School of Economics and Finance

Environmental Impact of High Yield Variety Rice Cultivation in Bangladesh: A Study Based on Farm Level Data

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material, which has been accepted for the award of any other degree or diploma in any university

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Abstract

Bangladesh is often identified as one of the most important countries that cause degradation of natural resources while employing intensive agricultural technology in high yield variety (HYV) rice cultivation. Many studies demonstrate the environmental consequences of intensive agricultural practices in the literature; however, no consensus has been reached yet on concocting appropriate measurement approaches that incorporate important agri-environmental attributes. This thesis aims to conduct a comprehensive evaluation of the environmental impact of HYV rice agriculture and thereby examine the potential for environmental sustainability in the context of Bangladesh agriculture. In this respect, this study aims at measuring the extent of environmental impacts, analysing environmental impact-induced loss in farm-level production efficiency and evaluating impact-specific external costs, involved with such intensive farming practices. Data on HYV rice production along with soil and water test information are collected from farm-level cross-sectional survey conducted in three north-western regions of Bangladesh for the crop year 2012/2013.

This thesis proposes a new indicator-based approach, a composite environmental impact index (CEII) that quantifies environmental impact variables belonging to means-based, effect-based and farmers' perception-based environmental objective groups and measures aggregate impact extent for a given HYV rice farm. Subsequently, using the production frontier-based approach, Data envelopment analysis (DEA), this thesis measures environmental impact (the CEII) adjusted production efficiency (i.e., eco-efficiency)and then compares with production efficiency estimates. In addition, this thesis identifies factors influencing the expected level of eco-efficiency by applying interval regression model. Finally, 'Distribution-free Turnbull' estimator, under the theory of contingent valuation, is used to evaluate external costs produced in terms of different environmental impacts. In order to determine factors influencing farmers' willingness to pay for reducing on-farm environmental impactthe binary logistic regression model is employed.

The thesis reveals that around 27 to 69 per cent of the theoretical maximum level of environmental damage is created due to HYV rice cultivation. It is also found that the extent of different environmental impacts varies across different study regions; however, it declines in region where lower amount of farm chemicals are used to cultivate HYV rice. In addition, environmental impact-induced losses in production efficiency are found to be higher for regional farms producing lower amount of desirable output (HYV rice) and higher extent of environmental impacts (the CEII). It is revealed that, on an average, minimising environmental impact of the HYV rice production would help manage 14.4 per cent loss in production efficiency. This thesis also finds HYV rice farms generating considerable amount of external cost in terms of soil fertility problems followed by crop diseases, pest attack, soil's water holding capacity and soil erosion problems etc. On an average, for a given HYV rice farm, such external cost amount to BDT 2230 (equivalent to USD 28.71 on December 2013) per crop year. Furthermore, farmer-specific socio-environmental and agro-economic factors are found to be significantly related to expected level of eco-efficiency and farmers' maximum likelihood of willingness to pay (WTP) for an overall environmental improvement in farm areas.

This thesis, therefore, recommends that policy makers should consider the vulnerability of specific regions with respect to harmfulness of specific environmental impacts while allocating and redistributing natural resources in HYV rice agriculture. In addition, policy initiatives should be taken into account of socio-environmental and agro-economic factors increasing farm-level eco-efficiency and external cost of HYV rice cultivation while conducting environmental impact management projects.

Key words: Environmental impact; HYV rice agriculture; Production efficiency; Eco-efficiency; External cost; Composite environmental impact index; Data envelopment analysis; Contingent valuation.

JEL classifications: O10, O13, Q100, Q120, Q510, Q560.

CHAPTER ONE

Introduction

1.1 The context

Over the past 50 years, various anthropogenic activities have transformed the ecosystem more rapidly and extensively than any comparable period in human history. One such activity is 'agricultural intensification', which requires widespread use of high yielding crop varieties, causes intensive use of farm lands, and influences advanced irrigation practices and productive use of agro-chemicals. In developing countries, this intensification falls under the general heading of 'Green Revolution', which began in the late 1960s with the intention of obtaining higher yields to feed the growing population of the world (Alauddin and Quiggin, 2008; Hazell, 2009). However, the transformation in agricultural resource exploitation, which was induced by the green revolution, raises serious questions on the capability of ecosystems to provide resources in the long term (Tiwari et al., 1999). Intensive agricultural practices not only provide a higher level of yield but also produce a considerable amount of external costs in terms of environmental impacts on the production process (Yong-Kwang and Chang-Gil, 2007). Various researchers have repeatedly warned that the process of agricultural intensification initiates negative local consequences in the form of increased soil erosion, pressures on biodiversity and reduced soil fertility. These researchers have also warned of regional consequences, such as the pollution of ground water and the eutrophication of rivers and lakes, and global consequences, including impacts on atmospheric constituents and climate (Matson et al., 1997; Wilson, 2000; Ali, 2004; Rahman and Moral, 2006; Ciampalini et al., 2011). These consequences, in turn, cause agricultural production to stagnate and experience farm-level production inefficiency and a decline in productivity over time. Currently, it is clearly important to enhance environmental quality and the natural resource base on which an agricultural economy primarily depends.

Intensive agricultural practice requires widespread use of other inputs that are relative to the land input and is regarded as a land-saving production technology (Alauddin and Quiggin, 2008). In developing economies, where population pressure and the resulting decrease in the land-human ratio is the major challenge to achieve growth in agriculture production, agricultural intensification is the only option to raise outputs. However, the agro-ecological literature indicates that the crucial concern of agricultural intensification is whether it is being undertaken in a sustainable way (e.g., Matson et al., 1997; Alauddin and Quiggin, 2008). An increased level of agricultural production that is realized from intensive agriculture often accompanies agri-environmental risk and is the main challenge of 'sustainable agriculture'. Bangladesh, as an agriculture-based developing economy, faces this challenge of agricultural sustainability. This challenge has continued since the high yield variety (HYV) of rice and wheat were introduced in 1960 along with the increased utilization of farm chemicals. Compared with other South Asian countries, such as Nepal, Sri Lanka and India, Bangladesh is the most rice-intensive country, where the incidence of irrigation and the arable land-agricultural land ratio are highest (Weligamage et al., 2002; Alauddin and Quiggin, 2008). Additionally, FAOSTAT (2014) reports that Bangladesh is the most chemical fertilizer-intensive country followed by Pakistan, India and Nepal. The growing reliance on farm chemicals, increased level of irrigation incidence and falling trends in agricultural land-total land ratio pose potential threats to the sustainable use of natural and environmental resources in agriculture (Alauddin and Quiggin, 2008; FAOSTAT, 2014). Bangladesh has undergone a significant transformation in natural resource exploitation concerning agricultural intensification over the past several decades (Alauddin and Hossain, 2001). The unsustainable use of natural resources results in the inefficient allocation of environmental inputs (e.g., soil and water) in agricultural production and generates external costs in terms of environmental impacts (Tyteca, 1996; Picazo-Tadeo et al., 2011).

The present study therefore examines the environmental impacts of intensive agricultural practices in Bangladesh in the context of agricultural sustainability. Specifically, this study evaluates the extent of environmental impact and the resultant loss in farm-level production efficiency, and it analyzes the consequent threats on Bangladesh's agricultural sustainability. This study also evaluates external costs, which are involved with intensive farming practices, by analyzing the economic valuation of the farm-level environmental impacts.

In the next section, the agriculture-environment issue is explored regarding intensive agricultural practices. Specifically, the importance of improving environmental quality in agriculture and evaluating the environmental consequences on production efficiency are emphasized to address the problem of agricultural sustainability. The policy importance of calculating the economic values of farm-level environmental impacts is also explained. In the following section, the research problem is explained in terms of identifying the gaps in the previous literature followed by some important research questions. This section also explains the importance of analyzing Bangladeshi farmers' environmental perception. The research framework, study objectives, research hypotheses and significance of the study are outlined thereafter. The final section briefly identifies the structure of the thesis.

1.2 The agriculture-environment issue

1.2.1 Recognizing the agriculture-environment relation

Studies on ecological economics have frequently confirmed that intensive agricultural practices have contributed substantially to increases in world food production over the past several centuries (Farmer, 1986; Alauddin and Tisdell, 1991; Pimentel, 1996). However, it has also been analyzed that in the long term, these intensive agricultural practices will alter the ecosystem and restrict the flow of resource availability in agriculture (Matson et al., 1997; Wilson, 2000; Rahman, 2005; Xinshen et al., 2008; Alauddin and Quiggin, 2008; Calzadillaa et al., 2011; Oliveira et al., 2013). The environmental consequences of input mismanagement and its overuse are, accordingly, major concerns. These consequences include the destruction of beneficial insects, waterlogging and salinization of irrigated land, pollution of groundwater and rivers, poisoning of farm workers, and excessive dependence on high yielding crop varieties. The likelihood of a cause-and-effect relation between agriculture and environmental degradation has therefore been substantiated by many early studies from the perspective of agricultural sustainability (Matson et al., 1997; Wilson, 2000; Ali, 2004; Rahman and Moral, 2006; Alauddin and Quiggin, 2008; Ciampalini et al., 2011). Particularly, the impacts of agricultural activities on the environment have been analyzed by studies on ecosystem service and agriculture (e.g., Adger and Whitby, 1991; van der Werf and Petit, 2002; Swift et al., 2004; Collard and Zammit, 2006). Consequently, it is currently of agro-ecological importance to evaluate the extent of agriculture-induced environmental impacts, which would require the delineation of a clear pattern of this cause-and-effect relation.

1.2.2 Environmental impacts and the loss in the production efficiency of agriculture

The concept of sustainability in agricultural production apparently has great appeal regarding environmental and resource management systems (Pannell and Glenn, 2000). A workable approach to study sustainability at farm-level production consists of evaluating the nature of the farming practices that are employed and whether individual farmers are making efficient use of natural resources in achieving their economic objectives (Tadeo et al., 2011). For instance, an intensive farming practice, which is not being operated with efficient production decisions, can affect the production efficiency, environmental quality and, therefore, the sustainability in production (Aisbett and Kragt, 2010). In agriculture, an effectively employed production decision that involves the optimum utilization of natural resources would help manage the efficiency with which an ecological resource is used to produce food and meet human needs, which is defined as 'eco-efficiency' (OECD, 1998). The OECD (1998) strictly emphasizes the attainment of such eco-efficiency in agriculture. A farmer who is eco-inefficient not only increases the production costs but also amplifies the environmental impact of the farming activity (Asche et al., 2009; Tadeo et al., 2011). Because 'eco-inefficiency' results from overusing environmentally damaging inputs and exploiting natural resources in agriculture, 'eco-efficiency' can be acquired by improving farmers' managerial skill, in general, and by changing input combinations, in particular. Sherlund et al. (2002) discussed that in the absence of environmentally sustainable production conditions, technical inefficiency estimates become contaminated and rise sharply. As environmental pressure increases, the production efficiency decreases because both the value of farm outputs decreases and input costs increase. Consequently, this production inefficiency will induce a reduction in the production potential, which could be managed in the absence of environmental pressures. Therefore, it is most important to analyze the eco-efficiency in crop agriculture so that production efficiency can be improved satisfactorily to its maximum possible level.

1.2.3 Intensive agriculture and its negative externalities

The analysis on the potential for agricultural negative externalities concerning environmental degradation has been mentioned with importance in many studies (e.g., Wilson, 2000; Travisi and Nijkamp, 2004; Yong-Kwang and Chang-Gil, 2007; Abu et al., 2011). These authors substantiated that intensive agricultural practices, which are exploited by an eco-inefficient farm, will result in external costs in the production process. In this respect, agro-ecological studies have emphasized the analysis of the economic valuation of such environmental degradation in agriculture in terms of external costs (Gunatilake, 2003; Ulimwengu and Sanyal, 2011; Welle and Hodgson, 2011). Additionally, the restoration of a degraded landscape that was caused by intensive farming practices depends on the costs that are relative to the value of the output or the realized environmental benefits (Abu et al., 2011). Studies on agriculture and ecosystem service frequently indicate that agriculture is a prime supplier of ecosystem services (Aisbett and Kragt, 2010). Intensive farming practices, if undertaken sustainably, provide not only ecosystem services but also benefits to the producers (farmers) by providing a future flow of natural resources (capital) (Collard and Zammit, 2006; Porter et al., 2009). Power (2010) indicated that environmental benefits contribute to agricultural yields, which improves farmers' economic welfare when they engage in agribusiness. Certainly, the attainment of environmental benefits will provide farmers with economic welfare. Accordingly, the economic valuation of environmental impacts in agriculture is important to evaluate (Abu et al., 2011). However, studies on farmers' welfare implications under intensive farming systems are unfortunately lacking. Previous studies rarely quantify the contribution of different environmental impacts (i.e., soil erosion, soil toxicity, water depletion, water contamination, etc.) to the external costs that are involved in an intensive agricultural system (Aisbett and Kragt, 2010; Ulimwengu and Sanyal, 2011).

The economic valuation of environmental impacts in agriculture is of interest to agri-environmental policy makers. Policy makers require the values of external costs that are involved in a given production activity in social cost accounting, which helps them correct market imperfections that arise because of environmental degradation (Aisbett and Kragt, 2010). Specifically, farmers' welfare improvements may only be possible through agri-environmental policy interventions that attempt to manage environmental and natural resource conservation. Therefore, it is necessary to consider both the financial and welfare implications that are associated with any economic activity including agriculture (Collard and Zammit, 2006; Porter et al., 2009; Power, 2010). Moreover, external cost valuation helps in internalizing the externalities and ensures an environmentally friendly agricultural system. From a farm resource management perspective, external cost valuation is important because it contributes to improved environmental quality and ecosystem diversity and stimulates agricultural production (Collard and Zammit, 2006; Porter et al., 2009; Power, 2010).

1.3 Statement of research problem

1.3.1 Identifying research questions

The environmental consequences of intensive agricultural practices and their impact on agricultural sustainability have been discussed in several agro-ecological studies (e.g., Brown, 1988; Redclift, 1989; Shiva 1991; Rahman, 2003; 2005). These studies have also identified production technologies that are used for intensive cultivation practices as the factors that influence such impacts. Most of these studies have analyzed basic factors that have caused many environmental problems, such as chemical fertilizers, pesticides, irrigation, and mechanization, although these studies have rarely quantified the extent of the environmental impacts. Quantifying the extent of environmental impact requires an evaluation method that can potentially be used for different types of agricultural systems and farming practices. Binder and Feola (2010) determined that it is challenging to suggest an environmental impact evaluation method that considers agricultural multi-functionality, incorporates its multidimensionality and/or identifies its conflicting goals and trade-offs. Although they propose an evaluation approach, the studies on ecological indicators additionally emphasize the necessity of the method's validation (Girardin et al., 1999; Smith et al., 2000; Vos et al., 2000, Häni et al., 2003). However, these studies rarely check their proposed approach for methodological validation (e.g., Sharpley, 1995) in terms of its design, quality of providing relevant information on environmental impacts and its usefulness (Bockstaller and Girardin, 2003).

Environmental impact is an undesirable output that is produced by a given agricultural practice and results in production inefficiencies (Hoang and Rao, 2010). Previous studies on production efficiency in agriculture also have substantiated the importance of quantifying environmental impact (Rigby et al., 2001; Rasul and Thapa, 2003; Oliveira et al., 2013). In general, these studies evaluate either farming practice-related (e.g., overusing farm chemicals) (Rigby et al., 2001; Zhen and Routray, 2003; Wezel et. Al., 2014) or system-related impacts (e.g., soil erosion, soil reaction) (Rasul and Thapa, 2003; Oliveira et al., 2013; Palm et. Al., 2014) and their negative impacts on production efficiency. Previous studies rarely examine these agri-environmental attributes all together by analyzing the resulting effects on farm efficiency. The research on sustainable agricultural systems often recognizes the challenges in identifying and quantifying important agri-environmental attributes and incorporating the aggregate impact into an efficiency analysis (Keating et al., 2010). For instance, little or no attention has been directed in the research to farmers' opinions, awareness and perceptions. Specifically, for agriculture-environment management purposes, studies that fail to incorporate all of the important dimensions of the environmental impacts will therefore find an inefficient allocation of environmental inputs and provide ineffective policy implications (Gómez-Limón et al., 2012).

Considering the importance of managing environmental impacts, many studies have discussed market-based policy instruments (e.g., Arriagada and Perrings, 2011), and other studies have used the non-market-based economic valuation approach (Carlsson and Martinsson, 2001). However, the studies on environmental economics prefer to employ the non-market-based choice modelling of the contingent valuation technique to value environmental phenomena because it has public good characteristics (Carlsson and Martinsson, 2001; Abou-Ali and Carlsson, 2004; Carson and Hanemann, 2005; Kallas, 2007). Following the contingent valuation theory, most of these previous studies have evaluated the willingness to pay/accept a particular respondent group for an overall improvement in environmental consequences or for a particular management program. Intensive agricultural practices may cause different types of environmental impacts. The economic valuation of the overall impacts or of a particular impact may underestimate the external costs that an agricultural system creates. In this way, the evaluation of impact-specific external costs for a given agricultural system is worthwhile to calculate the aggregate external costs. Notably, the willingness to pay/accept approach has rarely been applied to evaluate the impact-specific contribution to external costs that a given agricultural practice causes. The economic valuation of external costs is necessary to incorporate environmental impacts to analyze social cost accounting and environmental policy suggestions.

In developing countries, environmental policy has become an integral part of the policy process. Specifically, for developing economies, environmental policy implementation is distinctly important and can help achieve sustainability in agricultural production. Additionally, the types and extent of the environmental impacts of a given agricultural practice vary across different agro-ecological zones and physiographic units (Wilson, 2000; Rahman, 2005; Xinshen et al., 2008; Alauddin and Quiggin, 2008). Agri-environmental policy analysis therefore requires a review of a given economic condition and agro-ecological aspect. For instance, because it has an agriculture-based developing economy, it is important that Bangladesh focus on environmental policy reforms that will reduce the environmental impacts of a given agricultural practice. Therefore, this thesis addresses important research questions (Figure 1.1) on the agriculture-environment issue in general and on agriculture in Bangladesh in particular, which is one of the least studied countries in the agro-ecological literature.

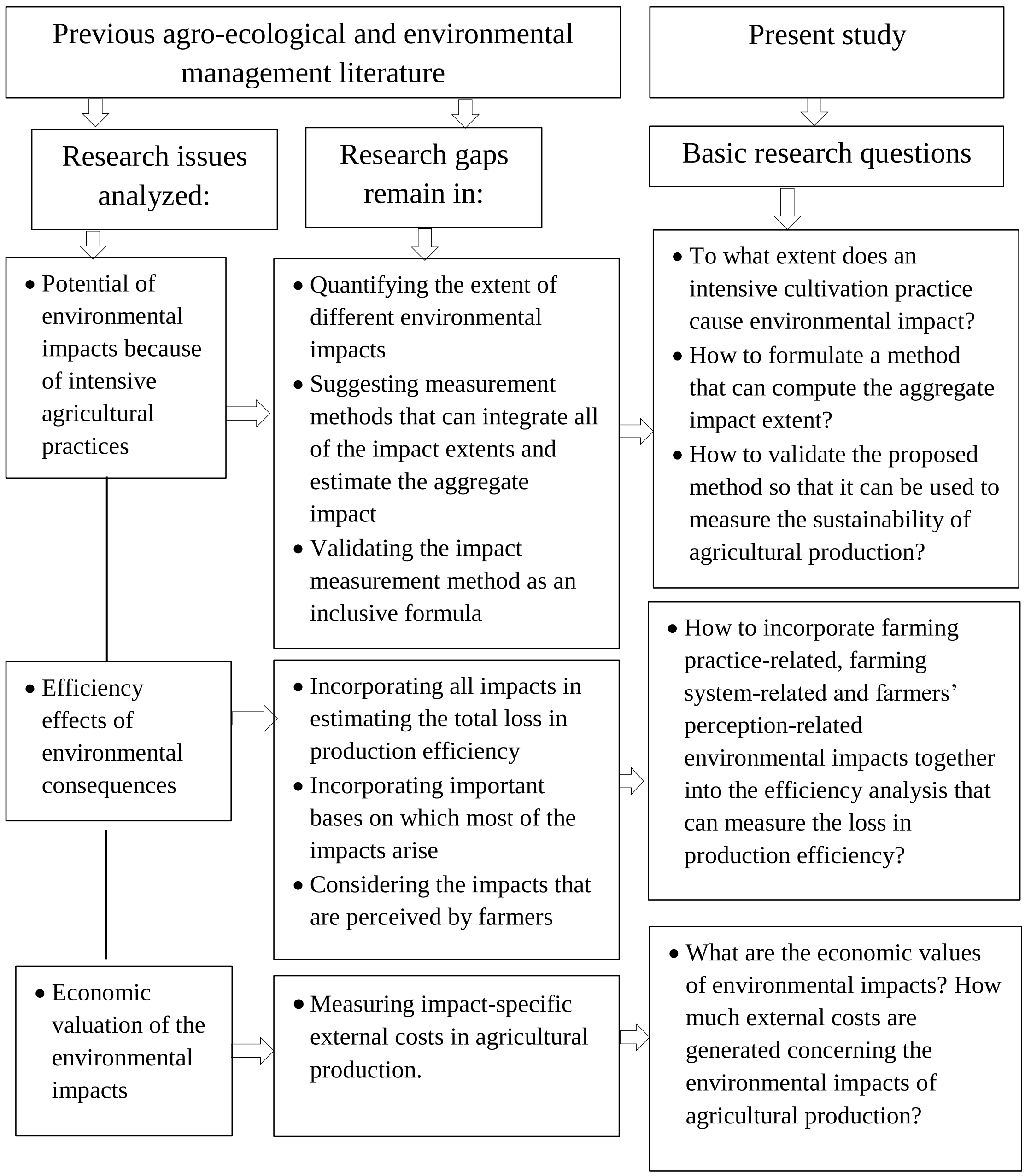

Figure 1.1: Research problem and the research questions

1.3.2 Bangladesh high yield variety (HYV) rice agriculture and environmental problems

In Bangladesh, approximately half of the total population and nearly 99 per cent of the rural population are associated with agriculture (BBS, 2008; BBS, 2011); most of these farmers engage in HYV rice farming. The HYV rice cultivation in Bangladesh is highly dependent on fixed input resources, namely, fertile land to cultivate, safe and sufficient water sources to irrigate and a suitable atmosphere and climatic condition to grow. However, after increasing until 1990, the ratio of agricultural land to the total land area in Bangladesh has declined, which suggests that the cultivation practices have been intensive (Alauddin and Quiggin, 2008). Moreover, irrigation efficiency in most developing countries, such as Bangladesh, is declining because of the cultivation of irrigation feed crops such as HYV rice and wheat (Alauddin and Quiggin, 2008). Compared with the 1960s and 1970s, in recent times, the ground water table has fallen in many areas of Bangladesh (Shamsudduha et al., 2009). Agricultural externalities concerning the degradation of land and water resources can stagnate agricultural production (Tisdell, 2007; Zaks, 2010; Moss and Schmitz, 2013). Over the years, these declining trends in crop production will limit the potential to increase productivity. Rice is one of the most important and staple food grains in Bangladesh, and it is necessary to conduct an in-depth study on HYV rice production and its negative externalities that analyzes their counter effect on production efficiency. Identifying the major affected areas of the environment and quantifying the extent of the environmental impacts of rice farming is necessary to ensure a higher level of rice production in Bangladesh. The problem of environmental degradation, particularly in HYV rice agriculture, is more serious in the northern and western districts of Bangladesh (Alauddin and Quiggin, 2008). Accordingly, in investigating these environmental issues, it is important to focus on these areas of Bangladesh.

HYV rice agriculture, which requires the use of environmentally detrimental inputs, lends itself to resource mismanagement (Poit-Lepetit et al., 1997). The problem becomes serious particularly when production activity is conducted by millions of small farmers with little knowledge of chemical input application and its dire consequences on the environment. In Bangladesh, only a small proportion, 18.18 per cent, of the farmers' attitude regarding the use of agrochemicals is environmentally favorable, whereas the highest proportion, 81.75 per cent, of farmers do not have a favorable attitude (Robbani et al., 2007). Essentially, Bangladeshi farmers' environmental awareness has the desired impact on resource allocation and long-term productivity in agriculture in general and HYV rice cultivation in particular (Rahman, 2005). Therefore, it is important to study Bangladeshi farmers' environmental perception and behavior when analyzing the environmental impacts of HYV rice agriculture and their effects on farming efficiency.

1.4 Research framework

Considering the necessity of evaluating farm-level environmental impacts in intensive cultivation practices, such as HYV rice agriculture, and the impact of these practices on production efficiency, a conceptual framework for the study has been developed and is depicted by Fig 1.2. The research framework is developed by conceptualizing that growing population and growing food demand initiates seed-fertilizer-irrigation technology-based intensive farming practices. This intensive farming technology in HYV rice cultivation, for instance, results in the desirable output of rice yield and the undesirable output of environmental impact. As an important driving factor, farmers' environmental consciousness may help manage the production of undesirable outputs. Otherwise, environmental impact, as an output component of HYV rice production, is an agricultural negative externality that contributes to losses in production efficiency. An adequate level of environmental consciousness helps farmers manage the impact-induced loss in farm-level production efficiency and internalize the agricultural negative externalities. The present study therefore illustrates the conceptualized issues to provide some policy suggestions on environmental sustainability in agriculture in a developing economy context.

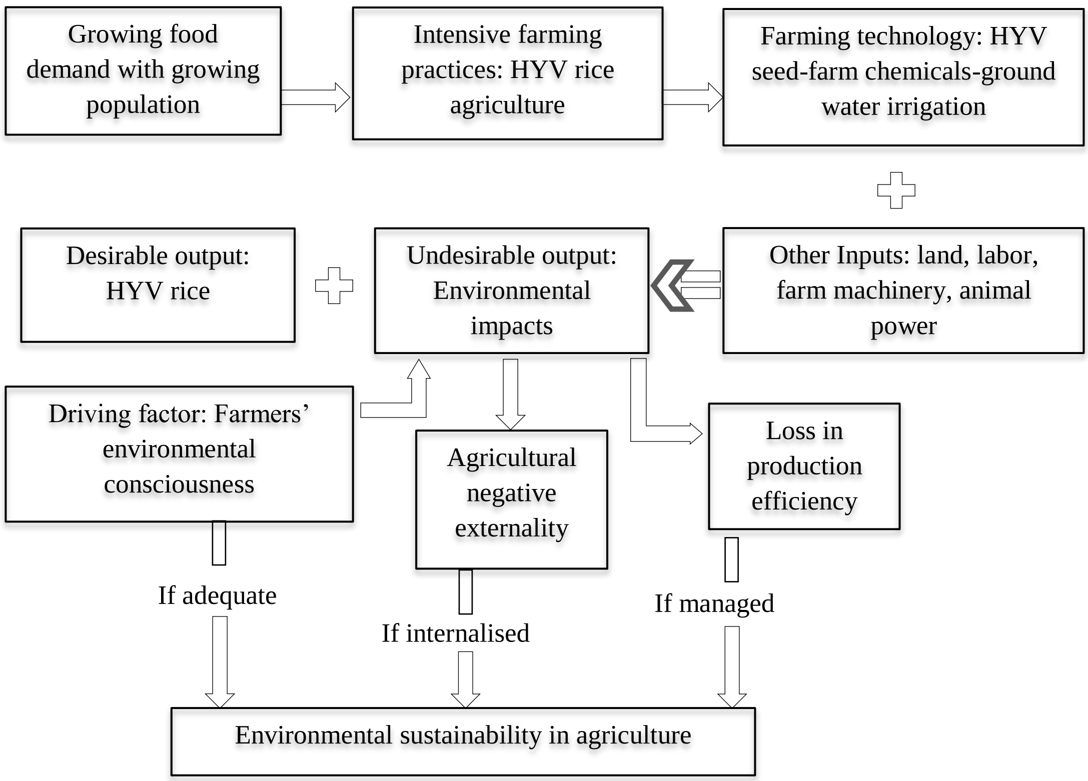

Figure 1.2: Conceptual framework of the study

1.5 Objective of the study

The main objective of this study is to conduct a comprehensive evaluation of the environmental impact of HYV rice agriculture and to examine the potential for agricultural sustainability in Bangladesh. This research analyzes the soil- and water-related environmental impacts that are predominantly experienced by HYV rice farmers. An in-depth farm survey analysis at the local level is performed to quantify the impacts, estimate the economic value of these impacts and measure the loss in farm-specific production efficiency because of these impacts. This study is designed as an assortment of agri-environmental (soil- and water-related impacts) and agro-economic (HYV rice production: input costs-output price) and welfare (farmers' willingness to pay for impact management) analyses that include the relevant issues that concern the intersection of agriculture and the environment.

The primary survey attempts to identify the different environmental impacts of HYV rice farming and farmers' specific socio-environmental and agro-economic determinants of the resulting loss in production efficiency. Additionally, my survey attempts to explore the factors that influence farmers' willingness to pay to reduce environmental impacts and evaluates impact-specific economic values in terms of external costs. Therefore, the specific objectives of this study are to

i. Quantify the extent of the environmental impacts that are predominantly experienced by HYV rice farmers in Bangladesh;

ii. Evaluate the loss in production efficiency that is caused by the environmental impacts by analyzing eco-efficiency; and

iii. Analyse the economic valuation of the environmental impacts to examine the welfare implications of the environmental phenomena that are associated with HYV rice agriculture.

1.6 Hypotheses of the study

The overall idea behind this study is that although intensive farming practices contribute to increased agricultural production, they create adverse impacts on the environment. Additionally, these impacts vary across agro-ecological units and are regionally diverse. As a counter effect, this diversity results in declining yields and restricts the future flow of environmental resources for agriculture. Following these ideas on the agriculture-environment issue, this study hypothesizes[1] that (i) intensive agricultural practices do not have adverse impacts on different environmental attributes such as soil and water quality, farmers' and fisheries' health, etc.; (ii) environmental impacts do not cause a loss in production efficiency; (iii) the likelihood of farmers' willingness to pay for on-farm environmental impact management does not help reduce the environmental impacts; and (iv) farmer-specific demographic, socio-environmental and agro-economic factors do not influence the environmental impact-induced loss in production efficiency and farmers' willingness to pay to reduce the environmental impacts.

1.7 Significance of the study

[1] The hypotheses are suggested in the null form with open alternative hypotheses (Rahman, 1998).

The proposed research will have immense significance to the literature of growth and the environment and particularly to the policy makers of and environmental experts in Bangladesh agriculture. The objectives of this research, the methods that are employed to achieve these objectives and the nature of the investigated research problems contribute to the expansion of knowledge in the following ways. First, the quantification of the undesirable output component will help us understand the extent of the environmental impacts and the negative agricultural externalities. Moreover, the incorporation of the environmental impact factor into the efficiency formula explains the environmental impact-adjusted production efficiency. Effectively, this explanation helps farmers make production decisions that conserve the environment and that manage the natural resource exploitation in agriculture. Additionally, a willingness to pay analysis encourages the farmers' participation in an environmental management program, motivates them to be environmentally conscious and helps them recognize the importance of implementing environmental regulations such as command and control options.

1.8 Outline of the thesis

This thesis has been organized and divided into seven chapters (Figure 1.3). Chapter 2 reviews the statistical trends of the agro-economic and agro-ecological aspects of Bangladesh. An analysis of the statistical trends portrays the status of agricultural sustainability in Bangladesh as the background of the agriculture-environment issue.

Chapter 3 discusses the data sampling procedure and explains the overview of the research design. A description of the study area that was selected for the survey of this study is also explained here.

Chapter 4 introduces a new indicator-based approach to quantify the farm-level environmental impacts of HYV rice agriculture. In addition, the proposed method is explained and illustrated for a set of primary survey data on Bangladeshi HYV rice farms. This chapter analyzes the estimated measures of different environmental impacts and the aggregate impact that is produced by HYV rice cultivation.

Chapter 5 describes the procedure of incorporating aggregate environmental impacts into the eco-efficiency model. For the same set of data, this chapter estimates the resultant loss in farm-specific production efficiency because of environmental impacts by analyzing the eco-efficiency (i.e., environmentally adjusted production efficiency) and the production efficiency.

Chapter 6 evaluates the economic values of different environmental impacts regarding the external costs that are involved in HYV rice production. Specifically, the farm size-wise and study region-wise economic values of different environmental impacts along with overall impact are evaluated in monetary terms. The final chapter contains the study summary and policy implications of the study's findings.

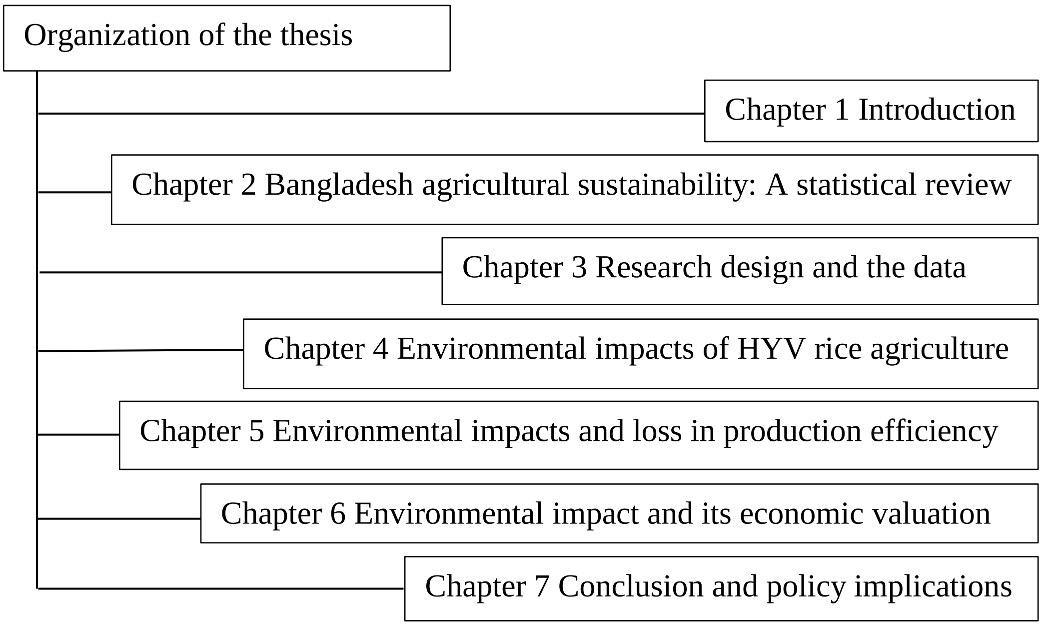

Figure 1.3: Thesis outline

CHAPTER TWO

Bangladesh's agricultural sustainability: A statistical review

2.1 Introduction

The concept of sustainable agriculture emphasizes different directions of agriculture that involve different countries and regions (Zhen and Routray, 2003). Bangladesh as a developing country is facing challenges in every facet of its economic development. One challenge is to maintain agricultural sustainability or to manage the causes behind any unsustainability. Different types of agro-economic and agro-ecological objects may interrupt agricultural sustainability. This chapter explains some important agro-economic and agro-ecological aspects in terms of the statistical trends in Bangladesh's agriculture. A critical review of different agricultural and agro-ecological statistical trends and their structural indicators is represented to explain their sustainability status. This effort will substantiate the need to analyze the agro-ecological dimensions of sustainable production activities as the background of the environmental problems in Bangladesh's agriculture. Furthermore, an analysis of the identified trends that are required to be decreased for a considerable state of sustainability allows us to explain the economic interpretation of these agri-environmental attributes.

This chapter starts with Section 2.2, which provides a conceptual overview of agricultural sustainability. This section briefly describes the importance of analyzing important dimensions of agricultural sustainability and their statistical trends as the criteria of sustainability measurement. Using statistical trends, Section 2.3 critically reviews Bangladesh's agro-economic and agro-ecological attributes. This section explains whether the trends are economically, environmentally and socially favorable to agricultural sustainability. Section 2.4 briefly describes the attributes of rice agriculture and provides evidence of natural resource exploitation scenarios in Bangladesh's rice agriculture. Section 2.5 concludes the chapter.

2.2 Agricultural sustainability: A conceptual overview

Previous studies have analyzed various aspects of sustainable agriculture to define the concept of agricultural sustainability. One of the most widely accepted views of sustainable agriculture is explained in the report of the American Society of

Agronomy (ASA, 1989). According to this report, 'agriculture' that ensures environmental quality and the natural resource base, human food and fiber, economic viability and the improved living standards of farmers and other social aspects is referred to as sustainable. Basically, this idea incorporates three important and interrelated dimensions of sustainable agriculture. Theoretically, these dimensions of sustainability in agriculture can be distinguished as ecological (environmental), economic and social, and the environmental dimension is the most fundamental. In addition to manmade capital, the level of agricultural production solely depends on inputs from environmental and natural resources. Ecological sustainability therefore concerns the maintenance of the global ecosystem or 'natural capital' (the stock of an environmentally provided asset) both as a source of inputs and as a repository for waste (Goodland, 1995). Certainly, the other two dimensions have their specific importance in sustainability analysis. The 'economy' is automatically considered a crucial factor. Without the economy, no agribusiness can survive. Additionally, without farmers' participation, group action, and institutional promotion as social criteria, no agribusiness could be operated. However, the key features of agricultural sustainability should be based on more than simple economic and social criteria, and an analysis of the environmental dimension and ecological equity have significant importance (DFID, 2004).

A definition of agricultural sustainability is difficult to express in a single context. Generally, sustainability analysis depends on its important measurement criteria (Figure 2.1). For instance, a normative dimension of sustainability analysis addresses the measurement of the economic, social and ecological aspects of agriculture. The spatial dimension addresses local, regional and national aspects of the agricultural sector of a given economy. An analysis of the temporal dimension moves within the long- and short-term aspects of agriculture and uses a dynamic approach to measure temporal sustainability (von Wirén-Lehr, 2001). However, the normative dimension is more fundamental because it must be analyzed either in a spatial or temporal context. For instance, the environmental aspect of the normative dimension can be studied both spatially (i.e., local, regional or global) and temporally (i.e., short or long term). Specifically, the normative dimension of sustainability analysis on a local level is important and challenging. In this regard, Pretty (1995) notes that in empirical research, when specific parameters or criteria are selected, it is possible to say whether certain trends are stable, increasing or declining; the author explains that this is a good way to analyze sustainability measurement issues. For instance, intensive agricultural practices that cause land degradation, beneficial pest extinction, water depletion, and deforestation can be considered unsustainable in conserving resources. Conversely, farming activities that ensure a balanced dose of chemical applications, maintain crop diversification and regularly change irrigation water sources are considered sustainable for resource conservation. The trends of these agricultural activities and practices can therefore be used to represent their sustainability status.

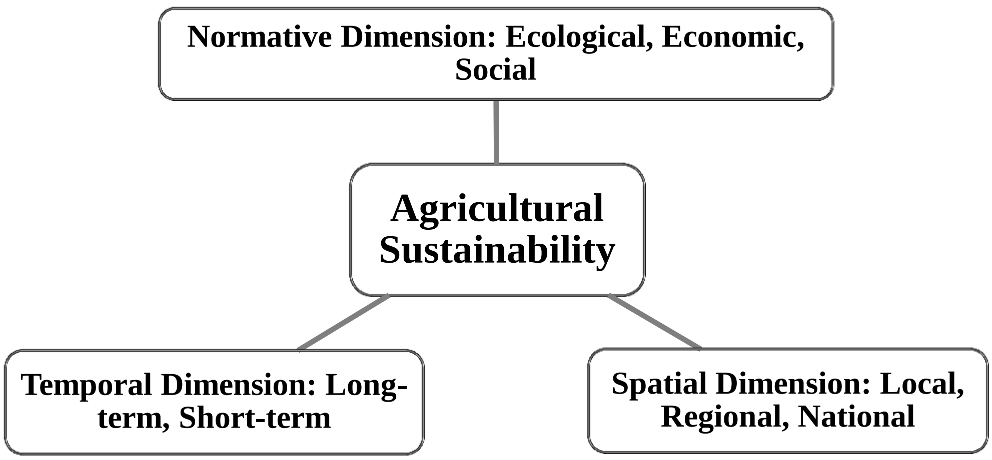

Figure 2.1: The three tiers concept of agricultural sustainability

The sustainability concept and the importance of its dimensions and measurement criteria have always been important issues to study in agronomic research. Beus and Dunlop (1994) consider agricultural practices such as the use of pesticides and inorganic fertilizers and the maintenance of diversity as measures of sustainability. However, Lynam and Herdt (1989) suggest that sustainability in agriculture can be measured by analyzing the changes in yields, total factor productivity, farm profitability and stability. In this regard, Rasul and Thapa (2003) extend this viewpoint and emphasize the sustainable management of land and water resources as a major requirement to measure agricultural sustainability. Researchers also consider the status and trends of specific social indicators to define sustainability in agriculture (Ikerd, 1993; Pretty, 1995; Tisdell, 1996; Rasul and Thapa, 2003). In this respect, the input self-sufficiency status, income equity, food security trend, and the risks and uncertainties that are involved in crop cultivation have been included. It is therefore important to review the trends of several agro-ecological, agro-economic and socio-agricultural parameters that are consistent with sustainability in agriculture. According to Pretty (1995), this can be done by analyzing how these indicators have performed in previous years.

2.3 Statistical review of Bangladesh agricultural sustainability: A critical approach

2.3.1 Agro-economic attributes

2.3.1.1 Cereal yield stability and agricultural sustainability

A non-increasing population is a prime condition to achieve agricultural sustainability in developing countries because per capita food grain production reflects food self-sufficiency and therefore ensures production stability. Because the basic idea of sustainable food production is to feed the growing population, the crop production growth rate should run faster than the production growth rate of the population. An increased level of per capita grain production also strengthens food security.

In Bangladesh, because of the technological changes in agriculture, average cereal production doubled in 2013 from the average cereal production in the 1970s (The World Bank, 2013). However, the growth rate in cereal yield follows a falling trend over several years. Table 2.1 shows that the average growth rate of cereal yield remained at 0.93 per hectare of arable land from 1971-1981 and decreased in successive years. Recently, from 2004-2013, this rate became 0.74. The falling trend in the average growth rate in cereal yield implies that agricultural land productivity has also been falling in the past several decades. In addition, the growth rates in the food and livestock production indexes were also falling during the same period of time. Simultaneously, the country was experiencing increasing trends in the growth rate of its population density (Table 2.1). Consequently, the average level of per capita arable land decreases at a rate of 132 per cent every ten years (The World Bank, 2013). Therefore, the cereal yield and food supply trends are evidently unfavorable to agricultural sustainability. Two factors are restraining the potential for yield stability. First, the population is increasing at a much higher rate than the yield to feed. Second, average cereal production is increasing at a decreasing rate, which implies declining trends in land productivity and a lower extent of the sustainability potential in agriculture.

Table 2.1 Trends in agricultural production and population growth rates: Bangladesh

Years	1971 to 1981	1982 to 1992	1993 to 2003	2004 to 2013	Trend
Cereal yield	0.93	0.82	0.79	0.74	Decreasing
Crop production index	0.89	0.80	0.81	0.69	Decreasing
Food production index	0.87	0.81	0.78	0.68	Decreasing
Livestock production index	0.82	0.91	0.88	0.70	Increasing followed by decreasing
Population density	0.80	0.76	0.81	0.85	Decreasing followed by increasing

Note: Crop production and food production index base (2004-2006 = 100); Cereal yield (unit: kg per hectare) average rate of growth for every 10 years, Population density (unit: number of population per square kilometer) growth rate.
Source: The World Bank, 2013; BBS, 2011

2.3.1.2 Food security and agricultural sustainability

Food security is considered one of the major indicators of socio-agricultural sustainability. An economy that has a satisfactory level of food security has the potential for agricultural sustainability. Countries in Africa and Asia, where agriculture is practiced primarily by small-scale farmers, have always been faced with additional challenges in food security issues (Kahane, 2013). In Asia and a developing country such as Bangladesh, food security not only helps achieve important development goals but also ensures a sustained agricultural economy. Bangladesh’s national-level data show that daily per capita calorie intake remains slightly above the absolute poverty line (2122 Kcal/cap/day). A declining trend in this attribute is observed from 1992 to 2005 but shows a significant increase in the next five years from 2005 to 2010 (Table 2.2). Table 2.3 shows that the rate of increase in daily per capita protein intake consistently followed an inverted U-shaped pattern from 1996 to 2010. The rising trend in food security absolute values can be treated as an influencing factor to fight poverty in a developing economy. On the contrary, the falling rate of increase in food security absolute values is considered an obstacle to achieve long-term agricultural sustainability.

Unacceptable levels of continuing food and nutrition insecurity remain considerable challenges to emerging economies. To maintain food security and nutrition requirements in the long term, an increased level of yield and the productivity of inputs are both required through effective agronomic practices. This increase requires creating low-risk, high-return market settings for a developing country's farmers (George, 2014).

Table 2.2 Food security pattern across survey years in Bangladesh

Survey year	Calorie intake(kcal/cap/day)			Protein intake(gram/cap/day)		
	National	Rural	Urban	National	Rural	Urban
1992	2266.6	2267.8	2258.1	62.72	62.29	65.49
1996	2244.0	2251.1	2209.1	64.96	64.45	67.50
2000	2240.3	2263.2	2150.0	62.50	61.88	64.96
2005	2238.5	2253.2	2193.8	62.52	61.74	64.88
2010	2318.3	2344.6	2244.5	66.26	65.24	69.11

Source: BBS, 2010; 2012

Table 2.3 Protein intake pattern in Bangladesh: Rate of growth

Year	1996	2000	2005	2010	Trend
National protein intake	0.97	1.03	0.99	0.94	Increasing followed by decreasing
Rural protein intake	0.96	1.04	1.00	0.94	Increasing followed by decreasing
Urban protein intake	0.97	1.03	1.00	0.93	Increasing followed by decreasing

Source: BBS, 2010; 2012

2.3.1.3 Structural stability in agriculture

Structural change in agriculture can be used to determine the potential of achieving the sustainability goal. Certainly, the potential for agricultural sustainability is higher if all of the structural components grow favorably. For instance, one of the important components of agricultural structure is the distribution of farm households. Theoretically, a farm household is defined as a holding whose net cultivated area is a 0.05 acre or more. The percentage of rural farm households with respect to the percentage of total households is decreasing at a high rate. In the census year from 1983-84, rural farm households were recorded as 72.70 per cent of the area's total households. This proportion follows a decreasing trend in the successive census years, i.e., 66.18 and 56.74 per cent in 1996 and 2008, respectively (Table 2.4). Rapid urbanization and changing employment to the non-agricultural sector are the two important reasons behind this scenario. The long-term falling trend in the number of farm households is considered an indicator of agricultural unsustainability.

Land fragmentation is considered another structural variable that generates a vulnerable situation for agricultural profitability in terms of the loss of arable land, loss of production and a rise in input costs. Agricultural lands are becoming fragmented by the division of large farms into medium and then small holdings. The percentage of small farm holdings has been increasing at a high rate in every census year (Table 2.4). This trend will create difficulties in managing this unsustainable condition. The available crop area for an individual farmer will then be reduced along with production. The per capita cultivated area was recorded as 2.00 acres in 1984 and fell to 1.5 and 1.26 acres in the successive census years of 1996 and 2008, respectively (Table 2.4). When the falling trends of this important attribute persist, agricultural sustainability is threatened.

The impact of land fragmentation on land ownership status is important concerning both social and economic sustainability in agriculture. The increasing trend in the number of landless farm holders apparently causes difficulties in attaining sustainability goals. The transfer of land ownership for social reasons causes the farm size to gradually become smaller. Changes in farm land ownership and the replacement of experienced farmers with new farmers increase the risk of a significant amount of unrealized profits in crop production. Sometimes, the transfer of farm land ownership causes the transfer of agricultural land to non-agricultural purposes. In the census year of 1996, the proportion of owner farm households to the total farm households was recorded as 67 per cent, whereas it fell to 65 per cent in the next census year of 2008. In addition, a 3 to 5 per cent increase in the number of tenant farm holdings was also observed in these two census years (BBS, 2008). Both tendencies of ownership transfer by selling farm land or other non-selling transfers are alarming in Bangladesh. Dividing crop land into small pieces by selling it causes most of the households to have less land. In rural areas, the number of households that obtain less land is increasing at a rate of 83 per cent every ten years (The World Bank, 2013). The sustainable rate of agricultural production is considerably conditional on farms that are operated by trained, experienced, skilled and educated farmers who have owned the land for a long time. Therefore, the previous census years' data on the structural component shows that Bangladesh's agricultural structure is not growing sustainably.

Table 2.4 Structural parameters of agriculture in three consecutive census years in Bangladesh

Census years	1984	1996	2008	Trend
Rural farm household (% of the total household)	72.7	66.2	58.7	Decreasing
Small farm (% of the total farm household)	70.3	79.9	84.3	Increasing
Medium farm (% of the total farm household)	24.7	17.6	14.2	Decreasing
Large farm (% of the total farm household)	4.94	2.52	1.54	Decreasing

Rural landless household (% of the total household)	8.67	10.2	12.8	Increasing
Rural agricultural labor household (% of the total household)	39.8	35.9	34.9	Decreasing
Cultivated area per farm holding in rural areas (in acre)	2.00	1.50	1.26	Decreasing
Arable land per capita (in hectare)	0.09	0.07	0.05	Decreasing

Source: BBS, 2008; BBS, 2011

2.3.1.4 Bangladesh's economy and agricultural stability

In Bangladesh's economy, agriculture has always been a top contributor to its Gross Domestic Product (GDP). However, in the past several years, the net output from the agricultural sector as a percentage of GDP has shown a decreasing trend (The World Bank, 2013). In the census year of 1983-84, 31.48 per cent of GDP is the value that is added from the agricultural sector, which falls to 25.67 and then to 19.01 per cent in the census years of 1996 and 2008, respectively. This decreasing trend is a cause for concern in agronomic growth and development and sustainability analysis. Although showing a sustainable growth rate of GDP in other sectoral overheads, the agriculture and forestry sector experienced a decline in the GDP growth rate after the 1980s. The GDP growth rate decreased at an average rate of 131 per cent in each successive census period (Table 2.5).

The employment structure in Bangladesh's economy is unfavorable to achieve agricultural sustainability. The percentage of employment in agriculture as total employment increases at a rate of 92 per cent from 1984 to 1996 but decreases at a higher rate in 2008 (almost 131 per cent) (Table 2.5). This finding implies that farmers are leaving farming as a major business because of migration from rural to urban areas or the current generation wants to change their parents' agri-business to some current employment of interest. This socio-economic attitude causes many agricultural labor households to decline in the rural economy. A continuous fall in the percentage of rural labor households in three consecutive census periods is thus evident (Table 2.4). The diversification of income source as a major cause of this unstable scenario in the agriculture employment sector is an important determinant of its overall sustainability.

The support services for capital availability such as extensions, training, marketing, and credit services are considered other underlying factors that ensure economic sustainability in agriculture. In developing countries, access to extensions and credit services usually favors large farmers (Axinn 1988; Dang, 2001). Equality in accessing support services and capital availability can ensure social stability and encourage farmers to improve production while conserving resources. A drastic increase in agriculture credit disbursement that has been reported by Bangladesh Bank validates that capital availability does not create any obstacle to agriculture's advancement. However, a high peak of yearly overdue credit and its increasing trend certainly indicates that recession threatens the economy. On average, overdue agriculture credit is growing at a rate of 80 per cent annually (BBS, 2010) (Table 2.5), which is a matter of concern regarding sustainability issues in Bangladesh's agriculture.

Table 2.5 Agro-economic parameters in three consecutive census years in Bangladesh

Census years	1983	1996	2008	Trend
Growth rate of GDP in the agriculture and forestry sector (%)	6.92	5.03	4.02	Decreasing
Agriculture value added (% of GDP)	31.5	25.7	19.0	Decreasing
Employment in agriculture (% of total employment)	58	63	48	Increasing followed by decreasing
Disbursement of agriculture credit (million BDT)	20773.5	77690.5	173893	Increasing
Overdue agriculture credit (million BDT)	7556.7	49204.2	59429.2	Increasing
Production of chemical fertilizer (thousand metric tons)	816.52	1839.85	1801.25	Increasing followed by decreasing
Import of chemical fertilizers (thousand metric tons)	357.00	867.69	1649.99	Increasing
Import of pesticides (metric tons)	3503.86	5998	23708	Increasing

Source: BBS 2008; BBS, 2011

2.3.1.5 Input self-sufficiency and agricultural sustainability

One of the best ways to determine the input self-sufficiency in agriculture is by analyzing the economy's import trend of agricultural inputs. For sustainable growth in its agricultural sector, an economy must be self-sufficient in the input supply for agricultural production. Dependency on external sources for the supply of agricultural inputs and its increasing trend shows the unsustainable condition of the economy. In Bangladesh, the production of chemical fertilizers increased satisfactorily until 1996. However, in the census year of 2008, this trend slightly decreased (Table 2.5). Moreover, the import of chemical fertilizers grew at a significant rate in the three successive census years. In the fiscal-year of 2008-09, 40 per cent of the total estimated demand for chemical fertilizer came from domestic production, and 60 per cent came from external sources (BBS, 2011). In the next fiscal-year of 2009-10, these scores become 35 and 65 per cent, respectively.

Therefore, the external source dependency for fertilizer input increases, which restricts the sustainable growth of agricultural production.

According to recent economic reports, fertilizer imports have risen and the domestic production of fertilizer has declined in Bangladesh. In addition, nearly the total amount of the demanded pesticide is supplied by external sources. The increased rate of pesticide importation from 1984 to 2008 shows that Bangladesh is also not self-sufficient in pesticide inputs. Subsidies in farm inputs reduce agro-environmental sustainability primarily by creating price distortions and by promoting the production of input intensive crops, the waste of natural resource inputs, the use of marginal and fragile lands, and rent-seeking behavior (ESI, 2005). In Bangladesh, the fertilizer subsidy has followed a rising trend across several years (Figure 2.2). Along with input self-sufficiency, food self-sufficiency is also an important factor to bring sustainable development to agriculture. Food grain imports in the past several years have also followed an increasing trend (Figure 2.3). Compared with 2005, in the financial year of 2010 to 11, Bangladesh doubled its food grain imports.

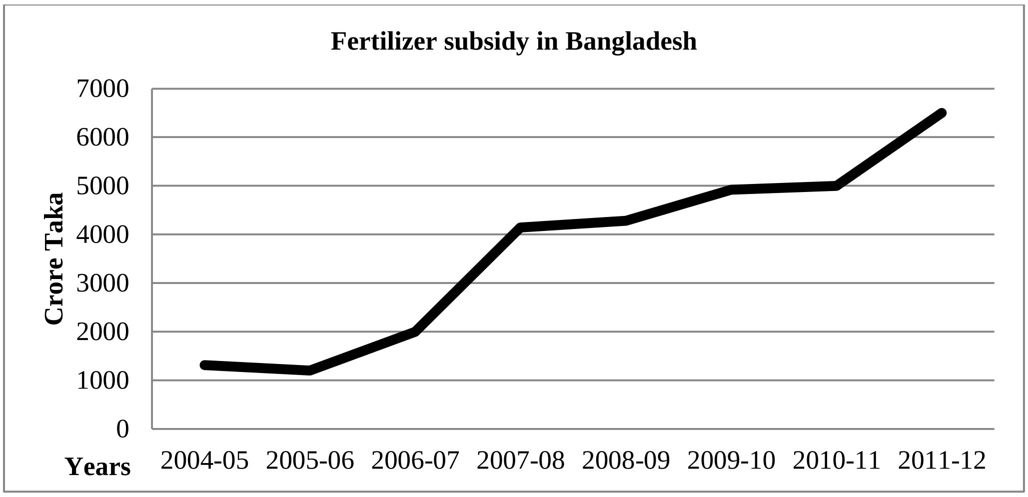

Figure 2.2: Fertilizer subsidies in Bangladesh

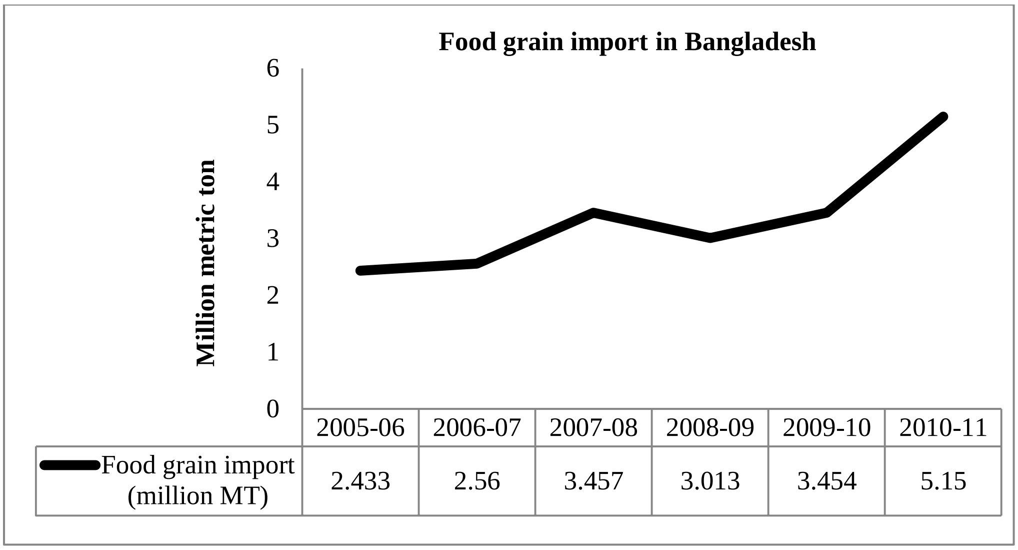

Figure 2.3: Food grain import in Bangladesh

2.3.2 Agro-ecological attributes

2.3.2.1 Agricultural emissions and sustainability

Soil fertility management and water management are two important activities that concern agricultural emissions. The proper management of soil fertility and water availability implies that the rates of fertilizer and pesticide application should be based on the current soil fertility status and level of occurrence of pests and diseases. Because farm chemicals are applied to the irrigated fields, crop residues are major sources of agricultural emissions. Chemical fertilizers (nitrogenous, potash, and phosphate fertilizers and ground rock phosphate) that were applied per hectare of arable land were just 188.64 in 2000, whereas this number increased to 281.7 kg in less than ten years (Table 2.6). Similarly, the amount of annual pesticide consumption jumped from 25,466.43 metric tons in 2005 to 48,690.19 metric tons in the next three years. The excessive use of fertilizers and chemical pesticides from agricultural activities has a certain negative impact on even production. This excessive use also has a negative impact on soil and water, and alters the chemistry and levels of nutrients, which leads to the eutrophication of water bodies. The obvious results of these impacts are fresh water unavailability and higher levels of emissions. The per capita availability of renewable internal freshwater resources is drastically decreasing in Bangladesh, which was recorded as 766.36 cubic meters in 2002 and fell to 670.51 cubic meters in 2013 (The World Bank, 2013). Also a yearly rising tendency in agricultural methane emissions and nitrous oxide emissions has been aggravated by the increasing rate of farm chemical utilization. Almost 83 per cent of total nitrous oxide emissions are caused by agriculture alone, which is a concern in analyzing agricultural sustainability.

