie per capita per day in 2050	
		Mymensingh	Bangladesh
Run 1	5.00	6503.22	4866.01
Run 2	7.78	6881.84	4949.31
Run 3	10.56	7260.70	5025.69
Run 4	13.33	7639.57	5099.70
Run 5	16.11	8018.43	5177.01
Run 6	18.89	8397.29	5251.72
Run 7	21.67	8776.16	5326.43
Run 8	24.44	9155.02	5401.14
Run 9	27.22	9533.88	5475.85
Run 10	30.00	9912.75	5550.56

Table A3.12: Sensitivity of Food Protein Outcome to Fish Yield Changes

	Future fish yield growth (%)	Total protein per capita per day in 2050 (grams)	
		Mymensingh	Bangladesh
Run 1	5.00	320.76	274.22
Run 2	7.78	352.64	279.50
Run 3	10.56	371.88	283.46
Run 4	13.33	391.12	287.21
Run 5	16.11	410.36	291.18
Run 6	18.89	429.60	294.97
Run 7	21.67	448.84	298.76
Run 8	24.44	468.08	302.56
Run 9	27.22	487.31	306.35
Run 10	30.00	506.55	310.15

Table A3.13: Sensitivity of Food Calorie Outcome to Fish Price Changes

	Future fish price growth (%)	Kilocalorie per capita per day in 2050	
		Mymensingh	Bangladesh
Run 1	-2.00	7588.41	4966.45
Run 2	-1.33	7991.84	4966.45
Run 3	-0.67	8685.23	4966.45
Run 4	0.00	8685.23	4966.45
Run 5	0.67	8685.23	4966.45
Run 6	1.33	8685.23	5005.53
Run 7	2.00	8685.23	5014.04
Run 8	2.67	8685.23	5014.04
Run 9	3.33	8685.23	5014.04
Run 10	4.00	8685.23	5014.04

Table A3.14: Sensitivity of Food Protein Outcome to Fish Price Changes

	Future fish price growth (%)	Total protein per capita per day in 2050 (grams)	
		Mymensingh	Bangladesh
Run 1	-2.00	373.41	279.35
Run 2	-1.33	399.21	279.35
Run 3	-0.67	444.22	279.35
Run 4	0.00	444.22	279.35
Run 5	0.67	444.22	279.35
Run 6	1.33	444.22	282.31
Run 7	2.00	444.22	282.93
Run 8	2.67	444.22	282.93
Run 9	3.33	444.22	282.93
Run 10	4.00	444.22	282.93

Table A3.15: Sensitivity of Food Calorie Outcome to Rice Yield Changes

	Future rice yield growth (%)	Kilocalorie per capita per day in 2050	
		Mymensingh	Bangladesh
Run 1	1.00	7490.18	4506.77
Run 2	2.00	8065.83	4916.60
Run 3	3.00	8641.47	5326.43
Run 4	4.00	9217.12	5736.26
Run 5	5.00	9792.76	6146.08
Run 6	6.00	10368.40	6555.91
Run 7	7.00	10944.05	6965.74
Run 8	8.00	11519.69	7375.56
Run 9	9.00	12095.34	7785.39
Run 10	10.00	12670.98	8195.22

Table A3.16: Sensitivity of Food Protein Outcome to Rice Yield Changes

	Future rice yield growth (%)	Total protein per capita per day in 2050 (grams)	
		Mymensingh	Bangladesh
Run 1	1.00	417.41	281.66
Run 2	2.00	429.43	290.21
Run 3	3.00	441.44	298.76
Run 4	4.00	453.45	307.32
Run 5	5.00	465.47	315.87
Run 6	6.00	477.48	324.42
Run 7	7.00	489.49	332.98
Run 8	8.00	501.51	341.53
Run 9	9.00	513.52	350.08
Run 10	10.00	525.54	358.64

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CHAPTER FOUR

IMPLICATIONS OF AQUACULTURE GROWTH IN BANGLADESH ON PRODUCTIVITY OF WATER USE AND GROUNDWATER EXTRACTION

4. 1. INTRODUCTION

The use of water in agriculture is essential for growing food and other necessary commodities. Seventy percent of the earth's surface is covered by water, but most of it cannot be used for agricultural production as less than a third of 1% of that water is in a form that is easily usable, with 0.009% in exploitable lakes, 0.0001% in rivers, and 0.31% as accessible groundwater (Daly & Farley, 2004). Water is classified as a renewable resource because the natural stocks of water can be replenished through the hydrological cycle, but the rate of refilling can be significantly slower than rates of extraction for a region, resulting in water scarcity for certain areas over a period of time (Daly & Farley, 2004). Through advancement of technologies, human beings have become the dominant force behind changes in water resources in the world (Rockstrom et al., 2014). When overexploitation of water resources diminishes the water stock of an area, this impact can feed back into the activities that caused the decline in the first place through ecological and socioeconomic mechanisms, and make these activities (such as agriculture) more expensive and difficult. Therefore, it is important to take account of how productively we are using water, and whether we are crossing any thresholds that might have adverse consequences.

The largest sectoral user of water in the world is the agriculture sector (Shiklomanov, 2000; World Bank, 2017). Changes within the agriculture sector can therefore have significant impacts on the productivity and sustainability of water use. Among many crops that use large quantities of irrigation water in the production system, rice occupies one of the top positions (Mekonnen &

Hoekstra, 2011; GRiSP, 2013). Another agricultural sub-sector that has been rapidly expanding over the last few decades is freshwater aquaculture (Bostock et al., 2010; Bosma & Verdegem, 2011). Since aquaculture uses significant amounts of water, it is important to understand the impact of the growth of this sector on water resources. Also, aquaculture growth is more concentrated in certain regions of the world, and Bangladesh is one of the countries that have experienced very high growth rates (FAO, 2018). It is also a country where protein consumption has been low, and studies have shown that the growth of freshwater aquaculture has been playing a favorable role in that aspect (Belton et al., 2014). Overexploitation of groundwater for crop production has already raised concerns about groundwater depletion in Bangladesh (Shamsudduha et al. 2009; Jahan et al. 2010; Shamsudduha et al., 2011). Therefore, while the growth of aquaculture can have positive impacts on the food security and nutrition status of the country, it will be important to understand how it is influencing the water productivity and use of groundwater. Water productivity can have different meanings to different people, and hence it is important to specify what is being discussed here (Cook et al., 2006; Ali & Talukder, 2008). This concept can be applied to various geographical scales and sectors (Cook et al., 2006). In agriculture, water productivity is used to define the relationship between agricultural output and the amount of water involved in the production process, expressed as agricultural production per unit volume of water (Ali & Talukder, 2008). In this research, water productivity is defined as the physical mass of production measured against gross inflow, net inflow, or depleted water for the rice and fish production systems (Molden et al., 2010). Since aquaculture is often replacing rice production in Bangladesh, which is the main user of agricultural water so far, this paper will compare water use between rice and fish production systems in order to understand the direction and magnitude of change. This aspect of freshwater aquaculture expansion has not been studied so far.

In this essay, there are two main issues that will be addressed. The first is how aquaculture growth in Bangladesh is changing water productivity by substituting irrigated rice production, where the use of water will be considered relative to agricultural output. The second is to understand how aquaculture growth is changing groundwater use, where the quantities of groundwater extraction irrespective of the output it generates will be considered. This paper will build on the system dynamics model developed in the land use change paper of this dissertation, by adding a water use module that estimates water use in rice and fish production.

4. 2. BACKGROUND

4. 2. 1 Water Use in Crop Production and Aquaculture

People learned to apply irrigation in agricultural production systems thousands of years ago, but with the advancement of technologies, the coverage of land under irrigation has increased massively over the last century. Globally, irrigated area increased from 62 million hectares in 1900 to 324 million hectares in 2000, which has inevitably increased freshwater use in agriculture (Siebert et al., 2013; FAO, 2016). Irrigation has allowed multiple cropping seasons in different parts of the world, increasing cropping intensity. Together with high yielding varieties and fertilizers, irrigation has been one of the most crucial drivers of the Green Revolution (FAO, 2016). The contribution of irrigation can be understood from the fact that 40% of global food production is from 20% (or less) of irrigated cultivable land (Khan & Hanjra, 2009; FAO, 2016). However, the increase of freshwater use in agriculture has raised some concerns like over exploitation of groundwater and subsequent lowering of water tables, decline of stream flows, salinity intrusion, increase in flooding and/or water logging, conflict over use of water resources, etc. (Shiklomanov, 2000; Khan & Hanjra, 2009; FAO, 2016)

Agricultural production is a major user of freshwater in quantitative terms as it accounts for about 70% of global freshwater consumption (Shiklomanov, 2000; World Bank, 2017). Water withdrawal for irrigation varies widely across the world, ranging from 5,000 to 25,000 m^3 per hectare, while the global average is about 7,700 m^3 per hectare (Shiklomanov, 2000; FAO, 2016). Figure 4.1 shows that the concentration of irrigated area in South and South East Asia is relatively high in the northern parts of India and Bangladesh.

Rice is the main irrigated crop of the world, covering 29% of the total irrigated crop area (FAO, 2016). Total seasonal water input to rice fields is up to 2–3 times more than that for other cereals (GRiSP, 2013). Depending on soil types, climatic conditions, rice varieties, etc. water use in rice production can be from 0.8 m^3 per kg rice produced to more than 5 m^3 per kg, with an average of about 2.5 m^3 per kg (GRiSP, 2013). Aquaculture, on the other hand, can be a more water efficient food production system (Ahmed et al., 2014). However, its water productivity also varies significantly with production techniques or the intensity of production. Ranging from an extensive pond to highly intensive pond, water use can be as high as 45 m^3 per kg, or as low as 0.4 m^3 per kg of fish produced (Verdegem, 2006; Verdegem and Bosma, 2009; Waite et al., 2014; Bostock et al., 2016).

