ECONOMIC ANALYSIS OF NUTRIENT MANAGEMENT PRACTICES FOR WATER QUALITY PROTECTION

by

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Dedication

This thesis is dedicated first of all to Mrs. Diana Amon-Armah (Nee: Afaribea Brenu), my lovely wife for her support, encouragement and to my father (Mr. Moses Armah) and all my loved ones who have supported me in various ways.

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Abstract

The main purpose of this study was to evaluate the effect of alternative cropping systems on farm net returns, and nitrate-N and sediment yields in Thomas Brook Watershed (TBW). The study involved integrated bio-physical and economic optimization modelling. Crop yield and nitrate-N pollution response functions were estimated and then used in trade-off analysis between farm returns and environmental quality improvement. Five crop rotation systems were evaluated for seven fertilizer levels under conventional tillage (CT) and no-till systems (NT). Nitrate-N leached, as well as estimated maximum economic rate of N (MERN) fertilizer level and marginal abatement costs depended on crop type, rotation system, and tillage type. The most cost effective cropping systems that met restrictions on Health Canada maximum limit on nitrate-N in water included corn-corn-corn-alfalfa-alfalfa under NT for corn-based cropping systems, potato-winter wheat-carrot-corn under CT for vegetable horticulture-based and potato-barley-winter wheat-potato-corn under NT for potato-based cropping systems.

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CHAPTER 1 : INTRODUCTION

1.1 Background

In recent years, water pollution has become a key environmental quality concern in Canada, especially Atlantic Canada. Improving water quality by reducing nutrient and sediment pollution is a primary goal of federal and provincial governments in Canada. Various studies have linked non-point sources of water pollution with agricultural production in Atlantic Canada (Moerman and Briggins 1994; Trattrie 2004; Janmaat 2007; Fuller et al 2010). Agricultural production can generate residuals and negative effects such as sediments, excess nutrients, pesticides, heavy metals, and disease organisms (Libby and Boggess 1990).

Intensification of agricultural production poses a threat to surface water and groundwater quality (Goss et al 1998), and this trend is likely to continue in the rural and agricultural regions of Atlantic Canada (Roy et al 2009). Intensive agriculture, with the use of chemical fertilizers, pesticides and manure, along with row crop management affect surface water and groundwater pollution. Soil erosion caused by agricultural production also leads to water pollution and sediment loading (Ecology Action Center 2010).

Groundwater is a major source of drinking water in Atlantic Canada. About 29% of the population in Newfoundland and Labrador, 50% in Nova Scotia, 64% in New Brunswick, and almost 100% of Prince Edward Island rely on groundwater as drinking water source (Stratton et al 2003). Thus, groundwater quality protection in the region is a major priority. An assessment of N loss from agricultural lands indicated that 3% of farmland in Atlantic Canada is at risk of producing runoff or seepage water that has nitrogen levels above 14 mg L^{-1} (MacDonald 2000).

Agricultural-induced pesticides, phosphorus, *Escherichia coli* (*E. coli)* and nitrates are routinely found in groundwater, and they pose health hazards to humans and animals (Shortleet al 2001). Excessive levels of nitrates in drinking water can adversely affect human health, and are linked to health problems such as methemoglobinemia in infants, and stomach cancer in adults (Wolfe and Patz 2002). Increased concentration of crop nutrients in surface water systems can lead to eutrophication, and impair aquatic life (Beegle and Lanyon 1994). Eutrophication has been observed in agricultural watersheds and in estuaries and coastal water systems across Atlantic Canada (Chambers et al 2001).

The heightened agricultural non-point source pollution problems in Atlantic Canada have prompted various federal and provincial government initiatives to maintain or improve water quality, (Ecology Action Center 2010). The 2007 Nova Scotia Environmental Goals and Sustainable Prosperity Act (NS EGSPA) is a key government legislative response that integrates environmental sustainability with economic prosperity. Among 21 goals of the NS EGSPA, 5 of them focus on water issues, including: (i) improvements to drinking water treatment; (ii) upgrades to wastewater treatment facilities; (iii) new regulations for the treatment of wastewater stored in septic tanks; (iv) a policy for no-net-loss of wetlands; and (v) a comprehensive water resource management strategy by December 2010 (Ecology Action Center 2010).

The Annapolis Valley is the most intensive agricultural region in Nova Scotia (Sinclair et al 2008; Brooks and Holtz 2009a). The Annapolis Valley is microcosm of water quality issues in rural and agricultural regions of Atlantic Canada (Timmeret al 2005; Gauthier et al 2009), primarily because the region demonstrates a range of water issues present in rural and agricultural areas of Eastern Canada (Brooks 2009; Ecology

Action Center 2010). This makes agriculture an important source of non-point source pollution in the region (Fuller et al 2010).

The Annapolis Valley is about 100 km in length, has five main watersheds (i.e., Annapolis, Cornwallis, Canard, Habitant, and Pereau), and is located between the North and South Mountains, near the Bay of Fundy (Gauthier et al 2009). Over the past few decades, water quality in the Cornwallis watershed in the Annapolis Valley has deteriorated as a result of nutrient (and fecal) contamination (Allen 1999). Most communities in the Annapolis Valley have switched to groundwater supplies because surface water systems were not sufficient to meet water quality and quantity needs (Timmer et al 2005).

Nitrogen (N) and Phosphorus (P) levels that cause eutrophication have been observed in the Thomas Brook Watershed (Nova Scotia Department of Agriculture 2004). Groundwater in the Annapolis Valley is susceptible to nitrate pollution from agriculture and other activities on the predominantly sandy soils (Blair 2001). A 1994 survey of well water quality in agricultural areas of Nova Scotia reported nitrate levels above the Health Canada maximum contaminant limit of 10 mg L^{-1} (Moerman and Briggins 1994). Figure 1.1 illustrates the proportion of wells with nitrate concentration exceeding Maximum Contaminant Levels (MCL) in Kings County, Nova Scotia. The Nova Scotia Department of Environment well water monitoring program indicate that an average of 20% of wells tested during 1989 -2009 exceeded the Health Canada MCL for drinking water nitrates (Figure 1.1). The maximum concentration levels observed was 39.1 mg L^{-1} on average, almost four times the MCL. Furthermore, recent studies in the Thomas Brook Watershed suggest that high nitrate-nitrogen concentrations in

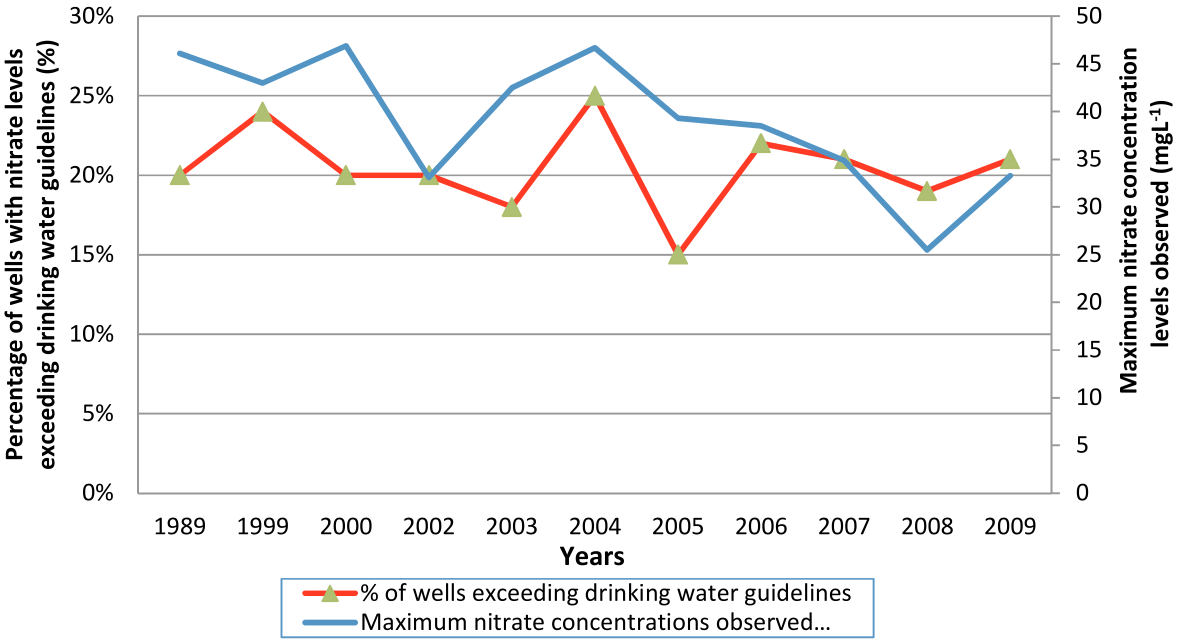


Figure 1.1: Proportion of wells in Kings County, Nova Scotia with nitrate concentration levels exceeding MCL, and maximum nitrate concentrations observed (1989 – 2009)[a].

[a]Total number of wells surveyed ranged from 130 wells (in 2005) to 142 wells (in 1999).

Source: Nova Scotia Department of Environment (2010).

groundwater can also contaminate surface-water systems, especially during summer months (Gauthier et al 2009).

Besides nitrates, various studies report concerns with sediment loading and surface soil loss from agricultural lands in Nova Scotia (Table 1.1). Soil erosion is a natural process that can be accelerated by various agricultural management practices, and can result in sediment loading (Shelton et al 2000). Sediment loading can reduce stream size and water quantity, and also serves as a medium for transporting nutrients off farm into water systems. In 1996, about 30% of croplands in Nova Scotia were considered as "having high risk of" soil erosion (Shelton et al 2000). Chambers et al (2002) also noted

Table 1.1. Reported concerns with sediment loading and surface soil loss from agricultural lands in Nova Scotia.

Study	Main findings
Shelton et al (2000)	Most of Canada's cropland is susceptible to soil erosion by tillage under conventional crop management practices. In 1996, about 30% of croplands in Nova Scotia were classified as *having high risk of* or *intolerable to* soil erosion. Risk of soil erosion also increased by 3% in Nova Scotia.
Jamieson et al (2003)	Study indicated that the presence of fecal microorganisms and harmful bacteria in stream was mostly from stream sediment and were substantially impacted by agricultural activities in Thomas Brook Watershed.
MacMaster (2008)	Sediments carry not only phosphorus, *E. coli* and other harmful bacteria into water systems, but may also carry harmful viruses into the Annapolis river in Nova Scotia.
Sinclair et al (2009)	Study reported a positive linear relationship between sediment transport and bacterial transport into water systems in Thomas Brook Watershed.

that more than 75% of phosphorus loss into surface water is linked to sediment loading. Reported concerns with sediment loading in the Thomas Brook Watershed are linked to runoff from agricultural fields (Jamieson et al 2003). Studies also indicate that sediment loading from agricultural lands in the Thomas Brook Watershed is a major water quality issue (Jamieson et al 2003; Sinclair et al 2009).

Sandy loam is the dominant soil type in the Thomas Brook Watershed (Cann et al 1965), making such farmlands susceptible to erosion and sediment loading. Sinclair et al (2009) reported a positive linear relationship between *E. coli* and total suspended solids (TSS) loading during 2005 and 2006 growing seasons in Thomas Brooks Watershed, and concluded that the processes of sediment transport and bacterial transport are linked. Sediments transport not only phosphorus, *E. coli* and other harmful bacteria into water systems, but can also carry harmful viruses (MacMaster 2008). Thus, sediment load reduction can simultaneously decrease other water quality pollutants that negatively affect human health.

Policy makers are interested in strategies to improve or manage water quality in the Annapolis Valley. Farmers are concerned with surface soil depletion and soil erosion (sedimentation) resulting from current cropping systems (Athwal et al 1996; Jamieson et al 2003; Tattrie et al 2004). Reducing soil depletion and erosion not only helps improve water quality, but can also increase efficiencies in input use and, ultimately, farm income.

Managing the multiple agricultural pollution problems in the Annapolis Valley suggest management and stewardship strategies on a watershed-scale basis. Qui (2005) suggests that an efficient way to improve water quality is through watershed-scale management. A successful watershed-scale management has the potential to improve water quality and other environmental indicators while maintaining community economic viability (Born and Genskow 2001). Water quality management at a watershed-scale can generate benefits such as: (i) facilitating development of partnerships among stakeholders in the watershed; (ii) focusing attention of partners on key links and relationships; and (iii) integrating water quality and quantity with farmland use and management (Timmer et al 2005). On the other hand, watershed-scale management may be difficult to accomplish, and requires very complex combinations of skills and resources such as collaborative planning, democratic decision making, integration of knowledge, sciences, and policies, and watershed partnerships (US National Research Council 1999).

Best Management Practices (BMPs) have potential to minimize and/or control nutrients and sediment pollution. Voluntary BMPs can generate multiple benefits to various stakeholders. Yet, the costs and environmental benefits of BMPs are rarely measured beyond small plots and experimental fields (Stuart et al 2010). The Watershed Evaluation of BMPs (WEBs) project was launched in 2004 to measure and validate the economic and water quality impacts of selected agricultural BMPs at seven watershed sites across Canada (Stuart et al 2010). This study contributes to the WEBs project by analyzing the economics of implementing Nutrient Management Plans (NMPs) for water quality protection at the Thomas Brook Watershed.

1.2 Economic Problem

Protecting water quality at the source can be less expensive compared with treating contaminated water systems (Job 1996), and has become a priority for water quality management in the Annapolis Valley (Timmer et al 2007). Given that source water pollution has been linked to agricultural land use and practices, agricultural watershed-scale protection strategies have generated interest among farmers, water resource stewardship and policy makers, and surface water and groundwater users.

Agri-environmental policies and regulations can help increase environmental benefits from agricultural production. For example, provincial guidelines on manure management are aimed at promoting effective use of animal manure on farms while at the same time helping to protect the environment (Nova Scotia Department of Agriculture 2006). NMPs have also become a common approach not only to manage non-point source pollution from agriculture, but are also accepted tools for implementing specific federal and provincial government's farm environmental risk management programs (Afari-Sefa et al 2008). Nutrient Management Planning (NMP) allows farmers to balance nutrient application rates, and time nutrient availability with crop needs, thereby helping to minimize nutrient loss into water systems and improve farm profitability (Beegle and Lanyon 1994; VanDyke et al 1999; Brethour et al 2007). NMP can generate benefits to farmers such as cost savings from more efficient fertilizer application and other input use. In addition, society as a whole can benefit from improvements in ecosystem biodiversity, water quality and quantity improvements, and amenity benefits (USEPA 1993; D'Arcy and Frost 2000; Muthukrishnan et al 2006). Society as a whole can benefit from reduced risk of water pollution, reduced cost of treating water, and improvements in human health and aquatic ecosystems. Trade-offs to generating these benefits may include changes to existing practices, and BMP establishment and maintenance costs.

NMP involves soil nutrient testing, equipment calibration, erosion control, timing of fertilizer application, and record keeping (Ribaudo and Johansson 2007). These activities can result in additional cost to farmers. The benefits and costs to farmers for implementing NMPs is an empirical issue, and depends on factors such as farm size, crop type, crop rotation patterns and market prices (Huang and Lantin 1993; Yiridoe et al 1998; Wu and Babcock 1998). In addition, little is known about how agri-environmental regulations and BMPs affect farmers' decisions and, ultimately, net returns and impacts on the environment. The effectiveness of government policies and regulations, and NMPs ultimately depend on farmers' economic decision choices (Qiu 2005), who often face multiple (economic and environmental) objectives.

1.3 Research Problem

Addressing the non-point source pollution problems entails multiple economic and environmental objectives. Economic goals are aimed at providing suitable policy options that will increase social welfare without net cost to farmers. Policy analysts and research scientists are concerned with balancing agro-ecosystem health and farm profitability (Faeth and Westra 1993).

Complying with different policies and regulations that target single pollutants can be costly (Weersink et al 1998; Jatoe 2008). Targeting a single contaminant may result in negative impacts on other resources or pollutants (Lakshminarayan et al 1995). Potential gains can be generated from addressing multiple contaminants and associated objectives simultaneously, to improve effectiveness of pollution control policies (Connor et al 1995). Soil conservation and crop rotation techniques can also be integrated with other management strategies (Chambers et al 2002). This can allow for the achievement of economic objectives, cost effective policy options and farmers' better understanding of the consequences of production decisions in the Thomas Brook Watershed.

1.4 Purpose and Objectives of the Study

The purpose of this study was to evaluate the effect of alternative cropping systems on farm returns, and nitrate and sediment yields in the Thomas Brook Watershed. Cropping systems were defined as a combination of crop choice, tillage system type, crop rotation patterns, and nutrient application rates. Specific objectives of the study were:

1) *To investigate the effects of alternative cropping systems commonly managed in the Thomas Brook Watershed (TBW) in the Annapolis Valley, on crop and pollutant (i.e.,* $NO_3^- - N$ *and sediment) yields.*

The Soil and Water Assessment Tool (SWAT) biophysical simulation model was used to simulate alternative cropping systems and assess their effects on crop yield, and nitrate and sediment yields.

2) *To estimate input-output relationships for selected cropping systems.*

Crop yield response to nutrients is commonly used to determine input-output relationships in most agricultural processes (Llewelyn and Featherstone 1997).

Production functions have been used to describe such relationships. Crop yields and N pollution production functions for different cropping systems were compared using biological, statistical and economic approaches and the functional forms (i.e., yield response function) that best represent or predict input-output relationship for each crop was selected. The yield response functions were then used to estimate the maximum economic rate of nitrogen (MERN).

3) *To develop a farm optimization model, and use the model to evaluate trade-offs in terms of loss in farm returns associated with incremental reductions in nitrate-N pollution for selected cropping systems. Specifically, marginal abatement costs (MAC) of reducing nitrate-N pollution were evaluated for selected cropping systems in the Thomas Brook Watershed using SWAT simulated data.*

Crop yield and associated nitrate–N pollution production functions estimated in the previous objective allowed for estimating the MACs. An economic optimization model was used to investigate input combinations that maximize farm profit and minimize pollutant levels. The model was used to solve different constraint levels to identify the optimal (cost effective) cropping systems for achieving specified levels of nitrate-N pollution abatement.

1.5 Outline of Thesis

The remainder of the thesis is organized into six chapters. The study area and data used for the study are described in Chapter two. In addition, a review of factors affecting nitrate leached and sediment load in agricultural watersheds is presented in Chapter two. Chapter three involves statistical analysis of the effect of nutrient management planning on crop yields, $NO_3^-{-}N$ leached and sediment loading. A comparison of crop yield and pollution production response to nitrogen fertilization models using SWAT-simulated data for watershed management is presented in chapter four. Also in chapter four, crop and pollutant response function were estimated using regression analysis, and the Marginal Economic Rates of Nitrogen (MERN) determined for various cropping systems. Trade-offs between farm profitability and pollution reduction in Thomas Brooks Watershed were assessed in chapter five. The final chapter presents a summary of the research, major findings, as well as contributions of the thesis research.

CHAPTER 2 : STUDY AREA, DATA DESCRIPTION AND LITERATURE REVIEW

2.1 Study Area

Thomas Brook Watershed (TBW) forms part of the larger Cornwallis Watershed and is near the town of Berwick, in Kings County, Annapolis valley, NS (Figure 2.1). The Annapolis Valley consists of about 19% of the agricultural land in Nova Scotia (Statistics Canada 2007). Apples, grain crops, strawberry and potato are major crops grown in the region (Gauthier et al 2009; Sinclair et al 2009). TBW covers about 784 ha of the 26 000 ha Cornwallis Watershed (Jamieson et al 2003). Thomas Brook originates from the North Mountain, and discharges into the Cornwallis River, north of the town of Berwick. Thomas Brook Watershed lies within the geographical coordinates 45^{o} $08^{'}$ and 64^{o} 44' (Gauthier et al 2009).

The Thomas Brook consists of two upper streams which merge into a larger water system at approximately one-third of the distance along the watershed (Jamieson et al 2003). The Thomas Brook is rarely greater than 2 m in width, and the main channel of the stream network is 5.8 km in length (Tattrie et al 2004). The watershed has an average slope of 3.5% (Figure 2.2). The channel grade in the upper third of the watershed is steep at about 9%, while the lower portion of the watershed is less steep at about 0.5%–1.3% (Sinclair et al 2008).

Agricultural activities account for about 54% of land use in the TBW, with the remaining 46% accounting for riparian, forest and residential land uses. Land use within the lower two-thirds of the watershed consists primarily of pasture and cropland (Figure 2.3). Although a variety of soil types exist in the watershed, the predominant soil types

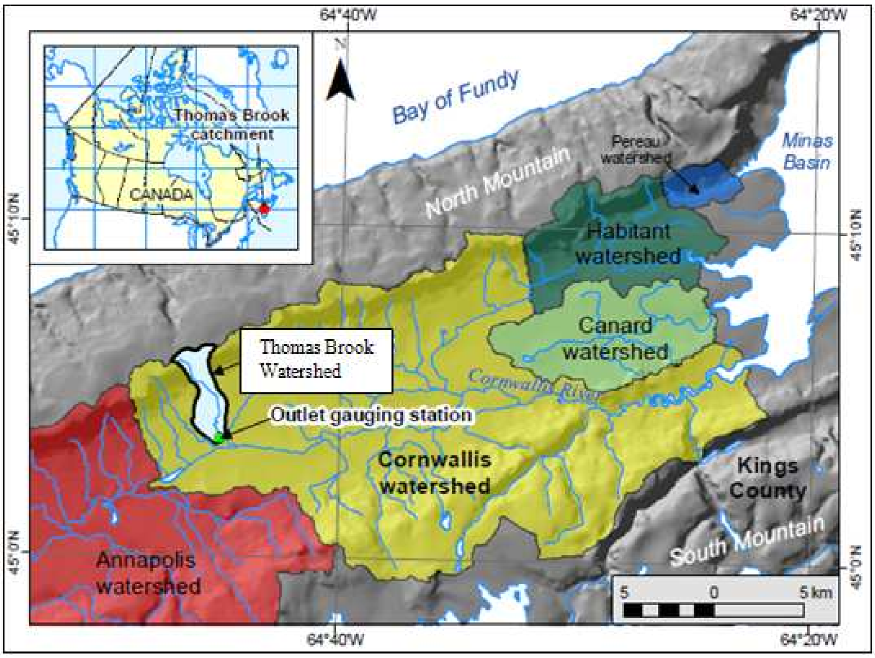


Figure 2.1: Location of the Thomas Brook Watershed, Annapolis Valley (Nova Scotia).

Source: Gauthier et al (2009).

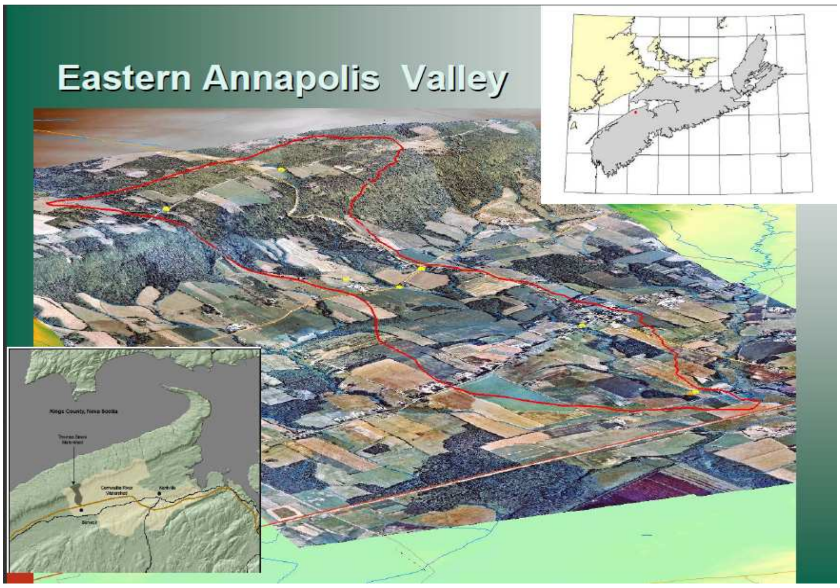
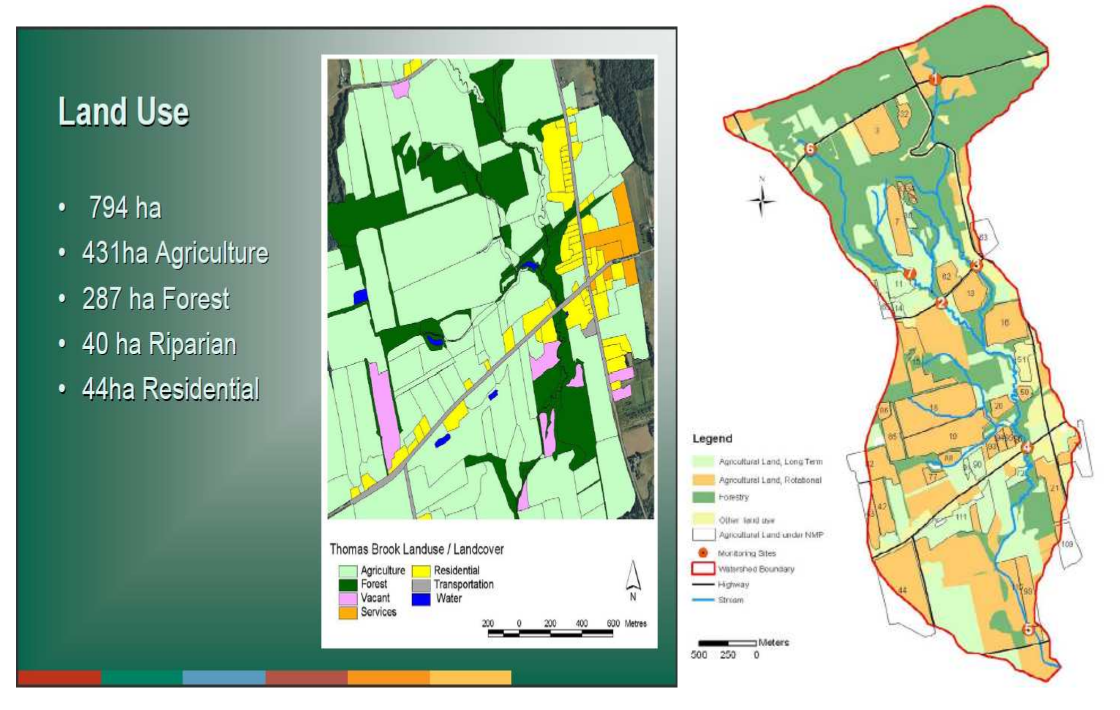


Figure 2.2: An elevated view of Thomas Brook Watershed area in the Annapolis Valley.

Source: Hebb (2007).



Land Use

- 794 ha
- 431ha Agriculture
- 287 ha Forest
- 40 ha Riparian
- 44ha Residential

Figure 2.3: Land uses in Thomas Brook Watershed.

Source: Hebb (2007) and Stuart et al (2010).

Table 2.1. Soils types in Thomas Brook Watershed.

Soil Name	Textural Class
Acadia	Silty clay loam
Bridgeville	Loam
Cornwallis	Loamy sand
Cumberland	Loamy sand
Debert	Sandy loam
Hopewell	Sandy loam
Horton	Sandy loam
Kentville	Sandy loam
Kingsport	Sand
Millar	Sand
Nictaux	Loamy sand
Pelton	Sandy loam
Somerset	Loamy sand
Torbrook	Sandy loam
Wolfville	Sandy loam
Woodville	Sandy loam

Source: Ahmad (2010).

are sandy loam and are reddish brown in color (Table 2.1) (Cann et al 1965; Ahmad 2010). Average annual precipitation is approximately 1100mm.

Average daily temperature in the area ranges from 1.3˚C to 12.2˚C, with a mean annual temperature of 6.8 ˚C (Environment Canada 2009).

2.2 Overview of Nutrient Management Planning in Nova Scotia

The nutrient management plan (NMP) was first launched in 2004, as part of initiatives under the Environmental Farm Plan (NS EFP) by the government of Nova Scotia in collaboration with the Nova Scotia Federation of Agriculture (van Roestel 2012). The primary goal was to address water quality issues (van Roestel 2012). The NS EFP is a voluntary program designed to help farmers identify and assess environmental risks. The NMP program emphasizes more proactive approach and requires soil analysis, manure analysis, nutrient spreader calibration, and knowledge of crop inputs and requirements (Nova Scotia Federation of Agriculture 2008).

An NMP developed by a farmer is valid for up to 3yrs, after which it can be renewed. The program is currently voluntary and funded by the government of Nova Scotia Farm Investment Fund (NSFIF). Although the program is voluntary, NMP is required in some counties in Nova Scotia (e.g., Kings County), for farmers requesting building permits for extension of livestock housing systems (van Roestel 2012).

According to the Nova Scotia Federation of Agriculture (2008), 100% of an initial NMP development cost up to $1,500 was covered under the NSFIF. Any additional cost above $1500 was cost shared at 50%. If the NMP was renewed after an initial 3yr plan, 75% funding was provided (up to $750) (Nova Scotia Federation of Agriculture 2008). Beginning in 2009, 50% of the cost of renewal plans has been funded for amounts up to $1500 (van Roestel 2012).

2.3 Description of Cropping Systems

The major crops cultivated in the Thomas Brook Watershed include apples, grain crops, potatoes and strawberries. This study focuses on crop rotation patterns that involve grain crops, potatoes (P) (*Solanumtuberosum*) and carrots (R) (*Daucuscarota).* The grain crops include grain corn (C) (*Zea mays* L), barley (B) (*Hordeumvulgare*), and winter wheat (W) (*Triticumaestivum*L). Alfalfa (A) (*Medicagosativa* L) is common leguminous forage integrated in the crop rotations. Grain corn and potato-based rotations were selected due to their economic importance in the region. A five-year crop rotation pattern was selected for grain-corn-based and potato-based cropping systems. Five-year rotation provides a representative rotation length that allows for recommended frequency of potatoes and grain-corn in rotation with other crops (Jatoe 2008). The cropping systems studied are summarized in Table 2.2. Each crop rotation system was assumed to be managed under both conventional tillage and no-till management. Cropping systems for different grain-corn-based and potato-based rotations were simulated using the Soil and Water Assessment Tool (SWAT) to assess their effects on crop yield (and ultimately farm profitability), and water quality.

In the SWAT model simulations, conventional tillage (CT) is assumed to consist of mouldboard ploughing (at a depth of about 150mm) in the Fall to achieve a 95% mixing efficiency, followed by secondary tillage operation during the following Spring (Ahmad et al 2011). Tandem Disk is assumed to be used to obtain a mixing efficiency of 60% (at a depth of about 75mm), followed by a finishing harrow operation to obtain a mixing depth of 55% (at a depth of about 100mm) in the Spring. A generic no-till option in SWAT was selected for all no-till (NT) cropping systems managed. NT gives a mixing efficiency of 5% at a depth of about 25mm. The CT treatment reflects existing

Table 2.2. Cropping systems studied.

Rotation systems	Cropping sequence[a]	Tillage system[b]	N Fertilizer rates (%)[c]
Grain corn-based cropping system	CCAAA	CT	110% 100%, 90%, 75%, 50%, 25% and 0% of recommended N rates.
	CCAAA	NT	
	CCCAA	CT	
	CCCAA	NT	
Potato-based cropping System	PBW^{F}PC	CT	
	PBW^{F}PC	NT	
	PCBPC	CT	
	PCBPC	NT	
Vegetable-horticulture-based cropping system	PW^{F}RC	CT	
	PW^{F}RC	NT	

[a] W^{F} = winter wheat feed, P=Potato, R=Carrot, C=Grain corn, B=Barley, A=Alfalfa.

[b] NT practice applies only to the grain crops (Barley, winter wheat and grain corn) and Alfalfa. Potatoes and Carrots were assumed to be managed under conventional tillage only, consistent with the practice study area.

[c] The various N fertilizer rates studied included 110% 100%, 90%, 75%, 50%, 25% and 0% of rates in nutrient management plans for the study region.

tillage practice in the study area. Details of grain-corn cropping systems commonly managed by farmers and recommended practices on all the crops used in the grain-corn-based, potato-based and vegetable-horticulture-based rotations in the study area are presented in Table 2.3 and Table 2.4.

A NT treatment was investigated along with CT management because a conservation tillage system such as NT has potential to address nitrate and sediment problems in the area. A total of 70 cropping systems are investigated (5 cropping sequence × 2 tillage systems ×7 N fertilizer rates). As noted earlier, cropping systems involve a combination of crops in a rotation system under different tillage treatments and managed under various N fertilizer rates (110% 100%, 90%, 75%, 50%, 25% and 0% of NMP recommended amounts). Potatoes and carrots were assumed to be managed under CT only. Hence in a NT system (such as) Potato-Wheat-Carrot-Corn rotation under NT management, all grain crops are managed under NT, while potatoes and carrots are

Table 2.3. Schedule of cultural and management practices for various crops.

Crop	Date	Activity	Details	Fertilizer and Manure rates (kg/ha)[a]
Alfalfa	1-May	Planting	Alfalfa (Legume/Mixed Forage)	
	1-May	Fertilizer	10-10-30	220
	1-May	Tillage	Tandem Disk Reg	
	1-May	Tillage	Finishing Harrow	
	15-Jun	Harvest Only		
	17-Jun	Fertilizer	08-00-45	220
	30-Aug	Harvest and Kill		
	1-Nov	Tillage	Mouldboard Plow Reg	
Grain corn	10-May	Fertilizer	Dairy Fresh Manure	3750
	17-May	Fertilizer	34-00-00	110
	17-May	Tillage	Tandem Disk Reg	
	17-May	Tillage	Finishing Harrow	
	18-May	Planting	Grain corn	
	31-Oct	Harvest & Kill		
	1-Nov		Moldboard Plow Reg	
Potato	1-May	Tillage	Tandem Disk Reg	
	1-May	Tillage	Finishing Harrow	
	1-May	Fertilizer	15-15-15	1000
	3-May	Planting	Potato	
	1-Sep	Harvest & Kill		
	1-Nov	Tillage	Moldboard Plow Reg	
Barley	10-May	Fertilizer	Dairy Fresh Manure	2250
	18-May	Tillage	Tandem Disk Reg	
	18-May	Tillage	Finishing Harrow	
	20-May	Planting	Barley	
	20-Jun	Fertilizer	17-17-17	34
	31-Aug	Harvest & Kill		
	1-Nov	Tillage	Moldboard Plow Reg	
Winter wheat	23-Sep	Fertilizer	Dairy Fresh Manure	3000
	1-Oct	Tillage	Generic fall plow	
	1-Oct	Tillage	Tandem Disk Reg	
	3-Oct	Planting	Winter wheat	
	5-Aug	Harvest & Kill		
Carrot	1-May	Tillage	Tandem Disk Reg	
	1-May	Tillage	Finishing Harrow	
	1-May	Fertilizer	15-15-15	450
	3-May	Planting	Carrot	
	1-Sep	Harvest & Kill		
	1-Nov	Tillage	Moldboard Plow Reg	

[a] Dairy Fresh Manure is measured in gallons per hectare

Jack van Roestel (2010) – (Extension specialist for Annapolis Valley Region)

Table 2.4.Summary of key recommended cultural/agronomic practices for selected crops.