Table 2.6 Agricultural emission attributes in Bangladesh

Years	2000	2005	2008	2010	Trend
Agricultural methane emission (thousand metric ton of CO_2 equivalent)	65720.9	66521.8	67364.4	70353.4	Increasing
Agricultural nitrous oxide emission (% of the total)	82.72	82.74	83.95	--	Increasing
Fertilizer consumption (Kg per hectare of arable land)	188.63	197.74	200.06	281.7	Increasing
Yearly pesticide consumption (metric ton)	15632.2	25466.4	48690.2	--	Increasing
Area equipped for irrigation as a percentage of total arable land (percentage)	44.54	52.36	54.58	56.05	Increasing
Forest area (percentage of total land area)	11.27	11.17	11.11	11.05	Decreasing

Note: “—“ indicates data not available.
Source: The World Bank, 2013; FAO, 2013

2.3.2.2 Bangladesh’s agro-ecology and sustainability

The ecological soundness of the environment partially depends on the ecological soundness of agriculture. Agricultural activity directly uses natural resources, the major components of ecology, and it therefore plays a vital role in maintaining ecological sustainability. Similarly, stability in every ecological dimension is one of the foremost requirements of bringing sustainability to agriculture. One of the most accepted and current measures of ecological sustainability are the ecological footprint. When the footprint is larger, ecological soundness is greater. Basically, the ecological footprint measures the biologically productive land that is required to sustain a country's population at the current consumption levels. The countries whose footprints exceed their own arable land area are consuming at levels that are unsustainable in the long term. According to the Report on the Environmental Sustainability Index (2005), Bangladesh’s ecological footprint has been estimated as 0.50 hectare (Table 2.7). This estimate implies that the biologically productive land (e.g., agriculture, forestry, fishery, etc.) that is required per person is 0.05 hectare. However, in the 1984 census year, per capita arable land was reported as 0.09 hectare, which fell to 0.07 in the next census year of 1996 and was followed by a second fall to 0.05 hectare in 2008. The ecological footprint score, i.e., 0.05, equaled the per capita arable land score in 2005 (The World Bank 2013, ESI, 2005). In 2011, the per capita arable land fell to 0.04 because of population growth and increased consumption. This decrease also had a certain impact on the ecological footprint.

When the footprint is smaller, the amount of biologically productive land is less, which suggests a potential threat to ecology.

Ecological instability that is caused by intensive agricultural practices can be indicated well by the level of eutrophication. The extensive and continuous use of farm chemicals is an initiator of this type of pollution. In Bangladesh, dissolved oxygen concentration accounts for 6.70 mg per liter of water, whereas the world's highest measure of this concentration is 13.76 mg (Table 2.7). Because the highest value implies the lowest eutrophication, Bangladesh is more than half of the world's highest eutrophication. The eutrophication estimate that results from phosphorus concentration also reflects an unfavorable condition. The highest level of this pollution in the world is 0.67, and in Bangladesh, it is 0.29 mg per liter of water. Bangladesh is thus just below half of the highest eutrophication level in both measures. Regardless of the reason, i.e., farm or industrial chemicals, eutrophication has an important impact on the health of aquatic resources, the agriculture and the ecosystem. This impact can be on fresh water unavailability, the reduction in farm output or both. For instance, the yearly extraction of groundwater should not exceed the yearly recharging of groundwater reserves from rain and surface water. Therefore, the amount of irrigation water should be based on the water demand of different crops during the growth period. Almost 88 per cent of the country's fresh water withdrawal is only for agriculture (The World Bank, 2013). Moreover, approximately 23 per cent of the national territory suffers from severe water stress, which affects the availability of water for environmental services and human well-being. The regional distribution of water availability relative to the population and consumption needs is as important as overall water availability. These factors are certainly unfavorable in Bangladesh. To ensure a sustaining ground water level and the pollution-free surface water sources that are available for agriculture, managing the extent of this pollution is essential. To sustain ecological diversity in underwater plants and other marine life, it is therefore important to abate eutrophication.

On-ground agriculture (crop cultivation, forestry, etc.) and under-water agriculture (fishery, other aquatic vegetables) both depend on a frequent and sustainable water supply. In a specified area and time span, the use of renewable water resources should not exceed the formation of new stocks. As a riverine country, Bangladesh has significant potential in its fisheries along with its crop agriculture. Fish stocks are an important component of marine ecosystems. A sustainable fishery culture is also a concern because, in Bangladesh, the overfishing index accounts for 6 out of 7 (theoretical maximum). Overfishing puts pressure on the ecosystem and threatens biodiversity. The national bio-diversity index is 0.54 out of 1 in Bangladesh. To reach even near the acceptable threshold of level 1, Bangladesh has a long way to go.

Only 1.85 per cent of the total energy consumption comes from hydroelectric and other renewable sources in Bangladesh. When the proportion of hydroelectric and other renewable energy sources is higher, the reliance on more environmentally damaging sources such as fossil fuels and nuclear energy is less. In Bangladesh, irrigation is solely based on the motor operated diesel engine. The major source of energy for irrigation is fossil fuels; therefore, this agriculture mostly uses environmentally damaging energy sources.

Table 2.7 Ecological indicators and their status in Bangladesh

Indicators	Value	Unit	Threshold value and explanation	Vulnerable to Sustainability
Ecological Footprint	0.50	Hectares of biologically productive land required per capita	If less than the per capita arable land, then ecology is threatened.	***
National Bio-diversity index	0.54	Score between 0 and 1	Large values correspond to high levels of species abundance, and small values reflect low levels of species abundance.	**
Water withdrawal for Agriculture	87.82	Percentage of total fresh water withdrawal Annually	100	***
Measure of Eutrophication (Dissolved oxygen concentration)	6.70	Mg per liter of water	Low levels correspond to high eutrophication: the world's lowest level is 0 and highest is 13.76.	**
Measure of Eutrophication (Phosphorus concentration)	0.29	Mg per liter of water	High levels correspond to high levels of eutrophication: the world's highest level is 0.67 and lowest is 0.	**
Productivity of Overfishing	6.00	Scores from 1-7	A high score corresponds to a greater degree of overfishing.	***
Hydropower and renewable energy production	1.85	Percentage of total energy consumption	A lesser proportion corresponds to a high reliance on an environmentally damaging source such as fossil fuels.	***
Percentage of national territory under severe water stress	22.88	Percentage of national territory in which water consumption exceeds 40 percent of the available	100	*

		water		
Environmental Hazard Exposure Index	1.31	An index of population-weighted exposure to high levels of environmentally related natural hazards	The theoretically possible range is from 0-4, and the world range is from 0-2.5.	***

Note: Severely vulnerable (***), Moderately vulnerable (**), Vulnerable (*)
Source: ESI, 2005; The World Bank, 2013

2.3.2.3 Climate change and agricultural sustainability

Bangladesh is one of the most vulnerable countries to climate change. ESI (2005) reports that the environmental hazard exposure index is 1.31 for Bangladesh. The world maximum of this index is 2.5 (Table 2.7). This index is a measure of vulnerability to natural disasters. This index identifies the exposure (how often and how severe the natural hazards are) and the sensitivity to these hazards (how strong the linkages are to social systems), as well as the resilience in society to these hazard's impacts. Therefore, the score of 1.31 indicates that it is challenging to manage frequent natural hazards, minimize their impact on society and address social sensitivity linkages. The Global Climate Risk Index (GCRI) 2010, from 1990-2008, assessed this country as the most vulnerable country to extreme climate events. This index further estimates that, on average, 8,241 people have died each year in Bangladesh while the cost of the damage was US $ 1,189 million per year and the loss of GDP was 1.81% in this period (NRSD, 2012).

Climate change and its impact on agricultural sustainability is one of the major concerns currently in the agronomic research. This concern is because agricultural production primarily depends on the climate's condition. Crop cultivation and its healthy growth are mainly conditional on climatic potentials such as rainfall, temperature, humidity, drought, flooding and the weather. Moreover, climate change may amplify the observed dynamics and trends, such as fewer but more intense rainfall events during the monsoon season, which will affect crop growth. Among all other sectors, crop agriculture is the most vulnerable to climate change. Crop agriculture exhibits a severe vulnerability potential in the physical vulnerability contexts of extreme temperature, salinity, droughts, cyclones, and storms and a moderate vulnerability from coastal flood inundation and flash floods (Table 2.8).

However, the vulnerability of the crop sector because of river floods is not severe but is considerable.

Table 2.8 Intensity of the impacts on different sectors because of climate change in Bangladesh

Sectors	Extreme Temperature	Coastal Flood Inundation	Salinity Intrusion	Drought	River Flood	Flash Flood	Cyclone and Storm Surges	Erosion and Total Accretion	Remarks point [SV-MV-V-NV]
Crop	***	**	***	***	*	**	***	---	4-2-1-1
Fishery	**	*	*	**	**	*	*	---	0-3-4-1
Livestock	**	**	***	---	---	*	***	---	2-2-1-3
Infrastructure	*	**	---	---	**	*	*	***	1-2-3-2
Industry	**	***	**	---	**	*	*		1-3-2-2
Biodiversity	**	***	***	---	**	---	---	*	2-2-1-3
Health	***	*	***	---	**	---	**	---	2-2-1-3
Human Settlement	---	---	---	---	---	---	***	***	2-0-0-6
Energy	**	*	---	---	*	---	*	---	0-1-3-4

Severe vulnerability (***)[SV]; Moderately vulnerable (**)[MV]; Vulnerable (*)[V]; Not vulnerable (---)[NV]
Source: MOEF (2005)

In Bangladesh, HYV rice is an important food grain that is being produced most frequently. However, an increased level of loss in HYV rice yield has been evident in the past several years because of climate change (BBS, 2011). Figure 2.4 depicts that compared with 2005-06, the amount of this damage doubled from 2006-07. In the next years from 2007-08, the quantity of the damage decreased slightly but followed an increasing trend in the next two years from 2009-10. Recently, in 2011-12, the quantity of the damage in HYV rice yield increased again. These trends indicate that frequent changes in the climatic condition create uncertainty particularly in HYV rice yield and potentially create such uncertainty for other crops as well.

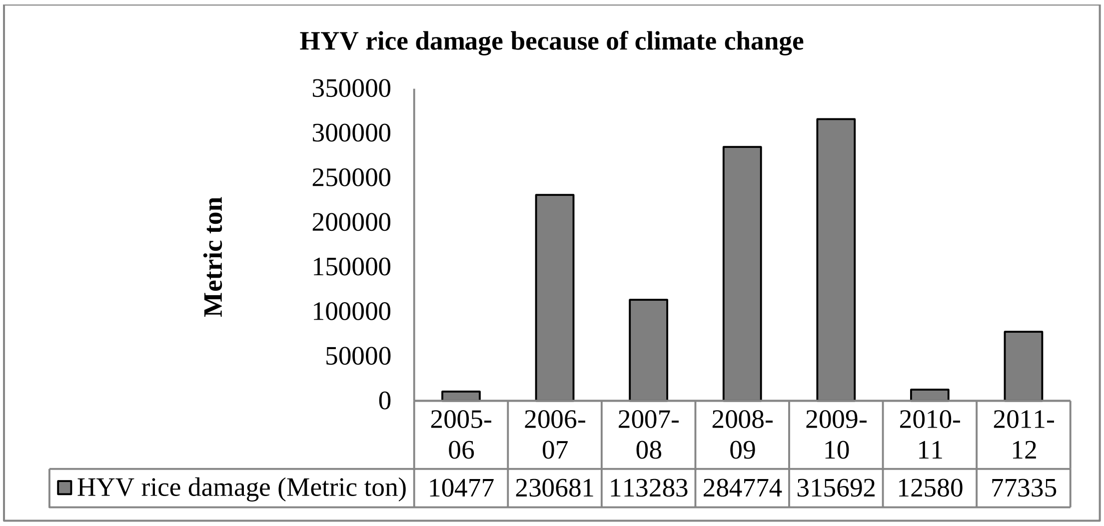

Figure 2.4: Bangladesh's HYV rice damage in previous years from climate change (BBS, 2011)

2.4 Bangladesh's rice agriculture: Analyzing statistical trends

2.4.1 Growth rate of rice crop yield

Because of Bangladesh's agriculture-based developing economy, it is economically desirable and ecologically preferential for Bangladesh to maintain a consistent pattern of the rice yield rate across several crop years. In this regard, increasing the rate of growth of the yield rate is the prime condition to ensure such consistency concerning sustainability in rice agriculture. However, a trend in the percentage changes of the annual yield rate data of Bangladesh's rice agriculture reports inconsistencies through previous crop years (Table 2.9). Figures 2.5 (a), (b) and (c) depict this inconsistent trend of the rate of rice yield growth. Specifically, the Aman variety shows a drastic tendency to decrease (Figure 2.5-a), whereas the Boro variety increased slightly after following a declining trend for three successive crop years (Figure 2.5-b). The Aus variety of rice began with a decline in the percentage change in the yield rate and increased in the following crop year. This increasing trend did not continue but rather declined considerably in the next two years (Figure 2.5-c).

Table 2.9 Bangladesh rice crop yield rate: Percentage change over previous years

Crop Year	2008-09 to 2009-10	2009-10 to 2010-11	2010-11 to 2011-12	2011-12 to 2012-13
	Percentage	Percentage	Percentage	Percentage
Variety				
Broadcast Aman	(+) 4.13	(+) 0.25	(-) 1.39	(+) 0.68
T. Aman	(+) 6.11	(+) 2.84	(-) 0.40	(-) 1.48
HYV Aman	(+) 1.63	(+) 4.25	(+) 1.10	No change
Total Aman	**(+) 11.87**	**(+) 7.34**	**(-) 0.69**	**(-) 0.80**

Local Boro	(+) 12.30	(+) 2.50	(-) 5.76	(+) 7.51
Hybrid Boro	(+) 2.62	(+) 1.17	(-) 1.40	(+) 0.37
HYV Boro	(+) 1.85	(+) 1.71	(+) 0.29	(+) 1.31
Total Boro	**(+) 16.77**	**(+) 5.38**	**(-) 6.87**	**(+) 9.19**
Local Aus	(-) 1.68	(+) 6.68	(+) 3.29	(-) 0.93
HYV Aus	(-) 3.19	(+) 7.73	(+) 5.68	(+) 0.13
Total Aus	**(-) 4.87**	**(+) 14.41**	**(+) 8.97**	**(-) 0.8**

Source: BBS 2009-13, Annual Reports on Estimates of Bangladesh Rice Crop

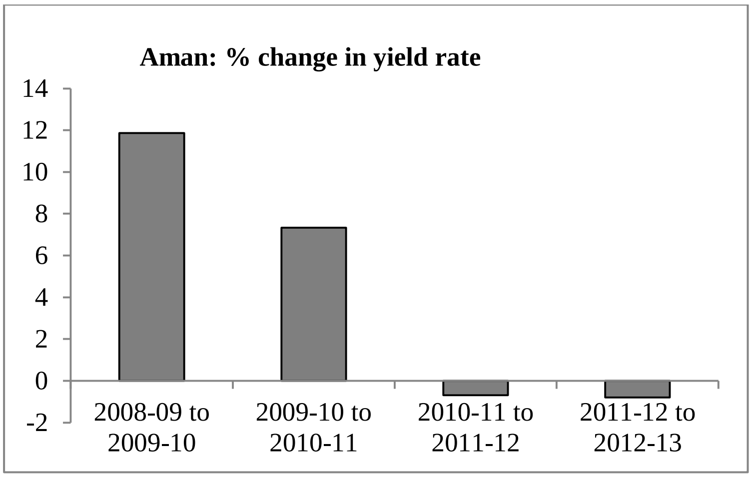

Figure 2.5-a: Percentage change in annual yield rate, Aman rice

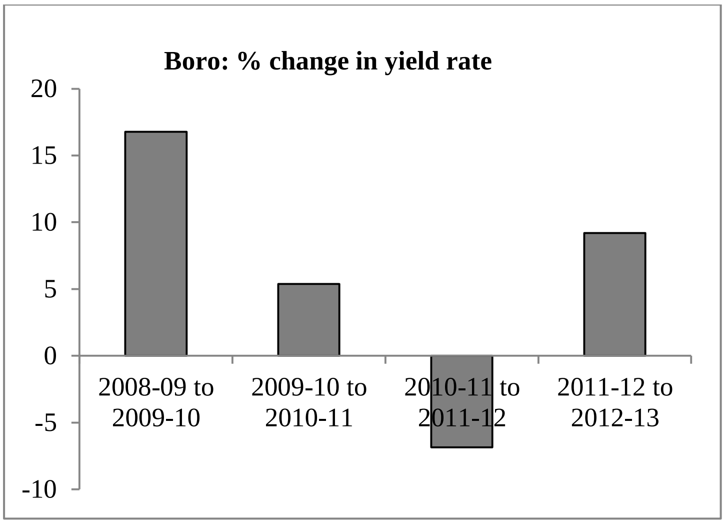

Figure 2.5-b: Percentage change in annual yield rate, Boro rice

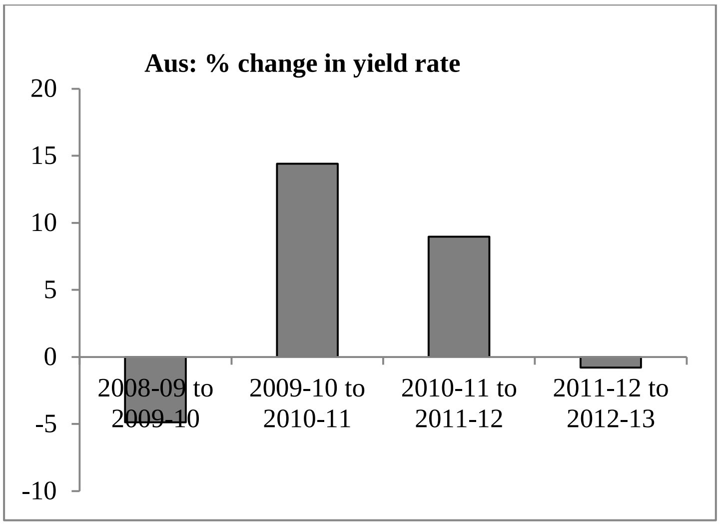

Figure 2.5-c: Percentage change in annual yield rate, Aus rice

2.4.2 Irrigation in rice agriculture and ground water depletion

Bangladesh has abundant water during the wet season. However, the scarcity of groundwater is a major challenge that appears during the drought season and in dry areas because of extensive irrigation practices. As one of the most important practices of modern agriculture, irrigation plays a vital role. Irrigation development has been the primary instrument for accelerating cereal production, such as HYV rice, to achieve food self-sufficiency and, therefore, sustainability in agriculture. The country's irrigation development started in the late 1960s in a major push to promote the 'green revolution'. The program initiates large scale groundwater extracted irrigation by installing shallow tube wells (STW), deep tube wells (DTW), and lifted surface water by low lift pumps (LLPs). In 2012, irrigation through surface water sources covered 21.31 per cent of the total irrigated area, and the remaining 78.69 per cent used ground water sources (BADC, 2012). This large-scale ground water extraction results in lowering the water table and is deteriorating to the ability of irrigation to sustain HYV rice production in the long term.

In Bangladesh, the water table goes beyond the suction limit of the STWs (7 meters) and the DTWs (11 meters) during the drought season and in dry areas. The ground water monitoring that was conducted by the Automatic Water-Level Recorder (AWLR) shows that the water table is gradually decreasing across several irrigation fields (BADC, 2012). For example, in 2010, 17 per cent of the total number of tested water stations was found with a ground water table that is more than 11 meters below the surface. Favorably, this percentage falls to 14 in 2011 and stays the same in 2012. However, ground water tables that are 10 meters below the surface are recorded in many areas of Bangladesh along with the study areas (Table 2.11), which is considered a critical level (Table 2.10). This trend in water table depletion is because of continuous large-scale irrigation and water extraction by DTWs from ground water sources. A study by Shamsudduha et al. (2009) found that groundwater levels are declining by 0.1–0.5 meter per year in the north-central, northwestern, and southwestern areas of Bangladesh where the intensive extraction of groundwater is conducted for dry season rice cultivation. Among different methods of irrigation, the cultivation plots that operate under power pumps and DTWs and STWs are increasing. However, the use of traditional sources for irrigation-fed rice crops followed an increasing trend that was followed by a decreasing trend across the past 7 years (Table 2.12). This trade-off between increasing trends in mechanized irrigation practices and the decreasing use of traditional sources indicates the potential for ground water depletion.

Table 2.10 Ground water table tested across various water stations in Bangladesh

Years	2010		2011		2012	
Ground water level	(%)	Total	(%)	Total	(%)	Total
Less than 7 m	51	90	51	75	55	86
7-11 m	32	56	35	53	31	49
Above 11 m (critical)	17	28	14	21	14	21
Total no. of stations tested	100	174	100	149	100	156

Source: BADC, 2012

Table 2.11 Ground water table in study regions: Dry season (April-June)

Regions/Districts	AWLR installed stations (Unions)	2010	2011	2012
Rajshahi	Paba	12.24 m	12.74 m	11.98 m
	Bagmara	14.74 m	14.58 m	14.73 m
Pabna	Bera	11.38 m	11.25 m	11.27 m
	Atgoria	11.15 m	10.26 m	10.38 m
	Chatmohor	12.00 m	12.20 m	12.70 m
Natore	Singhra	10.58 m	10.55 m	9.93 m
	Natore	10.05 m	10.45 m	---

Source: BADC, 2012

Table 2.12 Area irrigated by different methods for rice agriculture (in thousand acre)

Years	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	Trend
Power pumps	1940	1982	2191	2371	2560	2696	2702	Increasing
Tube wells (Deep & Shallow)	9177	9252	10583	11161	11623	12129	12619	Increasing
Traditional	718	1207	1068	1037	963	871	875	Increasing

Sources*		followed by decreasing

*Figure includes Doons, Swing baskets & others
Source: BBS, 2010

In agricultural activities, extensive irrigation is not the only threat to natural resources such as water. The continuous use of farm chemicals can also potentially pollute agricultural water sources even more. For instance, a project report on Bangladesh's irrigation water quality shows that a considerable amount of damage has been done to the various water sources that are used for agriculture (BADC, 2012). In the Rajshahi district, one of the study areas, the average total alkalinity content that was found in DTWs sources is 312 mg/l, which is higher than sources such as STWs. However, DTW sources' alkalinity content was found as 350 mg/l on average in this district. Unexpectedly, all of these values are higher than the drinking and irrigation limits that have been established by irrigation water quality standards (Ministry of Environment and Forest, GOB, Water Quality Standards for Drinking and Irrigation by Bangladesh Gazette Notification in 1997). The average level of harmful Nitrate and Phosphate content in various water sources has also been reported to be above the drinking and irrigation limits. Moreover, the 'hardness' level of different water sources in the Rajshahi region has also exceeded the drinking limit and remains approximately 100 units below its irrigation limit (Table 2.13)

Table 2.13 Irrigation water quality test: Rajshahi district

Water Sources	Hardness (mg/l)			Nitrate (mg/l)			Phosphate (mg/l)			Total (mg/l)	Alkalinity	
	Average	DL	IL>	Average	DL	IL>	Average	DL	IL	Average	DL	IL>
DTW	209	200	300	20	10	10	32	6	10	312	100	100
STW	202	200	300	20	10	10	21	6	10	264	100	100
HTW	208	200	300	20	10	10	24	6	10	350	100	100
Pond	147	200	300	20	10	10	22	6	10	180	100	100

Note: DL: Drinking Limit; IL: Irrigation Limit; >: Greater than
Source: BADC, 2012

2.4.3 Soil erosion and land degradation in HYV rice agriculture

In agriculture, the removal of topsoil from a certain piece of farm land because of agricultural activities is defined as soil erosion. These activities include irrigating water, operating tractors for land preparation and using other farm machinery for cultivation purposes. FAO (2013) considers erosion a natural process; however, its rate can be greatly influenced by human activities, especially through agriculture and deforestation. Bangladesh is ranked 3rd among south Asian countries in the extent of soil erosion (FAO, 2015). The Global Assessment of Human-Induced Soil Degradation (GLASOD) identifies 5.0 degrees of land degradation and finds Bangladesh has a degree of 2.61 (FAO, 2015), i.e., it has a moderate to strong extent of soil erosion. The GLASOD explains countries such as Bangladesh, which has such a significant extent of soil erosion and land degradation that it is experiencing a drastic reduction in agricultural productivity and must restore the original biotic functions that have largely been destroyed. Particularly, the potential for erosion-induced land degradation is high in HYV rice agriculture in Bangladesh because it requires extensive irrigation and chemical fertilizers to grow. Moreover, the overgrazing and mechanized tilling that are involved with these chemical-intensive and irrigation-based farming practices leave the soil exposed and aggravate the land degradation condition of Bangladesh's agriculture.

2.4.4 Trends in rice price

To assess the status of the economic sustainability of rice agriculture, it is useful to read the level of output price, its annual trend and its seasonal pattern. Specifically, for rice crops, a satisfactory farm harvest price will definitely inspire and encourage marginal farmers in developing nations such as Bangladesh. A satisfactory price can be an important influencing factor on Bangladeshi rice paddy farmers to behave more environmentally, economically and socially. The 'harvest'-level output price is more effective than the 'wholesale' or 'retail' price level in determining farmers' economic motivation and environmental performance. In practice, these prices can enhance farmers' willingness to follow sustainable farming practices. Frequent fluctuations in farm harvest price levels have been evident for Bangladesh's rice paddies in the past 30 years. Consequently, this fluctuating trend in annual output price will potentially work against economic sustainability in rice agriculture. Moreover, an oscillating pattern of the annual rate of change in the harvest-level output price can discourage farmers to improve their environmental performance and also work against environmental sustainability in agriculture (Figure 2.6).

Thirty years of data on Bangladesh's rice statistics shows that the farm harvest price has always remained at a half point below the wholesale and retail prices (Figure 2.7). In 2007, the average farm harvest price was BDT 10,540 per ton, whereas it was BDT 19,445.83 for the wholesale price and BDT 20,603.33 for the retail price

(IRRI, 2013). An indiscriminate pattern of output price in three successive market phases might disrupt economic sustainability in Bangladesh's rice agriculture.

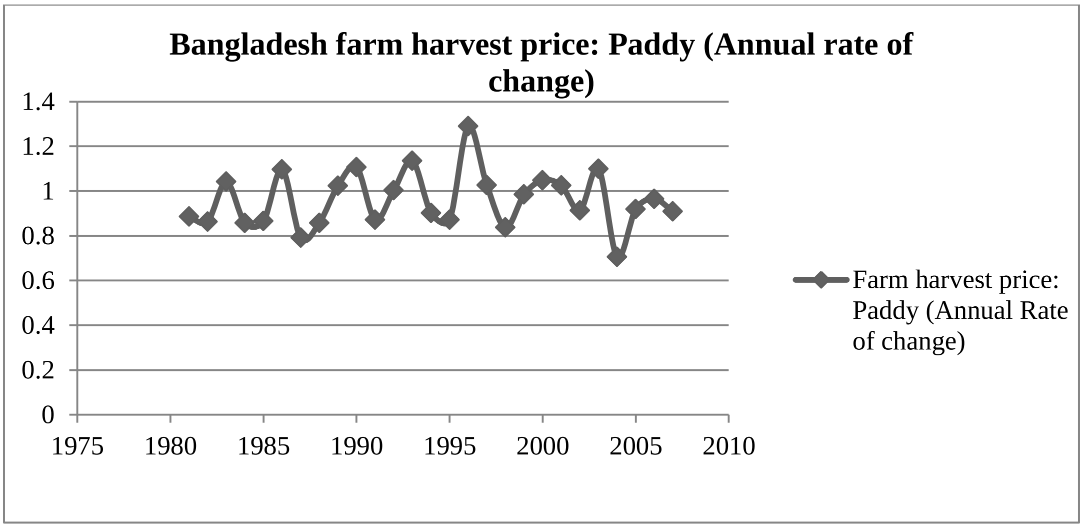

Figure 2.6: Annual rate of change in farm harvest rice paddy price (IRRI, 2013)

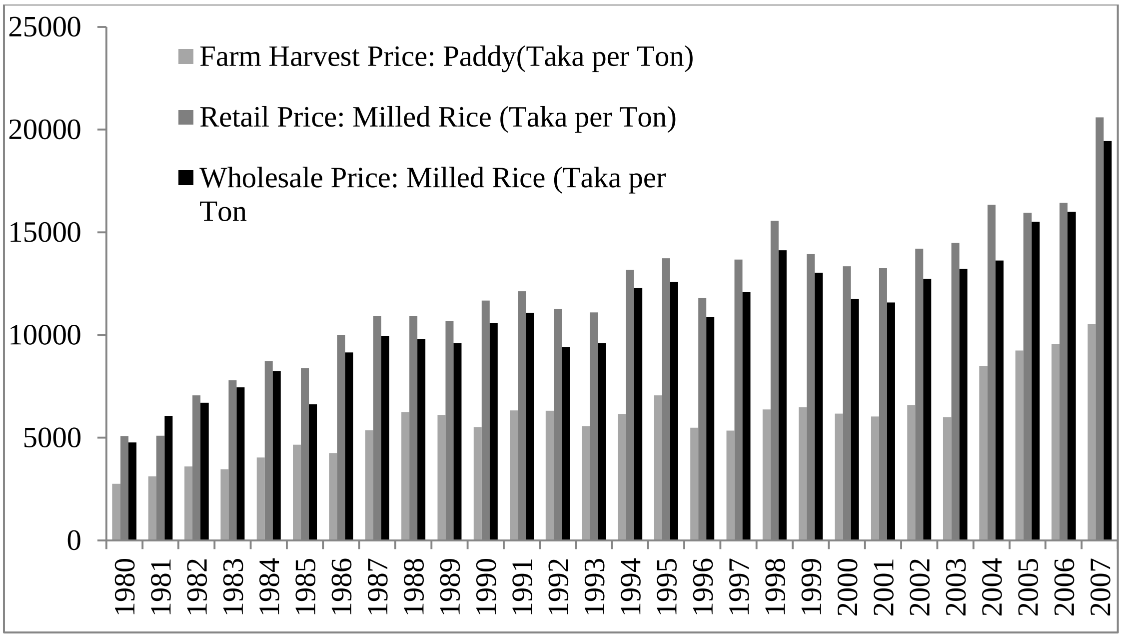

Figure 2.7: Farm harvest, retail and wholesale prices: Bangladesh rice paddy (IRRI, 2013)

2.4.5 Export-import scenario: Bangladesh's rice crop

In Bangladesh, the export value that is realized by selling rice crops in foreign countries has always been lower than its import value. The year wise trends of the country's rice crops' export-import values are represented in Table 2.14. Compared with the previous ten years, the highest amount of money was spent on rice crop imports in 2011. Moreover, a drastic fall in export values was also observed in a recent period of one year, from 2010 to 2011. Bangladesh does not achieve food self-sufficiency in general (Figure 2.3) and also faces an increased level of difficulties to attain self-sufficiency in its staple food grain, i.e., rice. These difficulties increase the country's dependency on imports for rice supply and therefore indicate unsustainable conditions in rice production.

Table 2.14 Export and import trends: Bangladesh's rice crop

Years	Export quantity (thousand ton)	Export value (thousand US $)	Import quantity (thousand ton)	Import value (thousand US $)
2011	1.14	825	1,308.62	637,221
2010	3.86	2,926	679.60	273,723
2009	4.96	3,455	40.24	14,116
2008	8.46	7,063	838.71	289,175
2007	18.55	5,973	615.84	155,419
2006	16.11	6,034	577.06	62,408
2005	4.51	4,054	705.14	135,307
2004	0.36	238	991.44	211,464
2003	0.35	188	1,250.71	219,575
2002	0.56	242	943.36	146,030
2001	1.50	400	152.13	22,420
2000	0.70	500	452.12	64,069

Source: IRRI, 2013

2.5 Conclusion

Sustainability in agricultural production through proper management practices is conditional on time, but once it is achieved and maintained for a long time, is a major development feat. Accordingly, this chapter has explored the sustainability status of Bangladesh's agriculture and identified rice as one of the most important crops, which involves agro-ecological, agro-economic and socio-agricultural impacts that affect sustainability. The natural resource degradation that is particularly influenced by HYV rice cultivation causes the potential for ecological and economic unsustainability in agriculture. Conversely, environmental impacts such as climate change along with soil- and water-related impacts can widely influence farmers' cultivation attitude and farming practices, which initiates social unsustainability in Bangladesh's agriculture. Farmers have a vital role to play in creating a sustainable agricultural system. Farmers who effectively manage their resource allocation decisions in the production process are able to alter the yield level, resource conservation and their economic welfare. This effective management will help the country's agricultural sector achieve a sustainable condition.

Considering the unsustainable condition of Bangladesh's agriculture and the importance of farmers' participation in managing agricultural sustainability, this thesis focuses on the analysis of the environmental impact of HYV rice agriculture and farm-level environmental performance. Therefore, the subsequent chapters address the design of appropriate research methodologies, conduct surveys, analyze the data and derive the policy implications.

CHAPTER THREE

Research design and data

3.1 Introduction

This chapter briefly outlines a research design that explores the research issues that was identified at the end of the previous chapter. Section 3.2 portrays the overview of the research design that is used to analyze the environmental impacts of HYV rice agriculture in Bangladesh. Section 3.3 exhibits the physiographic condition of the study area. The agro-ecological zones of the study area are also explained here in terms of agricultural prospects, the cultivation suitability, and the characteristics of the climatic conditions. This section also identifies HYV rice as the most cultivated food grain in these areas. The sampling and population of the study area and the data source and questionnaire formulation methods are explained in Section 3.4. The chapter ends with conclusions in Section 3.5.

3.2 Research design: An overview

Designing empirical research primarily concerns assessments of the knowledge claims that are being conveyed throughout the study. It also concerns the general procedure of the inquiry and the detail procedure of the data collection and data analysis that are going to be used. Quantitative and qualitative methods, the two broad research approaches in conducting empirical research, combine each of the above three elements of research design in specific ways (Creswell, 2013). From the perspective of these three elements, a researcher can analyze the advantages and suitability of a given approach over other approaches and choose the appropriate one. Ideally, this process helps the selected research approach interpret the processes of research design that identify a practical grounding of the philosophy behind the research.

Considering the basic elements of a research design (i.e., knowledge claims, strategies and methods of data analysis) and their specific ways of exposition for respective research approaches (i.e., qualitative and quantitative), this study selects a quantitative approach. A quantitative approach provides a better illustration of the study objectives and research questions. An overview of the research design for this study is depicted in Figure 3.1. In general, all of the major study objectives are illustrated by using primary-level survey data. For instance, objective I of measuring the extent of environmental impact in Bangladesh's HYV rice agriculture uses on-site soil and water test data. These data are collected during the survey by using scientific soil and water testing instruments on every farm land area that belongs to the respective farmers (or the respondents) (Appendix 3-I). Moreover, the data on farmers' perception-based environmental impact variables are collected by using a well-structured questionnaire during the same survey. The data on the variables such as HYV rice input costs, output prices and farmers' willingness to pay (WTP) for environmental impact-related variables, which refer to objectives II and III, respectively, are also collected in the primary-level field survey by using the same questionnaire. Different methods are used to estimate the collected data set and to illustrate the given study objectives. This study uses the Linear Scoring Function (LSF) and Likert scale methods to measure the index of undesirable output (i.e., the extent of environmental impacts) from HYV rice agriculture. The method of Data Envelopment Analysis (DEA) is used to evaluate farmers' production performance and farm-level environmental performance. The economic valuation of the environmental impacts from HYV rice agriculture is analyzed by using the Turnbull Estimator of the dichotomous choice Contingent Valuation (CV) method.

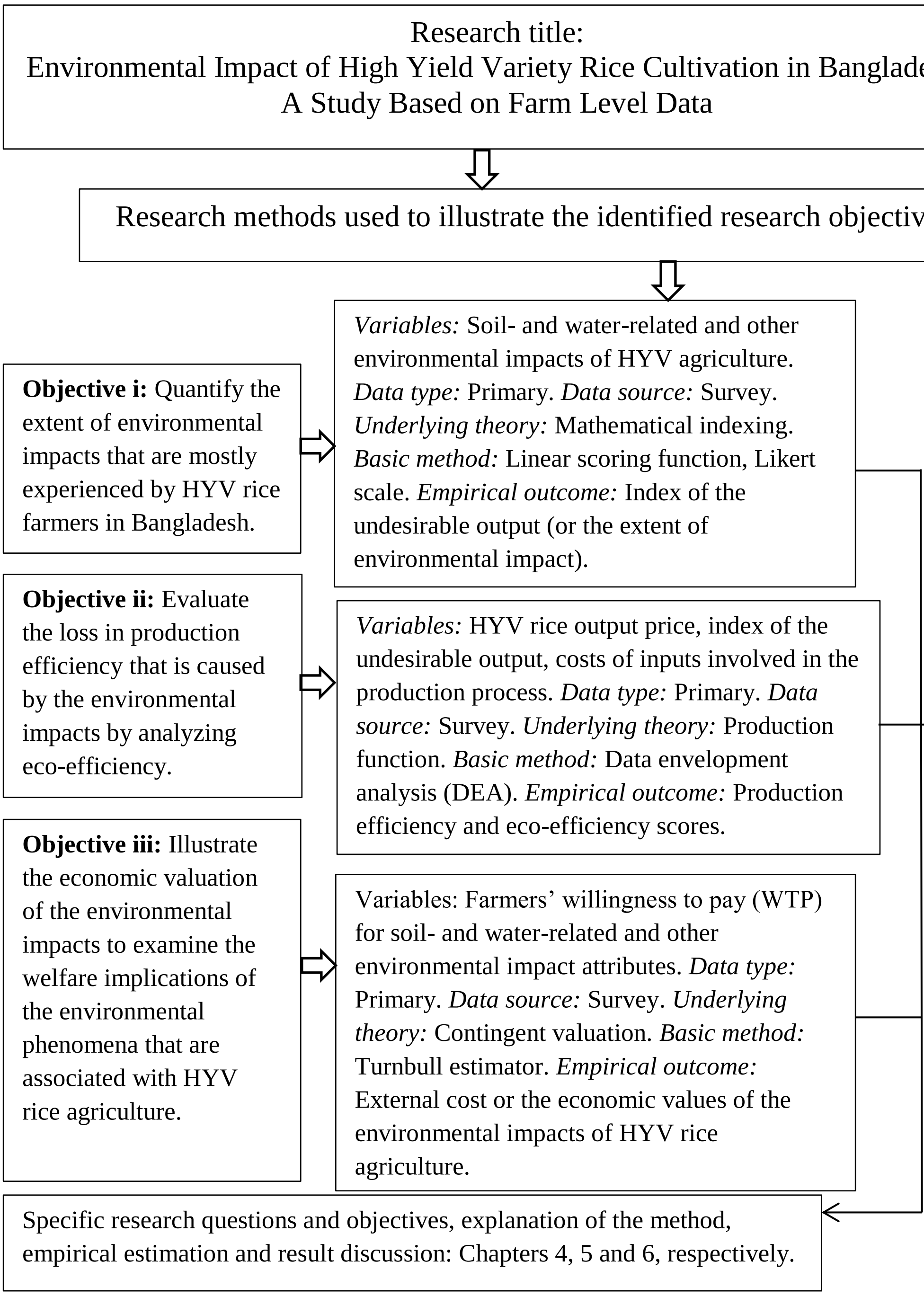

Figure 3.1: Overview of the research design

3.2.1 Linear scoring function (LSF)

Scoring function is a mathematical standardization procedure that is used to convert the measured values or subjective ratings to unit-less values that are usually between zero and one (Kumar and Shivay, 2008). In agro-ecological research, the procedure is generally used to evaluate the soil quality of the crop land. This procedure converts all the physical and chemical property measurements that are used to measure the soil quality into an integrated value or an index form. The following four general types of scoring functions are used to assess soil quality: (i) more is better (a higher measurement means higher quality, e.g., soil organic matter); (ii) less is better (a lower measurement means higher quality, e.g., soil salinity); (iii) optimum range (a moderate range of value is desirable, e.g., soil pH); and (iv) undesirable range (a specific range of value is undesirable).

Tesfahunegn (2014) indicated that this scoring function can be evaluated in a linear or non-linear form. However, linear scoring functions are mostly used and can easily be applied to agro-ecological research. There are three basic approaches to evaluate the linear scoring function. The *first* approach is the 'Liebig Linear Scoring Function' as outlined by Liebig et al. (2001). The approach ranks the soil property measures in ascending order for 'more is better' or descending order for 'less is better' by using all samples. Each indicator measure is then divided by the highest (for 'more is better') or lowest value (for 'less is better') so that this results in a score of 1 or close to it. The *second* approach transforms the soil quality indicator measures into a common range from 0.1 to 1.0 by applying the homothetic transformation equations (3.1) and (3.2) (Velasquez et. al., 2007). Tesfahunegn (2014) calls the approach the 'homothetic transformation method' of the LSF.

$$Y = 0.1 + \left(\frac{x-b}{a-b}\right) \times 0.9 \qquad (3.1)$$

$$Z = 1 - \left(\frac{x-b}{a-b}\right) \times 0.9 \qquad (3.2)$$

where Y and Z are the transformed values of the soil quality indicators, x is the indicator measure to be transformed, and a and b are the maximum and minimum threshold values for the indicator. Equation 3.1 is used for 'more is better' indicator measures, and Equation 3.2 is used for 'less is better' measures of a given soil property. The *third* approach of the linear scoring function, which was explained by Glover et al. (2000) and Masto et al. (2008), uses two equations, 3.3 and 3.4, for the 'more is better' and 'less is better' measures, respectively.

$$(Y) = \left(\frac{x-s}{t-s}\right) \qquad (3.3)$$

$$(Y) = 1 - \left(\frac{x-s}{t-s}\right) \qquad (3.4)$$

where Y is the transformed score, x is the soil property measure, and s and t are upper and lower threshold values, respectively. This approach is the 'Glover Linear Scoring Function Method' (Tesfahunegn, 2014). Because all three methods provide similar soil quality estimates, this study prefers the 'homothetic transformation method' of the LSF considering the type of data that were obtained from the survey.

3.2.2 The Likert scale

In socio-economic and economic welfare research, the idea of measuring unobservable phenomenon, such as an individual's attitude, opinion or perception, is important. One of the most popular methods for this purpose was provided by Rensis Likert (1932). According to Likert, an attitude measurement will be successful when the underlying study dimension has been conveyed to the respondents accurately. The respondents can then choose the response option so that it truly reflects their position in this dimension. This method not is only a simple way of evaluating a specific study criterion but also helps construct multiple-item measures with ease, which are known as **Likert scales**. A Likert scale can measure broader attitudes and values satisfactorily. The idea of a Likert scale that is most frequently used in surveys or research projects is illustrated below.

Table 3.1 Likert scale scoring: The agree-disagree approach

	Disagree			Agree		
Scale of point	0	1	2	3	4	5
Interpretation	None	Very low	Low	Medium	High	Very high
Weights	0	0.2	0.4	0.6	0.8	1.0

Source: Prepared using Likert Scale method

This approach is used by this study to measure HYV rice farmers' environmental perception. Basically, the objective here is to determine perception-based environmental indicator values, i.e., the extent to which a farmer considers a given environmental impact. Therefore, this study chooses the Likert scale, which has been used for decades in various study disciplines. Particularly, for farmers' perception-based impact observations, this Likert scale method helps transform the qualitative data into quantitative measures.

3.2.3 Data envelopment analysis (DEA)

Data envelopment analysis (DEA) is a linear programming-based non-parametric method that is generally applied to estimate production frontiers and, thus, the production efficiencies of decision making units (DMUs). In economics and operational research, research concern remains in evaluating and comparing the efficiencies of different DMUs that are involved in a similar production activity. Because of the presence of multiple inputs and outputs (which are related to production activities, resources and environmental factors) that are present in the given production technology, the basic formula for measuring the production efficiency (i.e., output/input) is inadequate, particularly for an efficiency comparison. For a given type of production activity, DEA satisfactorily measures the relative efficiency of DMUs (e.g., producers) with multiple inputs and outputs and leads to a best-practiced production frontier (Cook et al., 2014) (Detail explanation on the use of this approach for this thesis can be found in Chapter 5, Section 5.5 and Section 5.6). However the method has some limitations too[2].

The measurement of relative efficiency, which was addressed by Farrell (1957) and developed by Farrell and Fieldhouse (1962), constructs a hypothetical efficient unit by seeking a common set of weights for multiple inputs and outputs. Charnes et al. (1978) recognize that DMUs might put different values on inputs and outputs; therefore, each DMU should be allowed to adopt a different set of weights that are more favorable than the other DMUs. Following Dyson et al. (2012) and using the efficiency model according to Charnes et al. (1978), the efficiency of a target DMU j0 can be obtained as a solution to the following problem (Model 3.1), i.e., maximizing the efficiency of unit j0 subject to the efficiency of all units being less than or equal to one (<=1).

$$Max\ h_O = \frac{\sum_r u_r y_{rj0}}{\sum_i v_i x_{ij0}} \qquad \text{..(Model 3.1)}$$

$$s.t.\ \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \leq 1, \{\text{for each unit } j\}$$

$$u_r, v_i \geq \varepsilon$$

$$\varepsilon > 0\ \ (non-negativity)$$

The variables of the above problem are the weights, and the solution produces the weights that are the most favorable to unit j0 and also produces a measure of efficiency. However, the DEA model 3.1 is a fractional linear program. The linear

[2] Since the DEA is good at estimating relative efficiency, it can only explain how well a DMU is doing compared to peer DMUs but not compared to a theoretical maximum. Also, as it is an extreme point technique, researcher should take into acount of the measurement error.

version of Model 3.1 is shown below by using Model 3.2. The notations that are used here are the same as in the article that was prepared by Dyson et al. (2012).

$$Max\, h_0 = \sum_r u_r y_{rj0} \quad \text{...(Model 3.2)}$$

$$subject\, to: \sum_i v_i x_{ij0} = 100 (say)$$

$$\sum_r u_r y_{rj} - \sum_i v_i x_{ij} \leq 0 \;\; (j = 1...n)$$

$$u_r, v_r \geq \varepsilon$$

The measures of relative efficiency of the target DMU and the weights that lead to this efficiency can easily be derived by solving Model 3.2. To obtain the efficiencies of the entire set of DMUs, a linear program that focuses on each DMU in turn must be solved. This calculation will then help inefficient DMUs improve their performance to achieve the best-practiced frontier by changing the current level of outputs or inputs (Seiford and Zhu 2002). For instance, if inefficiency results due to existance of some undesirable factors such as outputs of pollutants or emissions, these undesirable outputs should be minimized. Particularly, in agricultural production, a variety of soil- and water-related environmental problems (undesirable outputs) arise along with the yield (desirable outputs). Therefore, inefficient farms, which would be identified in a DEA exercise, could improve their performance by reducing/minimizing the undesirable output or increasing the desirable output components (Seiford and Zhu 2002). To analyze these types of environmental impact factors (undesirable outputs), this study uses the DEA method and estimates the farm-level eco-efficiencies and production efficiencies.

3.2.4 Dichotomous choice contingent valuation: The 'Turnbull' estimator

The dichotomous choice CV technique is used to measure the value that farmers are willing to pay to reduce a specific farm-level environmental impact. Environmental economists argue that the CV method is the most effective method to evaluate natural resource valuation and an individual's WTP for environmental welfare. Usually, the method requires preparing survey questionnairies and conducting surveys to explore respondents' WTP for environmental impact mitigation and the economic valuation of the WTP (Carlsson and Martinsson, 2001; Abou-Ali and Carlsson, 2004; Carson and Hanemann, 2005; Kallas, 2007). For instance, in agriculture, if a respondent (farmer) agrees to a particular offered bid (t_j| j = 1, 2,…, M) to manage a specific environmental impact, his WTP is greater than or equal to this offered bid. Because the WTP for an improvement in farm-level environmental impacts is unobservable to the researcher in advance, this study uses a distribution-free Turnbull estimator (Turnbull, 1976; Cosslett, 1982) to measure the WTP values. Ideally, the estimator makes minimal assumptions regarding the distribution of the WTP. The estimator assumes to hold monotonic cumulative distribution functions (CDFs) for proposed bids, i.e., as bid amount (e.g., the percentage of farmers' monthly income) increases, the number of 'no' responses to each bid for a given environmental impact increases. Following Haab and McConnell (2002), it is assumed that WTP is a random variable with cummulative distribution function $F_w(W)$. Theprobability of a randomly choosen respondent having willingness to pay less than \$tj can therefore be written as: $\Pr(\mathrm{WTP} \le t_j) = F_w(t_j)(= F_j)$.

Imposing the monotonicity restriction, the log-likelihood maximization problem becomes [3]

$$\max_{F_1, F_2, .., F_M} \sum_{j=0}^{M} [N_j \ln(F_j) + Y_j \ln(1 - F_j)] \text{..} (3.5)$$

subject to $F_j \le F_{j+1} \big| \forall j$

where N_j and Y_j are the number of 'no' and 'yes' responses to the bid t_j, respectively. Following Haab and McConnell (1997, 2002), this study expresses the Turnbull distribution-free estimator and defines the expected lower bound WTP, E_{LB} (WTP), along with the variance of $V(E_{LB}(WTP))$ for M* distinct bids [4] as follows:

$$E_{LB}(WTP) = \sum_{j=0}^{M^*} t_j (F_{j+1}^* - F_j^*) \text{...} (3.6)$$

$$V(E_{LB}(WTP)) = \sum_{j=1}^{M^*} \frac{F_j^*(1 - F_j^*)}{T_j + T_{j+1}} (t_j - t_{j-1})^2 \text{.......................................} (3.7)$$

where F^*_j is the pooled CDF value and $(F^*_{j+1} - F^*_j)$ is the respective probability density function (PDF) of the WTP[5] for an environmental impact, i.e., the Turnbull estimate. By using the data on the proportion of 'no' responses for a given impact, for each of the randomly assigned bid amounts, the Turnbull estimator estimates the CDF followed by the successive PDF. Given the monotonicity assumption, the CDF values that break the monotonic order are pooled with the values from the previous

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[3] The notation and definitions of Equations 3.5 and 3.6 are similar to Haab and McConnell (2002).

[4] M* refers to particular bids after pooling because of the Turnbull monotonicity restriction.

[5] $F_j^* = N_j + N_{j+1} / T_j + T_{j+1}$, where T_j is the total number of respondents who offered the bid t_j.

bid. For a given environmental impact attribute, in a particular study region, Equation 3.6 thus calculates the lower bound WTP, E_{LB}(WTP) (Detail explation and process of calculation of the expected lower bound WTP can be found in Chapter 6, Section 6.7.3).

As a non-parametric estimator, the Turnbull has many of the following theoretical advantages over parametric models[6] (Haab and McConnell, 1997): (i) it provides an empirical distribution function with the necessary information to calculate a lower bound WTP and therefore eliminates the variation because of functional form; (ii) it always results in a positive estimate of WTP and provides an ease of econometric computation; (iii) it can be directly calculated from a data table of bids that are offered to the respondents, along with the number of both 'no' and 'yes' responses; and (iv) it potentially emphasizes the characteristics and implications of the CV questions and responses rather than on its statistical interpretation. As a CV method-based environmental impact valuation study, the WTP Turnbull values are empirically estimated by applying Equation 3.6 separately for different environmental impacts and an overall farm-level environmental impact.

3.3 Physiographic condition of Bangladesh and the study area

3.3.1 Basic geographical features: Bangladesh

Bangladesh is a low-lying, riverine country that is located in South Asia with a largely marshy jungle coastline of 710 km on the northern littoral of the Bay of Bengal. The country is formed by a delta plain at the confluence of the Ganges (Padma), Brahmaputra (Yamuna), and Meghna Rivers and their tributaries. Bangladesh's alluvial soil is highly fertile but vulnerable to flood and drought. Quaternary sediments, which are deposited mainly by the Ganges, Brahmaputra (Yamuna) and Meghna Rivers and their numerous distributaries, cover approximately three-quarters of Bangladesh. Hillocks and hills are confined to a narrow strip along the southern spur to the eastern and southern portions of the Sylhet district and to the Chittagong hill tracts (CHT) in the southeast of the country that border the Indian states of Tripura and Mizoram, as well as Myanmar.

In addition to these physiographic features, Bangladesh has a tropical monsoon climate that is characterized by heavy seasonal rainfall, high temperatures, and high

[6] Parametric models provide inconsistent estimates of expected WTP because they attempt to force a functional form to an unknown distribution function for which we have no prior knowledge of the form.

humidity. A vast diversity in physiographic and topographical features and the climate in a single country makes Bangladesh privileged with an agriculture that is favorable to its unique geographical entity. To analyze the country's physiographic characteristics, this study selects northwestern Bangladesh as the study area. Specifically, the physiographic unit that has the best potential for crop agriculture has been purposely chosen.

3.3.2 Identifying the study area physiography and cultivation suitability

Physiography is the terrain condition of a tract of land and reveals the condition of the surface of land that may vary across a geographical area. In this context, Bangladeshi land can be divided into three major categories of physical units, namely, floodplains, terraces, and hills, and each category has distinguishing characteristics. The physiography of the country has been divided into 24 sub-regions and 54 units (Appendix 3-II) (Table 3.2). Recently, Bangladesh's physiographic pattern and vast alluvial plains in the central, northern and western regions have undergone considerable alterations. The deposition of quaternary sediments has been influenced and controlled by structural activities. The eastward shift of the Ganges and Tista, as well as the significant westward shift of the Brahmaputra, during the past 200 years is evidence of epeirogenic movements even in recent days. According to Brammer (1997), the Northern and Eastern Hills comprise approximately 12 per cent, the terrace areas comprise 8 per cent, and the remaining 80 per cent consist of floodplains. Among the three physiographic units, the 'Floodplain' is the most important unit considering agricultural potentiality. Almost 88 per cent of the net cultivable land belongs to this physiographic unit (Alauddin and Hossain, 2001). In Bangladesh, the Floodplain plays an important role in ensuring economic viability in the agricultural sector.

Table 3.2 corresponds to Appendix 3-II and describes all three physiographic units along with their sub-regions. The major cultivation suitability and difficulties are also explained in Table 3.2 for each respective physiographic sub-region. Unlike 'The Terraces' and 'The Hills', 'The Floodplains' has fourteen basic sub-regions. In general, this unit has a high potential for agriculture. Each of The Floodplains' sub-regions has some cultivation challenges. For instance, flood intensity, late water draining, soil moisture status, river erosion, landslides and severe rainfall may cause cultivation challenges.

Table 3.2 Cultivation suitability in Bangladesh's physiographic units

Units	Legend	Sub-regions	Cultivation Suitability
The Floodplains:	1	i) Old Himalayan Piedmont Plain	Aus, Aman, Boro paddy with irrigation, wheat, mustard, pulse, vegetables. *Cultivation difficulties:* Seasonal inundation to variable depths, dry season droughts, sheet erosion.
	2	ii) Tista Floodplain	
	3	iii) Jamuna (Young Brahmaputra) Floodplain	
	4	vi) Old Brahmaputra Floodplain	
	5	v) Haor Basin	Early mature HYV *boro* paddy may be cultivated with the supply of surface water irrigation. *Cultivation difficulties:* Deep flooding coupled with flash floods. *Kharif* (monsoon) paddy cannot be grown. Late water draining restricts *Robi* crops.
	6	vi) Surma-Kushiyara Floodplain	
	7a-7d	vii) Meghna Floodplain - a. Middle Meghna Floodplain, b. Lower Meghna Floodplain, c. Old Meghna Estuarine Floodplain, d. Young Meghna Estuarine Floodplain	T. Aman in the monsoon and Aus by dibbling method grows in a restrictive order. *Cultivation difficulties:* Severe cyclonic storms, tidal flooding, river erosion limits dry land Robi crops.
	8	viii) Ganges River Floodplain	Aus/Jute followed by Rabi crops; Aus/Jute followed by transplanted Aman and Robi crops; Boro paddy with irrigation are suitable crops and cropping patterns. Wheat, Mustard, Pulse, groundnut, vegetables are grown. *Cultivation difficulties:* **No major cultivation difficulties. Very suitable for crops and pulses.**
	9	ix) Ganges Tidal Floodplain	In deeply flooded areas mixed Aus and broadcast Aman followed by Rabi crops, pulse, etc. In shallow flooded area, long time mature Robi crops. *Cultivation difficulties:* Conditional on flooding intensity, the required time to drain flooded water and the residual moisture status.
	10	x) Sundarbans	Mangrove forests. *Cultivation difficulties:* Regular flooding by tidal waves with brackish water, saline and acidic soil restricts crop cultivation.
	11	xi) Lower Atrai Basin	Aus, Aman, Boro paddy with irrigation, wheat, mustard, pulse, vegetables. *Cultivation difficulties:* No major cultivation difficulties except seasonal flooding in some places and droughts in dry seasons.
	12	xii) Arial Beel	Mixed Aus and Broadcast Aman followed by either Rabi crops or dry season fallow. *Cultivation difficulties:* Deep flooding during monsoons, water remains standing and drains slowly during dry season.
	13	xiii) Gopalganj-Khulna Peat Basin	Local Boro paddy may be cultivated on the margins of the beels.

			Cultivation difficulties: Almost unsuitable for agriculture.
	14	xiv) Chittagong Coastal Plain	T. Aman in the monsoon and Aus by dibbling method grows in a restrictive order. *Cultivation difficulties:* Calcareous alluvium soil, severe cyclonic storm, tidal flooding, river erosion limits dry land Robi crops.
	15	xv) Northern and Eastern Piedmont Plain	Trees, shrubs and poor grasses. Plantation crops consist of timber, rubber, tea, coffee, horticulture fruits. *Cultivation difficulties:* Not suitable for crop cultivation.
The Terraces:	16a 16b 16c	i) Barind Tract ii) Madhupur tract iii) Tippera Surface	On poorly drained sites in Barind tract, single transplanted Aman (monsoon) or Aus (early monsoon) crops. On the well-drained sites of the Madhupur tract, Jackfruit trees and Shal trees. *Cultivation difficulties:* A shortage of soil moisture during winter or dry season restricts Robi cultivation.
The Hills:	17a 17b	Northern and Eastern Hills a. Low Hill Ranges (Dupi Tila and Dihing Formations) b. High Hill or Mountain Ranges (Surma and Tipam Formations)	The natural vegetative cover for this region includes trees, shrubs and poor grasses. Plantation crops consist of timber, rubber, tea, horticulture fruits. *Cultivation difficulties:* Shallow soil underlain by hard rocks and a low moisture level in the dry season, severe rain and occasional landslides and flash floods.