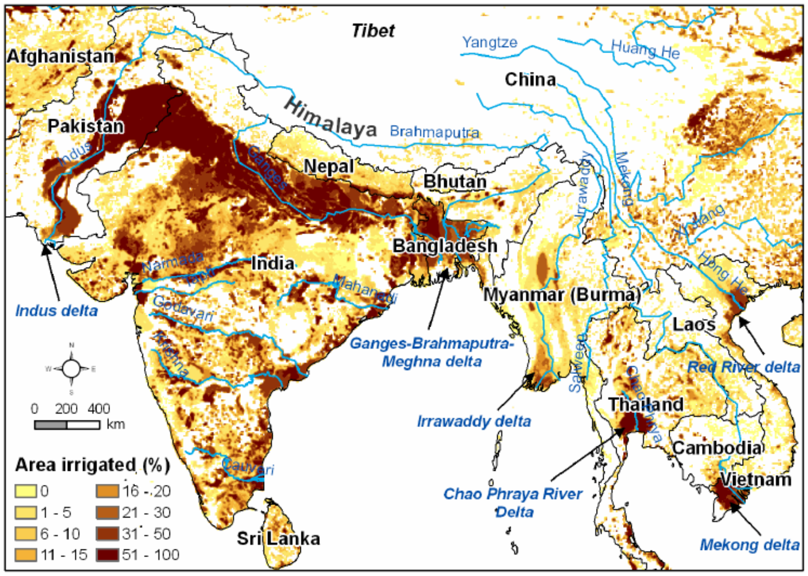

Figure 4.1: Proportion of irrigated area in South and Southeast Asian countries (Source: Siebert et al., 2006, cited in Shamsudduha et al. 2009)

Studies on Bangladesh have also shown that both rice and fish production systems use significant quantities of water, most of which is groundwater. On an average, 4 m^3 of water is used for producing one kg of Boro rice[1] (dry season rice) in the farmers' fields (BRRI, 2000, cited in Qureshi et al., 2014). Estimates of water quantity use in fish production from Bangladesh are not available, but several studies have mentioned that groundwater use is very common for commercial aquaculture (Jahan et al., 2015; Palash, 2015). A study based on a survey of 2678 farms mentioned that more than 80% of the farmers reported using groundwater, either as their primary water source, or to supplement rainfall (Jahan et al., 2015).

4. 2. 2 Groundwater Situation in the Region

The largest share of global water use is groundwater use. While global groundwater extractions (~1,500 km^3 per year) are smaller than global recharge (~12,600 km^3 per year), depletion of aquifers is a problem in many regions of the world (Aeschbach-Hertig & Gleeson, 2012). Several studies in India and Bangladesh have described a decline in groundwater levels in some areas, indicating reductions in aquifer storage from unsustainable groundwater extraction for both irrigation and urban water supplies (Rodell et al. 2009; Shamsudduha et al. 2009; Tiwari et al. 2009; Jahan et al. 2010; Shamsudduha et al., 2011; Kolagani et al., 2015). Long-term declining groundwater levels are detected in urban and peri-urban areas around Dhaka (>1 m/yr) as well as in north-western parts of Bangladesh (0.1–0.5 m/yr), where intensive extraction of groundwater is conducted for dry-season rice cultivation (Shamsudduha et al., 2009). Figure 4.2 shows trends in groundwater depth in Bangladesh, with red/darker shades indicating areas where the trend is declining.

Aquifers in Bangladesh are most commonly classified into “shallow” and “deep” categories in literature but the location of the contact between these two and the basis of hydrologic separation are not well defined (Michael and Voss, 2009, cited in Shamsudduha et al., 2011). Generally, aquifers that occur within the upper 80–100 meters below ground level (mbgl) of the stratigraphic sequence are identified as the shallow aquifers, while the deep aquifer occurs at greater than 100 mbgl (Ravenscroft, 2003, cited in Shamsudduha et al., 2011). Groundwater can be generally found in Bangladesh within 10 mbgl, however, the level can vary between north, northwestern, northeastern, central and southern parts of the country (Shamsudduha et al., 2011).

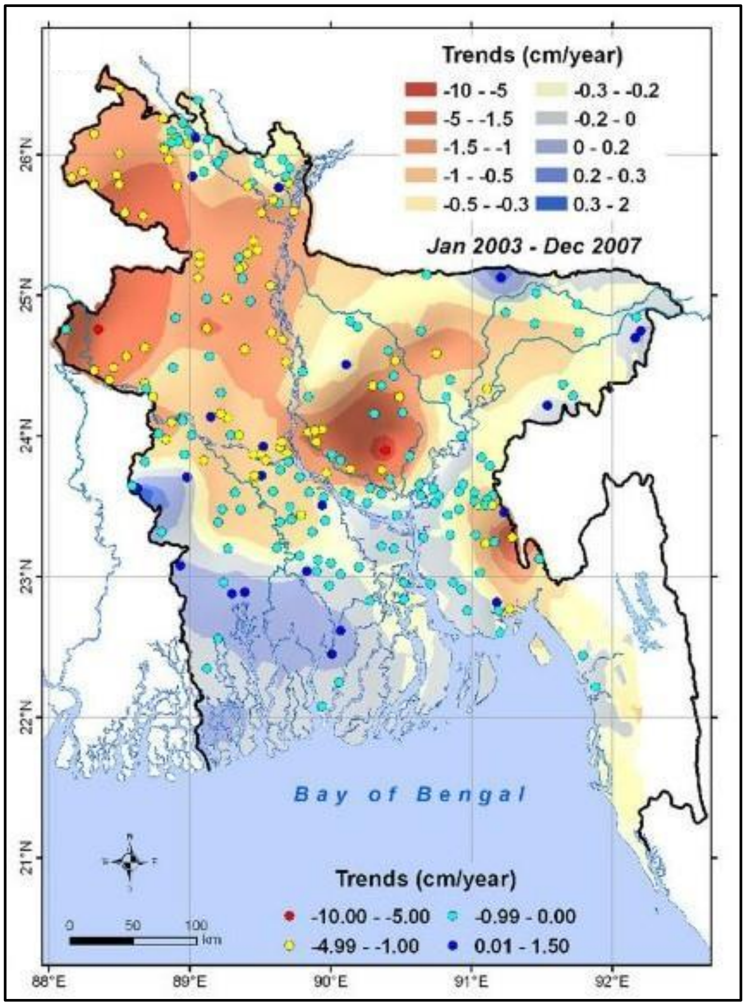

Figure 4.2: Groundwater storage changes in Bangladesh expressed as cm yr^{-1} for the period between 2003 and 2007 (Source: Shamsudduha et al., 2009)

Groundwater irrigation through power-operated pumps was introduced in Bangladesh during the 1970s, along with other Green Revolution technologies to produce high-yielding dry season Boro rice. By 2006, nearly 78% of the irrigated rice-fields were supplied by groundwater, out of which approximately 80% of the irrigation water was derived from low-capacity (average discharge rate 10 liters per second) shallow tubewells (STW; operates at depths up to 80 mbgl); while the rest was irrigated by high-capacity (average discharge rate 56 liters per second) deep tubewells (DTW; operates at depths above 80 mbgl) to produce Boro rice (Shamsudduha et al., 2011). Groundwater levels in shallow aquifers are subject to strong seasonal variations associated with monsoon rainfall and abstraction rates. Water extraction in the dry season for irrigation over a seven-month period can be recharged in the five-month monsoon period (Qureshi et al., 2014). However, when recharge is less than extraction, irrigation leads to groundwater depletion, resulting in a decline in water levels (Qureshi et al., 2014).

4. 2. 3 Challenges for Water Use in Bangladesh

Bangladesh has some alternative sources of surface water irrigation due to its network of rivers and canals, but historically, those have been more difficult to exploit in relation to demand for irrigation water for Green Revolution rice technologies, because of requirements of large scale irrigation projects that need development and maintenance of major infrastructure in some cases. Even groundwater extraction from deep aquifers has been less successful for similar (technological and institutional) reasons. On the other hand, groundwater irrigation via shallow tubewells, or the small scale option has achieved great success and expanded irrigation dramatically over the last three decades, and has contributed towards better food security outcomes (Qureshi et al., 2014). Water withdrawal in Bangladesh during 2008 was estimated as 35,870 million cubic meters per year, of which 88% was used in agriculture, 10% for municipalities, and 2% for industries (FAO, 2012). Again, 79% of that water was groundwater, and 21% was surface water (FAO, 2012). So, if groundwater tables keep going down water shortage can become a problem, and small scale irrigation will become one of the worst affected, as it may not remain feasible in some parts of the country in the future. Groundwater irrigation is therefore crucial to sustain agrarian growth to meet Bangladesh’s future food requirements (Qureshi et al., 2014).

The National Sustainable Development Strategy of Bangladesh aims to “Build capacity in water efficiency measurements and waste reduction in urban and irrigation sectors” (GED, 2013). The document also acknowledges the danger for overexploitation of groundwater, and says that “Groundwater exploitation should be regulated so that extraction does not exceed safe yield”. Furthermore, Bangladesh Delta Plan (BDP 2100) for water sector states that “The country needs to ensure sustainable water utilization, especially in the north-west and northcentral regions where water has gradually emerged as a scarce resource” (GED, 2015).

Several studies have explored the link between aquaculture and water use by addressing the impact of aquaculture on water quality (Anka et al., 2013; Ali et al., 2013; Belton et al., 2011). However, there has not been emphasis on the quantitative aspect of water use; that is, how the growth of aquaculture is influencing freshwater productivity or whether extraction is exceeding safe yield, especially in the north-west and northcentral regions. So, since: (a) groundwater tables are going down in some parts of the country, (b) rice production and aquaculture both use significant amounts of groundwater in the production process, and (c) rice and fish are the most important sources of calories and protein for Bangladesh, respectively, the change in water productivity and aquaculture’s contribution to groundwater extraction needs to be understood by researchers and policy makers for making agriculture and water policies that lead to sustainable use of water resources.

4. 2. 4 Research Questions

On the basis of the above situation, the research questions this essay is aiming to answer are as follows:

- Is aquaculture improving water productivity by substituting fish production for irrigated rice production in Bangladesh?

- Is the aquaculture growth increasing groundwater use in Bangladesh?

4. 3. METHODOLOGY

4. 3. 1 Conceptual Framework

This paper will build upon the system dynamics model of land use change from the previous paper, where we have modeled how land use is changing as a result of aquaculture growth. In this essay, the water balance approach will be applied in the rice field and fish ponds to calculate water use in rice and fish production to address the research question. Water balances consider inflows and outflows from basins, or service and use levels such as irrigation systems or fields, and the principle of conservation of mass requires that for a unit of area over a certain time period, inflows are equal to outflows plus any change of storage within the unit (Molden, 1997). According to Suh et al. (2010, p. 12), "Water balance is a system level analysis based on total water inflow and outflow of a region, which determine the change in water stock of the region over time". It is based on the law of conservation of mass which asserts that any change in the water content of an area during a specific time period must be equal to the difference between the amount of water added and the amount of water withdrawn (Zhang et al., 2008).

The water balance calculation is useful to understand water use of a system (Suh et al., 2010). This will help estimate water consumption in the production process, as well as the relative impact on groundwater extraction. Estimation of water budgets or water use for rice and fish production systems have commonly followed this approach, sometimes explicitly, but sometimes implicitly by not mentioning the equation (Nath & Bolte, 1998; Boyd et al., 2007; Luo et al., 2009). This paper is embedding a water balance model in the SD model created in the land use change paper. This will allow for modeling the relationship between the hydrologic system and socioeconomic aspects of the system, and enable the researchers to better understand how a change in one type of parameter affects other types of parameters (Beall et al., 2011).