Activity	Grain corn	Winter Wheat-Feed	Barley	Alfalfa	Potatoes	Carrots
Recommended Total N rate	180 kg ha^{-1}	11 4kg ha^{-1}	92 kg ha^{-1}	42 kg ha^{-1}	150 kg ha^{-1}	68 kg ha^{-1}
Timing of:						
Land preparation	May	Sept/Oct	May	May	May	May
Seeding	May	Sept 15- Oct 15 (350 seeds m^{-2} or 140 kg ha^{-1})	May	May	May (@ 2200 lb/acre)	May
Fertilizer application	May-June	Seeding/Monthly April & May	May/June	4-5 weeks before harvest	At seeding	At seeding
Harvesting	Sept-Nov.	August	Aug-Sept	June and Aug	July-Sept	Sept-Oct

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managed under CT. Each cropping system was simulated for 20 years to assess the cropping system effects on crop yields, sediment loading and nitrate-N leaching. Biophysical process in SWAT requires at least two years to initialize. Thus, output/yields from SWAT will be useful if simulated for longer periods.

2.4 Factors Affecting Nitrate-N Leached in Agricultural Watersheds

Fertilizer use has improved agricultural productivity over the decades. However, farmers tend to apply fertilizer in excess of recommended rates, partly as a yield risk management strategy (Sheriff 2005; Rajsic and Weersink 2008). Observed high $NO_3^-{-}N$ concentrations in ground and surface water systems in Kings County have been linked to excess fertilizer use on agricultural lands (e.g., Fuller et al 2010). Knowledge of the factors that affect $NO_3^-{-}N$ leaching from agricultural land-use provides background on strategies for managing $NO_3^-{-}N$ leached into water systems (Simmelsgaard 1998).

Studies suggest that no-till (NT) has the potential to reduce $NO_3^-{-}N$ leached compared with conventional tillage (CT) (Stoddard et al 2005; Lipiec et al 2011). NT management can increase water drainage, and can also result in small $NO_3^-{-}N$ concentrations in the drainage water. NT reduces the rate of nutrient leaching by increasing nutrient use efficiency especially by cereal crops (Malhi et al 2001; Fixen 2004). Mkhabela et al (2008) reported statistically significant lower $NO_3^-{-}N$ leached from NT compared with CT following surface application of cattle manure to assess the impact of NT and CT systems on $NO_3^-{-}N$ leached in 2003/2004 and 2004/2005 seasons at two field sites in Nova Scotia (Streets Ridge (SR) in Cumberland County and the Bioenvironmental Engineering Centre (BEEC) in Truro).

Zhu et al (2003) who conducted an experiment to investigate chisel-till and NT impacts on $NO_3^-{-}N$ leaching on silt loam soils planted to alfalfa, corn and soybean from 1991 to 2001 in central Pennsylvania reported no statistically significant effect of tillage management on $NO_3^-{-}N$ leached but observed nominally higher $NO_3^-{-}N$ leached from other tillage systems relative to NT systems as N-fertilizer rate was increased. Al-Kaisi and Licht (2004) also reported similar results as Zhu et al (2003) after comparing chisel plow and NT systems with strip tillage effect on corn N uptake and $NO_3^-{-}N$ movement through the soil profile with field experiments in Iowa State.

Other studies also report contrasting observations on the effect of tillage on $NO_3^-{-}N$ leached. Various studies reported that NT management systems resulted in higher $NO_3^-{-}N$ leached compared with CT system (Tyler and Thomas 1977, Nyborg and Malhi 1989, Dick et al 1989, Kranz and Kanwar 1995). Tyler and Thomas (1977) also found that $NO_3^-{-}N$ concentrations were higher in drainage water collected below soil depth of 106 cm under NT management than under CT for corn production. In summary, various studies on the impact of tillage on NO_3^-–N leached report mixed results and observations due to interaction and complications from various factors or from site specific conditions.

Soil structure also affects the level of NO_3^-–N leached. Simmelsgaard (1998) reported that average NO_3^-–N leached from soils with 5% clay (68 kg ha^{-1} yr^{-1}) were higher than average NO_3^-–N leached from soils of 12% clay (44 kg ha^{-1} yr^{-1}) which in turn was higher than average NO_3^-–N leached from soils of 20% clay (26 kg ha^{-1} yr^{-1}) across cropping systems studied. Addiscott (1996) noted that because sandy soils are more porous than loamy soils and heavy clay soils, sandy soils are more prone to NO_3^-–N leaching. Also, van Es et al (2006) found in a study on the effect of manure application and soil type on nitrate leaching that NO_3^-–N leached from sandy loams were on average 2.5 times higher (12.7 mg L^{-1}) than those from clay loam plots (5.2 mg L^{-1}) when planted to corn rotated with orchard grass.

In a study to assess the main effects of crop, N-level, soil type and drainage on NO_3^-–N leaching from Danish soils, Simmelsgaard (1998) noted that the type of crop and the crop rotation sequence were important factors that influenced NO_3^-–N leached levels. NO_3^-–N in groundwater was higher in potato fields compared with cereal fields (Richards et al 1990; Zebarth et al 2003). Winter cereals following canola resulted in high rates of NO_3^-–N leaching (71-78 kg ha^{-1} yr^{-1}) compared with winter cereals following winter cereals (46 kg ha^{-1} yr^{-1}), and to grass following barley (24 kg ha^{-1} yr^{-1}) (Simmelsgaard 1998).

Different crops also have unique N use-efficiencies and, therefore, have different effects on the amount of $NO_3^- - N$ leached per year. Addiscott (1996) reported that, in studies conducted at Rothamsted, U.K., canola tended to be less efficient in N fertilizer use than potatoes, which in turn was less efficient in N fertilizer use than sugar beet. Winter wheat was most efficient in N use than potatoes and sugar beet resulting in only 6 to 8% of N application lost by leaching on winter wheat fields (Addiscott 1996). The finding suggests that mono-cropping especially of crops with less N use-efficiency, exacerbates $NO_3^- - N$ leaching.

Addiscott (1996) also noted that other factors besides N-fertilizer levels applied affects $NO_3^- - N$ leaching. The interaction between N-fertilizer and other factors such as crop type, tillage system and soil type (i.e., soil physical properties) also influences $NO_3^- - N$ leached. In addition climatic conditions, atmospheric N level, rainfall and seasonal factors can affect fertilizer use by crops and hence $NO_3^- - N$ leached (Addiscott 1996; Hansen and Djurhuus 1997; Fuller et al 2010; Lipiecet al 2011; Kellman and Smith 2011). In this study, the objective was to focus on factors associated with crop production systems such as crop type, rotation pattern, tillage type and fertilizer application rates, and assess their effects in reducing $NO_3^- - N$ leached in the TBW.

2.5 Factors Affecting Sediment Transport

Various studies suggest that tillage type greatly affects surface soil loss and sediment transport (e.g., Richardson and King 1995; Truman et al 2005; Montgomery 2007). Sediment yield can be reduced by switching from CT to conservation tillage or NT systems (Truman et al 2005; Montgomery 2007). NT has the potential to reduce sediment load by about 98% (Mostaghimi et al 1987). Increased surface crop residue traps sediments, and hence reduces sediment loading. Surface crop residue level can increase by about 30% by switching from CT to conservation tillage (Conservation Tillage Information Center 1990). Malhi et al (2011) noted that under conservation and no-till management, oxidation of soil organic matter is reduced because of reduced mixing of the soil, resulting in slower degradation of crop residue compared with CT. However, applying NT and conservation tillage systems to reduce sediment loss may also result in increased nitrate leaching (Cao et al 1994; Rees et al 2002; Richards and Baker 2002; Mays et al 2003).

Other studies suggest that besides tillage type, the type of soil also affects soil erosion and sediment transport into streams or reservoirs. Quansah (1981) reported that sandy soils were more susceptible to sediment load or transport than clayey loam soils and clayey soils.

Crop type and rotation sequence also affect sediment loading (Carroll et al 1997). Rotations which incorporate high surface residue crops or closely grown crops (such as wheat barley, oats, hay and other forage crops) can reduce sediment load by providing vegetative cover and improving soil organic matter (Sandretto and Payne 2007). Edwards et al (1998) reported from field experimental trials of Prince Edward Island (PEI) potato production, that sediment loss from potato fields was higher than losses from forage and grain crops under similar tillage management by about 13 tonnes ha^{-1} yr^{-1}. Jatoe et al (2008) also observed consistent results as Edwards et al (1998) by simulating potato production under various rotation systems in PEI with SWAT. Carroll et al (1997) also reported that grain crops such as wheat (which generates a relatively less crop residue) can help reduce the risk of sediment loading compared with broad leaf groups like the sunflower.

In general, to minimize sediment loading, Carroll et al (1997) suggests switching away from crops with low surface residue. In field experiments conducted in Benton County, Washington, Alva et al (2002) observed that crop residue from potato fields were lower (17.9 tha^{-1}) compared with wheat (33.9 tha^{-1}), and corn (48.6 tha^{-1}). Nuttall et al (1986) noted a positive correlation between crop yields and crop surface residue. As crop yields increase with increasing fertilization, the associated crop residue levels also tends to increase.

Soil structure also influences sediment load (Lal 2004). However, soil structure is also influenced positively by increased soil organic matter (SOM). SOM increases with surface crop residue. Bronick and Lal (2005) noted that increased manure and N-fertilizer application levels improve soil structure, which in turn helps to reduce sediment load. Nuttall et al (1986) also reported that N fertilizer application level can have indirect effects on sediment loading through high crop/surface residue and soil organic matter levels.

The direct effect of N fertilizer application on sediment loading is nebulous. Increases in crop yield from increased N fertilization can result in reduced sediment loading. Optimizing N fertilizer rates to balance crop yield levels and surface residue from crops harvested can help reduce sediment loading. A combination of cropping and management systems (i.e., N fertilization rate, tillage system, crop type, and crop rotation patterns) is considered in this study.

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CHAPTER 3 : STATISTICAL ANALYSIS OF THE EFFECT OF NUTRIENT MANAGEMENT PLANNING ON CROP YIELD, NITRATE LEACHING AND SEDIMENT LOADING[1]

3.1 Abstract

Government priorities related to the provincial Nutrient Management Planning (NMP) programs include improving program effectiveness (for environmental quality protection), and promoting more widespread adoption. Understanding the effect of NMP on both crop yield and water quality parameters in agricultural watersheds requires a comprehensive study that takes into consideration several of the key NMP factors and farming conditions. This study used the Soil and Water Assessment Tool (SWAT) to investigate the effects of crop and rotation sequence, tillage type, and nutrient N application rate on crop yield and the associated groundwater $NO_3^-{-}N$ leached and sediment loss in the Thomas Brook Watershed, located in the most intensively managed agricultural region of Nova Scotia, Canada. Cropping systems were evaluated for seven fertilizer application rates and two tillage systems (i.e., conventional tillage (CT) and no-till (NT)). The analysis reflected cropping systems commonly managed by farmers in the Annapolis Valley region, including grain corn-based and potato-based cropping systems, and a vegetable horticulture system. ANOVA models were developed and used to assess the effects of crop management choices on crop yield and two water quality parameters. Results indicate that tillage system did not have a significant effect ($p > 0.05$) on crop yield and $NO_3^-{-}N$ leaching, but significantly affected sediment loading ($p < 0.05$). In general, NT significantly reduced sediment load. Crop yield and groundwater $NO_3^-{-}N$ leached were influenced by nutrient N level, across several cropping systems. The analysis identified nutrient N rates in combination with specific crops and rotation systems that can be managed to help control $NO_3^-{-}N$ leaching while balancing impacts on crop yield.

Abbreviations: NMP, Nutrient Management Planning; SWAT, Soil and Water Assessment Tool; TBW, Thomas Brook Watershed; CT, conventional tillage; NT, no-till; ANOVA, Analysis of Variance.

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[1] A version of this chapter has been submitted for consideration for publication in *Journal of Environmental Quality*.

3.2 Introduction

Nutrient Management Planning (NMP) involves identifying specific major crop nutrient requirements (e.g., N, P, and K), and managing farming practices with potential to improve environmental quality (Beegle and Lanyon 1994; Van Dyke et al 1999). On-farm NMP can be cost-effective for farmers while also helping to improve environmental quality (Beegle et al 2000). Challenges with NMP may involve changes to existing agricultural practices, such as switching from one tillage system to another, changing crop type or rotation sequence.

Fertilizer use has improved agricultural productivity over the decades. However, farmers tend to apply fertilizer in excess of recommended rates, partly as a yield risk management strategy (Sheriff 2005; Rajsic and Weersink 2008). A survey reported that about 20% of residential drinking water wells in Kings County, Nova Scotia had $NO_3^-{-}N$ concentrations about 3 times higher than the Health Canada Maximum Contaminant Limit (MCL) of 10 mg L^{-1} (Nova Scotia Department of Environment 2010). Observed high $NO_3^-{-}N$ concentrations in groundwater and surface water systems in Kings County, Nova Scotia have been linked to excess fertilizer use on farmlands (Fuller et al 2010). Thus, knowledge of the factors that affect $NO_3^-{-}N$ leaching from agriculture can help in developing strategies for managing $NO_3^-{-}N$ leached into water systems (Simmelsgaard 1998).

Sediment loading from farm fields is also a major source of water pollution in the Annapolis Valley region of Nova Scotia (Jamieson et al 2003; Sinclair et al 2009). Wagner et al (2002), for example, noted that sediment loads from farm-fields transport particulate matter and pesticides, were linked to fish kills in Atlantic Canada. Sediment loading is also medium for transporting harmful bacteria and viruses into water systems.

The recreational value of water systems and other natural ecosystems are also negatively affected by sediment from agricultural lands (Harker et al 2000).

The Annapolis Valley is the most intensively managed agricultural region of Nova Scotia, Canada, with reported concerns with groundwater nitrate pollution from agricultural production on predominantly sandy soils (Blair 2001; Gauthier et al 2009). In addition, farmers are concerned with surface soil loss (Jamieson et al 2003; Sinclair et al 2009; Ecology Action Center 2010). In response to the environmental problems from agriculture production, the provincial government is encouraging farmers to implement Environmental Farm Plan (EFP) and other stewardship practices such as NMP programs (Nova Scotia Agricultural Awareness Committee 2008).

Government priorities with the provincial NMP program include improving program effectiveness, especially for water quality protection (Nova Scotia Agricultural Awareness Committee, 2008), and promoting more widespread adoption. The program is currently voluntary, with farmers provided with funding for initial NMP implementation. However, there is speculation that NMPs will become mandatory in the future (Nova Scotia Agricultural Awareness Committee 2008).

As with the rest of the Atlantic Canada, recommended N fertilizer rates for the Annapolis Valley reflect field experimental studies outside the region (i.e., for central Canada) (Belanger et al 2001; Huffman et al 2008). NMP effectiveness is linked, in part, to concerns that existing crop nutrient recommendations, particularly nutrient N, are not only excessively high, but also outdated (Nova Scotia Agricultural Awareness Committee 2008). Nutrient requirements for individual crops depend on various factors and their interactions, including crop type (Simmelsgaard 1998; Zebarth et al 2003), tillage choice (Fixen 2004; Stoddard et al 2005; Lipiec et al 2011; Malhi et al 2011), and rotation sequence (Addiscott 1996; Lipiec et al 2011). In addition, the effects of these factors and their interactions on crop nutrient requirements depend on micro-climatic and other site-specific conditions (Beegle et al 2000). An understanding of the effect of NMP on both crop yield and water quality parameters in agricultural watersheds in the Annapolis valley requires a comprehensive study that takes into consideration several of the key NMP factors and farming conditions. Validated watershed simulation models can be employed as a tool for examining these complex interactions in a cost-effective manner.

The purpose of this study is to investigate the effects of alternative cropping systems commonly managed in the Thomas Brook Watershed (TBW) in the Annapolis Valley, on crop and pollutant (i.e., $NO_3^- - N$ and sediment) yields. Important NMP factors considered in this study include tillage management, crop choice and rotation sequence, and nutrient N fertilization rate. The Soil and Water Assessment Tool (SWAT) simulation model was used in this study to simulate site-specific conditions such as watershed hydrology and climatic conditions.

3.3 Research Methods

3.3.1 Study Area

The Thomas Brook Watershed (TBW) (Figure 3.1) is a relatively small watershed of about 784 ha in the upper portion of the larger 360 km^2 Cornwallis River Watershed, which is one of the largest watersheds in the Annapolis Valley. The Annapolis Valley is the most intensively managed agricultural region in Nova Scotia. Thomas Brook is a small stream with the main stream channel less than six km long. The Thomas Brook stream network consists of two upper streams that merge into a single water system approximately one-third of the distance downstream along the watershed (Figure 3.1).

The watershed is spatially complex, with variable land use, soils and topography. Agricultural land use account for the largest portion of the watershed area (57%). Crops commonly grown in the watershed include corn and small grains (Sinclair et al., 2009). Sandy loam soils are dominant in the watershed (Cann et al 1965). Average annual precipitation is about 1100 mm. Daily (1971-2000) normal minimum temperature is 1.3°C, while the maximum averaged for the same period is 12.2°C, with a mean temperature of 6.8 °C (Environment Canada, 2009).

3.3.2 The SWAT Model

The Soil and Water Assessment Tool (SWAT) is a watershed scale model used to simulate water, sediment, and nutrients for watersheds with varying soil, landuses and land management practices (Arnold et al 1998; Neitsch et al 2005). It is one of the most widely used tools for modeling agricultural watersheds with mixed landuses (Migliaccio and Srivastava 2007). SWAT uses the Soil Conservation Service (SCS) curve number to simulate surface runoff. Soil erosion and sediment yield estimation are simulated using the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975).

In addition, SWAT nutrient load and transportation algorithms are based on the Erosion Productivity Impact Calculator (EPIC) model (Williams 1995). The model allows for incorporating diverse crop rotation schedules, fertilizer application rates, and tillage management options.

3.3.3 SWAT Model Inputs and Construction

In this study, the SWAT model calibration and validation was performed in two stages, reflecting research objectives under a larger multi-disciplinary (hydrology-

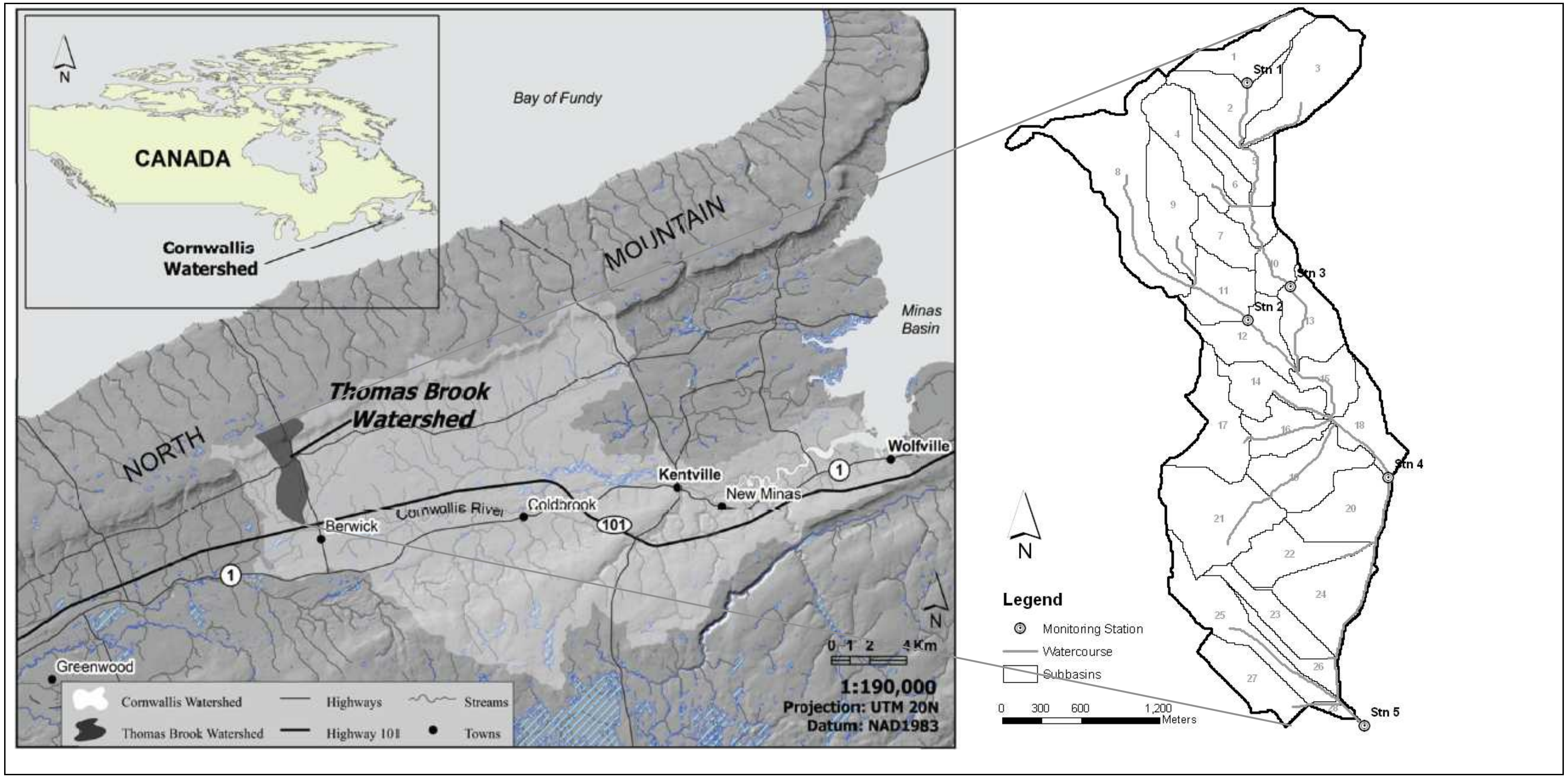

Figure 3.1: Location of Thomas Brook watershed within the larger Cornwallis River system.

Source: Adopted and modified from Ahmad (2010).

biophysical-Economics) research project for the Thomas Brook watershed. The first stage involved model calibration and validation to address watershed hydrology and pollutant transport research objectives (Ahmad 2010; Ahmad et al 2011). In the second stage, the calibrated and validated SWAT model was adapted to evaluate its performance in simulating selected on-farm management practices commonly managed in the study area. In SWAT modeling, both GIS-based spatial data and temporal input information such as precipitation and air temperature are required. Spatial information used included digital elevation model (DEM), soil and land use information data layers. The DEM was used to develop the stream network, and divide the watershed into hydrologically-linked subbasins.

A 10 m resolution DEM was used for TBW watershed delineation and stream network development (Table 3.1). The watershed was delineated into 265 Hydrologic Response Units (HRUs) and 28 subbasins. Land use and soils data were adapted to reflect existing field conditions, and primary crop rotations in the watershed. Soil information used was from the Canadian National Soil Information System's (CANSIS) national soil database, and updated using various soil survey reports for the area. After loading the spatial data layers and defining slope classes in the watershed, the subbasins were further sub-divided into HRUs. Temporal input information used to construct the TBW SWAT model included two primary climatic variables: precipitation and air temperature. The climatic information used was collected from the weather station located in Greenwood, Nova Scotia, managed by Environment Canada.

3.3.4 SWAT Model Calibration and Evaluation

As part of the larger research initiative, the TBW SWAT model was calibrated for hydrology, sediment, a limited set of crops (mainly corn and wheat), and the

Table 3.1. Model input data for Thomas Brook Watershed.

Data Type	Data Description	Source
DEM	10 m resolution digital elevation model	Nova Scotia Land Information Service
Soils	CANSIS data with modification to number of soil parameters as per various soil survey reports	Canadian National Soil Information System (CANSIS)
Land use	GIS map was generated from data collected	WEBs Project
Weather	Daily precipitation and minimum and maximum daily temperature	Environment Canada Greenwood Weather Station

recommended crop nutrient N using a monthly time step (Ahmad et al 2011). In the watershed hydrology study, parameters sensitive to different SWAT model routines were identified by running a sensitivity analysis. The model calibration also involved comparing SWAT-simulated monthly stream flows with observed data collected at monitoring station 4 within the TBW (Figure 3.1).

The calibrated SWAT model was further used for sediment, crop yield, $NO_3^-{-}N$ and total nitrogen (TN) export validation for TBW. A manual trial and error procedure was used as was done for model hydrology calibration. Key model parameters adjusted and their final calibrated values are reported in Table 3.2, and model performance statistics summarized in Table 3.3. Monthly simulation results were compared with observed data for sediment, $NO_3^-{-}N$, and TN export, while for crop yield yearly model outputs were matched without changing the parameters for the previous variables. As part of the applied economics study, SWAT modeling was further refined in this study and included calibrating and validating the model for winter wheat. The model validation

Table 3.2. Summary of key SWAT parameters used for model calibration for flow, sediment, crop yield, NO_3-N, and Total Nitrates.

Parameter	Initial Value	Calibrated Value
Flow		
Baseflow alpha factor (ALPHA_BF)	0.048	0.0025
Maximum canopy storage—Modified for forest HRUs only (CANMX mm)	0.0	7.0
SCS curve number for moisture condition II (CN2)		35 – 87
Soil evaporation compensation factor (ESCO)	0.95	0.5
Surface runoff lag coefficient (SURLAG)	4.0	1.0
Groundwater delay (GW_DELAY days)	31.0	1.0
Groundwater 'revap' coefficient (GW_REVAP)	0.02	0.2
Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN mm)	0.0	0.0
Groundwater recharge to deep aquifer (RCHRG_DP)	0.05	0.11
Sediment		
USLE equation soil erodibility (K) factor		0.01 – 0.32
Manning roughness coefficient for main channel (CH_N2)	0.014	0.08
Manning roughness coefficient for tributary channel (CH_N1)	0.014	0.025 – 0.10
Manning roughness coefficient for overland flow (OV_N)	0.10	0.10 – 0.80
Linear parameter to calculate sediment load (SPCON)	0.0001	0.00015
Exponent parameter to calculate sediment load (SPEXP)	1.0	1.0
Peak rate adjustment factor for sediment routing in the subbasin (ADJ_PKR)	1.0	0.81
Peak rate adjustment factor for sediment routing in the main channel (PRF)	1.0	0.65
Crop yield		
Biomass energy ratio (BIO_E) for barley	35.0	32.0
Biomass energy ratio (BIO_E) for spring wheat	35.0	32.0
Biomass energy ratio (BIO_E) for winter wheat	30.0	27.0
Harvest index (HVSTI) for corn	0.50	0.55
Harvest index (HVSTI) for barley	0.54	0.33
Harvest index (HVSTI) for winter wheat	0.40	0.35
Harvest index (HVSTI) for alfalfa	0.9	0.85
Leaf area index (BLAI) for barley	4.0	1.8
Leaf area index (BLAI) for spring and winter wheat	4.0	3.0
Nitrogen		
Rate coefficient of humus active nutrients mineralization (CMN)	0.001	0.003
Nitrate percolation coefficient (NPERCO)	0.2	0.33
Organic carbon in the soil layer (SOL_CBN %)	0.1	3.5

Table 3.3. SWAT model statistics for TBW on monthly time step for stream flow, sediment, NO_3-N, and Total Nitrates.

Variable	Calibration			Validation		
	R^2	NSE	PBIAS	R^2	NSE	PBIAS
Stream flow	0.90	0.88	-4.14	0.73	0.69	16.58
Sediment	0.66	0.47	41.70	0.48	0.31	23.00
NO_3-N	0.79	0.78	-1.90	0.65	0.64	5.90
Total Nitrates	0.67	0.63	16.30	0.84	0.83	-3.40

results suggest that, the SWAT model performed satisfactorily for sediment, $NO_3^-{-}N$ and TN. Further details of the SWAT model sediment and nitrogen performance are described in Ahmad et al. (2010).

3.3.5 Data

The SWAT model calibrated and validated for TBW conditions was used to generate crop yield, $NO_3^-{-}N$ and sediment load data for various cropping systems assumed to be managed in the watershed. Nitrates leaching focused on nitrates transported vertically through the root zone to groundwater systems (as opposed to total nitrate loading at the watershed surface water outlet). The cropping systems studied are summarised in Table 3.4. In this study, the cropping systems were distinguished by crop type, rotation sequence, nutrient N rate, and tillage type. The crops and rotation systems were selected in consultation with extension specialists, and reflect representative cropping systems for the region. Crops assumed to be managed include grain crops (i.e., barley, grain corn, and winter wheat) and vegetable crops (e.g., carrots, and potatoes). Although potatoes are not a dominant crop in TBW, it is one of the economically important crops grown in the Annapolis Valley. Similarly, alfalfa was chosen as leguminous forage commonly incorporated into selected rotation systems. The resulting

Table 3.4. Cropping systems studied.

(a) Farming systems

Rotation systems	Cropping sequence[a]	Tillage type[b]	N Fertilizer rates (%)[c]
Grain corn-based cropping system	CCAAA	CT	110% 100%, 90%, 75%, 50%, 25% and 0% of recommended N rates.
	CCAAA	NT	
	CCCAA	CT	
	CCCAA	NT	
Potato-based cropping System	PBW^FPC	CT	
	PBW^FPC	NT	
	PCBPC	CT	
	PCBPC	NT	
Vegetable-horticulture-based cropping system	PW^FRC	CT	
	PW^FRC	NT	

(b) Nutrient N application rates

	Nutrient N rates (kg N ha^{-1})								
Crop	Inorganic N	Organic N	Total N (100%)	110%	90%	75%	50 %	25%	0%
Grain Corn	37	143	180	198	162	135	90	45	0
Alfalfa[d]	42	-	42	46.2	37.8	31.5	21	10.5	0
Winter wheat	-	114	114	125.4	102.6	85.5	57	28.5	0
Barley	6	86	92	101.2	82.8	69	46	23	0
Potato	150	-	150	165	135	112.5	75	37.5	0
Carrot	68	-	68	74.8	61.2	51	34	17	0

Notes: [a] Crops are denoted by: W^F=winter wheat feed, P=Potato, R=Carrot, C=Grain corn, B=Barley, A=Alfalfa.

[b] NT management applies only to grain crops (i.e., winter wheat and grain corn). In both tillage treatments, potatoes and carrots were assumed to be managed under conventional tillage only, consistent with the practice in the study area.

[c] Nutrient N applications rates considered included 110% 100%, 90%, 75%, 50%, 25% and 0% of rates recommended in nutrient management plans for the study region.

[d] "-" denotes no crop nutrients added.

cropping systems studied reflect important dominant cropping systems in the study area and included grain-corn-based cropping systems, potato-based cropping systems, and a vegetable horticulture-based system (Table 3.4).

The crops were assumed to be managed under conventional tillage (CT) and no-till (NT) systems, except for carrots and potatoes. Carrots and potatoes were assumed to be grown under CT management only, reflecting the practice in the study area. CT involved mouldboard ploughing in the Fall, followed by a tandem disk operation and finishing harrow (secondary tillage) in the Spring. No-till systems simulated in SWAT involved a generic NT mixing operation at seeding. Although NT management is not the dominant tillage management system in the TBW area, it was used to compare its potential impacts on soil conservation and water quality improvement (Tong and Naramngam 2007).

The crop nutrient N rates in NMP recommendations for the study area were adjusted to investigate the effect of fertilizer application rate, resulting in seven fertilization levels (i.e., 110%, 100%, 90%, 75%, 50%, 25%, and 0% of the NMP recommended rates). NMP recommended nutrient N rates for the crops studied are summarized in Table 3.4 for grain corn (180 kg N ha^{-1}), barley (92 kg N ha^{-1}), potatoes (150 kg N ha^{-1}), winter wheat (114 kg N ha^{-1}), and carrots (68 kg N ha^{-1}). In addition, area extension specialists typically recommend 42 kg N ha^{-1} for alfalfa. For all crops (except potatoes and carrots), the timing of field operations such as land preparation, planting, fertilizer application, and harvesting were based on NMP data collected from a sample of farmers in the TBW. Farm management practices simulated for potatoes and carrots reflect official recommendations by the Atlantic Field Crops Committee (Atlantic Field Crops Committee 1978).

The crop rotation scenarios were assumed to be applied to all agricultural crop lands in the whole watershed. Permanent pasture and range lands cover floodplain areas of the watershed and were not considered cultivable. The SWAT model simulations were run for a 20 year (1989-2008) period. A first five-year rotation cycle was assumed to be SWAT model initialization or warm-up period, while output data for the remaining 15 years for crop yield and the associated $NO_3^- {-} N$ leached, and sediment load were analyzed.

3.3.6 Statistical Analysis

Analysis of variance (ANOVA) was performed to assess the main effects of tillage type (η_i), nutrient N rate (δ_j), and crop rotation system (ψ_k), as well as interaction effects $(\eta\delta)_{ij}$, $(\eta\psi)_{ik}$, $(\delta\psi)_{jk}$, and $(\eta\delta\psi)_{ijk}$ on crop yield, $NO_3^- {-} N$ leached and sediment loading. A ($\eta \times \delta \times \psi$) factorial model (i.e., 2×7×5 factorial for corn, 2×7×2 factorial for alfalfa, winter wheat and barley, and 2×7×3 for potatoes) was applied to the data as illustrated in Eq. [3.1]. An ANOVA table for the factorial model is summarized in Table 3.5.

$$Y_{ijkt} = \bar{\theta} + \eta_i + \delta_j + \psi_k + (\eta\delta)_{ij} + (\eta\psi)_{ik} + (\delta\psi)_{jk} + (\eta\delta\psi)_{ijk} + \varepsilon_{ijkt} \begin{cases} i = 1,2 \\ j = 1,2\ 3,4,5,6,7 \\ k = 1,2,\dots,c \\ t = 1,2,3,4\dots,n \end{cases} \quad (3.1)$$

where Y_{ijkt} denotes crop yield or $NO_3^- {-} N$ leached or sediment loading from the i^{th} tillage type, with the j^{th} N rate, and k^{th} rotation system managed in year t.

$\bar{\theta}$ = the overall mean.

η_i = main effect of tillage type.

Table 3.5. Summary of ANOVA model of main and interaction effects on crop yield, nitrate-N leached and sediment loading.

Source of Variation	Sum of Squares (SS)	Degree of Freedom (DF)	Mean Square (MS) (SS/DF)	F_0 (MS/MS_E)
η	SS_η	2-1	$\frac{SS_\eta}{2\text{-}1}$	$\frac{MS_\eta}{MS_E}$
δ	SS_δ	7-1	$\frac{SS_\delta}{7\text{-}1}$	$\frac{MS_\delta}{MS_E}$
ψ	SS_ψ	ψ -1	$\frac{SS_\psi}{\psi\text{-}1}$	$\frac{MS_\psi}{MS_E}$
$\eta \times \delta$	$SS_{(\eta\delta)}$	(2-1) × (7-1)	$\frac{SS_{\eta\delta}}{(2\text{-}1) \times (7\text{-}1)}$	$\frac{MS_{\eta\delta}}{MS_E}$
$\delta \times \psi$	$SS_{(\delta\psi)}$	(2-1) ×(ψ -1)	$\frac{SS_{\delta\psi}}{(2\text{-}1) \times (\psi\text{-}1)}$	$\frac{MS_{\delta\psi}}{MS_E}$
$\eta \times \psi$	$SS_{(\eta\psi)}$	(7-1) × (ψ -1)	$\frac{SS_{\eta\psi}}{(7\text{-}1)\times(\psi\text{-}1)}$	$\frac{MS_{\eta\psi}}{MS_E}$
$\eta \times \delta \times \psi$	$SS_{(\eta\delta\psi)}$	(2-1) × (7-1) × (ψ -1)	$\frac{SS_{\eta\delta\psi}}{(2\text{-}1)\times(7\text{-}1)\times(\psi\text{-}1)}$	$\frac{MS_{\eta\delta\psi}}{MS_E}$
Error	SS_E	2 × 7 × ψ × (n-1)	$\frac{SS_E}{2\times 7\times\psi\times(n\text{-}1)}$	
Total	SS_{TOT}	(2 × 7 × ψ × n)-1	$\frac{SS_{TOT}}{(2\times 7\times\psi\times n)\text{-}1}$	

δ_j = main effect of nutrient N application rates.