Sources: Based on Hossain (1991); Bramar (1997); Alauddin and Hossain (2001)

With exceptional topographical features, the highest extent of cultivation suitability can be observed in the sub-region of the ‘Ganges River Floodplain’ (Table 3.2). No significant cultivation challenges exist in this sub-region; therefore, it is suitable for a wide range of crop varieties, such as jute, sugarcane, wheat, mustard, pulse, groundnut, vegetables and many other crops. Similar to the other ‘Robi’ season crops, this region is especially suitable for rice paddy cultivation. The topography and the soil property of this area ensure the ability to grow in three seasons Aus, Aman and Boro rice, which are rarely found in all other sub-regions and physiographic units. Therefore, the high cultivation suitability with no usual climatic challenges defines the ‘Ganges River Floodplain’ as the most important agricultural region of Bangladesh.

3.3.3 The study area agro-ecology

The ‘Ganges River Floodplain’ that is identified as the study area covers two climatic zones named Zones D and E (Appendix 3-III). *The Northwestern zone (D)* is characterized by less extreme temperatures and less heavy rainfall. However, the

Western zone (E) that comprises the greater Rajshahi district and parts of adjacent districts is the driest area in Bangladesh with rainfall generally below 1,500 mm. Both climate zones are thus suitable for cultivating irrigation feed crops such as HYV rice and wheat in the dry season. Moreover, in the wet and winter seasons, a wide range of climate-suitable crops and a variety of vegetables are grown here.

To explain this region-specific climatic condition together with its crop cultivation suitability, agro-ecological study classifies Bangladesh into 30 different agro-ecological zones (AEZs) (Appendix 3-IV). AEZs are generally categorized by latitude, elevation, temperature, seasonality and the extent of rainfall during the growing season. The analyses of AEZs are useful because each AEZ exhibits a similar climatic condition and its ability to support rain-fed or irrigation-based agriculture. For instance, most parts of the 'Natore' district, one of the study regions, are characterized by AEZ 5, and the rest of the area contains AEZ 12 features (Table 3.3). Likewise, another study region, 'Rajshahi', comprises the features of AEZs 5 and 11. The 'Pabna' district, which was also selected for this present study, falls under AEZs 11 and 12. Table 3.3 depicts all three AEZs with their names, areas, and land types along with the respective location names (districts) that were purposely chosen. The soil's physical properties in these AEZs and its general feature of chemical reaction are represented in Table 3.4. For instance, the soil in the Lower Atri Basin (AEZ 5) is chemically reactive by nature and predominantly has heavy acidic non-calcareous clay. The Cation Exchange Capacity (CEC) is low to medium in this zone (Appendix 3-V). The CEC depends directly on the soil's organic matter (OM) content (i.e., when there is more clay and OM in the soil, the CEC is higher). OM and other essential nutrients are low to medium in this zone. In general, the CEC of most soils increases with an increase in soil pH. Slightly alkaline soil with higher levels of pH thus influences the CEC in the High Ganges River Floodplain (AEZ 11). However, the AEZ 12, i.e., the Low Ganges River Floodplain, has a high CEC and K nutrients with low to moderate OM content in general. A medium to high level of the CEC acts favorably to reserve essential nutrients in the plant root zone. Silt loams and silty clay loams have a soil texture with neutral to slightly alkaline soil reaction features and considerably represent the AEZs of 11 and 12, which are very suitable for agriculture purposes.

Table 3.3 Study area's agro-ecological zones

AEZ no. and	Area	Land type and	Area name (Districts)

name	Km^2	Hectare	Type**	percentage (%)	
#5 Lower Atrai Basin	851	85,105	MHL MLL LL	8 21 65	Most parts are in Naogaon and Natore*, and small parts are in Rajshahi*, Bogra and Shirajganj.
#11 High Ganges River Floodplain	13,205	1,320,549	HL MHL MLL	43 32 12	Nawabganj, Rajshahi*, Southern Pabna*, Kustia, Meherpur, Chuadanga, Jhinaidah, Magua, Jessore, Satkhira and Khulna.
#12 Low Ganges River Floodplain	7,968	796,751	HL MHL MLL LL	13 29 31 14	Natore*, Pabna*, Goalanda, Faridpur, Madaripur, Gopalganj, Shariatpur, Eastern Kushtia, Magura and Narail, North-eastern Khulna and Bagerhat, Northern Barisal, South-western Dhaka, Munshiganj and Manikganj.

*Districts selected as study areas
**HL: High Land; MHL: Medium High Land; MLL: Medium Low Land; LL: Low Land
Source: Banglapedia, 2014

Table 3.4 Soil physical property of the study area agro-ecology

AEZ no. and name	Soil reaction	Soil physical property
AEZ 5. Lower Atrai Basin	Dark grey, heavy acidic clays predominate and Non-calcareous	Organic matter, CEC and status of essential nutrients are low to medium.
AEZ 11. High Ganges River Floodplain	Slightly alkaline olive-brown silt loams and silty clay loams and Calcareous	Organic matter is low to high, CEC is medium, and K-bearing minerals are medium to high; but the Zn and B status is low to medium.
AEZ 12. Low Ganges River Floodplain.	Neutral to slightly alkaline reaction, dark grey and calcareous brown Floodplain soils, silt loams and silty clay loams to heavy clays and Calcareous.	Organic matter content is low in ridges and moderate in the basins; CEC is high and the K status and the Zn and B status is medium.

Source: Banglapedia, 2014

3.3.4 Rice paddy cultivation suitability in the study area

Rice paddy cultivation suitability in the selected AEZs is depicted well by the Bangladesh Rice Crop Zoning Map that is provided by the Bangladesh Agricultural Research Council (BARC) (Appendix 3-VI). Some locations of AEZs 5, 11 and 12 are very suitable and some are moderately suitable for Aman and Boro rice cultivation and less or unsuitable for Aus rice cultivation. For instance, the BARC indicates that most parts of the selected study regions of Rajshahi, Natore and Pabna fall under the Aman zone 1, Boro zone 1 and Aus zones 3 and 4[7]. Apart from other varieties of Aman and Boro rice, the HYVs of the two rice paddies are mostly grown here in these AEZs. The annual reports on the estimates of Bangladesh rice crops that

[7] As the zone number increases, rice cultivation suitability decreases, i.e., zone 1 implies the highest suitability, whereas zone 4 implies the lowest suitability.

are published by the Bangladesh Bureau of Statistics (BBS) clearly depict that HYV rice cultivation occupies the highest portion of the total cultivation area and remains consistent in each crop year and for all crop seasons in Bangladesh (Appendix 3-VIII). Even the regional-level aggregate data show that this scenario of cultivating more HYV rice also remains consistent in the study areas (Appendix 3-VIII). Except for only the Aus rice in the Pabna district, the area coverage of the HYV rice of Aman, Boro and Aus are higher than the HYV rice of other sub-varieties (e.g., Broadcast, Local transplanted or Hybrid) in the Rajshahi, Natore and Pabna districts. Some of the major factors that influence fertilizer and irrigation-based HYV rice cultivation here are the favorable climatic conditions that prevail during planting and harvesting time, the non-occurrence of natural calamities during these crop seasons, the distribution of fertilizer subsidies and rural electrification for irrigation. Because of these factors, Bangladeshi farmers generally prefer to grow HYV rice rather than other local sub-varieties of Aman, Boro or Aus.

3.4 Sampling

3.4.1 Selection of the specific study area

This thesis selects three northwestern districts of Bangladesh as the study regions, which are named Rajshahi, Natore and Pabna (Figure 3.2). The specific reasons behind this selection are the following:

- These regions belong to the physiographic unit 8, i.e., the Ganges River Floodplain, which is identified as suitable for crops and has no major cultivation difficulties (Table 3.2);
- The AEZs that belong to these regions comprise land levels that are mostly suitable for irrigation-fed HYV crops (e.g., rice, wheat, etc.) (Table 3.3);
- Most parts of these regions have neutral to slightly reactive soil properties and silty clay loams, which are favorable to rice cultivation (Table 3.4);
- HYV rice, one of the major grains, is cultivated in these regions, and the area that is used for HYV rice cultivation has also been following increasing trends in these regions over the past five crop years (Appendix 3-VIII, Table 3A.2); and
- These regions are identified as the Aman and Boro zones for the available HYV rice types, and HYV Aman and HYV Boro are crops that are mostly grown in these regions (Appendix 3-VI).

A total of nine unions, otherwise known as shires (i.e., three unions from each of the three districts of Rajshahi, Pabna and Natore), are selected for field survey purposes (Table 3.5). These unions are the Shilmaria, Deloyabari, Nowpara, Shaikola, Haripur, Bilchalan, Biprobilghoria, Piprul and Madhnagar unions. Generally, agriculture is the main occupation and rice is one of the most important crops that is primarily cultivated by these areas' farmers. Agriculture extension union offices provided me with the list of villages that belong to its jurisdiction. This study performs a detailed discussion with the union extension officers on different agri-environmental attributes of some of the villages that belong to the selected unions. By using the given village list, one village from each of the unions is randomly chosen to sample the respondent's selection (Table 3.5). The names of these villages are Shadhonpur, Dulalpara, Kashipur, Kathenga, Shonaharpara, Panchsoyail, Bashudevpur, Hapania, and Teghoria. Specific reasons for the selection of these villages are as follows.

- These villages have a relatively higher proportion of farm households than other non-agricultural households.
- HYV Aman and HYV Boro rice cultivation are the two most important rice paddy types and are mostly grown here.
- Ground water table depletion problems are often reported by the HYV rice farmers of these villages.
- Pest attacks and crop disease problems along with declines in the expected level of yield have been reported by farmers who cultivate HYV rice here.
- The agriculture extension sub-assistant officers who work in these villages have observed a higher rate of farm chemical application in these areas' farms.

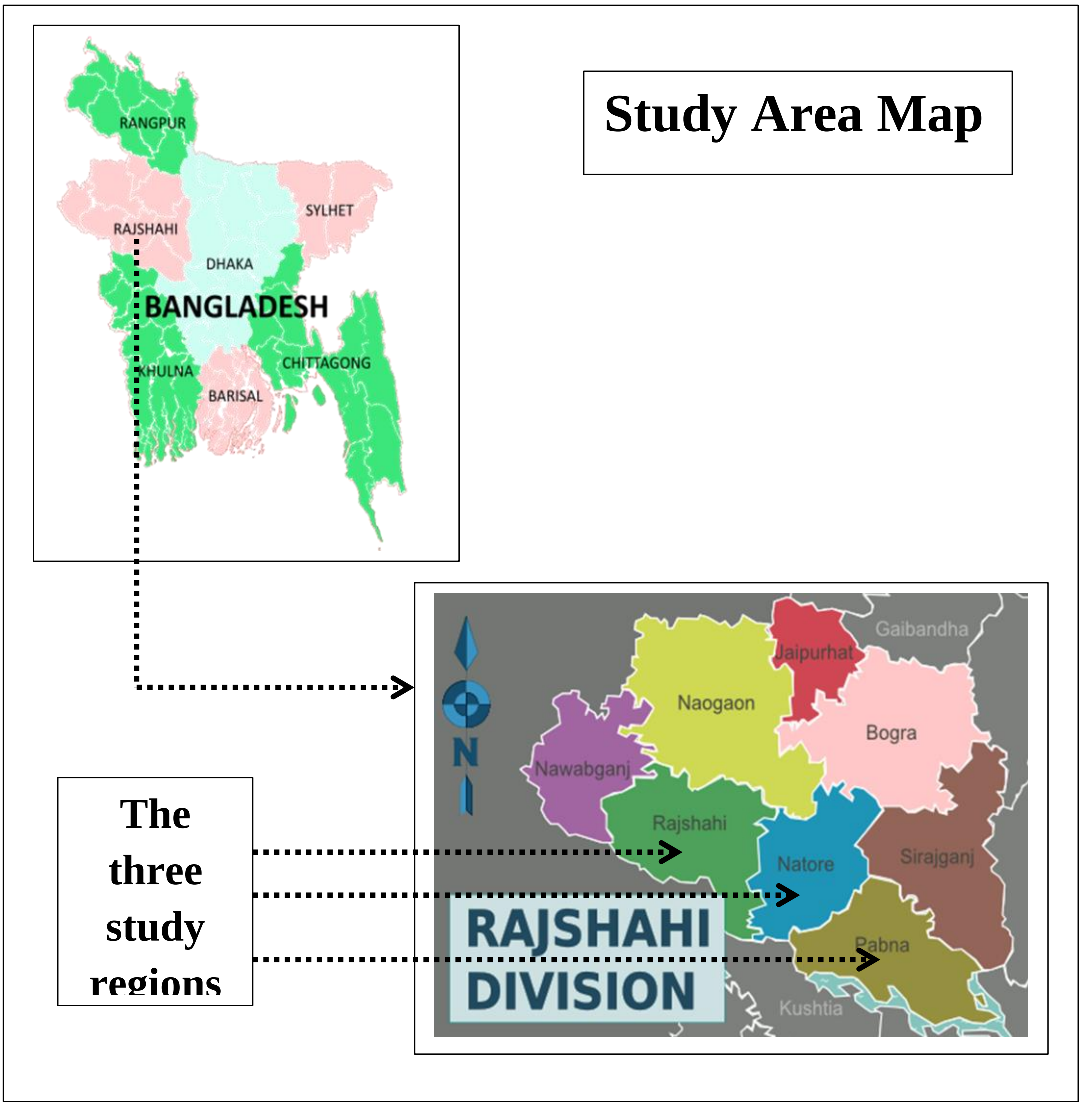


Figure 3.2: Three study regions

3.4.2 Population and data sampling

The total farm households that belong to the selected villages are considered the population for this survey. Then, the required sample size (the number of farmers who are required to be interviewed in the survey) is calculated by using Equation 3.8 (Cochran, 1977).

$$n_r = \frac{z^2 p(1-p)}{d^2} \qquad (3.8)$$

where

n_r = required sample size
$z = 1.96$ (95% confidence level)
$p = 0.5$ (proportion of estimated population that maximizes the sample size)
$d = 0.05$ (error limit of 5 %)

Equation 3.8 derives the required number for the sample size of the survey, which is 384 (three hundred and eighty-four). Therefore, the required sample size for a population of 2,085 is 384. However, Bartlett et al. (2001) mentioned that for survey research, 5 per cent of the population can be regarded as a sufficient sample size. The required sample size (i.e., 384) exceeds 5 per cent of a population of 2,085 (i.e., 105). Following Bartlett et al. (2001) and using Cochran's (1977) correction formula (Equation 3.9), this thesis derives the minimum returned sample size. The final sample size is then 324, which is approximately 15 per cent of the total population. Because the crop lands that are cultivated by these selected villages' farmers or farm households have similar agri-environmental conditions, they are operated by using nearly similar farming practices. This similarity makes the respondent groups homogeneous, which can be considered representative of the entire population (Blaikie, 2009).

$$n_m = \frac{n}{1+(n/N)} \quad \text{...(3.9)}$$

$$= \frac{384}{1+(384/2085)} = 324 \text{(approximately)}$$

where, n_m = Minimum returned sample size required
n = Resulting sample size from equation 3.8
N = Total number of farm households (The population : 2,085)

Therefore, this study attempts to survey 330 randomly chosen HYV rice farms, i.e., 15 per cent of the farm households in each of the selected villages (Table 3.5). From the respective Union Agriculture Extension Offices (UAEOs), the total number of enlisted registered rice farm households for each village is collected. The list of the registered farm households provides the names and addresses of the rice farmers. Afterwards, a computer-generated random number table is used to perform the random sampling that selects 330 farm households for the survey. This study attempts to get back more than 308 samples after performing a data cleaning procedure (Table 3.5).

Table 3.5 Population and the sample size

Regions	Unions	Villages	Number of registered farm households (Population)	Required Sample size (15% of the population)	Number of samples collected
Rajshahi	Shilmaria	Shadhonpur	350	52	55
	Deoyabari	Dulalpara	150	23	25
	Nowpara	Kashipur	240	36	38
		Sub-total	**740**	**111**	**118**
Natore	Biprobilghoria	Basudevpur	250	37	40
	Piprul	Hapania	250	37	40
	Madhnagar	Teghoria	150	23	25
		Sub-total	**650**	**97**	**105**
Pabna	Shaikola	Kathenga	300	45	45
	Haripur	Sonaharpara	227	34	37
	Bilchalan	Panchsoyail	145	21	25
		Sub-total	**695**	**100**	**107**
All regions		**Grand total**	**2,085**	**308**	**330**

Source: UAEOs display board

3.4.3 Survey questionnaire

A well-structured questionnaire is prepared to collect the required information during the field survey (Appendix 3-VII). The questionnaire includes two broad categories; one category is used during the face-to-face interview, i.e., for the respondents' only (part I), and the other category is used by the interviewer only (part II). Part I includes the following information:

- Farmer-specific socio-economic and socio-environmental living attributes, such as farmers' general information, income structure, expenditures on durables, on- and off-farm occupations, living facility and living standard;
- Agricultural attributes that cover three major crop seasons (HYV Aus, HYV Aman and HYV Boro), such as land ownership status, land holdings, costs that are involved with land preparation, irrigation and labor, chemical and organic fertilizers and pesticide application rates and costs, the rice variety-specific yield rate and output price;
- Farmers' awareness and perception of agri-environmental attributes, such as soil-related environmental problems, namely, less fertility, hardness or compactness, erosion, salinity, water logging, water holding capacity problem, and soil reaction, water-related environmental problems, namely, surface and ground water contamination, ground water table depletion, water salinity, and water reaction, the health-related problems of using farm chemicals such as arsenic including skin allergies or irritation, breathing difficulties, etc., farmers'

perception of other environmental problems, namely, crop disease, pest attacks, beneficiary pest extinction, fish catch reduction, etc.; and

- Farmers' willingness to pay for an improvement in specific environmental problems, such as soil- and water-related problems, health-related difficulties and other environmental impacts, and dichotomous choice questions on selected offered bids to obtain an improvement in the environmental impact condition.

Part II of the questionnaire includes the following information:

- The environmental impact measurement in HYV rice fields, such as a farm-specific onsite soil and water test, for example, the crop land's soil test, ground water test (irrigation sources) and surface water test (irrigation drainage reservoirs), etc.

A pilot survey is conducted in Basudevpur village in the Natore district to identify the changes that may need to be made to the prepared questionnaire. The entire questionnaire is then finalized after incorporating several changes that were identified during the pilot survey. Therefore, the final design of the questionnaire is used for the survey's purpose in all selected villages. The survey is administered during the time period of October to December 2013 and covers the information for the past three crop seasons (October 2012-February 2013: HYV Boro; March 2013-June 2013: HYV Aus and July 2013-September 2013: HYV Aman).

3.4.4 Data analysis

Table 3.6 summarizes the statistical data analysis tools and software that are used. After the survey, the completed questionnaires are manually coded for data entry purposes. The data on 330 samples are entered into Microsoft Excel 2010 spread sheets. All the entered data are then cleaned by producing frequency charts, which examine the outliers and identify the samples that have missing information or inconsistencies. In particular, this study finalizes 317 samples for the final analysis. The descriptive statistics, graphs and charts and the task of estimating the environmental impact index and economic values of the environmental farm-level impacts are all performed satisfactorily by using Microsoft Excel 2010. However, command-based software DEAP 2.1 is used to estimate the related farm-level efficiency issues. My study also uses the SATA 11 and SPSS 16.0 software to run regression models (Table 3.6).

Table 3.6 Data that analyze the statistical tools and computer software

Statistical tools	Purpose	Software
Mean, standard deviation,	For analyzing the description of	Microsoft Excel 2010

minimum, maximum, ANOVA	different farm-specific attributes, the variables that are used for model estimation, etc.	
Charts, graphs radar diagrams	For depicting statistical trends of agricultural attributes, regional variations in environmental impacts, environmental impact wise variations in farmers' willingness to pay, etc.	Microsoft Excel 2010
Environmental impact index	For measuring the index of undesirable output (environmental impact) in HYV rice agriculture.	Microsoft Excel 2010
Production efficiency and eco-efficiency scores	For analyzing farmer-specific production performance and environmental performance.	DEAP 2.1
Interval regression model	For analyzing the factors that determine the environmental impact induced loss in production efficiency.	STATA 11
Environmental impact-specific willingness to pay	For analyzing external costs in terms of environmental impacts that are involved with HYV rice agriculture.	Microsoft Excel 2010
Binary logistic regression model	For analyzing the determining factors of farmers' willingness to pay for an environmental improvement.	SPSS 16.0

3.5 Conclusion

This chapter explains the research design that outlines the basic research methods that are applied to illustrate the major study objectives. This thesis applies the homothetic transformation method of LSF and the Likert scale method to measure the environmental impact index. This thesis also uses Data Envelopment Analysis (DEA) to estimate farm-level eco-efficiencies and production efficiencies. Furthermore, this thesis chooses the distribution-free Turnbull estimator that evaluates the economic values of different environmental impacts in agriculture by applying the dichotomous choice CV method and using farmers' WTP information. This chapter justifies the selected study area by analyzing the physiographic and cultivation suitability conditions. Specifically, this study selects the areas that are some of the most important HYV rice agriculture zones in Bangladesh and conducts a primary survey. By using the primary data and following the research design, the next three empirical chapters of this thesis illustrate a comprehensive evaluation of the environmental impacts of HYV rice cultivation of Bangladesh.

CHAPTER FOUR

Environmental impacts of HYV rice agriculture

4.1 Introduction

An analysis of environmental impacts as a measure of environmental sustainability in agriculture is important for managing agricultural sustainability as a whole. Particularly in rice agriculture, environmental impacts largely arise because of chemical-intensive and irrigation-based farming practices. High yield variety (HYV) rice agriculture, as one of the most cultivated food grains in Bangladesh, requires these types of farming practices and creates many environmental problems. The farm-level data in analyzing the extent of the environmental impacts of HYV rice agriculture is helpful in managing farm-level environmental problems and the level of production as well. The measurs of environmental impacts can also be used as an operational tool to evaluate the environmental sustainability of Bangladesh's HYV rice agriculture.

This chapter evaluates the environmental impacts of HYV rice agriculture in three northwestern regions of Bangladesh by using survey data that were collected during the field survey. Section 4.2 reviews the previous literature that has focused on the ecological dimension and has emphasized the use of environmental impacts as an indicator when measuring agricultural sustainability. Section 4.3 specifies the research gaps in the existing literature and is followed by specific research questions. Section 4.4 establishes the specific objectives of this present empirical chapter. A brief overview of the agriculture-environment interactions concept is outlined in section 4.5. This section describes the natural resources that are affected by intensive agriculture such as HYV rice. A conceptual overview of different environmental impact indicator interactions in HYV rice agriculture is also represented in this section. Section 4.6 explains the method design and the suggested approach to measure environmental impacts. Description of the data and analysis of the result are presented in Sections 4.7 and 4.8, respectively. Section 4.9 concludes the chapter.

4.2 Literature review

4.2.1 The ecology and the environment in measuring agricultural sustainability

A wide range of sustainability measurement approaches have been proposed and used by researchers in the previous literature by using the three tiers concept of agricultural sustainability (Figure 2.1). Notably, most of these studies have strongly emphasized a consideration of the ecological and environmental attributes. For instance, to focus on national- and international-level agricultural sustainability issues in developed countries, the OECD (1998) expounded a common framework, the Driving force-State-Response (DSR), with thirteen selected agro-ecological indicators. The FAO (2000), however, proposed five agro-ecological and agro-economic indicators to assess the general situation of agricultural production in developing countries. Except for a few, most of the agro-ecological indicators that were suggested by the OECD and FAO are only suitable for analyzing aggregate-level data that primarily focus on the spatial dimensions (i.e., regional or national perspective) of agricultural sustainability. For agro-ecological research, the ecological and economic sustainability attributes of agriculture are important to analyze. Accordingly, Senanayake (1991) focused on the economic and ecological attributes when analyzing the normative dimension of agricultural sustainability. His article uses aggregate-level national data and does not consider any social attributes as a component of normative dimension analysis.

The importance of the normative dimension of agricultural sustainability has been widely discussed by previous agro-ecological studies and particularly recognized as the most precise way to analyze farm-level local data. Zhen and Routray (2003) proposed the Ecological-Economic-Social (EES) approach concerning the normative dimension and identified fifteen EES indicators. Basically, these authors identified EES indicators that are used to analyze farm-level agricultural sustainability. No measurement method has been developed using the EES approach to measure agricultural sustainability. In contrast, Senanayake (1991) developed the index of ecological sustainability by using some selected parameters and evaluated the relative sustainability of different farming systems. However, he did not incorporate the farming practices for the respective farming systems, which is considered one of the most important bases in farm-level sustainability analysis. Therefore, Rigby et al. (2001) emphasized that the farming practices that relate to environmental indicators is one of the best criteria to evaluate sustainable agriculture. Their analysis proposed farm-level agro-ecological indicators to measure the index of sustainable agricultural practices [SAP] that are based on patterns of input use. These authors discussed the relation between two different farming systems, i.e., organic and conventional, with agricultural sustainability. They found that for some types of input use categories, the impact of organic agriculture on sustainability is six times higher than the impact of conventional agriculture. However, their study concluded that their measured index compared the relative hazards to sustainability that are posed by different farming practices only and should not be regarded as a means to calculate the quantitative impacts of a particular farming system.

In their effort, Stockle et al. (1994) proposed a rational approach to quantitatively evaluate the relative sustainability of conventional and conservation farming systems. Their article provided a conceptual framework that uses nine specific economic, ecological and social attributes. These authors used a Statistical Simulation Modelling [SSM] technique to perform a 100-year simulation of wheat/barley/pea rotation under conventional and conservation tillage. The application of this method revealed that conservation tillage initiates a dramatic increase in the fraction of soil that is covered by crop residues and a proportional reduction in soil erosion by water. This technique is useful to assess the relative sustainability of farming systems; however, it is conditional on a low accuracy.

To obtain more accuracy in analyzing the relative sustainability of farming systems, Oliveira et al. (2013) proposed an indigenous development scheme [EDS]. Their proposed EDS is executed by farming families as a local initiative that reflects the inventive drive of the farmers against agro-ecological uncertainty. A set of systemic properties that are measured by multidimensional indicators for farming systems was used here to evaluate this scheme. The findings revealed that the innovations encourage improvements in the various components of extensive agri-environmental and social sustainability. The EDS enables more sustainable land use through chemical, physical and biological improvements to the soil in the farming systems that were studied. Concerning social sustainability, the EDS ensures family employment and increased income and improves farmers' resources and their control over them.

Evidently, both farming practices and farming systems must be considered the bases for selecting and analyzing the ecological, economic and social attributes in agricultural sustainability analysis. Rasul and Thapa (2003) successfully incorporated these two important bases in selecting farm-level agro-ecological indicators. Their research exclusively examined and evaluated the environmental soundness, economic viability and social acceptability of both ecological and conventional agricultural systems. By considering the respective farming practices, these authors first measured all relevant indicators of ecological and conventional farming systems. Following this assessment, these authors compared the resulting sustainability trends of the two systems. The findings suggest that ecological agriculture is relatively more sustainable, and it can be economically and environmentally viable compared with the conventional agricultural system. This research study is considered one of the most complete and operational farm-level studies in the agro-ecological research.

The environment and ecology, as one of the most important dimensions, have always been considered, evaluated and incorporated into the studies on agricultural sustainability. Ecologically efficient agricultural technologies that are favorable to natural resource conservation minimize on-farm and off-farm environmental damage and manintain consistent output level over the crop years; certainly help achieve sustainability in agricultural production because natural resources are fundamental to any type of agricultural production system. Many environmental problems are connected to some specific farming practice and some particular agricultural system (e.g., the intensive cultivation practice of the modern agriculture system). The damage that the agri-environment is experiencing, if evaluated quantitatively, can be the best way to get an idea of the present state and the potential to manage agricultural sustainability. Natural and environmental resource conservation in agriculture is thus regarded as prime concern in the present study context.

4.2.2 Environmental impact as an indicator to measure agricultural sustainability

Different types of environmental impact indicators have been reviewed, analyzed and presented in the field of agro-ecological research and sustainability analysis (Table 4.1). For instance, Taylor et al. (1993) proposed the Farmer Sustainability Index (FSI) that selects farm-level agro-ecological indicators to analyze sustainable farming practices. These authors state that agricultural sustainability could be analyzed by the situation whether a farmer use agricultural chemicals and synthetic fertilizers. The FSI accounts for 33 farm production practices in Malaysia. Insect control, weed control, disease control, maintenance and soil fertility management, soil erosion and multiple purpose practices are the five groups that include the 33 respective practices. By analyzing these FSI values, these authors found that farmers are using sustainable insect control measures more and behaving comparatively less sustainably in disease control, weed control, soil erosion and even for maintaining the soil fertility in the study area.

Girardin et al. (2000) also evaluated how farmer's production practices affect agro-ecosystem components in France, but they proposed two types of indicators , namely, the Agro-Ecological Indicator (AEI) and the Indicators of Environmental Impact (IEI). The AEI explains the impacts of a single production practice on all concerned environmental components, such as cropping pattern, crop succession, crop covering, nitrogen fertilization, phosphorus fertilization, organic matter, irrigation, pesticides, and ecological structures. The IEI explains the impacts of all production practices on a specific environmental component such as surface water quality, ground water quality, air quality, soil quantity, soil structure, soil chemical status, non-renewable resources, fauna/flora, and landscape. The AEI may be effective in establishing an agro-environmental control panel for the farm-level analysis.

Dalsgaard and Oficial (1997) analyzed an agricultural system that will generate negative impacts on the environment. Their research evaluated the ecological soundness of an integrated agricultural system by analyzing Agro-Ecological System Attributes (AESA) and using a mass-balance model. Similar to other indicator-based approaches, AESA also incorporates important agro-ecological variables in the context of Philippine agriculture. This study covered one input-related environmental objective (such as land use), one emission-related matter (i.e., nitrifying issues), and two system- and state-related issues (such as agricultural biodiversity and system biomass). The comparative analysis suggested that the farms that are ecologically sound can be productive, profitable, and manageable, given the access to labor and secure tenure.

Similarly, Van Cauwenbergh et al. (2007) focused on the farming system to evaluate the agro-ecological sustainability in Belgium. These authors used a compact hierarchical methodology and formulated an approach called the 'Sustainability Assessment of the Farming and the Environment' (SAFE) to identify and select ecological indicators as the effect of farming activities.

To extend the agro-ecological sustainability analysis, Häni et al. (2003) additionally incorporated economic and social aspects along with ecological and environmental aspects and proposed the Response Inducing Sustainability Evaluation (RISE) approach. For instance, energy, water, soil, biodiversity, emission potential, plant protection, waste and residues are indicators to measure ecological sustainability. The indicators from economic and social attributes such as cash flow, farm income, investments, local economy and social situations are also identified to measure these sustainability dimensions. This study hypothesized higher ‘Sate’ (current condition) and lower ‘Driving force’ (pressures on the farming system) values as desirable. Therefore, this study measured the extent of ecological, economic and social sustainability in a compact mode. These authors tested the RISE to evaluate the actual situation of a farm; they presented a follow up polygon by taking corrective measures and identified the actual one to explain the changes in resulting sustainability.

Vereijken (1997) designed a new method that considers both the integrated and the ecological arable farming systems in Europe. This author first identified the shortcomings of the current farming system in the economic, ecological and social contexts. These shortcomings were transformed into a set of multi-objective parameters (MOP) to quantify them. Basically, this research proposed the MOP method to evaluate the state of the farming system such as landscape quality, natural biodiversity, and air, water, soil and product (food) quality. Although it covers the environmental, economic and social dimensions, the MOP method considers the local effects only and is also conditional on a long time frame for data collection.

To address the same issue of environmental impact on agro-ecological sustainability, López-Ridaura et al. (2005) proposed a different approach called the Multi-scale Methodological Framework (MMF). Their research analyzed the environmental impact management system for peasant agriculture and assessed the agro-ecological sustainability at multi-scale levels (e.g., development agencies, research institutions, NGOs and other stakeholders). Productivity, stability, resilience, reliability and adaptability are five attributes of environmental resource management systems, which are defined concerning different scale and discipline properties. The MMF also presents the strategy to derive site-specific criteria and the indicators of attributes at different scales by performing stakeholder consultations in the respective fields. However, the study did not quantify the indicators at different scales or their relations and trade-offs but only proposed the framework of sustainability assessment on the basis of environmental impact management issues, objectives and constraints.

Mayrhofer et al. (1996) focused on land use intensification and the quality of landscape management as important components of an environmental resource management system. To quantify the indicator, their study evaluated farmer production practices by assigning scores. This method is called ‘Ecopoints’ [EP] and is used to derive an acceptable level of payments to farmers that favor environmental conservation motives. The estimated payment level is expected to inspire both crop and livestock farmers to behave desirably and maintain the landscape quality and agricultural biodiversity in the survey area. The study was initially conducted for agricultural farms in lower Austria; later in 1998, 1,500 farms successfully participated in the implementation project as part of its further implications. However, according to the pollution control theory, paying the polluter to change his or her behavior on environment conserving practices has always been considered a less efficient measure than imposing pollution restrictions (such as pollution tax and or pollution standard) on the pollution/polluter.

4.3 Lacks in existing research

Various types of environmental impact indicators are selected that correspond to different evaluation methods in addressing agricultural sustainability. However, it is difficult to find a universal measurement method that is effective for a set of specific indicators that belong to a given agricultural system or farming practice and that may be useful measuring sustainability in every respect. Binder and Feola (2010) argued that the environmental impact evaluation methods that have been suggested for assessing the sustainability of agricultural systems may have some shortcomings in considering the multi-functionality of agriculture, incorporating multidimensionality, utilizing and implementing knowledge assessments, and/or identifying conflicting goals and trade-offs. Therefore, following Binder and Feola (2010), this thesis explores that some lackings in existing research remain in: (i) incorporating relevant dimentions of sustainaility while formulating environmental impact indicator; (ii) validating environmental impact measurement methods; (iii) considering developing countries (e.g., Bangladesh) as least-focused study areas; (iv) focusing on HYV rice agriculture and its environmental impacts, particularly in Bangladesh; and (v) emphasizing and incorporating farmer’s perception-based environmental attributes into the environmental impact measurement formula and/or method.

- *Incorporating sustainability dimensions*

Previous agro-ecological studies have evidently recognized the importance of analyzing environmental aspects as a fundamental dimension of a sustainability analysis. Different types of environmental attribute groups have been purposely assessed. Notably, the AESA, the SSM and the SAP cover three groups of environmental attributes (i.e., input related, system related and emission related). In contrast, the agro-ecological sustainability indicator was formulated by considering only one environmental attribute group (either input related or system related) in the FEI, SAFE and MMF methods (Table 4.1). Among the methods that are mentioned in Table 4.1, the RISE potentially covers different agricultural sectors such as crop, livestock, poultry and dairy farms in analyzing agro-ecological sustainability; however, it incorporates only two environmental attribute groups. Generally, a set of indicators from each objective group is identified to quantify the extent to which these objectives are attained. The inter-linkages between indicators have rarely been considered, although composite frameworks have been built, for example, in the RISE (Häni et al., 2003).

In assessing environmental impact as an indicator of agricultural sustainability, the scale of effect of the RISE, AESA, EP, MOP, FEI and SAP approaches is for 'local' only. The environmental impact indicators, particularly for a farm-level sustainability analysis, should be applicable to a range of objectives that include the local, regional and global effects. In this regard, the SAFE method is the only study that considers three scales of effect, namely, local, regional and global.

Table 4.1 Review of studies used to asses environmental impact of agriculture

Method name	References	Object focused	Scale	Environmental attribute groups	Target groups/ users	Country focused
Farmer Sustainability Index (FSI)	Taylor et al. (1993)	Cabbage Farm	Local	Input related	Farmers, Policy makers	Malaysia
Agro-ecological Indicator (AEI) and Indicators of Environmental Impact (IEI)	Girardin et al. (2000)	Arable Farm	Local, Global	Input related, System related	Farmers, Farm advisors	France
Agro-ecological System Attributes (AESA)	Dalsgaard and Oficial (1997)	Integrated Farm	Local	Input related, Emission related, System related	Researchers	Philippines
Sustainability Assessment of the Farming and the Environment (SAFE)	Van Cauwenbergh et al. (2007)	Farms in general	Local, Regional, Global	System related	Researchers, Policy makers	Belgium
Multi-scale Methodological Framework (MMF)	López-Ridaura et al. (2005)	Farms in general	Regional, Global	System related	Researchers, Policy makers	Mexico

Response Inducing Sustainability Evaluation (RISE)	Häni et al. (2003)	Crop, Livestock, Poultry, Dairy Farm	Local	Emission related, System related	Farmers	Brazil, Canada, China and Switzerland
Sustainable Agricultural Practice (SAP)	Rigby et al. (2001)	Crop Farm	Local	Input related, Emission related, System related	Researchers, Policy makers	England
Statistical Simulation Modelling (SSM)	Stockle et al. (1994)	Crop Farm	Local, Temporal	Input related, Emission related, System related,	Researchers	America
Endogenous development scheme (EDS)	Oliveira et al. (2013)	Fruit Farm	Local	Input related, System related	Farmers	Brazil
Multi-objective parameters (MOP)	Vereijken, (1997)	Arable Farm	Local	System related	Farmers, Researchers	Europe
Eco-points (EP)	Mayrhofer et al. (1996)	Crop and Animal Farm	Local	Input related, System related	Farmers, Local Governments	Austria

Source: Author's compilation

- *Validating proposedmethod of measuring environmental impact indicator*

In general, a set of indicators from different environmental attribute groups has been identified by previous studies to quantify the impact extent and express the proposed method. Van der Werf and Petit (2002) noted that quantifying a selected indicator is challenging because each indicator can explore an actual evaluation of environmental impact and ensure its applicability, usefulness and robustness. To ensure the evaluation's accuracy, these authors suggested the determining of science-based threshold values to define the environmental impact indicators and their extent.

Most importantly, the evaluation methods that explain in terms of science-based threshold values must undergo a validation procedure. The studies on ecological indicators have also advised the necessity of validation (Girardin et al., 1999; Smith et al., 2000; Vos et al., 2000, Häni et al., 2003); however, they rarely checked their proposed method for methodological validation (e.g., Sharpley, 1995). According to Bockstaller and Girardin (2003), an indicator-based method is considered a valid approach if it is scientifically designed and provides relevant information and is useful to its end users. Specifically in agriculture, it is also essential for a 'valid method' to ensure its experimental applicability in different agro-economic contexts.

- *Bangladesh remains as one of the least-focused study areas*

Following the importance of analyzing the environmental impact of agriculture, the agro-ecological literature that is mentioned in Table 4.1 has widely discussed this issue in the context of both developed and developing countries. However, the country-specific experimental exercise for the proposed evaluation method is performed more frequently for developed nations than for developing countries and less developed nations. Agro-ecological sustainability as a development issue should essentially be analyzed for developing economies. For instance, as an agriculture-based developing country, Bangladesh has been less focused on by the early agro-ecological studies. According to my best knowledge, no previous study has proposed an environmental impact evaluation method that can explore Bangladesh's agricultural sustainability in a comprehensive way.

- *Focusing on HYV rice agriculture and its environmental impacts in Bangladesh*

In analyzing the environmental impact indicators of agricultural sustainability, in most of the previous literature, methods such as RISE, SAP, SSM, AEI and MOP have focused on arable farms or crop farms in general. In other studies, approaches such as FSI and EDS, have selected cabbage farm and fruit farm, respectively, as the object to be studied. However, the rest of the literature that is mentioned in Table 4.1 does not even consider any particular type of farm. The environmental impact indicators and the measurement approaches may vary for different types of crop farms. For instance, the HYV rice crop, which is largely subject to intensive cultivation practices, generates a specific set of environmental impacts and is therefore required to be focused on individually in a separate study context.

In recent years, the most alarming consequence of intensive agricultural activities is that the growth rate in net agricultural production is slowing down. This decline implies that there is a counter effect of intensive agricultural activities on production itself. Both crop production and the quality of the environment are affected by this process. An analysis of the data on yield trends at the district level shows that despite rising input levels, yields have been declining or are stagnant on approximately two-thirds of the area that is planted with HYV rice in the *boro* season during the past decade and stagnant throughout the country in the *aman* season (Alauddin and Quiggin, 2008). The results of long-term trials by the Bangladesh Rice Research Institute (BRRI) also indicate that intensive rice cultivation can result in declining yields, even under good management and with the recommended doses of all nutrients being applied **(**Charkarborty, 2004**)**. The causes of this declining productivity have not yet been fully explored. However, considerable evidence indicates imbalances in nutrient availability as the main cause **(**Charkarborty, 2004**)**. Both the requirements of soil nutrients and the potential for nutrient depletion are far greater in the case of HYV rice than for the traditional varieties. The statistical review that is represented in Section 2.3 also substantiates that Bangladeshi agriculture in general and HYV rice agriculture in particular is not only stagnant by nature but also unsustainable for almost every agri-environmental attribute.

- *Incorporating farmers' perception-based impact attributes*

A farm-level agro-ecological study on environmental impacts essentially requires the incorporation of farmers' perception and awareness of the environmental problems. The perceptions regarding the impact of intensive agricultural practices on the environment may vary among individual farmers, farm sizes, agro-ecological conditions, etc. Some studies have found that farmers perceive soil-related problems with high importance (Wachenheim and Rathge, 2000; Roper Starch Worldwide Inc., 2000), whereas other studies have found that water pollution-related environmental problems is the main problem (Thomas et al., 1996; Wachenheim and Rathge, 2000). However, farmers rarely perceive the risk of the damage to air quality and atmospheric constituents.

Particularly in Bangladesh rice agriculture, the studies on environmental impact have always emphasized investigating farmers' environmental perception (Rahman, 2003, 2005; Rokonuzzaman, 2012; Rakib et al., 2014). However, except for several studies, most of the previous studies have qualitatively analyzed (farmers') environmental perception. For instance, Rokonuzzaman (2012) assessed Bangladeshi rice farmers' opinions on environmental impacts such as bio-diversity, water pollution, pure water shortage, beneficial organism extinction and health hazards by using a qualitative 'agree-disagree' approach. The author revealed that Bangladeshi rice farmers strongly agree that farm chemicals are causing water pollution and beneficiary organism extinction. However, these farmers strongly disagree on the rice monoculture induced pressures on biodiversity and the health hazard risks. Similarly, Rakib et al. (2014) followed a qualitative approach in analyzing farmers' perception of climate change because of the environmental pressure that is created by agricultural production in Bangladesh. The survey of their study found that the farmers feel that the temperature in the study area has increased and rainfall has decreased because of environmental stress. The farmers also feel a rapid change in the climatic condition and consequently, an accelerated change in the crop production rate, their livelihood pattern and their socioeconomic status. In contrast, Rahman (2003, 2005) quantitatively analyzed Bangladeshi rice farmers' environmental perception by using farm-level data. The study measured the index of farmer's environmental awareness by assigning weights to farmers' perception of some specific environmental impacts. The study then incorporated the farmers' environmental awareness index into the profit function as a factor of fixed inputs. However, it is important not only to consider farmers' environmental perception indicator as a factor of production but also to incorporate it into aggregate environmental impact accounting. Accordingly, this study proposes incorporating 'farmers' perception-related' environmental impacts along with 'farming practice-related' and 'farming state or system-related' impact indicators into aggregate impact accounting and in analyzing the production function.

The studies on Bangladesh rice cultivation, production and productivity-related issues, marketing and selling issues and other economic implications of farming activity analysis are numerous in the agronomic research. However, the environmental impact assessment for HYV rice cultivation has always been the least studied issue in this regard. According to my knowledge, no previous study quantitatively evaluates the environmental impacts of intensive agricultural practices in developing countries such as Bangladesh. Therefore, it is necessary to propose a quantitative approach that measures the present state of agricultural sustainability in terms of environmental impacts in Bangladesh. Additionally, to suggest corrective measures for farmers, the proposed method necessarily must be tested in suitable study plots where farmers are practicing intensive agriculture and thus generating considerable potential for natural resource depletion. Therefore, this present thesis addresses the research problem by focusing on (i) defining on-farm environmental impacts and impact groups (ii) formulating environmental impact measurement method (iii) construction of formula measuring impact indicators and (iv) application of the proposed measurement method in developing country contex, e.g., Bangladesh. Hence, this thesis outlines following research questions.

- To what extent does an intensive cultivation practice, such as HYV rice cultivation, cause environmental impacts in Bangladesh?
- How to formulate an indicator-based formula that computes the aggregate extent of the environmental degradation in agriculture?

- How to validate the proposed formula as an indicator-based operational tool for measuring environmental sustainability in agriculture?

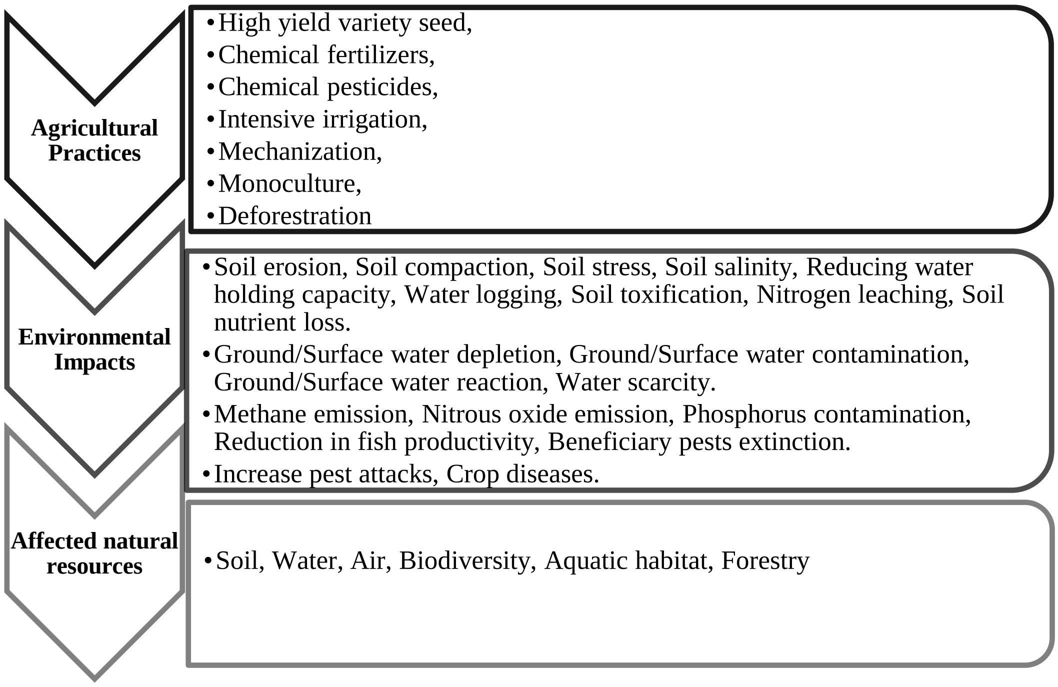
4.4 Study objective

The main objective of this present chapter is to quantify the extent of environmental impacts that are predominantly exprerianced by HYV rice farmers in Bangladesh. Following this main objective and the research problem context (which is discussed in Section 4.3), the specific objectives are to:

- Estimate quantitatively the extent of environmental impacts of HYV rice agriculture in the northwestern regions of Bangladesh;
- Develop a composite environmental impact indicator that incorporates important agri-environmental attributes and measures the environmental sustainability of HYV rice agriculture; and
- Validate the approach so that it satisfies the necessary conditions of indicator validation and is applicable to analyze the environmental sustainability of a given type of farming activity.

4.5 The agriculture-environment interaction: A conceptual overview

Increasing evidence shows that during the past several decades, the environment and natural resources have been affected by agricultural pollution, especially from the widespread use of HYV cereal seeds, such as HYV rice, wheat, maize, etc. A continuous increase in chemical inputs such as nitrogenous fertilizers and pesticides results in the pollution of agricultural land, which leads to declining productivity (Pingali and Rosegrant, 1994). Furthermore, an intensive monoculture practice with chemical fertilizers and extensive irrigation exhaust the soil's organic matter and interrupts a plant's healthy growth (Baker, 1993). Likewise, heavy machinery that is operated on farm land in the presence of irrigation water generates environmental problems such as soil erosion and many more short- and long-term impacts. Agricultural pollution of the soil and water, its emission into the atmosphere, and its negative impacts on biodiversity threaten aquatic life and wildlife habitats (Figure 4.1). Consequently, the resulting potential for declining agricultural productivity makes the global motive to feed the growing population more challenging to achieve.



Source: Bouwer, (1990); Bouwman, (1996); Singh, (2000); Robertson, et al., (2000)

Figure 4.1: Agriculture-environment interactions

4.5.1 HYV rice agriculture and its effects on natural resources

Different types of environmental problems are frequently observed in HYV rice farm areas that operate under intensive agricultural practices. Some of the most common soil degradation problems that HYV rice farmers particularly face are the soil's texture-related, chemical reaction-related and/or physical property-related problems (Table 4.2). For instance, porous or sandy soil, compacted or hard soil, a clay type of soil and erosive soil are texture-related soil problems that may be present in a HYV rice field. Moreover, when large-scale soil reaction occurs by either becoming acidic or its alkaline properties, then farmers face significant difficulties in managing the soil for cultivation. Likewise, salinity and toxicity are two other soil problems that can often be observed where cultivation practices are intensive. However, among these three classifications of soil-related impacts, fertility problems such as soil nutrient loss and nitrogen leaching are mostly experienced by the farmers.

A greater risk of water resource depletion can result from intensive water extraction for irrigation. Undoubtedly, irrigation-fed HYV rice agriculture accounts for the highest percentage of fresh water withdrawals more than any other type of agriculture. A degradation of water resources may be generated in the depletion and contamination of and disturbances in water's physical properties (Table 4.2). For example, a decrease in the ground water table causes water scarcity for irrigation in the long term and makes surface water unavailable thereafter. Likewise, low fish productivity and threats to aquatic or marine life can result from water contamination problems. Therefore, the application of farm chemicals and irrigation are the two most important factors that are responsible for eutrophication, arsenic contamination and other water reactions, as well as ground water source depletion.

Chemical fertilizers, pesticides and modern irrigation-based agriculture are responsible for many emissions that affect the air and the entire atmosphere (Table 4.2). For instance, chemical emissions in the form of methane and nitrous oxide are frequent and most common in chemically intensive irrigated rice cultivation. The potential for chemical pollution that is generated by farm pesticides, herbicides and other medicines that are applied to the field is not minor. Similar to water contamination, chemical pollution influences nature to release ozone depleting gases, acidifying gases and photo-chemical oxidant substances, which contaminate the atmosphere. Atmospheric emissions are the most important spatial issues discussed in the field of environmental economics. Terrestrial and aquatic eco-toxic emissions and human eco-toxic emissions in agriculture are examples of atmosphere-related spatial problems.

Table 4.2 Environmental problems in agriculture

	Soil degradation-related problems	
Texture	• Porous/sandy • Compacted/hard	• Clay type • Erosive
Chemical reaction	• Acidic • Alkaline	• Toxic • Saline
Fertility	• Nutrient loss • Nitrogen leaching	
	Water pollution-related problems	
Water depletion	• Lowering ground water level • Ground and surface water scarcity	
Water contamination	• Low fish productivity • Threatens aquatic habitat • Pressure on biodiversity	
Water physical property	• Water reaction • Eutrophication • Arsenic contamination	
	Atmospheric emission-related problems	
Air	• Methane emission • Nitrous oxide emission • Pesticide emission	
Atmosphere	• Ozone depleting gases • Acidifying gases • Photo-chemical oxidant creating substances	
Spatial	• Terrestrial eco-toxic emission • Aquatic eco-toxic emission	

- Human toxic emission

Source: Prepared following: Bouwer, (1990); Bouwman, (1996); Singh, (2000); Robertson, et al., (2000)

4.5.2 Indicator interactions and counter interactions

A wide range of environmental problems can result directly from agricultural activities. Among them, some problems can also be generated as counter effects. Consequently, these impacts are sometimes the reason for other environmental impacts as well. For example, farm chemicals cause soil nutrient loss, which, in turn, is responsible for soil fertility loss and causes interruptions to a plant's healthy growth. This unidirectional impact generation process can create counter impacts such as crop diseases. Table 4.3 portrays the numerous environmental impacts and counter impacts that result from HYV rice cultivation.

Table 4.3 Environmental impacts and counter impacts that result from HYV rice cultivation

HYV rice cultivation		
Activities	**Direct impacts**	**Counter impacts**
Farm chemicals	Soil toxicity	➢ Health impacts
	Soil salinity	➢ Soil fertility loss
	Nitrous oxide emission	➢ Ozone depletion ➢ Health impacts
	Methane emission	➢ Photochemical smog
	Destroys beneficiary pests	➢ Increased harmful pests
	Loss of soil nutrients	➢ Soil fertility loss ➢ Increased crop diseases
	Eutrophication	➢ Fish catch reduction ➢ Destroys underwater habitat ➢ Pressure on biodiversity
Farm machinery	Lowers soil level	➢ Water logging ➢ Nitrous oxide emission
	Soil erosion	➢ Lowers soil level ➢ Water logging
	Soil compaction	➢ Water logging
Irrigation	Water induced soil erosion	
	Lowers ground water level	➢ Water scarcity
	Dries out soil water layers	
	Dries out top soil	➢ Lowers soil water's holding capacity

Source: Prepared following: Clapham, (1980); Dobbie et al., (1999); Singh, (2000); Lal, (2001); Alauddin and Quiggin, (2008)

Machineries for harvesting and postharvest treatments are frequently used in HYV rice farms. The increasing use of tractors, power tillers, combine harvesters, irrigation pumps and other power-operated machines induce large scale automation but generate many environmental problems in the cultivation of rice and upland crops, seed and seedling production. The frequent use of heavy machinery, such as tractors and power tillers, makes the soil's texture porous and grinds out soil particles more evenly. As a consequence, the soil becomes erosive in texture, which lowers the top soil level in the long term and deprives the soil's water holding capacity. On the contrary, machines such as seeders, weeders and harvesters compress and compact soil particles and result in water logging problems. The use of farm spray tools and pesticide applicators not only induces the potential for atmospheric pollution by spreading into the air but also creates human health impacts.

The continuous and large-scale water extraction for irrigation gradually reduces underground water reserves. A decrease in the ground water table and the installation of high horse powered engines to catch this decline works as a vicious circle. Ground water depletion from successive irrigation causes water scarcity, dries out soil layers and makes the soil's texture rough and erosive. Similarly, surface soil erosion may also be generated because of irrigation water in the form of water induced erosion.

High-yielding crop varieties grow well when they are provided with an adequate and timely supply of plant nutrients, which are supplied mainly in the form of chemical fertilizers. Generally, fertilizers are needed for all types of long-term crop production to achieve a considerable level of yield that makes the effort of farming worthwhile. As a beneficial side-effect of fertilizer application, soil fertility can be improved that results in more stable yield levels and a better (nutrition-induced) resistance to some diseases and climatic stress. However, all the quantities of fertilizers that are applied to the soil are not fully utilized by plants. Approximately 50 per cent of fertilizers that are applied to crops are left behind as residues (Das, 2004). Fertilizers and pesticides in chemical form create soil degradation, water depletion, atmospheric emissions and ecological problems overall. Continuous chemical deposition makes soil toxic, influences the soil's reaction and affects plant growth adversely. The chemical run off with irrigation water into adjacent water sources generates eutrophication that is followed by a loss in fish production. Apparently, the continuous eutrophication because of higher nitrate and phosphate concentrations makes fresh water supply less available in the field area. Eventually, fresh water sources become scarce for further crop cultivation, which results in water scarcity. These threats to aquatic habitat also put pressure on ecological biodiversity. Moreover, the pressure on biodiversity may be aggravated because of beneficiary pest destruction that is caused by chemical pesticide application. In addition, the photo-chemical smog and ozone depleting and acidifying gases that are emitted from farm chemicals not only cause atmospheric pollution but also affect human health adversely (Table 4.3). Obviously, threats to the ecosystem can gradually intensify with the increased use of farm chemicals.

4.6 Method design

4.6.1 Evaluation approach and basis

Many farming system-related impacts can be addressed as the basis for environmental impact analysis. For example, organic farming, chemical-based fertilization farming, conventional agriculture, a monoculture system, integrated farming, farming with a specific indigenous method, etc. may involve different sets of environmental impacts. Previous studies have additionally addressed farming practices such as seeding technology, fertilizer application, pesticide use, tilling practices, and irrigation management as the bases of environmental impact evaluation. It is theoretically presumed that impact evaluation on the basis of both farm production practice and the farming system works effectively because they analyze the local scale of impact (Van der Werf, and Petit, 2002). However, in a farm-level study, environmental impact evaluation on the basis of farmers' perception is particularly considered much more important than farm production practice and the farming system. For a given 'farming system', the farmer exercises 'production practices', generates environmental impacts and thus experiences the resource extraction and pollution problems as well. Therefore, this thesis emphasizes their (farmers') 'perception' of agri-environmental attributes for impact indicator accounting. It is hypothesized that farmers' perception that is measured by analyzing their opinions on environmental impact intensity has a considerable role to play in an agri-environmental sustainability analysis. Following Figure 4.2, the present study assesses the farm-level environmental impacts on the bases of production practices, farming system and the farmer's perception in a composite mode.

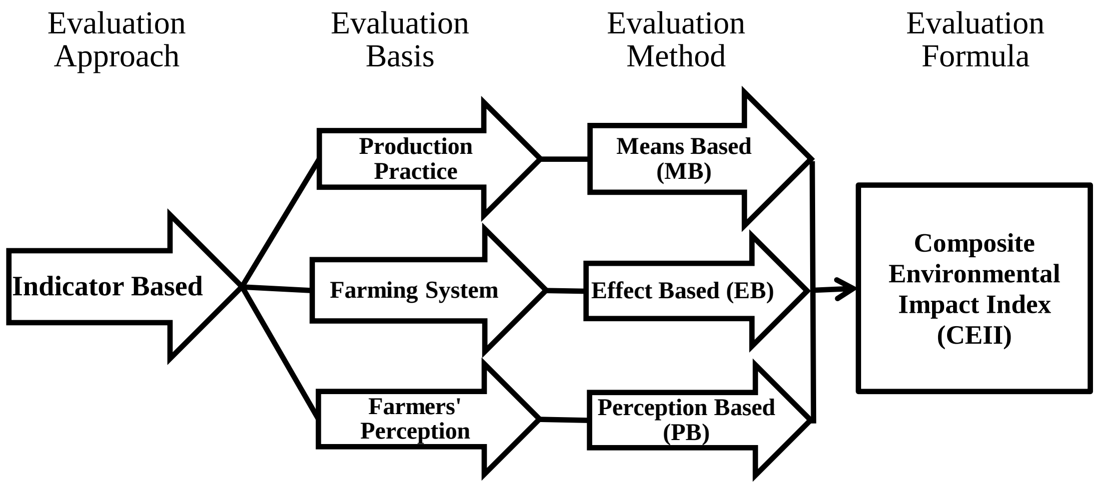


Figure 4.2: Environmental impact evaluation approach

4.6.2 Evaluation method

The agricultural emission and pollution of the environment primarily depend on the state of the farming system. The state of the farming system, in turn, depends to a large extent on farming practices and on climatic factors, such as rainfall and temperature (Van der Werf and Petit, 2002). However, farming practices depend exclusively on farmer's environmental awareness and their perception of the environmental impact of their agricultural activities. Considering all of these interdependent agro-ecological aspects, this study presents an alternative indicator-based composite approach. This approach aggregates a means-based method, effect-based method (Van der Werf and Petit, 2002) and perception-based method as shown in Figure 4.2. The means, effect and perception-based methods consider environmental indicators that relate to farming practices, the farming system and farmers' perception, respectively. For instance, chemical fertilization (e.g., the proportion of applied nitrogen fertilizer to the recommended dose) is considered to assess the nitrogen contamination risk as a means-based indicator, whereas the soil's chemical reactivity, such as soil alkalinity and acidity, is an example of an effect-based indicator. Farmers' perception on experiencing soil fertility loss and health risks because of an increased rate of fertilizer application is considered a perception-based indicator. Accordingly, the proposed environmental impact evaluation approach, which is represented below in Figure 4.3, incorporates the most relevant environmental attribute groups in a composite manner.