The water balance in a rice field can be expressed through the following equation:

precipitation + irrigation = seepage + percolation + evapotranspiration + harvest biomass….. (1)

Similarly, water balance in a fish pond can be expressed through the following equation:

precipitation + irrigation = seepage + percolation + discharge or water exchange + evaporation + harvest biomass …. (2)

We will get only evaporation from the fish pond, but both evaporation and transpiration from rice fields, as transpiration occurs through the rice plants. Here, seepage is the horizontal flow of water from the soil, and percolation is the downward movement of water through the soil. Since seepage and percolation happen simultaneously, and it is hard to differentiate between them, studies have often considered them together (Singha et al., 2014). Then we have water discharge from fish ponds, as remaining water is supposed to be discharged from a pond after a certain period (usually a year). Water in harvest biomass is a very small quantity (0.75 m^3/ton for fish) and is usually ignored for this calculation (Boyd et al., 2007).

So, water consumption in rice production mainly happens through evapotranspiration, seepage and percolation. Outflows of water by seepage, and percolation are 25–50% of all water input in heavy soils with shallow water tables and 50–85% in coarse textured soils with deep water tables (GRiSP, 2013). So, seepage and percolation depends on soil types. Also, on an average to produce 1 kg of rice, 1.4 m^3 of water is lost through evapotranspiration (Bouman, 2009).

The majority of water consumption in freshwater aquaculture is due to surface evaporation, seepage and water exchange/drainage at harvest (Verdegem, 2006). Evaporation rates vary with the location and the temperature. Studies from the USA, Thailand, and Honduras have shown that evaporation from ponds varies between 610 to 2180 mm per year (Verdegem, 2006). Seepage loss depends on soil porosity, methods of pond construction, structural changes to the pond basin, and pond management practices (Boyd, 1982, cited in Nath & Bolte, 1998). Seepage losses are between 1825 and 3650 mm per year (Yoo & Boyd, 1994; Nath & Bolte, 1998). Also, if a pond of 1 meter depth is drained once a year, then drainage or water exchange consumes 1000 mm of water. Sources for water are precipitation and irrigation, where irrigation is applied to supplement the deficit from rainfall.

In order to calculate water productivity, we also need to consider the physical mass of production or the economic value of production. Since we will be comparing rice water productivity with fish water productivity, it is reasonable to estimate water productivity in terms of economic or energy value as the numerator, in order to make them comparable. The specific formula is presented in equation (3) below. So, we can calculate water productivity in terms of rice or fish output as follows (Molden et al., 2010):

$$\text{Water Productivity} = \frac{\text{Rice or Fish Output}}{\text{Net Water Inflow}} \quad \ldots\ldots\ldots (3)$$

We can calculate different types of water productivity in this approach. For example, we can calculate productivity of total water consumed via evaporation, percolation and seepage. Or, we can calculate water productivity for groundwater use only, by plugging groundwater use in the denominator of equation (3). It is important to discuss three concepts of water use here: blue water, green water, and grey water. Blue water use refers to the irrigation water withdrawn from below the ground or surface water, green water use refers to the rainwater used in a production system, and grey water use refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Chapagain et al., 2010; Mekonnen & Hoekstra, 2011). In this paper, we shall refer to total water consumption as the sum of blue and green water, and we will estimate water productivity in terms of total water consumption and groundwater (blue water) consumption.

4. 3. 2 Water Module Overview

The water balance models are constructed using the Stella Architect software in the system dynamics modeling framework used in the land use change paper. The model structure for the water module is shown in Figure 4.3. This common structure is applicable for both the national and district geographical scales that were used for the land use change paper. In order to show water use in a system dynamics setting using the water balance principle, two stocks of water are used, one for rice field and one for fish ponds, which depict quantity of water per hectare of land. The water supply is coming from rain water and supplemental irrigation, and going through percolation, seepage, evapotranspiration or evaporation, or water discharge in the case of the fish pond (as explained before). The discharge component in the fish part is necessary because there is a significant amount of standing water in a fish pond, and it is supposed to be cleared after a certain period, and this flow is taking that into account. There is a small amount of standing water in the rice field during certain stages of its growth as well, but it is significantly smaller than the water level in fish ponds, and it goes away through evaporation, so we are ignoring that amount in this model.

So, we can add the inflows and outflows to that stock to estimate water use and calculate water productivity. The flows are measured in millimeters per year. They are calculated by multiplying daily rates for rainfall, percolation and seepage, evapotranspiration or evaporation by the number of days water is expected to be flowing through the system as a part of the production process. In case of fish, this figure is 365, as fish ponds are filled up throughout the year, and in case of rice, this figure is set at 180, which is the estimated number of days there will be rice standing in the field. However, the irrigation flow is calculated based on the water balance principle, which suggests that the net of percolation, seepage, and evapotranspiration or evaporation minus rainfall will be the amount required as supplemental irrigation.

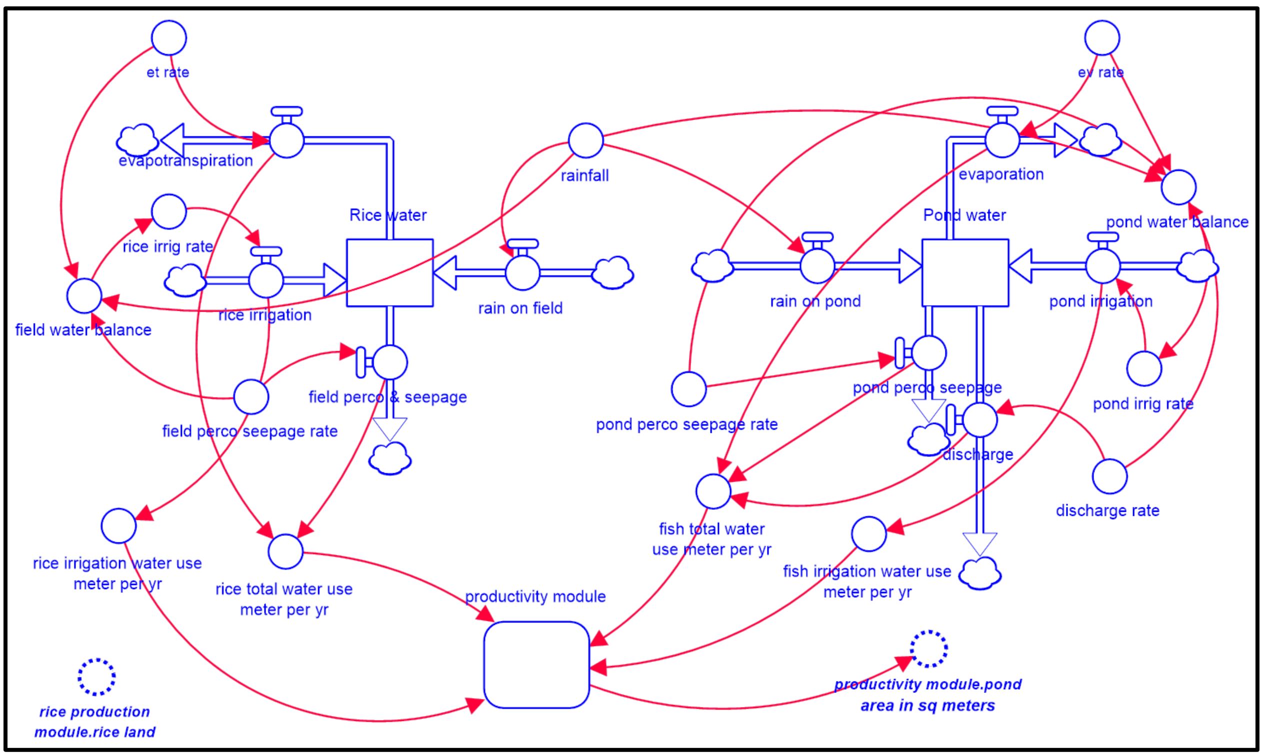

Figure 4.3: Water balance models for rice and fish production

Inside this water balance model there is the productivity module (Figure 4.4), which basically performs simple mathematical calculations to estimate total water use in rice and fish production systems, and by dividing outputs, they also calculate water productivity. These calculations are done for both cases of total water use, and irrigation water use. The model structures are the same for both Bangladesh and Mymensingh.

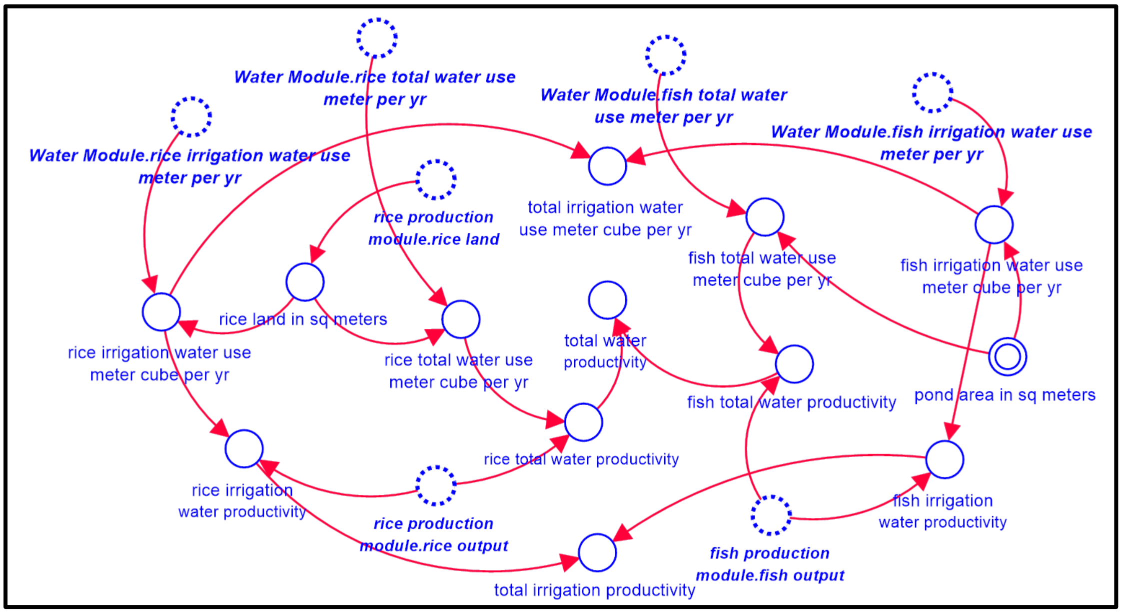

Figure 4.4: Water productivity module

4. 3. 3 Data for Water Productivity Calculations

Data for calculating water productivity have been collected mostly from secondary sources. Rainfall data has been obtained from the yearly report of the Bangladesh Bureau of Statistics. Evaporation (or evapotranspiration), percolation and seepage have been obtained from reports published by Bangladesh Rice Research Institute, expert interviews, and other published papers. Data on evaporation, percolation, seepage, etc. in the rice field for Bangladesh are available, but not for fish farming. However, according to Verdegem and Bosma (2009), and some expert interviews, the processes are not fundamentally different in a fish pond compared to a rice field. Also, there are data on pond evaporation, percolation, seepage from other countries (Nath & Bolte, 1998; Verdegem & Bosma, 2006; Boyd et al., 2007).