ψ_k = main effect of crop rotation system.

$(\eta\delta)_{ij}$ = effect due to interaction of i^{th} tillage type and j^{th} nutrient N application rate.

$(\eta\psi)_{ik}$ = effect due to interaction of i^{th} tillage type and k^{th} crop rotation system.

$(\delta\psi)_{jk}$ = interaction effect of tillage type, nutrient N application rate and rotation system.

$(\eta\delta\psi)_{ijk}$ = interaction effect of tillage type, N fertilization application rate and crop rotation system.

ε = error term (associated with uncontrollable or random factors) assumed to be normally and independently distributed with mean zero and constant variance ($\varepsilon_{ijkt} \sim NID(0, \sigma^2)$) for all *ijkt*.

The two tillage types (CT and NT) are denoted by i, and the seven levels of fertilizer/manure application rates (kg N ha $^{-1}$) specified in Eq. [3.1] are denoted by j. In addition, k represents distinct rotation systems (e.g., five distinct rotation systems for grain corn), and t represents cropping year in each rotation system (these are considered as replications for each crop).

The total sum of squares (SS_{TOT}) for the data was calculated using the relationship:

$$SS_{TOT} = \sum_{I=1}^{2}\sum_{J=1}^{7}\sum_{K=1}^{\psi}\sum_{t=1}^{n} Y_{ijkt}^2 - \frac{Y_{....}^2}{2\times7\times\psi\times n} \tag{3.2}$$

The sums of squares for the main and interaction effects were evaluated as follows:

Main tillage effect (SS_η):

$$SS_\eta = \frac{1}{7\times\psi\times n}\sum_{i=1}^{2} Y_{i...}^2 - \frac{Y_{....}^2}{2\times7\times\psi\times n} \tag{3.3}$$

Main nutrient N rate effect (SS_δ):

$$SS_\delta = \frac{1}{2\times\psi\times n}\sum_{j=1}^{7} Y_{.j..}^2 - \frac{Y_{....}^2}{2\times7\times\psi\times n} \tag{3.4}$$

Main crop rotation effect (SS_ψ):

$$SS_\psi = \frac{1}{2\times7\times n}\sum_{j=1}^{k} Y_{..k.}^2 - \frac{Y_{....}^2}{2\times7\times\psi\times n} \tag{3.5}$$

In addition, the following two-way interaction effects were evaluated.

Tillage and fertilizer/manure interaction:

$$SS_{(\eta\delta)}=\frac{1}{\psi\times n}\sum_{i=1}^{2}\sum_{j=1}^{7}Y_{ij..}^{2}-\frac{Y_{....}^{2}}{2\times 7\times\psi\times n}-SS_{\eta}-SS_{\delta} \tag{3.6}$$

Tillage and rotation interaction:

$$SS_{(\delta\psi)}=\frac{1}{7\times n}\sum_{i=1}^{2}\sum_{k=1}^{c}Y_{i.k.}^{2}-\frac{Y_{....}^{2}}{2\times 7\times\psi\times n}-SS_{\eta}-SS_{\psi} \tag{3.7}$$

Fertilizer/manure and rotation interaction:

$$SS_{(\eta\psi)}=\frac{1}{2\times n}\sum_{j=1}^{7}\sum_{k=1}^{c}Y_{.jk.}^{2}-\frac{Y_{....}^{2}}{2\times 7\times\psi\times n}-SS_{\delta}-SS_{\psi} \tag{3.8}$$

Furthermore, three-way interaction of tillage and fertilizer/manure and rotation were specified as:

$$SS_{(\eta\delta\psi)}=\frac{1}{n}\sum_{i=1}^{2}\sum_{j=1}^{7}\sum_{k=1}^{c}Y_{ijk.}^{2}-\frac{Y_{....}^{2}}{2\times 7\times\psi\times n}-SS_{\eta}-SS_{\delta}-SS_{\psi}-SS_{\eta\delta}-SS_{\delta\psi}-SS_{\eta\psi} \tag{3.9}$$

The error sum of squares was determined using the relationship:

$$SS_{E}=SS_{TOT}-\frac{1}{n}\sum_{i=1}^{2}\sum_{j=1}^{7}\sum_{k=1}^{c}Y_{ijk.}^{2}-\frac{Y_{....}^{2}}{2\times 7\times\psi\times n} \tag{3.10}$$

Equation 3.11 was used to describe the outputs in the simulations, except for carrot which was a 2×7 factorial.

$$Y_{ijt}=\bar{\theta}+\eta_{i}+\delta_{j}+(\alpha\delta)_{ijt}+\varepsilon_{ijt}\begin{cases} i=1,2\\ j=1,2\ 3,4,5,6,7.\\ t=1,2,3.\end{cases} \tag{3.11}$$

The null hypothesis tested was that there was no significant cropping system (main or interaction) effect on the outputs (i.e., crop yield, $NO_3^{-}{-}N$ leached or sediment loading). Thus: $H_o: \eta_i = 0$ for all *i*; $\delta_j = 0$ for all *j;* $\psi_k = 0$ for all *k;* $(\eta\delta)_{ij} = 0$ for all (*i, j*)-pairs; $(\eta\psi)_{ik} = 0$ for all (*i, k*)-pairs; $(\delta\psi)_{jk} = 0$ for all (*j, k)*-pairs*;* and $(\eta\delta\psi)_{ijk} = 0$ for all (*i, j, k*)-triples. The alternate hypothesis implies that at least one of the levels of a factor (main or interaction) has a significant effect on output: $H_a: \eta_i \neq 0$ for at least one *i*; $\delta_j \neq 0$ for at least one *j;* $\psi_k \neq 0$ for at least one *k;* $(\eta\delta)_{ij} \neq 0$ for at least one (*i, j*) – pair; $(\eta\psi)_{ik} \neq 0$ for at least one (*i, k*) - pair; $(\delta\psi)_{jk} \neq 0$ for at least one (*j, k*) - pair; and $(\eta\delta\psi)_{ijk} \neq 0$ for at least one (*i, j, k*) - triple.

P-values for F-ratios were tested at $\alpha = 0.05$, and H_o was not rejected if $p > \alpha$. Mean comparisons were done using the Least Significant Difference (LSD) method. Preferred cropping system combinations within the levels (*i, j, k*) or (*i, j,* for carrots) were those that predicted high levels of crop yields and low levels of $NO_3^-{-}N$ leached and sediment loading. The statistical analysis was conducted in SAS version 9.2 (SAS 2008).

3.4 Results and Discussion

The ANOVA results suggest that across all crops, the main effect of nutrient N rate and the main effect of rotation significantly affected crop yields and associated $NO_3^-{-}N$ leached (Table 3.6). None of the effects due to interaction between cropping system factors considered significantly influenced crop yield and associated $NO_3^-{-}N$ leaching. On the other hand, sediment load was significantly influenced by interaction effect of tillage and crop rotation for selected crops managed (Table 3.6). In addition, sediment load was significantly influenced by the main effects of tillage type and the main effect of rotation ($p \leq 0.001$). Details of cropping system effects on crop yield, nitrate-N and sediment load are discussed in the following sections.

Table 3.6. Summary of statistical results of the main effects of cropping system factors and their interactions on crop yield, nitrate-N leached and sediment load.

Variable	Source of Variation	Degrees of Freedom (DF)	General effect[a]
Crop Yield	η	1	*NS*
	δ	6	***
	ψ	ψ -1	***
	$\eta \times \delta$	$(2-1) \times (7-1)$	*NS*
	$\delta \times \psi$	$(2-1) \times (\psi -1)$	*NS*
	$\eta \times \psi$	$(7-1) \times (\psi -1)$	*NS*
	$\eta \times \delta \times \psi$	$(2-1) \times (7-1) \times (\psi -1)$	*NS*
Nitrate Leached	η	1	*NS*
	δ	6	***
	ψ	ψ -1	***
	$\eta \times \delta$	$(2-1) \times (7-1)$	*NS*
	$\delta \times \psi$	$(2-1) \times (\psi -1)$	*NS*
	$\eta \times \psi$	$(7-1) \times (\psi -1)$	*NS*
	$\eta \times \delta \times \psi$	$(2-1) \times (7-1) \times (\psi -1)$	*NS*
Sediment Load	η	1	***
	δ	6	*NS*
	ψ	ψ -1	***
	$\eta \times \delta$	$(2-1) \times (7-1)$	*NS*
	$\delta \times \psi$	$(2-1) \times (\psi -1)$	*NS*
	$\eta \times \psi$	$(7-1) \times (\psi -1)$	***
	$\eta \times \delta \times \psi$	$(2-1) \times (7-1) \times (\psi -1)$	*NS*

[a]NS = not significant; *** Significant at $p \leq \alpha = 0.001$.

3.4.1 Effect on Crop Yields

The main effects of nutrient N rate and the main effect of crop rotation ($p < 0.001$) significantly accounted for observed variations in grain corn yield ($p < 0.001$). Means comparison of significant main effects of the cropping systems suggest that, at 162 kg N ha^{-1} rate (which is 18 kg N ha^{-1} lower than the recommended NMP rate), average grain corn yields were not significantly different. Tillage did not have a significant effect on grain corn yield (Figure 3.2).

There was no significant difference between average grain corn yield from PWRC, CCCAA and CCAAA rotation systems. By comparison, average grain corn yield from PWRC, CCAAA and CCCAA were higher than grain corn yield from PBWPC and

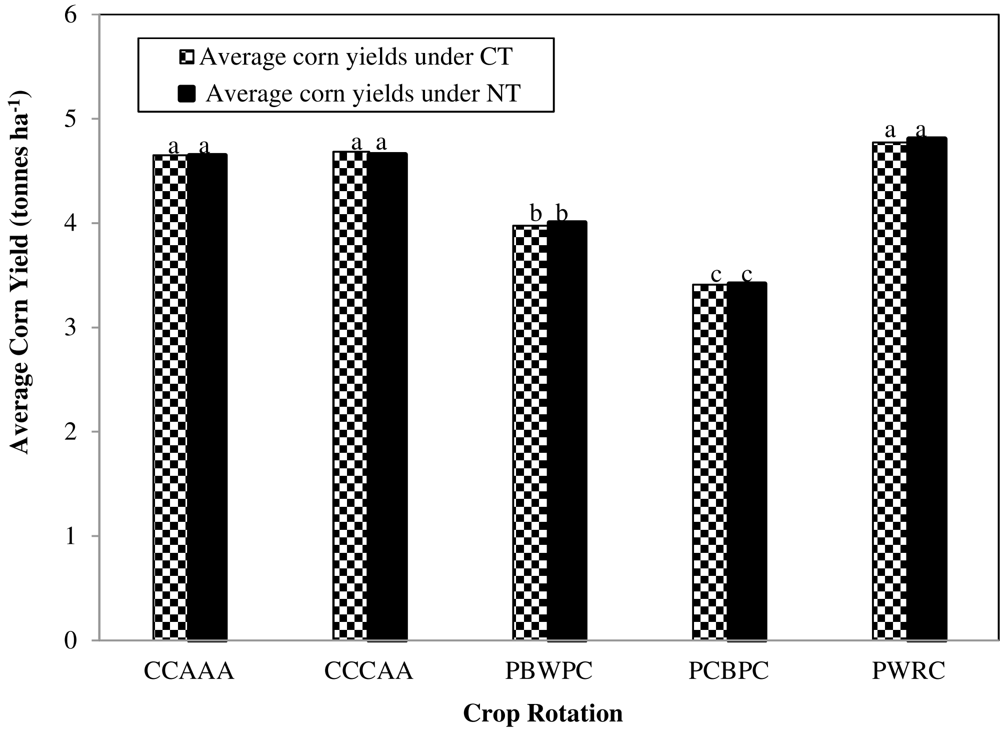

Figure 3.2: **Main effects of tillage and crop rotation sequence on grain corn yield**
Notes: i) Within and across rotation systems, mean yield followed by the same lower case letter indicate no significant difference in grain corn yield according to LSD test, α = 0.05.

PCBPC (Figure 3.2). Overall, average grain corn yield was highest in PWRC managed under NT (4.807 t ha^{-1}), followed by PWRC under CT (4.775t ha^{-1}), and lowest in rotations involving PCBPC, under NT (3.421 t ha^{-1}) and under CT (3.418 t ha^{-1}).

The overall model for potato yield were similar for PBWPC, PCBPC and PWRC rotations (p = 0.0728). The main effects of tillage and main effect of rotation, as well as their interaction did not significantly affect potato yield. On the other hand, the main effect of nutrient N significantly influenced potato yields, as expected. Mean comparisons suggest that nutrient N application rate of 112.5 kg N ha^{-1} below the recommended NMP rate did not significantly reduce average yield of potato (Table 3.7), and was consistent with reports that traditional nutrient N rates applied by farmers in the

Table 3.7. Main effect of nutrient N rate on average yield of potatoes.

Nutrient N rate (kg N ha^{-1})	Average potato yield (tonnes ha^{-1})[a]
0	8.559^{b}
37.5	15.08^{a}
75	16.806^{a}
112.5	17.029^{a}
135	17.062^{a}
150	17.077^{a}
165	17.082^{a}

[a] Average yield of potatoes across nutrient N levels followed by the same lower case letter indicate no significant difference according to LSD test, $\alpha = 0.05$

study area are not only outdated, but also excessive (Nova Scotia Agricultural Awareness Committee, 2011).

The overall model significantly explained variations in winter wheat yield from PBWPC and PWRC ($R^2 = 71\%$) (Figure 3.3). Winter wheat yield was significantly influenced by the main effect of nutrient N rate (F = 14.16, $p < 0.001$), and the main effect of rotation sequence (F = 18.09, $p = 0.001$). The results further suggest that winter wheat yield from PBWPC and PWRC were similar for nutrient N applications ranging from 85.5 to 114 kg N ha^{-1}. In contrast, average winter wheat yield from PWRC under CT and NT systems were higher (by 0.4 t ha^{-1}) compared with winter wheat yield from PBWPC managed under the two tillage systems (Figure 3.3).

As with the results for other crops, the overall ANOVA model significantly explained variations in barley yield ($R^2 = 72\%$, $p < 0.001$). The main effects of nutrient N rate was significant on barley yield (F = 23.55; $p < 0.001$), while the main effects of rotation and of tillage were not significant. Further analysis of the main effect of nutrient

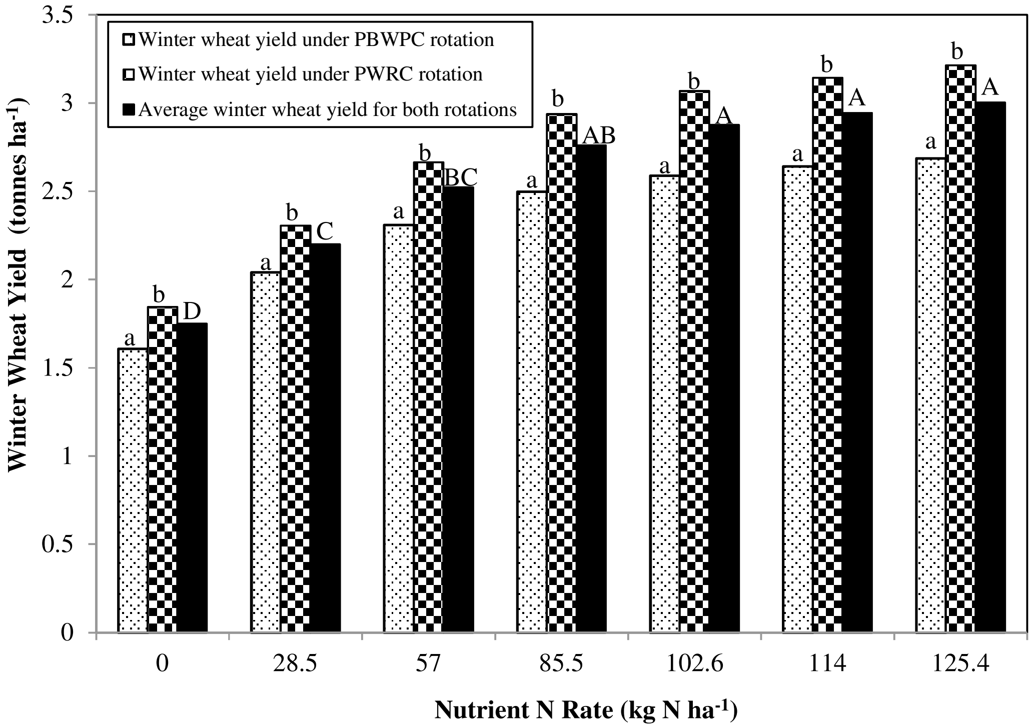

Figure 3.3: Main effects of nutrient N rate and of rotation sequence on winter wheat yield.

Notes: i) Within each nutrient N level, mean yields followed by the same lower case letter indicate no significant difference in winter wheat yield.

ii) Across nutrient N rates, average yields followed by the same upper case letter indicate no significant difference in mean yield of winter wheat, according to LSD test, α = 0.05.

N rate suggests that average yields of barley were similar for nutrient N rates ranging from 82.8 to 101.2 kg N ha^{-1} (Table 3.8).

In contrast to the findings for the grain crops, variations in alfalfa yield from CCAAA and CCCAA were not significantly explained by the model (R^2 = 0.2%). Both the main effects and interactions considered resulted in no significant effect on alfalfa yield ($p > 0.05$). Although the results were not statistically significant, actual alfalfa yield increased slightly by 0.241 t ha^{-1} (from 12.100 to 12.341 t ha^{-1}) when nutrient N rate was increased from 0 to 10.5 kg N ha^{-1}. Further increases in nutrient N level beyond 10.5 kg

Table 3.8. Main effect of nutrient N rate on average yield of barley.

Nutrient N rate (kg N ha^{-1})	Average barley yield (tonnes ha^{-1})^{a}
0	0.9645^{d}
23	1.525^{c}
46	2.0199^{b}
69	2.3313^{ab}
82.8	2.4361^{a}
92	2.4814^{a}
101.2	2.513^{a}

[a] Across nutrient N rates, mean yield of barley followed by the same lower case letter indicate no significant difference, according to LSD test, $\alpha = 0.05$.

N ha^{-1} resulted in a yield plateau. The alfalfa yield results are consistent with field observations in which most farmers in the TBW area tend not to apply chemical fertilizer to alfalfa.

The factors considered (i.e., nutrient N rate, and tillage type) and their interaction did not significantly affected average carrot yields (p = 1.000). However, actual carrot yields increased slightly from 21.200 t ha^{-1} to 25.186 t ha^{-1} when nutrient N rate were increased from 0 kg N ha^{-1} to 17 kg N ha^{-1}. Beyond nutrient N rate of 74.8 kg N ha^{-1}, carrot yields resulted in a plateau.

3.4.2 Effect on Nitrate Leached

Among all the crops considered, the main effects which resulted in differences in level of $NO_3^-{-}N$ leached were nutrient N rate and rotation system (p < 0.0001). This finding is consistent with Liang et al (2011) who examined the effects of N fertilization rate, rainfall, and temperature on nitrate leaching for rainfed winter wheat fields in Taihu watershed, China. Similarly, in a study of the effects of type of cultivation, soil type and drainage on annual levels of $NO_3^-{-}N$ leached, Simmelsgaard (1998) reported that crop type and rotation sequence were important factors which influenced $NO_3^-{-}N$ leaching. In a field study in Nova Scotia, Canada, Mkhabela et al (2008) reported a significant effect of tillage on $NO_3^-{-}N$ leached.

Other studies report contrasting findings on the effect of tillage on $NO_3^-{-}N$ leached. For example, in an experiment on two farm fields in Iowa, USA, Al-Kaisi and Licht (2004) reported no significant effect of tillage on level of $NO_3^-{-}N$ leached. In this study, the main effect of tillage type and the interaction effects considered were not significant on level of $NO_3^-{-}N$ leached for all the crops considered. The lack of significance may be to SWAT not representing the effects of tillage on key soil properties, such as organic matter content and soil structure. Means comparison revealed differences in $NO_3^-{-}N$ leached depending on the crop.

The means comparison of main effects suggest that for nutrient N applied at 162 kg N ha^1, grain corn yield were similar to yield generated with fertilization rates from 180 to 198 kg N ha^{-1}, while the level of $NO_3^-{-}N$ leached declined significantly from 64 to 53 kg N ha^1. In general, across fertilization rates, $NO_3^-{-}N$ leached from grain corn fields was lowest for PWRC and highest for PCBPC (Figure 3.4).

Variations in $NO_3^-{-}N$ leached from managing potatoes under different rotation systems, tillage type and fertilization rates were significantly explained by the ANOVA model ($p < 0.001$, $R^2 = 93\%$). The results suggest that potato yields were not significantly higher for nutrient N levels above 37.5 kg N ha^{-1}. In contrast, reducing nutrient N rate from 150 kg N ha^{-1} to 37.5 kg N ha^{-1} reduced $NO_3^-{-}N$ leached from 121.89 kg N ha^{-1} to 33.132 kg N ha^{-1} (Figure 3.5). Overall, nitrate leached from potato fields was lowest for PBWPC and PWRC rotations (Figure 3.5).

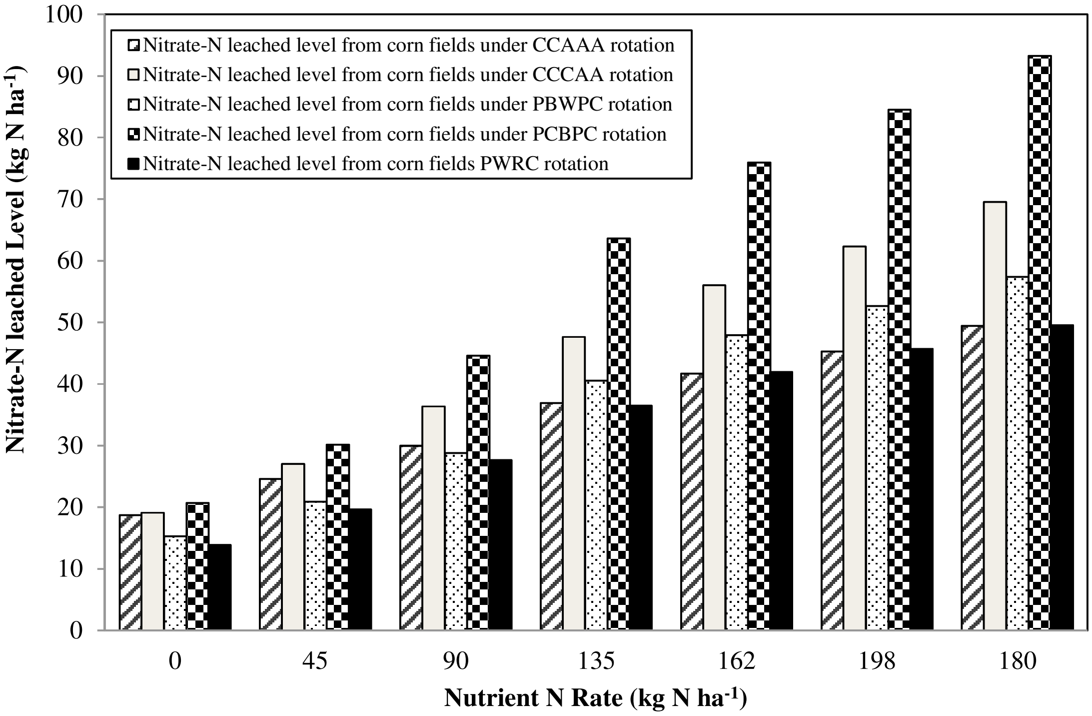

Figure 3.4: Comparison of nitrate-N leached (kg N ha^{-1}) under grain corn, for alternative rotation systems.

As with NO_3^-—N leaching from corn and potato fields, the ANOVA model for NO_3^-—N leached from winter wheat fields in PBWPC and PWRC were significant ($p <$ 0.0001, R^2 = 50%). NO_3^-—N leached from winter wheat fields was significantly influenced by the main effect of nutrient N rate (F = 18.84, $p < 0.0001$), while the main effect of rotation and of tillage, as well as the interaction effects assessed did not influence NO_3^-—N leaching.

In contrast to the winter wheat yield results which showed a plateau for fertilization levels above 85.5 kg N ha^{-1}, reducing nutrient N level from 114 to 85.5 kg N ha^{-1} resulted in significant reduction in NO_3^-—N leached by 11.84 kg ha^{-1}, on average, for

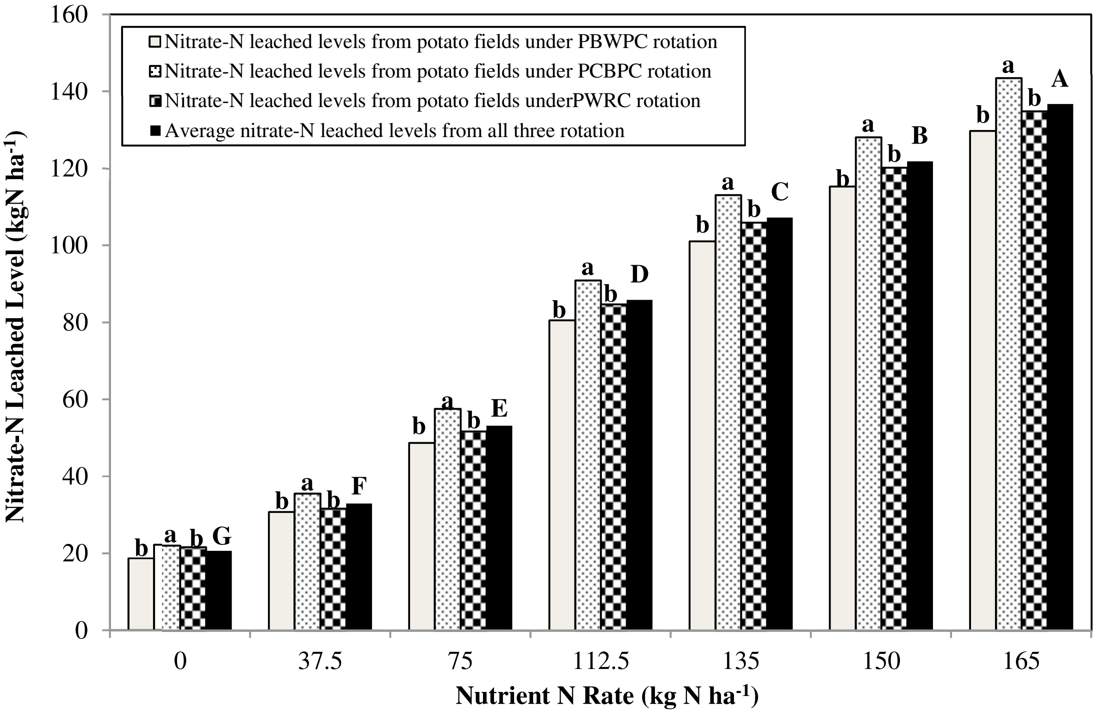

Figure 3.5: Main effects of nutrient N rate and rotation sequence on nitrate-N leached for potato fields.

Notes: i) Within each nutrient N rate, mean $NO_3^-{-}N$ leached amounts followed by the same lower case letter indicate no significant difference.

ii) Across nutrient N rates, average $NO_3^-{-}N$ leached followed by the same upper case letter indicate no significant difference from winter wheat fields, according to LSD test, $\alpha = 0.05$.

PBWPC and PWRC (Table 3.9). The main effect of nutrient N rate also had a significant effect on $NO_3^-{-}N$ leached from barley production (F = 86.10, $p < 0.0001$). Similarly the main effect of rotation significantly influenced $NO_3^-{-}N$ leached (F = 16.40, $p = 0.0002$). The analysis suggest that although barley yields were not significantly higher for fertilization rates above 69 kg N ha^{-1}, significant reduction in nitrate pollution can be attained by nutrient management. For example, reducing fertilization rate by 25% (from 92 to 69 kg N ha^{-1}) resulted in a 6% reduction in barley yield while reducing $NO_3^-{-}N$ leached by 22% (Figure 3.6).

Table 3.9. Main effect of nutrient N rate on nitrate-N leached from winter wheat production.

Nutrient N rate (kg N ha^{-1})	Average NO_3^-−N leached levels from winter wheat production[1]
0	22.325^{d}
28.5	28.138^{cd}
57	36.976^{c}
85.5	47.846^{b}
102.6	55.085^{ab}
114	59.681^{a}
125.4	65.456^{a}

[1] Across nutrient N fertilization rates, average NO_3^-−N leached from winter wheat production followed by the same lower case letter indicate no significant difference, according to LSD test, α = 0.05.

Another interesting finding was that NO_3^-−N leached from barley production in PBWPC was significantly lower than NO_3^-−N leached from barley in PCBPC by about 9 kg N ha^{-1} (Figure 3.6), consistent with for grain corn production. Thus, crop choice and rotation management can help improve groundwater quality while ensuring appreciable crop yield to farmers. Variation in NO_3^-−N leached from carrot production was significantly explained (R^2= 73%) by the ANOVA model. NO_3^-−N leached from carrot fields were influenced by the main effect of fertilization rate (F = 14.01, $p < 0.05$). Reducing the nutrient N rate for carrot from 68 to 34 kg N ha^{-1} improved groundwater quality by reducing NO_3^-−N leached by 35.7 kg N ha^{-1}.

The ANOVA model for alfalfa was significant in explaining variations in NO_3^-−N leached ($p < 0.0001$). The main effect of nutrient N rate on NO_3^-−N leaching was significant (F=16.78; $p < 0.05$), suggesting that NO_3^-−N leaching increased substantially with increasing fertilization rate. However, low levels of fertilization from 0 to 10.5 kg N

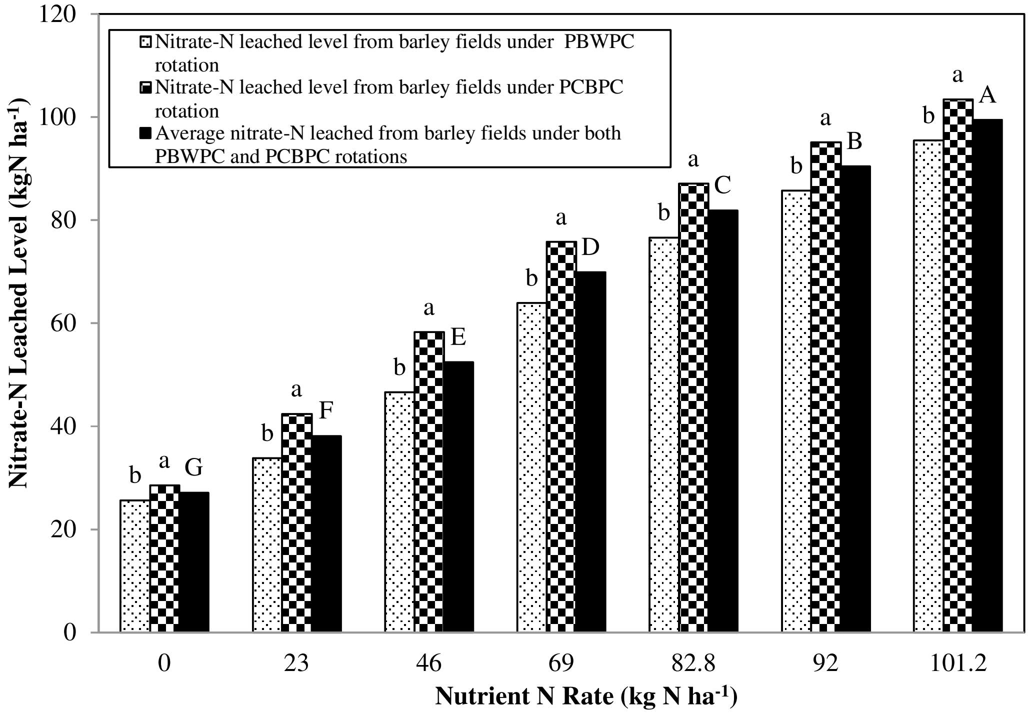

Figure 3.6: Main effect of nutrient N rate and of rotation sequence on nitrate-N leached from barley fields.

Notes: i) Within nutrient N rate, mean $NO_3^-{-}N$ leached amounts followed by the same lower case letter indicate no significant difference in $NO_3^-{-}N$ leached levels.

ii) Across nutrient N rates, average $NO_3^-{-}N$ leached followed by the same upper case letter indicate no significant difference from winter wheat fields, according to LSD test, $\alpha = 0.05$.

ha^{-1} did not significantly increase $NO_3^-{-}N$ leaching from alfalfa fields, but resulted in a nominal increase in actual alfalfa yield.

Overall, tillage type did not have a significant effect crop yields and $NO_3^-{-}N$ leached. When tillage system was switched from CT to NT, actual yields reduced by less than 0.1 t ha^{-1}, on average. The observed reduction in actual $NO_3^-{-}N$ leached under NT relative to CT is consistent with Tyler and Thomas (1977). A contrasting finding was reported for Zhu et al (2003) and Al-Kaisi and Licht (2004). Increased water infiltration and drainage due to increased surface residue accumulation from NT systems tends to increase $NO_3^- - N$ leached under NT (Richards and Baker 2002; Mays et al 2003).

3.4.3 Effect on Sediment Load

In general, sediment loads were affected by the main effects of tillage type and rotation system. Overall, sediment load decreased when tillage system was switched from CT to NT management, consistent with findings by Chambers et al (2000), Richardson and King (1995) Truman et al (2005), and Montgomery (2007). In a review of field studies on the effect of tillage treatment on sediment loading, Chambers et al (2000) reported sediment load reduction under NT compared with a CT system. Studies by Richardson and King (1995), Truman et al (2005) and Montgomery (2007) also suggest that tillage type significantly affects surface soil loss and sediment transport.

The main effect of rotation also significantly affected sediment loads. This finding is consistent with field studies by Carroll et al (1997), Edwards et al (1998), Sandretto and Payne (2007), and SWAT simulation modelling by Jatoe et al (2008) and Tong and Naramngam (2007). Tong and Naramngam (2007), for example, reported that continuous soybeans resulted in the highest reduction in sediment loading compared with corn–soybean and soybean–corn rotations.

There are limited studies on the direct effect of nutrient N fertilization on sediment load. In this study, the SWAT-simulated sediment loads tended to decrease with increasing nutrient N rate, however, the differences were not statistically significant. The equation for predicting soil loss in SWAT is the (Modified Universal Soil Loss Equation (MUSLE). Thus, the effect of fertilization on soil loss predictions is influenced by indirect effects, and is accounted for in the surface cover and management factor (C). In the rest of this section, the main effects and interaction effects of tillage, crop type and rotation are discussed.

Among the ten grain corn-based cropping systems, sediment load was lowest for CCCAA under NT management (1.438 t ha^{-1}), followed by sediment load from CCAAA (1.470 t ha^{-1}) (Table 3.10). Among all the cropping systems considered, the highest grain corn yields (and lowest $NO_3^-{-}N$ leached) were observed for grain corn in PWRC rotation. However, average sediment load from grain corn fields in PWRC were higher than sediment load from grain corn fields in CCAAA and CCCAA rotations (Table 3.10). For the potato-based cropping systems, sediment load from potato fields was significantly influenced by the main effect of tillage (F = 8.19, $p = 0.005$), and the main effect of rotation (F = 11.84, $p < 0.0001$). For PBWPC and PCBPC rotation systems under NT management, sediment load was lower by 1.09 t ha^{-1}, on average, compared with CT systems. Similar to the grain corn-based cropping systems, both $NO_3^-{-}N$ leached and sediment loads were lower under PBWPC and PWRC than for potato fields from PCBPC (Table 3.11).