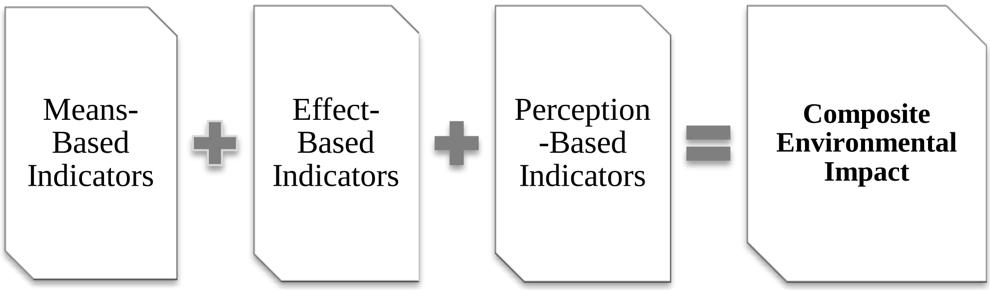


Figure 4.3: Alternative indicator-based approach

4.6.3 Evaluation formula: Composite Environmental Impact Index (CEII)

Environmental impact indicators can be measured by using laboratory or field tested scientific methods that are calculated on the basis of their characteristics or they can be based on expert advice. From the perspective of this measurement approach, Girardin et al. (1999) distinguished two types of environmental indicators. One type is *simple indicators*, which are measured by using a model of an indicative variable, and the other type is *composite indicators*, which are measured by an aggregation of several *simple indicators* (Bockstaller and Girardin, 2003). The present study uses the indicator-based impact evaluation approach and compiles indicatores in a composite mode. Therefore, the model is named the Composite Environmental Impact Index (CEII). Accordingly, the model incorporates three separate types of indicative variable groups or environmental impact indicator sets as simple indicators. Therefore, the compilation of three sets of simple indicators by using the proposed evaluation approach (following the design that is depicted in Figures 4.2 and 4.3) is structured and formulated using statistical additive aggregation procedure (Equation 4.1).

$$CEII_i = \sum_{m=1}^{n} M_m + \sum_{e=1}^{k} E_e + \sum_{p=1}^{l} P_p \quad \text{.......} (4.1)$$

where

$CEII_i$ = Composite Environmental Impact Index of the ith farmer/farm

M_m = Means-Based Indicators (m=1…n)

E_e = Effect-Based Indicators (e = 1…k)

P_p = Perception-Based Indicators (p = 1…l)

4.6.4 Indicator selection

This thesis selects a set of environmental impact indicators that belong to their respective measurement bases and are mostly recognized by the agro-ecological studies on HYV rice agriculture (e.g., Girardin et al., 2000; Rahman, 2005). For Means-Based Indicators, the crop concentration index (CCI), soil stress factor (SSF) and nitrogen risk factor (NRF) variables are selected. These are means-based indicators because the measurements of these indicators are based on farming practice-related attributes. The Effect-Based Indicator group contains attributes such as soil pH (SpH), soil compaction (SCM), soil salinity (SSL), surface water pH (SWpH), and ground water pH (GWpH). These are effect-based indicators because the measurements of these indicators are based on farminng state-related environmental impacts/attributes. A set of environmental impact variables is selected for Perception-Based Indicators, which is proposed as an important component of the CEII. This group includes problems that relate to soil fertility (SFP), soil water holding capacity (SWH), water logging (WLG), water depletion (WDP), soil erosion (SER), pest attacks (PAP), crop diseases (CDP), health impacts (HI) and a reduction in the fish catch (RFC). All of these indicators are called perception-based indicators because measurements of these indicators are based on farmers' perception on environmental impact attributes. Following the proposed approach, the CEII, the selected indicators are then estimated quantitatively by using Equation 4.1.

4.6.4.1 Environmental impact indicators that are evaluated by a means-based method

- The crop concentration index (CCI): A measure of crop diversity

The sustainability of agro-biodiversity largely depends on crop diversification. Crop varieties that take in different types of nutrients in major portions, if cultivated alternatively, can help maintain agro-biodiversity. For instance, the crops that are more efficient in using soil nutrients require less chemical fertilizers. Additionally, pest- and disease-resistant crop varieties can reduce the need for pesticides. Similarly, drought-resistant crop varieties can help save water by reducing irrigation. To increase crop diversity, farmers must focus on how crops interact with one another, the soil, the environment, and the production margins. Ecologically, the reason to increase crop diversity is to create a proper environment for subsequent crops, reduce plant diseases, manage weed populations and lessen the pressure on biodiversity as a whole. This study considers the extent of HYV rice crop concentration as a measure of crop diversity.

Specifically, the 'Herfindahl Index' of crop concentration is used for this purpose (Equation 4.2). The Herfindahl Index estimates the proportion of area that is used to cultivate a specific crop (i.e., HYV rice) relative to the total farming area for a given farm. The index is named after the economist Orris C. Herfindahl and Albert O. Hirschman and is defined as the sum of squares of the cultivated area shares of all crops. Accordingly, the result can range from 0 to 1.0, and estimated values that are close to 1 mean a higher crop concentration, a greater potential for monoculture and a resulting increase in pressures on biodiversity.

$$CCI_i = \sum_{j=1}^{N} s_j^2 \quad \text{...(4.2)}$$

where s_j is the share of cultivated area by crop j in the ith farm concerned, and N is the number of crop varieties that are cultivated. Thus, in a farm with two types of crops, e.g., HYV rice and a non-rice crop, which generally has 80 per cent and 20 per cent of cultivation area shares, respectively, the CCI is equals to $0.80^2+0.20^2 = 0.68$. This result implies that 68 percent of the total cultivated area of the farm is concentrated on HYV rice cultivation. Increases in the CCI generally indicate a decrease in crop diversity and an increase in the concentration of a specific concerned crop such as HYV rice. However, ideally, a decrease in the CCI implies an increase in crop diversity.

- Soil stress factor (SSF): A measure of mechanized tilling impact

Certainly, heavy farm machinery such as tractors, power tillers, and harvesters are responsible for many soil-related problems in HYV rice cultivation (Table 4.3). The potential for this environmental impact may be aggravated when a heavyweight tilling vehicle has been operated repeatedly for land preparation purposes. This machinery is supposed to perform tilling repetition to prepare a compacted surface for planting. However, the number of tilling operations depends not only on soil property but also the capacity of the machine that is used. Tillage hastens the breakdown of organic matter that is needed for good soil structure (Kok et al., 1996).

In Bangladesh, the number of tilling operations for HYV rice bed preparation generally varies from 2 to 6 depending on the type of tilling machine. In my survey, it was also found that farms may use one or two or even three types of tilling methods simultaneously to prepare a specific cultivation bed. Therefore, it is hypothesized that the number of repeat tilling that is required to till a piece of land is less with a tractor than a power tiller. The traditional tilling method that uses machinery such as bullock operated tools certainly requires higher numbers of repeat tilling to prepare the same piece of land. Therefore, my study formulates the soil stress factor (SSF) by calculating the pattern of land tilling practice for a given HYV rice farm as in Equation (4.3):

$$SSF_i = \left[\sum_{t=1}^{3} t\right] \times r \quad \text{...(4.3)}$$

Where, t is the weight values of the tilling machine [i.e., t = Bullock (1); Power tiller (2); Tractor (3)]; r is the number of tilling for land preparation [r = 2, 3, 4, 5, 6]. Therefore, the theoretical maximum value of the soil stress factor that is caused by tilling practice is 36 [sum of all weights (1+2+3=6) multiplied by the highest number of tilling found in the survey (i.e., 6)]. Whereas, the minimum value of SSF is 2 [minimum weight for tilling method used (i.e., 1) multiplied by the minimum number of tilling observed in the survey (i.e., 2)]. Using these threshold ranges between 2 to 36, this study also computed the actual SSF to a normalized SSF impact score by applying the optimum scoring function. [8] Therefore, the normalized score of SSF ranged from 0 to 1 and implies that when the score is higher and close to 1, the impact of mechanized tilling in terms of the soil stress factor is larger.

- N risk factor (NRF): A measure of soil nitrate contamination

Along with other chemical fertilizers, nitrogen fertilizers enable HYV rice farmers to realize higher yields that influence modern agriculture. However, fertilizers are not only effective in driving crop yield in nutrient poor areas but also frequently generates substantial negative impact on the soil. For instance, the application of nitrogen fertilizers if practiced intensively at a higher rate, resulting nitrate contamination would be detrimental to the soil health. More adverse fact is that plants are able to utilize less than one-half of the nitrogen fertilizer applied externally; some of the remaining nitrogen fertilizer leaches into and pollutes the soil, water sources and the atmosphere (Appendix 4-I for the nitrogen reaction cycle in HYV rice fields) and rest of it is supposed to be abated by the environment (Schindler and Hecky, 2009). However, recurrence of such practice in a monoculture

[8] Detail discussion on scoring function can be found in Chapter 3, Section 3.2.1 and following section 4.6.5 of this chapter.

farming system gradually lowers the natural abatement capacity and increases the nitrate chemical load.

In Bangladesh, average use of nitrogen fertilizer is accounted for 251 million metric ton annually, which implies the potential for nitrogen contamination (BER, 2012). Such potential would be higher when farms apply Urea and/or NPKS (mixture of basic fertilizers for HYV rice) fertilizers that exceed the recommended dose. Following this idea, the study surveys the actual dose of nitrogen fertilizer that is applied for HYV rice cultivation and compares it with the recommended dose for the specific variety. Therefore, with this comparative measure, this study intends to determine an indicator that will measure the environmental impact in terms of the nitrate contamination in soil.

$$NRF_i = \frac{\text{Actual dose}\,(N_A)}{\text{Recommended dose}\,(N_R)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

Equation (4.4) measures the N-risk factor of the *ith* farm cultivating HYV rice in study areas. The recommended dose has been chosen for a specific HYV rice group by using the Fertilizer Recommendation Guide (FRG software: Online fertilizer recommendation system, SRDI). An increase in applied dose compared with that of recommended, i.e., an increase in NRF implies greater potential for nitrate contamination. For the proportions of NRF > 1, this study applies the optimal range scoring function and derives the normalized value ranges between 0 to 1, where 1 means the maximum risk of N leaching and run off. Theoretical threshold range for this factor is considered 1.05 to 2. It is assumed that double amount than the recommended dose would be the maximum possible, whereas no N-risk level (NRF=1) is considered here as minimum threshold level i.e., 1.05. When NRF<1, the study uses the raw value as it is because it falls within the normalized range score. However, farms with NRF=1 have been categorized as experiencing ‘no adverse impact of nitrogen fertilizers’ by assigning a zero value to explain the impact score.

4.6.4.2 Environmental impact indicators evaluated by effect-based method

Effect-based method generally consider direct quantitative measurement of environmental indicators. Such method focuses on the evaluation of the state of the farming system.

- Soil pH (SpH): A measure of soil reaction

Farm chemicals such as fertilizers and pesticides are designed to be toxic; therefore, their effect on the agricultural environment is detrimental. Higher levels of phosphoric farm chemicals that release more radionuclides and residues increase soil acidifying and/or alkaline substances (Appendix 4-II for soil pH-level change interactions in HYV rice fields). Soil acidity is thus one of the most important environmental indicators of measuring soil reaction. Modern agricultural practices such as chemical application can greatly accelerate the rate of acidification or alkalization (decrease soil pH or increase in pH, respectively). Particularly, soil under the irrigated rice fields has much potential to experience a decline in soil pH compared with the non-irrigated rice fields. If not managed effectively, the resultant acidification of topsoil and subsoils will eventually lead to lower yields and reduced pasture and crop options. This may contribute to wider catchments problems such as weed infestations, salinity and erosion.

Soil pH is measured by logarithmic scale. Therefore, a one unit change in the pH value represents a 10-fold change in soil reaction (i.e., acidity or alkalinity). For instance, soil with pH level 5.0 is 10 times more acidic than a soil having pH level of 6.0 and 100 times more acidic than that of 7.0. Just “a fractional” change in the pH level could be much more reactive for soil properties or for the crops as well. Using soil pH meter this study measure both soil acidity and soil alkalinity for all of the farms surveyed (Appendix 3-I for the soil pH meter). Depending on those values that come from the test it is intended to assert the present state of the HYV rice farms in terms of soil reaction. For soil acidity, the normalized impact values and theoretical threshold levels are used as explained in Table 4.4.

Table 4.4 Theoretical threshold level range for acidic and alkaline soil

	Lower bound pH	Upper bound pH	Function used to normalize
Acidic	4.0	6.9	Less is Bad (LBF)
Alkaline	7.05	8.5	More is bad (MBF)

Source: Rahmanipour et al., (2014)

- Soil compaction (SCM): A measure of the state of soil texture

Soil compaction is becoming a more serious problem for the modern agriculture projects. It occurs when soil particles become pressed together, reducing pore space between them. Heavily compacted soils contain few large pores and have a reduced rate of both water infiltration and drainage through the compacted layer, which causes greater surface wetness, water logging, more runoff, increased erosion, and longer drying time (Clapham, 1980). Wet fields would make the whole process of ploughing, planting and harvesting delayed and decrease crop yields. In addition, it slowdowns the exchange of gases and process of natural chemical interactions, causing an increase in the likelihood of aeration-related problems (DPI, 2005-2008). Generally, soil contains approximately 25 percent water and 25 percent air by volume. This 50 percent is referred to as pore space. The remaining 50 percent consists of soil particles (Frisby and Pfost, 1993). Soil compaction increases soil strength and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which leads to additional fertilizer requirement and increasing production cost (Frisby and Pfost, 1993). This study uses a pen type soil penetrometer to measure the soil compaction level for each farm (Appendix 3-I for the penetrometer). The theoretical threshold level for soil compaction states that soil surface which estimates 400-500 pound per square inches (psi) and over or 100 psi and below, is not suitable for cultivation at all.

- Soil salinity (SSL): A measure of salt deposition in soil surface

Soil salinity is the presence of additional salt in the surface or into soil layers. Generally, salinity can develop naturally, but human intervention disturbs natural process of ecosystems and the deposition of salt into rivers and onto land would be accelerated (Appendix 4-III for soil salinity cycle in HYV rice crops). A study by Ali (2004) states that soil under irrigated rice fields could experience up to 31 percent increase in soil salinity because of low-lift pump irrigation. The soil and groundwater in arid zones typically have a high salt content, and natural drainage is usually poor (Soule et al., 1990). Irrigation water that drains slowly from field, soil becomes waterlogged in the crop root zone. Continued application of irrigation water and seepage from unlined canals causes the salty groundwater to reach the surface. As the water evaporates from the soil, a salty white crust forms on the surface, leaving the land unfit for cultivation unless expensive reclamation procedures are used. These problems are present wherever large acreages of cropland are irrigated (Soule et al., 1990).

The salinity level is measured by using a salinity meter (Appendix 3-I for scientific electro conductivity meter). This tool analyzes soil quality by measuring salinity property in agriculture. The unit of salinity measurement is ‘Deci-siemens per meter’ (ds/m) and optimal range for this measure is 0.2–2 (ds/m) (Rahmanipour et al., 2014). For instance, soil salinity level that has crossed 2 or over implies severe problem. The estimated measure of soil salinity is then standardized by using the optimal range scoring function so that the normalized score ranges from 0 to 1. An increase in values near 1 means an increase in the soil salinity problem.

- Surface water pH (SWpH): A measure of eutrophication

Along with the problems of waterlogging, nitrification, salinization, etc., that affect irrigated fields; eutrophication of downstream water sources by agrochemicals, and toxic leachates is a serious environmental problem. Specifically, water pollution from fertilizers occurs when these are applied more heavily than crops’ absorptive capacity or when they are washed or blown off the soil surface before they can be incorporated. Such chemical load into the water sources is called eutrophication (Antle and Pingali, 1994). Resulting nitrogen, oxygen, phosphorus and hydrogen ion concentration in terms of nutrient overload pollutes the aquatic habitat extensively.

Phosphorus from fertilizer applications can be exported in erosive runoff (Matson et. Al., 1997). It is often considered the limiting nutrient in aquatic systems and thus a major contributor to eutrophication (Soule et al., 1990). Nitrate, which is highly soluble and easily transported in runoff, also contributes eutrophication substantially. In combination, these two fertilizers have contributed much to the degradation of streams and other bodies of water in agricultural regions (Appendix 4-IV for eutrophication cycle in HYV rice field).

Certainly, water pollution in terms of eutrophication influences the water reaction condition explained by pH. This in turn converts the water more chemically reactive. For instance, water with excessive Hydrogen ion lowers the pH below 7, implies very acidic and would definitely affect any marine life to sustain. On the contrary, alkalinization that is induced by eutrophication will result in raising the pH value above 7. Water pH is thus an important indicator to explain the extent of eutrophication when surface water sources are of concern.

- Ground water pH (GWpH): A measure of ground water contamination

Certainly there are some interactions between ground water and surface water. As a consequence of surface water pollution groundwater sources could also be polluted to a large extent. Sometimes it is called groundwater contamination, which is difficult to classify. However, chemical-intensive irrigation-based agriculture and its impacts on ground water aquifers are certain. Generally, ground water pollution potential increases where there is ongoing chemical leaching, radionuclide substances that are release into the soil or large scale water withdrawal for irrigation. Most of the chemical fertilizers and pesticides release toxic substances. This alters water's physical chemistry including acidity (change in pH), salinity, temperature, and eutrophication. Moreover, N ions from nitrogen fertilizers are easily soluble and leach through the soil layers toward groundwater level during periods of rain. Severe increases in chemical sensitivity that are followed by reductions in water quality may occur because of this nitrification process. A water pH meter is used to measure the ground water chemical sensitiveness by inserting the probe into water sample collected from ground water sources (Appendix 3-I for water pH meter). For this purpose, ground water sources that are mostly used for irrigation have been taken under consideration.

4.6.4.3 Environmental impact indicators evaluated by perception-based method

The idea of the perception-based method is to analyze a set of environmental impacts indicators that are not easily quantifiable in a farm-level primary survey study but frequently recognized by the HYV rice farmers. Particularly, in farm-level environmental impact analysis, farmers as the prime operator of farming activities, should essentially be incorporated. This could be done by incorporating their (farmers') opinion, thinking and perception of different environmental impacts. Satisfactorily, the necessity of analyzing social dimension of agri-environmental sustainability could also be addressed by this effort.

This study, therefore, select a set of nine such environmental impact attributes frequently experienced and recognized by HYV farmers in Bangladesh. For instance, *soil fertility problem* (SFP) is regarded as one of the most important environmental impacts in the field of HYV rice agriculture. Soil fertility depends on whether the soil contains all of the essential nutrients in required amount. HYV ice cultivation requires supplement deficient nutrients by using chemical fertilizers, which in long term destroys soil's natural nutrient build up process. Baker (1993) states that when chemical fertilizers have been applied over long periods, yields have eventually declined. In Bangladesh, IRRI scientists note that farmers need to apply up to 40 percent more nitrogenous fertilizer than they did ten years ago to produce the same amount of rice (IAD, 1994). In general, Bangladeshi HYV rice farmers recognize the soil fertility condition by examining the quantity of their yield.

One of the key functions of arable soil is to contain moisture and supply it to plants in time. The portion of the total available moisture store, which can be extracted by plants at the initial stage of growth, is called 'readily available water'. By having knowledge of the soil texture type, farmers can read the readily available moisture capacity so that irrigation water can be applied before plants have to expend excessive energy to extract moisture (Suzuki et al., 2007). Particularly, in HYV rice field, application of farm chemicals destroys the soil organic matter and carbonate level. Low soil organic matter, carbonate levels and stone content reduce moisture storage capacity (Suzuki et al., 2007) and initiates *soil's water holding capacity* (SWH) problem. On the contrary, when water enters into the soil faster than it can drain away or groundwater levels rise to near the surface, *water logging* (WLG) problem would arise (AQUASTAT glossary & water dictionary). In HYV rice fields, the WLG problem can be resulted from extensive irrigation under the condition of inadequate drainage capacity of the soil. Farmer can easily identify the WLG problem while they find water stagnates in the irrigated area because of poor drainage. Inefficient soil and water management, farm chemical application, irrigation fed crop lands and obstruction of natural drainage systems are the main factors responsible for disrupting the balance of inflow and outflow of water.

Ground water depletion (WDP) is one of the widespread environmental problems in HYV rice paddy cultivation. Major reason for this problem is the 'irrigation'. HYV rice paddies are suitable to cultivate in arid areas but are conditional on a sufficient freshwater supply. Ground reservoir is considered the prime source of irrigation water supply. Ensuring continuous water supply into HYV rice plot depends largely on the size of the aquifer below. Excessive water withdrawals for irrigation and climate change vulnerability are two basic reasons for lowering ground water table. In Bangladesh, this environmental problem is a widely discussed issue in irrigation engineering. Replacing shallow tube wells with engine operated deep tube wells, changing low horse powered irrigation pumps with the one having much higher capacity are frequently reported. In most of the study area ground water table falls to or below the level a high capacity power pump could reach. This issue is perceived by the farmers as well.

Specifically, in agriculture, *soil erosion* (SER) could be defined as a process that removes soil layers and carries them away from crop fields to adjacent water bodies or other land. Erosion thus results in loss of soil and loss of its valuable nutrients that are necessary for crops to grow. Overgrazing as a component of the intensive cultivation practices may intense soil erosion problem. For example, overgrazing deteriorates the soil texture and makes it vulnerable for cultivation (Mortlock, 2007). Furthermore, overgrazing can generate both on-site (at the place where the soil is detached) and off-site (where the eroded soil ends up) environmental degradation. However, agricultural mechanization is not the only cause of soil erosion but is one of the most important problems that are direct. Continuous application of chemical fertilizers and various types of pesticides are responsible for soil texture disruption followed by soil erosion. Irrigation influences water induced soil erosion while wind induced soil erosion may be generated by leaving fields coverless without crops or fellow for a long time. Farmers can identify the problem by observing their land level or top soil level that is getting lowered day by day.

Farmers also predict their expected output level by observing the extent of *crop diseases* (CDP) and *pest attack problems* (PAP). In recent times, scientists have established a link between increases in nitrogenous fertilizer and proliferation of pests in rice. When fertilizer applications increased, the amount of pests and diseases in rice has also simultaneously increased (Pimentel, 1977; Chakraborty et al., 1990). It has also been shown that increased nitrogen is often associated with more leaf disease because it provides a micro climate more conducive to fungal growth. When a plant is deficient of a particular element, some characteristic symptoms appear in form of various plant diseases. For example, when nitrogen is deficient, chlorophyll production is reduced and thus the yellow pigments appear (BARC, 2005). Soil pests, especially root nematodes, have also increased with agricultural intensification. Fisher (1981) state that pollution not only affects yields and the quality of crops but also increases the susceptibility of vegetation to damage by insects and diseases.

Nitrates from chemical fertilizers seeping out of soil into streams, rivers and lakes in excessive quantities enhance eutrophication of those water sources. This accelerates the growth of algae causing competition for oxygen with fish and other useful aquatic organisms and thereby results in *fish catch reduction* (RFC). The major causes of such reduction are numerous. Not only increased use of farm chemicals are responsible but also reduced access to monsoon season flood plains by fish because of roads and flood control embankments, and over fishing may be responsible for threats on fish population.

In Bangladesh, fish production over the years has shown a noticeable decrease. Among the many factors that have been cited as a cause for decline in fish production is the presence of pesticides in fresh water and crop fields (BMF, 1992). Alauddin et al. (1995), note that in Chittagong and Durgapur districts (Bangladesh), fish production in paddy fields has declined by 60 to 75 percent over the past decade following the Green Revolution. In addition to fish, shrimps, prawns, crayfish and crabs are also known to suffer from pesticides. Although detailed studies of pesticide poisoning are not available, Greaves (1984) state that there is evidence that insecticides can cause mortality in crabs and fishes. Pesticides not only affect the quantity but also contaminate the harvests of fish, shrimps, etc. and pose a serious health hazard to human beings.

Farm chemicals in the form of pesticides, insecticides and fertilizers can enter the human body that works with these chemicals for agriculture purpose. This entry may be caused by the inhalation of aerosols, dust, vapor and musk free inhalation while spraying. Additionally, certain *health impacts* (HI) may arise through the oral exposure of food or water intake and include nausea, gastroenteritis, etc. However, direct contact of farm chemicals has much more potential for health impacts such as skin problems. Skin irritation, allergy, arsenic and cancer are such examples of health problem that are often suffered by farmers. Also chemical spray directly initiates emission into atmospheric constituent. This in turn enters into human body again by inhalation.

Although often inconclusive, several studies have connected different health problems with exposure to chemicals from agriculture. For example, Parkinson's disease has been linked with exposure to pesticides (Ascherio et al., 2006), and studies have suggested that repeated exposure to low levels of organophosphates may result in biochemical effects in agricultural farmworkers (e.g., Lopez et al., 2007) and enhanced risks of certain cancers, such as leukemia or lymphoma.

4.6.5 Environmental impact measurement modelling

4.6.5.1 Optimal range scoring function for means and effect-based indicators

This study uses the homothetic transformation method (HTM) of the linear scoring function (Chapter 3, Section 3.2.1) to measure the soil and water quality indicators for the present study purpose. The scoring function is named as the optimal range scoring function (ORS) because most of the soil- and water-related indicator measures hold a threshold range (the range value is scientifically determined) with a minimum and maximum values. Therefore, the ORS function is used to convert distinctly measured indicator values into a specific range (0.1 to 1) following respective direction of extent (0.1 as lowest impact to 1 as highest impact). This could be expressed as Equation 4.5.

$$O_p(f) = F\{R(f), L(0,1)\}\text{..}(4.5)$$

where

$O_p(f)$ = Optimal scoring function

$R(f)$ = Range of function

L = Set of real numbers that range between 0 and 1.

For the ease of evaluation explanation, this study names 'more is bad' and 'less is bad' scoring functions instead of 'less is better' and 'more is better' scoring function, respectively. This is because the study intends to estimate the extent of environmental impact i.e., the bad quality and imply the transformed score 0.1 to 1 as lowest to highest impacts. Therefore, continuing from Equation 4.5, the HTM of the ORS function can be derived as follows:

If A is a set of environmental impact data,

$\{u, v\} \subseteq L, \textit{such that} \{u < v\}$

u equals the lower bound (lowest possible) and v equals the upper bound (highest possible) of the threshold range for a given impact.

$\textit{and } f \in F\{A, L(u, v)\}$

$$\textit{Then, } g = \{(x, y) : x \in L(u, v); y \in L(0,1)\}; y = \{(x-u)/(v-u)\}\text{.............................}(4.6)$$

Therefore, for 'more is bad'

$$y = (x-u)/(v-u)\text{..}(4.7)$$

For 'less is bad'

$$y = 1 - \{(x-u)/(v-u)\}\text{ for every x} \in \text{A}\text{...}(4.8)$$

To choose u and v values as real numbers the study decides to set u equals the lower bound (lowest possible) and v equals the upper bound (highest possible) of the threshold range for a given impact.

Following Rahmanipour et al. (2014), for Equation (4.7), this study takes a 90 percent of that proportion plus 10 percent to calculate the total. This alters the Equation (4.7) as:

$$y = 0.9\{(x-u)/(v-u)\} + 0.1\text{...}(4.7')$$

For 'less is bad' this study takes a 90 percent of that proportion and Equation (4.8) now becomes:

$$y = 1 - 0.9\{(x-u)/(v-u)\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.8')$$

Therefore, 'more is bad function' and 'less is bad function' are chosen depending on whether the original value of a given environmental indicator implies higher impact for higher value or lower impact for higher value and evaluate the given impact extent in an index form.

4.6.5.2 The Likert scale for perception-based indicators

The Likert scale method is used to measure the perception-based indicators in terms of HYV rice farmers' environmental perception. The effort here is basically to find out perception-based environmental indicator values, i.e., the extent, the farmer would think for a given environmental impact. For each recognized environmental indicator, farmers (respondent) choose the best option on a five-point Likert scale. For instance, when a farmer chooses point 4 for the 'pest attack problem', this implies that he is facing this problem to a high extent. Accordingly, Likert scale would then evaluate the opinion by assigning respective weight 0.8. Therefore, this thesis measures all of the perception-based indicators following such agree-disagree approach of Likert scale. Farmers could choose the response option so that it reflects their true perception in that dimension.

Table 4.5 Likert scale scoring for perception based indicators

	Disagree			Agree		
Scale of point	0	1	2	3	4	5
Environmental impact interpretation	None	Very low	Low	Medium	High	Very high
Environmental impact weights (Indicator values)	0	0.2	0.4	0.6	0.8	1.0

Source: Prepared using Likert Scale method

4.6.5.3 Normalization: Converting indicator measures to a 0-1 scale

A major function of an ecological indicator is to express information concerning a complex system in a simplified way so that decision support can be derived from the expression (Bockstaller and Girardin, 2003). For example, information regarding nitrogen fertilizer application, i.e., the *amount* applied per unit of land, would be considered an indicator of nitrogen risk. However, the value that measures the proportion of actual amount applied to the recommended dose would reflect the *extent* of nitrogen risk. Purposively, the later measure of nitrogen risk is more efficient because it supports the farmer with ecologically sustainable farming decision. Additionally, standardizing the nitrogen risk *extent* in a normalized score range will allow us to *compare* the extent with other types of environmental risks that are associated with the concerned issue.

Certainly, interpreting the raw value of the environmental indicator to a normalized form allows the user to express the extent in a comparative way. According to Bockstaller et al. (2008), this conversion calculates or measures whether a certain impact is more environmentally depleting. Riley (2001b) also describes indicator that expresses observations related to their corresponding reference point. Some study approach keeps the indicator measures without altering it by 95ormalization and others convert the result into a comparative mode in terms of a grade, points or score. Hulsbergen (2002) expresses indicator impact in the range from 0 to 1, while, Bockstaller et al. (1997) uses impact on the environment ranging from 0 to 10. However, Rigby et al. (2001) choose the scale between −3 to +3 expressing negative and positive effects. The measurement scale selection in evaluating the normalization functions and the range of values are subjective to study-specific interests. Following this idea, the present study interprets all of the indicators' actual values to normalized scores that range from 0 to 1. Purposively, the study sets threshold values for each indicator and used those in respective normalization formula (NF). The threshold range values should be determined by scientific method for indicators that are being measure using scientific tools. However, for other indicators, theoretical optimal range could also be evaluated using expert advice, group discussion and/or maximum-minimum value range found in survey data.

The ORS function is used purposively for specific normalization formulas dealing with respective indicators. 'More is Bad' (MBF) and 'Less is Bad' (LBF) are two such types of ORS functions. The proposed MBF and LBF are originated by standard scoring functions used to measure soil quality indicators (Andrews, et al., 2003; Qi, et al., 2009; Rahmanipour, et al., 2014). Therefore, MBF and LBF have been chosen on the basis of indicator sensitivity and to normalize all indicators within 0 to 1 score, which implies that a higher score has a higher impact. For example, in assessing the impact of soil acidity, a lower value of soil pH means a greater acidity problem [a pH of 4.5 is much more severe than a pH of 5.0 or more]; therefore, LBF has been selected to be normalized. In contrast, the soil alkaline indicator implies a greater problem for a higher pH value [a pH of 8 is much more severe than a pH of 7.5]; therefore, MBF has been used. Among all of the seventeen indicators that are selected for this study, Table 4.6 shows seven such impact indicators that are converted to normalized scores by using ORS functions. The Table 4.6 also shows threshold levels in terms of lower bound and upper bound values and respective NFs. Unlikely, rest of the ten environmental indicators do not required to be interpreted using the ORS functions. This is because, the methods used to measure those indicators results values ranging 0 to 1, thus satisfying the impact evaluation criteria by itself. One among these ten i.e., the CCI has been measured using Herfindahl Index and the estimate falls between 0 to 1, implying higher value as higher impact. The other nine environmental indicators, which are perception based, have been measure using a Likert scale. This method also satisfies measurement criteria of interpreting values on a 0 to 1 scale.

Table 4.6 Optimal range scoring function used and the threshold values

Indicators	Function type	Lower bound	Upper Bound	Normalization Formula (NF)
SpH (values <7)	LBF	4.0	6.90	$f(x) = 1 - 0.9(\frac{x - 4.0}{6.9 - 4.0})$
SpH (values >7)	MBF	7.05	8.50	$f(x) = 0.9(\frac{x - 7.05}{8.5 - 7.05}) + 0.1$
SCM	MBF	100	500	$f(x) = 0.9(\frac{x - 100}{500 - 100}) + 0.1$
SSL	MBF	0.20	2.0	$f(x) = 0.9(\frac{x - 0.2}{2.0 - 0.2}) + 0.1$
SWpH and GWpH (for values <7)	LBF	4.0	6.90	$f(x) = 1 - 0.9(\frac{x - 4.0}{6.9 - 4.0})$
SWpH and GWpH (for values >7)	MBF	7.05	8.50	$f(x) = 0.9(\frac{x - 7.05}{8.5 - 7.05}) + 0.1$
SSF	MBF	2	36	$f(x) = 0.9(\frac{x - 2}{36 - 2}) + 0.1$
NRF (for values >1)	MBF	1.05	2	$f(x) = 0.9(\frac{x - 1.01}{2.0 - 1.01}) + 0.1$

Note: MBF means 'more is bad for the environment function'; LBF means 'less is bad for the environment function'; x is the indicator's actual value; $f(x)$ is the indicator's derived impact score. For every indicator score, the value range is $0.1 \leq f(x) \leq 1$.
Source: Own

4.6.5.4 Composite Environmental Impact Index (CEII)

Present study models the environmental impact of HYV rice cultivation following Equation (4.1). The Composite Environmental Impact Index (CEII) empirical model incorporates means-based, effect-based and perceptions-based environmental indicators and expressed as in Equation 4.9.

$$CEII_i = \sum_{m=1}^{3} M_m + \sum_{e=1}^{5} E_e + \sum_{p=1}^{9} P_p \qquad \text{...}(4.9)$$

where the $CEII_i$ is the composite environmental impact index of the ith farmer, M_m is the means-based indicators [CCI, SSF and NRF], E_e is the effect-based indicators [SpH, SCM, SSL, SWpH and GWpH], and P_p is the perception-based indicators [SFP, SWH, WLG, WDP, SER, PAP, CDP, RFC and HI]. Three sets of different indicator groups containing a total of 17 selected indicators are defined by the CEII by statistical aggregation (Equation 4.9). The logic behind addition of the normalized values of these indicators are (i) itegrating indicators from relevant envitonmental objective groups through adding all of their (indicators') normalized values allows to evaluate environemntal sustainabiltiy of on-farm HYV rice agriculture; (ii) the CEII not only predicts the current impact but also offers information concerning the total risk or potential for environmental damage; and (iii) individually, each of these 17 impact values fall between 0 and 1, therefore, the theoretical maximum of the proposed CEII score could be estimed when added altogether (which is equal to 17). This implies that maximum possible impact that a HYV rice farm could create, would be of 17 units. In other way, proportion of the CEII for *ith* farm to that of the theoretical maximum level for a given crop year would be regarded as its respective impact extent in general. Therefore, the commensurability has been computed by applying mathemetical averaging procedure. This evaluates how far the given farm is to that of the theoretical highest. Specifically, for this study more near to the maximum impact value, means more environmental impacts created.

$$\delta_i = \frac{CEII_i}{CEII_H};\ 0 \le \delta_i \le 1 \quad \text{...(4.10)}$$

where δ_i is the impact commensurability, $CEII_H$ is the theoretical maximum value of the CEII (i.e., 17) and the $CEII_i$ is the composite environmental impact index of the ith farmer.

4.6.6 Method validation

In ecological economics, it is important to construct a versatile formula that could measure the extent of environmental impact of economic activities (e.g., agricultural production). Particularly for agriculture, several studies analyze desirable characteristics of a good indicator that ought to be satisfied (van der Werf and Petit, 2002; Payraudeau and van der Werf, 2005). Specifically, it is important to validate the proposed method by evaluating environmental indicators relative to the given study purpose. The CEII proposed by the present study satisfies most of those features that a good indicator should have. When the study issue is to measure environmental impact of HYV rice cultivation, impacts that are happening because of rice paddy cultivation should be considered. Therefore, all of the indicators selected for the present study are *research problem relevant* i.e., HYV rice cultivation related. Moreover, the proposed CEII formula is a *flexible* one. This could be used successfully to incorporate environmental indicators other than those 17 impacts considered. Other means-based indicators, effect-based indicators or perception-based indicators could also be incorporated easily into this CEII. Moreover, the CEII formulation is not only applicable for a particular type (e.g., rice) of agriculture but for other types as well. Certainly, this method can be used to measure the impact of agriculture, such as wheat, maize, pulse, etc. Therefore, the CEII ensures its *wide applicability*.

CEII defined by Equation 4.1 is a problem relevant, flexible and simple technique indicator. It is constructed in such a way that it can reflect all of the problems of issue concerned. Applicability of this farm-level composite indicator could be ranged from crop agriculture or livestock to fishery or even poultry. For assessing environmental impacts of any industry other than agriculture, this CEII could also be constructed. It is just required to incorporate study-specific, relevant environmental indicators.

Three groups of the indicator measurement bases would considerably satisfy the dimensions coverage requirement analyzing environmental sustainability. Practice-related environmental indicators reflect those impacts influenced by producer's production practice. System-related indicators indicate the environmental state of this production system. More importantly, perception-related indicators express environmental impact extent from the producer's point of view. It is difficult to consider all those impacts that are unobservable directly from short term primary survey. Indicators which require involvement of agricultural scientists, settlement of large scale scientific laboratory and/or need separate research projects to evaluate are also challenging. This study intends to measure such types of impacts by defining perception-based indicators. Inclusion of the perception-based indicators into the composite model Equation 4.1 thus successfully resolves the challenges to consider unobservable impacts.

Moreover, the proposed CEII formulation (Equation 4.1) could be applied for a given crop across several crop seasons for short term or long term basis. Such effort would allow us to investigate the temporal dimension of the sustainability in agriculture.

Doing the same across several regions (i.e., the local, national or international level) would allow the researcher to explain the spatial dimension of sustainability analysis. The effort would then satisfactorily meet up the challenge to reconcile three tiers of evaluating the agricultural sustainability (Chapter 2, Figure 2.1).

Table 4.7 CEII features check for validity

Desirable features of a good indicator		CEII features check		
		MBI[a]	EBI[a]	PBI[a]
Assessment base	Environmental impacts	Yes[b]	Yes	Yes
Expression of the impact on	Unit area or production unit	Yes	Yes	Yes
The result in the form of	Values preferable to score. Score is preferable to qualitative judgement	Value leading to score	Value leading to score	Score
Threshold values should be defined	Scientifically	Hypothetically	Scientifically	Theoretically
Data analysis should be	Individual plots level	Yes	Yes	Yes
Evaluate results using	Reference value	Yes	Yes	Yes
Confronting indicator values by	Submitting the design to a panel of experts.	Yes	Yes	Yes

a. **MBI: means-based indicators; EBI: effect-based indicator; PBI: perception-based indicators;**

b. **'Yes' means CEII satisfies the respective desirable feature;**

Source: Own; van der Werf and Petit (2002); Payraudeau and van der Werf (2005).

Table 4.7 lists down some important features (yellow shaded windows) of a good indicator substantiated by previous studies (e.g., van der Werf and Petit, 2002; Payraudeau and van der Werf, 2005). A comparative analysis between the *good* one and the *proposed* one (i.e., the CEII) has been portrayed correspondingly. It is notable that the CEII satisfies almost all of the desirable characteristics of the measure of an indicator. Hence, the CEII is validated as an alternative indicator-based formula of sustainability measurement in agriculture.

4.6.7 Indicator data collection

Soil samples are tested during end of the field visit (October 2013-December 2013) in December 2013, i.e., just after the harvesting period of the most recent crop season. Soil remains irrigation free and suitable to use soil testing probes in these days. However, such a one-month time frame is because harvesting time and irrigation water runoff time may vary for a particular crop season depending on land levels and/soil texture. For example, low land or medium low lands are considered more time consuming to run out irrigation water, whereas a soil texture with porous property and medium high lands or high lands are considered free of irrigation water sooner. The soil pH, soil compaction and soil salinity are also tested and measured accordingly for all the selected HYV rice farms in the same time range. Another reason for selecting that particular time is to obtain the most recent soil impacts created by last cultivation; disregarding the fact that some impacts may be caused by previous season cultivations as well. This is because, the study considers the past three crop season's data (HYV Aus, HYV Aman and HYV Boro) and presumed that measured values of soil-related impacts are for all of those successive seasons or for that given crop year. In this aggregated way, this study evaluates the environmental impacts of HYV crops that were cultivated in the past crop year (specifically, one crop year that includes three crop seasons) (Chapter 3, Section 3.4.3).

To measure ground water pH level, water sample is collected from ground water source that is being used to irrigate respective fields under consideration. Similarly, water samples from field adjacent surface water source are also collected to measure surface water pH for a given farm. The study carries out water testing survey within the same time frame selected to measure soil-related impacts (December 2013).

For means-based impacts, such as the soil stress factor, N-risk factor and crop concentration index, this study uses specific questionnaire sections (Appendix 3-VII). Data on these indicators are collected by interviewing farmers (respondents) operating a given farm during entire survey period. Similarly, data for perception-based indicators are also collected using questionnaire-interview sessions. However, a focus group discussion (FGD) among a group of HYV rice farms and primary investigator and the enumerator in a prior stage of the survey is performed. This effort is to determine a list of mostly recognized environmental problems so that a set of study relevant perception-based indicators can be selected.

4.7 Data description

Descriptive statistics of the farm-level (farmer-specific) environmental indicators for three study regions are presented below (Table 4.8). Two sets of data, that is, the actual and the normalized values of the indicators, are depicted here for this purpose. Actual values are those measured initially during the survey and the normalized values are those computed by transforming actual impact values by applying normalization formulas and respective methods (Section 4.6.5). A comparative description of these normalized impact values across three study regions is also represented in their order of rank in Table 4.9.

It is found that the types of environmental impacts and their extent varies considerably throughout study regions. Although this study chooses three consecutive study areas to represent some specific AEZ; climatic, topographical and physiographic differences may cause such regional variations. However, area wise differences in farming practice and farmers perception are two important factors that could be responsible to result in such regional disparity. For instance, impact scores for soil erosion (SER), crop concentration (CCI) and soil's water holding capacity problems (SWH) are ranked top in Natore, Pabna and Rajshahi regions, respectively. Among these three impacts, SER and CCI problems are directly influenced by HYV rice cultivation practice. Problem of soil's water holding capacity in Rajshahi could partly be reasoned by the area-specific topographical features or soil texture, however significantly subjective to farming practice as well. An analysis of data, disregarding such regional classification, evaluates CCI problem as the top most important impact. This implies that frequent monoculture practice in terms of highest CCI (0.80) imposes severe pressures on the agro-biodiversity in study area.

Lowest extent of the environmental impact caused by HYV rice cultivation varies extensively across different study regions. The SWH problem, with the highest impact value in the Rajshahi region reported, was found as the lowest in impact value for Natore, which ranks at the bottom (Table 4.9). Moreover, the nitrogen risk factor (NRF) score comes at the bottom in Pabna region ranking list. This implies the fact that unlike Rajshahi and Natore, farmers are applying nitrogen fertilizers fairly near to the recommended dose. Logically, water logging (WLG) problem holds the last rank there in Rajshahi region. Soil, which has the lowest capacity to hold enough moisture (SWH), may not have the water logging problem. In addition to these, consistently SpH is reported as the second to last environmental impact in three study regions. No variation across the study regions is observed for this impact indicator. Soil pH test during field survey thus finds a small amount of soil acidity or alkalinity problem in all of study areas. Likewise, one of the indicators that create environmental impacts consistently in farm areas is the pest attack problem (PAP). Unlike Rajshahi, PAP in Natore and Pabna remains in the similar rank of impact extent, ranges between 0.39 to 0.53 scores. Exceptionally, PAP problem is reported as one of the top five impacts in Rajshahi. Excessive farm chemicals application followed by beneficiary pest extinction may be responsible for increasing the PAP there.

The radar diagram (Figure 4.4) depicts a comparative picture of the impact extent for all of sample groups. Among means-based indicators, except the CCI, both SSF and NRF shows less impact values. However, little variations are found among study regions for the NRF scores. The CCI impact scores vary throughout the regions but shows higher impact values. Likewise, all of the effect-based indicators, other than soil compaction (SCM), show lower level of impact extent. The impact value of the SCM problem for three study regions concerning all region data is high. Perception-based indicators show large diversity in impact values across study regions. For example, in Rajshahi, soil erosion problem value is the lower than that of ‘Pabna’ or ‘all region’ sample groups but found as the highest in Natore region. SWH, PAP, SER, SFP problems also vary widely across study regions unlike RFC problem. CDP is evaluated as one of the most important problem in study area exhibiting fairly similar impact values.

Table 4.8 Actual and normalized indicator values: Regional basis

	Natore				Pabna				Rajshahi				All Region			
Indicators	Actual		Normalized		Actual		Normalized		Actual		Normalized		Actual		Normalized	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
CCI	0.69	0.20	0.69	0.20	0.90	0.20	0.90	0.20	0.80	0.19	0.80	0.19	0.80	0.20	0.80	0.20
SSF	8.79	2.48	0.28	0.07	5.58	0.97	0.17	0.07	8.48	6.56	0.25	0.06	7.65	2.41	0.23	0.07
NRF	0.23	0.12	0.23	0.12	0.08	0.10	0.08	0.12	0.31	0.20	0.31	0.21	0.21	0.18	0.21	0.19
SpH	7.03	0.19	0.17	0.07	7.03	0.16	0.09	0.06	7.03	0.17	0.13	0.09	7.03	0.17	0.14	0.10
SCM	315	119.75	0.58	0.27	376	70.85	0.72	0.27	356	116.84	0.67	0.26	350	108.16	0.66	0.24
SSL	0.70	0.11	0.35	0.06	0.72	0.08	0.36	0.06	0.41	0.09	0.20	0.05	0.60	0.17	0.30	0.09
SWpH	6.86	0.23	0.26	0.09	6.95	0.16	0.22	0.08	7.0	0.22	0.24	0.08	6.94	0.22	0.24	0.08
GWpH	6.98	0.21	0.26	0.05	6.86	0.26	0.27	0.05	6.98	0.15	0.20	0.02	6.94	0.22	0.24	0.07
SFP	0.29	0.11	0.29	0.11	0.34	0.16	0.34	0.16	0.49	0.24	0.49	0.24	0.38	0.20	0.38	0.20
PAP	0.42	0.22	0.42	0.22	0.39	0.15	0.39	0.15	0.75	0.12	0.75	0.12	0.53	0.24	0.53	0.24
CDP	0.77	0.12	0.77	0.12	0.69	0.16	0.69	0.16	0.80	0.51	0.80	0.51	0.76	0.32	0.76	0.32
SER	0.90	0.16	0.90	0.16	0.67	0.14	0.67	0.14	0.15	0.16	0.15	0.16	0.56	0.35	0.56	0.35
WDP	0.21	0.16	0.21	0.16	0.12	0.12	0.12	0.12	0.14	0.17	0.14	0.17	0.15	0.15	0.15	0.15
SWH	0.09	0.15	0.09	0.15	0.19	0.20	0.19	0.20	0.84	0.20	0.84	0.20	0.39	0.38	0.39	0.38
WLG	0.29	0.24	0.29	0.24	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.16	0.20	0.16	0.20
HI	0.80	0.08	0.80	0.08	0.73	0.36	0.73	0.36	0.19	0.21	0.19	0.21	0.56	0.37	0.56	0.37
RFC	0.73	0.31	0.73	0.31	0.70	0.31	0.70	0.31	0.75	0.22	0.75	0.22	0.72	0.28	0.72	0.28
Sample	103				101				113				317			

Source: Field survey 2013.

Table 4.9 Ranking indicator impacts scores across study regions

Regions	Natore		Pabna		Rajshahi		All Region	
Indicators Rank	Indicators Name	Mean	Indicators Name	Mean	Indicators Name	Mean	Indicator s Name	Mean
1.	SER	0.90	CCI	0.90	SWH	0.84	CCI	0.80
2.	HI	0.80	HI	0.73	CCI	0.80	CDP	0.76
3.	CDP	0.77	SCM	0.72	CDP	0.80	RFC	0.72
4.	RFC	0.73	RFC	0.70	PAP	0.75	SCM	0.66
5.	CCI	0.69	CDP	0.69	RFC	0.75	SER	0.56
6.	SCM	0.58	SER	0.67	SCM	0.67	HI	0.56
7.	PAP	0.42	PAP	0.39	SFP	0.49	PAP	0.53
8.	SSL	0.35	SSL	0.36	NRF	0.31	SWH	0.39
9.	SFP	0.29	SFP	0.34	SSF	0.25	SFP	0.38
10.	WLG	0.29	GWpH	0.27	SWpH	0.24	SSL	0.30
11.	SSF	0.28	SWpH	0.22	SSL	0.20	SWpH	0.24
12.	SWpH	0.26	SWH	0.19	GWpH	0.20	GWpH	0.24
13.	GWpH	0.26	SSF	0.17	HI	0.19	SSF	0.23
14.	NRF	0.23	WDP	0.12	SER	0.15	NRF	0.21
15.	WDP	0.21	WLG	0.10	WDP	0.14	WLG	0.16
16.	SpH	0.17	SpH	0.09	SpH	0.13	WDP	0.15
17.	SWH	0.09	NRF	0.08	WLG	0.10	SpH	0.14

Source: Own calculation

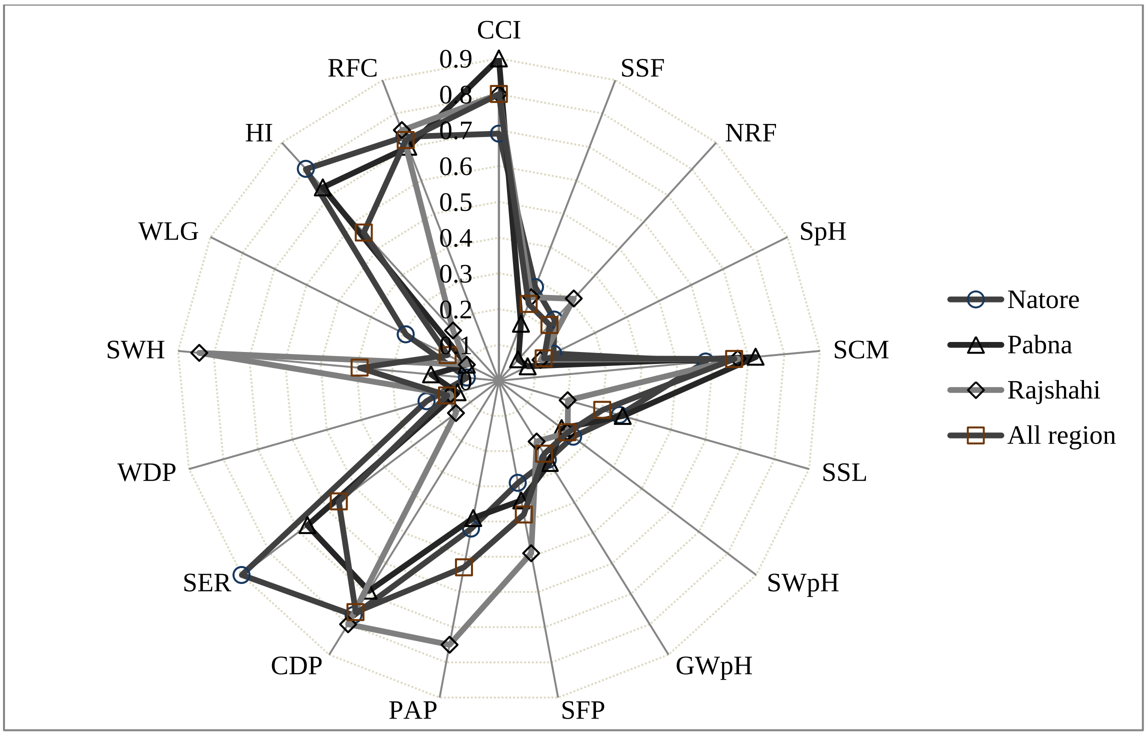


Figure 4.4: Radar diagram: Impact value (normalized scores) comparison across study regions

4.8 CEII result analysis

A descriptive statistics of the farm-specific composite environmental impact index (CEII) is presented below in Table 4.10. While comparing CEII of the entire sample, this study finds that HYV rice farms in the Rajshahi region created the highest environmental impact. Almost 11.70 units of impact have resulted there for producing HYV rice in the past crop year, whereas the minimum extent of impact (i.e., 4.48 units) was created by the respective HYV rice farms in the Pabna region. Analysis of the mean CEII values across three regions finds Natore as the highest impact creating region. This implies the fact that on average, Natore HYV rice farms are creating more environmental impacts than that of Rajshahi and Pabna. Quantity of farm chamical inputs might be identified as a factor that causes such regional variation in the extent of environmental impact (the CEII value). For exapmle, farmers of the Natore region are applying higher amount of farm chemicals in form of fertilizers and pesticides than Rajshahi and Pabna farmers (Table 5.1). Among the three study regions, the Natore region farms have the highest potential for environmental unsustainability in HYV rice agriculture followed by Rajshahi and Pabna regions. Different study regions may have different levels of environmental impact potential depending on several agronomic issues. Significant variations in regional mean CEII values across study regions has been verified by performing ANOVA statistics in the last segment of the Table 4.10. F-test evaluates that the difference between Natore and the other two regions, Rajshahi and Pabna, are statistically significant.

The notion of comparing an estimate (e.g., the CEII) with respect to its theoretical optimum (maximum) has been preferable (Liebig et al., 2001). This is because it allows the researcher to explain the extent of the measured value by itself alone. For example, the mean CEII value of 6.52 for the Pabna region expresses the impact score only, not the extent of the impact. In contrast, the mean 'δ Pabna', i.e., 0.384, expresses the extent of the composite impact CEII. This implies that on average, 38 percent of the theoretical maximumenvironmental impact because of HYV rice farming is created in the Pabna region. Therefore, the CEII commensurability (δ) is measured by performing ratio statistics following Equation 4.10 and is represented in Table 4.10.

In general, study result implies that the *i*th farm/farmer creates $CEII_i$ amount of environmental impact while cultivating HYV rice. Therefore, its commensurability δ_i explains the extent of proportional impact value regarding its theoretical maximum level. The empirical result reveals that 27 to 69 per cent of its theoretical maximum level of environmental damage is caused by HYV rice cultivation in the study area.

Surprisingly, farm size categorical CEII data analysis rejects the presumption that size of the farm would be one of the factors influencing the environmental impact. Unlike the regional variation, differences in mean CEII values among three farm sizes (large, medium and the small) are resulted as statistically insignificant (ANOVA Table 4.12).

Table 4.10 The CEII in terms of study region

	Number of sample	Minimum	Maximum	Mean	Std. Deviation
Region Wise CEII Statistics					
CEII_All Region	317	4.475	11.691	6.787	0.818
CEII_Natore	103	5.162	8.825	6.992	0.746
CEII_Pabna	101	4.475	9.328	6.524	0.762
CEII_Rajshahi	113	5.089	11.691	6.833	0.872
Region wise commensurability (δ) statistics					
δ All Region	317	0.263	0.688	0.399	0.049
δ Natore	103	0.305	0.520	0.412	0.045
δ Pabna	101	0.263	0.549	0.384	0.051
δ Rajshahi	113	0.299	0.688	0.402	0.046

Region wise CEII variation (single factor ANOVA)

Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	11.55094	2	5.775471	9.071784	0.000148	3.024496
Within Groups	199.9053	314	0.636641			
Total	211.4563	316				

Single sample t-test:

	df	t	P-value	t-critical (one tailed)	t critical (two tailed)
CEII_All Region	316	147.73	0.000	1.65	(+/-)1.96

Source: Own calculation, Estimation performed using MS Excel 2010

Table 4.11 The CEII in terms of farm size

	All Region	Natore	Pabna	Rajshahi
Large Farms:				
Mean	6.800455	6.901519	6.715879	6.779087
Std. Deviation	0.876978	0.58654	0.773687	1.087583
Medium Farms:				
Mean	6.779341	7.091714	6.509474	6.717773
Std. Deviation	0.772449	0.779614	0.801934	0.636881
Small Farms:				
Mean	6.782684	7.031586	6.340354	6.965515
Std. Deviation	0.798681	0.810291	0.675339	0.735201

Source: Own calculation, Estimation performed using MS Excel 2010

Table 4.12 Farm size wise CEII variation: Single factor ANOVA

Data Groups	Count	ANOVA						
Large Farms	108	Source of Variation	SS	df	MS	F	P-value	F Critical
Medium Farms	103	Between Groups	0.02442	2	0.0122	0.0182	0.982036	3.024
Small Farms	106	Within Groups	211.457	314	0.6734			
Total	317		211.482	316				

Source: Own calculation, Estimation performed using MS Excel 2010.

4.9 Conclusion

This chapter aims to quantitatively measure the environmental impact of HYV rice farms. Farmers, who are cultivating chemical-intensive and irrigation-based HYV rice have considerable potential for resulting environmental degradation and unsustainable agro-ecological conditions. This chapter investigates that agriculture-environment issue in the context of Bangladesh, which is a least touched study area by far. The effort here is to propose a suitable method of measuring farm-level environmental impacts of chemical-intensive agriculture. Therefore, this study proposes an alternative indicator-based approach (Figure 4.3). By using the approach and applying the evaluation formula (Equation 4.1) it evaluates the amount of impacts generated by HYV rice agriculture in the study area. The approach incorporates three most important measurement dimensions to evaluate farm-specific aggregated environmental impact and defines this as the composite environmental impact index (CEII). The CEII measures the amount of the extent of environmental impact, whereas the CEII commensurability (δ) (Equation 4.10) evaluates the proportion of the extent of this impact. Significant variations in regional CEII are found, however, and the CEII variations across different farm sizes are statistically insignificant (Tables 4.10 and 4.12).