Interviews of water modeling expert, crop water use expert, aquaculture scientist, crop and aquaculture extension agents, and fish farmers were conducted for getting expert opinion on the water use model for rice and fish production systems, and check suitability of data from the literature. More details about the interview process have been mentioned in section 3.3.5.1 (Primary Data Collection) of the previous paper. Interview schedule of the interviews are presented in the Appendix 4A. We have decided upon the data to parameterize the model based on the published literature mentioned in the previous paragraph, and the expert interviews. The data is presented in the Appendix 4B.

4. 3. 4 Sensitivity Analysis

The systems dynamics model required assumptions to be made about parameters, and therefore it can be subject to a degree of uncertainty that must be understood in order to evaluate the confidence on the model. Sensitivity analysis is an examination of how responsive models are to fluctuations in the values of model parameters (Hekimoglu and Barlas, 2010). Also, given that some parameter values can change over time, sensitivity analysis provides an indication of how a model will change over time and to what degree of accuracy.

In this research, a uni-variate sensitivity analysis has been conducted, which tests for sensitivity of model outcomes to changes in parameters through "one-at-a time approach". The sensitivity analyses were performed through the Stella Architect software. To accomplish this, different variables were selected and reasonable estimates of anticipated variation were assessed. Stella was then allowed to run for 10 iterations using the described variable distribution of one variable at a time, while reporting the effected output (water productivity or water use volume) over time.

4. 4. RESULTS AND DISCUSSION

4. 4. 1 Water Productivity Outcomes

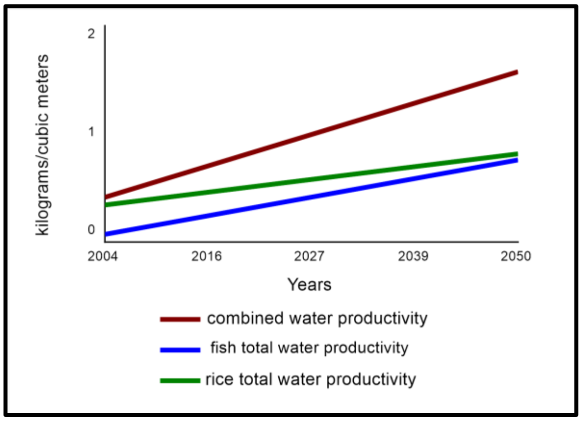

Figure 4.5a: Water productivity trend for total water use in Mymensingh

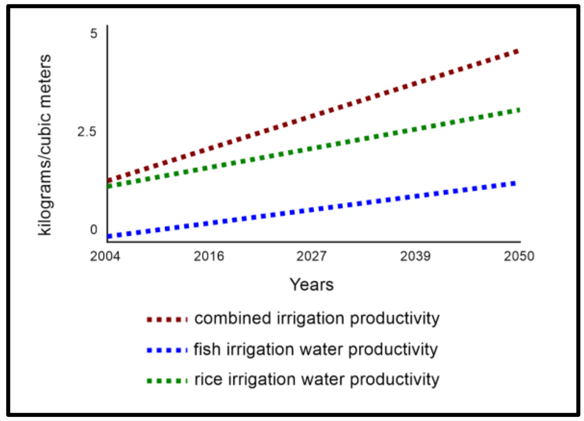

Figure 4.5b: Water productivity trend for irrigation water use in Mymensingh

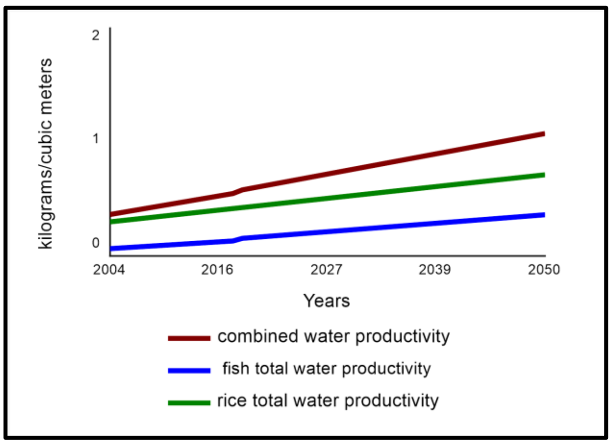

Figure 4.5c: Water productivity trend for total water use in Bangladesh

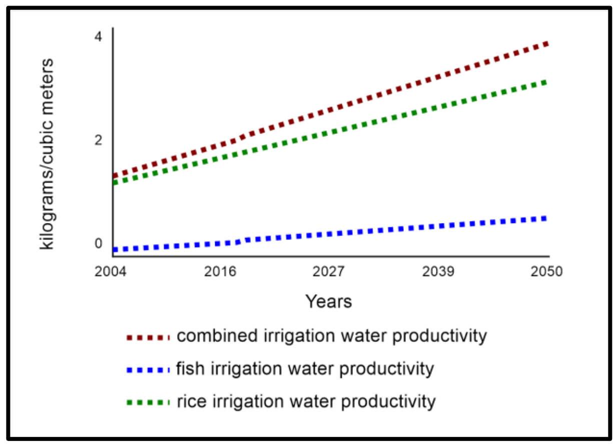

Figure 4.5d: Water productivity trend for irrigation water use in Bangladesh

The results show that water productivity combining both rice and fish production is generally increasing, both in the case of Mymensingh, and Bangladesh. At the initial period, rice water productivity is higher than fish water productivity in all cases, meaning that more water is being used to produce a kilogram of fish than a kilogram of rice. However, in case of total water productivity for Mymensingh (Figure 4.5a), the fish water productivity ultimately surpasses rice water productivity. This is because of the high fish yield growth rate observed in Mymensingh. If we observe the irrigation water productivity graphs, we can see that they are also showing an increasing trend. The fish water productivity is increasing faster than the rice water productivity, due to faster fish yield growth. The concept of growing more crops with less water is also known as growing more crop per drop (Carriger & Vallée, 2007, Ahmed et al., 2014). This research is showing that aquaculture growth in Bangladesh is leading towards more crop per drop.

4. 4. 2 Volume of Water Use

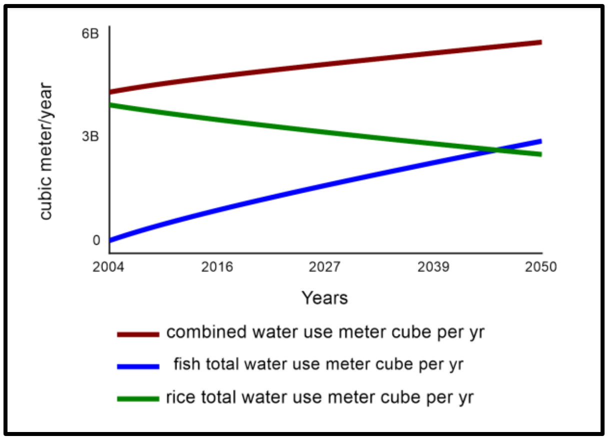

Figure 4.6a: Total water use for rice and fish production in Mymensingh

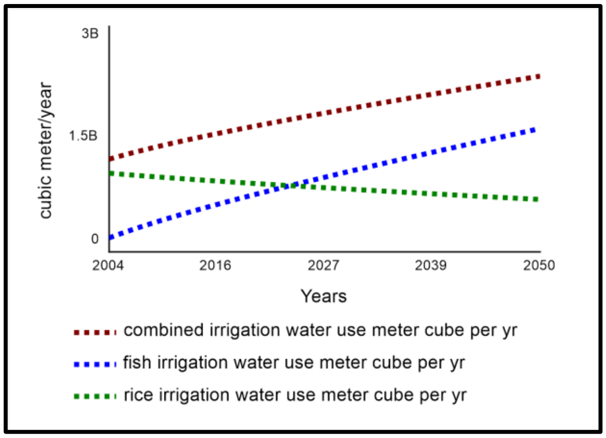

Figure 4.6b: Irrigation water use for rice and fish production in Mymensingh

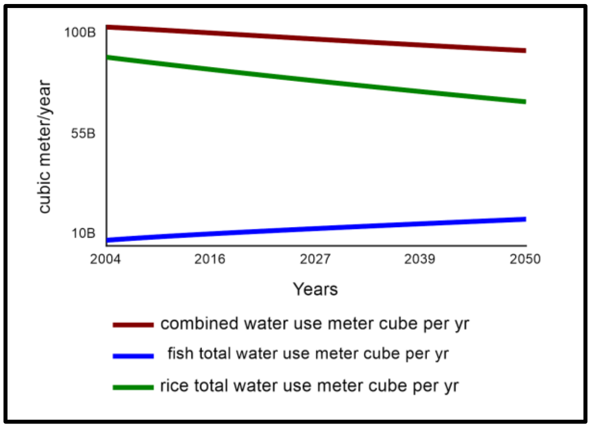

Figure 4.6c Total water use for rice and fish production in Bangladesh

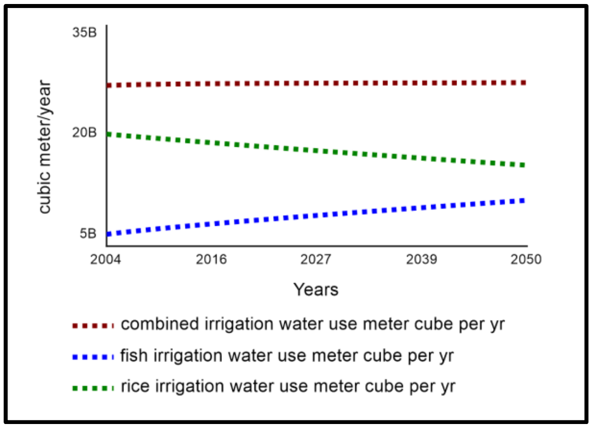

Figure 4.6d: Total water use for rice and fish production in Bangladesh

The results show that the trend in total volume of water use combining both rice and fish production is increasing in Mymensingh (Figure 4.6a), but decreasing in Bangladesh (4.6c). We need to decompose the results to get a better understanding. In Mymensingh, the total volume of water use in rice is declining, as area is declining over time. However, the total volume of water use in fish is increasing, as fish area is increasing over time. The net impact is that total water use is increasing, as fish production occupies a significant amount of land in Mymensingh. In Bangladesh, the direction of change is the same for the same reasons, but the net impact is different, because fish production occupies a smaller proportion of land in the whole country. However, it can be inferred that if the conversion process continues, and there is no change in technology, eventually, total water use will start increasing again.