As with the findings for grain corn and potatoes, sediment loads from winter wheat fields were significantly influenced by the main effect of tillage type (F = 16.90, $p < 0.05$), and the main effect of rotation sequence (F = 4.74, $p < 0.05$) (Table 3.12). In addition, sediment load from winter wheat fields in PBWPC and PWRC were influenced by the interaction effect of tillage and rotation (F = 22.52, $p < 0.05$). Furthermore, sediment load from winter wheat fields under PWRC were similar under both tillage systems (Table 3.12), while for PBWPC, sediment load was higher under CT (4.348 t ha^{-1}) than under NT (1.899 t ha^{-1}) (Table 3.12). Sediment yield from barley crop fields was

Table 3.10. Pair-wise comparison of the effect of crop rotation system on average grain corn yield, and associated nitrate-N leached and sediment load.

Crop rotation comparison	Difference in average grain corn yield (t ha^{-1})	Difference in average NO_3-N leached (kg ha^{-1})	Difference in average sediment loads (t ha^{-1})
PWRC - CCCAA	0.1188 (ns)	-13.014*	2.1678*
PWRC - CCAAA	0.1392 (ns)	-2.819 (ns)	1.9717*
PWRC - PBWPC	0.8012*	-5.230 (ns)	1.9692*
PWRC - PCBPC	**1.3749***	**-26.560***	**0.5254**(ns)
CCCAA – CCAAA	0.0204 (ns)	10.195*	-0.1961 (ns)
CCCAA – PBWPC	0.6825*	7.784*	-0.1986 (ns)
CCCAA – PCBPC	1.2561*	-13.546*	-1.6424*
CCAAA – PBWPC	0.6621*	-2.411 (ns)	-0.0025 (ns)
CCAAA – PCBPC	**1.2357***	**-23.741***	**-1.4463***
PBWPC – PCBPC	0.5736*	-21.330*	-1.4438*

Note: * denotes significance at α = 0.05; ns denotes not significant at α = 0.05 according to LSD test.

Table 3.11. Pair-wise comparison of crop rotation sequence for nitrate-N leached and sediment load from potato production.

Crop rotation comparison	Difference between means for $NO_3^-{-}N$ leached (kg ha^{-1})	Difference between means sediment load (t ha^{-1})
PCBPC – PWRC	5.698*	1.923*
PCBPC – PBWPC	9.440*	1.389*
PBWPC – PWRC	**-3.742**(ns)	**0.535**(ns)

Note: * denotes significance at α = 0.05; ns denotes not significant at α = 0.05 according to LSD test.

lower for PCBPC rotation under NT management (2.862 t ha^{-1}) than for PBWPC (4.985 t ha^{-1}). Similarly, sediment loads from alfalfa fields were significantly affected by the interaction between tillage and rotation sequence (F= 4.26; p = 0.04) (Table 3.13). In contrast to the findings for corn, winter wheat, and potatoes, sediment loss from managing carrots was not significant (p = 1.000).

Table 3.12. Interaction effect of tillage system and rotation sequence on sediment load from winter wheat fields under CT and NT systems.

Tillage type	Crop rotation pattern	Sediment load from winter wheat production	
		Mean (t ha^{-1})[1]	Std. Dev
CT	PBWPC	4.3482^a	2.1337
CT	PWRC	2.5979^b	1.2249
NT	PBWPC	1.8899^c	0.6962
NT	PWRC	2.5392^b	1.0534

[1] Mean sediment loads followed by the same letter are not significantly different according to LSD test (α = 0.05).

Table 3.13. Interaction effect of tillage system and rotation sequence on sediment load from alfalfa fields under CT and NT systems.

Tillage type	Crop rotation sequence	Sediment loads from alfalfa production	
		Mean (t ha^{-1})[1]	Standard Deviation
CT	CCAAA	5.094^a	1.985
CT	CCCAA	5.838^a	1.858
NT	CCAAA	1.495^b	0.762
NT	CCCAA	1.348^b	0.371

[1] Mean sediment loads followed by the same letter are not significantly different according to LSD test (α = 0.05).

The ANOVA results suggest that PBWPC has potential to reduce NO_3^-–N leached from barley production, compared with PCBPC. However, depending on priorities in terms of emphasis on particular water quality parameters (i.e., sediment load versus NO_3^-–N reduction) the decision on choice of rotation system may be complicated by the associated trade-offs to be made.

In summary, tillage type had a significant effect on sediment loads for all cropping system scenarios. In general, sediment loss across tillage treatments were less than 6 t ha^{-1}, on average, consistent with Agriculture and Agri-Food Canada (1998) soil loss classification for farms in Nova Scotia. Significant reduction in sediment loads from grain corn production under NT was observed for CCAAA and CCCAA (Table 3.10).

Results suggest that, NT system with crop rotations that included legume or forage or grain crops were especially important in reducing sediment load, consistent with Sandretto and Panye (2007) and Jatoe et al (2008). Forage and grain crops generate surface residue which help reduce sediment loss into water systems (Carroll et al 1997). In addition, although nutrient N rate did not have a significant effect on sediment loading, actual sediment loads decreased as nutrient N rates were increased. This would be expected as the C factor is influenced by biomass levels. Studies suggest that increased N fertilizer and manure application can improve soil structure and crop residue levels, thereby helping to reduce sediment loss (Bronic and Lal 2005; Nuttal et al1986). On the other hand, the increased N fertilization tends to increase $NO_3^- - N$ leached into groundwater systems

3.5 Summary and Conclusions

Nutrient management planning priorities in Nova Scotia agriculture include promoting more widespread adoption for environmental stewardship, especially water quality improvement. Farmers in Nova Scotia tend to apply fertilizer in excess of recommended rates. In addition, crop nutrient requirements do not reflect existing cropping systems and climatic conditions in the region. SWAT simulation modeling, which accounts for important climate variables, watershed hydrologic characteristics and various farm management practices allows for a comprehensive study of the effect of nutrient management planning on crop production and the associated water quality impacts.

The cropping systems studied were distinguished by tillage type, crop choice and rotation sequence, and nutrient N fertilization rate, and reflect dominant cropping systems commonly managed by farmers in the study area. An ANOVA model was developed and used to evaluate the effect of several main and factor interaction effects.

Overall, tillage did not have a significant effect on crop yield and nitrates leached, but had a significant effect on sediment loading. The effect of rotation sequence and fertilization rate on both crop yield and nitrate leaching depended on the crop and other interaction effects considered. The results highlight particular nutrient N application rates in combination with specific crops and rotation systems that can be managed to help control $NO_3^-{-}N$ leaching and sediment loss while balancing impacts on crop yields.

3.6 References

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CHAPTER 4 : COMPARISON OF CROP YIELD AND POLLUTION PRODUCTION RESPONSE TO NITROGEN FERTILIZATION MODELS USING SWAT-SIMULATED DATA FOR WATERSHED MANAGEMENT

4.1 Abstract

The overall purpose of this study was to estimate pollution production and crop yield response to N-fertilization and to determine the Maximum Economic Rates of Nitrogen (MERN) fertilization for various cropping systems. This study applied the Soil and Water Assessment Tool (SWAT) model to simulate crop yield and pollutant loads for corn, potato and vegetable-horticulture based crop rotation systems in TBW. Seven fertilizer levels, five crop rotation systems and two tillage types were evaluated. Response functions were estimated using regression analysis based on three main assessment criteria (i.e., visual assessment of shape of curves, biological (i.e. crop growth) assessment criteria, and statistical/econometric, and micro-economic criteria). The Mitscherlich-Baule model best represented potato, carrot and alfalfa yield response, while the quadratic model best represented corn, winter wheat and barley yield response to N fertilizer rates. The quadratic functional form best represented nitrate-N leached response to N fertilizer. For all crops, coefficients of the regression models estimated differed depending on the management options. MERNs for crops depended on (i.e., were highly sensitive to) the crops managed in previous years. Results suggest that famers tend to over-apply N to carrots, potatoes, and alfalfa. In addition farmers tended to under apply N fertilizer to barley in PCBPC rotation, and grain corn for all corn rotations considered.

4.2 Introduction

Nutrient management planning is important for both crop production and nutrient pollution reduction. Optimizing field crop nutrient use requires knowledge of the technical agronomic-economic relationships and effects of crop nutrients and related agronomic factors on crop yield and nutrient pollution production. Yield response to nutrients is commonly used to determine input-output relationships in crop production, and the associated technical relationships estimated as production functions (Llewelyn and Featherstone 1997).

Identifying the optimal nitrogen (N) fertilizer application rate for particular cropping systems is a major factor that affects farm profitability, and the impact of agricultural production on the environment (Cerrato and Blackmer 1990; Hasen and Djurhuus 1996; Lord and Mitchell 1998; Arregui and Quemada 2008; Limon-Ortega 2009). As with most parts of the Atlantic region, recommended N fertilization rates for the Annapolis Valley, Nova Scotia, reflect field experimental studies for central Canada (Belanger et al., 2001; Huffman et al., 2008). Also current nutrient N recommendations are considered to be excessively high, and also outdated (Nova Scotia Agricultural Awareness Committee 2008). Various studies have examined the response of different crops to nitrogen fertilizer use, and related ecological and environmental impacts under different soil regimes. Production and management decisions connected with the optimal level of N fertilizer application commonly involve fitting a mathematical model to crop yield or pollution production data generated from applying various rates of N fertilizer.

Estimated yield response to N fertilization can be used to assess potential crop yield under different soil nutrient regimes. There is renewed interest in such applications because of growing interest in more sustainable and environmental-friendly cropping systems, and potential efficiencies from reduced fertilizer application. The technical relationships can also be used to generate criteria to help prioritize and optimize allocation of limited inputs among competing uses (Doorenbos and Kassam 1979; Arregui and Quemada 2008). In addition, the estimated response function for a production process, along with other economic information, allow for assessing returns to investment on an input (Lauer 1986; Frank et al 1990).

Various factors influence the nature of a crop response to one or more inputs (Heady and Dillon 1961). Thus, it is not likely that a single mathematical model or production function can be used to predict relationships under varying cropping and management conditions. The simple quadratic functional form, for example, is commonly used to represent corn yield response to nitrogen fertilizer use. However, Cerrato and Blackmer (1990) reported that a quadratic-plus-plateau functional form best fitted corn yield response to N-fertilizer in a study for six different field plots in Iowa. Similarly, after fitting data on nitrate leached from nitrogen fertilizer use for various sites and years to selected mathematical functional forms, Lord and Mitchell (1998) found that the cubic functional form provided the best fit compared with a bilinear or linear-plus-exponential curve.

The lack of multi-year field experimental data is a major constraint to evaluation and application of crop production response to input use (French 1977; Segarra 1989; Jalota et al 2007). Generating multi-year field experiment data is often constrained by lack of research money, time to conduct such studies over several years, and lack of other resources. In addition, application of the Mitscherlich-Baule mathematical model, for example, requires a minimum set of input types and several response rates of the farm inputs under investigation (Llewelyn and Featherstone 1997). A common approach to addressing the multi-year field data limitation involves using simulation or engineering methods as proposed by French (1977), and has been used in more recent applications (e.g., Segarra 1989; Llewelyn and Featherstone 1997; Yiridoe et al 1997; Jalota et al 2007). Properly calibrated and validated biophysical modeling is a technically sound and cost-effective approach to generate data for such integrated agronomic-economic investigations (Antle and Capalbo 2001). In this study, data for estimating the yield and pollution production functions were generated using the SWAT model, calibrated and validated for the Thomas Brook Watershed in Nova Scotia.

The purpose of this study was to compare selected mathematical models used to describe crop and pollution production response to N fertilizer application rates and estimate input-output relationships for selected cropping systems. Data for the statistical/econometric analysis were generated by using the SWAT model to simulate various cropping systems assumed to be grown in the Thomas Brook Watershed. The cropping systems studied reflect production systems commonly managed by farmers in the Annapolis Valley region of Nova Scotia. These included: i) a corn-based cropping systems (C-C-C-A-A, C-C-A-A-A); ii) a potato-based cropping systems (P-B-W^F-P-C, P-C-B-P-C); and iii) a vegetable horticulture systems (P-W^F-R-C)[2]. In addition, the different rotation systems were compared under conventional tillage and no-till management.

Specific objectives of the study included the following:

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[2] The crops studied included: W^F = winter wheat feed, R=Carrot, P=Potato, C=Grain corn, B=Barley, A=Alfalfa.

1) *To review and consolidate literature on the mathematical economic characteristics of selected functional forms commonly used to describe input-output relationships for crop production and nitrate leaching.*

Specifying a mathematical functional form for a crop production process with specific production and site conditions requires knowledge of the nature and properties of the mathematical model. This review will provide theoretical background on alternative mathematical functional forms commonly used to fit response data.

2) *To assess and consolidate selected criteria commonly used to evaluate and select mathematical functional forms for describing pollution production and crop yield response to N fertilization.*

Various studies suggest that R^2 or adjusted R^2, used alone, is not adequate to justify selection of a mathematical functional form (Babcock and Blackmer 1994; Belanger et al 2000). Thus, it is important to consider other criteria commonly used to evaluate and identify mathematical models for yield response analysis.

3) *To estimate pollution production and crop yield response to N-fertilization for the crops studied.*

The rest of this section is organised as follows. Mathematical economic characteristics of selected functional forms commonly used to describe input-output relationships in crop production and nitrate leaching are reviewed in the next section. Criteria commonly used to evaluate and select mathematical functional forms are reviewed in section three. The uses and applications of response functions are briefly discussed in section four. This is followed by a description of methods used for the empirical analysis. The final sections include results and discussion, and a summary and conclusion.

4.3 Review of Mathematical Economic Properties of Selected Response Functions

4.3.1 Introduction

Functional form specification and choice of a suitable mathematical functional form is a research challenge, in part, because economic theory alone, does not provide straightforward specific guide to econometric model specification (Godfrey and Wickens 1981). Various economists and researchers have applied different methods for estimating various response functional forms. Strategies commonly used in estimating of response functions can be classified into the following general categories.

A first approach generally involves fitting input and output data to one specific mathematical model, without considering other possible mathematical models. A second procedure involves fitting data to a more generalized flexible functional form. Examples include, the generalized Box-Cox model (e.g., Berndt and Khaled 1979), and the fourier flexible functional form (e.g., Gallant 1982). Other applications include, translog, generalized Cobb- Douglas, and the generalized Leontief functional forms (Peterson and Ding 2005; Hyytiäinen et al 2011) to describe input-output relationships.

In practice, response function estimated for a particular cropping system and site conditions may not always be representative of all farming conditions and other sites (Heady and Dillon 1961; Babcock and Pautsch 1997; Yadav et al 1997; Rajsic and Weersink 2008). Thus, generalising a response function for different regions may be misleading, and result in inaccurate implications for both private and social economic decisions.

Some flexible functional forms allow for substitution among production inputs, and varying elasticity of substitution. The research interest in this study focused on output response to nutrient N applications, thereby limiting application of some flexible functional forms.

In addition, applications involving Taylor Series or Fourier transformation of the "true but unknown underlying production function" (Stackhouse 2011), may not be applicable in the case of a production function of one variable-input. Estimates of a "true but unknown underlying production function" may be biased and compromise validity of t, F, Durbin-Watson and other statistical tests that rely on best linear unbiased estimates (BLUE) (Stackhouse 2011). Driscoll and Boisvert (1991) also noted that flexible functional forms are generally not able to precisely characterize an underlying biological relationship/technology. In connection with this problem, White (1980) noted that, "reliance on the Taylor approximation interpretation is imprecise if not a totally misleading practice" (page 163). While Byron and Bera (1983) disagreed with White (1980), Diewert and Wales (1989) noted that empirically estimated flexible functional forms do not satisfy appropriate theoretical curvature conditions, and proposed methods to impose curvature conditions. To date, there is no consensus among applied economists regarding general estimation approach, nor decision on choice of flexible functional forms or Taylor series approximations.

A third procedure involves fitting input-output data to a suite of selected mathematical models, selected based on findings from related studies, and determining the mathematical model that best fits the data using economic, econometric and biological (i.e., crop growth) assessment criteria. Applications of this approach include Lanzer and Paris (1981); Cerrato and Blackmer (1990); Babcock (1992); Makowski and Wallach (2002); and Mooney et al (2008). Another approach involves non-parametric estimations of response function.

Each of the approaches highlighted above have their advantages and analytical challenges. In general, there is no consensus among economists regarding which method is “best”. In this study, several mathematical models selected based on related studies were evaluated for the input-output data for each crop. A similar approach was used for nitrate leaching response to N fertilizer application. The remainder of this section provides a review of selected functional forms. Some mathematical functional forms that have been fitted to crop yield and nitrate-N leached response to N fertilization in earlier studies are summarized in Table 4.1 and 4.2. The overview provides context for the selection of functional forms considered in this study.

4.3.2 A Linear Functional Form

A production function is linear when a change in output with respect to a unit change in a variable input is constant. Mathematically the slope of a linear function (MPP) is constant. A linear equation for a single input – single output production situation may be represented as:

$$Y = a + bX \qquad (4.1)$$

where b represents the slope or (MPP) marginal physical product, X represents a variable input (e.g., amount of fertilizer), Y represents output level (or yield) and a is the intercept term. Linearity implies $f_X=\partial Y/\partial X=b$, and $\partial MPP /\partial X = 0$. If $b = 0$, then Y is independent of X. A linear production function (Figure 3.1, panel A) does not exhibit diminishing marginal returns. However $b < 0$, (a negative slope) implies the existence of only stage three of a production process. Thus, the first two stages of production may not exist, in which case $b < 0$ does not satisfy important conditions for a typical agricultural production process (Beattie et al 2009).

Table 4.1. Mathematical functional forms commonly used to fit nitrate leached data.

Crop	Cropping sequence(s) as specified by authors[a]	Soil type	Functions	Author(s)
Barley	5 year continuous Spring Barley	Sandy to loam	Exponential	Hansen and Djurhuus (1996)
Spring Wheat, Winter Wheat, and Winter Barley	P-SW P-WW S-WW WW-WB	Sandy loam	Cubic	Lord and Mitchell (1998)
Corn, Soy bean, and Winter Wheat	CC C-SB-WW C-C-SB-WW		Quadratic	Yiridoe et al (1997)

[a] Crops are denoted by: P=Potato, SW=Spring Wheat, WW=Winter Wheat, WB=Winter Barley

Table 4.2. Mathematical models commonly used to fit selected crop production systems.

Crop	Cropping sequence(s) as specified by authors[a]	Functional form	Study
Barley	N/A	Inverse quadratic	Shaohua et al (1999)
	N/A	Quadratic-plus-plateau	Arregui and Quemada (2008)
Potato	N/A	Exponential	Lauer (1986)
	N/A	Quadratic	Belanger et al (2000)
Corn	CC C-SB-WW C-C-SB-WW	Quadratic	Yiridoe et al (1997)
	V-C CL-C WW-C NC-C		Roberts et al (1998)
	N/A		Martinez and Albaic (2006)
	N/A		Grimm et al (1987)
	N/A	Quadratic-plus-plateau	Cerrato and Blackmer (1990)
	N/A		Frank et al (1990)
	Nine years continuous corn	Mitscherlich-Buale	Llevelyn and Fertherstone (1997)
	N/A	von Liebig	Grimm et al (1987)
	WW-SM	Linear-plus-plateau	Cui et al (2008)
Winter Wheat	N/A	Quadratic-plus-plateau	Arregui and Quemada (2008)
	N/A	von Liebig	Grimm et al (1987)
	N/A	Quadratic	Grimm et al (1987)
	Mono-crop	Linear-plus-plateau	Cui et al (2010)

[a] Crops are denoted by: C=Corn, SB=Soybean, WW=Winter wheat, V=Hairy velch, CL=Crimson clover, SM=Summer maze, NC=No Cover crop, N/A=Cropping sequence were not specified by authors.

The intercept term a implies that without the variable input use, there is still some level of output denoted by $Y = a$. In crop production, such a situation suggests that crop yields are influenced by a residual nutrient effect (Lord and Mitchell 1998). A positive slope, or $MPP = b > 0$ implies a constantly increasing output with increasing X. In general, isoquants of a linear functional form have constant slopes. For a two-input situation, a change in the level of one input can compensate for a change in the level of the other input (Chambers 1988).

Excessive application of a particular variable input (e.g., water or fertilizer) can result in a decline in production or even destroy the crop. Although the linear function does not represent biological processes such as crop yield response to N fertilization, it could be used in fitting nitrate response to N fertilization (Fox et al 2001). In other words, the relationship between nitrate leaching and N fertilizer application rate could be linear. The linear functional form does not represent input-output relationships in the long-run for crop production processes due to the law of diminishing marginal returns.

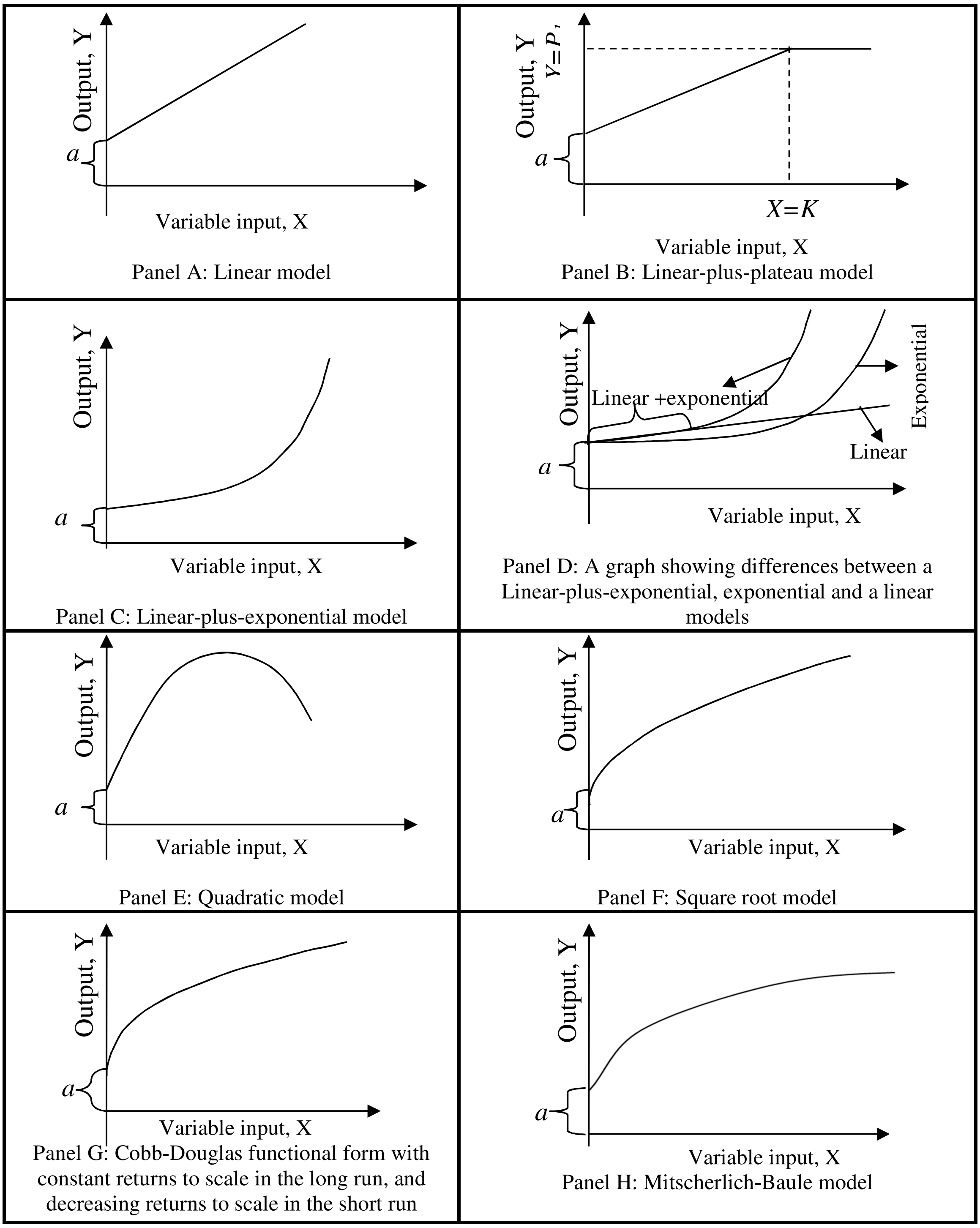
4.3.3 Linear-plus-plateau Functional Form

An output may initially increase at a constant with respect to additional units of input, and then plateau beyond a point (where additional units of the variable input do not decrease or increase output level). The linear-plus-plateau functional form (Figure 3.1, Panel B) is represented as:

$$Y = a + bX, \quad if \quad X < K \tag{4.2}$$

$$\text{and } Y = P_l \quad if\, X \geq K \tag{4.3}$$

where K represents the critical rate of variable input which occurs at the intersection of the linear response and the plateau level (Cerrato and Blackmer 1990). Equation (4.3)



Panel A: Linear model

Panel B: Linear-plus-plateau model

Panel C: Linear-plus-exponential model

Panel D: A graph showing differences between a Linear-plus-exponential, exponential and a linear models

Panel E: Quadratic model

Panel F: Square root model

Panel G: Cobb-Douglas functional form with constant returns to scale in the long run, and decreasing returns to scale in the short run

Panel H: Mitscherlich-Baule model

Figure 4.1: Graphical illustration of selected functional forms.

represents the plateau equation and P_l (i.e., plateau yield) is constant, and can be obtained by fitting the functional form to a specific production data.

4.3.4 Linear-plus-exponential Functional Form

A linear-plus-exponential (LPE) functional form (Figure 3.1, Panel C) can also be used to describe an input-output relationship (Lord and Mitchell 1998). For a single-input single-output case, the LPE functional form is expressed as:

$$Y = a + br^X + cX \qquad (4.4)$$

where Y is output, X is variable input, and a, b, c, and r are fitted constants. In a special case, r becomes e (i.e., exponent).

In Panel D of Figure 1, the difference between a linear-plus-exponential, exponential, and a linear functional form is illustrated. For crop production, any of these three functional forms (Figure 3.1, Panel D) is unlikely to describe crop yield response to N-fertilizer, but could represent nitrate leached response to N fertilizer usage (Hansen and Djurhuus 1996; Lord and Mitchell 1998). Nevertheless, it is possible to have a linear-plus-plateau response for crop production (Cerrato and Blackmer 1990; Chen et al 2004; Cui et al 2010).

4.3.5 Quadratic Functional Form

A single-input single-output quadratic functional form (Figure 3.1, Panel E) can be represented as:

$$Y = a + bX + cX^2 \qquad (4.5)$$

This representation denotes a second order polynomial function. The slope of the quadratic functional form is linear: $f_X = \partial Y / \partial X = MPP = b + 2cX$, and $\partial MPP / \partial X = 2c$. Furthermore, $\partial MPP / \partial X < 0$ implies diminishing marginal returns, and stage 1 production would not exist (Heady and Dillon 1961). Thus, instead of observing both increasing and decreasing marginal products, there is declining and negative marginal productivity. A negative slope of the quadratic functional form implies the existence of a third stage of production.

The isoquants are indirect, with the graph showing areas of positive, negative, zero and infinite slope, and convex to the origin (Beattie et al 2009). The quadratic functional form has been used in various studies to specify crop yield response such as for grain corn (Cerrato and Blackmer 1990; Yiridoe et al 1997; Roberts et al 1998), winter wheat (Grimm et al 1987), and barley (Shaohua et al 1999; Arregui and Quemada 2008) to fertilizer application.

Polynomial function restraints can be relaxed by (changing the order of the polynomial from say quadratic to cubic). The restraint for the quadratic functional form implies that MPP declines by a constant amount (Heady and Dillon 1961). Transforming a quadratic function to a cubic function with the MPP to decline at an increasing rate implies: $\partial MPP / \partial X = 2c + 6dX$. The multiple input case (Equation 4.6) allows for technical relationships among the inputs, and estimation of possible interaction terms.

$$Y = a + bX_1 + cX_2 + dX_1^2 + eX_2^2 + gX_1X_2 \qquad (4.6)$$

The technical relationships may be such that the inputs are complementary $(g > 0)$ or competitive $(g < 0)$ to each other. X_1 and X_2 can also be technically independent, in which case $g = 0$. Strict concavity implies that $b, c, >0$, and $d, e < 0$, while $(4d \times e) > g^2$ (Beattie et al 2009).

The properties of the quadratic functional form are such that yield can fall substantially with excess N fertilizer application. However, slight yield decreases at higher N fertilizer rates is possible (Rajsic and Weersink 2008). The quadratic function is also not homogenous with respect to variable inputs. On the other hand, Martinez and Albiac (2006) noted that polynomial functions, especially the quadratic functional form, is commonly used to specify crop response to N fertilizer and water use because of its mathematically tractable properties and ease of estimation.

4.3.6 Square Root Functional Form

The square root functional form (Figure 3.1, Panel F) can be represented as

$$Y = a + bX + cX^{0.5} \tag{4.7}$$

It has similar properties as the quadratic functional form, and is a simple compromise between the power or exponential functions and the quadratic function (Heady and Dillon 1961). As with the quadratic functional form, several studies have used the square root functional form to describe crop yield response to fertilization (e.g., Finger and Hediger 2008).

4.3.7 Cobb-Douglas Functional Form

The Cobb-Douglas functional form (Figure 3.1, Panel G) was first proposed by Knut Wicksell, and is widely used to represent input-output relationships (Grubbstrom 1995). However, it was statistically tested by Charles Cobb and Paul Douglas in 1928 (Grubbstrom 1995). The Cobb-Douglas functional form can be represented as:

$$Y = AX_1^aX_2^b \tag{4.8}$$

where X_1 and X_2 are variable inputs used to produce output Y. The Cobb-Douglas functional form allows for only complementary factors (Beattie et al 2009). In addition, production will not exist with just one input when there is no amount of the other input used in production. The marginal products of the two inputs are:

$$f_{X_1} = \frac{\partial Y}{\partial X_{1,}} = \frac{aY}{X_1}, \text{ and } f_{X_2} = \frac{\partial Y}{\partial X_2} = \frac{bY}{X_2}$$

The constants, a, and b represent elasticity of production using inputs X_1 and X_2 respectively.

Strict concavity implies that $0 < a < 1$, $0 < b < 1$, $0 < (a + b) < 1$ and $A > 0$. The magnitude and directions of A, a, and b when strict concavity holds reflect the existence of stage II production. The Cobb-Douglas functional form is homogenous of degree $(a + b)$. Thus, if the inputs are increased by a certain factor, output increases by some power of this factor.

It has been observed that all three stages of production cannot exist (Beattie et al 2009). The existence of one stage of production implies the other two stages of production do not exist. Isoquants of the Cobb-Douglas functional form are negatively sloped, and convex with respect to the origin. Grimm et al (1987) noted that the Cobb-Douglas, Mitscherlich-Baule and polynomial functional forms of varying degree (quadratic, three-halves, and square root) are commonly used to specify crop response production functions. However, unlike the quadratic, cubic and square root functional forms, the Cobb-Douglas functional form tend to be rejected in specifying crop yield response to N fertilizer application.

4.3.8 Von Liebig Functional Form

The von Liebig function can be represented as:

$$Y = min\ \{f_A(A,\ u_A),\ f_B(B,\ u_B),\ f_Z(Z,\ u_Z)\} \tag{4.9}$$

or

$$Y = \ min\{Y_m, (a_1+b_1X_1),\ (a_2+b_2X_2)\} \tag{4.10}$$

for a two variable input case, where Y is the realised output. A, B, and Z are levels of inputs, say fertilizer nutrients, and u_A, u_B, and u_Z are random disturbance terms related to the potential production functions, $f_A(A, u_A)$, $f_B(B, u_B)$ and $f_Z(Z, u_Z)$. The functions $f_A(A, u_A)$, $f_B(B, u_B)$ *and* $f_Z(Z, u_Z)$ represent individual response to the different variable inputs. In equation (4.10), Y_m is the maximum yield when neither X_1 or X_2 is limiting. The von Liebig hypothesis is sometimes relevant only to the multiple input situations (Kaitibie et al 2007). However, a single nutrient input, characterized by a linear relation with a plateau, known as linear response plateau (LRP) can be represented as a single input von Liebig function.

In recent years much interest in crop yield response functions have focused on functional forms that allow for growth plateau such as the von Liebig response function (Llewelyn and Featherstone 1997). A linear von Liebig model would not allow for factor substitution, but this is possible for a non-linear von-Liebig model (Paris 1992). Moreover, the factors are technically independent if neither is limiting, but technically complementary at the kink in the von Liebig production function curve (Beattie et al 2009). Thus, the nature of the von Liebig curve is weakly concave if the coefficients b_1 and b_2 associated with the variable inputs X_1 and X_2, respectively, are ≥ 0 in equation 4.10. Several studies have used the von Liebig functional form to describe input-output relationships for crop yield and fertilizer rates. Ackello-Odutu et al (1985), for example, reported that the von Liebig function represents a better specification of crop response compared with polynomial functions.

4.3.9 Mitscherlich-Baule Functional Form

The Mitscherlich-Baule functional form allows for factor substitution (or technically complementary factors). The Mitscherlich-Baule functional form (Figure 3.1, Panel H) also allows for a plateau growth (Frank et al 1990; Llewelyn and Featherstone

1997). Such properties make the Mitscherlich-Baule model more flexible in predicting crop response. It also allows for relationships between multiple inputs, unlike the von Liebig model which does not allow for factor substitution or the quadratic model which allows only for factor substitution. Elasticity of production of a Mitscherlich-Baule functional form allows reasonable flexibility to accommodate limited factor substitution (Frank et al 1990).

The Mitscherlich-Baule function can be represented as:

$$Y = \beta_1\,[1 - exp\left(-\beta_3(X_1 - \beta_4)^{\beta_7}\right)]\,[1 - exp\left(-\beta_5(X_2 - \beta_6)^{\beta_8}\right)] \qquad (4.11)$$

where β_1, β_3 and $\beta_5 > 0$ if strictly concave, or β_1, β_3, β_5, β_7 and $\beta_8 > 0$ if strictly quasi-concave (Beattie et al 2009). For crop production, β_1 represents Y_m as in the von Liebig model, or the asymptotic yield. β_4 and β_6 may represent variable input rates at the X intercept when yield equals to zero (e.g., nitrogen or water). β_3 and β_5 may represent initial output response slope.

When $\beta_7 = \beta_8 = 1$, the function exhibits only stage 2 of the production process. Stages 1 and 2 of production are exhibited for input X_1 if $0 < \beta_7 < 1$, and for input X_2 if $0 < \beta_8 < 1$. Llewelyn and Featherstone (1997) noted that Mitscherlich-Baule model estimation requires at least six levels of one input and four levels of another. The Mitscherlich-Baule functional form has been used to specify corn yield response to N fertilization and irrigation water use (Frank et al 1990; Llewelyn and Featherstone 1997).

4.4 Model Comparison and Assessment Criteria

Criteria used to assess mathematical model performance in describing yield response to input use, and pollution production commonly involves various economic, econometric/statistical and non-economic (e.g., biological characteristics in the case of crop growth) methods. The econometric/statistical assessment is normally preceded by non-economic screening techniques, such as visual evaluation of graphical plots of the yield data, and knowledge of the biological and/or growth characteristics of crops and pollutants.