In general, result of this chapter implies that the *i*th farm/farmer creates $CEII_i$ amount of environmental impact while cultivating HYV rice. Therefore, its commensurability δ_i explains the proportion of the extent of the impact value regarding its theoretical maximum level. The empirical result reveals that 27 to 69 per cent of its theoretical maximum level of environmental damage is caused by HYV rice cultivation in the study area. Particularly, crop concentration, crop diseases, reduction in fish catch, soil compaction and soil erosion are found as top five environmental impacts that contribute approximately 50 per cent to 80 per cent for rising up the CEII in study area as a whole. Considering the agriculture-environment issue, measuring both the amount and the degree of environmental impact are useful. The effort considerably helps assess the potential for agricultural sustainability. Higher value of the CEII means higher impacts resulted from a given types of agriculture (e.g., HYV rice crop). This in turn implies higher potential for environmental unsustainability in agriculture. Among the three study regions, the study finds Natore region farms have the highest potential for environmental unsustainability in HYV rice agriculture followed by Rajshahi and Pabna regions.

The environmental impact evaluation method CEII is applicable to measure different sustainability dimensions. For instance this could be applied successively for a given crop across several crop seasons for short term or long term basis. Such effort would allow investigating temporal dimension of environmental sustainability in agriculture. Doing the same across several regions (local, national or international) would explain the spatial dimension. Therefore, the CEII could be validated as an alternative indicator-based method of sustainability measurement in agriculture (Table 4.7).

There are two basic approaches measuring environmental sustainability in agricultural production (Hoang and Alauddin, 2012). The first one involves the development of various indicators to explore differences among production units (farms); that the present chapter discusses. The second approach focuses on the production frontiers that derive efficiency and productivity measures. Agriculture primarily produces the desirable output (e.g., HYV rice crops) along with some undesirable outputs (e.g., water pollution, soil degradation, etc.) in terms of environmental impacts. To achieve maximum production efficiency, a production unit should take into account of both components, desirable and undesirable outputs, in sustainability analysis. For specific agriculture such as a HYV rice crop, the amount of environmentally ‘bad’ (impacts) aspects that are produced along with the ‘good’ (rice crop) should be considered when calculating true production efficiency. The following chapter is thus designed to address the second approach of measuring agricultural sustainability with production efficiency measures.

CHAPTER FIVE

Environmental impact of HYV rice agriculture and the loss in production efficiency

5.1 Introduction

Agricultural production, which attempts increasing production efficiency, is conditional on limiting its impacts on the environment. This condition is because the growth in agricultural productivity and its sustainability primarily depend on the quality of the natural resource (natural capital) and the efficient management of the resource extraction. Therefore, previous studies recognize the importance of analyzing different environmental dimensions, defining relevant agri-environmental attributes and incorporating these attributes into the efficiency and productivity measures (Taylor, et al., 1993; Stockle, et al., 1994; Rigby, et al., 2001; Van der Werf and Petit, 2002; Van Cauwenbergh, et al., 2007; Hoang and Rao, 2010). Evaluating the pollution risk of a production activity and the environmental damage extent are the major concern in these studies. This would help implementing environmental management projects, reduces environmental impacts, improve production efficiency and ensure sustainability for both the environment and business (Nishitani, et al., 2012). Particularly, for agriculture as a natural resource depleting production activity, it is worthwhile to evaluate environmentally adjusted measure of the production efficiency i.e., the eco-efficiency.

This study intends to evaluate eco-efficiency of Bangladesh HYV rice agriculture by incorporating environmental impacts into the efficiency model. For a set of farm-level primary data, this chapter particularly evaluates the environmentally adjusted production efficiency i.e., the eco-efficiency and thereby explains environmental impact induced loss in production efficiency. Section 5.2 reviews previous literature that focus on production frontier-based approach while incorporating environmental impacts in measuring the environmental efficiency (or eco-efficiency) of a given production sector. This section also reviews literature explaining how environmental impact indicators are defined and used as a denominator of measuring the eco-efficiency. Bangladesh HYV rice agriculture and its production efficiency loss because of environmental impacts analyzed by early studies are also highlighted at the end of this section. Section 5.3 discusses research gaps followed by identifying specific research questions while section 5.4 specifies research objectives. Section 5.5 represents a conceptual overview of the production efficiency and eco-efficiency notions in general and particularly in agriculture. Section 5.6 discusses the methods design and section 5.7 explains the data. The results are described in Section 5.8. Thereafter, the conclusion is represented in sections 5.9.

5.2 Literature review

5.2.1 Environmental efficiency: Frontier-based approach

A large body of operational research uses the production frontier-based approach to analyze the environmental efficiency production activities. For instance, Färe et al. (1996) and Sarkis and Cordeiro (1998) evaluated environmental efficiency and ecological efficiency, respectively, for fossil-fuel electricity-generating plants in the United States using the production frontier-based approach, the data envelopment analysis (DEA). Färe et al. (1996) decompose overall factor productivity into an undesirable (pollution) component and an input-output efficiency component. While, Sarkis and Cordeiro (2012) consider simultaneously the 'good and bad' outputs into their proposed DEA model determining joint ecological and technical efficiencies. Yaisawarng and Klein (1994) also study the pollution components. However, these authors name it as the 'emissions outputs' of electricity generating coal-burning plants in US using the production frontier-based approach, i.e., the DEA. Inclusion of such emission outputs into their productivity analysis helps determining actual portion of their plants and of net electricity generation that would lie in the decreasing returns region of the production set.

Korhonen and Luptacik (2004) recognize the advantages of using production frontier-based approach, particularly the DEA, dealing with difficulties of measuring actual performance of a given firm that jointly produce desirable and undesirable outputs (e.g., pollution). The study estimates true efficiency of a given set of power plants' in European country by considering pollutant factors into their proposed DEA model. Similar to other available studies (e.g., Sarkis and Talluri, 2004), their study considers the pollutant factors as the inputs so that the DEA can decrease pollutants or undesirable factors and inputs and increase desirable outputs. Sueyoshi and Goto (2011) consider the environmental factor as an undesirable output (the total amount of CO_2 emission) along with two inputs and two desirable outputs using the DEA and evaluate Japanese electric power companies' environmental efficiency. The DEA, as a production frontier-based approach, is also used by Ismail et al. (2013) in their study conducting the overall eco-efficiency of some selected petroleum companies. By incorporating environmental pollutant emission data into their proposed DEA, the study finds that such eco-efficiency measure is worthwhile as an environmental impact management tool. The DEA-based environmental efficiency analysis provides useful information for the companies' environmental management projects (Dyckhoff and Allen, 2001; Sarkis and Talluri, 2004).

Like energy production sectors, agricultural sector and its environmental efficiency are also studied using the frontier-based approach in the field of operational research on agricultural sustainability. Hoang and Coelli (2011) empirically estimate environmental efficiency of agricultural sector in analyzing environmental total factor productivity for year 1990 to year 2003 in thirty OECD countries. Their frontier-based analysis reveals that the OECD countries could be able to reduce around fifty per cent less eutrophication risks while producing a given level of output by changing input combinations. This would thereby significantly improve environmental efficiency and environmental total factor productivity. Similar results are also found in a separate study by Hoang and Alauddin (2012). Their study on an agricultural data set for thirty OECD countries additionally emphasizes that these countries can make their agricultural production systems more environmentally sustainable with a change in input allocations, and they therefore can also achieve economic sustainability.

Agricultural production and its economic viability analysis using the DEA are also demonstrated by Reig-Martínez and Picazo-Tadeo (2004). Their study analyze a set of Spanish citrus farms and find that the number of economically non-viable farms could substantially be reduced by managing inefficient farms identified by the DEA. Similar to other production sectors, this study recommends the production frontier-based DEA approach for agriculture as an appropriate analytical tool to explore the possibilities of short-term economic viability.

Environmental efficiency that can ensure economic viability is important to analyze considering environment-depleting agricultural activities. Chemical-based agricultural activities generate frequent environmental degradations. Following such importance, a study by Graham (2009) evaluates the impact of chemical fertilizers application on ground and surface water for selected dairy farms in South-East Australia. As an effort, the study uses environment depleting inputs along with conventional inputs and outputs (dairy products) while formulating their DEA.

Using data envelopment analysis, Serra et al. (2014) propose farm-level technical and environmental efficiency measures on a sample of Catalan arable crop farms. Environmental efficiency measures as analyzed in this study focuses on nitrogen and pesticide pollution. Their DEA analysis reveals that nitrogen pollution inefficiencies could be minimized substantially under good growing conditions.

Considering the usefulness of the production frontier-based DEA in ecologically motivated applications, Poit-Lepetit et al. (1997) analyzed the environmental impacts that generated technical inefficiencies for French cereal production. Evidently, their estimated DEA shows that technical inefficiency could be reduced persistently by minimizing the environmental impacts generating input use. Specifically, the study suggests that substantial potential for limiting environmental impacts of agricultural inputs could be ensured by using such production frontier-based approach.

In general most of the previous studies use the production frontier-based approach and consider the environmental pollution factor as undesirable outputs in analyzing environmental efficiency. Specifically, the approach could satisfactorily incorporate both types of output components; the desirable and undesirable outputs into environmental efficiency analysis. Essentially, this requires defining a composite environmental pollution factor (i.e., undesirable output component), so that the pollution factor would combine different environmental impact attributes, present there in a given production process. However, previous studies face challenges in identifying environmental factors and defining the undesirable output component while incorporating the component together with conventional inputs and desirable outputs into the DEA-based environmental efficiency models.

5.2.2 Environmental factors in measuring eco-efficiency

Operational research on environmental management suggests a number of environmental impact attributes and alternative terminologies defining undesirable component while evaluating the eco-efficiency. For instance, to investigate the impact of the pollution performance of a set of given production units on their market valuation, Cormier et al. (1993) develop a ‘pollution performance index’. The index is defined as the ratio of the sum of actual pollution levels recorded for a given plant to the sum of pollution standard set by the Environment Ministries for the plant particularly. However, such pollution performance index estimates the pollution level relative to the standard that may vary depending on the types of plants (or industries) concerned.

Martin et al. (1991) and Beede et al. (1993) define ‘pollutant intensity index’ of a given plant or a firm as the ratio of the total pollutant risk to the total manufacturing activity. In their study, this pollutant intensity index is used in evaluating industrial waste management and/or ranking the industrial sectors in terms of pollutant intensities. Basically, such effort of measuring and ranking pollutant intensities explains respective pollution performance of various firms of a given industrial sector. In this purpose, Jaggi and Freedman (1992) use ‘overall pollution index’ by combining three environmental indicators such as biochemical oxygen demand, suspended solids and the pH reaction level. The index is computed as a sum of the ratios of all three observed values of indicators to their respective largest values observed in the sample and multiplying by 100.

Wehrmeyer (1993) considers the ratio of ambient concentration of the energy factors and the effluent factors of production to its legal limit in a functional form and explains the result as the extent of damage to the environment. Additionally the study measures the ratio between the actual discharge of all of its factors concerned and their respective legal limit. ‘Overall environmental performance’ is then computed and explained by summing those two ratios for a given firm.

Tyteca (1996) defines ‘standardized aggregate environmental performance’ indicators by expressing values falling between 0 and 1 (0 as bad environmental performance and 1 as that of the good). Three categories of factor, i.e., inputs, products as desirable outputs and pollutants in the form of undesirable outputs are used there in modelling the DEA measures such environmental performances. For undesirable outputs, the study standardizes physical, chemical and biological units of the pollution indicators by using statistical normalization procedure and computes it as an aggregate form of score. The study also suggests that DEA not only allows researcher to measure environmental efficiencies but also to examine the nature and causes of environmental inefficiencies (bad environmental performance).

Sarkis and Talluri (2004) use energy (or raw materials) and labor as inputs and four outputs; sulphur dioxide (SO_2), nitrogen oxides (NOx), and carbon dioxide (CO_2), and usable energy. Except the usable energy other three outputs are defined as undesirable outputs. However, their DEA model treats these undesirable outputs as inputs so that these can be minimized similar to other inputs. This study defines the 'eco-efficiency score' as a ratio of usable energy to the aggregated value of inputs and undesirable outputs.

An eco-efficiency analysis of production activities such as agriculture requires attention to define the undesirable output factor. Specifically, as a relevant part in evaluating expected level of production efficiency, environmental performance could usually be addressed by defining eco-efficiency i.e., by evaluating environmental indicators (impacts) functioning there in agricultural farms. Being inspired by the DEA notion and its advantages in using environmental attributes, eco-efficiency in agriculture could be explained as how well the farm is performing environmentally. Following this idea, Ismail et al. (2013) suggest that eco-efficiency can be addressed in terms of environmental productivity and defined as the ratio of yield value per unit of environmental impact. However, Reinhard et al. (2002) define environmental efficiency as the ratio of minimum feasible level to observed level of an environmentally detrimental input used there in agricultural farms.

Many agri-environmental studies explain the notion of environmental efficiency in terms of 'nutrient balance' approach and define the eco-efficiency as the differences between the total amount of nutrients in inputs and outputs (e.g., Tellarini and Caporali, 2000; van der Werf and Petit, 2002; Yli-Viikari, et al., 2007; Hoang and Alauddin, 2010). These studies measure pollution as the nutrient balance; and explain the reductions in pollution while there is reduction in the nutrient balance by reducing the amount of input nutrient. The farms with the smallest nutrient balance would cause the least air and water pollution and are thus identified as environmentally efficient (Hoang and Alauddin, 2012).

A nutrient balanced approach of measuring environmental performance and evaluating agricultural sustainability is conditional on considering zero nutrient contents for immaterial inputs (e.g., land, labor, capital, etc.). Particularly, in empirical studies on agricultural efficiencies, such presumption of zero content property of non-zero inputs is widely criticized because inputs such as land, labor and capital involve considerable amount of costs (both monetary and environmental) in agricultural production and making them zero will not help the DEA model to explore farms' true efficiency.

Hoang and Rao (2010) also argues that nutrient balance approach treats non-material inputs ambiguously and consequently lacks generalized weights that are applicable for various materials that are involved in the production process. Therefore, their study defines 'cumulative exergy balance' approach that calculates the difference between cumulative exergy in inputs and exergy in outputs in agriculture. This approach as an ecological efficiency measure potentially captures the effects of resource extraction and pollution in a comprehensive way (Bastianoni, et al., 2005; Chen, et al., 2009; Hoang and Alauddin, 2011; 2012). Following the second law of thermodynamics Hoang and Rao (2010) explains that the amount of exergy which goes back to the environment is high-entropy wastes and thus has the potential power to pollute. The ecological perspective of sustainability suggests that those farms which have the smallest cumulative exergy balance are those which extract the least total and cumulative resources from the ecosystem, and cause least cumulative pollution (Hoang and Alauddin, 2012).

Generally, studies on environmental efficiency define and formulate environmental impact indicators as a denominator of measuring the eco-efficiency. Therefore, eco-efficiency of agricultural production simply implies the notion of producing crops while generating minimum level of environmental impacts. This entails the idea of producing maximum outputs using minimum inputs while reducing environmental or ecological impacts compatible with the nature's absorptive capacity. In this regard, DEA shows desirable potential by incorporating environmental aspects in form of the ratios of desirable outputs to undesirable outputs and inputs into the efficiency model in such a way that explains comparative analysis of environmental performances. Specifically, non-parametric efficiency measures such as the DEA can usefully and effectively allow the derivation of environmental performance indicators. Specifically, the ecologically motivated DEA helps analyze the environmental impact as a major cause of a declining farm's true production efficiency. Therefore, in evaluating environmental sustainability, analyzing eco-efficiency by using a production frontier-based DEA is useful.

Depending on the topographical features and climatic conditions, different countries and regions may have different types of environmental impacts while producing different agricultural crops. Therefore, it is necessary to study the evidence of environmental impact generated production inefficiency focusing on a given country context and for a given type of agriculture.

5.2.3 Environmental impact and production inefficiency: Bangladesh studies

During the past few decades Bangladesh environment and natural resources have been affected because of agricultural pollution, influenced by widespread cultivation of chemical-intensive crops such as HYV rice. As a chemical-intensive irrigation-based agriculture, these high yielding modern varieties not only induces potential risk in terms of generating agricultural pollution but also leads to declining productivity (Alauddin and Tisdell, 1991). While analyzing productivity data, Rahman and Salim (2013), find that Bangladesh agriculture has been experiencing negligible improvement in technical efficiency (i.e., 0.01 per cent per annum) across the period from year 1948 to year 2008. A declining productivity scenario, particularly for Bangladesh HYV rice farms, is also shown by Alam et al. (2011). The study examines the changes in technical efficiency for rice farms using a balanced panel data over a period of 1987 to 2004. Their result indicates that technological progress increased significantly but technical efficiency has declined over the study period. The technical efficiency was 83 per cent in 1987 and 74 per cent in 2000, whereas it was 60 per cent in 2004 for HYV rice.

High level of inefficiency present there in modern rice production certainly indicates that Bangladeshi rice farmers are not fully efficient (Rahman, 2011; Alam, et al., 2011). Similar to other studies (e.g., Sharif and Dar, 1996), Rahman (2011) finds that although the return on modern rice is significantly higher than the return on traditional rice, a high level of inefficiency and decreasing return to scale exists in modern rice production. Sharif and Dar (1996) analyzed the potential for HYV rice cultivation in small farms compared with other traditional rice varieties in Bangladesh. The study finds that with traditional varieties such as *Aman* rice, the level of technical efficiency is higher than the technical efficiency of HYV rice cultivation. Evidently, Bangladesh Economic Review (BER) reports inconsistent percentage changes of the annual yield rate data on Bangladesh HYV rice agriculture through the previous crop years (BER 2005-2012) (Chapter 2, Section 2.4 and Table 2.9 for inconsistent pattern of Bangladesh HYV rice yield growth rate). Inconsistent growth rate in annual HYV rice yield rate and resultant decline in its technical efficiency implies that there remains substantial scope to increase production by improving technical efficiency alone.

It is substantially noted by substantial agro-ecological research that inconsistency in HYV rice production could be explained by the extent of agricultural pollution and environmental impact factors (e.g., Wadud and White, 2000; Rahman and Hasan, 2008; 2011). For instance, to evaluate farm-level technical efficiency, Wadud and White (2000) identified environmental factors that considerably influence the technical efficiency of rice farmers. Particularly, their study identified an increase in the soil degradation problem as a major cause of realizing this technical inefficiency.

Evidently, a study by Rahman and Hasan (2008) reveals that environmental factors significantly influence farm productivity and technical efficiency in Bangladesh. The study analyzes that improvement in environmental production conditions such as soil fertility through soil conservation and crop rotation could considerably improve technical efficiency.

In an addition to its effect on productivity and technical efficiency, also Rahman and Hasan (2011) find environmental conditions influencing considerably on farm profitability and farmers' resource allocation decisions. In this regard, the study particularly highlights land suitability, soil fertility, pest infestation, weed problems and weather conditions as some of those environmental constrain that would affect farms' output supply and input demands.

Focusing on the weather condition as a cause of initiating technical inefficiency, Chowdhury (2010) finds considerable level of inefficiency in irrigation water inputs use that exists among Bangladeshi dry season rice farmers. Water is in short supply during the dry season winter months in Bangladesh and inefficient extraction of irrigation water thereby generates considerable risk of water depletion. Moreover, the study finds that irrigation water input inefficiencies compared with other input inefficiencies are higher in seven hydrological regions surveyed.

For a set of major crops data, the study by Rahman (2013) argues that it is not only the irrigation water but also the pesticide input which is used inefficiently by crop farmers. In Bangladesh, use of farm chemicals in form of pesticides increases at an alarming rate. It is approximately 10 per cent per annum while the corresponding yields growth rate of major crops is only 1 per cent annually. Increasing growth rate of pesticide application certainly indicates pest infestation problems in Bangladesh agriculture. Such types of environmental conditions (pest infestation problem) results in a steady declining rate in pesticide productivity followed by a decline in overall crop productivity.

In an addition to irrigation and pesticide input inefficiencies, Coelli et al. (2002) found that Bangladeshi rice farmers use chemical fertilizers inefficiently. They (farmers) frequently use chemical fertilizers more than the recommended dose in the study area. Such attitude of overusing chemical fertilizers and inefficient management of other inputs allocations result considerable allocative inefficiencies in Bangladesh rice production.

Therefore previous studies substantiate that Bangladesh HYV rice agriculture is experiencing declining trends in productivity and production efficiency because of agriculture generated environmental impacts. It is not only important to identify, perceive and analyze different environmental impacts but also measure the extent of such environmental causes at which the technical efficiencies are declining.

5.3 Research gaps

The operational research on environmental management focuses on different types of production sectors to measure environmental efficiency but commonly uses the production frontier-based approach. These include environmental efficiencies in energy production sector (Färe et al., 1996; Korhonen and Luptacik, 2004; Ismail et al., 2013), industrial sector (Yaisawarng and Klein 1994) and in agricultural industry (Poit-Lepetit et al., 1997; Dyckhoff and Allen, 2001; Hoang and Alauddin, 2010; 2012), etc. Three categories of factors, i.e., desirable outputs, undesirable outputs (environmental impact) and inputs are generally considered in formulating such DEA models that intends to evaluate relative environmental performances. However, some studies define such environmental (pollution) factors as bad output and the resulting product as good output while formulating their DEA problem (Sarkis and Cordeiro 2012; Cherchyey et al., 2013).

In agro-ecological studies of efficiency modelling, the eco-efficiency denominator, i.e., the environmental impact factor, is usually demarcated as the ‘undesirable output’ (Scheel, 2001; Seiford and Zhu, 2002; Amirteimoori et al., 2006). However, the challenge has always been in identifying different types of environmental impacts to define the undesirable output component. Few studies are there in operational research on eco-efficiency that could consider a variety of environmental impact attributes estimating environmental efficiency (Sarkis and Talluri, 2004). The difficulty here is to identify most influential environmental impacts among available indicators and to formulate a composite index incorporating all those identified impacts. Aggregation of environmental pressures into a single environmental damage index is thus a major challenge of eco-efficiency measurement.

As an effort Picazo-Tadeo et al. (2011) analyze *farming practice*-related one environmental impact and *farming state*-related four environmental impacts to define the undesirable output variable and incorporate it into their proposed model of environmental efficiency. These are crop specialization, nitrogen balance, phosphorous balance pesticide risk, and energy balance, respectively. Graham (2009) considers *farming state-related* environmental impacts such as the measure of nitrogen leaching and runoff as a proxy measure to evaluate the impact of chemical fertilizers application while modelling dairy farm’s environmental performance. Similarly, Reinhard et al. (2002) surveyed Dutch dairy farm data and studied the *farming practice*-related environmental impacts to evaluate how efficiently the farm is in using environmentally detrimental inputs, e.g., nitrogen fertilizer. However, Rahmanipour et al. (2014) analyze soil physical property data collected from selected sample sites of agricultural plots there in Qazvin province of Iran. Specifically, their study substantiates the importance of analyzing ‘soil quality’ as one of the most important *farming state*-related environmental phenomena. Many other studies also assess *farming state*-related environmental impacts i.e., the nutrient balance as an indicator of environmental damage while defining the undesirable output factor (Tellarini and Caporali, 2000; van der Werf and Petit, 2002; Yli-Viikari et al., 2007; Hoang and Alauddin, 2010; Nguyen et al., 2012).

The importance of evaluating socio-environmental aspects has been discussed by many recent studies on environmental performance and sustainability analysis (e.g., Ostrom, 2009; Ture, 2013). It is argued that analyzing human-environment interactions while evaluating the impacts of some production activities on the environment would represent the sustainability analysis as an inclusive one. Specifically, *farmers' perception*-related environmental impacts that represents socio-environmental aspect of the environmental sustainability in agriculture, is relevantly important. This, along with farming practice-related and state-related environmental impacts, has never been considered in a compact mode by previous agro-ecological studies on environmental efficiency.

In general, most of the agro-ecological studies formulate the undesirable output component by using aggregate-level pollution data for a given production activity. Aggregate-level pollution data on relevant environmental attributes are often less available and externalizes potential difficulties in analyzing the environmental damage extent in agriculture. Farm-level data would be worthwhile to address such agriculture-environment issue in this regard. Assessing environmental sustainability explained by the eco-efficiency measures using the farm-level data is a difficult task (Picazo-Tadeo et al., 2011). A workable approach to evaluate environmental efficiency at the farm level consists of evaluating whether the farmers are making efficient use of natural capital such as land and water. As a decision making agent, farmers' opinion and perception on farm-level environmental pollution is essentially important to analyze in this regard. Along with agro-ecological researchers, farmers could also perceive the extent of a variety of environmental impacts as the influencing factors lowering the level of farm production (Rahman, 2003; 2005). According to my best knowledge, no previous study has considered *farmers' perception*-related environmental impacts while defining the undesirable output factor and measuring the eco-efficiency of agricultural farms.

Significant divergence in environmental efficiency may result from the same types of production activities. This could be reasoned by different ways in which undesirable output components are dealt with or because of different possible trade-offs between environmental impacts are generated and environmental resources used as inputs (Färe et al., 1996). Therefore, environmental impact factor (or the undesirable output factor) accounting essentially requires reconciling relevant dimensions and aspects of a given production process and for a given country context. Effectually, in agricultural production, eco-efficiency measure that incorporates such composite environmental damage component (containing farming practice-related, state-related and farmers' perception-related impacts) would effectively be used as an operational tool to address the sustainability.

In common, using farm-level data on Bangladesh agriculture, early studies analyzed energy efficiency (Rahman and Barmon, 2012; Rahman and Rahman, 2013; Rahman and Hasan, 2014), technical efficiency (Sharif and Dar, 1996; Coelli, et al., 2002; Alam, et al., 2011; Bäckman, et al., 2011), and input productivity, etc. (Dasgupta, et al., 2007; Chowdhury, 2010; Rahman, 2013) in agriculture. Early studies also substantiate that Bangladesh agriculture is experiencing declining trends in productivity because of environmental constraints. However, environmental efficiency measures and analyzing the extent of environmental impact induced loss in production efficiency are rarely focused by previous literature. Particularly, such analysis for farm-level data on HYV rice agriculture, which generates considerable impacts on the farm environment, has never been done before.

Considering the existing research gaps in early studies the present chapter outlines some specific research questions. These are:

- How to combine farming practice-related, farming state-related and farmers' perception-related environmental impacts altogether into the efficiency analysis that could define the undesirable output factor for HYV rice agriculture in Bangladesh?
- How to incorporate the undesirable output component in production efficiency model that could measure the farm-level environmental efficiency or the eco-efficiency?
- How to evaluate environmental impact induced loss in production efficiency in Bangladesh HYV rice agriculture?
- What are the factors that would help realize the expected level of eco-efficiency in Bangladesh's HYV rice agriculture?

5.4 Objectives

Given the main objective of evaluating the loss in production efficiency due the environmental impacts in Bangladesh HYV rice agriculture, the present chapter specifies following specific objectives:

- Defining undesirable output factor of HYv rice cultivation by incorporating different environmental impacts present there in HYV rice farms in north-western Bangladesh.
- Estimating the production efficiency followed by environmental efficiency or the eco-efficiency for the selected set of HYV rice farms in the study area.
- Analyzing the gap between production efficiency and eco-efficiency that would explain the loss in production efficiency.
- Determining factors influencing the expected level of HYV rice farmers' eco-efficiency.

5.5 Conceptualizing production performance and environmental efficiency

5.5.1 The production performance

Production performance analysis has always been a prime concern among researchers studying the theory of efficiency and productivity (Fried, et al., 2008). Basic motivation behind the notion is to investigate three important issues. The *first* issue addresses whether a production unit is performing desirably in terms of production. The s*econd* issue exercises how well it is performing relative to the theoretical best. The *third* issue identifies production unit, whose performance is required to be improved among all other units present there in a particular production domain. Performance measurement technique varies depending on the nature of the research focus (Harold, 1993). For instance, national- or international-level performance of a production sector may be represented by analyzing macroeconomic indicators. Growth, revenues, labor unemployment, export-import balance, benefit-cost analysis, price level, and investment dynamics could be mentioned in this regard. However, performance of a production unit or a firm could well be explained by microeconomic indicators such as profits, cost effectiveness, average output, input optimization, labor productivity, capital formation, and most importantly by production efficiency.

In general, production efficiency would occur while the economy uses all of its available resources efficiently. In microeconomic theory, it is explained well by the notion of Production Possibility Frontier (PPF) (Black, et al., 2000). Firms that are operated using best-practiced production technologies could ensure efficiency. By improving such technologies a firm could extend its PPF outward implying efficient production with more output. It also indicates 'efficient production' when a production unit achieves the lowest level of its input cost. Equivalently, highest level of output produced could be indicated as efficiency potential in productivity analysis. Theoretically, a production unit is considered to perform efficiently in the long run when its marginal cost equals its average cost. Apart from these microeconomic techniques, the literature in efficiency and productivity prefers production efficiency as the best way to measure production performance (Fried, et al., 2008).

5.5.2 Efficiency as a measure of production performance

The idea of considering both inputs and outputs into a single model to measure production performance of a production unit has been well established by the theory of efficiency and productivity. In general, a production unit producing maximum quantity of output with least amount of inputs is said to be operating efficiently. Therefore, production efficiency minimizes costs/quantities of input subject to a given level of output.

Theoretically, the efficiency of a production unit (or decision making unit: DMU) could be measured by the production frontier. This involves measurement of the distance from observed point of inputs combination to that on the frontier (Coelli, et al., 2005). However, to measure economic efficiency (EE) the very first production frontier model proposed by Farrell (1957), uses the isoquant of an efficient farm and decomposes EE measure into allocative efficiency (AE) and technical efficiency (TE) in multiplicative form (expressed as EE = TE x AE). Therefore, production efficiency is important to evaluate because it explains the performance of a DMU (e.g., agricultural farm) by measuring the effectiveness of some specific inputs for a given level of outputs.

However, Farrell's pioneer work of economic efficiency leads to develop several approaches in analyzing efficiency and productivity. 'Stochastic Frontier' approach (Aigner et al., 1977; Meeusen and van den Broeck, 1977) and the 'Data Envelopment Analysis' (DEA) (Charnes et al., 1978) are two such seminal contributions in this regard. As a non-parametric approach, production performance measurement issues could be effectively analyzed by the later one, i.e., the DEA. This method is initially introduced in 1978 and researchers from various disciplines frequently appreciate this method and acknowledge its usefulness in modelling processes to evaluate DMUs' performances.

DEA uses mathematical models to select the 'fully efficient firms' from the data in a way to construct the piece-wise frontier (Ismail et al., 2013). The other strength of DEA is that it reduces the errors while estimating efficient frontier by minimizing its priori assumptions in such mathematical modelling. Because it requires very few assumptions, this approach has substantial potential for using and analyzing the complex (even unknown) nature of the input-output relations that are involved in a given set of DMUs. As discussed by Cooper et al. (2011), DEA can also be used to evaluate the same production activities that have been previously analyzed by other methods but in a different way to provide more relevant insights. Basic motivation behind DEA is thus to discuss and compare 'efficiencies' of each DMU in a straightforward way. Straightforward in the sense that it does not require formulation of explicit assumptions to measure efficiencies unlike that of various types of linear or nonlinear regression models. Such notion of the DEA approach in measuring production performances defines efficiency in two basic ways (Coelli et al., 2005). The Extended Pareto-Koopmans definition states that the attainment of full efficiency by any DMU is conditional on the fact that none of its inputs or outputs can be improved without worsening some of its other inputs or outputs. However, a theoretically possible level of maximum (full) efficiency cannot be derived from most of the research problems in social sciences. The second definition of the efficiency, i.e., the relative efficiency, could be used to address this challenge. Therefore, the strength of the relative efficiency notion relies in its applicability; i.e., it requires empirically available information only to measure efficiency. According to relative efficiency concept, a DMU is said to be as completely (100%) efficient based on available information if and only if the performances of other DMUs does not show that some of its inputs or outputs can be improved without worsening some of its other inputs or outputs. The definition itself disregards the need for any particular assumptions or weights that may be a necessity in analyzing relative importance of different inputs or outputs. Moreover, a DEA model, measuring relative efficiency, does not require any explicit specification of functional relation that is available there between inputs and outputs.

Because it does not need any presumptions of production units' functional behavior, it is relevant for this present study to consider such flexibility and applicability of the DEA. This study focuses on formulating the DEA models for measuring production efficiency of a DMU relative to a set of peer DMUs (e.g., agricultural farms cultivating HYV rice crop). Therefore, by analyzing such relative performance this study intends to estimate best-practiced frontiers. It is important because this will help us evaluate differences in various DMUs' (HYV rice farms) production performances. In this respect, the DEA is useful and applicable as it can identify factors responsible for causing such difference in DMUs.

For agriculture as an economic activity, sustainability in production or yield primarily depends on the operational skills of the farmer. This in turn entails sustainability of economic incentives that effectively motivate the farmers to remain in agribusiness. However, agricultural practices that fail to incorporate environmental protective measures and resource conservation would potentially face decreasing productivity. Consequently, such agricultural systems will likely to be neither economically nor socially viable. Agricultural farms that face a decreasing productivity trend will eventually lose their production capacity and the production efficiency as well (Hoang and Alauddin, 2012). It is thus essential to analyze environmental performances along with production performance when agricultural entities are concerned.

5.5.3 Environmental efficiency in agricultural production

The process of agricultural production directly interacts with natural resources and therefore impacts the environment. To sustain productivity growth in agriculture that depends on the environment and natural capital resources, it is important to analyze performance that could generate environmentally adjusted measures. Theoretically, farmers are required to ensure efficient utilization of marketable inputs to remain profitable and competitive in doing farming activities. However, agriculture not only uses marketable inputs such as cultivation machines, fertilizers, insecticides and seeds but also depends on the availability of some important non-marketable inputs (e.g., natural capital resources such as soil, water, and the atmosphere in general).

Natural capital, having public good characteristics in it, however, could be overused and undervalued by farmers in the production activities (Graham, 2009). Therefore, environmental impact of production activities is important to consider which would ensure efficient use of such inputs.

Literature in sustainable agricultural production system generally concern two core aspects while analyzing environmental performances. One aspect addresses natural resources extraction (e.g., soil, and/or water), and the other aspect concerns pollution to the environment because of cultivation practices (Hoang and Rao, 2010). Particularly, DEA is useful and effective in analyzing the environmental dimensions of a production activity. As one of the most important advantages of DEA, it allows the formulation of mathematical modelling and evaluates efficiencies for this environmental phenomena where there is a lack of conversion units to derive a common scale (Tyteca, 1996). Therefore, an ecologically generalized DEA can potentially be derived. Similar to production efficiency, the present study uses DEA in measuring the environmental efficiency (or eco-efficiency) that explains how efficiently a farm is performing environmentally relative to other farms in HYV rice cultivation.

The main function of eco-efficiency measures is to provide requisite information for decision making agents (e.g., farmers). Measuring eco-efficiency by applying DEA would efficiently derive inefficiencies because of environmental problems in such a way that allows farmers to arrive at an optimum decision. In this regard, Kuosmanen and Kortelainen (2005) identify two more purposes of measuring environmental efficiency. One purpose is that it could be considered the most cost-effective way that may minimize environmental pressures. The other purpose is that it is often easier to adopt policies that target efficiency improvement by evaluating eco-efficiency than to restrict the level of production (or economic activities). Eco-efficiency, therefore could certainly be considered a critical part of farms' competitive strategy (Porter and Van der Linde, 1995).

5.5.4 Conceptualizing the eco-efficiency

Since the 1990s, when it started to become recognized as a useful operational tool for sustainability analysis (Fritsch, 1995), a variety of criteria have been used to explain the concept of the eco-efficiency. For example, at the macro-level, eco-efficiency can be explained as maximizing GDP growth while minimizing its potential negative environmental impact (Picazo-Tadeo, et al., 2011). In contrast, eco-efficiency at a micro-level means creating more economic value with less environmental degradation. To generalize the idea of Keeble et al. (2004), eco-efficiency addresses the producing or delivering of goods while reducing the ecological impacts to a level that is compatible with earth's absorptive capacity.

One of the widely accepted definitions of the eco-efficiency is proposed by the world business council for sustainable development (WBCSD): 'Eco-efficiency is reached by delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing environmental impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity' (DeSimone and Pop-off, 1997). It is necessary to specify and operationalize such "comprehensive" definition of the eco-efficiency in terms of environmental impact indicators (Dyckhoff and Allen, 2001) that could evaluate the environmental performances. As an intuitive definition of the eco-efficiency, environmental performance of a production unit is described as a ratio of economic value added to the environmental damage generated there in production operations.

Taking into account of those eco-efficiency concepts, for agriculture particularly, the present study defines the eco-efficiency as the environmental impact adjusted production efficiency that minimizes the environmental impact of a given farm. Specifically, HYV rice farms' eco-efficiency would entail the idea of producing maximum rice outputs using minimum conventional inputs while reducing environmental impacts, generated there in the production process.

5.6 Analytical framework

5.6.1 Identifying and measuring environmental factors in defining undesirable output component

Different types of environmental impacts with different levels of the impact's extent may arise in the field of HYV rice agriculture. By reviewing previous literature and performing focus group discussion prior to the field survey, this present study identifies a list of seventeen most important environmental impacts frequently experienced there in Bangladesh HYV rice farms. Using the alternative indicator-based approach (AIA) represented there in Figure 4.3 (Chapter 4) this study aggregates these environmental impact indicator values into a composite form. Equation 4.1 explains the aggregation formula that is named as the composite environmental impact index (CEII). The CEII quantifies the aggregate impact on the environment while doing HYV rice cultivation for a given farm. The formulation methods and calculation procedure is described in detail in Chapter 4 (Section 4.6.4 and 4.6.5, Table 4.6) and the CEII model specification is represented there by Equation 4.9.

In measuring HYV rice eco-efficiency, the present study evaluates the undesirable output component, which is defined by the CEII. Therefore, the undesirable output factor CEII satisfactorily incorporates three separate types of environmental impact variable groups or environmental impact dimensions. These are production practice-related (i.e., means-based impacts: MBI), system- or state-related (i.e., effect-based impacts: EBI) and perception-related (farmers' perception-based impacts: PBI) environmental impacts (See Appendix 5-I for estimated values of the CEII for all of the observations).

5.6.2 Incorporating the CEII (undesirable output) into the eco-efficiency model

To measure HYV rice eco-efficiency, this present study chooses the DEA as it is recommended by various operational research and shows desirable potential incorporating environmental factors into the efficiency model (Poit-Lepetit, et al., 1997; Dyckhoff and Allen, 2001; Hailu and Veeman, 2001; Hoang and Alauddin, 2010; 2012). Seiford and Thrall (1990) identify various advantages of the DEA compared to other parametric or econometric approach. Most important one among those is that it uses linear programming (LP) models to solve optimization problems. Versatile property of the LP model, the technique to convert a LP model into dual from the primal extends the scope of the DEA to address optimization problems.

Additionally, Charnes et al. (1985a, 1985b) remarked that DEA easily analyzes these variables in performance evaluation problems, which are not even elements of an economic domain. Attributes such as environmental impacts in the form of pollution that are generated in the production process are an example in this regard. Sarkis and Talluri (2004) illustrate that DEA is characterized with relative efficiency and multifactor productivity measures that uses LP optimization to determine the relative efficiencies of different production units. They thereby explain its suitability to assess environmental performance by addressing research questions in reference to the ecological problems generated by the organizations. DEA has accordingly gained much attention in analyzing organizational decision making problems and proven its usefulness as a quantitative tool in evaluating the performances of different types of production entities. Eco-efficiency estimation by applying DEA[9] thus competently summarizes different environmental impacts and allows decision making units to arrive at an environmentally sustainable production decision.

5.6.2.1 Specification of the DEA-based production efficiency and eco-efficiency models

When the LP-based optimization problem involves the contraction of the bad outputs with the contraction of other conventional inputs and increase the good outputs the ecologically generalized DEA would effectively work solving eco-efficiency problems. Being inspired by the DEA notion and its potentiality in dealing with environmental attributes, this present study defines eco-efficiency in HYV rice agriculture as the estimate that implies how efficiently the farms could perform productively while full adjustment of the environmental impact component is ensured. Three categories of factors i.e., HYV rice as desirable outputs, CEII as undesirable (bad) output (i.e., the environmental impact) and land, labor, fertilizer, pesticide, irrigation, tilling and HYV rice seed as inputs are considered while formulating such DEA model. Following the idea, the proposed efficiency model assumes that there are ***I*** homogeneous farms (DMUs: HYV rice farms); consuming ***J*** inputs for producing outputs ***R*** (HYV rice: sub-variety HYV Aus, HYV Aman, and HYV Boro). The outputs corresponding to indices ***{1…Z}*** are desirable (good) outputs and the outputs corresponding to indices ***{Z+1, Z+2,…R}*** are undesirable (bad) outputs i.e., MBI, EBI and PBI are production practice-related means-based impacts, farming state-related effect-based impacts and farmers' perception-related perception-based impacts, respectively. This corresponds to the CEII when aggregated additively using equation 4.9. The proposed efficiency model represents all outputs as a weighted sum, but using negative weights for undesirable outputs. Suppose, ith farm produces y_{ri}^{g} units of desirable output (i.e., the HYV rice) and

[9] Brief overview of the theory of Data Envelopment Analysis (DEA) method is discussed in Section 3.2.3 Chapter 3.

y_{si}^{b} units of undesirable output (i.e., the CEII) by using x_{ji} units of jth input. At first, the production efficiency (ProE) is measured using Model 5.1. This study then incorporates undesirable outputs CEII into the model 5.1 and run a separate DEA (i.e., the Model 5.2) to measure the eco-efficiency (EcoE) (Charnes, et al., 1994; Korhonen and Luptacik, 2004). Model 5.2, is basically standard input-oriented DEA and based on the idea of incorporating all outputs as a weighted sum. However, this considers negative weights for undesirable outputs. In the EcoE model 5.2, the undesirable outputs behave similar to inputs such that the HYV rice farms reduce the inputs and adjust the undesirable outputs to increase true production efficiency or environmental efficiency (i.e., the EcoE) (Scheel, 2001; Seiford and Zhu, 2002; Amirteimoori, et al., 2006). Therefore, solving Model 5.1 and 5.2 would result out a pair of efficient frontiers that measure production efficiency (ProE) scores and CEII adjusted production efficiency i.e., the eco-efficiency (EcoE) scores, respectively. Korhonen and Luptacik, (2004) tested DEA models incorporating bad outputs different ways: (i) subtracting the bad output from the good output in the numerator [maximization problem]; (ii) adding the bad output with inputs in the denomenator while holding good output in the numerator [maximization problem], (iii) subtracting inputs from good output and taking this as a ratio to the bad output [minimization problem]; and (iv) adding bad output with inputs and taking this as a ratio to good output [minimization problem]. These authors found that all of these seemingly different models give similar results. This thesis considers the first model suggested by Korhonen and Luptacik, (2004). Following Seiford and Zhu (2002), this thesis hypothesized that EcoE would result in higher efficiency scores than that of the ProE because it involves full adjustment of the environmental impact extent happened in a given farm. Therefore, the production efficiency score and the eco-efficiency score could be cmpared. This would evaluate the level of efficiency after minimizing environmental impacts in agriculture.

Production efficiency model (ProE):

$$Max\ \ ProE_o = \frac{\sum_{r=1}^{Z} \mu_r y_{ro}^{g}}{\sum_{j=1}^{J} v_j x_{jo}} \text{..(Model 5.1)}$$

$$s.t.\ \frac{\sum_{r=1}^{Z} \mu_r y_{ri}^{g}}{\sum_{j=1}^{J} v_j x_{ji}} \le 1, \{i = 1,2,....I\}$$

$$\mu_r, v_j \ge \varepsilon, \mathrm{r} = 1,2,....\mathrm{z};\ \mathrm{j} = 1,2,....\mathrm{J}$$

$$\varepsilon > 0\ \ (non-negativity)$$

Using a standard technique (See, Model 3.2, Chapter 3), to transform the fractional models 5.1 and 5.2 into a linear version (Charnes, et al., 1978), following sets of equations are found, which are represented by Model 5.1′ and 5.2′, respectively.

Input-oriented linear programming model for ProE:

$$Max\, h_P = \sum_r \mu_r y_{r0}^{g} \qquad \text{...(Model 5.1}'\text{)}$$

$$subject\, to: \sum_j v_j x_{j0} = 1$$

$$\sum_r \mu_r y_{ri}^{g} - \sum_j v_j x_{ji} \le 0\ \ (i = 1...I)$$

$$u_r, v_j \ge \varepsilon$$

E**co-efficiency model (EcoE):**

$$\max\ \ \mathrm{EcoE}_o = \frac{\sum_{r=1}^{Z} \mu_r y_{ro}^{g} - \sum_{s=z+1}^{R} \mu_s y_{so}^{b}}{\sum_{j=1}^{J} v_j x_{jo}} \text{..(Model 5.2)}$$

$$s.t.\ \ \frac{\sum_{r=1}^{Z} \mu_r y_{ri}^{g} - \sum_{s=z+1}^{R} \mu_s y_{si}^{b}}{\sum_{j=1}^{J} v_j x_{ji}} \le 1,$$

$$\{i = 1,2,....I\}$$

$$\mu_r, v_j \ge \varepsilon, \mathrm{r} = 1,2,....\mathrm{z};\ \mathrm{j} = 1,2,....\mathrm{J}$$

$$\varepsilon > 0\ \ (non-negativity)$$

Input-oriented linear programming model for EcoE (Primal):

$$
\begin{aligned}
&Min\, g_A = \theta - \varepsilon 1^T (S^b + S^g + S^-)\\
&subject\ \text{to}: Y^g \lambda - S^g = y_{r0}^g\\
&\mathrm{Y}^{\mathrm{b}} \lambda + S^b = y_{s0}^b\\
&X\lambda - \theta x_{j0} + S^- = 0\\
&\lambda, S^-, S^g, S^b \geq 0\\
&\varepsilon > 0
\end{aligned}
$$

Input-oriented linear programming model for EcoE (Dual):

$$
Max\, h_E = \sum_r \mu_r y_{r0}^g - \sum_s \mu_s y_{s0}^b \qquad \text{...(Model 5.2}')
$$

$$
\begin{aligned}
&subject\,to: \sum_j v_j x_{j0} = 1\\
&\sum_r \mu_r y_{ri}^g - \sum_s \mu_s y_{si}^b - \sum_j v_j x_{ji} \leq 0 \ \ (i = 1 ... I)\\
&\mu_r, \mu_s, v_j \geq \varepsilon
\end{aligned}
$$

This study uses DEAP 2.1 software and choose Multistage-Input oriented-Constant return to scale DEA to run the Model 5.1′ and Model 5.2′ for a given set of HYV rice farm data on inputs, rice outputs and environmental impact as undesirable outputs.

5.6.3 Modelling determinants of expected eco-efficiency: The interval regression model

Technically, the eco-efficiency score, which is derived by solving Model 5.2′, ensures the full adjustment of the environmental impact (undesirable output) that occurred and therefore explains a farm’s true production efficiency. On the contrary, the production efficiency, which is derived by solving Model 5.1′, expresses efficiency scores with no adjustment of the environment impact factor (the undesirable output variable). The factors that influence the likelihood of achieving an expected level eco-efficiency on a no adjustment to full adjustment scale of eco-efficiency are important to analyze in this regard (Figure 5.1).

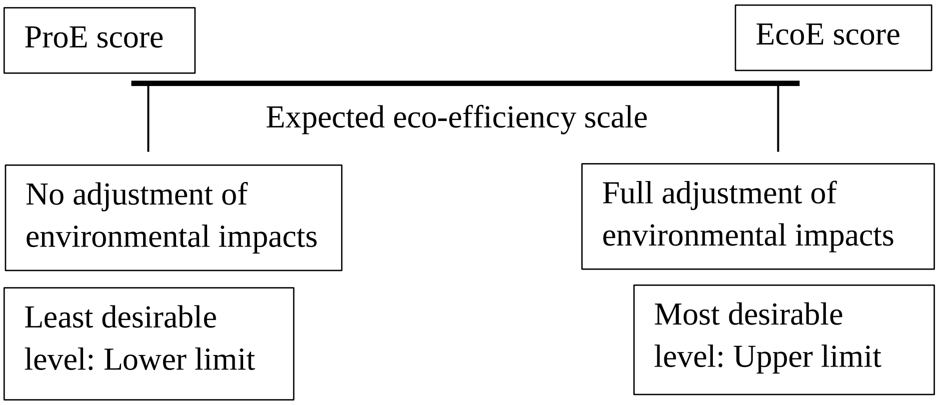


Figure 5.1: Diagrammatic representation of the expected eco-efficiency scale

Although it is theoretically desirable but empirically difficult to capture factors influencing full adjustment level, i.e., the EcoE using farm-level primary data. This is because this study uses relative performance approach of the DEA that estimates two sets of best-practiced efficiency frontiers, i.e., the ProE and the EcoE, which measure production efficiency and environmental efficiency, respectively, relative to other similar production units present there in a given production domain. Empirically socio-economic and socio-environmental factors determining the expected level of eco-efficiency is more worthwhile than determining the relative eco-efficiency. It is therefore hypothesized that expected value of the environmental efficiency (eco-efficiency) for a given HYV rice farm would lie within this threshold efficiency values, the ProE (as lower bound) and the EcoE (as upper bound).

Specifically, in the efficiency Model 5.1, where the undesirable output component is not adjusted, i.e., zero amount of undesirable output, y_b^0, to be subtracted from the desirable output, the efficiency will be comparatively lower and is therefore the lower bound. In the efficiency Model 5.2, where the undesirable output component holds some positive value y_b^+ that is to be subtracted from the desirable output for the upper bound of the expected eco-efficiency.

To examine determinants of the expected level of environmental efficiency, this study uses the interval regression model. Interval regression model is used when it is known into what interval each observation of the outcome variable falls, but it is not known the exact value of the observation ought to be (Manski and Tamer, 2002; Conroy, 2005).

Following Stewart (1983), Caudill and Jackson (1993) and Cook and McDonald (2013), the interval regression model is expressed as Equation 5.1.

$$y_i^* = X_i\beta + \varepsilon_i \qquad (5.1)$$

where y_i^* is the unobserved dependent variable, and only the interval threshold (the production efficiency (ProE) and the eco-efficiency (EcoE) that contains the dependent variable of y_i^* (expected eco-efficiency)) are observed. X_i denotes the $M \times 1$ vector of explanatory variables, and ε_i are independently identically and normally distributed random variables with a zero mean and variance of σ^2. The conditional distribution of the unobserved dependent variable is given by

$$y_i^* \big| X_i \sim N(X_i\beta, \sigma^2) \quad i = 1,...N.$$

If the real number line were partitioned into k mutually exclusive and exhaustive categories with boundaries $A_k\,(k = 0,.....,K)$, then it is observed $y_i = k$ if

$$A_{k-1} \le y_i^* \le A_k \qquad (5.2)$$

where A_{k-1} and A_k are the lower (ProE) and upper (EcoE) thresholds, respectively, for the *ith* farm. The exercise in this framework is to obtain consistent and asymptotically efficient estimates of the unknown parameters of β an σ^2 in the model. One approach to obtaining these estimates is the method of maximum likelihood. For interval censored data, the probability that $y_i = k$, that is, the probability that falls in the *kth* category is given by

$$\begin{aligned} P(y_i = k) &= P(A_{k-1} \le y_i^* \le A_k) \\ &= P\{[(A_{k-1} - X_i\beta)/\sigma)] \le (y_i^* - X_{i\beta})/\sigma] \le (A_k - X_i\beta)/\sigma]\} \\ &= F[(A_k - X_i\beta)/\sigma] - F[(A_{k-1} - X_i\beta)/\sigma] \qquad (5.3) \end{aligned}$$

where F[•] denotes the standard normal cumulative distribution function for the random disturbance error (ε). For an independent random sample of *n* observations, the likelihood function is the product of these probabilities that is taken across the *kth* categories and over the *n* observations, i.e.,

$$L = \prod_{i=1}^{n}\prod_{k=0}^{K}\{F[(A_k - X_i\beta)/\sigma] - F[(A_{k-1} - X_i\beta)/\sigma)]\}^{\delta_{ik}} \text{ ....(5.4)}$$

where $\delta_{ik} = 1$ if the *ith* observation falls in the *kth* category, and $\delta_{ik} = 0$ otherwise. Therefore, the log-likelihood function is:

$$L = \sum_{i=1}^{n}\sum_{k=0}^{K}\delta_{ik} \ln\{F[(A_k - X_i\beta)/\sigma] - F[(A_{k-1} - X_i\beta/\sigma]\} \text{ ....(5.5)}$$

Partially differentiating Equation 5.5 with respect the unknown parameters (β, σ) and setting the derivatives equal to zero yields consistent and efficient estimates of the β and σ (Caudill and Jackson, 1993). SATA 11 software is used for estimating parameters of the factors influencing expected eco-efficiency because STATA estimates the maximum likelihood estimators while running the interval regression (Cook and McDonald, 2013).

5.6.3.1 Interval regression model specification

A total of eight explanatory variables are selected for this study to explain the expected environmental efficiency for a given HYV rice farm. As for example, farmers' education, age, their access to extension service and cultivation experience are hypothesized as directly related to improve expected eco-efficiency of rice cultivation (Sharif and Dar, 1996). This is because cultivation experience and an extension service contact will make farmers more conscious when they use environmental resource inputs and farm chemicals, which will help achieve the expected level of eco-efficiency. Similarly young age farmers having lower level of basic education could never improve their eco-efficiency level up to an expected level. Young aged farmers cannot gather more cultivation experience and efficient decision making capabilities than middle aged farmers.

Following Alam et al. (2011) this study additionally assumes farmers' land ownership status and their agricultural income share as two important influencing factors. Because of their private property right, farmers who own their cultivable land is supposed to be using it in a more environment friendly way. As a proxy measure of farmer's subsistence pressure, share of earning member in his family could also be used to explain their expected eco-efficiency. This is because; increasing proportion of earning member would potentially reduce farmer's subsistence pressure, which in turn appreciates their environmental awareness (Rahman, 2005) in agriculture.

As an indicator of their environmental consciousness, this study emphasizes the analysis of farmers' living standards in terms of their household pollution status. Farmers, who use environment friendly energy source (e.g., solar power) for household purpose, follow proper disposal of household waste, use healthy sanitary system and pure water sources to drink, are supposed to be aware of environmental pollution. Such socio-environmental living standard would thus not only reflect farmers' environmental consciousness but also helps realizing expected level of environmental efficiency in farm production (See Appendix. 5-II for detail procedure constructing farmers' socio-environmental living index: SELI). Higher value of the SELI means lower potential for creating household pollution. The interval regression model Equation 5.1 as follows using Equation 5.6.

$$\begin{aligned} y_i^* = \beta_0 &+ \beta_{1i} AGE_i + \beta_{2i} EDU_i + \beta_{3i} EARN_i + \beta_{4i} AGIN_i + \beta_{5i} EXP_i + \beta_{6i} LNDW_i \\ &+ \beta_{7i} EXTN_i + \beta_{8i} SELI + \varepsilon_i \qquad \text{...(5.6)} \end{aligned}$$

where y_i^* is the expected eco-efficiency, i.e., the dependent variable for the *ith* farm. The interval threshold (the production efficiency ProE and the eco-efficiency EcoE) that contain the dependent variable y_i^* are observed by using Models 5.1′ and 5.2′ for the *ith* farm. AGE and EDU are the age and the year of schooling of the *ith* farmer, respectively. EARN is the earning member share for the *ith* farmer, i.e., the proportion of the number of earning members to the number of total family members. Farmers' agriculture-income share, i.e., their proportion of monthly income from HYV rice agriculture to total income from other agriculture and off-farm sources, is expressed as the variable AGIN. The next explanatory variable EXP is the number of years that is spent on HYV rice cultivation, i.e., the experience of the *ith* farmer. The status of extension service that is taken in the past crop year is evaluated by the variable EXTN that takes values 1 if the service is taken and is 0 otherwise for the *ith* farmer. The share of self-owned land, i.e., the proportion of self-owned holdings to total land holdings, is expressed by using the variable LNDW. Finally, the SELI variable describes the Socio-Environmental Living Index of the *ith* farmer who cultivates HYV rice.

5.7 Data

Model 5.1′ and Model 5.2′ are illustrated with an empirical application to a panel of Bangladesh HYV rice farms. Purposively my study collects primary data on production and environmental impacts of HYV rice agriculture by performing a survey there in three north western regions. Table 5.1 describes data on production factors used here in this study for modelling the ProE and the EcoE. While in Chapter 4, Table 4.8 and 4.9 represent environmental impact data for CEII, which are the normalized scores of the raw values collected there during the survey. A summary statistics of farmers' socio-economic and socio-environmental attributes considered here for this study is represented there in Table 5.2.

The farm-level primary survey finds that on average, Rajshahi farms produces HYV rice output valued BDT 55,583.96 per acre of land while the environmental damage index, i.e., the CEII (undesirable output) is 6.83 for this region. However, Pabna region farms produce lowest CEII, i.e., 6.53 (Table 5.1) and helps to realize the highest amount of output. Compared with the other two regions, the undesirable output index is evaluated as highest in Natore (i.e., CEII: 6.99). My survey finds soil erosion problem, crop disease and health impacts, fish catch reduction and intensive monoculture practice (expressed by crop concentration index) as some of the major environmental impacts influencing the value of CEII in this region (Chapter 4, Table 4.9). In Rajshahi, reduction in soil's water holding capacity is found at the top of the impact ranking list followed by crop concentration index crop disease and pest attack problems. These impacts are thus mostly responsible for raising the CEII in Rajshahi HYV rice farms. While most important influencing factors raising Pabna region's CEII are high crop concentration index, a greater amount of health impacts from farm chemicals and soil compaction problem.

Compared with the other two regions, Rajshahi farmers are applying highest quantity of chemical fertilizers per acre of land while Natore farmers are applying the highest quantity of the chemical pesticides. Moreover, Natore and Rajshahi farmers are using the irrigation input more intensively than that of the Pabna farmers. In these regions, the labor input cost is also higher than that of in Pabna region. Costly varieties of HYV rice seeds are purchased and cultivated by Rajshahi farmers compared with the other two regions' farmers. The descriptive statistics of HYV rice inputs use shows that comparatively, all inputs, except the land input, are allocated in a more efficient way by the Pabna farmers (Table 5.1). However, land rental value in Pabna region is almost double compared with Rajshahi and Natore. This may be partially explained by the reason why this area's farmers hold higher proportion of the land (99 per cent of their total land holdings) by own and rarely rent a piece of cultivable land (Table 5.2). The mean age of the farmers in Pabna is 53 years (approx.), whereas it is 47.46 and 46.24 in other two study regions, Rajshahi and Natore, respectively. Higher age of the HYV rice farmers producing lower CEII in Pabna would help hypothesize a direct relation between farmers' age and expected eco-efficiency. Mean years of farmers' schooling ranges 6.52 to 7.86 and their HYV rice cultivation experience ranges 14.3 to 15.3 years. Approximately 68 to 71 per cent of the family members earn in a family of the farmer and higher proportion thus implies lower subsistence pressure for farmers. In this regard the survey data shows that Rajshahi and Natore farmers are facing more subsistence pressure than that of Pabna farmers. Moreover, 53 to 67 per cent of their monthly income comes from agriculture, whereas Pabna farmers acquire 71 per cent of their income from agriculture alone. Additionally, 30 per cent of the Pabna farmers frequently contact agriculture extension services to obtain efficient farming ideas and expert suggestions, whereas only 11 and 19 per cent of farmers in Rajshahi and Natore seek extension services, respectively. The socio-environmental living index is also higher in Pabna than in Rajshahi and Natore. This result implies that Rajshahi and Natore farmers are not very conscious of generating household pollution. This finding can also be explained by the reason why these farmers use more farm chemicals and intensive irrigation for HYV rice agriculture and have less potential to achieve the expected level of eco-efficiency.