Now, if we focus on the volume of irrigation water being used, we can see that it is increasing fast for Mymensingh, and slower for Bangladesh. Again, the difference is from the fact that Mymensingh has a faster conversion rate from rice production to fish farming. Since a large portion of this irrigation water is extracted from below the ground, this result is an illustration that aquaculture expansion can have adverse consequences on the groundwater level in areas of rapid expansion.

4. 4. 3 Results from Sensitivity Analysis

In this section, the changes in model output we want to observe are changes in water productivity, and changes in irrigation water use, due to changes in (annual) parameter values of fish yield growth rate, rainfall, and evaporation or evapotranspiration. More data on different runs are provided in the Appendix 4C.

4. 4. 3. 1 Sensitivity of Water Productivity to Changes in Fish Yield

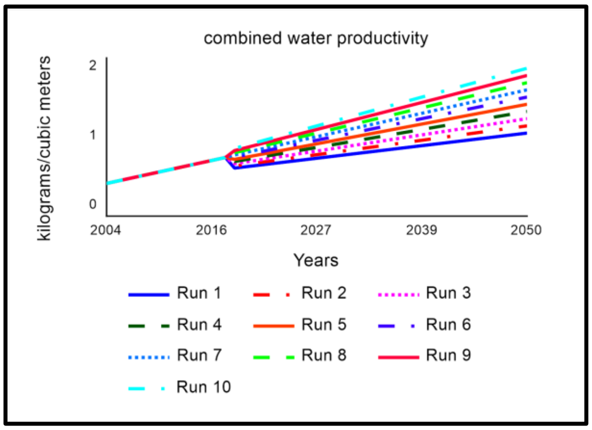

Figure 4.7a: Sensitivity of water productivity to changes in fish yield growth rate in Mymensingh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

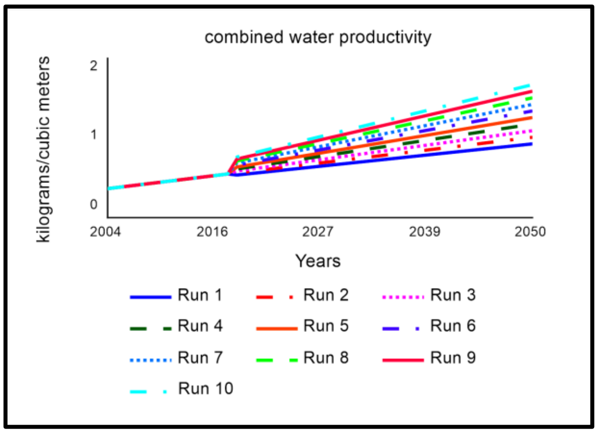

Figure 4.7b: Sensitivity water productivity to changes in fish yield growth rate in Bangladesh. Runs 1 to 10 represent fish yield change from 5% to 30% per year.

Sensitivity analysis for water productivity due to changes in annual growth of fish yield between 5%-30% shows that the water productivity changes proportionately to the change in yields in both the cases of Mymensingh and Bangladesh (Figures 4.7a & 4.7b). This shows that there is numerical change in model outcomes due to change in fish yield growth, but there is no behavioral change of the model, as it behaves in a predictable way despite the change.

4. 4. 3. 2 Sensitivity of Water Productivity to Changes in Rainfall

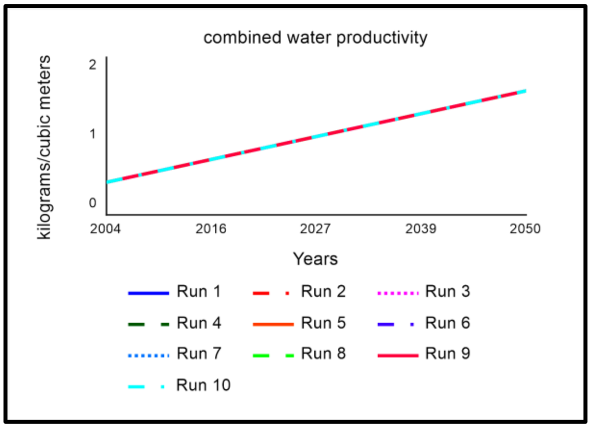

Figure 4.8a: Sensitivity of total water productivity to changes in rainfall in Mymensingh. Runs 1 to 10 represent rainfall change between 4.5mm and 6.5mm per day.

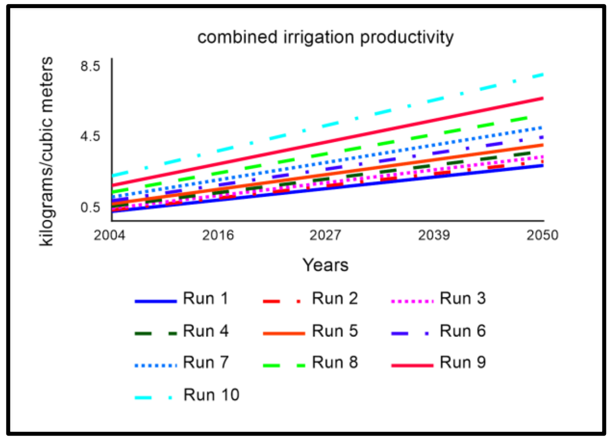

Figure 4.8b: Sensitivity of irrigation water productivity to changes in rainfall in Mymensingh. Runs 1 to 10 represent rainfall change between 4.5mm and 6.5mm per day.

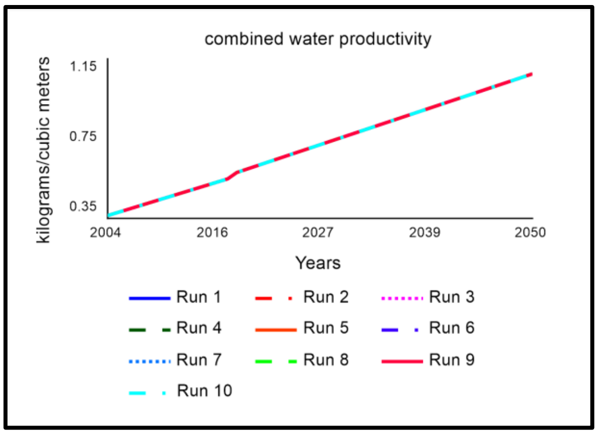

Figure 4.8c: Sensitivity of total water productivity to changes in rainfall in Bangladesh. Runs 1 to 10 represent rainfall change between 4.5mm and 6.5mm per day.

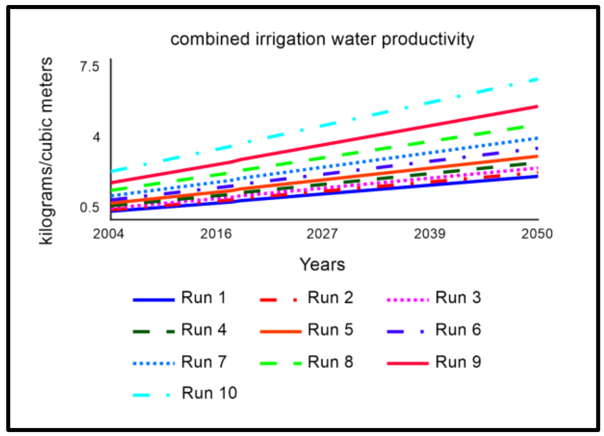

Figure 4.8d: Sensitivity of irrigation water productivity to changes in rainfall in Bangladesh. Runs 1 to 10 represent rainfall change between 4.5mm and 6.5mm per day.

Sensitivity analysis for water productivity due to variations in rainfall shows that the model outcome for changes in total water productivity does not show any response, neither for Mymensingh nor Bangladesh (Figures 4.8c and 4.8d). This is expected as the impact of the change in rainfall is offset by changes in irrigation water application. This is demonstrated in Figures 4.8b and 4.8d, where any change in rainfall changes the irrigation water productivity proportionately in both the cases of Mymensingh and Bangladesh. So, this shows that there is numerical change in irrigation water productivity due to change in rainfall, but there is no behavioral change of the model, as it behaves in a predictable way despite the change. This also sheds light on how any future decline in rainfall can change lower the productivity of irrigation water, as more irrigation will be required to produce the same amount of agricultural output.

4. 4. 3. 3 Sensitivity of Irrigation Water Use to Changes in Rainfall

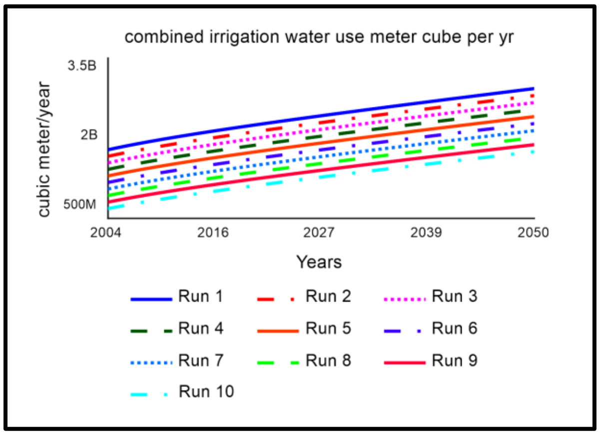

Figure 4.9a: Sensitivity of irrigation water use to changes in rainfall rate in Mymensingh Runs 1 to 10 represent rainfall change between 4.5mm and 6.5mm per day.

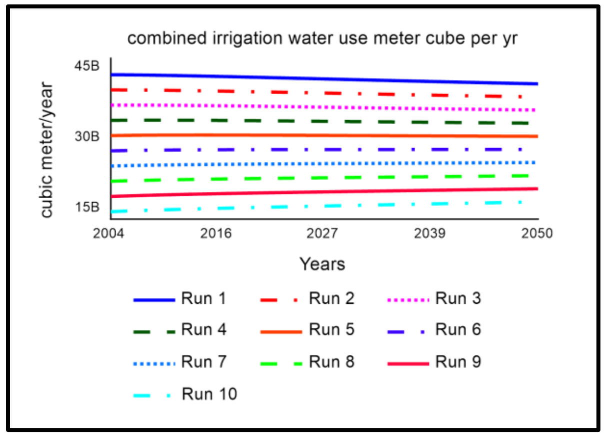

Figure 4.9b: Sensitivity of irrigation water use to changes in rainfall rate in Bangladesh. Runs 1 to 10 represent rainfall change between 4.5mm and 6.5mm per day.