Econometric/statistical criteria commonly used to compare alternative mathematical functional forms include:

(i) The coefficient of determination (e.g., Alivelu et al 2003);

(ii) Residual distribution (e.g., Stephens 1974; Belanger et al 2000);

(iii) Point ranking and deviation from regression residuals (e.g., Shaohua et al 1999);

(iv) Non-nested hypothesis testing (e.g., Frank et al 1990); and or

(v) A combination of the above.

The response function is essentially a purely technical relationship that has no economic content. In this study, it was important to attain a correct technical and biological representation of the input and output relationships. Another important interest was to ensure that the response function allows for further economic analysis. The economic criteria used to compare and choose from alternative production response functional forms include:

(i) Using economic theory to ensure properties that make the production function useful in economic analysis for example, the production response function should be continuous, able to predict all three stages of production once inputs are varied, and also be twice differentiable in N, such that the marginal products and the rate of change of the marginal products could be assessed (Chambers 1998).

(ii) Also, another economically practical approach to choosing a preferred production response function is to examine potential misspecification of optimal solutions (this is done by accessing the maximum rate of input use and corresponding maximum yield, and the economically optimal solution) for the different functional forms. In addition, misspecification cost for optimal solutions from the different functional forms could be assessed to help select the best choice of best fitted functional forms (e.g., Llewelyn and Featherstone 1997).

A brief review of selected econometric/statistical criteria follows.

4.4.1 Normality Test

The distribution of actual (or observed) crop yield has received much attention among analysts since Day (1965). However, there is no consensus among applied economists about the nature and importance of the crop yield distribution test. In addition, there are alternative statistical methods or procedures that can be used to assess normality of crop yields. Ramirez et al (2003) noted that the method or procedure used depends on the type of data. On one hand, some analysts have argued that incorrect identification of crop yield distribution can affect both farmer and non-farmer economic decisions (Just and Weninger 1999; Sherrick et al 2003). For example, incorrectly identifying crop yield distribution may influence specification or estimation of trend behaviour or crop yield response to inputs (e.g., N-fertilizer). This can in turn directly or indirectly adversely affect farmers and policy decision making regarding issues such as risk management (or reduction of pollutants) and crop insurance policies (Just and Weninger 1999; Sherrick et al 2003).

Some analysts such as Day (1965), Buccola (1986), Nelson and Preckel (1989), Ramirez (1997), and Ramirez et al (2003) argue that crop yield data are not necessarily normally distributed. In contrast, Just and Weninger (1999), and Atwood et al (2003) contend that crop yield data must be normally distributed as a condition for response function estimation. Further research on these issues is needed.

4.4.2 Coefficient of Determination

Alivelu et al (2003) compared three functional forms (Mitscherlich's model, Linear-plus-plateau, and Quadratic-plus-plateau) to select the best model for rice response to Nitrogen, Phosphorus and Potassium (N-P-K) fertilization. The comparison was based on coefficient of determination (R^2) values. Hartinee et al (2010) also compared the linear, linear-plus-plateau, quadratic, and the quadratic-plus-plateau functions to select the best functional form for rice response to N, P and K based on R^2 values. Both Alivelu et al (2003) and Hartinee et al (2010) observed that all of the models compared had high R^2 values (i.e., $R^2 > 90\%$). In spite of similar observations for R^2 values, all the functional forms considered generated different economically optimum rates of fertilization and, therefore, different optimum yields. Alivelu et al (2003) and Hartinee et al (2010) concluded that R^2 values are not reliable when used alone. Thus, additional assessment criteria such as checking residual distribution of crop yields are useful to help accurately determine of accurate economic optimum rates of N fertilization.

Using R^2 values alone for comparing and identifying the best functional form could lead to misleading costs and benefits to producers (Cerrato and Blackmer 1990; Rajsic and Weersink 2008). Also model comparison based on R^2 is often biased when comparing linear models with non-linear models or models with no intercept (Kvalseth 1985; Anderson-Sprecher 1994). In addition, the use of R^2 to compare transformed and untransformed models or models with different dependent variables (e.g., y, y^, and y*) can lead to biased selection of best fit (Scot and Wild 1991).

4.4.3 Residual Distribution

Cerrato and Blackmer (1990) reported R^2 values ranging from 0.92 to 0.95 for five functional forms compared, and noted that R^2 statistics alone can result in a false sense of confidence about the suitability of functional forms to describe yield response to N-fertilizer rate. Cerrato and Blackmer (1990) also noted that predicted maximum yields provide limited basis for selection of one functional form over the other. Cerrato and Blackmer (1990) generated a distribution of regression residuals for each model considered using the Kolmogorov test as proposed by Delong (1985). The Kolmogorov (K-S) test was used to eliminate functional forms with non-normal distribution of regression residuals.

The residual normality test was also used by Rajsic and Weersink (2008) (together with the coefficient of determination (R^2)) to select functional forms for grain corn yield response to N-fertlizer. Rajsic and Weersink (2008) used the Anderson-Darling (A-D) test (Stephens 1974) to identify which regression residuals were normally distributed. Rajsic and Weersink (2008) noted that regression residuals with non-normal distribution could lead to bias estimation.

4.4.4 Non-Nested Hypothesis Testing

Llewelyn and Featherstone (1997) compared five functional forms (i.e, quadratic, square root, linear von Liebig, Mitscherlich-Baule, and the nonlinear von Liebig) using a non-nested hypothesis test proposed by Davidson and McKinnon (1981). Llewelyn and Featherstone (1997) used the *J*-test and *P*-test procedures to compare various functional forms. The *J*-test can be used for pair-wise comparison of both linear and non-linear functional forms, while the *P*-test is preferred for non-linear functional forms. For both procedures, a pair-wise comparison of two or more functional forms is made, and a t-test is used to test the hypothesis that one functional form is a better predictor than the other(s).

Frank et al (1990) also compared three functional forms (quadratic, von Liebig and Mitscherlich-Baule). The authors also used various non-nested test statistics including the *J*-test, *P*-test, *N*-test derived from a likelihood ratio (Cox 1961, 1962; Pesaran 1974), and the adjusted *N*- and *W*-test which correct for small sample size. Frank et al (1990) noted that a *P*-test used to jointly compare more than two functional forms is more powerful than a pair-wise comparison with more than two competing hypotheses. When the analysis involves a considerable number of alternative functional forms to be estimated for several cropping systems, then the individual pair-wise comparisons increase several-fold, thereby increasing the time and effort required for the analysis

4.4.5 Point Ranking Method

Shaohua et al (1999) used a total point ranking method (with the residual sum of squares) to compare a quadratic model with three inverse yield functional forms. Specifically, Shaohua et al (1999) compared the differences (absolute values) between the predicted and observed yields of each crop at each nitrogen rate for four functional forms. The largest difference was scored 1 point, while the smallest difference was given a score of 4 points. Intermediate values were rated as 2 or 3. Shaohua et al (1999) then selected the functional form with the highest score (4 points) as the best specification for the crop yield response to fertilizer use. The point ranking method is quite similar to the analysis of the deviation from regression residuals (i.e., observed yields – predicted yields) as used by Cerrato and Blackmer (1990) and Alivelu et al (2003). In the deviation from regression graph, points above the horizontal line indicate that the model under-predicted yields, while points below the horizontal line indicate over-prediction by the model. It is assumed that when assessing the deviation from regression residuals for different functional forms or models, the model with more points ‘on’ the horizontal line or ‘very close’ to the horizontal line on both sides (and evenly distributed) provides the best fit.

4.4.6 Potential Misspecification Costs

Potential misspecification cost reflects the returns farmers will likely lose if input-output relationships are wrongly specified. With this method, the optimal input rate is obtained from the estimated functional forms. The optimal rates are then used to generate predicted optimum yields, which are in turn used in generating net returns from predicted yields for all functional forms estimated. It is assumed that the important cost incurred is the cost of fertilizer or manure and the application cost (e.g., Llewelyn and Featherstone 1997). The cost of misspecification reflects a decline in net return observed when the optimal levels of inputs from an incorrect functional form are used instead of the ‘true’ functional form (Llewelyn and Featherstone 1997). The functional form that gives the lowest cost of being used incorrectly is preferred.

Finger and Hediger (2008) assessed only the potential misspecification cost in comparing functional forms estimated for corn yield response to nitrogen and water use. On the other hand, in addition to assessing potential misspecification costs, Frank et al (1990) and Llewelyn and Featherstone (1997) also used the non-nested hypothesis testing methods to assess the best model for corn yield response to N fertilization and irrigation water used. Cerrato and Blackmer (1990) assessed the potential misspecification costs after assessing the coefficient of determination, and the residual distributions of response functions estimated for corn yield response to nitrogen fertilization.

In summary, more than one criterion is commonly used to assess functional forms. A summary of statistical criteria commonly used in comparison and assessment of functional forms in selected studies is presented in Table 4.3. In this study, normality of crop yields will not be considered since there is no consensus on its application. Also, the non-nested hypothesis testing methods will not be considered. The methods sections provide details of procedures used in estimating best fit functional forms.

4.5. Potential Uses and Applications of Response Functions

Response functions can be used to describe relationships in production processes (Heady and Dillon 1961). Crop yield and nutrient pollution production functions can also be used to identify important determinants in a production process, and magnitude of the importance of each factor (National Academy of Sciences 1961, Cubas et al 2010). Response functions allow for the identification of feasible combinations of inputs and outputs that maximize output for given levels of inputs (Moglen and McCuen 1990).

Estimating a response function for a particular crop at a given site can allow future prediction and economic decisions. Crowther and Yates (1941) used response functions to determine optimal level of fertilizer inputs and helped to reduce and standardize fertilizer application for field experiments in England during World War II. The initiative was prompted in part by a critical shortage of inputs during the war. A contemporary application of crop yield response functions still involves optimizing input use and efficiency (Day and Sparling 1977; Antle and Capalbo 2001; Little 2004; Murugesan et al 2007).

Response functions have been used in economic optimization analysis to simultaneously model economic and environmental problems (Yiridoe and Weersink1998). Thus, response function estimation can assist with multiple-objective economic decision making and environmental management. Economic and environmental

Table 4.3. Summary of statistical methods used in comparison and assessment of functional forms.

Statistical Methods	Study
Residual sun of Squares + Total point ranking	Shaohua et al (1999)
Coefficient of determination + Residual Distribution	Rajsic and Weersink (2008)
Non-nested hypothesis test + Potential misspecification costs	Frank et al (1990), Llewelyn and Featherstone (1997)
Coefficient of determination + Residual Distribution + Deviation from regression	Alivelu et al (2003)
Coefficient of determination + Residual Distribution + Deviation from regression + Potential misspecification costs	Cerrato and Blackmer (1990)

management decisions and objectives may involve optimizing economic and ecological objectives subject to various constraints (e.g., Moglen and McCuen 1990;Yiridoe and Weersink 1998; Mimoumi et al 2000).

Malkina-Pykh and Pykh (1998), and Malkina-Pykh (2002) noted that the relationship between the environment and ecosystem response structure can be described using response functions. In addition, by estimating response functions, the performance and growth patterns of crops under different management conditions, and the ecological and environmental impacts of each condition can be better understood (Shaohua et al 1999). Response functions can also help in decisions involving balancing crop production with sustainable environmental stewardship.

4.6. Methods

4.6.1 Study Area

Thomas Brooks Watershed (TBW) is located in the Annapolis Valley region of Nova Scotia, and it’s one of nine watersheds being studied under a national Watershed Evaluation of Beneficial Management Practices (WEBs) project. The Watershed Evaluation of BMPs (WEBs) project was first launched in 2004 to measure and validate the economic and water quality impacts of selected agricultural BMPs at seven watershed sites across Canada (Stuart et al 2010).

Agricultural land use covers the largest area (57%) of TBW. TBW is about 784 ha and is a sub-watershed in the larger 26, 000 ha Cornwallis Watershed. The study was conducted on a watershed basis because studies suggest that watershed-scale management has the potential to improve water quality and other environmental indicators while maintaining community economic viability (Born and Genskow 2001; Qui 2005).

4.6.2 Data

Crop and nitrate yield data were obtained using the Soil and Water Assessment Tool (SWAT) model simulations. The cropping systems simulated included two tillage systems, seven recommended Nutrient Management Plan (NMP) fertilizer/manure rates (kg) and five different crop rotation patterns (Table 4.4). The SWAT model was first calibrated and validated as part of a larger research study using field data. Cropping systems were simulated for 20 years, with the first five years considered as an initialization period. SWAT outputs were summarized, and crop yields generated on dry matter basis were adjusted for moisture content. For example, grain corn was assumed to be sold by farmers and therefore was adjusted to 15.5% moisture content (Avila-Segura et al 2011).

4.6.3 Statistical Analysis and Functional Form Estimation

In this study, functional forms were selected by initial visual screening. In addition, key biological, economic and statistical considerations including the coefficient of determination (R^2), and distributions of residuals response functions estimated (Cerrato

Table 4.4. Cropping systems studied.

Rotation systems	Cropping sequence[a]	Tillage system[b]	Fertilizer/manure rates (%) of recommended NMP [c]
Grain corn-based cropping system	CCAAA	CT	110% 100%, 90%, 75%, 50%, 25% and 0% of recommended NMP fertilizer/manure rates.
	CCAAA	NT	
	CCCAA	CT	
	CCCAA	NT	
Potato-based cropping system	PBW^{F}PC	CT	
	PBW^{F}PC	NT	
	PCBPC	CT	
	PCBPC	NT	
Vegetable-horticulture-based cropping system	PW^{F}RC	CT	
	PW^{F}RC	NT	

[a] Cropping sequence is denoted by: W^F = winter wheat feed, P=Potato, R=Carrot, C=Grain corn, B=Barley, A=Alfalfa.

[b] NT practice applies only to the grain crops (winter wheat and grain corn). Potatoes and Carrots were assumed to be managed under conventional tillage only, consistent with the in the study area.

[c] The various N fertilizer rates studied included 110% 100%, 90%, 75%, 50%, 25% and 0% of rates in nutrient management plans for the study region.

and Blackmer 1990) were used for selecting response functions. The point ranking method (Shaohua et al 1999) was also used.

All data were entered into Minitab® version 15 and initial box plots were generated. A visual inspection helped to eliminate mathematical functional forms that were not consistent with biological and crop growth processes. All mathematical functional forms were estimated using SAS version 9.2 and Minitab® version 15 statistical softwares. Non-linear functional forms were estimated using the Non-Linear regression (NLIN) procedure in SAS.

After finding the deviations from regression residuals (using total point ranking method (Shaohua et al 1999), normality of distribution of residuals were checked using both the A-D test and the K-S test. The A-D test for normality was a priority consideration, and if residuals were not normally distributed, the K-S test was used. The two alternative residual normality tests were selected for several reasons. First, the two are appropriate for small samples, although they can also be used for large samples. Second, they are in the commonly used literature (Stephens 1974; Chakravarti 1967).

The A-D test tends to be a stronger test than the K-S test, and also imposes more weight on the tails of the distribution than the K-S test (Stephens 1974; Chakravarti 1967). The two residual distribution tests were used to reduce the risk of having to transform the functional forms (Lalonde 2005). The assumption of normality holds when the null hypothesis is not rejected (i.e., $p \geq 0.05$).

If more than one response model had normal distribution of residuals, the next criterion assessed was the total point ranking, and then the R^2. Functional forms that predicted maximum nutrient N fertilizer rates and yields close to expected maximums (from simulated data and provincial average yields) were selected and then used to determine maximum economic rate of N (MERN) fertilization. The functional form with a realistic MERN is assumed to translate into optimal profits.

4.6.4 Estimation of MERN

The economic model to assess the effect of NMPs begins with a simple base model in which farms within a watershed are presented as multi-product production units, consistent with Baumol et al (1982). Each profit maximizing farmer is assumed to produce good outputs (i.e., crop yield) and bad outputs (i.e., nitrate leached). Outputs are influenced by choice of farm inputs used, and cropping system (e.g., Yiridoe and Weersink 1998; Romstad et al 2000; Wossink and Swinton 2007). It is also assumed that a production process using a unique cropping system to generate a positive output, Y, from crop r, is a function of a single variable input (X) (e.g., nitrogen fertilizer), and a set of production technology combinations (tillage (i) and rotation (k)) which can be termed as exogenous factors. Besides output, Y, crop r in a production process also generates nitrate-N leached into groundwater, denoted by V, which also depends exogenously on a set of technology choice (i, k).

Crop (r) yield from a technology combination (i, k) can be represented by a production function: $Y_{ik} = f(X)$, and its associated nitrate-N production function given by: $V_{ik} = h(X)$. Consistent with Chambers (1988), the crop production function is assumed to be twice continuously differentiable, with crop yield increasing at a decreasing rate with X. This implies that $f_X > 0$ and $f_{XX} \leq 0$.

4.6.4.1 Private decision problem

In the private decision problem, it is assumed that an individual farmer maximizes profit from production, and ignores negative externalities associated with crop production. The profit–maximizing problem of the farmer can therefore be represented as:

$$\underset{\{X\}}{\text{Max}}\ \pi = pY_{ik} - wX, \tag{4.12}$$

$$\text{where, } Y_{ik} = f(X), \tag{4.13}$$

where p is the unit price of output Y, and w is the unit cost of input X.

The profit maximizing problem can be reformulated as:

$$\underset{\{X\}}{\text{Max}}\ \pi = pf(X) - wX \tag{4.14}$$

The first order conditions imply that,

$$pf'(X) = w \tag{4.15}$$

or re-arranging,

$$f'(X) = \frac{w}{p} = X_{MERN} \tag{4.16}$$

From equation 4.15, the Maximum Economic Rate of Nitrogen (MERN) is obtained as a function of price of nitrogen fertilizer (w) and price of crop output (p) (Equation 4.17).

$$X_{\mathrm{MERN}} = f(w, p) \tag{4.17}$$

Substituting,

$$Y_{MERN_{(ik)}} = f(X_{MERN_{(ik)}}) \tag{4.18}$$

and maximum farm returns becomes;

$$\pi_{ik}^{*} = pf(X_{MERN_{ik}}) - wX_{MERN_{ik}} \tag{4.19}$$

Since Y is not only endogenously dependent on X but exogenously depends also on the agricultural technology combinations, X_{MERN} will exogenously depend on technology combinations and crop type. The associated bad output produced at MERN, $V_{MERN_{(ik)}}$ is also a function of X_{MERN} for a particular technology combination: ($V_{MERN_{(ik)}} = f(X_{MERN})$).

4.7 Results and Discussion

4.7.1 Evaluation of Crop Yield Response Functions Using Visual and Statistical Assessment criteria

Based on a visual assessment of predicted and observed yields, the Mitscherlich-Buale (M-B) model provided the best fit for most crops for all the cropping systems considered (e.g., Figure 4.2 to Figure 4.6). The graphs (e.g., Figures 4.2 to 4.6) also suggest that the total point ranking criterion could be very misleading if used alone. For example, comparing point ranks (where $\sum(Observed - Predicted)$ closest to zero is preferred) between the normal quadratic model, and the quadratic model with an intercept and only one co-efficient for grain corn response suggests that the quadratic model with an intercept and only one co-efficient best described corn yield response with normal

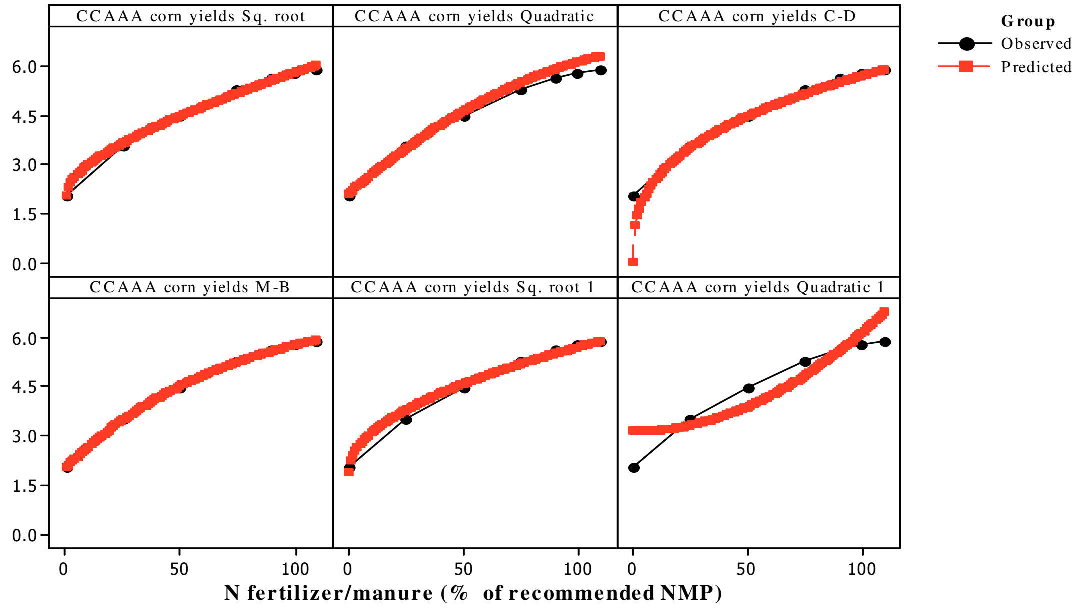


Figure 4.2: Scatter plots for alternative functional forms estimated for corn yield response to N fertilizer in CCAAA rotation under conventional tillage.

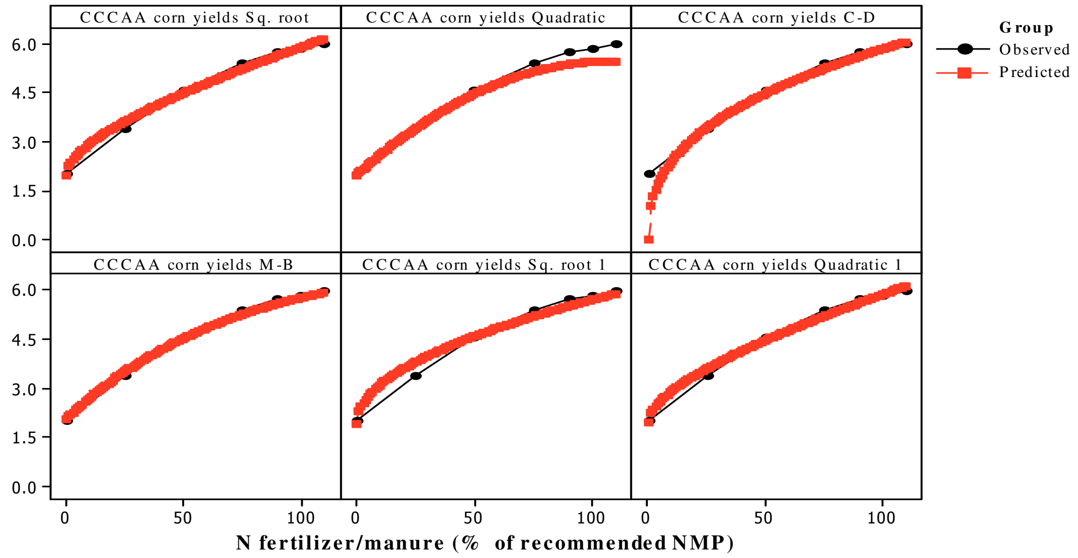


Figure 4.3: Scatter plots for alternative functional forms estimated for corn yield response to N fertilizer in CCCAA rotation under conventional tillage.

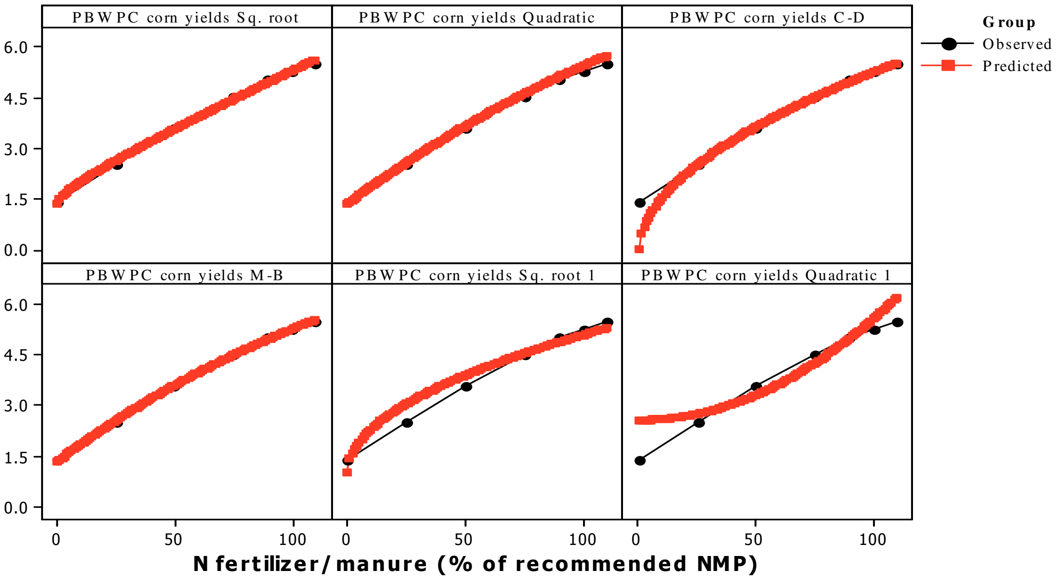


Figure 4.4: Scatter plots for alternative functional forms estimated for corn yield response to N fertilizer in PBWPC rotation under conventional tillage.

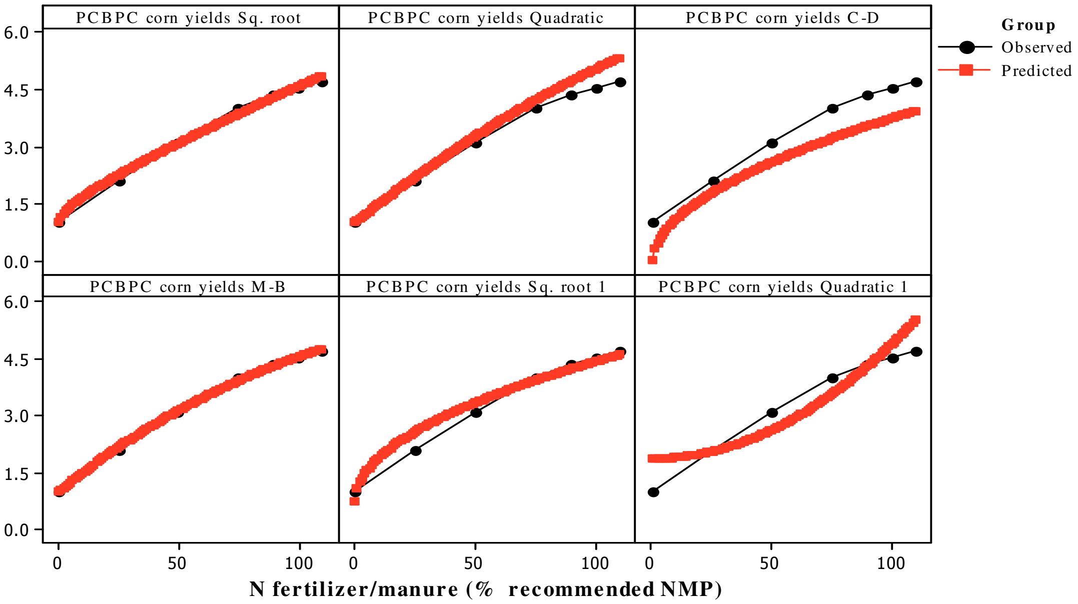


Figure 4.5: Scatter plots for alternative functional forms estimated for corn yield response to N fertilizer in PCBPC rotation under conventional tillage.

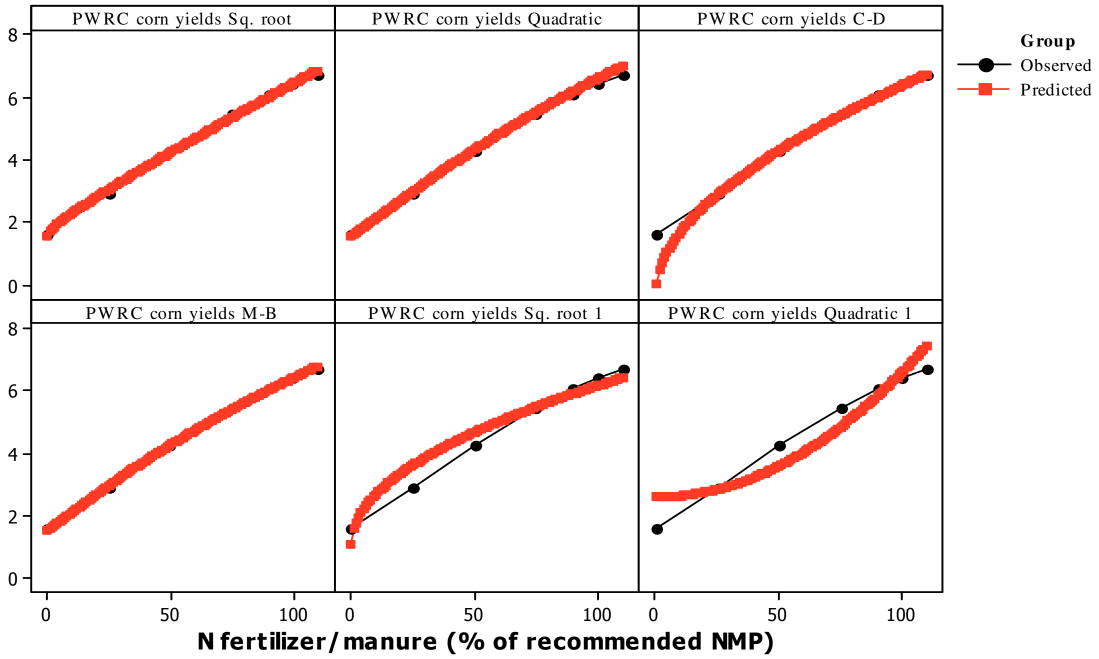


Figure 4.6: Scatter plots for alternative functional forms estimated for corn yield response to N fertilizer in PWRC rotation under conventional tillage.

distribution of residuals and best point ranks (Table 4.5). However visual assessment of observed and predicted plots suggests a different outcome (Figures 4.2 to 4.6).

In general, the M-B, square root and quadratic models tended to provide the best fit for grain corn, barley and winter wheat yields for most cropping systems (Table 4.6). The distribution of residuals for grain corn response to nutrient N in CCAAA, CCCAA and PWRC rotation, and for barley in PBWPC were non-normal based on the A-D test. The square root functional form generated normal distribution of residuals based on the K-S test for grain corn in PWRC (Table 4.6).

Alivelu et al (2003) noted that the M-B model was not preferred compared with the plateau models when normality of the distribution of residuals criterion was considered. A similar finding was observed in this study, in which the LPP functional form generated normally distributed residuals for carrots, potatoes and alfalfa. On the

Table 4.5. Comparison of functional forms estimated for corn yield response to nutrient N for alternative crop rotations under conventional tillage.

Rotation patterns	Functional forms							
	Square root with two coefficients				Quadratic with two coefficients			
	Equation	R^2 (%)	A-D test	$\sum(Observed - Predicted)$	Equation	R^2 (%)	A-D test	$\sum(Observed - Predicted)$
CCAAA	$Y = 2.024 + 6.071X + 6.269X^{0.5}$	71.4	p<0.005	-5.9E-14	$Y = 2.079 + 33.481X - 72.149X^2$	71.7	p<0.005	6.9E-14
CCCAA	$Y = 1.931 + 6.820X + 6.395X^{0.5}$	77.0	p<0.005	7.6E-14	$Y = 1.957 + 35.951X - 79.427X^2$	77.8	p<0.005	3.0E-14
PBWPC	$Y = 1.356 + 15.299X + 2.763X^{0.5}$	95.9	p>0.250	4.4E-16	$Y = 1.359 + 28.213X - 35.945X^2$	96.1	p>0.250	2.7E-15
PCBPC	$Y = 1.005 + 11.988X + 3.318X^{0.5}$	27.5	p=0.090	6.2E-15	$Y = 0.995 + 28X - 45.669X^2$	27.7	p=0.086	7.9E-14
PWRC	$Y = 1.547 + 21.073X + 2.567X^{0.5}$	92.2	p=0.012	-8.2E-15	$Y = 1.534 + 33.719X - 36.617X^2$	92.4	p=0.008	2.3E-14
	Cobb Douglas (C-D)				Mitscherlish Baule (M-B)			
CCAAA	$Y = 225.045X^{0.358}$	55.4	p<0.005	125.5	$Y = 7.027(1 - exp^{(-7.607(X+0.045))})$	71.7	p<0.005	9.5E-8
CCCAA	$Y = 272.684X^{0.395}$	67.3	p<0.005	189.3	$Y = 7.172(1 - exp^{(-7.658(X+0.041))})$	77.7	p<0.005	3.2E-7
PBWPC	$Y = 370.237X^{0.527}$	95.2	p>0.250	35.8	$Y = 10.043(1 - exp^{(-3.329(X+0.044))})$	96.1	p>0.250	4.4E-7
PCBPC	$Y = 174.385X^{0.532}$	15.7	p<0.005	97.1	$Y = 7.332(1 - exp^{(-4.585(X+0.032))})$	27.7	p=0.087	1.0E-5
PWRC	$Y = 693.314X^{0.573}$	89.6	p<0.005	68.1	$Y = 14.318(1 - exp^{(-2.673(X+0.042))})$	92.4	p=0.009	2.6E-7
	Square root with only one coefficient				Quadratic with only one coefficient			
CCAAA	$Y = 1.887 + 8.997X^{0.5}$	70.2	p<0.005	-8.2E-14	$Y = 3.145 + 83.6184X^2$	57.7	p>0.250	-1.5E-14
CCCAA	$Y = 1.778 + 9.459X^{0.5}$	76.4	p<0.005	-3.4E-14	$Y = 3.102 + 87.831X^2$	62.0	p>0.250	5.8E-14
PBWPC	$Y = 1.014 + 9.638X^{0.5}$	92.2	p=0.098	3.5E-15	$Y = 2.258 + 95.313X^2$	84.9	P=0.169	2.7E-15
PCBPC	$Y = 0.736 + 8.706X^{0.5}$	26.7	p=0.021	-6.9E-14	$Y = 1.887 + 84.6X^2$	23.7	P=0.043	3.1E-15
PWRC	$Y = 1.076 + 12.037X^{0.5}$	87.9	p=0.017	0	$Y = 2.607 + 120.26X^2$	82.6	P>0.250	2.7E-15

Table 4.6. Selected crop yield response functions for alternative cropping systems using statistical criteria.