Table 5.1 Descriptive statistics of HYV rice inputs and outputs

	Desirable Output price TK per Acre	Chemical Fertilizer Kg per Acre	Pesticide Kg per Acre	Irrigation Cost BDT per Acre	Seed Cost BDT per Acre	Tilling Cost BDT per Acre	Labor Cost BDT per Acre	Land Rental Value BDT per Acre	CEDI (Un-desirable Output)
					Rajshahi: Number of Farms 113				
Mean	55,583.96	236.19	4.43	5,648.25	6,253.35	2,453.35	16,383.49	17,551.84	6.83
Std. Dev.	14182.58	55.43	2.26635	2186.14	6791.81	599.17	6081.35	17437	0.87
					Pabna: Number of Farms 101				

Mean	60,549.36	181.23	3.48	4,557.76	1,528.25	1,669.35	14,499.68	30,469.44	6.53
Std. Dev.	10170.55	30.02	0.99	2431.52	707.12	235.10	4966.56	5903.52	0.77
Natore: Number of Farms 103									
Mean	58,823.17	221.87	5.54	6,354.01	1,680.76	2,505.00	19,075.33	15,227.79	6.99
Std. Dev.	21488.39	52.09	2.73	3,725.97	1885.27	1037.53	16185.37	6348.32	0.74

Source: Field survey October –December 2013.

Table 5.2 Summary statistics of farmers' socio-economic and socio-environmental attributes

	Rajshahi		Pabna		Natore	
Name and Description	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
Age (years) [AGE]	47.46	13.89	52.65	13.32	46.24	12.97
Schooling years [EDU]	6.52	4.41	7.08	4.73	7.86	3.62
Earning member share [EARN]	0.68	0.1	0.71	0.13	0.67	0.12
Agriculture-income share [AGIN]	0.67	0.26	0.71	0.27	0.53	0.27
HYV rice cultivation experience (years) [EXP]	14.3	3.83	15.3	3.98	14.9	4.62
Extension service taken in the past crop year [EXTN]	0.11	0.30	0.30	0.46	0.192	0.39
Share of self-owned land [LNDW]	0.9	0.2	0.99	0.49	0.79	0.26
Socio-Environmental Living Index [SELI]	0.74	0.09	0.79	0.1	0.71	0.12

Source: Field survey October –December 2013

5.8 Analysis of empirical results

5.8.1 Production efficiency and eco-efficiency

Table 5.3 presents a statistical description of the production efficiency score (ProE) and the eco-efficiency score (EcoE) for HYV rice farms across the study regions (See Appendix 5-III for ProE and EcoE scores of all farms). The three-region average result shows that HYV rice farm's production efficiency is 74.7 per cent while the eco-efficiency is 89.1 per cent for the same set of farms. This implies the fact that minimizing environmental impacts would allow the HYV rice farms to achieve higher efficiency than farms do not minimize environmental impacts along with production inputs. This is because, adjusting the environmental impact output component increases farms' efficiency from 74.7 per cent to 89.1 per cent. In other words, it could be said that HYV rice farms in the study area would achieve true production efficiency up to 89.1 per cent if they could minimize producing the undesirable output (environmental impacts) appropriately. Technically, it could also be explained in a way that on average, Bangladesh HYV rice farms are producing 40 per cent of its theoretical maximum[10] level of composite environmental impact and are thus responsible for restraining farms to achieve true efficiency in HYV rice production.

Regional-level analysis shows that on average, production performance of the Rajshahi farm household is 72.6 per cent while minimizing the environmental damage component influences the efficiency score up to 88.6 per cent. Given all other inputs combinations same, HYV rice farmers in this region could improve their production efficiencies by 16 per cent. Similarly, up to 6.6 percent and 20.3 per cent improvement in production efficiency could be achieved by Pabna and Natore region farmers, respectively. Among the three study regions, Natore farms perform in more environmentally inefficient ways, which can effectively be justified by the highest index of undesirable output that is produced there (mean CEII for Natore: 6.99) (Table 5.1).

The estimated production efficiency score (Table 5.3) is similar to the production efficiency score of other studies on Bangladesh HYV rice agriculture (e.g., Rahman, 2011; Bäckman, et al., 2011, etc.). In their studies, Rahman (2011) and Bäckman et al. (2011) found that the mean level of technical efficiency of self-selected modern rice farmers is 82 per cent and 83 per cent, respectively. It is also mentioned that there remains substantial 'scope' to increase production by improving technical efficiency (Rahman, 2011) and achieve substantial gains in output with available resources and existing technologies (Bäckman, et al., 2011) in Bangladesh HYV rice agriculture. The present chapter successfully explains the 'scope' in terms of achieving environmental efficiency or eco-efficiency. Given the existing production technology and available inputs, minimizing such an amount of environmental impact (undesirable output) along with a simultaneous increase in desirable output (the HYV rice) could result in minimizing loss in production efficiency or acquiring true production efficiency.

Table 5.3 The Production efficiency and eco-efficiency scores

	Rajshahi		Pabna		Natore		All region	
	ProE	**EcoE**	**ProE**	**EcoE**	**ProE**	**EcoE**	**ProE**	**Eco E**

[10] The theoretical maximum level of $CEII_m$ is 17.0 [This study has 17 types of environmental impact indicators to formulate the composite one, each of which holds a maximum impact value of 1] $CEII_{ave}/CEII_m$=6.78/17.0=0.3988 (approximately 40 per cent).

Mean	0.726	0.886	0.862	0.928	0.659	0.862	0.747	0.891
Std. Dev	0.197	0.109	0.103	0.061	0.196	0.124	0.190	0.105
Max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Min	0.079	0.593	0.593	0.796	0.161	0.551	0.079	0.55
Scope to improve the efficiency (mean EcoE-mean ProE)	0.16 (16%)		0.066 (6.6%)		0.203 (20.3%)		0.144 (14.4%)	
Number of Farms	113		101		103		317	
Efficiency Range	% of the Sample Farms							
0-0.09	0.89	0	0	0	0	0	0.32	0
0.10-0.30	0.89	0	0	0	0	0	0.63	0
0.31-0.50	12.39	0	0	0	28.16	0	13.24	0
0.51-0.70	33.63	8.85	7.92	0	36.89	13.59	26.49	7.57
0.71-0.90	30.97	45.13	58.42	41.58	19.42	43.69	35.96	43.53
0.91-1.00	21.24	46.02	33.66	58.42	15.53	42.72	23.34	48.89

Source: Own calculation

5.8.2 Determinants of expected eco-efficiency

Table 5.4 presents coefficients of the interval regression model that would explain the factors determining the expected level of eco-efficiency for HYV rice farms. The log-likelihood ratio test, shown below there in Table 5.4, represents that the model as a whole is statistically significant. This implies that all of the explanatory variables, as a group, contribute significantly explaining the expected eco-efficiency. The interval regression model specifically identifies the extension services contact status and land ownership parameters as statistically significant for this study. The result is similar to the study by Alam et al. (2011), who found that in Bangladeshi agriculture, owner operators are clearly more efficient than the tenants. Farmers, who cultivate self-owned land and seek extension services frequently, will more likely follow environmentally friendly land management practices and substantial control over generating environmental impacts. Additionally, the farmers who continue to contact agricultural extension services will benefit from receiving expert advice on HYV rice cultivation techniques, which ensures efficiency in environmental resources and input management in rice production. As one of the statistically significant socio-economic factors, the estimated model identifies the earning member share as positively related to the expected value of eco-efficiency. The study by Rahman (2005) also found that subsistence pressure affects farmers' environmental awareness. Additionally, this study finds that a lack of HYV rice income, compared with other income sources, restrains the scope of increasing farmers' environmental efficiency. A considerable amount of income that is realized from HYV rice agriculture initiates economic incentives and improves eco-efficiency. These economic incentives will be ensured by the gross returns of HYV rice production because the gross return on modern rice is significantly higher than the gross return of traditional rice in Bangladesh (Rahman, 2011).

The interval regression model additionally estimates that improvement in farmers' educational status raises the expected level of eco-efficiency. Obviously, education helps farmers explore their environmental awareness (Rahman, 2005) and makes them conscious of using environment depleting inputs. This present analysis could not find farmers' age and their experience estimates as statistically significant. However, the relation with the dependent variable satisfies the hypothesized direction. Contradictions in analyzing the direction of the relation between farmers' age and their efficiency have been found in previous literature. Some studies find young farmers who do less off-farm work would perform more efficiently (Alam et al., 2011; Bäckman et al., 2011) but some other find it as positively related (e.g., Sharif and Dar, 1996). Apart from these, social-ecological status has been evaluated by recent studies as an important factor determining natural resource management (Estoque and Murayama, 2014). This thesis estimates the variable 'farmers socio-environmental living index' is positively related to the farm-level expected eco-efficiency. This implies that environmentally aware farmers would not only be expected to live better life style and release less household pollution but also manage natural resource extraction in a way that improves their environmental efficiency in agriculture.

Table 5.4 Estimated interval regression model:
Determinants of the expected eco-efficiency in Bangladesh HYV rice farms

Number of observations: 317	Dependent variable 1	ProE
Uncensored observations: 57		
Interval observations: 260	Dependent variable 2	EcoE

Explanatory variables	Interval regression estimates	Standard Error	Probability values	z
Constant	0.6719597	0.0712563	0.000	9.43
AGE	0.0002744	0.0006037	0.649	0.45
EDU	0.0031674	0.0020314	0.119	1.56
EARN	0.1203036	0.060032	0.045	2.00
AGIN	0.0322237	0.0267104	0.228	1.21
EXP	0.0000549	0.0018725	0.977	0.03
LNDW	0.0491592	0.0204598	0.016	2.40
EXTN	0.0565894	0.0195992	0.004	2.89
SELI	0.0514514	0.0700405	0.463	0.73
Log-likelihood	- 370.32			
LR $chi^2(8)$	24.67			
Prob: chi^2	0.0018			

Source: Own calculation

5.9 Conclusion

As an operational tool for evaluating environmental sustainability in agriculture, this chapter measures eco-efficiency of HYV rice agriculture in north western Bangladesh. The major challenge of assessing eco-efficiency or environmental efficiency is integrating relevant environmental damage factors into a single impact index. As an effort a composite environmental impact index (CEII) has been used. The CEII incorporates three groups of environmental indicators. These are farming practice-related (MBI), farming system-related (EBI) and farmers' perception-related (PBI) environmental impacts groups. The CEII is incorporated into the production efficiency model as an undesirable output factor in terms of an eco-efficiency denominator. The resulted CEII-adjusted production efficiency estimates Bangladeshi HYV rice farmers' environmental efficiency in terms of eco-efficiency scores. Technically, the eco-efficiency score explains the true production efficiency of a given farm when all of its undesirable outputs has been minimized. Moreover, without incorporating the undesirable output factor CEII, production efficiency scores are estimated. The gap between production efficiency and eco-efficiency score evaluates the extent of environmental impact-induced loss in production efficiency for a given farm.

Analyzing environmental impact-induced efficiency loss in agricultural production would help decision making units (farms) promoting environmental sustainability. On average, production efficiency of Bangladesh HYV rice farms is 74.7 per cent while the eco-efficiency of the same set of farms is 89.1 per cent. This implies that with available resource and existing production technology, Bangladesh HYV rice agriculture is experiencing approximately 14.4 per cent loss in production efficiency by producing undesirable output (i.e., the environmental impact component, CEII). Minimizing the environmental impacts in HYV rice production that helps realize an expected level of eco-efficiency (or the true production efficiency) significantly relates to farmers' socio-economic and socio-environmental attributes. These include proportion of earning members in farmers' family, self-ownership of agricultural land and their (farmers') visit to agriculture extension service centers. Additionally, farmers' age, education, experience of doing HYV rice agriculture, agricultural income share and their socio-environmental living standard directly relate to the expected level of the eco-efficiency in the study area.

For developing economies such as Bangladesh, realizing an increased level of HYV rice production and limiting its environmental impacts essentially requires the collective efforts of the government and the farmers. Agricultural practice would result with external costs in the production process if exploited intensively by an eco-inefficient farm. To internalize such externality, performing an economic valuation of the external costs is important. Particularly, analyzing economic valuation of impact-wise external cost is of immense significance in this regard. The next chapter analyzes economic valuation of the environmental impacts in Bangladesh HYV rice agriculture.

CHAPTER SIX

Environmental impact of HYV rice agriculture and its economic valuation

6.1 Introduction

Over recent decades, efficiency analysis of agricultural production has extended its traditional market orientation toward a non-market orientation of interest. Certainly, the attainment of efficient resource allocation is the basic intuition behind both of these research orientations. However, the role of efficient resource allocation decisions are especially important for economic activities (e.g., agriculture) with externalities (e.g., environmental impacts) and in all cases where property rights are not clearly defined (Colman, 1994; Gunatilake, 2003; Tegtmeier and Duffy, 2004). For instance, the external cost of emissions and pollution that is produced by agricultural production has always been bypassed or underestimated by private decision making farms. This underestimation is because the market cannot efficiently allocate these agricultural negative externalities, which have ill-defined property rights.

Incorporation of environmental impacts into production efficiency analysis could be explained by the eco-efficiency measures. The eco-efficiency estimation addresses measuring whether and to what extent environmental pollutions (impacts) are being allocated (minimized) efficiently in agricultural production. It serves as the basis for improving resource allocation decision, while the external cost analysis of the environmental impact, as a non-market economic valuation, potentially ensures such improvement (Colman, 1994; Gunatilake, 2003). Economic valuation of the natural resources and environmental impacts helps determine the welfare implications of the environmental phenomenon that is associated with any course of an economic activity such as agriculture. Particularly, environmental impacts of agriculture, as the negative externality, if internalized by analyzing its economic valuation would help achieving environmental sustainability and thereby contribute overall sustainability in agriculture as well (Tisdell, 2007; Zaks, 2010; Moss and Schmitz, 2013).

Following such importance, present chapter extends the market oriented eco-efficiency analysis towards non-market oriented economic valuation of the environmental impacts considering Bangladesh HYV rice agriculture. Section 6.2 reviews literature those use a common method, the contingent valuation (CV), to economically evaluate environmental phenomena in analyzing welfare effects of a given change in natural resource allocation. Studies on economic valuation of environmental resource management in agriculture are also reviewed here in this section. Important agri-environmental issues that have been ignored or even not been addressed by previous economic valuation studies are discussed in Section 6.3. Section 6.4 explores represent some specific research questions. Section 6.5 outlines specific objectives to be illustrated in this chapter. A theoretical background of economic valuation of the environmental resources is presented in Section 6.6. Section 6.7 explains the methodology and Section 6.8 presents the data. Result analysis and chapter conclusion are presented in sections 6.9 and 6.10, respectively.

6.2 Literature review

6.2.1 Economic valuation in environmental resource management

Because of its public good nature, environmental impacts do not have market price. Hypothetical choice contingent valuation (CV) approach is generally applied to evaluate external cost associated with the production activity. Mostly, the CV approach analyzes individual's willingness to pay (WTP) for managing the externality or the attainment of the environmental welfare derived from environmental impact management activities (Carlsson and Martinsson, 2001; Abou-Ali and Carlsson, 2004, Carson and Hanemann, 2005; Kallas, 2007). Theoretically, willingness to pay refers to the amount an individual would agree to pay to reduce something that generates disutility (Hanemann, 1991; Cawley, 2008; Yang, et al., 2014). For instance, farmers' WTP amount refers to the value that they would agree to pay for managing a given type of environmental impact, which influences inefficiencies in environmental resources allocation in agriculture. Therefore, the WTP values could be explained by the external cost involved in the given production process. Studies on environmental economics and management use willingness to pay (WTP) estimates fromthe CV approach for evaluating natural resources extraction and environmental degradation.

For instance, Day and Mourato (1998) analyze the value that the Beijing residents would agree to pay for managing negative externalities caused by industrial expansion. It is observed that industrial expansion is generating increased amount of surface water pollution in many rivers in China. Using the CV approach, considerable amount of non-use value (or external cost) of water pollution, in terms of Beijing residents' WTP for having clean river water, is then evaluated in the study survey.

Longo et al. (2006) economically evaluated the externalities of a hypothetical program that promotes renewable energy production. Similarly, the study uses the CV method and assesses WTP of a sample of Bath residents in England for a higher price of electricity that internalize the external cost that is caused by fossil fuel technologies. Specifically, the study assesses respondents' preferences for renewable energy policy that encourages private and public benefits in terms of air pollution and climate change management and energy security. Their CV exercise reveals that Bath consumers are willing to pay a higher value for electricity that internalize such energy production externalities and thereby ensures consumers' welfare.

Therefore, CV and WTP analysis are useful in evaluating the economic valuation of the externalities that are associated with any production activities. It is also substantiated in a study by Abou-Ali and Carlsson (2004). Here, they assess the welfare effects of improved health status by analyzing respondents' WTP for improved water quality. For this purpose, by using the choice experiment, the study surveys a random sample of Cairo metropolitan households in Egypt. The random parameter logit model, applied here in the study, finds a significant WTP probability of the Cairo residents for improved water quality that ensures improvement of their health status. They find that improved water quality would serve environmental benefits, improve welfare effects and influence economic benefits as well.

Following the advantage of analyzing environmental benefits, Bateman et al. (2006) also performed an economic valuation of the water quality improvements of an urban river in Birmingham, UK, using the WTP approach. However, the study uses both contingent ranking (CR) and CV techniques for this purpose. The contingent ranking exercise, applied here in this study, finds that respondents are willing to pay GBP 8.64, GBP 21.34 and GBP 31.50 for a small, medium and large improvement in water quality so that it could be suitable for fishing, boating, swimming, under-water wildlife and plants. The estimated ordered logit model evaluates that ranked position for accepting a given water quality improvement policy scheme is negatively related to payments required for the policy implementation and positively related to the water quality attributes. Using the same set of data the study also performs comparative analysis of the CV results and CR results. Strong internal consistency in the relations between the observed and theoretically expected values of the parameters are found for the CV approach. While CR valuation over estimates the CV valuations as the WTP response rate comes significantly higher for the CR survey than that for the CV survey.

Considering such advantage of the CV approach, Welle and Hodgson (2011) estimate the economic value of environmental benefits by evaluating the property owners' WTP for restoring lakes in two watersheds in Minnesota, U.S. By using the CV method and an alternative model the study finds that mean value of the WTP would exceed the $30 amount for many households. Therefore, it is suggested that revenue of $30 a year could be collected from all water utility customers and from those who live closest to the improved quality surface waters. This is because the study finds water utility customers residing far away are less likely to perceive a net gain from lake restoring policies. Following the idea, it is also evaluated that the differences between lakeshore and non-lakeshore property ownership patterns, recreational use, income, and other socio-economic and watershed characteristics have significant influences on the WTP probabilities.

It is not only the environmental benefit and social welfare of managing production pollutions but also ecological benefit of natural and environmental resources conservation that are evaluated economically by environmental management studies using the WTP measures. For instance, Blomquist and Whitehead (1998) economically evaluate ecological benefits of wetland preservation by measuring respondents' WTP for activities conserving natural resource such as wetlands. The study finds that respondents, who are aware of environmental benefits of the wetland preservation, are willing to pay more. In this regard, a study by Olorunfemi (2009) finds that it is not only the amount of respondents' WTP but also the proportion of respondents that decreases consistently as distance from the ecological amenity source increases. An important suggestion is thus articulated by both of these studies that respondents' knowledge and access to the environmental resource quality would lead more valid economic valuation of changes in environmental resource allocations.

Considering the importance of analyzing ecological benefit of environmental resource conservation, Naald and Cameron (2011) evaluate economic value of preserving the biodiversity in terms of reducing species' morbidity in U.S. Given the wake of environmental disaster that influences extinction threats for different species, the study evaluates humans' WTP a premium for conserving conventionally grown species. The conjoint choice stated preference survey, used by this study finds that as an effort to reduce species morbidity, people are willing to pay more for humanly raised species than conventionally raised species.

Additionally, Amigues et al. (2002) analyzed the ecological benefit of habitat preservation by performing economic valuation in their study. By using the CV method they analyze farm households' WTP, who live in the adjacent area of the Garonne River, in France and the willingness to accept (WTA) of households, who own land on the river banks, to provide a strip of riparian land for habitat preservation. The study reveals that farmers are willing to accept the amount consistent with their crop revenue for providing a piece of land. Similar to other ecological studies (e.g., Blomquist and Whitehead, 1998; Olorunfemi, 2009, etc.), this study also finds that the adjacent farmers will not likely agree to pay for a habitat preservation program.

As Longo et al. (2008) suggested, the ecological and environmental benefits of natural resource conservation projects are important to evaluate, and economic valuation research should also focus on managing a particular production sector (e.g., agriculture) to provide different environmental and ecological benefits. For instance, agriculture, as an important component of conserving ecological constituents, should be considered with much importance in evaluating agriculture and its ecological benefits.

6.2.2 Economic valuation of environmental resource in agriculture

Drake (1992) evaluates ecological benefit of preserving agricultural landscape by analyzing Swedes' WTP. It is revealed that the respondents are willing to pay annually 541 SEK (Swedish Krona) per person for agricultural landscape preservation projects. It is also found that the respondents' WTP is significantly and positively correlated to their income and level of education while negatively to their age. Most importantly, the study finds respondents' positive attitudes toward the WTP for preservation of the agricultural landscape in the study area.

To analyze ago-ecological welfare, Broch et al. (2013) similarly evaluated Danish farmers' willingness to participate in afforestation contracts that provided groundwater protection, biodiversity conservation or recreation by using the CV approach. The study assesses farmers' willingness to accept (WTA) as compensation amount that is required to enter into an afforestation project. Hackl et al. (2007) also assess local compensation payments for farmers to provide landscape amenities in Alpine tourist communities. This economic valuation of agri-environmental positive externalities found that the compensation payments potentially occur in less-favored areas such as communities where the provision of agricultural landscape services is relatively low and the countryside diversity seems to be endangered. The study thereafter expressed the potential scope to improve the ecological welfare in these study areas.

To focus on the environmental benefits of agricultural amenities, Michaud et al. (2012) investigated consumers' WTP a premium price for two environmental attributes of a non-food agricultural product. The study evaluates individual preferences for rose flowers production with an eco-label and a carbon footprint. The data, analyzed using a mixed logit model, reveals that consumers are willing to pay a significant amount of premium, both for reducing the carbon footprint and for getting eco-label (that ensures minimum environmental impacts) producing non-food agricultural product and ensuring ecosystem services (e.g., amenities) as well.

Studies on environmental management in agriculture not only require focusing on respondents' WTP (a premium) or WTA (a compensation) to provide ecosystem service but also analyzing their WTP for managing agriculture generated environmental problems. This is because agriculture that provides ecological benefit in terms of environmental resource conservation at the same time would have much potential of generating environmental problems. Evidently, a large body of literature also shows that recently, environmental degradations have arisen because of intensive agricultural practices (e.g., Rahman, 2003, 2005; Alauddin and Quiggin, 2008, etc.). Given the increasing risk of environmental impacts in agriculture, it is now essential to evaluate agricultural negative externalities and analyze efficient management of natural resource extraction in farm production.

In this regard, Travisi and Nijkamp (2004) particularly note that deterioration of the farmland ecosystem is the negative externality of chemical pesticides generates variety of environmental uncertainties. To analyze such uncertainties, their study evaluates consumers' WTP for environmentally friendly foodstuffs while discussing the importance of reducing the environmental impacts of chemical pesticides. The proposed choice experiment attaches a monetary value to the negative environmental effects such as reduction of farmland biodiversity, groundwater contamination and human intoxication. The study survey consumers' preferences in Italy and finds that in general consumers are willing to pay a substantial amount for agricultural foodstuff produced in environment friendly ways. Potentially, this in turn, would provide producers' (farmers') economic welfare, positively influence their profit and encourage producing foodstuff or cultivating crops using environment benign technologies.

In a survey that was conducted in small-scale Tanzanian farms, Amare et al. (2012) examined the influencing factors behind producers' (farmers') decisions to adopt environmentally friendly and improved production technology. The study suggests that if farmers, who have better access to adequate local supply of improved seed, information and private productive asset, human capital and potential for getting desirable price of their output, would feel encouraged to adopt improved production technology. The study additionally finds that the adoption of improved technology, in terms of using an improved variety of maize/pigeon-pea, positively influences farmers' income and increases their consumption expenditure, which improves farm household welfare. It is suggested that managing environmental functions of the agriculture in such a way would potentially ensure its economic and social functions (Kallas, 2007).

Economic valuation of agricultural multi-functionality is analyzed in several agro-ecological studies (e.g., Brunstad, et al., 2005; Kallas, 2007) with much more importance. As for example, Kallas (2007) evaluates the agricultural system of cereal steppes in Spain and uses choice experiments for performing an economic valuation of different function of the agriculture. Depending on their socioeconomic characteristics, an existence of significant demand for economic, environmental and social functions of the agriculture is found, by this study, among the individuals surveyed. Similarly, Brunstad et al. (2005) emphasized the importance of agricultural multi-functionality. However, these authors emphasize more on its ecological (landscape preservation) and social (food security) functions. Particularly, it is noted that agricultural land is a key component ensuring both landscape preservation and food security. For a data set surveyed in Norway, the study suggests that it would be more efficient and cost-effective to install land-extensive farming techniques as it could well execute its social and ecological functions by ensuring food security and agricultural landscape preservation, respectively.

Previous studies substantiate that ecological or environmental function of agriculture is the fundamental one which would help with providing its economic and social functions. To manage its environmental function, it is important to use environmentally friendly production technology and manage the environmental impacts of agriculture. As an important research issue, particular focus should be placed on the type of agriculture that generates many environmental degradation problems and therefore requires restoring its environmental functions. In this regard, economic valuation of environmental impacts caused by intensive agricultural practice is of immense significance. In this regard, studies on resource and environmental management widely substantiate the fact that WTP approach effectively addresses such environmental impact valuation problems (Baker, et al., 1988). The approach helps quantifying the qualitative data, on environmental attributes, in terms of economic values.

Following this potential for measuring environmental attributes, Baker et al. (1988) noted that for agriculture particularly, a farmer's WTP can be a comprehensive measure. It explains farmers' assessment of a given technology, which could effectively reflect his perception of its impact on production system and his attitudes toward the risk involved with. Effectively, environmental risk, involved with chemical-intensive and irrigation-fed farming technology, could therefore be addressed by analyzing farmers' WTP for managing an environmental problem. Baker et al. (1988) also noted that it is often difficult to perform economic valuation with on-farm trials or a farm-level study because of high statistical variability in experimental and non-experimental factors and the difficulties in valuing non-market inputs and outputs. The willingness-to-pay (WTP) technique is proposed to complement other techniques for addressing such evaluation difficulties.

6.3 Research gaps

- Selecting an applicable valuation approach

Previous studies mostly perform the CV surveys for evaluating the proportion of total respondents agree or disagree for an offered WTP price (e.g., Olorunfemi, 2009). Some other studies extend the analysis and prefer to estimate the likelihood of respondents' WTP for an environmental improvement by applying econometric techniques such as the ordered logit, conditional logit, probit models, etc. (Abou-Ali and Carlsson, 2004; Bateman, et al., 2006; Michaud, et al., 2012). Some of the early studies evaluate the value that the respondents would agree to pay for an environmental benefit using a well-structured choice experiment questionnaire (Day and Mourato, 1998; Longo, et al., 2008; Abou-Ali and Carlsson, 2004; Welle and Hodgson, 2011). CV method-based WTP studies that evaluate the WTP values using either iterative biding, payment card or dichotomous choice questions are also common in previous literature. A hypothetical choice exercise dealing with WTP analysis would never be considered as complete unless the 'value' is estimated along with the 'likelihood' of paying for the stated service. For a contingent valuation exercise, literature analyzing both the willingness to pay and the value the respondents would be willing to pay in a single study context, are not frequently available.

Among those very few available literatures that evaluate both likelihood of the 'willingness to pay' and the value of the 'willing to pay' studies usually prefers using dichotomous choice contingent survey questions conducting the CV exercise (Day and Mourato, 1998; Travisi and Nijkamp, 2004; Kouser and Qaim, 2013). Evidently, the dichotomous choice CV exercise is considered an efficient approach evaluating the WTP measures of the environmental welfares. However, those studies have mostly applied random utility models for this purpose (Day and Mourato, 1998). One of the most important disadvantages of such parametric model lies in the risk of misspecification. The estimated model often differs radically from the true-but-unobservable model which would result wrong magnitude and size of the covariate effects and invalid hypothesis tests (Haab and McConnell, 2002). In general environmental phenomena mostly remain unobservable to the researcher in advance or prior to the research. Therefore, it is difficult formulating an appropriate utility function of the environmental welfares concerned. Non-parametric treatment of dichotomous choice contingent valuation evaluating the WTP would then be of immense significance (Haab and McConnell, 2002). Economic valuation studies mostly address environmental phenomena but could rarely apply distribution-free estimators of the WTP measures (e.g., Hite, et al., 2002). Specifically, the distribution-free estimator, which evaluates farmers' WTP for managing environmental problems in a farm-level dichotomous choice CV survey, has never been applied before in agro-ecological management studies.

- Selecting an appropriate respondents group

Economic valuation of environmental welfare analysis, which generally uses the WTP or WTA technique of the CV approach, primarily and essentially requires selection of an appropriate respondent group (Gunatilake, 2003). As a choice-based technique, there, the respondents need to assess their choices to go for a given environmental welfare attribute. Specifically, economic valuation in a CV approach discusses the evaluation of respondents' preference concerning an offered monetary value that purchases/provides the particular welfare that is requested. Theoretically, respondent group receiving the concerned environmental benefit, will pay and the respondent group providing such benefit, will accept an amount. When the study issue is analyzing the environmental problems, it is worthwhile to select the polluting party (as respondent group) who will pay a fee or incur a cost for the pollution reduction. Additionally, suffering party, who will accept a compensation for such sufferings, could be selected as respondent group. Depending on the respective study issue, 'respondent group' selection has always been a challenging task for environmental management studies.

Ecological and environmental management studies generally prefer to select respondent groups that will benefit from the attainment of ecological and environmental benefits that are derived from a natural resource conservation program. Some of those studies select *residents of a community* as the respondent group and evaluate their WTP for receiving ecological resource conservation welfare (Day and Mourato, 1998; Abou-Ali and Carlsson, 2004). While other studies select *property owners* as respondents and evaluate their WTA for providing ecosystem goods and services while contributing resource conservation program (Welle and

Hodgson, 2011). In their choice experiment as the respondent groups, some agro-ecological studies, particularly, prefer to select *consumers* and analyze their WTP for getting environment safe agricultural products (Travisi and Nijkamp, 2004; Longo, et al., 2006; Michaud, et al., 2012). WTA analysis that considers *farm households* as the respondent group is also common in the studies that analyze agriculture and its ecological benefits (Amigues, et al., 2002; Broch, et al., 2013). For these studies that analyze agriculture and its detrimental impacts on the environment, it is important to consider *farmers* as the respondent group and the polluter who releases environmental pollution.

Economic valuation in terms of *farmers'* WTP for an improvement in environmental impact would potentially influence their welfare, efficient allocation of natural and environmental resource and ensure agro-ecological benefits as well. It is more relevant and effective to select *farmers* as the respondent group and analyze their WTP while conducting the CV studies, which has rarely been done by previous agro-ecological and environmental management studies. Although some studies consider farmers as the respondents group, the study focus remains on analyzing their (farmers) WTA a compensation for releasing less environmental impacts (Amigues, et al., 2002; Broch, et al., 2013). It is the farmer, who would be benefited primarily if they would manage farm-level environmental impact; conversely it is them, who are responsible for producing farm-level environmental impacts (pollution). Therefore, it is worthwhile to choose farmers as the respondent group and analyze their WTP for adoption of environment friendly production technology or reducing farm-level environmental impacts in terms of managing farm-level external costs.

- Evaluating environmental impact-specific WTP in agriculture

Economic valuation of environmental impacts associated with any course of an economic activity (e.g., agricultural production) essentially requires identifying important impact (or pollution) attributes. True economic values can never be derived if some important environmental attributes have been ignored in the economic valuation exercise. Therefore, it is important to identify and consider all of these important impacts in a single study.

Economic valuation of the environmental and ecological benefits of industrial water pollution management (Day and Mourato, 1998; Abou-Ali and Carlsson, 2004;

Bateman, et al., 2006; Welle and Hodgson, 2011), renewable energy production, conserving the ecological landscape, such as biodiversity, wetlands, and afforestation (Blomquist and Whitehead, 1998; Amigues, et al., 2002; Olorunfemi, 2009; Naald and Cameron, 2011), are common in the early environmental management studies. Considering the agriculture, particularly the environmental impacts of pesticide application (Travisi and Nijkamp, 2004), soil degradation (Abu, et al., 2011), chemical-intensive food production (Jayne, et al., 1996), environmental benefit of improved technology adoption (Amare, et al., 2012; Michaud, et al., 2012), etc. have been generally addressed individually by previous agro-ecological management studies. As a reason to focus on a single attribute, Baker et al. (1988) noted that in agriculture particularly, the physical data on the environmental attributes are often insufficient, and it is considered a challenging task to assess the different attributes altogether. Because many environmental problems arise in agricultural production, it is important but difficult to conduct economic valuation studies that encompass all relevant environmental attributes in a single study context. Impact-specific economic valuation is of immense importance in this regard, which has never been evaluated by early studies in a single study context. Such effort is also worthwhile because the valuations that the respondents (farmers) would make for different types and extents of environmental impacts may vary for different countries depending on their agro-ecological features and development feats.

- Focusing on developing country context

Being on a developing stage of economic growth, developing countries has always been struggling with welfare issues, either related to economic, social, or environmental concerns. Environmental welfare, having a substantial potential for the attainment of both economic and social welfares, is thus fundamental while to analyze developing nations' welfare issues (Kallas, 2007). The WTP technique of the economic valuation exercise is regarded as the best way addressing such environmental welfare issues. Day and Mourato (1998) also suggest that the WTP technique of the CV approach, as an economic valuation technique based on constructing hypothetical markets, can be successfully analyzed and interpreted for a particular context of developing countries. This is because developing countries are often characterized as having populations with less knowledge regarding the issue concerned, an illiterate condition and less ability to pay, as well as markets that may not be well-structured.

Available literature on CV approach dealing with the WTP considering the developing countries mostly concerned social issues such as living standard, improved quality water supply for household use (Whittington, et al., 1993a; Altaf and Hughes, 1994; Choe, et al., 1996) and public health programs (Swallow and Woudyalew, 1994) and ecological issues such as preservation of national parks and forest areas, forest protection (Navrud and Mungatana, 1994; Shyamsundar and Kramer, 1996; Hadker, et al., 1997; Shultz, et al., 1998). In analyzing economic valuation of environmental pollution and ecological soundness considering a particular production sector, Alberini and Cooper (2000) suggest that most of the early studies widely focus on industrial and energy producing sectors, which are for developed nations while less focus has been placed on agricultural sector and on developing countries. Agriculture, as one of the primary production sectors of the most developing countries, and its environmental impact issues, have never been evaluated using the CV approach and WTP technique. Specifically, Bangladesh, as an agriculture-based developing economy, doing intensive agriculture and generating considerable amount of environmental impacts, requires urgent research attention in this regard.

6.4 Exploring the research issue and identifying research questions

Different types of environmental impacts, which have the local scale of effect, are currently frequently experienced by Bangladeshi farmers while cultivating chemical-intensive and irrigation-based HYV crops such as rice, wheat and maize. Agro-ecological studies (e.g., Rahman, 2003; 2005) have also substantiated that HYV rice farmers, for instance, can readily recognize soil fertility, soil hardness and soil erosion problems along with the health risks and water contamination problems that are caused by the use of farm chemicals. However, harmful impacts of using farm chemicals may range from deterioration of agricultural natural capital and farmland ecosystems to the food safety-related issues (Travisi and Nijkamp, 2004). Evidently, in Bangladesh, historical analysis explores that chemical-based farming practice not only influences soil degradation and water depletion problems but also results decrease in agricultural production. Rahman and Parkinson (2007) show that soil fertility significantly influences both rice productivity and farmers’ resource allocation decisions in Bangladesh. The supply of agricultural production is considerably higher and input use is effectively low in fertile regions, where the soil contains desirable amounts of organic carbon, nitrogen, phosphorus and potassium components. This result implies that in areas having soil fertility problems have much more potential for a resulting decline in agricultural outputs.

In Bangladesh, as Hossain (2001) notes, the average level of top soil organic matter (OM) content declines by 20–46%, over the past several years because of intensive cultivation practices. It is found that depletion of such soil organic matter is the main cause of low productivity and consequently one of the most serious threats to achieving agricultural sustainability. Moreover, Bangladesh farm land soils have 50 per cent less amount of OM content (17 g/kg) than that of the threshold level (35 g/kg) a fertile soil should have (BARC, 1997; Hossain, et al., 2007). Consequently, declining trends in cereal yield growth rate have been observed here since the last three agriculture census years, which clearly indicates an unsustainable condition in Bangladesh crop yields (The World Bank, 2013).

Apart from this declining productivity scenario, FAO (2014), reports that the prevalence of food inadequacy, i.e., the percentage of population suffering from inadequate supply of food, has been remained stagnant here in the past decade. For developing economies such as Bangladesh, it is essential but difficult to increase the declining growth rate in cereal yield and decrease the prevalence of food inadequacy simultaneously, given the deteriorating condition of the farm land environment.

Essentially the challenge of realizing increased crop production, while limiting environmental impacts requires joint efforts of the government and the farmers. The cost of managing environmental degradations, implicitly given by the government in their environmental policy actions, must be appeared reasonable to the farmers who will ultimately incur it. However, farmers would also have responsibilities for limiting negative impacts of agriculture on the environment. Essentially this requires farmers’ access to improved production technologies such as soil fertility and nutrient management systems. As revealed by Farouque and Takeya (2007) most of the Bangladeshi farmers are resource poor and face different constraints practicing such improved crop production technologies that seek to increase agricultural production and safeguard the environment for future generations. In this regard, their study specifies the three most important constraints, namely, a lack of farmers' knowledge concerning an improved production technology, their (farmers) financial inability to purchase this technology and the unstable market price of these technologies during the crop season. This obligates farmers to use environmental depleting production technologies such as cheap chemical fertilizers and pesticides, low quality seeds and to result inefficient resource allocation decision.

The World Bank (2013) reports that 68.2 per cent of total methane emission and 83 per cent of total nitrous oxide emission, in year 2010 are the consequence of practicing chemical-intensive agriculture in Bangladesh. Moreover, every year, groundwater levels are declining by 0.1-0.5 meter in the north-central, northwestern, and southwestern areas of Bangladesh where intensive extraction of groundwater is conducted by HYV rice farmers (Shamsudduha, et al., 2009).

Because farmers serve vital roles in growing crops and managing the resource exploitation, their consciousness while using chemical inputs would ensure efficient resource allocation decision and help reducing environmental impacts by individual farm-level actions. Certainly, it is the farmers, who can either deplete or augment the quality of natural capital by making changes in their production decisions (Abu, et al, 2011) and likely to acquire the largest welfares, either in terms of profit or agricultural income from an improvement in environmental quality. In the long term, this will help them (farmers) maintain a future flow of natural capital and therefore a sustainability in agricultural production. Therefore, it is distinctly important to understand the awareness of their responsibility and analyze environmental impact-specific environmental management costs that would be willingly acceptable to the farmers.

Considering Bangladesh, as a developing country context and its agriculture-environment issue that mostly persist in case of HYV rice production, I specify my research questions as follows:

- Do Bangladeshi HYV rice farmers agree to pay for managing on-farm environmental impacts that they mostly face?
- What are the farmer-specific socio-economic and socio-environmental factors that influence their likelihood of the willingness to pay?

- What are the extent ofenvironmental impact-wise external costs in HYV rice agriculture?

6.5 Objectives

This present chapter illustrates the economic valuation of the environmental impacts to examine the welfare implications of the environmental phenomena that are associated with HYV rice agriculture in Bangladesh. The specific objectives are:

- Analyzing the likelihood of HYV rice farmers' willingness to pay in three north-western regions of Bangladesh.
- Determining factors influencing farmers' willingness to pay for an overall improvement in on-farm environmental condition.
- Evaluating environmental impact-wise external cost of HYV rice agriculture in the study area.

6.6 Theoretical background

6.6.1 CV approach in welfare analysis

Theoretically, there are two basic approaches for welfare estimation in economic literature: behavioral methods and stated preference methods (Gunatilake, 2003). Behavioral approach observes individual behavior in response to a change in public goods and from this behavior attempts to infer the value of changes in public goods. This typically involves with estimating the preference function such as utility or behavior such as demand function and calculating welfare measures. In stated preference approach, researcher construct contingent or hypothetical questions in a manner so that this includes responses that trade off improvements in public good and services for money. From the responses one can infer the value of changes in public goods. This method is more recently developed than the former and particularly the contingent valuation approach of this stated preference method is viewed as superior to the economists evaluating welfare measures (Gunatilake, 2003). The contingent valuation is a class of method that ensure the researcher to manage data with a defensible valuation estimates. Welfare measures that are particularly applied to estimate benefits of natural resources and environmental conservation, pollution prevention, sustainability in an endangered biodiversity and of many more ecological issues, could preferably be evaluated using the CV method (Siikamäki and Layton, 2007).

Valuation of environmental impactsthat ensures the efficiency of natural resource allocation is the basic rational behind the Pareto improvement approach. If benefits from natural resource utilization exceed the cost of resource extraction, it deemed worthwhile by the criterion. Information on demand and supply or information on surrogate markets is important here to see the benefit-cost balance (Gunatilake, 2003). However, many environmental commodities do not have such information available. When there are no indirect methods for valuing environmental quality changes, the only option is to directly ask people regarding their preference by following the stated preference method. The stated preferences in the CV method are contingent on the described situation. It has been used extensively to derive the welfare assessment of environmental quality changes (Boyle and Bishop, 1988; Araña and León, 2005; Siikamäki and Layton, 2007).

6.6.2 Economic approaches eliciting CV method

There are two types of CV measures in welfare economics. One is willingness to pay (WTP) and the other is willingness to accept (WTA). If the individual must provide the public good or service, the WTA measures would be appropriate, whereas if the individual must consume it, the WTP is the correct measure. However, the selection of WTP and/or WTA techniques in most of the economic welfare analysis of ecological services is challenging because of ill-defined property rights. For instance, the underground water sources that are used in agriculture may not belong to the farmer alone who is extracting it. Additionally, the land that the farmer is cultivating has both the use value (derived by direct utilization) and the non-use value such as option value (derived from individual WTP for uncertainty in future supply).

When selection of a measurement technique among the WTP and WTA is the major concern, WTA measures is regarded as theoretically appropriate. However, in practice, WTP measures are preferably used because of the difficulty in getting accurate WTA results. As more CV studies have been carried out, it becomes persistent that WTA measures are of order 3 to 20 times greater than WTP measures (Pearce, et al., 1989). An explanation for this disparity is that people value gains and losses asymmetrically (Kahneman and Tversky, 1979) because of their behavioral attachment of greater weight to losses than to comparable gains (Knetsch, 1994). The difference between WTP and WTA measures depends on individuals' income effect and on the substitution effect as well. Holding income effects constant, the fewer the substitute the greater the disparity (Hanemann, 1991). It is important to determine the better of the two measures because the use of WTA may overestimate values where WTP is the correct measure and vice versa (Knetsch, 1993). The appropriate measure choice technically depends on the nature of the environmental service that is being evaluated. However, for more practical purposes, the substantial documentation against WTA and the overestimation of its result leads us to choose WTP measures.

Economic valuation of environmental degradation in agriculture, as for an example, could better be analyzed by WTP technique of the CV approach. Theoretical rational behind such choice is that natural resources used in agricultural production have passive use value along with direct use value, which would underestimate the demand curve, if drawn from behavioral methods. For example, value of land may have been analyzed through a demand function in principle but unlike the behavioral method, CV method may provide the only hope for valuing its future service. Additionally, willingness to pay for improving land quality or water quality in an adjacent lake that has long history of depletion probably cannot be estimated with behavioral method. CV offers great flexibility in this circumstance.

Agriculture uses natural capital, which shows some basic properties of being public good and have passive use value, such as land, water and the atmosphere. Valuing the use of land, as an input of agricultural production, may take two forms. One is its economic value, measured by the amount of money required to rent a specific area for some particular crop cultivation. The other one, which is the option value, could be measured as farmers' WTP for maintaining the piece of land in such a way so that it could be used for the same purpose and with same satisfaction in future. For land as a vital input of any agricultural production, enforceable property right could not be assigned unless it is bought by the farmer alone. For water, no well-defined property right could be put for consuming resource as input but for the water extraction plants only. Therefore, in the present study context, I choose the CV approach and WTP measure to analyze economic values of environmental impacts (i.e., the passive or non-use value) in agriculture.

However, it is not only the appropriate measurement 'technique' but also the appropriate 'elicitation method' of the CV approach, which is important to choose for drawing out true valuation results. Analysis of strengths and weaknesses of different CV elicitation methods, represented in Table 6.1, suggests 'dichotomous choice' having much more potential as an appropriate method in this regard. Boyle and Bishop (1988) note that "in dichotomous choice method, respondents are asked to state whether they accept or reject a single take-it-or-leave-it offer for the item being valued. Respondents are not asked to state a specific dollar value". Their argument in favor of this method lies in its simplicity in survey application. Rather than to respond a complicated bidding format questions or to understand the complexities of anchored payment cards, respondents need to choose either 'yes' or 'no' response to a single value offer.

Table 6.1 CV elicitation methods and their strengths and weakness

Elicitation Method	Major strengths	Specific weaknesses	Generic suitability for present study
Open End	• No starting point bias • May directly measure what researcher wants to know. • A good check when conjunction with other methods.	• Information complexity leads to unrealistic responses in hypothetical situation.	*Not suitable*
Bidding game	• Provides 'thinking time' to elicit maximum WTP as desires.	• Sensitive to starting value. • Bidding frenzy may lead to over estimates.	*Not suitable*
Payment card	• Moderately low complexity. • Low interview bias	• Anchoring bias • Requires personal interviews	*Conditionally suitable.*
Dichotomous Choice	• 'Take it' or 'leave it' choices reduce hypothetic axioms and approximate the market. • Very small starting point bias • Small strategic bias	• Large samples are needed	*Suitable*

Source: Boardman, et al., (1996); Gunatilake, (2003)

6.7 Methodology

6.7.1 Questionnaire structure

As a stated preference method of welfare analysis, the accuracy of CV method-based hypothetical choice exercise solely depends on its survey design. Remarkably, Carlsson and Martinsson (2001) testify the validity of a hypothetical choice experiments over an actual choice experiment for an environmental project and finds both experiments as equally valid. In CV studies there may be large variations in survey instruments depending on the study issue. In this regard, Gunatilake (2003) suggests that CV survey design should have an introductory section providing the general context for preference to be made and description of the service to be valued followed by WTP elicitation questions and the manner in which the payment is to be made. These have great impact on the measurement results and are therefore important. If information provided to the respondents overstress the importance of the environmental problem concerned and overlook the management issues, the WTP estimates will be upward biased.

To increase the realism of the CV survey, it is also important to specify a payment method that is at least as close as possible to the actual payment method, depending on the context. That is, willing to pay the amount to whom and in what ways. For instance, particularly in agriculture, incurring an external cost reducing a given environmental impact, such as purchasing high priced environment friendly production technologies, installing environment conserving water extraction plants for irrigation and pest management programs, etc. could be various payment ways in this regard. Additionally, while conducting the survey, enumerators should debrief the questions to the respondents regarding the reasons for answering certain questions. Most importantly, WTP question should be carefully worded in the form of simple sentence so that these questions would not lead to confusion among the respondents. Validity and reliability of estimated WTP depends on these issues. Cummings et al. (1986) proposed five basic criteria that are useful in developing WTP survey instruments for researchers. Table 6.2 explains present CV exercise criteria that match the corresponding Cummings et al. (1986) proposed criteria.

Table 6.2 Comparing standard criteria for developing WTP survey

Cummings et al., (1986) proposed five general criteria developing WTP survey:	Criteria explanation in the present study context:
Respondents should be familiar with the good that is being valued.	Farmers as the respondents are supposed to be familiar with environmental impacts to evaluate such external cost.
Respondents should be given experience in both valuation and choice procedure.	The choice procedure is explained to the farmers while conducting the survey.
There should be as little uncertainty as possible regarding the details of the good.	Goods (environmental impacts), which are evaluated here, directly recognized and identified by the farmers from their

	experience.
WTP rather than WTA should be used in the valuation process.	WTP is chosen here for valuation exercise.
Attempts should be made to avoid anchoring and starting point biases.	Dichotomous choice method for CV elicitation, which is selected for this present study, has very small starting point bias.

Source: Prepared using Gunatilake, (2003)

Depending on the social and economic context, the researchers should be careful enough to choose an appropriate method for their given project. Following the standard format of a CV survey design explained by Gunatilake (2003) and Cummings et al. (1986), my WTP questionnaire ensures comprising three major sections. First section is structured for respondents' socio-economic attribute, socio-environmental living standard and agro-economic information and while the second section is organized with agriculture and environmental impact-related questions. Third section is arranged for dichotomous choice CV questions of randomly selected bids to evaluate farmers' WTP for managing farm-level environmental problems. For the ease of conducting whole survey a well-structured questionnaire is prepared (See Appendix 3-VII for the detail questionnaire) that incorporates necessary components of the WTP survey questionnaire structure, depicted below in Figure 6.1.

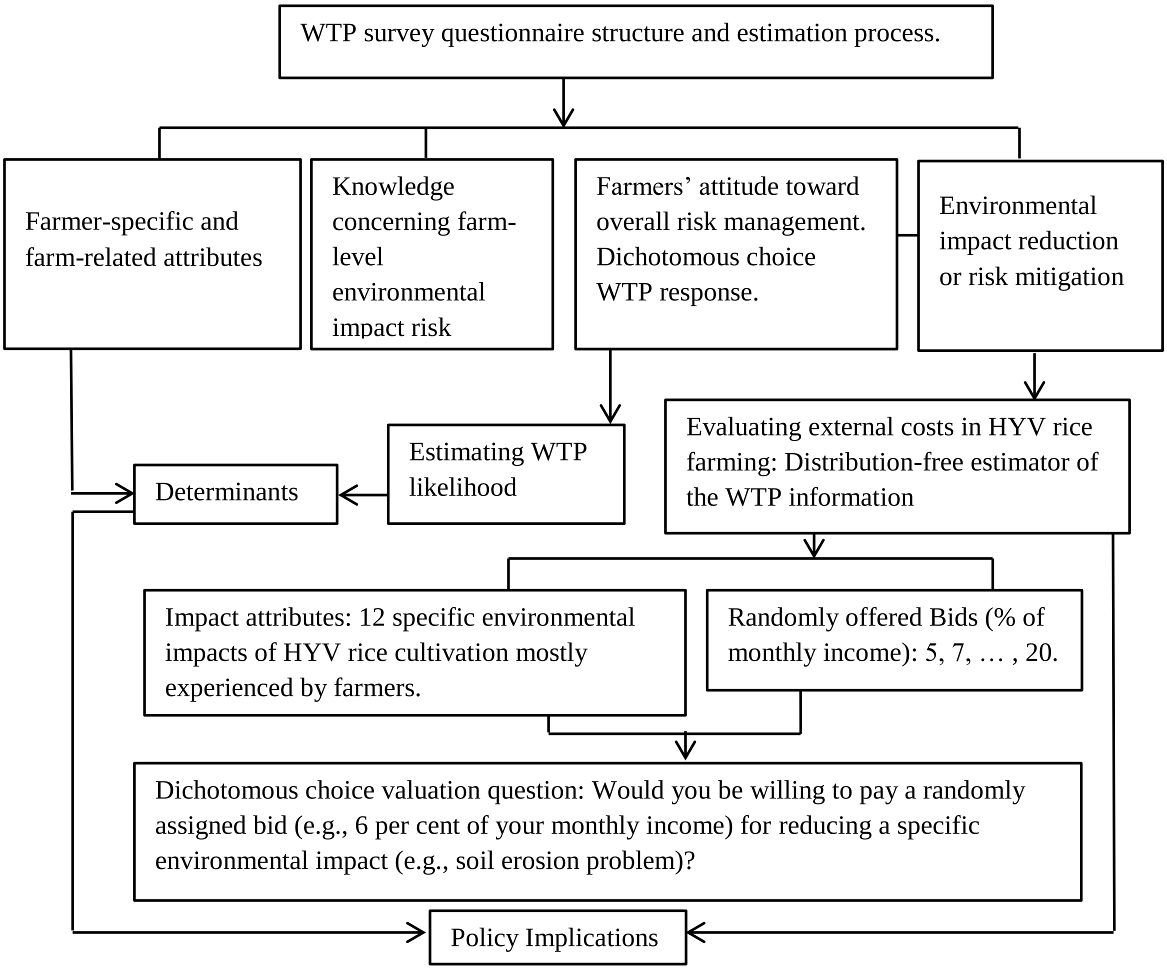


Figure 6.1: Conceptualizing WTP survey questionnaire structure and the estimation process.

6.7.2 Binary logistic regression model: Determining the likelihood of farmers' WTP for reducing farm-level environmental impact

In general, 'logistic regression model' is supported by previous environmental management studies determining factors influencing WTP likelihood (e.g., Abou-Ali and Carlsson, 2004; Bateman, et al., 2006; Michaud, et al., 2012, etc.). Following the idea, I use the binary logistic regression model to identify factors determining the maximum likelihood of HYV rice farmers' WTP for reducing farm-level environmental impact. This is because the logistic regression model contains dichotomous criterion dependent variable. A group of farmers in the total sample are willing to pay, and they hold a '1' outcome value, whereas the rest of the farmers who are not willing to pay hold a '0' outcome value. The latent variable binary logistic regression model (Bartholomew, et al., 2002), which maximizes the likelihood of farmers' WTP for reducing environmental impacts in HYV rice cultivation, involves best fitting the equation given the data as follows:

$$y_i^* = X_i\beta + \varepsilon_i \quad \text{...}(6.1)$$

$$= \begin{cases} y_i^* < 0 \text{ when } y = 0 \\ y_i^* > 0, \text{ when } y = 1 \quad i = 1, 2, ..., n. \end{cases}$$

where n is the number of observations, y_i is the binary outcome dependent variable (farmers' WTP), which can be constructed such that y_i is related to the latent variable y_i^* in a way that Equation 6.1 expresses, X_i is a vector of predictor variables, β is a vector of coefficients to be estimated, and the error term ε_i is distributed according to a standard logistic distribution (i.e., ε_i ~ Logistic[0,1]). The model assumes that for each i th observation, there is a continuous latent variable y_i^* (i.e., an unobserved random variable). It is hypothesized that farmers' WTP to reduce farm-level environmental impacts depends on various agro-economic and socio-economic factors (Kallas, 2007).

Therefore eight such predictor variables are selected by reviewing literature on the agriculture-environment issue for Bangladesh. For instance, 'proportion of agricultural income share' is hypothesized as the major determinant raising the likelihood of farmers' WTP. Evidently, in their study Welle and Hodgson (2011) find respondents' income and other socio-economic factors significantly influence their WTP probabilities. In Bangladesh, Rahman (2011) shows that gross return on modern variety rice (e.g., HYV rice) is significantly higher than that of traditional varieties. This would motivate farmers to remain in modern rice agribusiness and influence their willing to pay attitude positively for the agri-environmental risk mitigation programs. This is because Bangladeshi farmers' can easily realize the benefit of maintaining soil quality in increasing farm outputs, reducing cost of production and improving soil's water holding capacity and soil structure (Hossain, 2001).

As a proxy measure of farmer's subsistence pressure, 'share of dependent family member' could be used to explain their WTP likelihood. In his study Rahman (2005) finds that farmer's subsistence pressure negatively influences their environmental awareness in Bangladesh HYV rice agriculture. This could be hypothesized that more subsistence pressures would lead lower WTP probabilities for environmental management program as it discourages farmers' environmental awareness.

Apart from these, Alam et al. (2011) show that Bangladeshi rice farmers who are young in age and own their farm land are more efficient than the tenant farmers in terms of using agricultural inputs such as land, water, and other resources. This clearly implies the fact that young aged owner farmers may have better consciousness maintaining future flow of farm land resources and are thought to be more willingness to incur the payment as cost to sustain in agribusiness for long time. Therefore, my study chooses the 'proportion of self-owned farmland' and farmer 'age' as two important predictor variables. In an addition to these, farmer 'cultivation experience', 'extension contact' and 'institutional training on chemical-based farming practice' are hypothesized as directly related to their WTP motivation because all of these factors work in favor of influencing farmers' environmental awareness (Rahman, 2003; 2005).

As an important socio-environmental factor, this study also hypothesized that farmers who used to lead an environment depleting living style, i.e., they produce a considerable amount of household pollution, were rarely aware of their responsibility to reduce the environmental impacts of agriculture, which directly related to their WTP for environmental improvement. It is also substantiated by previous WTP studies that respondents' who are less likely to perceive the ecological or environmental benefit, would less likely to pay (Blomquist and Whitehead, 1998). In this regard, Welle and Hodgson (2011) show that respondents, who are more aware, are willing to pay more. In analyzing maximum likelihood of the WTP, respondents' knowledge, awareness and access to the information on environmental resource quality would work as significant driving factor (Olorunfemi, 2009). It could be inferred that Bangladeshi farmers who are aware of managing environmental quality, would show better WTP probabilities.

Table 6.3 presents the descriptive statistics of the predictor variables used for logistic regression analysis explaining HYV rice farmers WTP for reducing farm-level environmental impacts. Following Gujarati (2003), the binary logistic regression model is specified for the *ith* observation as Equation 6.2:

$$Logit(y_i) = \beta_0 + \beta_1 AGRIN_i + \beta_2 DEPT_i + \beta_3 LNDSLF + \beta_4 AGE_i + \\ \beta_5 CLX_i + \beta_6 INS_i + \beta_7 EXTN_i + \beta_8 SELI_i + \varepsilon_i \text{ ....(6.2)}$$

where *Logit(y_i)* is the log of the odds ratio in favor of the WTP likelihood, i.e., the ratio of probability that the farmer will be willing to pay to the probability that the farmer will not be willing to pay. $AGRIN_i$ and $DEPT_i$ are the *ith* farmer's income share from agriculture and the dependent member's share out of the total number of family members, respectively. $LNDSLF_i$ and AGE_i are the farmer-specific self-owned land proportion and his age, respectively. $CULX_i$, INS_i and $EXTN_i$ explain the *ith* farmer's cultivation experience and the status of receiving institutional training and extension services, respectively. The socio-environmental living standard of the *ith* farmer is expressed as the index, $SELI_i$. By using statistical software SPSS 16.0, this study runs the binary logistic regression model in Equation 6.2 and analyzed HYV rice farmers' WTP likelihood.