This section follows the previous section, and shows that any change in rainfall changes the volume of irrigation water use proportionately in both the cases of Mymensingh and Bangladesh (Figures 4.9a & 4.9b). Again, this shows that there is numerical change in irrigation water use due to change in rainfall, but there is no behavioral change of the model, as it behaves in the same pattern despite the change. This further illustrates the fact that a future decline in rainfall can increase the use of irrigation water, thus contributing to higher groundwater depletion.

4. 4. 3. 4 Sensitivity of Irrigation Water Use to Changes in Evapotranspiration and Evaporation

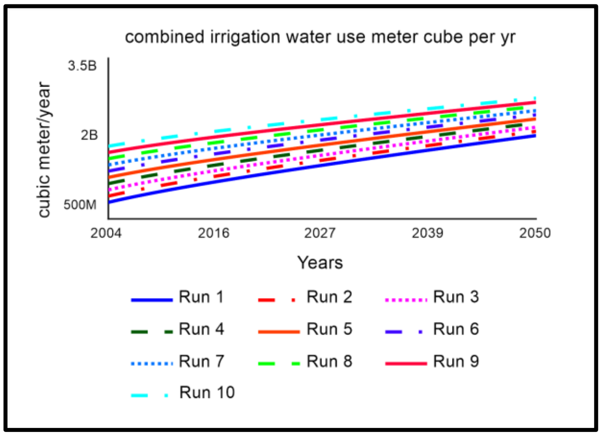

Figure 4.10a: Sensitivity of irrigation water use to changes in rice field evapotranspiration rates in Mymensingh. Runs 1 to 10 represent evapotranspiration change between 2.5mm and 4.5mm per day.

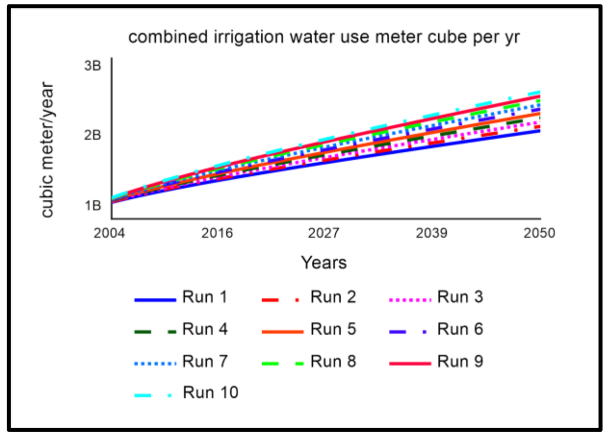

Figure 4.10b: Sensitivity of irrigation water use to changes in pond evaporation rates in Mymensingh. Runs 1 to 10 represent evaporation change between 3mm and 5mm per day.

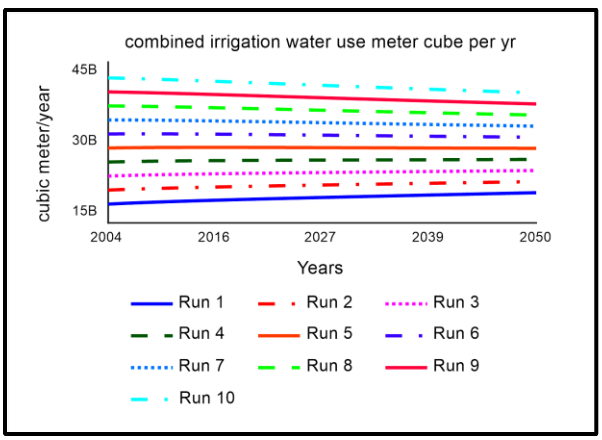

Figure 4.10c: Sensitivity of irrigation water use to changes in rice field evapotranspiration rates in Bangladesh. Runs 1 to 10 represent evapotranspiration change between 2.5mm and 4.5mm per day.

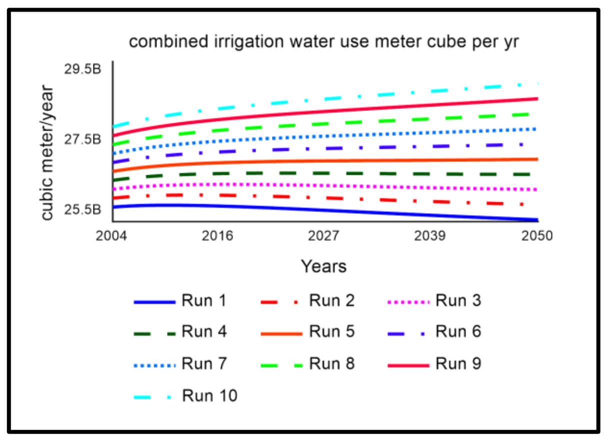

Figure 4.10d: Sensitivity of irrigation water use to changes in pond evaporation rates in Bangladesh. Runs 1 to 10 represent evaporation change between 3mm and 5mm per day.

Evaporation and evapotranspiration rates are dependent on temperature. So, with increase in global temperatures, these rates are also expected to increase. Both of them are expected to change in the same direction together, but here the sensitivity analysis is done one at a time. Testing for sensitivity of these rates to water use trends show predictable model behavior, just like in the cases of sensitivity of irrigation water use to changes in rainfall. Total water use is increasing in both Mymensingh and Bangladesh, in response to the changes in evaporation and evapotranspiration rates. In case of a high aquaculture concentration area like Mymensingh, the impact is higher for change in evaporation rates, as more water is used for fish in Mymensingh.

4. 4. 4 Results from Scenario Analysis

4. 4. 4. 1 Change in Temperature and Rainfall

In this section, we will construct a more comprehensive scenario of environmental change. There are several projections of temperature and rainfall changes in the long run for Bangladesh. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), average temperature can increase by 1.23^0C and rainfall can increase by 3.4% by 2050 (USAID, 2015). So, in Figure 4.11 we are showing the outcome for irrigation water use, under a scenario of such changes. Here, a change in temperature is increasing both evaporation and evapotranspiration rates, increasing demand for irrigation water. However, increase in rainfall is decreasing the demand for irrigation water.

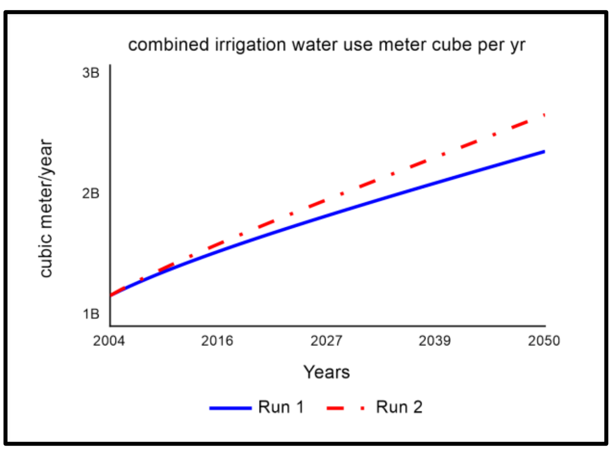

Figure 4.11a: Change in irrigation water use in Mymensingh due to changes in climate parameters.

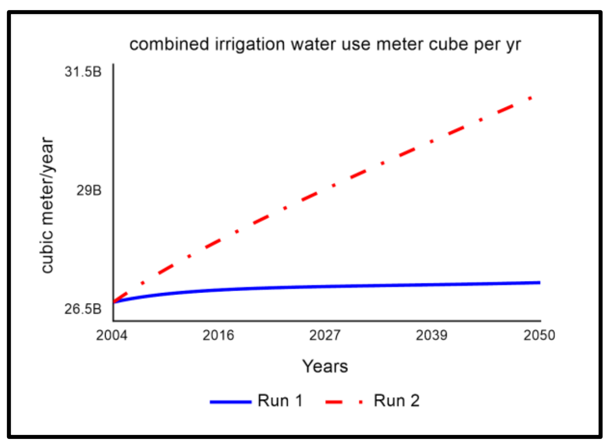

Figure 4.11b: Change in irrigation water use in Bangladesh due to changes in climate parameters.

The results show that climatic changes will lead to higher amounts of irrigation water use. Especially in case of Bangladesh (Figure 4.11b), the irrigation water use is increasing significantly compared to the baseline. Hence, it can be observed that climate change can cause higher level of stress on the water resources in the long run.

4. 4. 4. 2 Change in Temperature and Rainfall Combined with Faster Aquaculture Growth

In this section, we will show what happens if the environmental change scenario discussed in section 4.4.4.1, happens simultaneously with a faster aquaculture growth rate in Bangladesh. In order to build such a scenario, we are assuming that the concentration of other sections of the fish value chain is double than the baseline. Then, the land conversion rate in Bangladesh will accelerate.

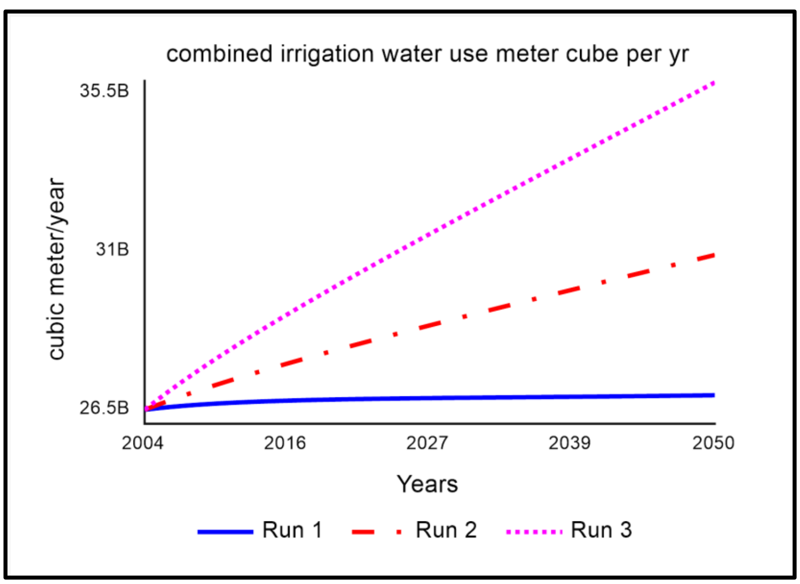

Figure 4.12: Change in irrigation water use in Bangladesh due to faster aquaculture growth as well as changes in climate parameters. Run 1 represents the baseline scenario, then run 2 represents only an environmental change scenario, and Run 3 represents faster aquaculture growth scenario in Bangladesh, along with environmental change

The result is shown in Figure 4.12. Here, Run 1 represents the baseline scenario, then run 2 represents the environmental change scenario described in section 4.4.4.1, and finally, Run 3 shows irrigation water use with faster aquaculture growth in Bangladesh (due to doubling of concentration of supporting industries), along with environmental change. It is clear from the Figure 4.12 that a faster growth of aquaculture at the national level, along with climatic stress can put further pressure on the groundwater resources of Bangladesh.