	Cropping System			Estimated Production Function Coefficients and Parameters[a]			Assessment Criteria		
Crop yield Production Function	Crop	Tillage	Rotation	(Intercept) (a)	(N-fertilizer (X)) (b)	(N^2) $(N^{0.5})$ (N^a) (c) (Plateau point)	A-D / K-S[b] test for normality	R^2 (%)	$\lvert\sum$(observed - predicted)$\rvert$
M-B	Corn	CT	PBWPC	10.043 (4.340)	3.329 (2.295)	0.043 (0.016)	p>0.25	96.1	4.4E-7
M-B		CT	PCBPC	7.332 (8.41)	4.585 (9.903)	0.032 (0.052)	p=0.09	27.7	1.0E-5
Square root		CT	PWRC	1.557 (0.323)	21.073 (6.635)	2.568 (3.099)	p=0.05[b]	92.2	-8.2E-15
M-B		NT	PBWPC	9.874 (4.058)	3.453 (2.298)	0.043 (0.016)	p>0.25	96.1	1.0E-7
M-B		NT	PCBPC	7.425 (9.149)	4.506 (9.857)	0.032 (0.052)	p=0.08	27.8	2.5E-6
Square root		NT	PWRC	1.553 (0.320)	21.248 (6.574)	2.586 (3.070)	p=0.05[b]	92.5	4.0E-15
M-B		CT	PCBPC	2.773 (0.563)	19.142 (14.198)	0.022 (0.016)	p>0.25	64.6	1.4E-6
M-B		NT	PCBPC	2.833 (0.629)	18.0965 (13.920)	0.0228 (0.017)	p>0.25	78.7	2.7E-9
M-B	Winter wheat	CT	PBWPC	2.894 (0.220)	13.514 (5.007)	0.060 (0.018)	p=0.10[b]	86.7	8.3E-7
M-B		NT	PBWPC	2.948 (0.233)	13.438 (5.070)	0.059(0.018)	p=0.10[b]	86.4	9.7E-7
LPP	Potato	CT	PBWPC	8.344 (2.101)	0.267 (0.119)	$Y = 17.41\ if\ N \geq 51kgN$	p>0.25	38.6	1.1E-14
LPP		CT	PCBPC	7.730 (1.789)	0.259 (0.101)	$Y = 16.01\ if\ N \geq 48kgN$	p=0.04	39.5	1.8E-15
LPP		CT	PWRC	9.976 (4.072)	0.279 (0.230)	$Y = 18.35\ if\ N \geq 45kgN$	p>0.25	26.9	5.3E-15
LPP		NT	PBWPC	8.394 (2.104)	0.266 (0.119)	$Y = 17.42\ if\ N \geq 51kgN$	p>0.25	38.4	1.7E-14
LPP		NT	PCBPC	7.770 (1.789)	0.258 (0.101)	$Y = 16.03\ if\ N \geq 48kgN$	p=0.04	39.4	1.6E-14
LPP		NT	PWRC	11.010 (3.654)	0.235 (0.207)	$Y = 18.52\ if\ N \geq 41kgN$	p>0.25	24.4	1.1E-14
LPP	Alfalfa	CT	CCAAA	11.976 (0.941)	0.015 (0.053)	$Y = 12.410\ if\ N \geq 13kgN$	p=0.17	0.5	5.3 E-15
LPP		CT	CCCAA	11.846 (1.008)	0.015 (0.057)	$Y = 12.290\ if\ N \geq 13kgN$	p>0.25	0.7	1.2 E-14
LPP		NT	CCAAA	12.279 (0.945)	0.006 (0.053)	$Y = 12.430\ if\ N \geq 10kgN$	p=0.18	0.1	7.1E-15
LPP		NT	CCCAA	12.250 (1.017)	0.003 (0.058)	$Y = 12.34\ if\ N \geq 14kgN$	p>0.25	0.1	3.7E-14
LPP	Carrot	NT	PWRC	21.248 (2.539)	0.158 (0.144)	$Y = 25.522\ if\ N \geq 18kgN$	p>0.25	23.3	1.8 E-14
LPP		CT	PWRC	21.152 (2.566)	0.161 (0.145)	$Y = 12.290\ if\ N \geq 20kgN$	p>0.25	23.4	3.6E-14

[a] Figures in parentheses are standard errors of coefficients.

[b] Residuals were normally distributed based on the Kolmogorov-Smirnov (K-S) test (Chakravart, Laha, and Roy, 1967).

Notation: A-D = Anderson-Darling test (Stephens, 1974); CT = conventional tillage; NT = no-till; MB = Mitscherlich-Baule functional form; LPP = Linear Plus Plateau functional form; PBWPC = Potato-Corn-Winter wheat- Potato-Corn rotation; PCBPC= Potato-Corn-Barley-Potato-Corn rotation; PWRC=Potato-Winter wheat-Carrot-Corn rotation; CCAAA = Corn-Corn-Alfalfa-Alfalfa-Alfalfa rotation; CCCAA = Corn-Corn-Corn-Alfalfa-Alfalfa rotation.

other hand, the LPP model is not consistent with biological growth (and micro-economic) characteristics.

Further analysis involving a power transformation (λ = -1) of crop yields suggest that the quadratic model provided the best fit for grain corn response in CCCAA and PWRC rotations , while the square root model provided the best fit for barley in PBWRC rotation (Table 4.7). In addition, the quadratic model provided best fit for corn in CCAAA rotation, and winter wheat in PBWPC rotation when a power transformation (λ = 2) was applied to the crop yields to obtain normality of residuals based on the A-D test (Table 4.7). Residuals of winter wheat response to nutrient N in PWRC were not normally distributed regardless of the model fitted and power transformations (λ = -2 to 2) applied to winter wheat yields (Table 4.7).

4.7.2 Evaluation of Crop Yield Response Functions Using Biological and Economic Assessment Criteria

The initial visual and econometric assessment of the crop yield response functions helped narrow down the choice sets. The biological or crop growth characteristics and micro-economic criteria were used to further refine the choice set of crop yield response models. The final choice of mathematical model was determined using crop growth or biological characteristics and applied micro-economic considerations.

Average input and output prices for 2010 cropping season were used in this study. N fertilizer cost data were obtained from Agro-Mart Group, a farm input retailer in Truro, Nova Scotia. In addition, farm-gate prices for crop outputs were obtained from Co-op Atlantic Canada (for grain crops) and Nova Scotia Department of Agriculture (for potato, carrot and alfalfa hay) (Table 4.8).

Table 4.7. Selected crop yield response functions for alternative cropping systems with transformations to achieve normality of residuals.

Crop yield Production Function	Cropping System			Power transformation of crop yields (λ)	Estimated Production Function Coefficients and Parameters[a]			Assessment Criteria		
	Crop	Tillage	Rotation[b]		(Intercept) (a)	(N-fertilizer) (b)	(N^2) ($N^{0.5}$)(N^a) (c) (Plateau point)	A-D test for normality	R^2 (%)	Point ranking |∑(observed - predicted)|
Quadratic	Corn	CT	CCCAA	-1	0.504 (0.014)	-4.296 (0.327)	13.674 (1.577)	p=0.20	91.3	2.4E-13
		NT	CCCAA	-1	0.490 (0.012)	-0.007 (0.000)	0.00004 (0.000)	p=0.38	91.0	1.4E-14
		CT	CCAAA	-2	0.196 (0.011)	-0.004 (0.00041)	0.000024 (0.000)	p=0.08	84.1	4.5E-15
		NT	CCAAA	-2	0.195 (0.011)	-0.004 (0.00043)	0.000024 (0.000)	p=0.17	83.1	3.8E-15
		CT	PWRC	-1	0.614 (0.022)	-5.816 (0.521)	18.113 (2.511)	p=0.50	94.7	9.5E-14
		NT	PWRC	-1	0.614 (0.022)	-0.0105 (0.001)	0.000059 (0.000)	p=0.49	94.7	3.3E-15
Square root	Barley	CT	PBWPC	-1	1.072 (0.049)	3.608 (1.976)	-3.301 (0.660)	p=0.13	89.0	30.97
		NT	PBWPC	-1	1.069 (0.048)	3.551 (1.942)	-3.279 (0.649)	p=0.10	89.3	31.13
Quadratic	Winter wheat	CT	PBWPC	2	2.605 (0.351)	55.578 (13.043)	-156.798 (99.099)	p=0.07	82.4	90.189
		NT	PBWPC	2	2.634 (0.373)	57.647 (13.865)	-160.052 (105.351)	p=0.07	81.9	93.715
M-B		CT	PWRC[b]		3.772 (0.884)	9.589 (7.733)	0.070 (0.039)	P<0.01	61.8	5.7E-9
M-B		NT	PWRC[b]		3.888 (1.010)	9.084 (7.742)	0.071 (0.041)	P<0.01	61.6	0.0001

[a] Figures in parentheses are standard errors of coefficients.

[b] Residuals were non-normally distributed regardless of power transformation (λ =2 to -2).

Notation: A-D = Anderson-Darling test (Stephens, 1974); CT = conventional tillage; NT = no-till; PBWPC = Potato-Corn-Winter wheat- Potato-Corn rotation; PWRC=Potato-Winter wheat-Carrot-Corn rotation; CCAAA = Corn-Corn-Alfalfa-Alfalfa-Alfalfa rotation; CCCAA = Corn-Corn-Corn-Alfalfa-Alfalfa rotation.

Table 4.8. Prices and price ratios used for determining MERN.

Crop	Fertilizer (N-P-K)	Fertilizer/Manure Prices [a] (\$tonnes^{-1})	Crop Prices (\$tonnes^{-1})[b]	Price Ratios (PN/PY)
Corn	34-00-00	480	230	2.87
	Dairy Fresh Manure	181		
Barley	17-17-17	609	175	4.51
	Dairy Fresh Manure	181		
Winter wheat	Dairy Fresh Manure	181	227	0.80
Potato	15-15-15	560	630	0.89
Alfalfa	10-10-30	581	114.24	10.16
	08-00-45	580		
Carrot	15-15-15	560	776.91	0.72

a: Fertilizer prices were obtained from Agromart group in Truro Nova Scotia.
b: Crop prices denotes farm gate crop output prices and were obtained from Co-op Atlantic Canada (grain crops) and Nova Scotia Department of Agriculture (potato, carrot and alfalfa hay).

Crop response models finally selected by considering all three model assessment criteria are presented in Table 4.9. Based on the biological and economic criteria, the quadratic model provided the best fit best for grain corn, barley and winter wheat (Table 4.9). However, in the initial visual and statistical assessment (for e.g., see Figures 4.2 to 4.6 and Table 4.5 for grain corn), the M-B model was mostly chosen preferred to the quadratic model estimated for some grain crops (e.g., grain corn in PBWPC and PCBPC) (Table 4.5). The square root and the M-B models selected based on visual and statistical assessment criteria did not generate expected maximum nutrient N fertilizer levels and, therefore, farm profits. In addition, the M-B model tends to predict very high maximum N fertilizer levels but very low MERN compared with the quadratic model, consistent with Alivelu et al (2007), and Llewelyn and Featherstone (1997).

The LPP model is not consistent with growth characteristics for potatoes, carrots and alfalfa, although residuals were normally distributed. On the other hand, the M-B model tends to accommodate plateau characteristics (Frank et al 1990; Llewelyn and

Table 4.9. Selected crop yield response models.

Crop yield Production Function	Cropping Systems		No-Till				Conventional Tillage			
			Parameter estimates[a]			MERN (kg ha^{-1})	Parameter estimates			MERN (kg ha^{-1})
	Crop	Rotation	(Intercept) (a)	(N-fertilizer) (b)	(N2) (N0.5) (c)		(Intercept) (a)	(N-fertilizer) (b)	(N2) (N0.5) (c)	
Quadratic	Corn	CCAAA	2.095 (0.328)	32.773 (7.737)	-68.690 (37.229)	217.63	2.079 (0.324)	33.481 (7.631)	-71.149 (36.722)	212.11
		CCCAA	1.959 (0.234)	34.457 (5.500)	-71.444 (26.469)	221.03	1.957 (0.235)	35.951 (5.522)	-79.427 (26.571)	208.22
		PBWPC	1.366 (0.213)	28.610 (5.011)	-37.414 (24.114)	343.90	1.359 (0.212)	28.213 (4.983)	-35.944 (23.977)	352.47
		PCBPC	0.997 (0.817)	27.933 (19.207)	-44.983 (92.424)	278.54	0.995 (0.817)	28.000 (19.216)	-45.669 (92.471)	275.09
		PWRC	1.541 (0.294)	33.915 (6.922)	-36.533 (33.308)	424.84	1.534 (0.297)	33.720 (6.985)	-36.617 (33.610)	421.19
Quadratic	Barley	PBWPC	0.933 (0.166)	29.108 (7.634)	-131.474 (71.874)	93.53	0.935 (0.167)	28.991 (7.685)	-129.070 (72.353)	94.82
		PCBPC	0.975 (0.224)	29.410 (10.321)	-143.926 (97.172)	86.49	0.968 (0.226)	29.302 (10.400)	-140.080 (97.920)	88.48
Quadratic	Winter wheat	PBWPC	1.620 (0.069)	14.755 (2.557)	-52.350 (19.427)	133.31	1.629 (0.072)	15.189 (2.677)	-53.651 (20.337)	134.12
		PWRC	1.843 (0.142)	16.992 (5.2780)	-50.393 (40.116)	160.68	1.859 (0.146)	17.061 (5.421)	-49.035 (41.193)	165.83
MB	Potato	PBWPC	17.498 (1.265)	35.760 (28.902)	0.018 (0.017)	137.10	17.517 (1.267)	35.679 (28.915)	0.0183 (0.017)	137.22
		PCBPC	16.124 (0.985)	40.028 (30.155)	0.016 (0.014)	123.13	16.144 (0.983)	40.039 (30.215)	0.016 (0.014)	123.03
		PWRC	18.461 (2.064)	46.586 (83.794)	0.017 (0.032)	109.26	18.5642 (2.122)	40.7954 (74.807)	0.022 (0.043)	118.72
MB	Alfalfa	CCAAA	12.397 (0.433)	220.10 (2336.1)	0.015 (0.162)	0.00	12.432 (0.419)	284.300 (12473.8)	0.060 (0.676)	0.00
		CCCAA	12.288 (0.461)	193.30 (1759.0)	0.017 (0.156)	0.00	12.340 (0.556)	116.400 (3901.3)	0.042 (1.409)	0.00
MB	Carrot	PWRC	25.439 (1.146)	161.300 (586.8)	0.011 (0.040)	36.11	25.5074 (1.148)	154.2 (522.6)	0.0116 (0.039)	37.40

[a] Figures in parentheses are standard errors of coefficients.

Featherstone 1997) and consistent with the crop growth (biological and economic) characteristics of these crops (potatoes, carrots and alfalfa). Based on the biological and economic assessment criteria used, the M-B model was preferred to the LPP model for potatoes, carrots and alfalfa (Table 4.9).

Results of the estimated MERNs suggest that farmers tend to over apply nutrient N to alfalfa, carrots and potatoes for all the cropping systems, as the NMP recommended N rates were higher than MERN (Table 4.9). On the other hand, farmers tended to under apply nutrient N to grain corn, barley in PWBPC rotations and winter wheat. Although extension specialists in the study area recommend some amount of nutrient N to alfalfa, economic assessment of MERN suggests that it is economically unprofitable to apply any amount of nutrient N to alfalfa. This finding is consistent with observed practice among farmers in the study area. The MERN also depended on both rotation system (preceding crop(s)) and tillage type (Table 4.9).

4.7.3 Evaluation of Nitrate-N Leaching Response Functions Using Visual and Statistical Assessment Criteria

$NO_3^-{-}N$ leaching response to nutrient N from alfalfa fields in all alfalfa rotations, barley fields in PCBPC rotation and carrot fields in PWRC rotation were best predicted by the quadratic model for both tillage systems (Table 4.10). $NO_3^-{-}N$ leaching response to nutrient N from grain corn fields in CCCAA rotation was best described by the linear model, based on the K-S test for normality of the distribution of residuals (Table 4.10). None of the residual distributions were normal for $NO_3^-{-}N$ leaching response to nutrient N from winter wheat fields in PBWPC under NT management, regardless of the models fitted. Consistent with Fox et al (2001) $NO_3^-{-}N$ leaching response to nutrient N from barley fields in PBWPC was best described by the linear model (Table 4.10).

Table 4.10. Comparison of some selected nitrate-N leaching response functions for alternative cropping systems

Production Function	Cropping System			Estimated Production Function Coefficients and Parameters[a]			Assessment Criteria		
	Crop	Tillage	Rotation	(Intercept) (α)	(N-fertilizer) (β)	(γ^2) ($\gamma^{0.5}$) (γ)	A-D / K-S[b]	R^2 (%)	|∑(observed-predicted)|
Linear	Corn	CT	CCCAA	15.541 (4.651)	0.430 (0.062)		p=0.11[b]	43.8	4.8E-13
Quadratic		CT	PBWPC	14.907 (5.527)	114.047 (129.979)	496.609 (625.472)	p=0.13	79.3	6.8E-14
Quadratic		CT	PCBPC	20.227 (9.369)	191.409 (220.348)	887.139 (1060.335)	p>0.25	52.9	3.8E-13
Quadratic		CT	PWRC	13.398 (0.789)	118.613 (18.566)	226.359 (89.343)	p=0.10	98.5	1.4E-13
Linear		NT	CCCAA	17.046 (4.640)	0.477 (0.062)		p=0.14[b]	50.0	7.5E-13
Quadratic		NT	PBWPC	15.019 (5.413)	118.556 (127.295)	528.429 (612.556)	p=0.11	81.5	5.7E-14
Quadratic		NT	PCBPC	20.266 (9.505)	201.423 (223.542)	889.538 (1075.704)	p>0.25	53.6	1.5E-13
Quadratic		NT	PWRC	13.883 (0.550)	150.224 (12.946)	260.677 (62.299)	p>0.25	99.5	1.2E-13
Linear	Barley	CT	PBWPC	19.573 (4.991)	694.232 (72.727)		p=0.07	82.8	4.2E-13
Linear		NT	PBWPC	20.113 (4.807)	702.087 (70.051)		p=0.10	84.0	1.1E-14
Quadratic	Winter wheat	CT	PBWPC	21.135 (3.832)	223.099 (142.299)	798.868 (1081.193)	p=0.14	97.2	7.9E-13
Quadratic		CT	PWRC	21.574 (7.192)	196.065 (267.084)	1348.585 (2029.315)	p>0.25	43.0	2.5E-14
Quadratic		NT	PWRC	23.841 (7.190)	138.758 (267.014)	1685.841 (2028.785)	p>0.25	41.4	1.3E-13
Quadratic	Potato	CT	PBWPC	18.144 (4.237)	233.523 (119.573)	2729.248 (690.474)	p>0.25	94.3	5.3E-13
Quadratic		CT	PCBPC	21.330 (5.623)	298.577 (158.707)	2716.958 (916.457)	p>0.25	90.1	3.3E-13
Quadratic		CT	PWRC	18.553 (2.320)	265.008 (265.008)	265.008 (378.075)	p>0.25	99.1	4.2E-13
Quadratic		NT	PBWPC	18.229 (4.291)	236.273 (236.273)	2732.148 (699.233)	p>0.25	94.2	4.4E-13
Quadratic		NT	PCBPC	21.578 (5.571)	302.499 (157.228)	2719.349 (907.916)	p>0.25	90.3	8.5E-14
Quadratic		NT	PWRC	22.731 (2.534)	184.887 (71.502)	3070.938 (412.892)	p=0.21	98.8	2.9E-13

[a] Figures in parentheses are standard errors of coefficients.

[b] Residuals were normally distributed based on the Kolmogorov-Smirnov (K-S) test (Chakravart, Laha, and Roy, 1967).

Notation: A-D = Anderson-Darling test (Stephens, 1974); CT = conventional tillage; NT = no-till; MB = Mitscherlich-Baule functional form; LPP = Linear Plus Plateau functional form; PBWPC = Potato-Corn-Winter wheat- Potato-Corn rotation; PCBPC= Potato-Corn-Barley-Potato-Corn rotation; PWRC=Potato-Winter wheat-Carrot-Corn rotation; CCAAA = Corn-Corn-Alfalfa-Alfalfa-Alfalfa rotation; CCCAA = Corn-Corn-Corn-Alfalfa-Alfalfa rotation.

For models tested that had non-normal distribution of residuals, a power transformation of λ = -2 to 2 was applied to $NO_3^- -N$ leaching yields. The inverse quadratic model was the best fit functional form. $NO_3^- -N$ leaching response to nutrient N from carrot fields was best described by the inverse square root functional form. Residuals for $NO_3^- -N$ leaching from corn fields in CCAAA under CT, and alfalfa fields in CCAAA under both NT and CT systems were non-normal regardless of models fitted or power transformation (λ =2 to -2) applied (Table 4.11). The nitrate-N pollution response functions finally selected based on statistical assessment criteria are presented in Table 4.12.

A further analysis in this study involved estimating marginal abatement cost (MAC) functions reflecting of loss in farm returns from reducing nitrate leachate using the response functions estimated in this chapter. Theoretical considerations suggest that MAC functions should be twice continuously differentiable. Based on the assumption on twice differentiability of the MAC functions, the quadratic model was selected to replace of linear models initially selected based on the statistical assessment criteria for grain corn in CCCAA under CT and barley in PBWPC under both CT and NT (Table 4.12 and Table 4.13).

It was observed that transformations tend to complicate further analysis, consistent with Lalonde (2005). The use of inverse quadratic and square root models selected for the estimation the MACs was not possible because they resulted in non-closed form expressions for the MAC functions developed and hence could not be analytically expressed into a finite number. Thus, the quadratic functional forms were

Table 4.11. Selected nitrate-N leaching response functions for alternative cropping systems with transformations to achieve normality of residuals

Crop yield Production Function	Cropping System			Power transformation of nitrate yields (λ)	Estimated Production Function Coefficients and Parameters[a]			Assessment Criteria		
	Crop	Tillage	Rotation[b]		(Intercept) (α)	(N-fertilizer) (β)	(γ^2) ($\gamma^{0.5}$) (γ)	A-D test	R^2 (%)	|∑(observed-predicted)|
Quadratic	Corn	CT	CCAAA[b]		18.818 (3.617)	73.321 (85.089)	317.144 (409.459)	P<0.01	50.8	2.5E-13
		CT	CCCAA[b]		19.086 (5.761)	5.761 (0.005)	0.08753 (0.024)	p=0.01	44.8	7.2E-13
		NT	CCAAA	-1	0.053 (0.002)	102.531 (135.493)	679.204 (652.009)	p=0.59	76.1	8.8E-16
		NT	CCCAA	-1	0.053 (0.002)	-0.342 (0.055)	0.817 (0.269)	p=0.14	73.3	2.0 E-15
Quadratic	Alfalfa	CT	CCAAA[b]		36.483 (5.429)	520.247 (547.210)	1820.792 (11285)	p<0.01	23.9	1.6E-13
		CT	CCCAA	-1	0.032 (0.001)	-0.561 (0.153)	12592 (13285)	p=0.06	76.9	3.7E-16
		NT	CCAAA[b]		37.651 (5.964)	472.498 (601.167)	3.907 (3.167)	p<0.01	23.9	1.6E-13
		NT	CCCAA	-1	0.031 (0.001)	-0.582 (0.128)	4.504 (2.659)	p=0.12	70.8	5.6E-16
Quadratic	Barley	CT	PCBPC	-1	0.035 (0.001)	-0.493 (0.065)	2.460 (0.612)	p=0.09	92.6	6.8E-17
		NT	PCBPC	-1	0.035 (0.001)	-0.502 (0.065)	2.551 (0.616)	p=0.11	92.6	2.3E-16
Quadratic	Winter wheat	NT	PBWPC[b]		21.177 (3.881)	236.959 (144.104)	790.029 (1094.910)	p<0.01	77.2	1.7E-13
Square root	Carrot	CT	PWRC	-1	0.045 (0.003)	0.014 (0.163)	-0.131 (0.047)	p=0.07	84.6	2.9E-16
Square root		NT	PWRC	-1	0.045 (0.003)	0.016 (0.163)	-0.131 (0.047)	p=0.06	84.6	4.9E-17

[a] Figures in parentheses are standard errors of coefficients.

[b] Residuals were non-normally distributed irrespective of power transformation (λ =2 to -2).

Notation: A-D = Anderson-Darling test (Stephens, 1974); CT = conventional tillage; NT = no-till; PBWPC = Potato-Corn-Winter wheat- Potato-Corn rotation; PWRC=Potato-Winter wheat-Carrot-Corn rotation; CCAAA = Corn-Corn-Alfalfa-Alfalfa-Alfalfa rotation; CCCAA = Corn-Corn-Corn-Alfalfa-Alfalfa rotation.

Table 4.12. Nitrate-N leached functional forms selected based on statistical assessment criteria

Crop	Cropping System			Estimated Production Function Coefficients and Parameters[a]			Assessment Criteria		
	Production Function	Tillage	Rotation	(Intercept) (α)	(N-fertilizer) (β)	(γ^2) ($\gamma^{0.5}$) (γ)	A-D / K-S[b]	R^2 (%)	|∑(observed-predicted)|
Corn	Quadratic	CT	CCAAA	18.818 (3.617)	73.321 (85.089)	317.144 (409.459)	P<0.01	50.8	2.5E-13
	Linear	CT	CCCAA	15.541 (4.651)	0.430 (0.062)		p=0.11[b]	43.8	4.8E-13
	Quadratic	CT	PBWPC	14.907 (5.527)	114.047 (129.979)	496.609 (625.472)	p=0.13	79.3	6.8E-14
	Quadratic	CT	PCBPC	20.227 (9.369)	191.409 (220.348)	887.139 (1060.335)	p>0.25	52.9	3.8E-13
	Quadratic	CT	PWRC	13.398 (0.789)	118.613 (18.566)	226.359 (89.343)	p=0.10	98.5	1.4E-13
	Inverse quadratic	NT	CCAAA	0.053 (0.002)	102.531 (135.493)	679.204 (652.009)	p=0.59	76.1	8.8E-16
	Inverse quadratic	NT	CCCAA	0.053 (0.002)	-0.342 (0.055)	0.817 (0.269)	p=0.14	73.3	2.0 E-15
	Quadratic	NT	PBWPC	15.019 (5.413)	118.556 (127.295)	528.429 (612.556)	p=0.11	81.5	5.7E-14
	Quadratic	NT	PCBPC	20.266 (9.505)	201.423 (223.542)	889.538 (1075.704)	p>0.25	53.6	1.5E-13
	Quadratic	NT	PWRC	13.883 (0.550)	150.224 (12.946)	260.677 (62.299)	p>0.25	99.5	1.2E-13
Barley	Linear	CT	PBWPC	19.573 (4.991)	694.232 (72.727)		p=0.07	82.8	4.2E-13
	Inverse quadratic	CT	PCBPC	0.035 (0.001)	-0.493 (0.065)	2.460 (0.612)	p=0.09	92.6	6.8E-17
	Linear	NT	PBWPC	20.113 (4.807)	702.087 (70.051)		p=0.10	84.0	1.1E-14
	Inverse quadratic	NT	PCBPC	0.035 (0.001)	-0.502 (0.065)	2.551 (0.616)	p=0.11	92.6	2.3E-16
Winter wheat	Quadratic	CT	PBWPC	21.135 (3.832)	223.099 (142.299)	798.868 (1081.193)	p=0.14	97.2	7.9E-13
	Quadratic	CT	PWRC	21.574 (7.192)	196.065 (267.084)	1348.585 (2029.315)	p>0.25	43.0	2.5E-14
	Quadratic	NT	PBWPC	21.177 (3.881)	236.959 (144.104)	790.029 (1094.910)	p<0.01	77.2	1.7E-13
	Quadratic	NT	PWRC	23.841 (7.190)	138.758 (267.014)	1685.841 (2028.785)	p>0.25	41.4	1.3E-13
Potato	Quadratic	CT	PBWPC	18.144 (4.237)	233.523 (119.573)	2729.248 (690.474)	p>0.25	94.3	5.3E-13
	Quadratic	CT	PCBPC	21.330 (5.623)	298.577 (158.707)	2716.958 (916.457)	p>0.25	90.1	3.3E-13
	Quadratic	CT	PWRC	18.553 (2.320)	265.008 (265.008)	265.008 (378.075)	p>0.25	99.1	4.2E-13
	Quadratic	NT	PBWPC	18.229 (4.291)	236.273 (236.273)	2732.148 (699.233)	p>0.25	94.2	4.4E-13
	Quadratic	NT	PCBPC	21.578 (5.571)	302.499 (157.228)	2719.349 (907.916)	p>0.25	90.3	8.5E-14
	Quadratic	NT	PWRC	22.731 (2.534)	184.887 (71.502)	3070.938 (412.892)	p=0.21	98.8	2.9E-13
Alfalfa	Quadratic	CT	CCAAA	36.483 (5.429)	520.247 (547.210)	1820.792 (11285)	p<0.01	23.9	1.6E-13
	Inverse quadratic	CT	CCCAA	0.032 (0.001)	-0.561 (0.153)	12592 (13285)	p=0.06	76.9	3.7E-16
	Quadratic	NT	CCAAA	37.651 (5.964)	472.498 (601.167)	3.907 (3.167)	p<0.01	23.9	1.6E-13
	Inverse quadratic	NT	CCCAA	0.031 (0.001)	-0.582 (0.128)	4.504 (2.659)	p=0.12	70.8	5.6E-16
Carrot	Inverse square root	CT	PWRC	0.045 (0.003)	0.014 (0.163)	-0.131 (0.047)	p=0.07	84.6	2.9E-16
	Inverse square root	NT	PWRC	0.045 (0.003)	0.016 (0.163)	-0.131 (0.047)	p=0.06	84.6	4.9E-17

[a] Figures in parentheses are standard errors of coefficients.

[b] Residuals were normally distributed based on the Kolmogorov-Smirnov (K-S) test (Chakravart, Laha, and Roy, 1967).

Table 4.13. **Mathematical functional forms selected to replace models that were non-closed-form expression and those that were not twice continuously differentiable models for nitrate-N leached**

	Cropping System			Estimated Production Function Coefficients and Parameters[a]			Assessment Criteria		
Production Function	Crop	Tillage	Rotation	(Intercept) (α)	(N-fertilizer) (β)	(γ^2) ($\gamma^{0.5}$) (γ)	A-D test for normality	R^2 (%)	Point ranking $\lvert\sum$(observed-predicted)$\rvert$
Quadratic	Corn	CT	CCAAA	18.820 (3.620)	73.320 (85.089)	317.144 (409.459)	P<0.01	49.6	-3.6E-16
		CT	CCCAA	19.086 (5.761)	102.530 (135.490)	679.20 (652.010)	p=0.01	44.8	7.2E-13
		NT	CCAAA	19.360 (3.880)	119.080 (91.280)	240.700 (439.24)	P<0.01	57.1	8.8E-16
		NT	CCCAA	19.840 (5.770)	157.320 (135.600)	535.160 (652.540)	P<0.01	49.6	-3.6E-16
Quadratic	Alfalfa	CT	CCAAA	36.483 (5.429)	520.247 (547.210)	1820.792 (11285)	p<0.01	23.9	5.6E-17
		CT	CCCAA	31.840 (6.390)	420.270 (644.190)	12592.370 (13285.230)	p=0.01	76.9	2.4E-16
		NT	CCAAA	37.651 (5.964)	472.498 (601.167)	4557.930 (12398.03)	p<0.01	25.0	2.3E-16
		NT	CCCAA	32.530 (5.570)	529.900 (561.810)	10296.270 (11586.28)	p=0.01	56.5	6.2E-17
Quadratic	Barley	CT	PCBPC	28.620 (3.420)	555.250 (157.460)	1808.370 (1482.450)	P<0.01	95.0	-1.3E-16
		NT	PCBPC	28.500 (3.540)	577.28 (162.790)	1620.000 (1533.000)	P<0.01	94.7	-4.5E-17
Quadratic	Winter wheat	NT	PBWPC	21.180 (3.881)	236.959 (144.104)	790.029 (1094.910)	p<0.01	77.2	1.7E-13
Quadratic	Carrot	CT	PWRC	22.900 (8.340)	749.510 (519.40)	2897.190 (6616.030)	p<0.01	74.9	3.2E-16
		NT	PWRC	22.910 (8.340)	751.510 (519.11)	2897.190 (6612.380)	p<0.01	74.9	1.2E-16

[a] Figures in parentheses are standard errors of coefficients.

used instead of the inverse quadratic model for NT grain corn in CCAAA and CCCAA, barley in PCBPC under both CT and NT, and alfalfa in CCCAA under both CT and NT. The quadratic functional form was also used instead of the inverse square root models selected for carrot to allow for estimation of MAC in the next chapter (Table 4.12 and Table 4.13). Overall $NO_3^- - N$ leached response to nutrient N was best described by the quadratic model consistent with Yiridoe and Weerksink (1998).

4.7.4 Trade-Offs Between Crop Yields and Nitrate-N Leached

The estimated response functions were used to determine the MERNs for each crop, and then the associated crop yields and nitrate-N leached in alternative cropping systems. In a second step, the NMP-recommended nutrient N for each crop was also substituted into the estimated response functions to generate crop yields and associated $NO_3^- - N$ leached. Crop yields and associated $NO_3^- - N$ leached at MERN and NMP recommended N were compared to assess the trade-offs from using MERN compared with NMP recommended N rate (Table 4.14).

Overall, the level of $NO_3^- - N$ leached was influenced by changes in nutrient N rate, as expected. It was found that small changes (increase or decrease) in nutrient N rates resulted in proportionately higher changes in $NO_3^- - N$ leached, compared with corresponding changes in crop yields. For example, switching from the recommended rate to the MERN resulted in 64% reduction in $NO_3^- - N$ leached for alfalfa, 38% reduction for carrots, and 33% for potatoes (Table 4.14).

4.8 Summary and Conclusions

In this study, crop yield and pollution production response to N-fertilization were specified for individual crops for various cropping systems studied. The estimated

Table 4.14. Trade-offs between Nitrogen Rates, Crop Yields and Nitrate Leached Using MERN Compared with Recommended NMP Recommended Nitrogen Rate

Crop	Rotation	No-Till			Conventional Tillage		
		% change in nitrogen rate	% change in crop yields	% change in nitrate leached	% change in nitrogen rate	% change in crop yields	% change in nitrate leached
Corn	CCAAA	20.91	3.56	16.63	17.84	2.89	15.01
	CCCAA	22.80	4.08	23.30	15.68	2.47	17.36
	PBWPC	91.06	27.84	121.18	95.82	29.68	126.69
	PCBPC	54.74	15.76	70.35	52.83	15.06	67.84
	PWRC	136.02	44.78	152.70	134.00	44.00	145.98
Barley	PBWPC	1.66	0.29	1.85	3.06	0.55	2.17
	PCBPC	-5.99	-0.83	-5.01	-3.83	-0.57	-3.03
Winter wheat	PBWPC	16.94	1.33	14.28	17.65	1.42	14.88
	PWRC	40.95	4.71	45.63	45.47	5.46	48.37
Potato	PBWPC	-8.60	-0.14	-11.43	-8.52	-0.14	-11.35
	PCBPC	-17.92	-0.25	-21.92	-17.98	-0.25	-22.05
	PWRC	-27.16	-0.24	-33.43	-20.85	-0.23	-26.13
Alfalfa	CCAAA	-161.82	-3.37	-56.58	-165.48	-1.22	-61.73
	CCCAA	-144.56	-3.60	-64.06	-175.22	-0.72	-56.58
Carrot	PWRC	-46.90	-0.05	-38.42	-44.99	-0.05	-37.01

Note: % change implies: [(MERN - NMP recommended) ÷ NMP] × 100.
Negative figures denote a ‘decrease’.

response functions were then used to determine the Maximum Economic Rate of Nitrogen (MERN) for each crop and rotation system. Data for the analysis were generated using the Soil and Water Assessment Tool (SWAT) model. SWAT model outputs generated included crop yield, nitrate leached, and sediment yields. The estimated crop yield and nitrate-N pollution response functions were compared using biological (i.e., crop growth), economic and applied statistical assessment criteria. The analysis also allowed for determining trade-offs between crop yield and associated changes in water quality (measured in terms changes in nitrate-N leaching reduction) from changes in N fertilizer rate.