6.7.3 Expected lower bound WTP: The distribution-free Turnbull estimator

Dichotomous choice CV technique is used to measure the value of farmers' WTP for reducing some specific on-farm environmental impacts. By performing hypothetical choice exercise this study survey questions exploring farmers' WTP for environmental impact mitigation and economic valuation of the WTP. Section 3.2.4 in Chapter 3, explains the maximum likelihood estimator the present study intends to use for measuring such WTP values. Effectually, this study uses the distribution-free Turnbull estimator for this purpose (Turnbull, 1976; Cosslett, 1982).

This study considers M distinct randomly offered price amounts, indexed t_j for a set of 12 mostly experienced environmental impacts. Randomly assigned amounts take on values: 5%, 7%, 8%, 9%, 10%, 12%, 13%, 14%, 16%, 18%, 19%, 20% of HYV rice farmers' monthly income. If the ith farmer agrees for a particular offered bid (randomly chosen by the interviewer) to manage a specific environmental problem, the WTP is greater than or equal to that offered bid, i.e., $WTP_i \geq t_j$ otherwise, $WTP_i < t_j$. The Turnbull estimator assumes the WTP as a random variable with cumulative distribution function (CDF), $F_W(W)$, such that

$Pr\,(WTP \le t_j) = F_w(t_j)(= F_j)$ (Haab and McConnell, 2002). Potentially, the distribution-free Turnbull estimator makes minimal assumptions involving the distribution of willingness to pay. It assumes to hold monotonic CDFs for proposed bids, i.e., as price amount (% of farmers monthly income) increases number of 'no' response to each price bid for a given environmental impact increases. Following Haab and McConnell (2002), the step-by-step procedure to calculate the Turnbull distribution-free estimator is described below:

Step 1: For price bids indexed $j = 1......M$, calculate $F_j = N_j / N_j + Y_j$, where N_j is the number of 'no' responses to t_j, Y_j is the number of 'yes' responses to the same bid, and $T_j = N_j + Y_j$.

Step 2: Compare F_j and F_{j+1} from the beginning bid. For any $F_{j+1} \le F_j$ then pool cells j and $j+1$ into one cell with boundaries $(t_j, t_{j+2}]$, and calculate $F_j^* = \dfrac{N_j + N_{j+1}}{T_j + T_{j+1}} = \dfrac{N_j^*}{T_j^*}$. For any $F_{j+1} > F_j$, continue; no pooling required.

Step 3: Continue until cells are pooled sufficiently to allow for a monotonically increasing CDF.

Step 4: Calculate the PDF as the step difference in the final CDF: $f_j^* = F_j^* - F_{j-1}^*$.

This step by step calculation procedures derives a set of $f_1^* .... f_{M^*+1}^*$ and related $F_1^* .... F_{M^*}^*$, which have the property that proportion of no responses out of the total response declines as the bid price increases. Imposing the monotonicity restriction, the log-likelihood maximization problem becomes as Equation 3.5 (Chapter 3).

This thesis derives out a lower bound estimate for WTP for a multiple price case. Following Haab and McConnell (2002), Equation 6.3 expresses the formula of expected lower bound willingness to pay in terms of probability mass estimates, E_{LB} (WTP):

$$E_{LB}(WTP) = \sum_{j=0}^{M^*} t_j . f_{j+1}^* \quad \text{...(6.3)}$$

Step 5: Using Equation 6.3, multiply each offered price by the probability that willingness to pay falls between it and the next highest price.

Step 6: Sum the quantities for all offered bids and obtain the estimate of the lower bound on willingness to pay.

By following 5th step, a minimum estimate of WTP is found. The estimated proportion of the sample that has WTP falling between any two prices is assumed to have WTP equal to the lower of those two prices. This estimate offers a conservative lower bound on WTP for all non-negative distributions of the WTP, independent of the true underlying distribution. In practice, E_{LB} (WTP) represents the minimum expected WTP for all distributions of WTP defined from zero to infinity.

Moreover, one advantage of the lower bound estimate of the WTP is the distribution of estimator. Since, f_j^* are normal and t_j are fixed the E_{LB} (WTP) is also normal (normality property of the f_j^* is explained in Haab and McConnell, 2002) . Normality allows its variance worth computing (See Equation 3.7, Chapter 3 for variance formula). Because the E_{LB} (WTP) is a linear function of the asymptotically normal maximum likelihood distribution function estimates f_j^*, this will be normally distributes mean defined by Equation 3.6 and variance Equation 3.7 (See Chapter 3, Section 3.2.4 for these equations):

$$E_{LB}(WTP) \sim N\left(\sum_{j=0}^{M^*} t_j (F_{j+1}^* - F_j^*), \sum_{j=1}^{M^*} \frac{F_j^*(1-F_j^*)}{T_j + T_{j+1}} (t_j - t_{j-1})^2 \right) \text{........................(6.4)}$$

Additionally, because of such asymptotic normality, the E_{LB} (WTP) has the ease of constructing a confidence interval or performing hypothesis tests. As noted by Haab and McConnell (1997), the distribution-free estimator, the Turnbull, has a number of theoretical advantages over the parametric models (Chapter 3, Section 3.2.4). The present study empirically estimates the WTP Turnbull values by applying Equation 6.3 separately for 12 different environmental impacts and for an overall environmental impact as well for a given set of farmers participating in the survey.

6.8 Data

Primary data on farm-level environmental impacts and farmers' WTP for reducing environmental problems are collected from HYV rice farms in three north western regions of Bangladesh. Among those three regions, 'Rajshahi' represents the high land agro-ecological unit and 'Natore' and 'Pabna' represent medium and low land units, respectively (Banglapedia, 2014). Table 6.3, provides a statistical summary of the HYV rice farmer's agro-economic and socio-environmental characteristics surveyed here for this study. On average 69 per cent of the total respondents (farmers) interviewed are willing to pay for an overall improvement in farm-level environmental impact. Mean age of the farmers is 49 years and on average, 31 per cent family members of the HYV rice farmers are dependent. On average, 64 per cent of their total income comes from agricultural source and 89 per cent of the total farm land holding is self-owned. Farmers' living style is moderately environment-friendly as the mean value of their socio-environmental living index (SELI) comes as 75 per cent (Detail description of the SELI formulation is represented in Appendix 5-II). In the study area, farmers are associated with agricultural activities for 32 years on average while only 21 per cent of the sample group have agriculture-related institutional training. In addition to this, approximately 50 per cent farmers reply positively that they used to visit extension services for cultivation and input management purpose in the past crop year.

Table 6.3 Summary statistics of the variables used in logistic regression model

No of observation: 317	Min	Max	Mean	Std. Deviation
Farmers' Willingness to pay (WTP) (yes 1 and 0 otherwise)	0	1.00	0.688	0.464
Farmers age (years)[AGE]	20	90	48.76	13.51
Agriculture income share [AGRIN]	0.04	1	0.6403	0.286
Cultivation experience (years) [CULX]	7	75	31.729	14.50
Institutional training received (yes 1 and 0 otherwise) [INS]	0	1.00	0.215	0.411
Self-owned land proportion [LNDSLF]	0	1	0.890	0.349
Socio-environmental living index [SELI]	0.46	1.00	0.750	0.113
Extension service received (yes 1 and 0 otherwise) [EXTN]	0	1.00	0.501	0.501
Dependent member share out of total family member [DEPT]	0	0.75	0.310	0.119

Source: Field survey October –December 2013.

6.9 Result analysis

6.9.1 Factors influencing farmers' WTP likelihood

Binary logistic regression analysis is conducted to predict factors influencing the likelihood of HYV rice farmers' WTP for an environmental improvement. Table 6.4 represents the estimated coefficients of those predictor variables. Overall prediction success is 73.8 per cent (41.4 per cent correct prediction for not willing to pay and 88.5 per cent for willing to pay). The test of full model against a constant only model is statistically significant. This implies that the predictors effectively distinguishes between the two response groups (chi square = 62.197, $p < 0.000$).

The Wald statistics test demonstrates that agricultural income share, socio-environmental living index, subsistence pressure and extension contact predictors make significant contributions to prediction (p-values are statistically significant at the level of 95% confidence interval). As expected, the estimated coefficient for agricultural income share shows direct relation while the proportion of dependent family member share is inversely related to the WTP likelihood. The result can well be justified by the study of Farouque and Takeya (2007), who found that in Bangladesh, resource-poor marginal farmers often face financial constraints in terms of subsistence pressure or low income to seek out environmental impact management programs. In an addition, social-ecological status has been evaluated by many recent studies as an important factor that determines natural resource management (e.g., Estoque and Murayama, 2014), and this study also reasonably finds that the SELI variable is directly related to WTP for an environmental improvement in the study area. Frequent contact with extension services also influences the WTP positively because environmental management desirably requires farmers' participation that is primarily preceded by extension service programs. This result can be justified by the studies, where Rahman (2003; 2005) found that agricultural extension services improve farmers' environmental awareness in Bangladesh.

The estimated logistic model could not find farmer' cultivation experiences, proportion of self-owned farm land, age and institutional training as statistically significant predictors. However, among those insignificant predictors, coefficients for age, proportion of self-own land and cultivation experience variables follow the hypothesized direction of the relation with the dependent variable. In evaluating

WTP for ecological benefit of preserving agricultural landscape Drake (1992) also finds that respondents' WTP is significantly and negatively related to their age. Therefore, the model represented in Table 6.4 effectively analyzes factors influencing HYV rice farmers' attitude and willingness toward environmental risk mitigation in farm land areas.

Table 6.4. Binary logistic regression model

Independent Variables	Coefficient	Std.Er.	Wald	Sig.
AGRIN	2.954	0.520	32.33	0.000
SELI	4.418	1.242	12.66	0.000
DEPT_MEM	-2.551	1.187	4.620	0.032
CULX	0.005	0.012	0.181	0.670
LNDSLF	0.569	0.463	1.510	0.219
EXTN	0.812	0.281	8.367	0.004
AGE	-0.018	0.013	1.846	0.174
INS	-0.315	0.344	0.837	0.360
Constant	-2.624	1.335	3.862	0.049
Chi-square (8)	62.197			0.000
Classification Table				
Dependent Variable		Predicted		
		WTP		Percentage Correct
Observed		0	1	
WTP	0	41	58	41.4
	1	25	193	88.5
Overall Percentage				73.8

Source: Own calculation

6.9.2 Evaluating CV responses for different environmental impact attributes

Approximately 69 per cent of the total respondent says that they are willing to pay and the rest of them reply as 'no', i.e., they are not willing to pay for an overall improvement in the on-farm environmental impact. Table 6.5 (a-c) reports the distribution of 'no' responses for each environmental impact attributes and conveniently contains all of the necessary information to estimate the Turnbull. Each entry represents proportion of 'no' responses out of the total number of respondents (farmers) offered a particular price range as their WTP amount for a given environmental impact in the study area. For instance, out of the total 46 numbers of HYV rice farmers, offered a random bid (ranged 5-10 per cent of their monthly income) of WTP for reducing soil fertility problem, 21 no. of farmers reply 'no' while the rest of them reply 'yes' in Pabna region. For environmental impact such as, soil erosion, the proportion of 'no' response out of the total number offered, is 10/12 for the random bid ranged from 11 to15 per cent of their monthly income. The CV questions for randomly offered bids are separately asked for 12 different environmental impacts along with the attribute called 'overall environmental impact'. Remarkably, it is observable from Table 6.5 (a-c) that WTP 'no' response proportion for reducing a specific environmental impact increases as bid range increases. In raw data, it is assumed that 'no' response proportion for each successive bid amount (e.g., t_j per cent of farmer's monthly income) does not hold such monotonic property. However, after imposing the monotonicity restriction while calculating the Turnbull CDFs, the CV response proportions are found as represented in Table 6.5 (a-c).

Table 6.5 (a) Response to CV questions by environmental impacts and bid range* Pabna farms

Bid Range (% of monthly income)	5-10	11-15	16-20
Soil Fertility	21/46 (0.456)	11/15 (0.733)	20/22 (0.909)
Pest attack	19/27 (0.703)	11/23 (0.478)	13/14 (0.928)
Crop Diseases	22/48 (0.458)	14/19 (0.736)	12/14 (0.857)
Soil Erosion	24/43 (0.558)	10/12 (0.833)	14/14 (1.00)
Soil Compaction	24/39 (0.615)	7/8 (0.875)	13/14 (0.928)
Soil Salinity	25/44 (0.568)	8/10 (0.8)	21/22 (0.954)
Water Holding capacity	16/26 (0.615)	8/10 (0.8)	20/22 (0.909)
Water Logging	19/50 (0.38)	12/17 (0.705)	20/22 (0.909)
Water Contamination	17/47 (0.361)	11/19 (0.578)	20/22(0.909)
Fish catch reduction	12/48 (0.25)	11/19 (0.578)	18/22 (0.818)
Health impact	18/36 (0.5)	27/36 (0.75)	17/17 (1.00)
Soil toxicity	24/39 (0.615)	19/23 (0.826)	14/14 (1.00)
Overall impact	23/39 (0.589)	15/19 (0.789)	13/14 (0.928)

* Table entries are the number of no response/total numbered offered each bid range. Percentage of the 'no' response proportion is reported in the parenthesis.
Source: Field survey October–December 2013.

Table 6.5 (b) Response to CV questions by environmental impacts and bid range* Rajshahi farms

Bid Range (% of monthly income)	5-10	11-15	16-20
Soil Fertility	8/39 (0.205)	7/19 (0.368)	10/20 (0.50)
Pest attack	11/39 (0.282)	4/7 (0.571)	20/27 (0.740)
Crop Diseases	12/39 (0.307)	6/12 (0.50)	22/28 (0.785)
Soil Erosion	9/27 (0.334)	3/6 (0.50)	13/21 (0.619)
Soil Compaction	11/14 (0.785)	3/6 (0.50)	24/28 (0.857)
Soil Salinity	15/27 (0.556)	2/3 (0.667)	18/18 (1.00)
Water Holding capacity	10/25 (0.40)	7/12 (0.583)	17/18 (0.945)
Water Logging	21/41 (0.512)	13/16 (0.813)	6/6 (1.00)
Water Contamination	8/26 (0.307)	6/12 (0.50)	16/21 (0.761)
Fish catch reduction	24/39 (0.615)	6/7 (0.857)	18/18 (1.00)
Health impact	10/39 (0.256)	6/12 (0.50)	22/24 (0.917)
Soil toxicity	14/28 (0.50)	4/6 (0.667)	14/18 (0.778)

Overall impact	8/39 (0.205)	7/19 (0.368)	10/20 (0.50)

*Table entries are the number of no response/total numbered offered each bid range. Percentage of the 'no' response proportion is reported in the parenthesis.
Source: Field survey October–December 2013.

Table 6.5 (c) Response to CV questions by environmental impacts and bid range* Natore farms

Bid Range (% of monthly income)	5-10	11-15	16-20
Soil Fertility	12/47 (0.285)	6/15 (0.40)	22/28 (0.785)
Pest attack	7/38 (0.184)	10/26 (0.384)	19/23 (0.826)
Crop Diseases	5/30 (0.166)	11/28 (0.392)	23/28 (0.821)
Soil Erosion	13/47 (0.276)	9/19 (0.473)	25/28 (0.892)
Soil Compaction	17/40 (0.425)	10/15 (0.40)	26/28 (0.928)
Soil Salinity	14/29 (0.482)	18/22 (0.818)	24/25 (0.96)
Water Holding capacity	10/47 (0.212)	4/7 (0.571)	21/24 (0.875)
Water Logging	3/17 (0.176)	10/19 (0.526)	20/23 (0.869)
Water Contamination	9/29 (0.310)	7/12 (0.583)	19/23 (0.826)
Fish catch reduction	13/35 (0.371)	8/14 (0.571)	22/24 (0.917)
Health impact	10/21(0.476)	7/11 (0.636)	22/24 (0.917)
Soil toxicity	20/32 (0.625)	3/4 (0.75)	22/24 (0.917)
Overall impact	20/37 (0.54)	9/11 (0.818)	13/14 (0.928)

* Table entries are the number of no response/total numbered offered each bid range.
Percentage of the 'no' response proportion is reported in the parenthesis.
Source: Field survey October–December 2013.

6.9.3 Evaluating environmental impact-specific WTP values

Table 6.6 represents environmental impact-specific E_{LB} (WTP) estimates along with respective standard errors (Standard errors are calculated using Equation 3.7, Chapter 3). The three-region average value of the Turnbull E_{LB} (WTP) estimates show that HYV rice farmers are willing to pay approximately 10 per cent of their monthly income for soil fertility, crop diseases and pest attack problems and more than 8 per cent for water holding capacity, soil erosion and water logging problems. This result can easily be explained by the study by Hossain (2001), who revealed that Bangladeshi farmers can easily recognize soil fertility-related problems whenever they experience interruptions in a crop's healthy growth, reductions in the soil's water-holding capacity and weak soil structures and a resulting decrease in the yield.

The regional average E_{LB} (WTP) estimate also reveals that farmers agree to pay a considerable proportion, i.e., more than 7 percent of their monthly income, to tackle with water contamination, fish catch reduction and soil compaction problems. In their study Travisi and Nijkamp (2004) similarly evaluate that respondents' are willing to pay a good amount (15 Euros per household per month) to avoid the pesticide contamination of farmland soil and aquifer. Specifically, farmland water sources could easily be contaminated by agricultural pollution, which should be managed by installing water quality management programs. In this regard, Hite et al. (2002), found that residents evaluate their mean WTP as US$48.46 for an improvement in river water quality that was damaged because of agricultural non-point pollution (e.g., nutrient depletion).

Farmers in the study area also evaluate a higher value for health damage impact because of using farm chemicals and are willing to pay approximately 7.46 per cent of their monthly income for reducing such impact. This implies that Bangladeshi HYV rice farmers are well aware of the health impacts that may be caused by frequent and continuous use of farm chemicals. A study by Kouser and Qaim (2013) also found that farmers WTP value is US$ 39.50 per acre for the benefit of reduced health effects from reducing chemical pesticide use. Because of lower chemical pesticide use, significant health advantages in terms of fewer incidents of acute pesticide poisoning and also environmental advantages in terms of higher farmland biodiversity and lower soil and groundwater contamination are found by this study.

Soil toxicity and soil salinity problems are two environmental impacts that have the lowest WTP values in the study area. The result can be justified by the study where Rahman (2005) found that Bangladeshi HYV rice farmers are more aware of readily identifiable impacts than indirect impacts such as soil toxicity (or contamination) and water contamination problems. In general, HYV rice farmers' WTP has been evaluated with higher values for direct impacts that are readily visible in farm land areas. My study finds that HYV rice farmers' willingness to pay values are substantially larger for directly observable environmental attributes (e.g., soil fertility, pest attach, crop diseases, fish catch reduction, etc.).

The expected WTP estimates are also converted into money terms and represented in Table 6.6 with respective region columns. Regional mean total income (that includes income from both agriculture and non-agriculture sources) is used to measure such monetary values. Such estimates show that Rajshahi region farmers are willing to pay the highest amount (BDT 4.67 thousand) for reducing impacts on soil fertility and that Natore and Pabna farmers prefer to bear the highest portion of their monthly income for crop diseases (BDT 3.89 thousand) and fish catch reduction problems

(BDT 3.75 thousand), respectively. This is because farmers in the respective study regions may face these particular types of environmental impacts frequently and are therefore sufficiently aware to pay a considerable amount to manage these problems. Likewise, a study by Rahman (2005) finds that in Bangladesh, HYV rice farmers perceive ‘reduction in soil fertility’ and ‘reduction in fish catch’ followed by ‘crop diseases’ and ‘pest attack’ problems as the most important environmental impacts.

On the contrary, the lowest value, BDT 1.50 thousand, is assessed for managing soil salinity problem by Rajshahi region farmers. Such a result is obvious because this study area belongs to AEZ 11, which has the least or no saline property in the soil (See Chapter 3 for soil properties of this study area). Consequently, farm chemical induced salinity problem would to be lower comparative to other environmental problems. For Natore region, it is the soil toxicity problem (BDT 1.79 thousand only) for which farmers assess the lowest value. As the environmental impact, farmers could recognize it (soil toxicity) rarely because it is better identifiable through scientific experiments. A striking result is found for Pabna region in this respect. Farmers in this area evaluate the water contamination problem as the least important problem; therefore, they wish to pay the lowest amount, only BDT 1.61 thousand, for water quality management purposes. The basic reason behind such assessment would be the fact that as a low land ‘Beel’ area, every year, fresh water washes out irrigated fields and thereby limits such contamination problem. Therefore, farmers experience less problems of water contamination because of HYV rice cultivation in this region. Moreover, Pabna farmers use comparatively lowest amount of farm chemicals than that of the Rajshahi and Natore farmers do, which helps keeping water contamination problem lower in this area (Table 5.1, Chapter 5).

TheoreticallyWTP values of managing environmental problems could be expressed in terms of the external cost. For instance, HYV rice farmers’ WTP value for managing overall environmental impact is BDT 2.23 thousand, which implies that HYV rice cultivation is causing an external cost of BDT 2.23 thousand in terms of generating on-farm environmental problems. According to the theory of valuing environmental and natural resource (Haab and McConnell, 2002; Gunatilake, 2003), the higher the amount of external cost generated in given production activity (e.g., agriculture), the greater the amount and higher the extent of such negative externality (e.g., environmental impacts).

The radar diagram in Figure 6.2 effectively portrays the regional variations in environmental impact values, i.e., the expected WTP Turnbull estimates. Considerable variations for soil fertility, soil's water holding capacity, water logging, water contamination, fish-catch reduction and soil compaction problems are found across three study regions. Although, Pabna and Natore farmers evaluate the health impact and soil toxicity problem with nearly similar impact values, Rajshahi farmers do it differently and wish to pay more for those two problems. However, for pest attack, crop diseases and soil erosion problems, Pabna regions' farmers are not willing to pay as much as Rajshahi and Natore regions' farmers do. Notably, soil salinity problem is identically evaluated in all three study areas.

Table 6.6 Lower bound expected willingness to pay [E_{LB} (WTP)]

	Rajshahi		Pabna		Natore		Three-Region Average	
	E(WTP) [a]	BDT [b]	E(WTP)	BDT	E(WTP)	BDT [b]	E(WTP)	BDT [b]
Soil Fertility	13.48 (0.86)	4.67 (1)	7.20 (0.76)	2.62 (5)	11.53 (0.89)	3.83 (2)	10.74	3.71(1)
Pest Attack	10.22 (0.96	3.64 (3)	6.02 (0.99)	2.19 (6)	11.48 (0.68)	3.82 (3)	9.33	3.22(3)
Crop Diseases	10.49 (0.88)	3.54 (4)	7.33 (0.80)	2.67 (4)	11.73 (0.71)	3.89 (1)	9.76	3.37(2)
Soil Erosion	10.70 (1.09)	3.71 (2)	4.88 (0.69)	1.78 (9)	10.45 (0.78)	3.47 (5)	8.68	3.00(5)
Soil Compaction	10.12 (1.02)	3.51 (6)	4.51 (0.79)	1.64 (11)	7.65 (0.81)	2.54 (9)	7.43	2.56(10)
Soil Salinity	4.33 (0.89)	1.50 (12)	5.18 (0.73)	1.89 (8)	5.65 (0.75)	1.88(11)	5.05	1.76(12)
Water Holding Capacity	7.44 (0.92)	2.58 (8)	8.58 (0.90)	3.12 (2)	10.85 (0.94)	3.61 (4)	8.82	3.10(4)
Water Logging	5.88 (0.70)	2.04 (10)	8.48 (0.73)	3.09 (3)	10.02 (0.94)	3.33 (6)	8.13	2.82(6)
Water Contamination	10.19 (1.06)	3.53 (5)	4.42 (0.73)	1.61 (12)	8.53 (1.08)	2.84 (7)	7.71	2.66(7)
Fish Catch Reduction	4.41 (0.78)	1.53 (11)	10.30 (0.74)	3.75 (1)	8.02 (0.80)	2.67 (8)	7.58	2.65(8)
Health Impact	9.84 (0.76)	3.41 (7)	5.73 (0.74)	2.09 (7)	6.81 (1.09)	2.26(10)	7.46	2.59(9)
Soil	7.40	2.57 (9)	4.67	1.70	5.39	1.79(12)	5.82	2.02(11)

Toxicity	(1.09)		(0.66)	(10)	(1.02)			
Overall Impact	8.12 (0.78)	2.82	5.29 (0.83)	1.95	5.84 (0.92)	1.94	6.42	2.23
Farm size wise E_{LB} (WTP) for improving overall impact								
Large farms	13.48 (1.75)	4.67 (1)	6.4 (1.95)	2.33 (1)	5.80 (2.38)	1.93 (1)	8.56	2.98 (1)
Medium farms	6.32 (1.19)	2.19 (2)	6.4 (1.33)	2.33 (2)	5.05 (1.22)	1.69 (2)	7.60	2.07 (2)
Small farms	5.27 (0.50)	1.83 (3)	3.91 (0.61)	1.43 (3)	4.59 (0.67)	1.53 (3)	5.88	1.60 (3)

[a] Estimate value unit: % of monthly income, Standard errors are reported in parentheses.
[b] BDT unit: Thousand Taka, Rank orders are reported in parentheses. USD 1.00 = BDT 77.68 (on 31st December 2013)
Source: Own calculation

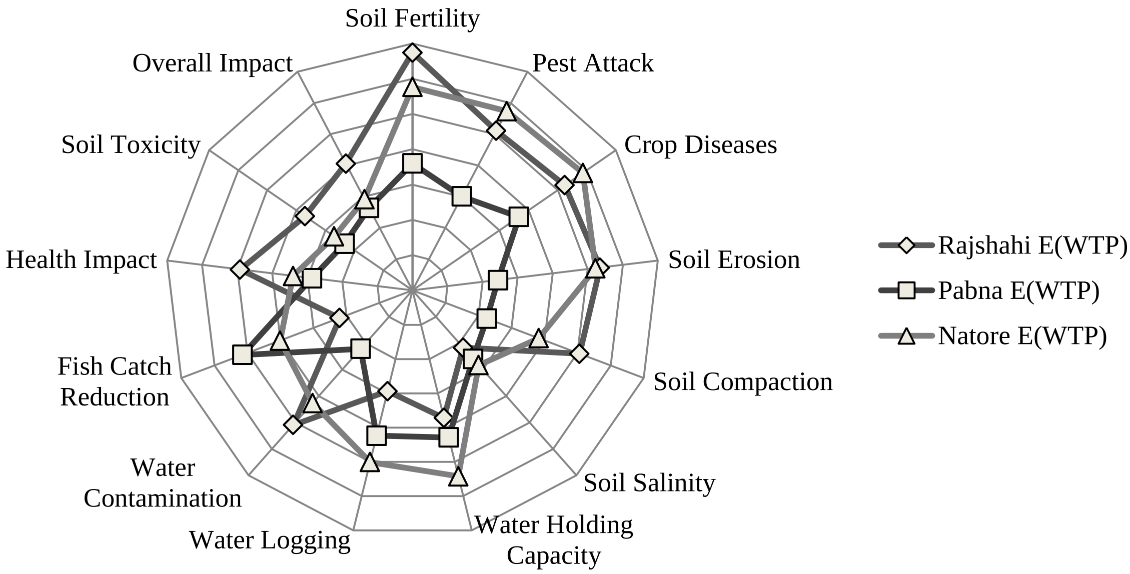


Figure 6.2: Radar diagram: Regional variations in WTP values (BDT)

6.10 Conclusion

The main objective of this present chapter was to economically evaluate farm-level environmental impacts of HYV rice cultivation in Bangladesh. As an effort, farmers' willingness to pay for managing such impacts, explained by their environmental consciousness and awareness is evaluated using the WTP measure of the CV method. Dichotomous choice approach is used to elicit the CV approach. External costs of different environmental impacts are thereby evaluated by applying distribution-free estimator in terms of HYV rice farmers' WTP for managing those specific impacts. Additionally, farmer-specific socio-environmental and agro-economic factors influencing farmers' WTP likelihood is estimated by performing binary logistic regression estimation.

The major findings that are obtained in this chapter are as follows: first, approximately 69 per cent of respondents (i.e., HYV rice farmers) show positive attitude toward WTP for reducing farm-level environmental impacts. Second, the likelihood of their WTP significantly depends on some farmer-specific agro-economic (agricultural income, dependent member share extension contact) and socio-environmental attributes (e.g., SELI). Third, on average, the HYV rice farmers are willing to spend 6.42 per cent of their monthly income for overall environmental impact management purpose. This implies that HYV rice agriculture is generating external cost equivalent to 6.42 per cent of farmers' monthly income (which is approximately BDT 2,230.00) per crop year per farm in the study area. The fourth and final finding is that regional variations in producing such external costs for different environmental impacts are also evident.

As the values of non-marketed outputs, the economic values of environmental impacts that are derived in this way may potentially help environmental policy makers to incorporate environmental phenomena into the economic analysis and ensure an effective internalization of agricultural negative externalities (Tisdell, 2007; Zaks, 2010; Moss and Schmitz, 2013). Additionally, environmental impact management policies should consider farmers agro-economic and socio-environmental factors that would strengthen farmers' belief on agri-environmental policy and its effectiveness. Potentially, this would influence their (farmers') motivation toward farm-level environmental risk management programs and efficient allocation of natural resources in agriculture. Most importantly, impact-specific economic valuation provides policy makers and environmental management team with useful information for policy reforms and social cost accounting in Bangladesh agriculture.

CHAPTER SEVEN

Conclusions and policy recommendations

7.1 Introduction

The present study investigates environmental impact of HYV rice agriculture in three north western regions of Bangladesh. In doing so, it measures the extent of environmental impact, estimates the environmental impact-induced loss in production efficiency and evaluates the external cost arisen because of such agricultural negative externality. By using farm-level primary data (surveying 317 number of HYV rice farms), the analytical discussion of the thesis, therefore, covers the following major areas:

- Environmental impacts of HYV rice agriculture.
- Efficiency changes because of environmental impacts of HYV rice agriculture.
- Economic valuation of environmental impacts in HYV rice agriculture.

Analytical linkages between basic objectives and major findings of the study are established in Section 7.2 with respect to the inherent hypotheses. Subsequently, implications of the major findings and empirical results are analyzed on the basis of the established linkages in Section 7.3. Finally, in Section 7.4 some policy options and recommendations are put forward on the basis of those implications of the study findings. At the end, Section 7.5 describes the scope for further research and limitations of the study along with major contributions.

7.2 Summary of findings

Major findings together with results of the hypothesis tests are presented below along with the three basic objective categories:

(a) *Quantitative measurement of farm-level environmental impacts of HYV rice agriculture*

Intensive agricultural practice (such as HYV rice cultivation) is characterized by releasing negative impacts on the environmental resources (such as soil, water and the atmosphere). Environmental impacts of such intensive cultivation practices are often qualitatively defined and underestimated because of the challenges in quantifying these phenomena while analyzing agricultural sustainability. The present study quantitatively estimates the extent of different environmental impacts of HYV rice agriculture and formulates a composite environmental impact index (CEII) that numerically expresses all of those impacts in an aggregated way. In doing so, the study analyses 17 farming practice-related, farming system (state)-related and farmers' perception-related environmental impacts of HYV rice agriculture. The relative importance of different environmental impacts and their degree of adverseness are explained by ranking values of different impacts.. Reconciliation of the three assessment bases of the environmental impacts into the CEII is proposed to serve as an operational tool measuring environmental sustainability in agriculture. This method is used to measure environmental impact of high yield variety (HYV) rice cultivation in three districts of the north-western Bangladesh using data for a given crop year. Several important facts emerged from the findings of this empirical study:

- Approximately 27 to 69 per cent of the theoretical maximum level of environmental damage is created because of HYV rice cultivation[11]. Additionally, one sample t-test statistically verifies that the CEII values are significantly different from zero across study area. This confirms the fact that considerable amount of environmental impacts are generated in the study area.
- Significant variations in regional mean CEII values across the study regions justify the reason why it is important to conduct region wise environmental impact analysis. However, no variations in mean composite environmental impact index (CEII) values are found to be statistically significant for different farm sizes (large, medium and small farms) in the study area. Heterogeneity in farm sizes may have less potential for influencing environmental impacts than differences in agro-ecological and physiographic factors in study regions.
- All region analysis of environmental impact-wise scores identifies the crop concentration as the first major environmental impact. Farmers in study area are highly concentrated in HYV rice cultivation using the major portion of their

[11] While the theoretical maximum CEII score for this particular study is 17.0, the estimated all region CEII ranges between 4.475 (minimum score) to 11.691 (maximum score).

cultivable land. Such farming practice, defined as the monoculture, disrupts plant root zone, increase soil nutrient imbalances and affects future cultivation by creating adverse pressures on farm bio-diversity. Crop diseases problem followed by reduction in fish catch, soil compaction, soil erosion, health impact, pest attack, soil water holding capacity and soil fertility problems, etc. are found as some of the subsequent impacts in the rank list.

- Except for a few exceptions, values of different environmental impact considerably decline with farmers' perception-related and farming system (state)-related to farming practice-related environmental impactsin HYV rice farms. For instance, state-related impacts, such as soil salinity, surface and ground water pH and soil pH, and farming practice-related impacts, such as the soil stress factor, nitrogen risk factor, etc., are found at the middle and lower middle parts of the ranking list, respectively.They hold relatively lower impact values than farmer's perception related impacts.
- Water logging and water depletion problems hold bottom three and bottom second positions in the ranking list, respectively. This impliesthat farmers in the study area experience such problems relatively less frequently. This may be because the soil property, in general, is considerably porous and sandy in these regions; therefore, a limited extent of water logging will arise. In addition to this, as the reason for lower impact value of the water depletion problem, my survey finds that farmers manage the impact temporarily by installing high power irrigation pumps in the study area. However, in long term, this would affect the water depletion condition more adversely (BADC, 2012).

These findings provide evidence against the null Hypothesis 1 and confirm that intensive agricultural practice, such as HYV rice agriculture, have adverse impacts on different environmental attributes such as soil and water quality, negative impacts on crops (in terms of pest attack and crop diseases), farmers' health and fisheries, etc.

(b) Loss in production efficiency because of the environmental impacts of HYV rice agriculture

Farm chemicals and extensive irrigation practices generate ecological and environmental resources constrain in agriculture and create environmental impact-induced inefficiencies for HYV rice farms. Agricultural inefficiencies have always been evaluated by comparing estimated efficiency score with the theoretical maximum efficiency score (i.e., 100 per cent efficiency). The percentage of inefficiency that arises because of environmental impacts has rarely been segregated econometrically considering the challenge of quantifying the aggregate environmental impacts at the farm level. As the second major objective, this part of the present study, concerns evaluating environmental impact-induced loss in production efficiency. In doing so, this study analyze how efficiently the HYV rice farms could perform in terms of managing environmental impacts. The study defines satisfactorily the CEII as the undesirable output factor produced in a given HYV rice farm. Because the CEII quantifies the aggregate impact on the environment it is incorporated into the production efficiency formula by imposing negative weights together with the desirable outputs (HYV rice) and inputs. The study defines such efficiency model as the eco-efficiency. By applying the DEA, the study, thereafter, estimates two efficiency scores for a given set of inputs and desirable outputs (HYV rice). One is the eco-efficiency score, which is environmental impact (CEII) adjusted production efficiency, and the other one is the production efficiency score, which does not adjust the undesirable output factor, the CEII. Subsequently, environmental impact-induced loss in production efficiency is evaluated by estimating the gap between production efficiency and eco-efficiency scores. At this stage, it is considered that the expected level of eco-efficiency score is unknown; however, it certainly ranges between the production efficiency and the eco-efficiency scores. Therefore, the factors that influence the expected level of HYV rice farmers' eco-efficiency (i.e., environmental impact adjusted production efficiency) are determined by using the interval regression model. The data come from the same set of HYV rice farms that were surveyed in three regions of northwestern BangladeshSeveral important findings emerge from this part of the study:

- The survey finds that the farms in the respective regions, where the chemical fertilizer and pesticide application rate along with the land tilling and irrigation extents are relatively higher, the index of the undesirable output (the mean of CEII) is also higher. The value of the desirable output is the highest for the regional farms where the lowest environmental impacts (the index of undesirable output) were evaluated (Table 5.1, Chapter 5). This finding implies that the

HYV rice farms that produce relatively lower amounts of undesirable output have the potential to produce higher amounts of desirable output.

- Result of the efficiency estimates shows that, on average, Bangladesh HYV rice farms' eco-efficiency (EcoE) are 89.1 per cent while the production efficiency (ProE) is 74.7 per cent only. This implies that, given all other technologies same, minimizing environmental impacts helps Bangladesh HYV rice agriculture to improve the efficiency from 74.7 to 89.1 per cent. However, there remains scope to improve eco-efficiency of Bangladesh HYV rice agriculture.
- The region wise estimates of the production efficiency, eco-efficiency and the respective mean undesirable output factor (the CEII) show that where the environmental impact (undesirable output) is higher, the gap between production efficiency and eco-efficiency is also higher. The regional mean CEII's for Pabna, Rajshahi and Natore are 6.524, 6.833 and 6.992, respectively, whereas gap between the regional mean value of the production efficiency snd eco-efficiemcy are 6.6 per cent, 16 per cent and 20 per cent, respectively.
- The result of the efficiency estimates reveals that the percentage of the total sample lies within a given range of efficiency scores and satisfactorily increases as environmental impacts are minimized (Table 5.3, Chapter 5). For instance, considering all region data, approximately 59.3 per cent of the total sample of farms lie within the efficiency range 0.71 to 1.00, whereas it increases to 92.42 per cent for the same efficiency score range when a full adjustment of the environmental impacts are ensured by performing eco-efficiency estimations. With available resources and existing production technology, minimizing environmental impact in HYV rice production will help realize an expected level of eco-efficiency (or the true production efficiency).
- One of the most important findings comes out of the interval regression analysis is that the expected level of eco-efficiency significantly and directly depends on the proportion of earning members in farmers' family, self-ownership of agricultural land and their (farmers') visit to agriculture extension service centers. Other explanatory variables such as farmers' age, education, experience of doing HYV rice cultivation, agricultural income share and socio-environmental living standard are not found as statistically significant. However, these variables follow the hypothesized direction of the relation with the

dependent variable. The log-likelihood chi square test satisfactorily verifies the difference between the constant only model and the full model (with all these explanatory variables). This implies that the model as a whole is statistically significant and explains the importance of all those farmer-specific socio-economic and agro-economic factors acquiring expected eco-efficiency.

Therefore the above mentioned findings provide strong evidence against the null Hypothesis 2 and establish that environmental impacts cause considerable loss in production efficiency. Additionally, this part of the study also rejects the null Hypothesis 3 and confirms the fact that some of the important socio-economic and agro-economic factors have significant potential for influencing the expected eco-efficiency (or true production efficiency).

(c) Economic valuation of environmental impacts in HYV rice agriculture.

The third major objective is concerned with evaluating economic values of the environmental impacts of HYV rice agriculture. Considering the importance of drawing out welfare implications of the environmental phenomenon associated with HYV rice agriculture the study analyzes farmers' probability of willingness to pay (WTP) for an overall improvement in farms' environmental condition. In a following step achieving this major objective, farmer-specific agro-economic, socio-environmental factors are determined, which influences the maximum likelihood of their WTP. Furthermore, the economic valuation of environmental impacts in terms of farmers' WTP values are estimated in the next step for different types of impacts that are experienced in HYV rice fields (12 specific environmental impacts). Analysis of such economic valuation is performed by applying dichotomous choice contingent valuation (CV) method. Distribution-free estimator, the Turnbull Estimator, is used that evaluates farmers' mean WTP for managing different environmental impacts. The distribution-free estimator satisfactorily evaluates farm-level environmental impact-wise economic values. Several important findings are also emerged from the outcome of the empirical analysis:

- In the study area, farmers' WTP response is considerably positive, i.e., on average 69 per cent of the total respondents (farmers) are willing to pay for an overall environmental improvement. Notably, the field survey also finds agriculture as the primary source of their income. Approximately 64 per cent of

HYV rice farmers' total income comes from agricultural sources. Higher prospect of agricultural income potentially encourage farmers to incur some cost for managing farm-level environmental impacts. The survey also finds that major portion of their (farmers') cultivable land holdings is self-owned (89 per cent), and this influences their desire to pay for reducing environmental impacts.

- Average level of farmers' socio-environmental living index (SELI) in the study area is evaluated as 0.75 on a 0 to 1 scale. As higher index value implies better socio-environmental condition, such finding ensures the fact that farmers' living style is moderately environment-friendly. Farmers in the study area are less likely to produce household pollutions. Satisfactorily, they use specific place for waste disposal purpose and environment friendly energy sources, such as bio-gas and natural gas, for household purpose. Additionally, HYV rice farmers in the study area have moderate awareness of environmental pollution as they live mostly in half concrete type houses, use healthy sanitary systems and pure drinking water sources.
- Approximately 50 percent farmers respond positively that they used to visit extension services for getting cultivation knowledge and input management guiding in the past crop year. This explains why considerable numbers of farmer (69 per cent) are willing to pay for managing farm-level environmental impacts.
- Significant findings that come out from the binary logistic regression model evidently substantiate that farmers' agricultural income share, socio-environmental living standard and their extension contact status are directly related and proportion of dependent member in the family is indirectly related to maximum likelihood of their (farmers') WTP. The logistic regression model as a whole successfully predicts 73.8 per cent observations and identifies those factors influencing farmers' WTP. Although, other predictor variables such as farmers' age, cultivation experience, institutional training, and proportion of self-owned lands do not appear to be statistically significant. However, chi-square test confirms that the model, as whole, is statistically significant.
- Environmental impact-specific economic valuation, the Turnbull estimates, finds that farmers are willing to pay the highest proportion of their monthly income (10.74 per cent) for reducing soil fertility problem. However, they agree to pay

lowest proportion of their monthly income (5.05 per cent) for managing soil salinity problem in the study area.

- WTP values decline as one moves along readily identifiable and mostly experienced impacts to indirectly or lately observable and less experienced impacts. On average, farmers are willing to pay approximately 8.13 to 10.74 per cent of their monthly income for impacts such as soil fertility, crop disease, pest attacks, soils' water holding capacity, soil erosion and water logging problems. All of these problems could readily be recognized and frequently experienced by farmers. Among the impacts, such as ground water contamination, fish catch reduction, farmers' health impact, soil compaction problem, soil toxicity and salinity problems, some are indirectly observable while others can be observed with delay. For managing these types of environmental impacts, farmers' WTP values are relatively lower (5.82 to 7.71 per cent of their monthly income).
- Mean WTP values for an overall environmental improvement in Rajshahi, Natore and Pabna farms are evaluated as 8.12, 5.84 and 5.29 per cent of the farmers' monthly income, respectively. Variations in ranked order of 12 specific environmental impacts, from highest to lowest WTP values, are found among all three regions. For instance, Rajshahi regions' farmers are willing to pay a highest amount (13.48 per cent) for reducing soil fertility problems while they show less desire to pay (4.33 per cent) for managing soil salinity problems. Natore region farmers are mostly concerned with combating crop disease problems and are willing to pay the highest portion of their monthly income (11.73 per cent) to address this problem. However, they are found as least concerned regarding soil toxicity problems because their WTP value for reducing this particular problem is 5.39 per cent. In the Pabna region, this study finds that farmers are willing to pay the highest amount (7.20 per cent) for managing the fish catch reduction problem. The reason behind such finding is that most of the HYV rice fields are found in 'Beel' areas (wetlands) and farmers generally cultivate HYV rice along with fish as an integrated farming practice. Although, water contamination is one of the major causes for reducing fish production in HYV rice fields, but strikingly, this region's farmers agree to pay the lowest amount (4.42 per cent) for reducing such problem. Reason behind such tendency might be is that farmers of this region are not aware of the direct

cause of reducing fish catch. Hence, they are willing to pay lower amount for water contamination problem.

- Slight disparity is found for regional mean WTP values among different farm sizes. Farmers WTP values increase as the size of farm holding increases. My study finds large farmers are willing to pay more than the medium farmers. Also medium farmers are found to be willing to pay more than small farmers. This implies the fact that farmers having bigger size of farm holding may have better ability to pay than that of medium and small farmers. The three-region average value of mean WTP evidently shows that large, medium and small farmers are willing to pay 8.56 per cent, 7.60 per cent and 5.88 per cent of their monthly income, respectively, for an overall improvement in farm environment.
- The study finds that HYV rice agriculture is generating external cost, in terms of overall environmental impact, equivalent to 6.42 per cent of farmers' monthly income (approximately BDT 2,230.00)[12] in the study area. Regional variations in producing such external costs for different environmental impacts are also evident from this study results. In Rajshahi region, highest amount of external cost i.e., BDT 4670.00 is generated in terms of reducing soil fertility condition in the past crop year. However, soil salinity problem generates lowest amount of external cost (BDT 1500.00) while doing HYV rice cultivation in this region. In Natore region, on average, a given HYV rice farm produces the highest amount of external cost (BDT 3890.00) in terms of crop disease problem while that of the lowest amount (BDT 1790.00) is evaluated for soil toxicity problems here. Considerable amount of external cost (BDT 3750.00) in terms of fish catch reduction is, however, caused by HYV rice cultivation in Pabna region. The lowest amount of external cost (BDT 1610.00) is accounted for water contamination problem in this particular region.

All of these aforementioned findings and facts therefore provide evidence against the null Hypothesis 4 and confirm that HYV rice farmers' are desirably willing to pay for reducing environmental impacts in the study area. This also implies that considerable amount (equivalent to farmers' WTP value) of external cost is caused in terms of different environmental impacts in the cultivation of HYV rice. Farmer-specific agro-economic and socio-environmental factors have significant influence

[12] USD 1.00 = BDT 77.68 (on 31st December 2013)

on the maximum likelihood of farmers' willingness to pay for reducing environmental impact; therefore, the null Hypothesis 5 is rejected.

7.3 Implications of major findings

Major findings of the present study asserts that intensive cultivation practices cause considerable extent of, soil and water-related, onsite environmental impacts, which results significant loss in production efficiency and, thereby, accounts for substantial amount of external cost in agriculture. The implications of such assertions are wide-ranging and multifaceted. For instance, environmental degradation, which arises from HYV rice cultivation, will have socio-economic and agro-ecological implications, implications on human health, food production and farmers' welfare, their attitude, perception and on agricultural sustainability, climate change, etc. Considering Bangladesh as the developing country context, implications of my study findings are described following these abovementioned categories.

(a)Socio-economic implications

Environmental degradation in agriculture may vary in its extents and by types; however, it can have some basic socio-economic implications, particularly in a developing economy such as Bangladesh. Environmental impacts and its resultant loss in agricultural production affect farmers' income and expenditure pattern and lower socio-economic status of the farmers (Udofia and Udom, 2011). Soil and water quality degradation, in terms of farm-level environmental impacts, threaten the major means of farmers' livelihood, i.e., the agriculture. When the main agents of agricultural activity are socio-economically vulnerable, the fundamental goal of a developing economy, i.e., the food security for the growing population, will remain unattainable. Moreover, an external cost that has been attributed to intensive agricultural practices is the major cause of market failure (Pretty, 2008). This is because market price of agricultural output does not include external costs and underestimate the social cost producing agricultural products. Such market failure in turn discourages sustainable use of natural resources in agriculture and, consequently, influences producer income group (i.e., the farmer) toward poverty (Duraiappah, 1996).

The majority of the farmers in Bangladesh are small-scale farmers, who are considered the key players in achieving growth in agricultural production. Poor economic condition of a majority farmer group, caused by environmental impact induced production inefficiency, would result economic loss in terms of decreased profit. Particularly, for an agriculture-based developing county, GDP would suffer most at this end; following after a decline in farmers' net income (Duraiappah, 1996).

(b)Implications on farmers' attitude

Environmental impacts of agriculture that account considerable amount of external cost discourage farmers' attitude investing into an impact management projects. However, in developing economies, variations in attitude among the farmers groups (small, medium and large farmers) depend on their size of asset holdings and economic viability (Pascual and Barbier, 2006; Barrett, 2008; Jouanjean, et al., 2014). This makes the small-scale farmers group unable to maintain the quality of their farm land and water resources and to experience decreased productivity and incomes. Eventually, such an aversive attitude increases the divergence between large- or medium-scale resource-rich farmers and small-scale resource-poor farmers.

Major constraints in participating in natural resource replenishment and conservation programs not only include farmers economic ability but also their knowledge and concern regarding the long-term return on environmental conservation projects, access to institutional support that internalizes agricultural externalities, economic incentives for natural resource conservation, etc. (Jouanjean, et al., 2014). Small-scale farmers mostly remain concerned regarding the certainty of future returns and exclusive property rights on their natural capital. Less knowledge regarding the importance of environmental and economic functions and the effects of environmental resource degradation in agriculture also work as the restraining factors that influence farmers' environmental impact management attitude.

(c)Implications on human health

Extensive use of agro-chemicals, which generate considerable extent of environmental impacts, has also had substantial potential for negative impacts on human health. Farmers, using seed-fertilizer-irrigation-based modern technology for agricultural production, often remain in close contact with farm chemicals. Regular and frequent contact with toxic substances affects farmers' health condition either instantly or in long term. Additionally, some types of insoluble toxic chemicals enter the human body indirectly after consuming the grain or vegetable, on which chemical pesticides and fertilizers have been sprayed or applied. These types of farm chemicals will also have much more potential for eutrophication. Generally, considerable amount of agro-chemicals applied into irrigated fields flow into surface water sources and leaches into groundwater reservoirs and ends up by polluting drinking water sources. Therefore, agro-chemical exposure results in number of chronic health effects, including lung damage, chemical burns, and blue baby syndrome in infants (caused by nitrate in groundwater) and a variety of cancers and reproductive and developmental impacts (Weisenburger, 1993).

(d)Implications on agro-ecological and ecosystem services

The agro-ecological implications of degraded farm lands and water quality because of intensive cultivation practices are wide-ranging. Nitrates and nitrites resulted out of chemical reaction between fertilizers and irrigation water pollutes aquatic habitats. Continuous runoff of chemical substances into polluted water sources annihilate the sanctuary of various aquatic species and different organisms including fish, snails, crabs, frogs, earthworms, and other insects and plants and threaten genetic diversification of the agro-ecosystem. This also restricts biomass recycling capacity, optimum availability of soil nutrients and disrupts nutrient flow balance.

By affecting biological interactions among agro-ecological components environmental degradation in agriculture also disrupts important ecological services. It can deplete the ecological condition in terms of destroying natural habitat and increasing pressures on biodiversity by influencing erosion or restricting angling opportunities by reducing water quality of streams and wetlands (Dale and Polasky, 2007). Disruption and degradation in natural habitat would constraint important pollinator services to neighboring farms (Ricketts, et al., 2004). Additionally, excessive farm chemicals, applied repeatedly into agricultural lands, would limit adjacent non-farm wetlands’ capacity to purify water sources for future agriculture. In long term this would also limit onsite pollution absorptive capacity of farm lands or other pasture lands and thereby affects ecosystem services as a whole.

(e)Implications on climate change

Agriculture is considered one of the primary sources of carbon emissions that contribute to climate change. On the contrary, it is also regarded as the major source of carbon sink, which limits climate change condition. In this respect, agricultural pollution and its implications on climate change are important. Intensive agricultural activities such as use of synthetic pesticides and chemical fertilizers are considered an important source of greenhouse gas emission (GHG). Nitrous oxide emission and methane emission from nitrogen fertilizers that are used in rice production are two of these important types of GHGs that contribute considerably to climate change (Yagi and Minami, 1990; Bouwman, 1996; Dobbie, et al., 1999). This influences depletion of soil organic carbon pool severely and contributes to carbon sink disruptions. Carbon pool depletion would cause further reduction in soil and water quality, and biomass productivity. It is then be aggravated by continuing climate change condition. The implications of agricultural pollution on climate change are critical and could take form in two major ways. These include it's potential for influencing carbon emission and restricting carbon sequestration[13] capacity of the soil.

(f) Implications on agricultural sustainability

Intensive agriculture, which comprises approximately half of global usable land (Tilman, et al., 2001; 2002), and its detrimental impacts on the environment will potentially contribute considerably to an unsustainable state of agriculture (Cassman, and Pingali, 1995). Adverse side effects of agriculture on the environment, in terms of negative externalities, impose external costs (Pretty, 2008) that often revealed as a delayed consequence of using production technologies. Therefore, environmental impacts and their resultant inefficiencies raise serious questions about acquiring long-term agricultural sustainability. The major concern of agricultural sustainability is to maximize current and future acquirement of environmental, economic and social welfares. However, external cost in agriculture would result loss in environmental welfare by limiting ecosystem services (Carpenter et al., 1998). This, in turn, would lead to a loss in farmers' economic welfare in terms of decreased profit and ends up jeopardizing farmers' social welfare in terms of reducing farm income and social status and increasing food poverty, etc. Such external costs would weaken the resilience and persistence capacity of an agricultural system, which are recognized as the important operational factors of agricultural sustainability, and fail to address its environmental, economic and social outcomes (Pretty, 2008).

[13] Carbon sequestration implies transferring atmospheric carbon di-oxide into long-lived pools and storing it securely so it is not immediately re-emitted.

7.4 Policy options

Important findings of this thesis and its' wide ranging implications, may be useful to agricultural and environmental policy makers. Following the present challenge to feed the growing population, intensive agricultural practice should be operated with great care, so that an environment-efficient sustainable cultivation system could be maintained. Intensive cultivation practices should strictly be conditional on minimizing their adverse impacts on the environment. Specifically, substantial advances in scientific and technological improvement and regulatory and policy changes are needed to manage environmental impacts of agricultural expansion. This is because; it is tougher to clean up agricultural pollution than to keep the pollution extent at a minimum level. This needs collective effort of the policy makers and farmers. Government should be stricter in controlling farmers' environment depleting activities and in enforcing the existing environmental regulations. In some cases, it should reform and revise existing policy and publish appropriate and up-to-dated policy structure. On the contrary, farmers should also be well aware of environmental consequence of intensive production and cooperate with government by following environmental degradation management policies. Considering Bangladesh agriculture, particularly for HYV rice agriculture, this study suggests following policy options for managing farm-level environmental impacts.

- Considering socio-economic implications of the environmental impacts, existing socio-economic security-based policy focus should be extended toward socio-environmental security-based policies. It is evident that environmental uncertainty, associated with intensive agriculture, has now evolved into environmental risk and could therefore contribute social risks and restrict farmers' socio-economic welfares in Bangladesh. Advising corrective measures for market failure situation, arisen by environmental impacts, is the common goal of both social and environmental policy interventions (Laurent, 2015). In this respect, a socio-environmental policy would be of immense significance, which would fulfil resource allocation and redistribution function of social welfare and at the same time ensure environmental welfare functions of efficient allocation and extraction of natural resources in agriculture. For instance, while allocating both types of resources, policy-makers should recognize current external cost of environmental impact (in social cost accounting) and use this information to project future social costs. Similarly, while redistributing resources, policy advisors should not only consider farmers' social status (e.g., income level, or employment situation) but also the vulnerability of some specific areas with respect to adverseness of specific environmental impacts in agriculture.

- Majority farmers group in Bangladesh is short-term profit-seeking and small-scale farmers. This is why in some cases existing policy recommendation, even though it is relevant, does not work effectually for farmers' welfare (Barkat, et al., 2007). Therefore, policy options are needed to build up farmers' environmental awareness, their knowledge of environmental service in agriculture and attitude for natural resources (capital) conservation in agricultural production. Desirably, Bangladeshi farmers are now becoming conscious of environmental damage and are willing to have some solutions. However, their willingness of participation should be enhanced through the use of public mass media, e.g., radio, television, newspapers, etc., which could influence their environmental awareness as well. Additionally, there is a need for strengthening agricultural extension services and other external institutions for ensuring proper use of production technologies and defining and explaining environmental problems to farmers. Farmers' awareness building program can also be executed by different campaigning programs and multi-expansionary approaches such as agricultural fair, farmers' field day, etc.
- While implementing environmental impact management projects, government and non-government organizations should provide farmers with supportive framework that encourage their participation, particularly, in terms of self-mobilization. Under the system of self-mobilization, farmers would take their own initiatives, develop contacts with institutions internalizing agricultural externalities for advice seeking purpose and learn extracting natural resources and using production technologies. In this regard, decentralized learning institutions with an easy access and rapid response system to farmers' queries could work as a supportive framework influencing self-mobilization motivation. Such institution should also provide farmers with information on the external costs of agriculture (the economic values of environmental impacts) when they are producing and experiencing production inefficiencies. This information will

work as an incentive for farmers to minimize these costs (or environmental impacts), which will improve farmers' agro-economic and agri-environmental welfare.

- The enforcement of existing land use policy and policy reformation, where it is inadequate, is needed in farm land areas that are cultivated under intensive production systems. Judicious use of cultivable lands and land defragmentation, which are the major goals of effective land use policy, are also the common goals of soil conservation policy; therefore, these strategies have the potential to manage the climate change risk. In this regard, restrictions on monoculture practices (e.g., repeated cultivation of chemical-intensive crop varieties and encouraging crop rotation systems) should be recommended as appropriate policy options. The implementation of crop diversification or a crop rotation program should be ensured by identifying suitable cropping patterns, effective farm operation practices, and proper timing of crop rotation. These approaches will manage the restoration of essential soil nutrients and increase the soil's carbon sequestration capability where it is deficient, which manages the climate change condition.
- A sufficient amount of public investment in environmentally resilient production technologies and human resources (e.g., agriculturalists and environmentalists) are needed to ensure agricultural sustainability. Additionally, the existing incentive structure for the private sector, which mostly remains less impressive in low-income developing nations (Pardey and Beintema, 2001) such as Bangladesh, should also be substantially expanded. A compensation structure that accurately reflects the economic values of agro-ecological services and ecosystem services will work to influence incentives for private sector investment in environmentally sustainable agricultural projects. Certainly, these collective efforts or joint ventures will effectually help the intensive production system move toward a more sustainable state.
- Considering the adverse health effects of agro-chemicals, a specific health policy is needed that can minimize farm chemical exposures to human health. In this regard, investment in research is also required to recognize and quantitate the potential for agro-chemical risk on human health. Policy makers should advocate decision makers at every sub-ordinate division so that advances in health and well-being can be expanded to the marginal levels. In this connection, an

appropriate policy framework that enhances farmers' socio-environmental living standards and ensures less potential for household pollution is also important. As some of the essential components, this policy framework should contain a provision of healthy living places, better health facilities, well managed waste disposal systems, pure drinking water, a healthy sanitary system, etc. Additionally, knowledge disseminations on family planning and reproductive health programs are necessary to reduce farmers' subsistence pressure and influence their agro-economic welfares.