4. 5. CONCLUSION

This paper has been built on a system dynamics model of land use change, adding a water use module that estimates water use in rice and fish production. There are two main objectives of this research: to learn how aquaculture growth in Bangladesh is changing water productivity by substituting irrigated rice production, and to understand how aquaculture growth is changing the volume of groundwater use. The study observed that the water productivity or 'crop per drop' combining both rice and fish production is generally increasing, both in the case of Mymensingh, and in Bangladesh as a whole. However, the trend in total volume of water use combining both rice and fish production is increasing in the high aquaculture concentration region of Mymensingh, but decreasing in the country overall. Since a large portion of this irrigation water is extracted from below the ground, this can have adverse consequences on the groundwater level in areas of rapid expansion. Furthermore, increase in global temperature or change in rainfall due to climate change, as well as faster aquaculture growth, can increase the use of groundwater. So, although aquaculture has the potential to generate more crop per drop, it can use a higher volume of groundwater per year which can subsequently contribute to lowering groundwater levels.

The policy implication from these findings is that aquaculture research and extension services should focus more on water saving technologies. Such technologies may include recirculating aquaculture, integrated agriculture aquaculture, aquaponics, etc. Also, since the groundwater tables and recharge rates are not same everywhere, policies should be made to restrict groundwater use in aquaculture in regions where water levels are an immediate concern, and regulate groundwater use in other areas where water levels can be a concern in the future. Such policy initiatives should also incorporate the development of alternative sources of water supply, like rain water capture and storage. Also, we have observed in the focus group discussions and the interviews that farmers respond to economic incentives. And, currently they are interested in getting export opportunities. So, if fish export can be promoted in such a way that encourages sustainable use of freshwater, then it can contribute towards reducing the problem of excess groundwater use. Similarly, if incentives can be given for water saving technologies, then water use in aquaculture can be decreased over time.

FOOTNOTE

1. There are three rice seasons in Bangladesh, with some overlapping between the timing of the seasons: Aus (April-August), Aman (April-December), and Boro (December-May). Currently, the boro season supplies the highest amount of rice and it is also the season which uses highest quantity of irrigation water due to dry weather prevailing at that time.

APPENDICES

Appendix 4A: All Interview Questionnaires

The research instruments were approved by the Institutional Review Board at Michigan State University (reference: STUDY00001030). All the conversations were in Bangla, the language of the researcher and all the experts. After the interviews, the recorded audio was transcribed first in Bangla, and then translated to English, which was then coded, and findings were used in the analysis for this paper. The focus group and individual interview questionnaires are presented in this section.

Appendix 4A. I. Focus Group Discussion Interview Protocol

Goals

- Introduce research
- Identification of socioeconomic and environmental context of the study areas in collaboration with stakeholders
- Describe and receive feedback on system structure and boundaries

Objectives

- Confirm reference timeline and system boundaries
- Check resources/ecosystem services
- Identify key drivers of change
- Corroborate model structure and facilitate parameterization

Activities

- Presentations
  - Introduction to project
  - Defining the system under study
    - Geographic scope
    - Key resource issues (land use change, water & energy use)
  - Timeline: present draft timeline in opening presentations
- Resource mapping

- Use available maps to start discussion
  - Check aquaculture concentrated areas
  - Less concentrated
- Annotate to identify land use types/resources/infrastructure
  - Roads, Housing Settlements, Markets
  - Input Suppliers
  - Ag Land
  - Water Bodies
  - Land Types
- Demonstrate how we'll turn this into maps

- Group discussion: feedback on research – conversation with stakeholders focus group style for
  - Opinions on current system structure: relationships between system components
  - Understanding farmer's land use and financing decisions
    - why they do what they do
    - types of land, and how they are used
  - Understanding farmers' motivation to invest in fish farming
    - farmers' motivation in fish farming
    - relationship between profits and investment
    - sources of financing (what proportion of capital is from loan)
    - how much reinvested for development
  - Discussing farmers' constraints to invest in fish farming
    - financial and physical constraints: why all farmers not convert
    - how much more land can be brought under aquaculture
  - Understanding the role of various institutions and government policy in this process
  - Understand water. energy, and other input use in fish and rice production systems
    - water use: depth of ponds, how much water (stock), how much refilled, sources of water
    - energy use: main purposes, sources and respective quantities

Appendix 4A. II. Questionnaire for Farmers

A. Basic Information about the Respondent

Name of the Interviewee Address Mobile Phone Age, Education & Household Primary Occupation Other Occupation Prior Occupation	

B. Land Information

	2017	2014	2010
Homestead area			
Pond area			
own			
leased in			
leased out			
Crop area			
own			
leased in			
leased out			
Other			

C. Income Sources

Sources	2017			2014	2010
Fish farming	qty	price	value	value	value
Gross Income					
Rice production					
Other crop production					
Livestock production					
Non-farm income					
Remittances					
Other Income					

D. Farm Expenditure

Sector	2017			2014	2010
	qty	price	value	value	value

Fish farming					
land use					
fingerlings					
insecticide					
lime					
feed					
medicine					
fertilizer					
machinery					
Others					
	2017			2014	2010
Labor	qty	price	value	value	value
family labor					
short term labor					
permanent labor					
Infrastructure					
new					
repairs					
Other expenses					
Total Expenses					
Crop farming					
land use					
seed					
fertilizer					
pesticides					
machinery					
family labor					
short term labor					
permanent labor					

E. Water Use

Purpose	2017			2010		
	quantity	source	price	quantity	source	price
Pond filling						

F. Fuel Use

Purpose	Source	2017		2014	2010
		Quantity	Price		

G. Local Economic Situation

1. How has the economy of your area changed over …….. years?
2. Have you (personally) experienced any economic change over this period?
    - Tell me about how your income/asset ownership/means of communication and transportation/consumption have changed

H. Crop Production Activities

3. When did you first start crop/rice farming? How did you obtain the land?
4. What are your sources of labor? What about other farmers in the area?
5. What are your sources of capital? What about other farmers in the area?
6. What are the other inputs you use? When you started, where did you buy inputs from? Are they different now?
7. What varieties do you cultivate? What about others in the area?
8. What are the sources of water for you? What proportion came from what source? Discuss this for others in the area.
9. What are the sources of energy for you? What proportion came from what source? Discuss this for others in the area.
10. What are the major constraints for rice/crop farming?

I. Motivation for Fish Farming (fish farmers only)

11. What was your main occupation before starting fish farming?
12. When did you become interested in aquaculture? Can you tell me a story about what motivated you the most? In which year did you make the shift? What motivated other people in your area to shift to fish farming?
13. Were there any fish farmers in your village back then? How well did you know them? How often would you interact with them?
14. How did extension agents talk about fish farming before the transition? In what ways did you see information about fish farming in mass media outlets (newspapers, radio, television, etc.) before the transition?
15. What are the main constraints for starting fish farming?

J. The Act of Shifting and Fish Production Activities (fish farmers only)

16. What did you need to do to start fish farming? How did you finance it? Is this same for other fish farmers? Please explain.
17. Did you start with existing ponds, or did you converted rice/crop lands? Did you own that land/pond?
18. What were the initial constraints?
19. Where did you buy fish seeds/fingerlings from? Are they different now? Discuss how the fish seed/fingerlings supply has evolved.
20. Where did you buy fish feed from? Are they different now? Discuss how the fish feed supply has evolved.
21. Where did you buy other inputs from? Are they different now? Discuss how the supply of other inputs has evolved.

22. Whom do you sell your product to? Were they different when you first started? Did they exist 10 years ago?
23. Where did you learn about techniques in aquaculture (farming practices)? What type of formal or informal training did you get?
24. What species do you cultivate? What about others in the area?
25. What are the sources of water for you? What proportion came from what source? Discuss this for others in the village.
26. What are the sources of energy for you? What proportion came from what source? Discuss this for others in the village.

K. Investment Decisions

27. How much money did you earn from rice/crop or fish farming in 2017? What about previous three years?
28. How much money did you spend on existing rice/other crop or fish enterprises in 2017? Can you please explain why you made this choice? What about previous three years?
29. How much money did you invest in expanding rice/crop farming in 2017? What about previous three years?
30. How much have you invested in new ponds and how much in new fish technologies in 2017? Can you please explain why you made these choices? What about previous three years?
31. Did you borrow money for fish farming in 2017? What about previous three years?
32. Did you convert any own rice/other crop land to fish farming over the last three years? Can you please explain why you made these choices?
33. Did you buy any farm machinery over the last three years? Why, or why not?
34. Did you introduce any new rice varieties, or crops, or fish species over the last three years? Why, or why not?
35. How have you intensified production (increase stocking density, feeding rates, etc.) over the last three years?
36. Have you invested in other agricultural (like livestock) or non-agricultural enterprises in 2017? Can you please explain your choice? What about the previous three years?

Appendix 4A. III. Questionnaire for Policy Makers and Extension Agents

Basic Information about the Respondent

Name of the Interviewee			
Address			
Mobile Phone		Date	
Expertise	☐ Fish Extension	☐ Rice Extension	☐ Policy Maker

1. Discuss land, water, and energy availability for agriculture
   - What are the major trends in land use in agriculture for Bangladesh/Mymensingh?
   - What are the major trends in sources and quantities of water use and energy use in agriculture for Bangladesh/Mymensingh?

2. Sketch and discuss current status of land, water, and energy use in crop and fish production
   - What are the key stocks within land distribution in the area? How are they changing?
   - How much water is being used in aquaculture? What are the sources?
   - How much energy is being used in aquaculture? What are the sources?
   - Data or research on land, water, and energy use in aquaculture

3. Identify the major drivers of land conversion to aquaculture, and intensification of fish farming
   - Who are the fish farmers? What are their main socioeconomic characteristics? How are they different from other farmers?
   - What motivates someone to engage in aquaculture? Please talk us through their decision making behavior (economic incentives, social attitudes, resource availability, etc.).
   - How does he/she finance it?
   - What motivates an existing fish farmer to expand fish farming? Please talk us through their decision making behavior?
   - How does he/she finance it?
   - What motivates a fish farmer to intensify fish farming? What are the main methods in intensifying production (new varieties/more inputs/machineries etc.)? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - Are there socioeconomic feedbacks that govern the behavior of conversion or intensification?