Tillage type and rotation sequence influenced the coefficients of the response functions estimated. In addition, the MERN for individual crops depended on crops planted in previous years (crop rotation sequence), as expected. The results suggest that farmers tend to over-apply N fertilizer to high value crops such as carrots and potatoes. In addition, farmers tended to over-apply N fertilizer to barley in PCBPC rotation, while under-applying N fertilizer to barley in PBWPC and grain corn in all grain corn rotations considered, as well as winter wheat.

It was found that switching from the recommended N fertilizer rate to the MERN can result in a 64% reduction in $NO_3^-{-}N$ leached for alfalfa, 38% for carrots, and 33% $NO_3^-{-}N$ for potatoes. On the other hand, use of the MERN resulted in only 4% decrease in alfalfa yields, 0.05% decrease in carrot yields and 0.25% decrease in potato yields. Cropping systems, especially tillage type and rotation pattern, affected the crop yields and pollution response to N fertilizer rate. Thus, analysis involving generalised response functions may not represent the effects of such cultural practices on crop yield and environmental quality.

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CHAPTER 5 : TRADE-OFFS BETWEEN FARM PROFITABILITY AND POLLUTION REDUCTION FOR WATERSHED MANAGEMENT

5.1 Abstract

In this study, a farm economic optimization model was developed and then used to evaluate trade-offs associated with loss in farm returns for incremental reductions in nitrate-N pollution for various cropping systems. Marginal abatement costs of reducing nitrate-N pollution were evaluated for selected cropping systems assumed to be managed in the Thomas Brook Watershed using SWAT-simulated data. Without regulations on nitrate-N pollution, whole-farm trade-off analysis suggests that corn-corn-alfalfa-alfalfa-alfalfa rotation under conventional tillage (CCAAA-CT) generated the highest farm returns and also reduced nitrate-N leached by 32% among corn-based cropping systems considered. In addition, without regulations on nitrate-N pollution, potato-winter wheat-carrot-corn rotation under CT generated the highest farm returns and the lowest nitrate-N leached, among vegetable-horticulture-based cropping systems. Similarly, among potato-based cropping systems, potato-barley-winter wheat-potato-corn rotation under no-till (NT) generated the highest gross margins and the lowest nitrate-N leached. The most cost-effective cropping systems that met the Health Canada maximum contaminant limit (MCL) (of 10mg L^{-1}) on nitrate-N in drinking water were consistent with the cost-effective cropping systems without regulations on nitrate-N pollution for vegetable-horticulture-based and potato-based cropping systems. However the cost-effectiveness of grain corn-based cropping systems suggests a shift from two years of corn and three years of alfalfa under CT management (CCAAA-CT) to three years of corn and two years of alfalfa under NT management (CCCAA-NT) due to regulations on nitrate-N pollution (MCL of 10mg L^{-1}).

5.2 Introduction

The intensification of agricultural production in OECD countries, with associated use of chemicals fertilizers, herbicides and pesticides have not only resulted in substantial increase in crop and livestock outputs, but have also tend to generate negative impacts on the environment. Application of nitrogen (N) fertilizer in excess of crop requirements can result in nitrate-N pollution, global warming and overall, climate change (Good and Beatty 2011). In addition, excessive application of N fertilizers increase nitrate-N loads in water systems, resulting in impairment of aquatic life, and drinking water quality for humans (Good and Beatty 2011).

A major contributor to water pollution in Canada is agricultural production (Ecology Action Center 2010). Various agricultural watersheds across Canada are susceptible to environmental (especially water) pollution from farming activities (Stuart et al 2010). Water quality protection has become an environmental quality objective across such watersheds in Canada.

Given that pollution and other negative outputs from agriculture tend to be generated as joint outputs (with crop and livestock outputs produced), it is important to balance the positive outputs from production with pollution problems by assessing and understanding important trade-offs to reducing the externalities (Heady and Vocke 1978; Yang et al 2007).

The Annapolis Valley in Nova Scotia is the most intensive agricultural region in the province, and generates over 50% of key agricultural products in the province (Stratton et al 2003). Thomas Brook watershed (TBW) in Kings County, Annapolis Valley, is characterised by mixed land-use systems with crop production as the dominant commodity group. Major economic crops managed within the watershed include strawberries, grain corn and small grains (e.g., barley and wheat) and are typically managed under conventional tillage (Gauthier et al 2009; Sinclair et al 2009; Ahmad et al 2011).

The TBW (and the Annapolis Valley region as a whole) are highly susceptible to groundwater pollution as a result of intensive agricultural production. Conventional tillage practices on the predominantly sandy loam soils in TBW makes more than 50% of the watershed susceptible to groundwater pollution from nitrates and sediment loading into the stream catchment (Blair 2001; Sinclair et al 2009). Indeed, high levels of nitrates and sediments in the TBW are a concern to agricultural administrators and farmers (Nova Scotia Department of Agriculture 2004). Between 1989-2009, for example, about 20% of drinking water wells tested in Kings County, Nova Scotia had average maximum concentration of nitrate levels of 39.1 mg L^{-1} (almost four times the Health Canada Maximum Contaminant Limit (MCL) of 10 mg L^{-1}) (Nova Scotia Department of Environment 2010). The nitrate pollution problem in the watershed has been linked to excessive nutrient N application and other farm management practices (Ecology Action Center 2010). A provincial Nutrient Management Planning (NMP) program was launched in 2004 as a strategy to help address both economic and environmental objectives of farmers, especially reduction of pollution of groundwater systems. Crop choice, rotation sequence, tillage systems and N fertilization rates are major aspects of NMPs that are commonly evaluated for economic and environmental impacts.

Optimizing NMPs to meet environmental objectives may not necessarily maximize economic objectives of farmers (Yang et al 2007; Sumelius et al 2005; Yiridoe and Weersink 1998). Thus it is important to assess trade-offs between economic and ecological goals from nutrient management planning.

Approaches used to assess trade-offs between production of good and bad agricultural outputs include enterprise budgeting (Langyintuo et al 2005; Myers et al 2008; Bhattarai et al 2008), green budgeting (Faeth 1993; Klaus and Axel 2004), use of computer-based decision support tools for whole-farm analysis (Bazzani 2005; Sterk et al 2006; Karmakar et al 2007), and mathematical programming (MP) techniques (such as multi-objective linear programming, goal programming and dynamic programming techniques) (El-Nazer and McCarl 1986; Bretas and Haith 1990; Mimouni et al 2000; Van Wenum et al 2004). In addition, MP techniques have been used to estimate marginal abatement costs associated with agricultural pollution reduction for specific cropping systems (Bystrom, 1998; Yiridoe and Weerksink 1998; Soloveitchik et al 2002; Sumelius et al 2005).

The methods commonly used to assess trade-offs between economic and environmental objectives can be classified into two groups: (i) monetary valuation of environmental impacts and incorporating the impacts into a monetary objective to be optimized; and (ii) the use of environmental quality indices as parameters in optimization models or in efficiency or trade-off frontiers (Roberts and Swinton 1996). The various approaches used to assess trade-offs tend to provide different perspectives on trade-off analysis.

Input data required for trade-off analyses can be enormous and complex, especially when several farming systems and scenarios are involved. To help address some of the data modeling challenges, bio-physical simulation modeling integrated with economic optimization analysis are commonly used for such economic-environmental trade-off analysis (Roberts and Swinton 1996; Antel and Capalbo 2001; Jalota et al 2007). Biophysical simulation modeling is a time efficient and cost-effective approach to generating data that can take several years and substantial financial and physical resources to generate (Antel and Capalbo 2001; Jalota et al 2007).

The usefulness of integrating bio-physical simulation modeling with economic analysis depends on careful calibration and validation of the simulation model. In this study, the Soil and Water Assessment Tool (SWAT) initially calibrated and validated for sediment transport under Thomas Brook Watershed (TBW) conditions by Ahmad et al (2011), was further calibrated and validated to access crop yield and nitrate-N leached under alternative cropping systems.

The purpose of this study was to develop a farm optimization model, and use the model to evaluate trade-offs in terms of loss in farm revenue associated with incremental reductions in nitrate-N pollution for various cropping systems. Specifically, marginal abatement costs (MAC) of reducing nitrate-N pollution were evaluated for selected cropping systems in the Thomas Brook Watershed using SWAT simulated data. Crop yield and associated nitrate–N pollution production functions estimated in the previous chapter were used to estimate the MACs.

A three step approach was used to achieve the study objectives:

4) *To develop enterprise budgets for the alternative cropping systems.*

Farm enterprise budgets were developed as a building block for the rest of the analysis (Roberts and Swinton 1996).

5) *To evaluate the efficient cropping systems that maximize farm profits while also minimizing $NO_3^-{-}N$ pollution.*

The eco-efficiency index framework (Kim and Dale 2008) was used to assess bio-economic efficiency for selected cropping systems. Although the approach has useful applications, it also has drawbacks, including limited parameters on the trade-offs, and levels of the economic and environmental objectives for a set of cropping systems.

6) To develop economic optimization models and use the models to estimate MAC of nitrate-N pollution associated with the various cropping systems.

An empirical framework (see Bystrom, 1998; McKitrick 1999; Yiridoe and Weersink 1998) was applied to determine MACs associated with reducing groundwater-N leaching for alternative cropping systems.

5.3 Trade-Offs Between Good and Bad Agricultural Outputs

Balancing the benefits to society as a whole from agricultural water quality improvements against the profits to farmers inherently leads to a decision problem with multiple objectives that tend to conflict with each other (Figure 5.1). Targeting each of the (multiple) objectives one at a time may be not only costly, but can result in unintended consequences and negative impacts on other objectives (Lakshminarayan et al 1995; Weersink et al 1998). On the other hand, there are potential gains generated from addressing multiple objectives simultaneously (Connor et al 1995). Multiple objective optimization is an approach that can be used to simultaneously optimize the various objectives subject to specific constraints such as pollution limits or resource limits.

Multiple objective optimization allows for determining possible trade-offs (also known as the Pareto optimal set) (Mimouni et al 2000). On the other hand, multiple objective optimization requires more detailed information about the relationships among various objectives for determining choice of the most suitable compromise solution (Mimouni et al 2000).

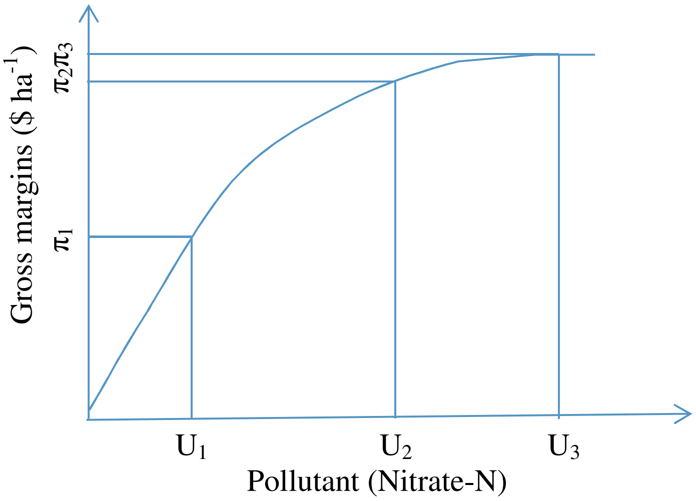

Figure 5.1: Conflicting objectives: increasing farm profits from crop production tends to increase pollution production.

Trade-off analysis allows analysts to explore implementation of alternative control systems and/or practices, while also meeting agricultural system performance requirements and resource constraints (Yang et al 2007). Trade-off analysis also helps to make the competing characteristics of different objectives and constraints more transparent (Ruhe et al 2003), while enhancing knowledge of the extent to which an improvement in one direction (e.g., minimizing pollution or maximizing farmers' profit) impacts on another objective (Figure 5.2).

The trade-off frontier curve in Figure 5.2 illustrates maximum limits of two outputs or objectives that can be achieved under limited resource conditions and technology choices (Gillespie, 2007). The frontier curve can be obtained from optimal solutions to a multi-objective optimization problem. The frontier curve stems from scarcity of farm inputs, and leads to choices and trade-offs or opportunity costs, as the production of more of one output is chosen or preferred or specialized compared with the other.

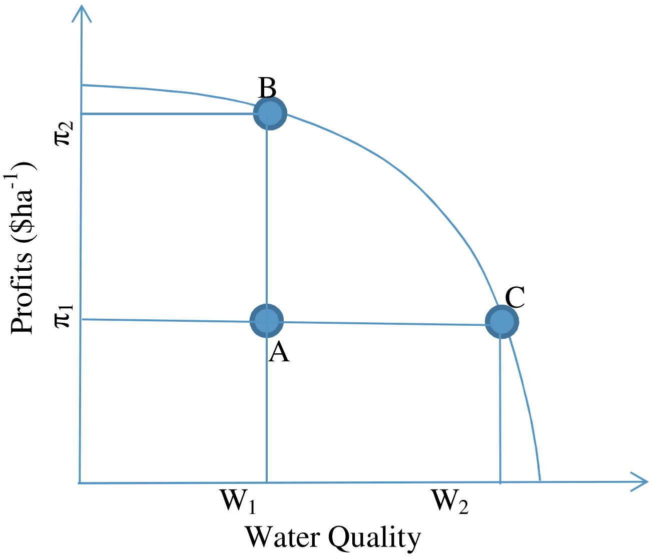

Figure 5.2: Trade-offs between multiple objectives

Under some conditions, existing management practices may represent *Pareto inefficiency* (see, for example, dominated point A in Figure 5.2), in which case farmers or other decision makers are not faced with opportunity costs. A point along the frontier, such as non-dominated points B and C, are said to be efficient, and indicates that an economy's scarce resources are being used efficiently. Points B and C are also considered as *Pareto efficient.* A farmer producing at point A (i.e., achieving π_1 (economic profit) and associated W_1 (water quality)) could actually be producing at point B to achieve π_2 (economic profits) or at point 'C' to achieve W_2. The balance (*Pareto efficient*) point for maximum possible economic profits while also generating the lowest water pollution (maximum possible water quality) constitute alternative choices along an efficiency frontier, between point B and C (Figure 5.2).

An important objective in this study involved evaluating the implications of reducing nitrate-N pollution and sediment transport to a water system on farmers' profits.

The farmer's economic profit was measured in terms of gross margins (or farm returns), above variable cost of production ($ ha^{-1}). Cost of groundwater quality improvements is assessed in terms of abatement cost associated with incremental reduction in groundwater-N leached.

Sediment abatement is also an environmental objective that can be linked to agricultural production. The relationship between sediment transport and nitrate-N leaching may be such that minimizing one pollutant leads to more of the other (Figure 5.3). Consequently, a compromise level of each pollutant can be determined by using goal programming techniques (Ragsdale 2008).

Vuuren et al (1998) noted that (potential) weights assigned to each objective in multi-objective optimization depend on various considerations, including the uses of and values placed on the water by the agri-environmental manager and economic decision makers. Given that water has a variety of uses, (such as drinking water, crop irrigation, various recreational uses, and maintenance of fish and wildlife habitats), water quality requirements may vary depending on the intended usage (Ott 1978). Different water quality requirements may imply different pollution indices or different levels of pollution indices to measure.

5.3.1 Some Approaches Used to Assess Trade-Offs

In this section, a brief overview of selected analytical approaches for trade-off/frontier analysis focuses on empirical methods commonly used in the literature. It is important to acknowledge that, besides the empirical approaches reviewed, decision support tools have also been used, with some (such as Stoorvogel et al 2001) specifically designed for agricultural production systems.

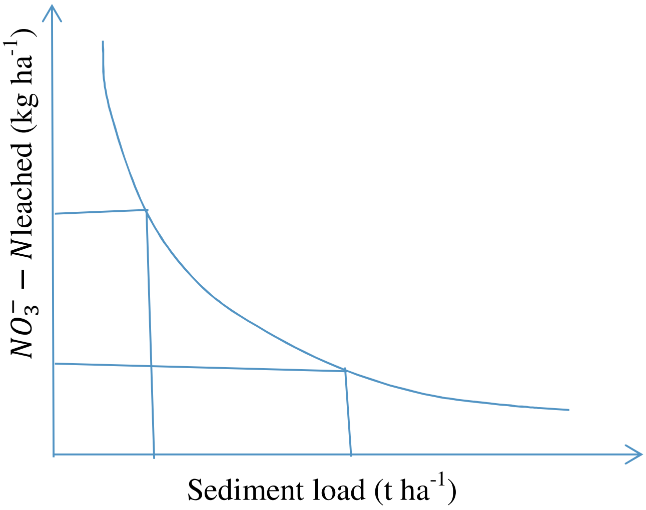

Figure 5.3: Trade-offs between nitrate-N leached and sediment transport.

Enterprise budgeting approach

In a study for Beltsville Agricultural Research Center in the United States, Kelly and Teasdale (1996) developed enterprise budgets for various cropping systems and then compared trade-offs among net returns, soil erosion and other dimensions of environmental quality. Other analysts have used variants of budgeting approaches such as simple farm enterprise budgeting (Langyintuo et al 2005; Myers et al 2008; Bhattarai et al 2007), and green budgeting (Faeth 1993; Klaus and Axel 2004) to estimate trade-offs between economic and environmental objectives.

Enterprise budgeting methods allow for assessment of profitability of alternative farming systems, but have limitations in quantifying the economic value of pollution reduction (Roberts and Swinton 1996). On the other hand, enterprise budgets form the basis for further economic-environmental analysis of trade-offs.

Eco-Efficiency index and dominance approach

The eco-efficiency index (EEI) method is another approach that has been used to assess trade-offs between farm profitability and environmental quality. Applications include the Eco-Efficiency Index (e.g., Kim and Dale 2008) and a variant of the EEI or the dominance approach (e.g., Hoag and Hornsby 1992). Eco-efficiency index estimation involves a weighted sum of economic and environmental impact quantified as a single value. Further evaluation of the index can be accomplished using various dominance criteria when several indexes are to be compared. With the dominance approach, relative weights for different criteria are used to assess and identify practices or systems which increase one objective while decreasing another (Xu et al 1995).

One advantage of the aggregate eco-efficiency index method is that it reduces the economic and environmental objectives to a single value. On the other hand, critics point to the subjectivity associated with assigning weights to the various criteria or objectives (Roberts and Swinton 1996; Jollands et al 2003). In addition, the EEI provides limited, if any, detail on component attributes, thereby complicating interpretation of the estimated index by policy makers/advisors (Jollands et al 2003).

Mathematical programming techniques

Trade-off/frontier analysis using mathematical programming (MP) methods is probably the most common in the literature. Due in part to the flexibility of such approaches relative to other trade-off techniques, El-Nazar and McCarl (1986), used MP methods to model various combinations of corn, potato, wheat and alfalfa in a four year rotation that maximize farm profits while also minimizing pollution, without imposing predetermined rotation sequences on the models.

Bretas and Haith (1990) used a linear programming model to maximize farm gross margins subject to groundwater quality constraints. The resulting trade-off frontiers obtained suggest that relaxing pollution levels increased net income for the potato farming systems considered. Mimouni et al (2000) used a multi-objective linear programming (MOLP) technique to generate data for trade-off frontiers and then evaluated optimal cropping systems that maximize gross margins while minimizing pollution. Mimouni et al (2000) generated trade-offs between optimal solutions for each objective.

Marginal Abatement Cost

Marginal abatement cost (MAC) represents the cost of reducing an incremental unit of pollution produced, and provides a link between the emission levels of a firm and the cost of reducing an additional unit of pollution (McKitrick 1999). Sumelius et al (2005) estimated MAC of N-fertilizer tax policies intended to reduce nitrate levels. Sumelius et al (2005) first estimated corn and associated nitrate-N leached response functions to N fertilization rates, and then applied data on corn and N fertilizer prices to generate the Maximum Economic Rates of N (MERN) fertilization. Sumelius et al (2005) developed a profit maximization function, subject to three nitrate pollution control policy assumptions. The resulting Lagrangian function was solved to obtain MACs for each policy assumption.

Yiridoe and Weersink (1998) estimated on-farm MACs associated with reducing groundwater-N leached under alternative farming systems, assuming various groundwater nitrate-N pollution restrictions. Yiridoe and Weersink (1998) used estimated crop yield and associated nitrates leached response functions to evaluate optimal N fertilization and on-farm abatement costs for eight cropping systems. MACs associated with the crop production systems were calculated by substituting specific parameters from crop yield and pollution functions into MAC equations derived from solving Lagrangian functions.

Bystrom (1998) also estimated nitrogen pollution abatement costs for wetlands in south-western Sweden, and empirically tested an approach that accounts for the effect of physical parameters on nitrogen pollution abatement cost in wetlands. Bystrom (1998) estimated wetland construction costs and abatement capacity of wetlands. Bystrom (1998) integrated estimated functions for wetland construction costs (as dependant on wetland size) and nitrogen pollution abatement (as a function of wetland size, level of nitrogen load and regional characteristics). As with Sumelius et al (2005), and Yiridoe and Weersink (1998), the two functions were integrated using a Lagrangian function, and marginal abatement costs estimated as Lagrangian multipliers.

In this study, the EEI method was used in an initial analysis to quantify measures of sustainability and trade-offs between crop productivity and nitrate pollution for a limited set of cropping systems considered in this study. In addition, MACs reflecting loss in farm revenue resulting from incremental reduction in nitrates leached were estimated for all the cropping systems considered in the previous chapters.

5.4 Economic Modeling

5.4.1 Eco-Efficiency Index

5.4.1.1 Background and applications

The eco-efficiency index (EEI) method has been used to assess trade-offs between agriculture productivity and pollution production (Brussaard et al 2010; Park et al 2010). As noted earlier, a main feature of the approach is that it summarizes performance of the agricultural production system into a single dimensionless (aggregate) index. Applications of this approach include Kim and Dale (2008), who developed an eco-efficiency index model to evaluate sustainable corn cultivation practices with high economic returns and low greenhouse gas emissions. Another application of the EEI method includes Reith and Guidry (2003) who applied eco-efficiency analysis to a 600-acre experimental farm in south-central Louisiana. The objective was to recommend useful targets for crop management and continuous improvement in environmental quality. van Passel et al (2007) also applied eco-efficiency modeling to measure the sustainability of dairy farms using the Flemish dairy sector as a case study. The authors then evaluated linkages between partial productivity measures, eco-efficiency index and overall sustainability.

EEI estimations have applications in policy development and evaluation, and is a simple method for assessing multiple production options (Jollands et al 2003). As noted earlier, challenges to application of the EEI method include choice of weights among constituents of the index, and evaluation criteria (Roberts and Swinton 1996; Jollands et al 2003).

Schaltegger and Sturm (1990) first proposed the EEI framework as a “business link to sustainable development”. The technique was later applied (and popularised) by Schmidheiny (1992) as a tool for sustainable business and environmental development. During the 1990s, the Business Council of Sustainable Development (BCSD) endorsed the technique as a useful tool. The EEI approach has been widely used around the world to understand business decision issues, such as achieving efficient resource use while minimizing pollution production (Schmidheiny 1992; Jollands et al 2004). Eco-efficiency models are multi-dimensional. Thus, it can be developed for different production situations (Schaltegger 1996).

5.4.1.2 Theoretical model of Eco-efficiency Index

In applications to assess trade-offs, eco-efficiency is expressed as a ratio of economic and environmental or ecological impacts (e.g., Park et al 2010; Jef et al 2010; Brussaard et al 2010; Huppes and Ishikawa 2005). EEI reflects a ratio of a measure of "economic value creation" to "environmental impact" (Schaltegger et al 2003):

$$EEI = \frac{Added\ economic\ value}{Ecological\ or\ environmental\ impact} \tag{5.1}$$

Kim and Dale (2008) adapted the original EEI to evaluate the effects of N fertilizer application on greenhouse gas (GHG) emissions for grain corn cropping systems in several counties in selected Corn Belt states in the US. The framework was used to identify economically and environmentally beneficial nitrogen fertilizer rates for the different counties. Kim and Dale (2008) estimated economic values added in terms of economic returns to N fertilizer application. Environmental impact was estimated as greenhouse gas emissions:

$$EEI = \frac{Economic\ Return\ to\ Nutrient\text{-}N\ Rate/(Y_0 \times P_{corn})}{Greenhouse\ Gas\ Emissions} \tag{5.2}$$

In this study, the EEI application is consistent with the framework by Kim and Dale (2008):

$$EEI = \frac{\{[(Y_{MERN}\text{-}Y_0)p - (w \times X_{MERN}) + A_c]/(Y_0 \times p)\}_{ik}}{\left\{exp\left(\frac{V_{MERN} - V_0}{V_0}\right)\right\}_{ik}} \tag{5.3}$$

where EEI represents eco-efficiency index;

Y_{MERN} represents average crop yield (t ha^{-1}), generated from N fertilizer applied at the maximum economic rate of nitrogen fertilization, *MERN*;

Y_0 represents average crop yield generated without applying N fertilizer (t ha^{-1});

p denotes output price of crop r (\$ tonne^{-1});

w is the unit price of N fertilizer (\$ tonne^{-1});

X_{MERN} (kg ha^{-1}) denotes N fertilizer applied at the MERN rate;

A_c represents variable cost associated with applying N fertilizer (\$ ha^{-1});

V_{MERN} is nitrate-N leached from crop production for fertilizer applied at *MERN* (kg N ha^{-1});

V_0 is nitrate-N leached from crop production for fertilizer applied at 0 kg per ha (kg N ha^{-1});

i denotes an index for tillage, while k is an index for rotation system.

In the eco-efficiency index analysis for this study, cropping systems reflect a combination of crop choice, tillage system and rotation sequence/system. The numerator in equation 5.3 represents the difference in economic returns from a crop in a selected cropping system using MERN compared with zero N fertilization rate. The denominator is an estimate of the difference in $NO_3^{-}-N$ leached from managing a crop with fertilizer applied at the MERN compared with level of leaching with no fertilizer applied. The index has no dimensions (Kim and Dale 2008).

Environmental impacts for the eco-efficiency index were estimated using an exponential functional form suggesting that, as pollution rate increases, eco-efficiency reduces by more than proportional level (Kim and Dale 2008). Alternative cropping systems generate different eco-efficiency levels. Cropping systems with high EEI are preferred, since such systems are better able to balance environmental and economic objectives. Sensitivity analysis can be conducted with eco-efficiency index models to determine the effects of changes to specific economic variables (such as input and output prices) on the EEI for a cropping system. Sensitivity analysis helps to assess the sustainability and stability of a cropping system in balancing farm profitability with environmental quality under changing economic conditions (Kim and Dale 2008).

5.4.1.3 Empirical modelling: Eco-Efficiency Index estimation

The cropping systems assessed are summarized in Table 5.1. The individual crops examined include grain corn, potato, and carrots. Representative corn-based cropping systems for the study area included CCAAA and CCCAA rotations. Similarly, representative potato-based cropping systems investigated were PCBPC and PBWPC. A vegetable-horticulture cropping system considered was potato-winter wheat-carrot-corn (PWRC) rotation.

Average yields for the major crops considered when N fertilizer was applied at MERN and under zero N fertilization were determined using crop response functions estimated in Chapter 4 (Table 5.2). Similarly, $NO_3^{-}{-}N$ leached at MERN and at zero N fertilization rates were determined using the nitrate-N leached response functions estimated in the previous chapter. Data on crop input (fertilizer and manure) were obtained from Agro-mart Group, a farm input retail outlet in Truro, Nova Scotia. Output prices for grain crops were obtained from Co-op Atlantic Canada, while output prices for potato, carrot and alfalfa hay were obtained from Nova Scotia Department of Agriculture (Table 5.3). Cost of fertilizer/manure applications were also obtained from farm enterprise budgets developed for Nova Scotia in this study.

5.4.2 Marginal Abatement Cost

5.4.2.1 Theoretical modelling and assumptions for private decision problem under groundwater nitrate restriction

The choice of a cropping system can significantly affect current and future farm

Table 5.1. Cropping systems used in eco-efficiency index analysis.

Crop	Tillage system	Rotation system[a]
Grain-corn based cropping system	CT	CCCAA
	NT	CCCAA
	CT	CCAAA
	NT	CCAAA
Potato-based cropping system	CT	PCBPC
	NT	PCBPC
	CT	PBWPC
	NT	PBWPC
Vegetable-horticulture systems	CT	PWRC
	NT	PWRC

Note: [a:]A= alfalfa; B= barley; C= corn; P= potato; W= winter wheat; R= carrot.

Table 5.2. Crop yield and associated nitrate-N leached for fertilizer application rates at MERN and at 0 under conventional tillage and no-till systems.

Crop	Crop rotation	Conventional tillage				No-till			
		Crop yield (t ha^{-1})		Nitrate leached (kg ha^{-1})		Crop yield (t ha^{-1})		Nitrate leached (kg ha^{-1})	
		MERN rate	0 kg N ha^{-1} nutrient N rate	MERN rate	0 kg N ha^{-1} nutrient N rate	MERN rate	0 kg N ha^{-1} nutrient N rate	MERN rate	0 kg N ha^{-1} nutrient N rate
Corn	CCAAA	4.78	2.22	29.41	18.82	4.69	2.07	32.58	18.80
	CCCAA	4.91	2.05	38.60	19.09	4.86	1.94	39.60	19.05
Potato	PBWPC	17.43	8.34	101.58	18.14	17.46	8.94	101.98	18.23
	PCBPC	16.06	7.73	99.19	21.33	16.09	8.89	100.05	21.58
Carrot	PWRC	25.43	21.12	22.25	22.25	25.49	20.05	48.88	22.267

Table 5.3. Output prices and fertilizer/manure and application costs.

Crop	(N-P-K) Fertilizer Type	Crop Price[b] (\$ tonne^{-1})	Fertilizer/Manure cost [a] (\$ tonne^{-1})	Fertilizer/Manure application cost (\$ ha^{-1})
Corn	34-00-00	230	480	22
	Dairy fresh manure		181	
Potato	15-15-15	630	560	22
Carrot	15-15-15	776.91	560	22

Note: [a] Fertilizer prices were obtained from Agro-mart Group, a farm input retailer in Truro Nova, Scotia.

[b] Crop prices represent farm gate crop output prices and were obtained from Co-op Atlantic, Canada (for grain crops), and Nova Scotia Department of Agriculture (for potato, carrot and alfalfa hay).

profitability, as well as environmental quality (El-Nazer and McCarl 1986). Thus, under groundwater nitrate restrictions, farmers' private decision choices concerning cropping system type become very important. The cropping system that maximizes farm profits while also minimizing nitrate-N pollution abatement cost is assumed to be the preferred choice of the farmer (Figure 5.4.)

Figure 5.4 illustrates the conceptual linkages between a good output (Y) produced and a bad output generated (V), under two alternative cropping systems. Input levels and associated crop outputs, nitrate leached and abatement cost with subscript "A" represent an alternative cropping system or production technology combination (crop choice, crop rotation and tillage).

At various N fertilization rates (X_I, X_2, X_{1A}, and X_{2A}), different output levels and associated profits (π_1, π_2, π_{1A}, π_{2A}), and nitrate-N leached levels (V_I, V_2, V_{1A}, and V_{2A}) are produced (Figure 5.4: panels A, B, and C). Figure 5.4 (panels E and F) conceptually shows the different profits and associated nitrate-N leached abatement costs for the alternative systems. Figure 5.4 indicates that profit levels for a particular crop are not only influenced by the N fertilization rate, but also the cropping system chosen. It is assumed that if nitrate-N leaching restriction is set at V_a^R, profit for cropping system 1 (π_1) is higher than that of system 2 (π_2), and MAC for cropping system 1 (AC_1) is higher than that for system 2 (AC_2). Thus, nitrate pollution abatement will severely impact cropping system 1 more than system 2 if (π_1- AC_1) < (π_2- AC_2).

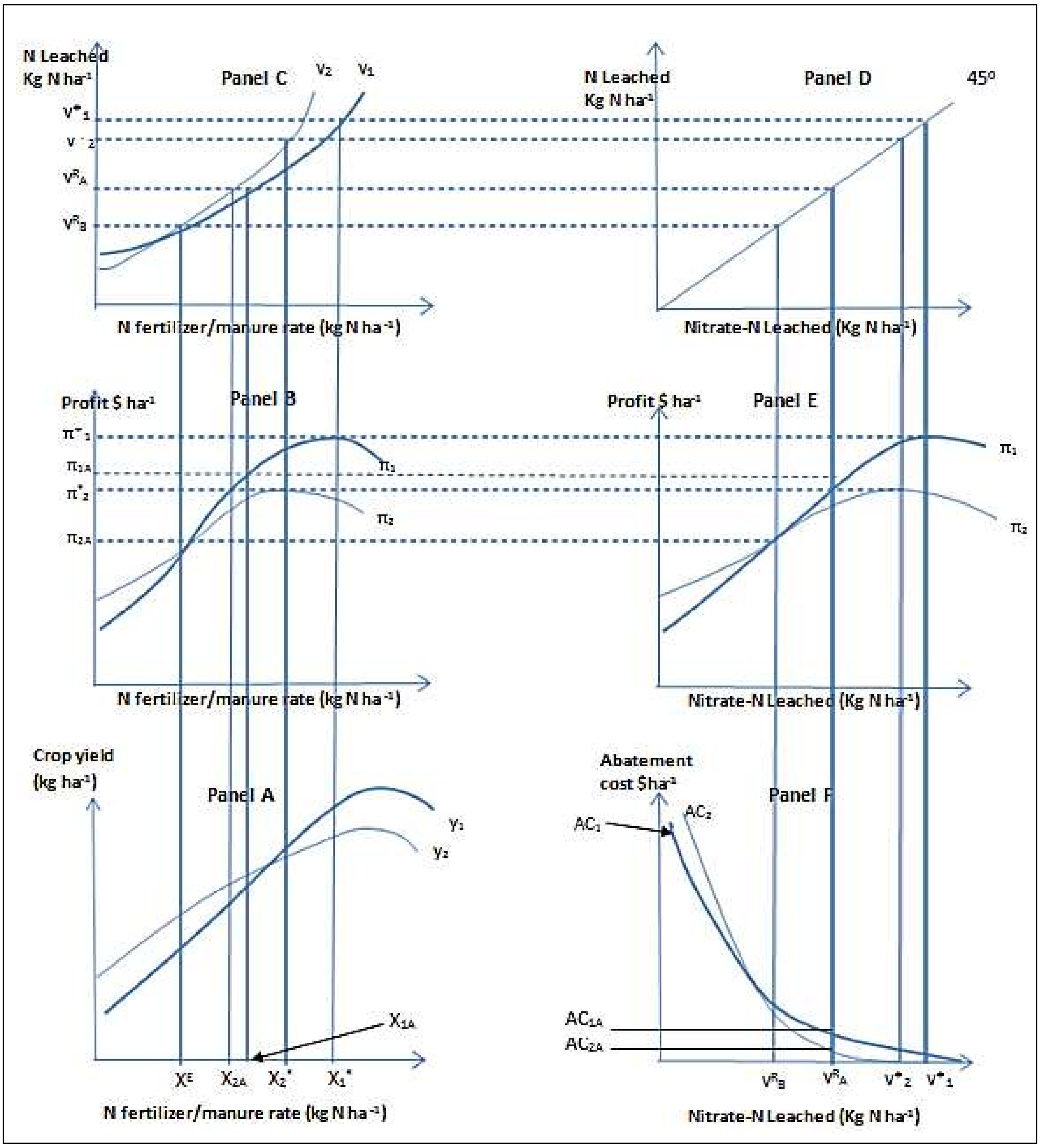

Figure 5.4: Conceptual linkages between a good output (crop yield) and a bad output (N-leached) produced for two alternative cropping systems, under varying N fertilizer rates.

Source: Adapted and modified from Yiridoe and Weersink 1998.