7.5 Scope for future research

The present study only considers HYV rice cultivation and analyzes its impact on the environment. However, future studies can be undertaken to determine whether other types of high yield verity crops, such as wheat or maize, and other types of chemical-intensive agriculture, e.g., fishery or poultry, generate environmental impacts, production inefficiency and external costs in Bangladesh's agriculture.

Different agro-ecological zones (AEZs) have different climatic and physiographic conditions, which may cause different types and extents of environmental impacts. In this study, I have covered only three AEZs, i.e., AEZs 5, 11 and 12. Future research can conduct a similar agro-ecological zone-specific survey. The findings of this survey will help policy makers with appropriate policy directions in the context of a given agro-ecological zone. Apart from this local and regional context, similar country-specific research can also be undertaken that will cover the global contexts.

The present study estimates environmental impacts considering only the recent crop year data. However, it is worthwhile to continue this study for successive crop years. Because environmental impacts of agriculture and its extent can change across a given span of time, annual basis estimates of the composite environmental impact index (CEII) that are conducted for several crop years will explore trends of environmental impact extents at the farm level. Future research can conduct this temporal analysis of farm-level environmental efficiency and thus open up environmental productivity research prospects.

Given these limitations, this present study contributes to the literature on agricultural sustainability, research on environmental and production efficiency in agriculture and agri-environmental policy decisions in the following respects.

- This study proposes an alternative indicator-based approach based on the CEII, which produces quantitative information on the extent of different farm-level environmental impacts. This CEII satisfactorily validates the proposed approach in terms of its flexibility, applicability and relevance to evaluate environmental sustainability in agriculture and also for other types of production activities such as industry.
- This study contributes to the research on environmental and production efficiency by providing information on the efficient allocation of natural resources by assessing environmental efficiencies. This information asserts the environmental sustainability potential in Bangladesh's HYV rice agriculture. Additionally, this study contributes to the literature on natural resources and environmental economics by guiding pollution generating producers with the efficient exploitation of natural resources, such as soil, water, etc.
- This is the first study that economically evaluates the farm-level environmental impacts in Bangladesh and explores information on the monetary values of farm-level environmental impacts. In this respect, this study contributes to environmental policy makers the external cost values of HYV rice agriculture. This information will help policy makers internalize specific agricultural negative externalities and implement agri-environmental regulations such as command and control options. Command and control options may include imposing taxes on farm chemicals and establishing environmentally friendly irrigation and mechanization standards, soil and water test service fees, etc.

APPENDICES TO CHAPTER THREE

Appendix 3-I: Soil and water testing instruments

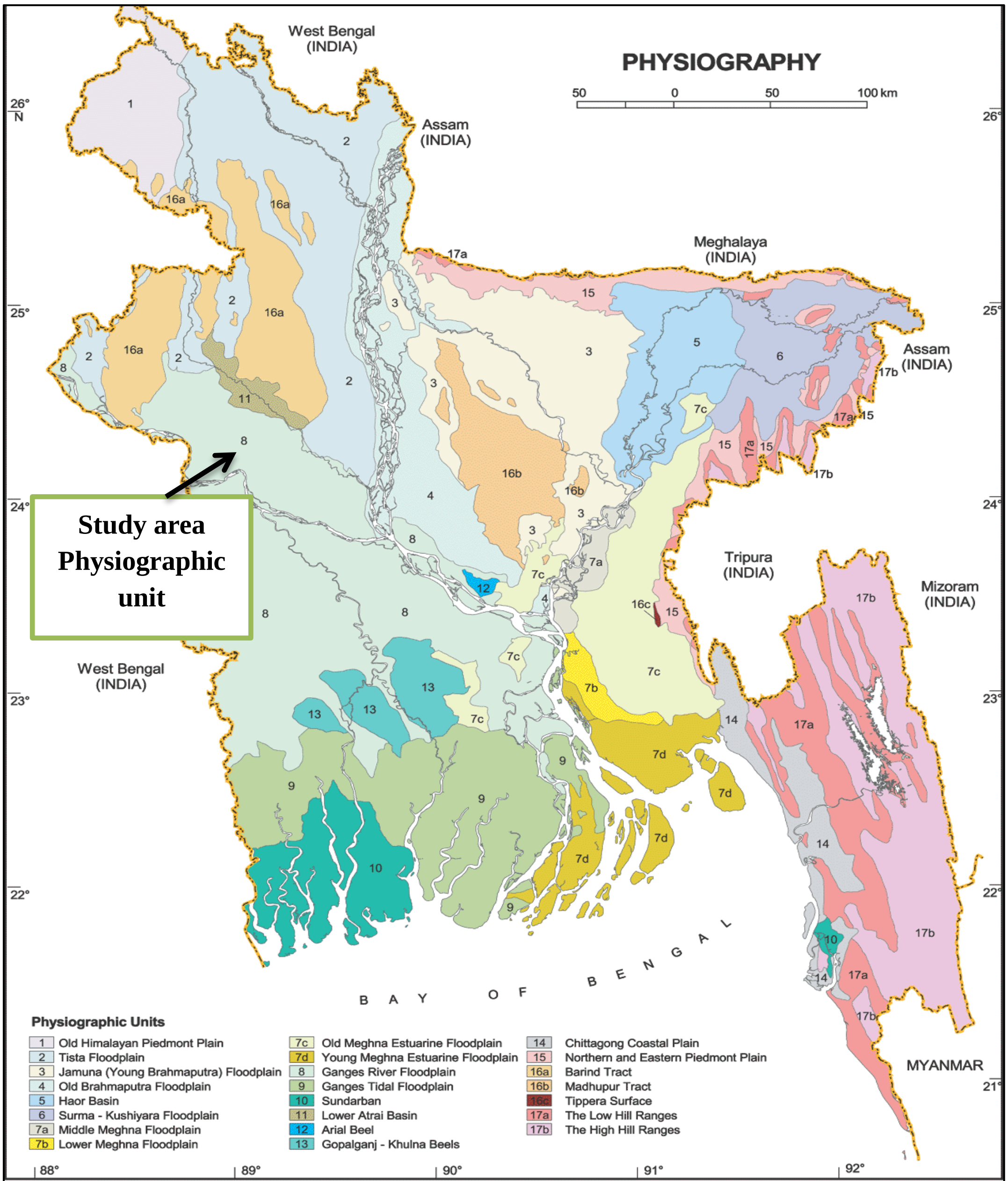
Soil pH meter measures soil acidity and alkalinity

Pen type soil penetrometer for measuring soil compaction

Soil salinity meter

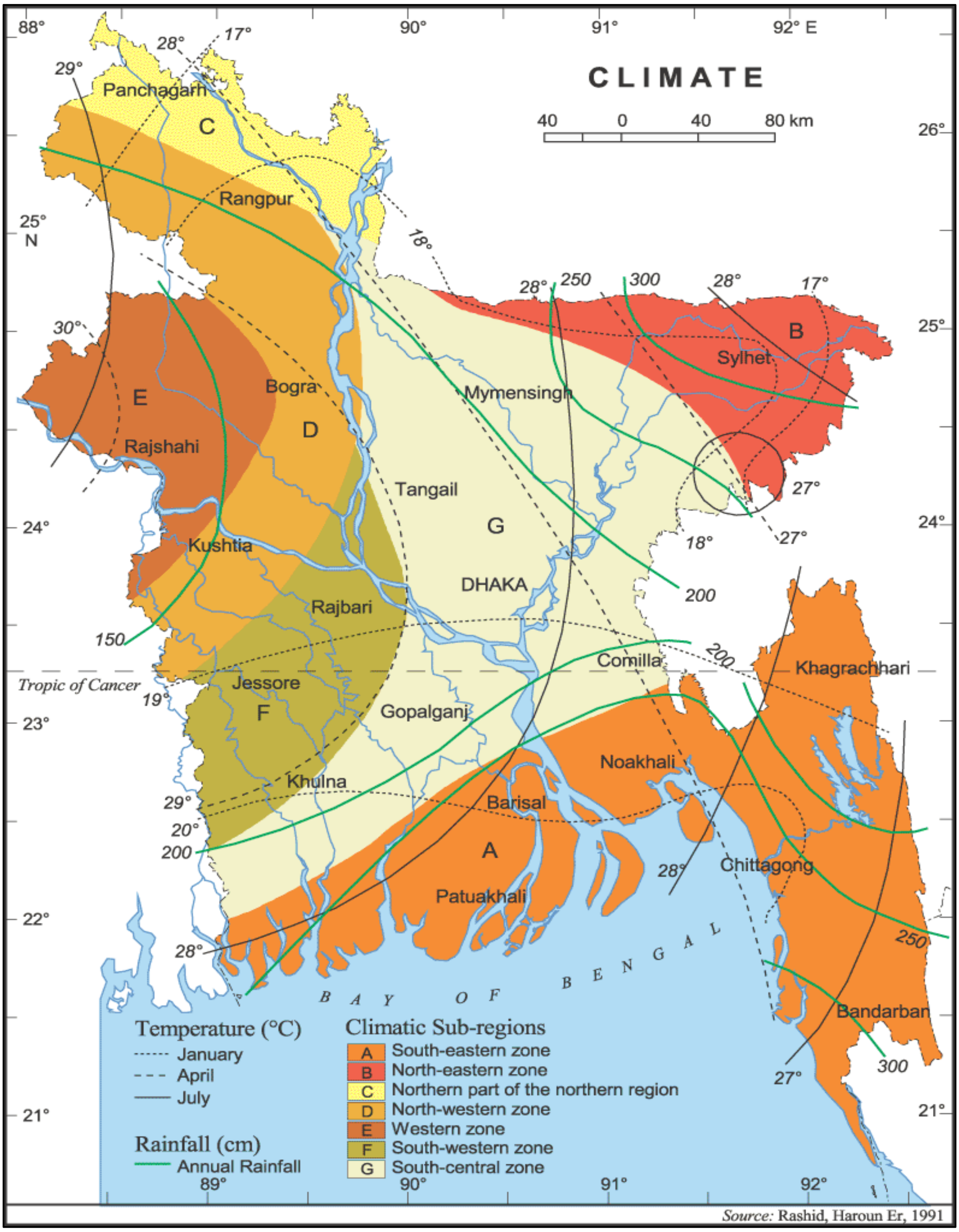
Water pH meter

Appendix 3-II: Bangladesh physiography

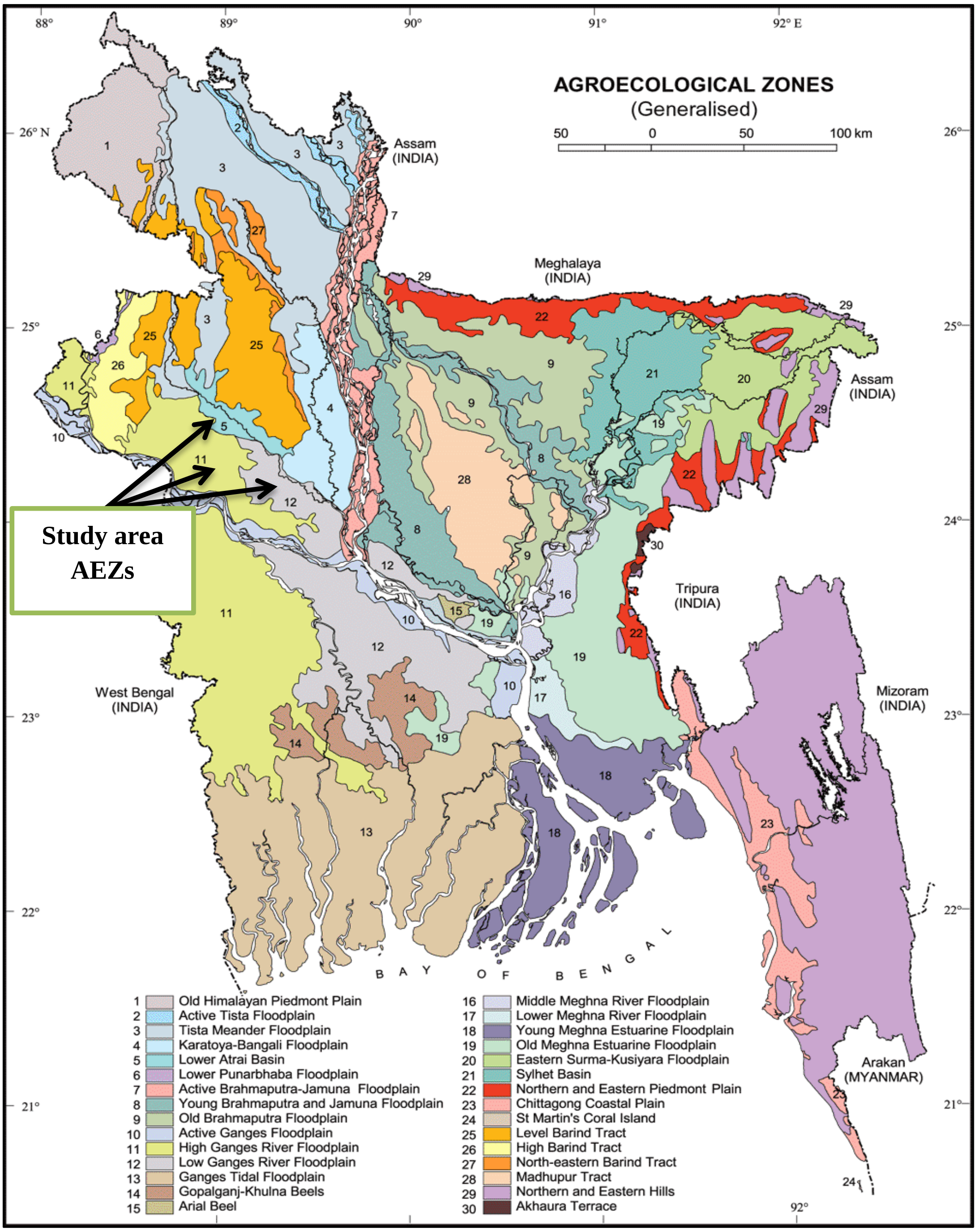


Source: Modified From *SRDI,1997; Rashid, 1991; Reimann, 1993*

Appendix 3-III: Bangladesh climate zone



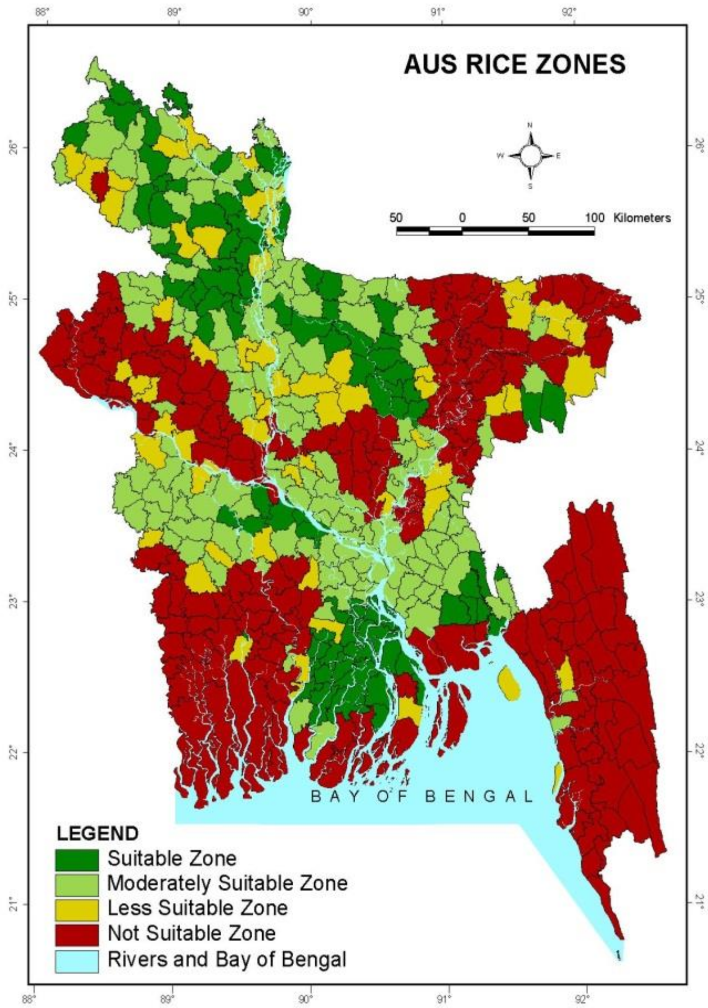
Appendix 3-IV: Bangladesh agro-ecological zones

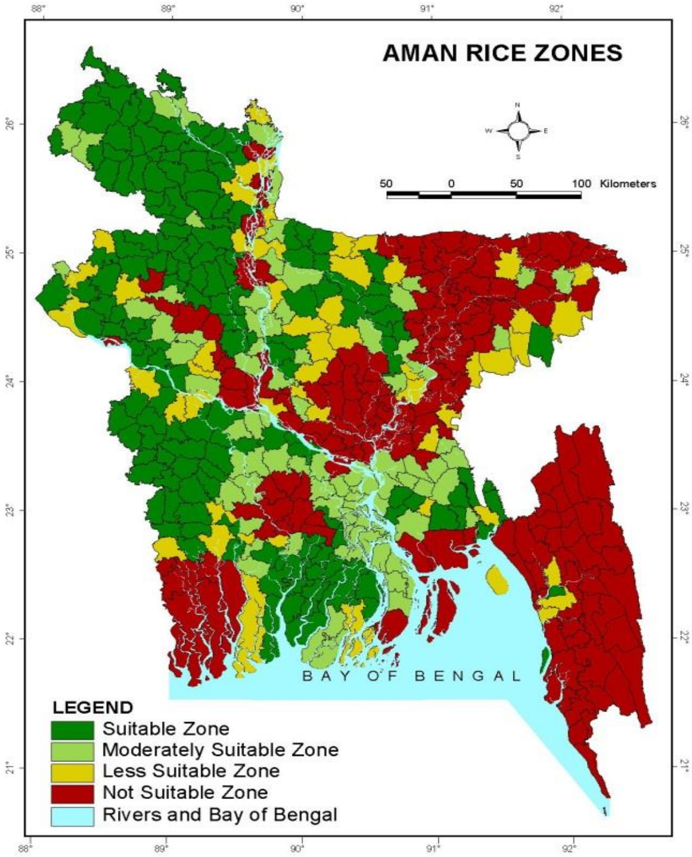


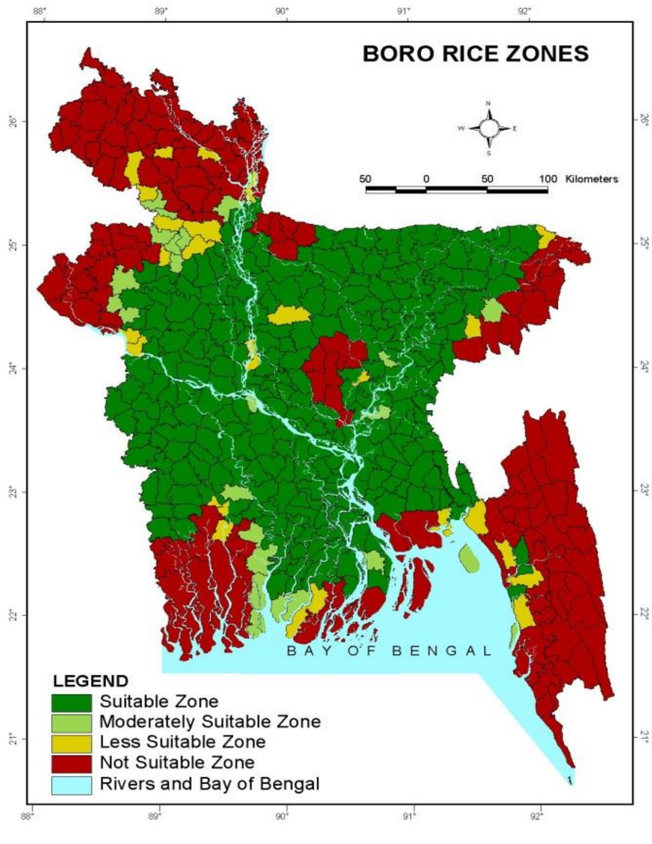
Appendix 3-V: Cation exchange capacity (CEC)

CEC: Soil particles and organic matter have negative charges on their surfaces. Mineral cations can adsorb to the negative surface charges or the inorganic and organic soil particles. Once adsorbed, these minerals are not easily lost when the soil is leached by water and they also provide a nutrient reserve available to plant roots. CEC of soil acts as nutrient reservoir for the plants. CEC status is thus an important physical property of the soil that would allow an agricultural researcher to determine appropriate amount nutrient supplement required for the given plant. Information on soil CEC helps a farmer to choose a specific fertiliser and its quantity required to be applied as well.

Appendix 3-VI: Three seasons rice crop zoning maps




AMAN RICE ZONES
50 0 50 100 Kilometers
BAY OF BENGAL
LEGEND
Suitable Zone
Moderately Suitable Zone
Less Suitable Zone
Not Suitable Zone
Rivers and Bay of Bengal


BORO RICE ZONES
50 0 50 100 Kilometers
BAY OF BENGAL
LEGEND
Suitable Zone
Moderately Suitable Zone
Less Suitable Zone
Not Suitable Zone
Rivers and Bay of Bengal

Appendix 3-VII: Survey questionnaire

Research questionnaire guidelines

Enumerator's Name		Sample no.	Date:

Part I: Respondents' part.

1. Farming experience

Farmer's general skill level:

1(1) Respondent no.		1(9) Age (years)	
1(2) District of residence		1(10) Sex (M/F)	
1(3) Village of residency (Union)		1(11) Education level(schooling years)	
1(4) Crop field county (village)		1(12) Experience as a farmer (years)	
1(5) Training on modern agri. (Yes/No)		1(13) Experience of modern agri. practice (years)	
1(6) Specialized course on modern farm practice/agricultural degree (Yes/No)		1(14) Formal training on modern agri.(Yes/No)	
1(7) Agriculture extension service availability (Yes/No)		1(15) Receive Extension Service (Yes/No)	

2. Socio-economic information

Income pattern

2(1) No of Family members		
2(2)No of earning members		
2(3)No of dependent members		
2(4)Occupation: Round the year (tick mark in appropriate box)	On farm sector	Off farm sector
2(4)Occupation: Seasonal (tick mark in appropriate box)	On farm Sector	Off farm sector
Income (Tk) from		
2(5)Agriculture related source	Rice	non-rice
2(6)Off-farm source		
2(7)Total income of the family		

Household expenditure structure

Purpose of expenditure	2(8) Food	2(9) Cloths	2(10) Education	2(11) Health	2(12) Energy	2(13) Transport	2(14) Recreation	2(15) other
Amount								
Unit of time[2]								
Expenditure per unit of time code: 1-per day, 2-per week, 3-per month, 4-per year								

Socio-environmental living facility

2(16) House category	Clay house	Tin shed Straw house	Semi Brick Build	Brick build
2(17) Sanitary system	Open place	Temporary/ non sanitary latrine	Sanitary without water seal latrine	Sanitary with water seal Latrine
2(18) Available Health Facility	Village doc	Health officer	Private Clinic	Hospital
2(19) Sources of drinking water	Pond/river	Well	Public water supply	Deep tube well
2(20) Sources of Energy	Timber/Cow-dung /Straw/ Dry leaves/ Kerosene	Electricity	Bio-gas /natural gas	Solar panel
2(21)Waste disposal site	Un-managed dump site	Burnt	Bury/inside pit	Specific waste-bins

3. Agricultural production

Land

Tenure status						
	Owned	Rented out	Mortgage out	Rented in	Mortgage in	Total land
3(1) Cultivable land (acre)						
3(2) Homestead (acre)						
3(3) Orchard (acre)						
Land plough method and cost per acre						
	owned	Rented in	Rent cost	Mortgage in	Mortgage cost	Total cost including maintenance cost
3(4) Tractor						
3(5) Power Tiller						
3(6) Bullock						

Irrigation methods and cost

Methods	owned	Rented in And cost	Mortgage in And cost	Electric bills (tk per month)	Other cost-free water source (Gov.)
3(7) Low lift pumps					
3(8) Shallow tube well					
3(9) Deep tube well (Engine operated)					
3(10) other					

Cropping season wise HYV rice cultivation

Crop Season	Months duration	Crop Variety (Tick mark)	3(11) Cost of seed Per kg	3(12) Total area under HYV variety	3(13) Other crops cultivation in free season (if any)
Kharif-I (pre-kharif)	Mar-Jun (4)	HYV *AUS*			
Kharif-II (full monsoon)	Jul-Sep (3)	HYV *AMAN*			
Rabi (winter)	Oct-Feb (5)	HYV *BORO*			

cropping pattern

3(14) Please name the varieties of HYV AUS planted in last season							Reason for choosing these varieties:	- - -
3(15) Please name the varieties of HYV AMAN planted in last season							Reason for choosing these varieties:	- - -
3(16) Please name the varieties of HYV BORO planted in last season							Reason for choosing these varieties:	- - -

Labour requirement

Work categories		Land preparation	Planting	Irrigation	Fertilizer/ insecticide application	Weeding	Harvesting	Threshing	Drying
3(17) No of Labour in use	M								
	F								
3(18) Cost per labour hour	M								
	F								
3(18) Total time of labour work per season	M								
	F								

Fertilizer application

Types	Urea	TSP	DAP	Zipsum	MOP	Organic	Other chemical
3(19) Quantity per acre							
3(20) Cost per unit							
3(21) Applied area in total acre							

Pesticides application

Types/Names	3(22) Quantity per acre	3(23) Cost per unit	3(24) Total area applied
1.			
2.			
3.			
4.			

Outputs:

Actual output for a single crop year	3(25) Karif-1 (HYV Aus)				3(26) Kharif-2 (HYV Aman)				3(27) Robi HYV Boro			
sub-variety names												
quantity (kg/acre)												

4. Agri-environmental information

HYV rice farmers' awareness (Please tick all applicable):

4(1) What are the soil related problems that you are facing in your land? (please tick appropriate))	☐ compaction ☐ fertility ☐ salinity ☐ toxicity	☐ erosion ☐ water logging ☐ poor water holding capacity ☐ others........
4(2) What are the water related problems faced during HYV rice cultivation? (please tick on appropriate)	☐ Surface water contamination ☐ Ground water contamination ☐ Lowering ground water level	☐ Water toxicity ☐ Water salinity ☐ others.............
4(3) Do you face any health related problem while using chemical pesticides and fertilizers?	☐ Arsenic problem ☐ Skin fungal problem ☐ Skin itching	☐ inhalation problem ☐ others............
4(4) Do you notice other impact like?	☐ Increase in crop diseases ☐ Increased pest attack ☐ others............	
4(5) Please list down major crop diseases found in your crop.	Bacterial Diseases: ☐ Bacterial blight ☐ Bacterial leaf streak ☐ Foot rot ☐ Grain rot ☐ Pecky rice (kernel spotting) ☐ Sheath brown rot ☐ Miscellaneous diseases ☐ Alkalinity or salt damage ☐ Bronzing ☐ Cold injury ☐ Panicle blight	Fungal diseases ☐ Aggregate sheath spot ☐ Black kernel ☐ Blast (leaf, neck [rotten neck], nodal and collar) ☐ Brown spot ☐ Crown sheath rot ☐ Downy mildew ☐ Eyespot ☐ False smut ☐ Kernel smut ☐ Leaf smut ☐ Leaf scald

	☐ Straight head ☐ White tip	☐ Narrow brown leaf spot ☐ Root rots ☐ Sheath blight ☐ Stem rot ☐ Water-mold (seed-rot and seedling disease)
4(6) Please specify pests that mostly attack your crop.	☐ Paddy stem borer ☐ Gall midge ☐ Swarming caterpillar ☐ Rice skipper ☐ Leaf folder (or) leaf roller ☐ Rice horned caterpillar ☐ Yellow hairy caterpillar ☐ Grasshopper ☐	☐ Spiny beetle ☐ Whorl maggot, ☐ Green leafhopper ☐ Brown plant leafhopper ☐ White backed plant hopper ☐ Mealy bug ☐ Rice ear head bug ☐ Thrips

<u>Farmers' environmental perception and willingness to pay information</u>

4(7). What is the fertility condition of your cultivable land? (Please tick)

A. Increasing B. Decreasing C. No change

4(8). Do you need to use more amounts of farm chemicals than the previous crop year?

- ☐ yes/no/not sure

4(9). In what extent the fertility of your soil is reducing? (Please mark your rank)

i. Very low rate of reduction	ii. Low rate of reduction	iii. Medium rate of reduction	iv. High rate of reduction	v. Very high rate of reduction

4(10). Do you think that one of the major reasons for using more farm chemicals is the eventual fertility reduction of your soil?

- ☐ yes/no/not sure

4(11). Suppose you are requested to pay a particular portion of your monthly income to improve the fertility condition of your soil: please tick on applicable one

- ☐ agree
- ☐ disagree [go to 4(13) question]
- ☐ not sure [go to 4(13) question]

4(12). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income)[14] to improve the soil fertility condition:

[14] Enumerator will pick an amount randomly and ask the respondents to say their agree-disagree opinion.

- yes/no/not sure

4(13). Does your crop suffer from diseases and pest attack problem?

- yes/no/not sure

4(14). At what extent the pest attack problem is increasing? (Please mark your priority)

i. Very low problem	ii. Low problem	iii. Medium	iv. High problem	v. Very high problem of pest attack

4(15). Suppose you are requested to pay a particular portion of your monthly income to tackle the pest attack problem in an environment friendly way, do you :(please tick on applicable one)

- agree?
- disagree? [go to 4(17) question]
- not sure [go to 4(17) question]

4(16) Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve the pest attack problem:

- yes/no/not sure

4(17). At what extent the crop disease problem is increasing in your field? (Please mark your priority)

i. Very low problem	ii. Low problem	iii. Medium	iv. High problem	v. Very high problem

4(18). Suppose you are requested to pay a particular portion of your monthly income to cure the crop diseases in an environment friendly way: please tick on applicable one

- agree
- disagree [go to 4(20) question]
- not sure [go to 4(20) question]

4(19) Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve the crop disease problem:

- yes/no/not sure

4(20). Is the top soil level of your cultivable land lowering day by day?

- yes/no/not sure

4(21). If yes, then, according to you at what extent the erosion is taking place? (Please mark your priority)

i. Very low rate of erosion	ii. Low rate of erosion	iii. Medium rate of erosion	iv. High Very rate of soil erosion	v. Very high rate of soil erosion

4(22). Suppose you are requested to pay a particular portion of your monthly income to protect your soil from erosion as a part of sustainable soil management programe, do you: (please tick on applicable one)

- agree?
- disagree? [go to 4(24) question]
- not sure[go to 4(24) question]

4(23) Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve soil erosion problem:

- yes/no/not sure

4(24). Is your soil becoming so compacted and hard day by day?

- yes/no/not sure

4(25). If yes, what is the grade that you assign of that above feature? (Please mark your priority)

i. Very low compaction	ii. Low soil compaction problem	iii. Medium compacted soil	iv. Highly compacted soil	v. Very highly compacted soil

4(26). Suppose you are requested to pay a particular portion of your monthly income to tackle soil compaction problem as a step to cultivate in an environment friendly way, do you: (please tick on applicable one)

- agree?
- disagree? [go to 4(28) question]
- not sure [go to 4(28) question]

4(27). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve soil compaction problem:

- yes/no/not sure

4(28). Is there any salinity problem in your HYV rice field?

- yes/no/not sure

4(29). What is the extent of increasing soil salinity? (Please mark your priority)

i. Very low soil salinity	ii. Low salinity problem	iii. Medium problem	iv. High salinity problem	v. Very high problem of soil salinity.

4(30). Suppose you are requested to pay a particular portion of your monthly income to cure the soil salinity problem, do you: (please tick on applicable one)

- agree?
- disagree? [go to 4(32) question]
- not sure? [go to 4(32) question]

4(31). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve soil salinity problem:

- yes/no/not sure

4(32). What is the water holding capacity of your soil? (Please mark your priority)

i. Very low capacity	ii. Low capacity	iii. Medium capacity	iv. High water holding capacity	v. Very high water holding capacity.

4(33). Is there any water logging problem that you face most often in your field?

- yes/no/not sure

4(34). What is the extent of such water logging problem? (Please mark your priority)

i. Very low problem	ii. Low problem	iii. Medium problem	iv. High water logging problem	v. Very high water logging problem

4(35). Suppose you are requested to pay a particular portion of your monthly income to tackle your soil's water holding capacity problem as a part of taking soil management service, do you: (please tick on applicable one)

- agree
- disagree [go to 4(37) question]
- not sure [go to 4(37) question]

4(36) Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve soil water holding capacity problem:

- yes/no/not sure

4(37). Are the field adjacent water sources polluting day by day?

- yes/no/not sure

4(38). What is the extent of the water contamination problem? (Please mark your priority)

i. Very low	ii. Low	iii. Medium	iv. High water contamination	v. Very high water contamination.

4(39). Suppose you are requested to pay a particular portion of your monthly income to control water contamination problem as a measure to restrict environmental pollution, do you: (please tick on applicable one)

- agree?
- disagree? [go to 4(41) question]
- not sure? [go to 4(41) question]

4(40). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve water contamination problem:

- yes/no/not sure

4(41). Is there any reduction of fish catch from those contaminated water sources?

- yes/no/not sure

4(42). Are the fishes of those contaminated water sources dying?

- yes/no/not sure

4(43). What is the fish catch reduction rate according to you? (Please mark your priority)

i. Very low rate reduction	ii. Low reduction	iii. Medium	iv. High fish catch reduction	v. Very high reduction in fish catch

4(44). Suppose you are requested to pay a particular portion of your monthly income to protect fishes from dying, do you: (please tick on applicable one)

- agree
- disagree [go to 4(46) question]
- not sure [go to 4(46) question]

4(45). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve fish catch reduction problem:

- yes/no/not sure

4(46). Do you use fertilizers more than the standard level in your soil during cultivation among the followings? Please tick all applicable.

- Lime
- Ash
- TSP
- DAP

4(47). Does your soil create any skin irritation or infection problem?

- yes
- no
- not sure

4(48). If yes, then according to you what is the extent of soil toxicity?

i. Very low toxic	ii. Low toxic	iii. Medium toxic	iv. High toxic	v. Very high soil toxicity

4(49). Suppose you are requested to pay a particular portion of your monthly income to receive health support for these skin problems, do you: (please tick on applicable one)

- agree
- disagree
- not sure

4(50). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to improve health impacts:

- yes/no/not sure

<u>Willingness to pay for overall improvement in environmental impacts</u>

4(51) Environmental impacts like soil and water depletion are required to be managed: Please tick.	Agree	Disagree
4(52) Do you think it is important for your field? Please tick.	yes	no
4(53) Do you think spending some money to improve your soil will	yes	no

benefit you in terms of production? Please tick.		
4(54) Would you like to forgo some specific portion of your monthly income for such environmental improvement? Please tick.	yes	no
4(55) Do you think it is better to switch into another crop which may cause less impacts on environment rather than paying? Please tick.	yes	no

4(56). Suppose, you are requested to pay a particular portion of your monthly income for cultivating HYV in an environment friendly way:

- Do you agree?
- Not agree

4(57). Please tick whether you would like to pay a randomly offered bid amount (5/6/7/8/9/10/11/12/13/14/15/16/17/18/19/20 per cent of your monthly income) to cultivate HYV rice in an environment friendly way.

- yes/no/not sure

Part II: For enumerators' only:

Soil Quality

Soil toxicity (pH level)	Soil Compaction (psi)	Soil Salinity (ds/m)

Water Quality

Surface water contamination (pH)	Ground water Contamination (pH)

Thanks for your time and cooperation.

Appendix 3-VIII:

Table 3A.1 Total area by type of rice variety cultivated: Bangladesh as a whole

Crop Year Variety	2008-09 Area (in Acre)	2009-10 Area (in Acre)	2010-11 Area (in Acre)	2011-12 Area (in Acre)	2012-13 Area (in Acre)
Broadcast Aman	9,96,180	11,75,080	10,52,822	9,49,018	9,12,926
Transplanted Aman	34,43,455	34,94,580	32,51,031	31,89,969	31,27,941
HYV Aman	91,44,990	93,23,203	96,47,080	96,50,145	98,22,394
Local Boro	3,01,890	2,65,221	1,95,300	1,79,012	1,62,957
Hybrid Boro	20,10,870	16,94,671	16,24,807	15,93,185	15,17,708
HYV Boro	93,41,557	96,71,268	99,67,871	1,01,13,855	1,00,81,907
Local Aus	9,28,970	8,32,230	7,80,426	7,08,486	6,52,905
HYV Aus	17,03,995	15,99,462	19,69,589	21,03,957	19,49,392

Source: BBS 2009-13, Annual Reports on Estimates of Bangladesh Rice Crop.

Table 3A.2 Area by type of rice variety cultivated: Study regions

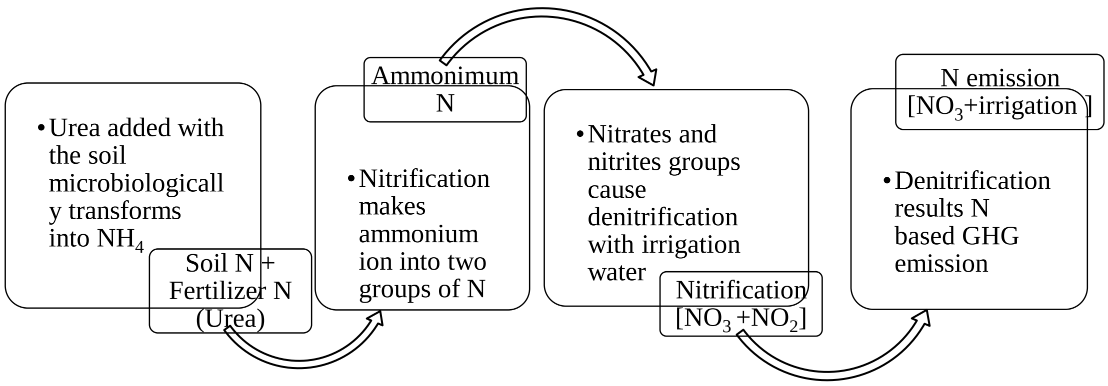
	Broadcast Aman	Transplanted Aman	HYV Aman	Local Boro	Hybrid Boro	HYV Boro	Local Aus	HYV Aus
Pabna (Area in Acre)								
2008-09	83040	1450	129305	3798	14049	155683	43850	10215
2009-10	100749	1568	136094	3471	5369	160214	35324	13676
2010-11	97130	1557	138593	3206	5200	159721	34440	19672
2011-12	80205	1452	130762	2837	3558	163026	33944	21563
2012-13	79522	1385	133514	2277	2774	169422	33613	20588
Rajshahi (Area in Acre)								
2008-09	990	8770	161255	189	25786	169640	8295	115160
2009-10	726	8539	177825	169	21799	154087	7498	69197
2010-11	380	9849	171591	18	14464	165825	1761	95767
2011-12	404	9559	170090	0	13784	175261	1736	105966
2012-13	136	4643	166308	0	11034	173593	1052	92413
Natore (Area in Acre)								
2008-09	54730	7710	107200	122	32202	139865	13525	13595
2009-10	57230	7860	111692	50	29922	133277	10123	11651
2010-11	47906	5380	118776	185	30189	120670	7700	19699
2011-12	49864	11342	124392	108	28470	125608	5727	20374
2012-13	41438	18649	116600	115	22785	120497	4779	20382

Source: BBS 2009-13, Annual Reports on Estimates of Bangladesh Rice Crop.

APPENDICES TO CHAPTER FOUR

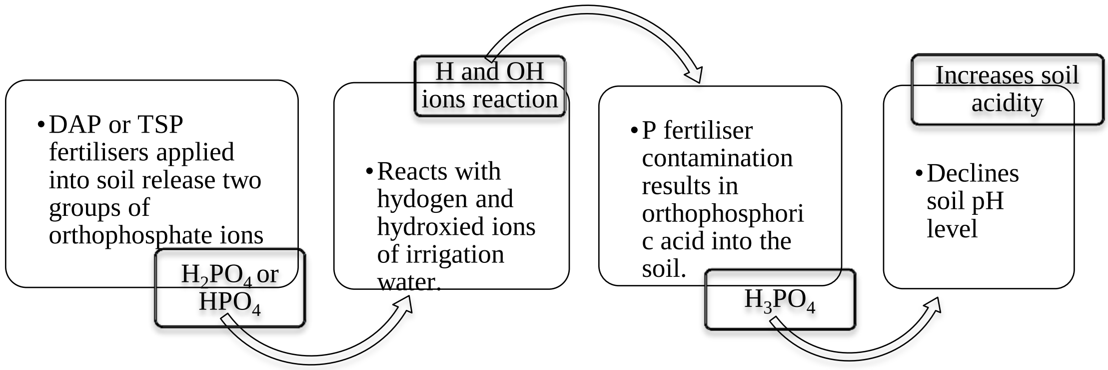
Appendix 4-I Nitrogen contamination interactions into the soil for HYV rice fields

The environmental dynamics of nitrogen is well known although studying and documentation of the detailed reaction of nitrogen that occurs in soil and water bodies is complex. However, impact on soil is considered as the initial impact of excessive nitrogen fertiliser application. For HYV rice cultivation, it is required to apply nitrogen fertilizers directly into the soil and to perform repeat application as well. As a consequence, a significant portion of the nitrogen fertilizer in the form of N_2O (Nitrous Oxide emission) contaminates the soil and emits greenhouse gases. In fact, agriculture is the second largest contributor to global greenhouse gases (GHGs) (Schindler and Hecky, 2009). Nitrogen contamination might be taken place in a variety of form into the soil. For example, it may be there in form of soluble organic N, Ammonium N, Nitrate N, Nitrite N or N associated with sediment as exchangeable ammonium N or organic-N. Risk of nitrogen contamination however depends on soil moisture, temperature, pH, etc. and on N cycle.



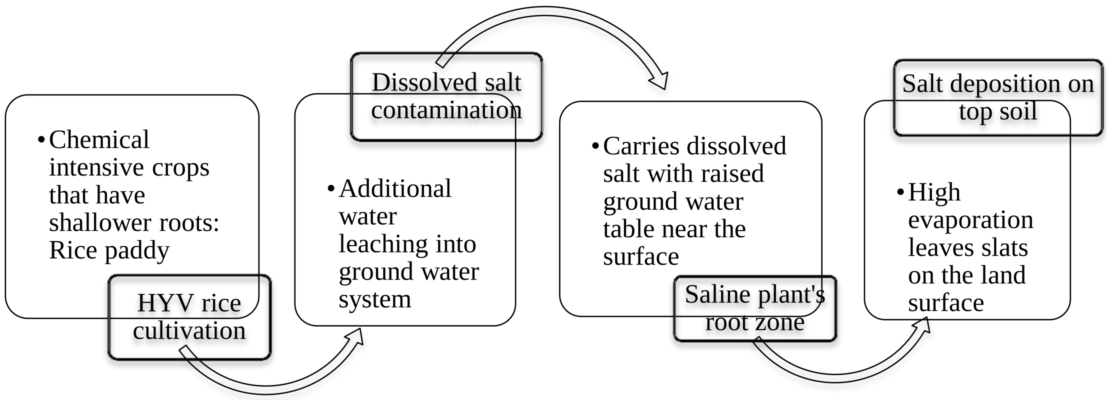
Appendix 4-II: P (Phosphorus) contaminations from phosphate fertilisers and soil pH in HYV rice fields.

DAP and TSP fertilisers contain ammonium phosphate, and phosphates are quite acidifying by nature. This is because, in DAP fertiliser contains nitrogen in the ammonium form that have higher potential for N contamination. Moreover sulphur coated urea has a greater surface acidifying effect than many other fertilizers. Likewise, phosphate contamination is one of the major reasons for declining soil pH. Orthophosphate ions released from **P** fertilizers react with irrigation water in the crop root area. Hydrogen ion and hydroxide ion present in the water then cause chemical reaction together with orthophosphate ions and result in phosphoric acid. Repeated use of sulphur coated urea, ammonium nitrate, ammonium sulphate or phosphate can cause a major decline in soil pH and disruptions in plant’s healthy growth.



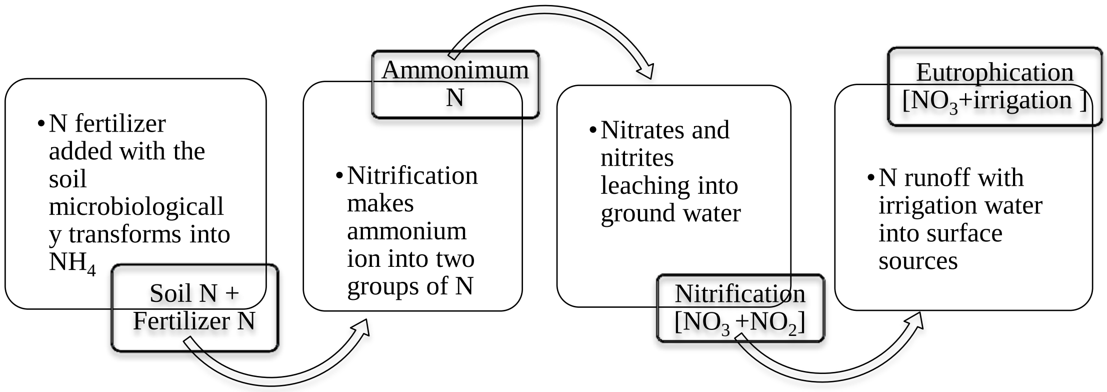
Appendix 4-III: Soil salinity cycle in HYV rice cultivation

In agriculture, soil salinity occurs where there is a removal or loss of native vegetation, and there is a replacement with chemical intensive crops and pastures that have shallower roots. This results in additional water leaching into the groundwater system. The groundwater table rises to near the surface in low-lying areas. It carries dissolved salts from the soil and the saline groundwater comes close to the soil surface within two meters of the plant root zone (Brammer, 1997). Subsequently, during the periods of high evaporation the process ends with leaving them on topsoil and increase soil salinity problem.



Appendix 4-IV: Eutrophication cycle in HYV rice field

In HYV rice fields, N (nitrogen) fertilisers while added with the soil transforms into ammonium ions. Such nitrification in the soil however makes two kinds of ammonium, one is nitrates (NO_2) and the other one is the nitrites (NO_3). These forms of N in the presence of irrigation water causes eutrophication.



APPENDICES TO CHAPTER FIVE

Appendix 5-I:

Table 5A.1 Composite environmental impact index (CEII):

Natore region CEII:

Sample N1-N15	Sample N16-N30	Sample N31-N45	Sample N46-N60	Sample N61-N75	Sample N76-N90	Sample N91-N103
6.985532	6.628124	7.075819	5.489072	6.216527	6.399327	7.118064
6.970307	7.168142	6.715068	6.157636	6.070983	6.545441	6.810869
6.840446	6.283008	7.573015	7.081848	7.224699	7.429748	6.163259
7.698459	7.045359	7.500674	5.451986	7.644977	7.088464	6.776086
8.824735	7.151636	7.658586	6.839832	8.504936	6.863904	5.8123
7.961336	6.504356	7.502554	8.600623	6.886858	5.971109	6.864827
6.730404	6.496826	7.98457	7.573995	7.042492	6.864618	6.775344
6.664052	6.565477	7.630436	7.298914	6.289186	7.655618	6.296395
8.322645	6.798536	8.072492	6.902645	7.523053	7.411768	7.852
7.064248	6.92669	8.22904	6.566164	7.650936	7.666199	7.669309
7.8114	8.548714	6.971334	6.935164	7.139375	6.492677	6.84935
7.622158	7.391522	6.885	5.1618	7.415344	6.102096	7.628259
6.985212	8.127458	5.873304	6.562409	6.456434	6.698486	7.356209
6.950782	7.333141	6.335843	6.096677	6.408471	5.708091	
5.616869	8.083205	6.078526	7.811755	6.707241	5.439916	

Rajshahi region CEII:

Sample R1-R17	Sample R18-R34	Sample R34-R51	Sample R52-R68	Sample R69-R85	Sample R86-R102	Sample R103-R113
7.352847	5.93278	6.531556	6.254202	5.089376	8.700627	7.051438
6.352473	6.85678	7.125784	6.713432	8.695368	7.694389	6.77279
6.493572	7.564674	8.212784	5.544588	6.621734	6.404135	6.241632
5.713413	6.912307	6.581043	6.735876	7.61432	7.512124	6.671963
6.793083	7.642053	6.817732	6.237153	7.860543	7.51032	6.07912
6.791231	6.552507	6.627732	6.750918	6.753797	6.948366	6.831043
6.716956	6.454519	8.044203	6.718411	7.243664	6.164284	6.00538
6.180684	11.69077	5.761667	6.9531	6.950142	7.4114	6.062185
6.988994	6.362375	5.122785	6.116986	6.93085	7.048721	7.368888
7.040343	5.998685	6.300123	8.438174	7.036419	6.366238	7.182056
6.180574	5.876884	5.517465	7.313685	7.659682	5.895466	6.540199
6.156808	6.086399	6.916429	7.483045	6.986158	6.724743	
8.77271	5.508547	7.540302	8.426687	6.926652	6.331375	
7.70564	6.469034	6.14472	8.300331	6.908888	6.437498	
7.061379	6.364352	6.569529	8.205886	6.864546	6.281035	
6.307572	6.657284	7.054816	7.701445	5.945616	6.501082	
6.399934	5.991834	6.656613	6.157385	6.752315	7.092156	

Pabna region CEII:

Sample P1-P15	Sample P16-P30	Sample P31-P45	Sample P46-P60	Sample P61-P75	Sample P76-P90	Sample P91-P101
6.549845	6.172395	6.935594	6.376056	5.738332	6.889267	6.851371
4.474594	5.966645	6.638245	6.395248	6.813444	8.035979	4.684517
6.386617	6.001895	5.554236	5.205767	6.617521	8.040671	5.661121
6.308745	6.407645	6.755371	5.987545	6.237056	6.718095	6.475267
7.653345	5.593943	6.807395	5.725694	6.842879	7.001571	6.445471
6.549694	6.289095	6.488767	5.532651	6.853781	6.834632	6.923971
6.824595	6.906781	6.971631	7.066537	5.100421	6.585126	6.880017
5.468744	7.234209	6.350757	8.394756	6.544024	7.414771	7.009421
5.74835	6.421707	6.405995	7.355671	7.151421	7.088879	7.345644
5.491377	6.241494	6.983539	5.715243	7.467043	6.793231	6.949045
6.128394	5.30869	7.045495	6.531479	7.299043	6.283995	7.124894
7.027845	5.572903	6.504686	6.804623	7.630931	6.900693	
5.968295	5.297618	7.051895	6.440871	6.541121	6.164819	
5.652294	5.068308	7.232994	6.355356	6.621981	7.207317	

6.919836	5.915435	9.327494	6.219707	5.938848	6.543081

Appendix 5-II:

Socio-environmental Living Index (SELI):

SELI is computed by the weighted sum of farmers' socio-environmental living attributes (e.g., House category, sanitation status, access to health facility, pure drinking water source, household energy source and waste disposal system) expressed below in Table 5A.2. It is assumed that the farmers who are living in full-concrete house and having best sanitation facility would have best environmental living standard. Also, easy access to best health facility, pure drinking water sources such as deep tube-well would help them living in an environment friendly way. In our study area, farmers, who use specific place for waste disposal is supposed to create less house hold pollution. Timber or straw burning for cooking and other purpose generates air pollution in terms of house hold smokes. Compared to electricity and bio-gas/natural gas, solar energy sources are the best environment friendly energy source in this regard. We, therefore, impose environment friendly activity weights on selected socio-environmental living attributes. By using Equation 5A.1, we then calculate farmers specific $SELI_i$. Farmer, whose SELI is close to 1 implies better environment friendly living standard and near to 0 otherwise.

Table 5A.2 Socio-environmental living index (SELI)

	Environment Friendly Activity Weights (*Ew*)			
Attributes (r)	**(1)**least	**(2)**good	**(3)**better	**(4)**best
1. House Category	Clay	Straw	Half-concrete	Full-concrete
2. Sanitation	Open place	Temporary Latrine	Sanitary Latrine (without water seal)	Sanitary Latrine (with water seal)
3. Access to Health Facility	Village Doctor	Health Centre	Clinic	Hospital
4. Drinking Water Source	Pond/River	Well	Supply	Deep Tube well
5. Household Energy Source	Timber/Straw/Cow dung/Dried leafs/Kerosene	Electricity	Bio-gas/Natural gas	Solar power
6. Waste Disposal	No Specific place to dispose	Burnt	Buried	Specific place/ Waste Bin

$$SELI_i = \sum_{r=1}^{6} Ew_r / 24 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5A.1)$$

Appendix 5-III

Table 5A.4
Natore region's productive efficiency (ProE) and eco-efficiency (EcoE):

Sample N1-N30		Sample N31-N60		Sample N61-N90		Sample N91-N103	
ProE	EcoE	ProE	EcoE	ProE	EcoE	ProE	EcoE
0.549	0.709	0.673	0.823	0.81	0.839	0.815	0.943
1	1	0.616	0.692	0.744	0.744	0.671	0.731
1	1	0.533	0.745	0.753	0.806	0.727	0.803
0.779	0.973	0.65	0.776	0.505	0.704	0.525	0.741
1	1	0.5	0.958	0.453	0.996	0.553	0.824
1	1	0.413	0.772	0.561	0.712	0.563	0.941
0.891	1	0.31	0.609	1	1	0.516	0.742
0.474	0.728	0.698	0.911	0.823	1	1	1
1	1	0.459	1	0.392	0.846	0.88	1
0.512	0.864	0.621	0.87	0.424	0.762	0.486	1
0.671	0.966	0.623	0.811	0.621	0.905	0.471	0.886
0.793	1	0.539	0.855	0.593	0.848	0.468	0.904
0.747	1	0.589	0.692	0.787	0.825	0.653	1
1	1	0.564	0.655	0.774	0.851		
1	1	0.492	0.551	0.761	0.871		
0.572	0.972	0.402	0.625	0.708	0.813		
0.499	0.834	0.526	0.575	0.426	0.722		
0.774	0.913	0.447	0.825	0.699	0.912		
0.592	1	0.509	0.691	0.411	0.776		
1	1	0.923	0.936	0.742	1		
0.161	1	0.417	0.849	0.84	0.941		
1	1	0.501	0.763	0.667	0.853		
0.482	0.677	0.49	0.728	0.688	0.883		
0.558	0.837	0.486	0.767	1	1		
0.69	0.903	0.731	0.813	0.673	1		
0.538	1	0.653	0.731	0.849	1		
0.881	0.93	0.409	0.608	0.58	0.784		
0.666	0.847	0.496	0.878	0.961	0.971		
0.502	0.914	0.59	0.687	1	1		
1	1	0.435	0.983	0.654	0.672		

Table 5A.5
Rajshahi region's productive efficiency (ProE) and eco-efficiency (EcoE):

Sample R1-R30		Sample R31-R60		Sample R61-R90		Sample R91-R113	
ProE	EcoE	ProE	EcoE	ProE	EcoE	ProE	EcoE
0.555	0.848	0.079	0.965	0.604	0.948	0.657	0.885
0.381	0.661	0.454	0.647	0.842	0.892	0.698	1
0.878	0.984	1	1	0.562	0.88	0.669	0.861
0.896	0.896	0.565	0.827	0.503	1	0.845	0.904
0.68	1	0.468	0.728	0.561	0.975	0.595	0.831
1	1	0.984	1	0.878	1	1	1
0.933	0.982	0.838	1	0.58	0.875	0.601	0.687
0.79	0.957	0.716	0.9	1	1	0.746	0.781
0.882	0.981	0.737	0.883	0.434	0.621	0.812	0.906
1	1	1	1	0.464	1	0.532	0.593
0.79	0.79	0.766	1	0.253	0.748	0.92	0.944
0.583	0.791	0.885	0.971	0.587	0.94	0.625	0.88
0.759	1	0.718	0.828	0.602	0.933	1	1
0.545	0.955	0.781	0.861	1	1	0.998	1
0.694	0.966	1	1	0.773	0.883	0.661	0.807
0.777	0.875	0.638	0.978	0.357	0.875	1	1
0.689	0.881	0.863	0.979	0.684	0.783	1	1
0.739	0.78	0.754	0.841	0.402	0.688	0.788	0.913
1	1	0.683	0.859	0.628	0.761	0.865	0.875
0.919	1	0.582	0.886	0.895	0.895	0.833	0.851

0.563	0.785	1	1	0.755	0.843	0.948	0.982
0.993	1	0.668	0.85	0.636	0.787	0.949	1
0.466	0.831	0.689	0.958	0.625	0.739	0.877	0.931
0.698	0.818	1	1	0.778	0.815		
0.584	1	0.455	0.819	0.537	0.685		
0.506	0.68	0.619	0.816	0.473	0.739		
0.321	0.633	1	1	0.471	0.781		
0.675	0.743	1	1	0.829	0.893		
0.55	0.671	0.79	0.979	0.743	0.767		
0.804	0.804	0.695	0.91	0.862	0.998		

Table 5A.6
Pabna region's productive efficiency (ProE) and eco-efficiency (EcoE):

Sample P1-P30		Sample P31-P60		Sample P61-P90		Sample P91-P101	
ProE	EcoE	ProE	EcoE	ProE	EcoE	ProE	EcoE
0.684	1	0.854	0.896	0.886	0.891	0.84	0.845
1	1	0.715	1	0.852	0.91	0.86	0.86
0.714	0.87	0.641	0.801	1	1	0.81	0.833
0.88	0.927	0.943	0.99	0.858	0.915	0.657	0.875
0.771	0.984	0.946	0.99	0.816	0.88	0.707	0.819
0.834	0.891	0.992	1	0.84	0.875	0.758	0.843
0.872	0.921	0.985	1	0.853	0.853	0.805	0.913
0.937	0.937	0.768	0.861	0.852	0.976	0.811	0.844
0.891	0.894	0.708	0.932	0.791	0.882	1	1
0.849	0.869	0.879	0.924	0.929	1	0.833	0.933
1	1	0.867	0.947	0.795	0.973	0.98	0.993
1	1	0.775	0.832	0.948	1		
0.885	0.893	0.734	0.932	0.78	0.843		
0.999	0.999	1	1	0.916	0.934		
1	1	0.898	1	0.842	0.864		
0.957	0.991	0.807	0.862	0.891	0.894		
0.861	0.891	1	1	0.958	1		
0.979	1	1	1	0.911	0.996		
0.909	0.927	0.985	0.985	0.829	1		
1	1	0.834	0.856	0.991	0.991		
0.951	0.951	0.82	0.853	0.758	0.863		
1	1	0.731	0.935	0.816	0.825		
0.95	1	0.783	0.913	0.783	0.903		
0.81	0.855	0.752	0.876	0.853	0.907		
0.995	0.995	0.851	0.862	0.976	0.976		
0.897	0.897	1	1	0.72	0.895		
0.603	0.981	0.943	0.949	0.976	0.978		
0.885	0.887	0.86	0.898	0.824	0.825		
0.622	0.796	0.787	0.92	0.849	0.931		
0.593	1	0.881	0.883	0.878	0.916		

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