4. Identify the major constraints of land conversion to aquaculture, and intensification of fish farming including land, labor, cash, feed or other inputs, technology, water, energy, etc.
   - What are the main barriers to expanding fish farming?
     - Why don’t all land owning or capable farmers engage in fish farming?
   - What are the main barriers to intensifying fish farming?

5. Discuss the potential changes in land use and intensification of aquaculture in future
   - What is the direction of resource use in fish production?
   - What will be the main limiting factors to aquaculture growth in the future? Please discuss in relation to land, water and energy availability.

6. Discuss the impact of aquaculture growth on sustainable use of land, water, and energy resources
   - What is the extent of pressure that an expanding aquaculture sector may exert on the natural resources of our country?
   - How is land use changing as a result of aquaculture growth? Are there indirect impacts?
   - Do you think we can grow sufficient food of different types (rice, vegetables, etc.) if aquaculture growth continues?
   - How is water utilization changing as a result of aquaculture growth?
   - How resilient are our water supply to an expanding aquaculture sector?
   - How is energy efficiency changing as a result of aquaculture growth?
   - How resilient are our energy supply to an expanding and intensifying aquaculture sector?
   - Identify major feedbacks that can influence the outcome of natural resources use

7. Discuss policy options for influencing long term outcomes
   - What policy tools are available to influence land, water, and energy use behavior of farmers?
   - What policy measures do you think should be used for ensuring sustainable use of land?
   - What policy measures do you think should be used for ensuring sustainable use of groundwater?
   - What policy measures do you think should be used for efficient use of energy?

Appendix 4A. IV. Questionnaire for Scientists

Basic Information about the Respondent

Name of the Interviewee			
Address			
Mobile Phone		Date	
Expertise	☐ Fish Scientist	☐ Rice Scientist	☐ Social Scientist

1. Discuss land, water, and energy availability for agriculture
   - What are the major trends in land use in agriculture for Bangladesh/Mymensingh/Trishal?
   - What are the major trends in sources and quantities of water use and energy use in agriculture for Bangladesh/Mymensingh/Trishal?

2. Sketch and discuss current status of land, water, and energy use in crop and fish production
   - What are the key stocks within land distribution in the area? How are they changing?

3. Identify the major drivers of land conversion to aquaculture, and intensification of fish farming
   - Who are the fish farmers? What are their main socioeconomic characteristics? How are they different from other farmers?
   - What motivates a crop farmer to convert to fish farming? Can you please talk us through their decision making behavior (economic incentives, social attitudes, resource availability, etc.)?
   - How does he/she finance it?
   - What motivates an existing fish farmer to expand fish farming? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - What motivates a fish farmer to intensify fish farming? What are the main methods in intensifying production (new varieties/more inputs/machineries etc.)? Can you please talk us through their decision making behavior?
   - How does he/she finance it?
   - What proportions of their income are reinvested to aquaculture for expansion and/or intensification?
   - Are there socioeconomic feedbacks that govern the behavior of conversion or intensification?

4. Identify the major constraints of land conversion to aquaculture, and intensification of fish farming including land, labor, cash, feed or other inputs, technology, water, energy, etc.
   - Why don’t all land owning or capable farmers engage in fish farming?
   - What are the main barriers to expanding fish farming?
   - What are the main barriers to intensifying fish farming?

5. Discuss the potential changes in land use and intensification of aquaculture in future
   - What is the direction of resource use in fish production?
   - What will be the main limiting factors to aquaculture growth? Please discuss in relation to land, water and energy availability.

6. Discuss the impact of aquaculture growth on sustainable use of land, water, and energy resources
   - How is land use changing as a result of aquaculture growth? Are there indirect impacts?
   - How is water utilization changing as a result of aquaculture growth?
   - How is energy efficiency changing as a result of aquaculture growth?

7. Identify the resilience of the natural resource systems to the intensification of resource use
   - Do you think we can grow sufficient food of different types (rice, vegetables, etc.) if aquaculture growth continues?
   - Do you think we can grow sufficient food of different types if aquaculture growth continues?
   - How resilient are our water supply to an expanding aquaculture sector?
   - How resilient are our energy supply to an expanding and intensifying aquaculture sector?
   - What is the extent of pressure that an expanding aquaculture sector may exert on the natural resources of our country?

8. Identify major feedbacks that can influence the outcome of natural resources use

Appendix 4B: Additional Data for Water Use Model

Table A4.1: Data for water productivity calculations

Variable	**Unit**	**Value**	**Source**
rainfall	millimeters per day	BGD: 5.68 Mym: 5.5	BBS, 2017
evapotranspiration	millimeters per day	BGD: 3.21 Mym: 3.31	Karim 2012
evaporation	millimeters per day	4.01 (global average)	Verdegem et al., 2006; Nath & Bolte, 1998; expert interviews
rice field seepage & percolation	millimeters per day	4.19	Singha et al., 2014
pond seepage & percolation	millimeters per day	5 (global average)	Verdegem et al., 2006; Nath & Bolte, 1998; expert interviews
rice field irrigation	millimeters per day	BGD: 1.72 Mym: 1.9	seepage & percolation + evapotranspiration - rainfall
fish pond irrigation	millimeters per day	BGD: 3.33 Mym: 3.51	seepage & percolation + evaporation - rainfall
fish pond water discharge	millimeters per year	1200	focus group discussions & expert interviews; Verdegem et al., 2006

Appendix 4C: Sensitivity Analysis for Water Use Change Paper

Table A4.2: Sensitivity of Water Productivity to Changes in Fish Yield

	Future fish yield growth (%)	Water Productivity in 2050 (kg/m^3)	
		Mymensingh	Bangladesh
Run 1	5.00	1.05	0.93
Run 2	7.78	1.14	1.01
Run 3	10.56	1.23	1.09
Run 4	13.33	1.32	1.17
Run 5	16.11	1.41	1.26
Run 6	18.89	1.51	1.34
Run 7	21.67	1.60	1.42
Run 8	24.44	1.69	1.50
Run 9	27.22	1.78	1.59
Run 10	30.00	1.87	1.67

Table A4.3: Sensitivity of Total Water Productivity to Changes in Rainfall

	Annual rainfall (milimeter)	Water Productivity in 2050 (kg/m^3)	
		Mymensingh	Bangladesh
Run 1	1643	1.58	1.08
Run 2	1724	1.58	1.08
Run 3	1805	1.58	1.08
Run 4	1886	1.58	1.08
Run 5	1967	1.58	1.08
Run 6	2048	1.58	1.08
Run 7	2129	1.58	1.08
Run 8	2210	1.58	1.08
Run 9	2291	1.58	1.08
Run 10	2373	1.58	1.08

Table A4.4: Sensitivity of Irrigation Water Productivity to Changes in Rainfall

	Annual rainfall (milimeter)	Water Productivity in 2050 (kg/m^3)	
		Mymensingh	Bangladesh
Run 1	1643	3.24	2.39
Run 2	1724	3.44	2.56
Run 3	1805	3.66	2.75
Run 4	1886	3.93	2.99
Run 5	1967	4.25	3.27
Run 6	2048	4.64	3.62
Run 7	2129	5.12	4.06
Run 8	2210	5.73	4.64
Run 9	2291	6.56	5.44
Run 10	2373	7.73	6.63

Table A4.5: Sensitivity of Irrigation Water Use to Changes in Rainfall

	Annual rainfall (milimeter)	Irrigation Water Use Volume in 2050 (km^3/year)	
		Mymensingh	Bangladesh
Run 1	1643	2.93	40.24
Run 2	1724	2.80	37.79
Run 3	1805	2.67	35.35
Run 4	1886	2.54	32.90
Run 5	1967	2.41	30.45
Run 6	2048	2.27	28.01
Run 7	2129	2.14	25.56
Run 8	2210	2.01	23.11
Run 9	2291	1.88	20.67
Run 10	2373	1.75	18.22

Table A4.6: Sensitivity of Irrigation Water Use to Evapotranspiration

	Daily evapotranspiration (milimeter)	Irrigation Water Use Volume in 2050 (km^3/year)	
		Mymensingh	Bangladesh
Run 1	2.50	2.06	20.64
Run 2	2.72	2.13	22.71
Run 3	2.94	2.21	24.78
Run 4	3.17	2.29	26.85
Run 5	3.39	2.37	28.91
Run 6	3.61	2.44	30.98
Run 7	3.83	2.52	33.05
Run 8	4.06	2.60	35.12
Run 9	4.28	2.68	37.19
Run 10	4.50	2.76	39.25

Table A4.7: Sensitivity of Irrigation Water Use to Evaporation

	Daily evapotranspiration (milimeter)	Irrigation Water Use Volume in 2050 (km^3/year)	
		Mymensingh	Bangladesh
Run 1	3.00	2.10	25.55
Run 2	3.22	2.15	25.93
Run 3	3.44	2.21	26.30
Run 4	3.67	2.26	26.68
Run 5	3.89	2.31	27.06
Run 6	4.11	2.37	27.44
Run 7	4.33	2.42	27.82
Run 8	4.56	2.47	28.19
Run 9	4.78	2.53	28.57
Run 10	5.00	2.58	28.95

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CHAPTER FIVE

CONCLUSION

This dissertation has shown that farmers have responded to economic incentives when engaging in freshwater fish production. This has led to conversion of land which was already under productive use. However, the continuation of the farmers' motivation to engage in aquaculture can be adversely affected by high entry costs and rising input prices. System dynamics modeling of land use change demonstrates that the net impact of the land conversion has been positive so far, and may remain positive in the future, if yield growth rates can be sustained for rice and fish production. The study also observed that aquaculture produces more crop per drop as its water productivity is higher than rice. However, the growth of freshwater aquaculture does have an impact on groundwater resources. When groundwater is used in a significant proportion to irrigate fish ponds, it can lead to higher rates of groundwater extraction compared to rice production. If the production is situated in a region where groundwater levels are declining, then aquaculture can further aggravate the problem. Furthermore, an increase in global temperature or changes in rainfall due to climate change can increase the use of groundwater. Hence, we can say that freshwater aquaculture growth can potentially push the sustainable boundary for freshwater use in Bangladesh in the long run. So, this factor should be taken into account in planning for further development of aquaculture. It is important to formulate policies that will sustain the benefits of aquaculture growth, but at the same time keep freshwater use within the safe operating space for human development. These policies should include focus on research and development to sustain fish and rice yields, further research on groundwater stocks, development of guidelines for groundwater use in agriculture, identification of zones with potential for high aquaculture growth with low groundwater (and other environmental) impacts, providing incentives for using water saving technologies, establishing fish processing and preserving facilities that will allow to make better use of what is being produced, and promoting export of fish and fish products in a way that encourages sustainable use of water.