With restrictions on pollution levels, a farmer's objective of maximizing profits (Equation 5.12) becomes constrained by the associated nitrate-N pollution level allowed (Equation 5.13). Thus, the farmer is faced with a secondary objective of minimizing nitrate-N pollution which conflicts his/her primary objective.

$$Max\,\pi = (pY_{MERN_{ik}}) - (wX_{MERN_{ik}} + C) \tag{5.12}$$

$$\text{s.t:} \quad Min\,nitrate - N\ leached = (V_{MERN_{ik}}) \leq \bar{V}_{ik} \tag{5.13}$$

where, π represents profit (\$ ha^{-1}) from managing crop r on L hectares of land, using tillage type i, and rotation system k;

p denotes output price for a given crop;

$Y_{MERN_{ik}}$ represents yield of the crop r from rotation system k and tillage system i;

i denotes index for tillage, and k denotes index for rotation sequence;

w is the unit cost of N fertilizer (\$tonne^{-1});

$X_{MERN_{ik}}$is the MERN applied to a crop under tillage type i and rotation sequence k;

C is the normalised cost of production, excluding N fertilizer cost;

$V_{MERN_{ik}}$ represents $NO_3^- - N$ leached (kg ha^{-1} yr^{-1}) from managing a crop in rotation system k and tillage system i;

$\bar{V}_{ik}$ represents $NO_3^- - N$ leaching restriction (kg ha^{-1} yr^{-1}) for a crop in rotation system k and tillage system i.

A Lagrangian function is obtained by integrating equations 5.12 and 5.13:

$$\mathrm{L}\,(p, w, \bar{V}_{ik}) \ = (p \times Y_{MERN_{ik}}) - (wX_{MERN_{ik}} + C) + \lambda[\bar{V}_{ik} - V_{MERN_{ik}}] \qquad 5.14$$

The first derivative of equation 5.14 with respect to λ, $\left(\frac{\partial L}{\partial \lambda}\right)$, and solving for X gives an expression for a new optimal N ($X^{**}{}_{ik}$) as a function the groundwater nitrate-N restriction level ($X^{**}{}_{ik} = f(\bar{V}_{ik})$). Consequently, the profit maximizing levels of nutrient N is adjusted from $X_{MERN_{ik}}$ to $X^{**}{}_{ik}$ as a result of the groundwater nitrate-N restriction. In addition, generating the first derivative of equation 5.14 with respect to $X_{MERN_{ik}}$, $\left(\frac{\partial L}{\partial X_{MERN_{ik}}}\right)$, and solving for λ gives the MAC function, $\left(\frac{d\pi}{d\bar{V}_{ik}}\right) = \lambda = f(p, w, X^{**}{}_{ik})$. Substituting $X^{**}{}_{ik} = f(\bar{V}_{ik})$ into the MAC function results in MAC relationship as a function of input and output prices, and groundwater nitrate-N restriction level ($\lambda = f(p, w, \bar{V}_{ik})$). Integrating the parameters of crop yield response with nitrate-N leached response functions obtained in the previous chapter (four) into MAC functions ($\lambda = f(p, w, \bar{V}_{ik})$) generates marginal cost levels for abating nitrates leached with groundwater restrictions, and represents a measure of trade-off or opportunity cost associated with incremental levels of nitrate pollution reduction attained under alternative cropping systems.

The shape of the crop yield and nitrate leached response functions estimated in the previous chapter are consistent with observed positive levels of the two outputs with no N fertilizer application. In addition, initial applications of N fertilizer increase both crop yield and nitrate-N leached levels. Further N fertilizer application tends to result in yield plateau, and then eventually decreases. The technical relationship between crop (or nitrate-N leached) yield and N fertilizer rate (i.e., rate of increase in yield, characteristics of the plateau, and rate of decrease of crop yield) tends to differ, depending on crop type and cropping system (agricultural technology). In order words, the magnitude and sign of the estimated regression parameters will reflect the biological and agronomic conditions. For example, for a quadratic crop response function, ($Y = a + bX + cX^2$), the signs (directions) of the parameters are such that, $a > 0; b > 0; c < 0$. Similarly, for a Mitscherlich-Baule crop response function, $a(1 - e^{-b(c+X)})$, $a > 0; b > 0; c > 0$. In addition, the a priori expectation for a quadratic nitrate-N leaching response function ($V = \alpha + \beta X + \gamma X^2$) suggest that, $\alpha > 0; \beta > 0; \gamma > 0$.

From equation 5.14, the MAC curve is downward slopping, and assumed to be twice continuously differentiable such that, $\frac{\partial \lambda}{\partial \bar{V}_{ik}} < 0$, and $\frac{\partial^2 \lambda}{\partial^2 \bar{V}_{ik}} < 0$. In general, at higher (lower) nitrate-N leached levels, the loss in farm revenue from incremental reductions in pollution (i.e., the MAC to the farmer) tends to be lower (higher). Thus, the MAC decreases as the regulated nitrate leaching levels increases (becomes less stringent), thereby generating a negative slope (Figure 5.4). Such theoretical properties require that the crop yield and pollution response functions are also twice continuously differentiable.

McKitrick (1999) noted that the MAC curve does not always have a smooth downward slopping curve, but may be kinked at some point, even for a simple case involving a single firm with one pollutant and one abatement strategy. McKitrick (1999) also noted that although the assumptions about twice continuous differentiability are important, in reality, the assumption tends to be easily violated. Furthermore, given that it is not realistic for a firm to invest or produce with negative levels of inputs, a boundary of non-negativity in activity levels is imposed on abatement efforts. A non-differentiable point which results in a kink in the MAC curve is observed when the non-negativity in activity levels is violated or when important constraints are not binding (McKitrick 1999). The integral of the MAC with respect to the regulated groundwater nitrate-N limit generates the pollution abatement cost.

5.4.2.2 Empirical modelling

Cost effectiveness and farm profit maximization depend not only on intensive management but also on extensive management choices. Extensive farm management choice involves management decisions that consider exogenous factors (agricultural technology), which indirectly affect farm revenue (such as crop rotation and tillage choices). In this study, the MAC modelling considered a combination of intensive and extensive management options. Applying both intensive and extensive management to economic optimization with environmental constraints implies a private decision maker who adopts the social regulations on pollution faces a problem of allocating available land (e.g., 1ha) to the production of a chosen crop, in a choice rotation system and tillage system (extensive choice). The analyst then determines, the N fertilizer rate (X^{**}) required to generate the highest returns with the least cost of complying with the social regulation.

In this study for TBW, MACs were estimated with 30 different extensive management options (i.e., combination of tillage and rotation systems for each crop), and one intensive management option (N fertilizer rate) assumed under groundwater nitrate-N leaching restriction. Individual crops considered included corn, potato, barley, winter wheat, carrot and alfalfa. The alternative cropping systems assessed are summarized in Table 3.4 (in earlier chapter three). The crops and rotation systems were selected in consultation with extension specialists for the study area, and reflect representative cropping systems for the region. Although potatoes are not a dominant crop in TBW, it is one of the economically important crops grown in the Annapolis Valley. Similarly, alfalfa was chosen as leguminous forage commonly incorporated into grain corn rotation systems. Although conventional tillage (CT) management is the dominant tillage system in the TBW, no-till (NT) systems, were assessed and their impacts compared with the CT alternatives (e.g., Tong and Naramngam, 2007).

The SWAT model calibrated and validated for TBW conditions was used to generate crop yield and $NO_3^-{-}N$ data for various cropping systems assumed to be managed in the watershed. The SWAT output data was used to investigate the effect of changes in the groundwater nitrate-N restriction level on farm returns and MAC associated with seven nutrient N fertilization levels (i.e., 110%, 100%, 90%, 75%, 50%, 25%, and 0% of the NMP recommended rates). Nitrate-N leached measured reflects $NO_3^-{-}N$ transported through the root zone to groundwater systems. The Health Canada maximum contaminant limit of 10 mg L^{-1} yr^{-1} was transformed to kg ha^{-1} yr^{-1} using drainage or soil water recharge data generated from the SWAT simulations. Drainage data was influenced by crop type, tillage, rotation, and nutrient N application level. Thus, the 10 mg L^{-1} yr^{-1} of nitrate-N leached transformations to kg ha^{-1} yr^{-1} varied within and between cropping systems.

In this study, farm returns (measured in terms of total revenue less variable cost) for individual crops were generated using farm enterprise budgets. Crop yields generated from substituting nutrient N specific to each rotation and tillage system into the associated response functions for each crop were used to estimate farm revenue. Nitrate-N leached from each crop-field was also generated by substituting nutrient N level for a particular cropping system into the associated nitrate-N leached response function. Nitrates leached for the different crops in alternative cropping systems were also converted from kg ha^{-1} to mg L^{-1} for each crop using a method described in Burton et al (1993).

Gross margins and MACs were first evaluated for individual crops produced within particular cropping systems. Further analysis was conducted by considering whole-farm cropping systems. Given the twice continuous differentiability requirement of

MAC functions, the quadratic functional forms were selected to fit nitrate-N leached response for barley in PBWPB rotation instead of linear functional forms selected based on certain statistical criteria in initial response function estimations (Chapter four). The quadratic functional forms was also selected to represent nitrate-N leaching response for managing corn (in CCAAA and CCCAA under NT systems), and nitrate-N leaching response associated with managing alfalfa (in CCCAA), barley (in PCBPC), and carrot (in PWRC) under both CT and NT systems.

Some of the mathematical models for the response functions that were initially selected based on some statistical criteria (Chapter four) had non-closed-form expressions for generating MACs. Such mathematical functions with no closed-form expressions could not be expressed into a finite unit or number. In addition, estimating the integral of the MAC functions, $\int \lambda(d\overline{V})$, with respect to nitrate-N leached regulation to obtain abatement cost using such non-closed-form expressions was not possible. In such cases the more appropriate alternative mathematical models were used. The optimal N demand (X^{**}) equations generated assuming restrictions on groundwater nitrate-N limits and MAC equations for alternative response functions assessed are summarized in Table 5.4.

5.5 Results and Discussions

5.5.1 Trade-Offs Without Nitrate Pollution Restrictions

Initial trade-offs analysis in the previous chapter (four) evaluated percentage changes in crop yields and the associated percentage change in nitrate-N leached, assuming farmers apply nitrogen fertilizer at the MERN relative to existing or recommended NMP rates. In this section, crop yield and N fertilizer prices were

Table 5.4. Equations for optimal N fertilization levels, and marginal abatement cost associated with nitrate-N leached restrictions.

Type of crop yield and associated nitrate-N response functions	Optimal N fertilization function $X^{**}{}_{ik} = f(\bar{V}_{ik})$	Marginal abatement cost function $\lambda = f(p, w, V^{-}\_ik\ )$
Quadratic crop yield and nitrate-N leaching response functions	$-\frac{1}{2}\left[\frac{\beta - \sqrt{\beta^2 + 4\gamma\bar{V}_{ik} - 4\gamma\alpha}}{\gamma}\right]$	$\frac{pb\gamma - pc\beta + pc\sqrt{\beta^2 + 4\gamma\bar{V}_{ik} - 4\gamma\alpha} - w\gamma}{\gamma\sqrt{\beta^2 + 4\gamma\bar{V}_{ik} - 4\gamma\alpha}}$
Mitscherlich-Buale crop yield with a quadratic nitrate leaching response function	$-\frac{1}{2}\left[\frac{\beta - \sqrt{\beta^2 + 4\gamma\bar{V}_{ik} - 4\gamma\alpha}}{\gamma}\right]$	$\frac{pabe^{\frac{1}{2}\left[\frac{b(2c\gamma+\beta-\sqrt{\beta^2+4\gamma\bar{V}_{ik}-4\gamma\alpha}}{\gamma}\right]} - w}{\sqrt{\beta^2 + 4\gamma\bar{V}_{ik} - 4\gamma\alpha}}$

where a, b, c represent crop yield response parameters, and α, β, and γ represent parameters for nitrate leaching response function.

incorporated in the analysis to generate farm net returns, measured in terms of gross margins (GMs) or total revenue above variable cost of production.

The estimated MERNs without considering restrictions on nitrate-N leached levels suggest that farmers in TBW tend to over apply nutrient N fertilizer to potato, carrots and alfalfa, while under applying to grains such as barley in some rotations. The finding about farmers over applying N fertilizer to economically important high value crops such as potatoes and carrots is consistent with Yadav et al (1997) and Rajsic and Weersink (2008). The contrasting finding for selected grain crops highlights the importance of site-specific NMP evaluations for individual crops and accounting for residual nutrients from preceding crops.

5.5.1.1 Variable costs and farm returns

Variable costs of production for individual crops and gross margins for the crops studied are summarized in Table 5.5. In general, farm returns were higher at the MERN than the returns from applying N fertilizer at the recommended rates, as expected. Estimated farm returns for potatoes in all the potato rotations studied, alfalfa in CCCAA under NT system, and carrots under CT were lower than returns from applying N fertilizer at the recommended rates (Table 5.5). Such low farm returns at the MERN were associated with the Mitscherlish-Baule crop response to nutrient N fertilizer/manure. Similar low farm returns were found for Llewelyn and Featherstone (1997) and Alivelu et al (2007), who noted that the M-B model tends to predict lower MERNs compared with the quadratic model. Thus, farm returns at the MERNs resulting from the M-B models tend to be lower than expected (Llewelyn and Featherstone 1997; Alivelu et al 2007). As expected, although the MERNs for some crops (e.g., barley and alfalfa) were lower than

Table 5.5. Total Variable Costs and Gross Margins (\$ ha^{-1}) for crops managed under alternative cropping systems at MERN and NMP recommended N rates.

Crop	Crop rotation	Total Variable Cost at MERN	Gross Margin at MERN	Total Variable Cost at NMP recommended N rate	Gross Margin at NMP recommended N rate	Total Variable Cost at MERN	Gross Margin at MERN	Total Variable Cost at NMP recommended nutrient N	Gross Margin at NMP recommended nutrient N
			Conventional Tillage				No-Till		
Corn	CCAAA	808.12	556.87	786.89	539.76	704.27	669.84	679.39	647.46
	CCCAA	805.55	574.28	786.89	559.72	706.51	692.80	679.39	665.13
	PBWPC	900.89	671.83	786.89	425.90	787.73	771.55	679.39	540.36
	PCBPC	849.75	355.84	786.89	260.85	744.52	471.70	679.39	371.24
	PWRC	946.32	1178.90	786.89	688.96	841.23	1310.56	679.39	806.84
Barley	PBWPC	271.93	169.61	269.70	169.43	289.40	149.01	288.19	148.96
	PCBPC	266.92	164.33	269.70	164.03	283.84	143.55	288.19	142.79
Winter wheat	PBWPC	404.65	208.55	401.01	203.62	417.66	185.47	414.16	181.04
	PWRC	410.39	347.91	401.01	318.00	422.61	320.15	414.16	295.22
Potato	PBWPC	2527.52	8465.36	2534.68	8473.93	2527.46	8453.12	2534.68	8461.73
	PCBPC	2519.58	7612.93	2534.68	7623.10	2519.63	7599.95	2534.68	7610.13
	PWRC	2517.17	9140.72	2534.68	9150.28	2511.87	9085.92	2534.68	9091.07
Alfalfa	CCAAA	502.22	900.63	550.98	869.24	526.62	841.80	575.38	840.79
	CCCAA	502.22	897.24	550.98	858.70	526.62	826.63	575.38	828.36
Carrot	PWRC	1580.93	18225.67	1598.06	19778.78	1580.20	18173.55	1598.06	18165.54

the NMP recommended N rates, gross margins at the MERN were higher than gross margins at NMP recommended N rates.

The results suggest that, in general variable cost of production and farm returns were highest for high value horticulture crops such as carrots and potatoes, compared with small grains and forage crop. The study also provides interesting insights on the effect of tillage on production costs and farm returns. In general, farm returns were higher for CT systems than for NT systems for all crops, except for grain corn (Table 5.5). As with the finding for crop yields, the highest gross margins for corn, potatoes, and winter wheat were generated from PWRC rotation, while the highest farm returns for barley were from PBWPC. In addition, results reveal interesting insights about the relative economic importance of the crops studied.

The results of the individual crop enterprise budget analysis were extended to whole-farm cropping systems involving all crops in each rotation (Table 5.6). Farm returns for whole-farm systems were compared with average yearly nitrate-N leached for each cropping system. In general, returns to farmers over variable costs increased by 1.2 to 3.6% assuming farmers apply fertilizer at the MERN compared with actual rates applied (Table 5.6). The associated nitrate-N leached for corn-based cropping systems under NT management decreased from 14% for CCCAA to 32% for CCAAA (Table 5.6).

In addition, nitrate-N leached decreased (38%) for CCAAA under CT, but increased slightly (by 0.6%) for CCCAA under CT (Table 5.7). Although the MERNs for grain corn were higher than NMP recommended N rate, rotating grain corn with forage or legume crops requiring little or no N fertilization tended to reduce average yearly nitrate-N leached. Results also suggests that under CT systems, a higher frequency of the forage or legume relative to the grain crops tended to decrease nitrate-N.

Table 5.6. Trade-offs among crop returns above N fertilizer cost and nitrate leaching.

Cropping systems	Crop rotation	Gross margin at MERN (\$ ha^{-1})	Gross margin at NMP recommended N rate (\$ ha^{-1})	% change in gross margins	Average nitrate-N leached per year at MERN (kg^{-1} ha^{-1} yr^{-1})	Average nitrate-N leached per year at NMP recommended N rate (kg^{-1} ha^{-1} yr^{-1})	% change in nitrate-N leached
(a) ***Conventional Tillage***							
Corn	**CCAAA**	**3815.62**	**3687.24**	**3.48**	**33.59**	**53.84**	**-37.62**
	CCCAA	3517.31	3396.57	3.55	54.38	54.06	0.60
Potato	PBWPC	17980.71	17746.82	1.32	86.97	77.21	12.64
	PCBPC	16101.88	15931.95	1.07	105.58	94.47	11.75
Vegetable-horticulture	**PWRC**	**28893.19**	**28376.05**	**1.82**	**84.62**	**77.75**	**8.82**
(b) ***No-Till***							
Corn	CCAAA	3865.07	3817.30	1.25	39.74	58.76	-32.36
	CCCAA	3731.67	3652.13	2.18	58.94	68.48	-13.92
Potato	**PBWPC**	**18012.27**	**17793.82**	**1.23**	**95.39**	**85.70**	**11.30**
	PCBPC	16286.85	16105.53	1.13	116.28	104.46	11.32
Vegetable-horticulture	PWRC	28890.18	28358.67	1.87	86.96	79.48	9.41

Note: % change implies: [(MERN - NMP recommended) ÷ NMP] × 100.
Negative figures denote a 'decrease'.

In contrast to the nitrate-N leached results for corn-based systems, a higher percentage in nitrate-N leached relative to the percentage increase in gross margins were observed for potato-based systems and vegetable-horticulture-based systems (i.e., 8% to 13%) for both tillage systems (Table 5.6). PBWPC under CT generated the highest increase in farm returns, and nitrate-N leached for potato-based cropping systems.

The results suggest that CCAAA under CT was preferred over the other corn-based systems considered and PWBPC under NT was preferred over the other potato-based systems considered (Table 5.6). Similarly PWRC under CT is the preferred choice among the vegetable-horticulture-based systems (Table 5.6). There were mixed findings and observations concerning the effects of tillage system on nitrate-N leaching due to interaction between crops in the whole-farm analysis and complications from other factors (Table 5.6), consistent with earlier studies (e.g., Lipiec et al 2011; Stoddard et al 2005; Tyler and Thomas 1977; Nyborg and Malhi 1989; Dick et al 1989).

5.5.1.2 Eco-efficiency index comparison

In this study, the EEI analysis was applied to selected (i.e., individual) crops in a rotation system (as opposed to whole-farm enterprises). The results for individual crops provide insights on the effect of rotation system (i.e., preceding crops and sequence) and tillage type on eco-efficiency. The results suggests that for potatoes, which is traditionally grown under CT management, growing the non-potato crops under NT management in rotation with potatoes generates a higher eco-efficiency than when the non-potato crops are managed under CT. For example, the EEI for potatoes with non-potato crops under the NT system for PCBPC was 0.0279 compared with 0.0273 under the CT system (Table 5.7). Similarly, for carrots, the EEI for the rotation system under NT was higher (EEI = 0.0521) than under CT (EEI = 0.0486).

There was an unexpected finding for the EEI for grain corn under the two tillage treatments. The EEI for the grain corn-based systems considered highlight the environmental benefits of more frequent forage production in corn rotation systems. For both tillage systems, the grain corn-based rotation with three (two) years of alfalfa (corn), CCAAA, generated higher EEIs than the rotation with two (three) years of alfalfa (corn).

Some studies suggest that NT management can enhance nitrate-N leaching compared with CT management (e.g., Tyler and Thomas 1977; Kranz and Kanwar 1995; Nyborg and Malhi 1989; and Dick et al 1989). For example, in a study for corn production under both NT and CT systems, Tyler and Thomas (1977) found that $NO_3^-{-}N$ concentrations in drainage water collected below soil depth of 106 cm were higher under

Table 5.7. Eco-efficiency index comparison for grain corn, potatoes and carrot production.

Crop	Crop rotation	Conventional tillage	No-till
Grain corn	CCAAA	**0.3107**	0.2192
	CCCAA	0.1195	0.0804
Potato	PBWPC	0.0107	0.0108
	PCBPC	0.0273	**0.0279**
Carrot	PWRC	0.0486	**0.0521**

NT management than under CT. Although the EEI results provide useful insights on long-term sustainability, the analysis provide limited perspectives on trade-offs between farm profitability and nutrient-N pollution.

5.5.2 Trade-offs with nitrate-N pollution restrictions

Trade-off analysis in the previous section (involving farm enterprise budgets and EEI) did not consider restrictions on N-leached levels. The results in this section are based on analysis in which it was assumed that farmers are faced with alternative intensive management options for growing various crops, and also have restrictions on level of nitrate-N leached.

5.5.2.1 Marginal abatement cost for alternative cropping systems

In this section, MACs associated with meeting the Health Canada maximum contaminant limit (MCL) of nitrate-N in water systems were estimated for all crops considered, and then the MCL was varied to generate the MAC curves.

The results summarized in Table 5.8 to 5.12 are consistent with the theoretical expectations (see Figure 5.1) in which less stringent nitrate-N leached restrictions results in higher farm returns (Figure 5.5). The MAC curves for all crops had negative slopes, as expected (see, for example, Figure 5.6 for corn production). The only exception was for alfalfa, to which farmers traditionally do not apply N fertilizer. The trade-off between farm returns and nitrate-N leached levels for corn production (Figure 5.5) illustrates the conflict between the economic and environmental quality objectives faced by a farmer. As nitrate-N leached regulations become less stringent, more N fertilizer/manure tends to be applied resulting in increasing nitrate-N pollution levels. Increasing N fertilizer rate generally increases crop yields (and farm revenue), while also increasing nitrate-N leached.

Among the alternative corn production systems considered, MACs associated with meeting the MCL was highest for CCAAA-CT (\$58.5 ha^{-1}), and lowest for PCBPC-NT (\$21.03 ha^{-1}) (Table 5.8). The trend in magnitude of the MACs across rotations was consistent for both CT and NT systems. In addition, MACs for corn production systems were generally lower among NT than CT systems. Farmers in the study area generally apply very little or no chemical fertilizer to alfalfa. Initial analysis of the alfalfa systems suggests boundary conditions of non-negativity in inputs with non-differentiable points (Table 5.9).

5.5.2.2 Cost effectiveness of nitrate-N pollution control

In this section, cost effectiveness of reducing nitrate-N leached to meet Health Canada MCL on nitrate-N is assessed for individual crop fields. The analysis was then extended by considering varying levels of stringency of nitrate-N pollution regulations. Systems with least MAC and highest farm returns are considered cost effective systems.

Cost effectiveness of meeting the Health Canada MCL restriction ($\bar{V}_{ik}$ = MCL)

The results summarized in Table 5.8 suggest that the abatement strategy with the highest farm returns for corn production was not the same strategy with the lowest abatement cost. The lowest abatement cost for corn production was associated with PCBPC-NT, while the highest farm returns was associated with PWRC-NT (Table 5.8).

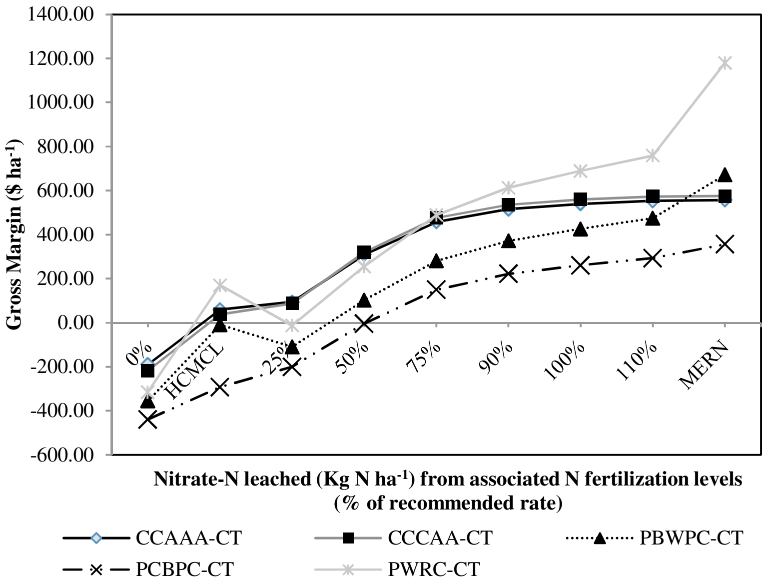

Figure 5.5: Gross margins increase with less stringent nitrate-N leached regulation levels for corn production under conventional tillage.

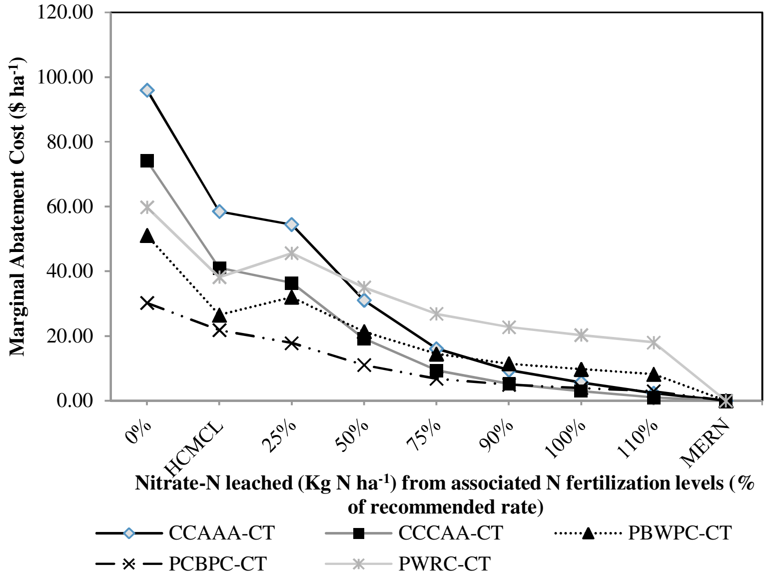

Figure 5.6: Marginal abatement cost under varying nitrate-N leached restriction levels for corn production under conventional tillage.

Table 5.8. Gross Margins ($ha^{-1}) and Marginal Abatement Costs ($ha^{-1}) for corn production, under alternative nitrate –N leaching restrictions and management options.

	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha-^{1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC
	CCAAA-CT[a]			CCCAA-CT			PBWPC-CT			PCBPC-CT			PWRC-CT		
0%[b]	18.82	-189.73	96.01	23.79	-217.78	74.20	24.49	-355.28	51.10	25.97	-439.06	30.19	23.57	-315.17	59.81
MCL[c]	22.17	60.14	58.52	19.09	37.99	41.01	14.91	-9.39	26.51	20.23	-292.27	21.85	13.40	169.82	38.21
25%	22.76	93.45	54.45	25.08	87.58	36.44	21.04	-109.76	32.03	30.64	-200.27	17.82	19.19	-12.98	45.59
50%	27.99	309.43	31.08	33.82	318.94	19.22	29.19	102.28	21.33	44.64	-4.02	11.08	25.91	255.11	35.01
75%	34.50	458.20	16.10	45.31	476.33	9.36	39.35	280.83	14.49	62.24	149.69	6.83	33.54	489.09	26.82
90%	39.02	515.20	9.45	53.52	535.24	5.24	46.42	371.89	11.45	74.52	221.49	4.96	38.55	613.11	22.74
100%	42.29	539.76	5.68	59.55	559.72	2.97	51.53	425.90	9.74	83.42	260.85	3.91	42.08	688.96	20.30
110%	45.77	553.57	2.35	66.02	572.37	1.01	56.96	474.56	8.22	92.91	293.41	2.98	45.76	759.36	18.05
MERN[d]	48.64	556.87	0.00	69.88	574.28	0.00	116.80	671.83	0.00	140.02	355.84	0.00	103.51	1178.90	0.00
	CCAAA-NT			CCCAA-NT			PBWPC-NT			PCBPC-NT			PWRC-NT		
0%	19.36	-78.46	57.75	19.84	-110.00	46.17	15.02	-246.26	49.93	20.27	-330.99	28.61	13.88	-206.03	47.53
MCL	23.59	132.85	43.12	25.33	102.51	32.61	24.54	91.38	26.17	26.17	-186.66	**21.03**	24.89	**227.33**	32.70
25%	25.21	199.00	38.76	28.00	183.61	28.15	21.42	2.67	30.97	31.13	-92.58	17.17	21.17	98.23	36.75
50%	32.03	412.47	24.83	38.33	410.67	16.98	29.97	216.76	20.45	45.60	103.93	10.79	29.51	368.47	28.54
75%	39.82	561.96	14.18	50.83	571.17	9.37	40.65	395.99	13.76	63.67	258.54	6.73	38.91	604.67	22.08
90%	44.97	620.94	8.92	59.37	635.54	5.87	48.09	486.80	10.80	76.24	331.19	4.92	45.06	730.05	18.82
100%	48.59	647.46	5.78	65.50	665.13	3.85	53.48	540.36	9.14	85.34	371.24	3.91	49.37	806.84	16.86
110%	52.37	663.75	2.89	71.97	684.08	2.05	59.21	588.36	7.66	95.02	404.59	3.01	53.85	878.18	15.04
MERN	56.68	669.84	0.00	80.76	692.80	0.00	118.29	771.55	0.00	145.38	471.70	0.00	124.75	1310.56	0.00

[a] CT denotes conventional tillage and NT denotes no-till systems.

[b] denotes percentage level of NMP recommended N rate.

[c] MCL denotes Health Canada maximum contaminant limit for N in drinking water.

[d] MERN denotes maximum economic rate of nitrogen.

Table 5.9. Gross Margins $(\$\ \mathrm{ha}^{-1})$ and Marginal Abatement Costs $(\$\ \mathrm{ha}^{-1})$ for barley and alfalfa production, under alternative nitrate –N leaching restrictions and management options.

Crop		Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC	Groundwater N leaching restriction level (kg N ha^{-1} yr^{-1})	Gross Margin	MAC
		PBWPC-CT			PCBPC-CT			PBWPC-NT			PCBPC-NT		
Barley	0%	21.13	-33.46	_	21.57	-27.57	9.83	25.79	-52.25	15.67	28.50	-44.85	7.55
	MCL	33.13	**50.23**	7.39	30.20	-15.50	**7.43**	33.48	-316.29	7.38	30.55	-374.77	**7.10**
	25%	26.69	53.11	13.80	26.80	59.23	8.28	34.31	34.56	6.96	42.63	42.03	4.91
	50%	33.09	115.78	7.42	33.45	120.10	6.70	47.23	97.04	3.33	58.48	102.26	2.81
	75%	40.33	154.55	4.66	41.52	155.03	5.17	64.56	135.17	1.33	76.05	135.85	1.10
	90%	45.08	166.35	3.60	47.05	163.54	4.30	77.07	146.36	0.51	87.41	143.21	0.22
	100%	48.42	169.43	3.03	51.03	164.03	3.74	86.29	148.96	0.07	95.32	n.c.	n.c.
	110%	51.89	168.69	2.54	55.23	160.37	3.21	96.21	n.c.	n.c.	103.51	n.c.	n.c.
		CCAAA-CT[a]			CCCAA-CT			CCAAA-NT			CCCAA-NT		
Alfalfa	0%[b]	36.48	900.63	7.26	31.84	897.2426	0.09	37.65	841.7988	19.79	32.53	826.6314	16.23
	MCL[c]	23.57	900.63	_[d]	23.58	897.2426	_	24.14	808.0068	_	24.01	792.8394	_
	25%	42.15	n.c.[e]	n.c.	37.64	n.c.	n.c.	43.11	n.c.	n.c.	39.23	858.3138	0.16
	50%	48.21	n.c.	n.c.	46.22	n.c.	n.c.	49.58	n.c.	n.c.	48.20	n.c.	n.c.
	75%	54.68	n.c.	n.c.	57.57	n.c.	n.c.	57.06	n.c.	n.c.	59.44	n.c.	n.c.
	90%	58.75	n.c.	n.c.	65.72	n.c.	n.c.	62.02	n.c.	n.c.	67.27	n.c.	n.c.
	100%	61.55	n.c.	n.c.	71.70	n.c.	n.c.	65.54	n.c.	n.c.	72.95	n.c.	n.c.
	110%	64.40	n.c.	n.c.	78.13	n.c.	n.c.	69.21	n.c.	n.c.	78.99	n.c.	n.c.

[a] CT denotes conventional tillage and NT denotes no-till systems.

[b] denotes percentage level of NMP recommended N rate.

[c] MCL denotes Health Canada maximum contaminant limit for N in drinking water.

[d] non differentiable point.

[e] The notation n.c. implies that the groundwater nitrate-N restriction was a redundant constraint.

On the other hand, the abatement strategy with the highest abatement cost was CCAAA-CT (Table 5.8). Although PCBPC-NT generated the lowest cost of pollution abatement, it also resulted in a negative (\$-186.66 ha^{-1}) farm returns (Table 5.8). As was found for corn, trade-offs associated with abatement strategies for barley production differed among alternative cropping systems. The abatement strategy with the lowest abatement cost was not the same as that with the highest farm returns. The barley production system with the lowest abatement cost was from PCBPC-NT at \$7.10 ha^{-1} while the production system with the highest abatement cost was from PCBPC-CT at \$7.43 ha^{-1} (Table 5.9).

Cost effectiveness assessment for winter wheat production systems suggests that at MCL of 10mg L^{-1}, PWRC-CT was the preferred abatement strategy with the highest farm returns and lowest abatement cost (Table 5.10). The same cropping system (PWRC-CT) was cost effective among carrot production systems, with the highest farm returns and the lowest abatement cost (Table 5.12). As with the results for winter wheat and carrots, the potato production system with the lowest abatement cost was the same as that which generated the highest farm returns. Overall, PBWPC-NT was the preferred cost effective management option for potato production. The abatement cost associated with MCL was very high (\$8624.30 ha^{-1}) for producing potato under PWRC-NT (Table 5.11).

Cost effectiveness of meeting alternative nitrate-N pollution regulations

Varying the nitrate-N restriction levels, $(\bar{V}_{ik})$, allowed for assessing alternative trade-off scenarios. Generally, farm returns increased as pollution standards became less stringent. Consistent with Yiridoe and Weerksink (1998) who generated net returns and abatement cost for corn and winter wheat production for Southwestern Ontario.

Table 5.10. Gross Margins (\$ ha^{-1}) and Marginal Abatement Costs (\$ ha^{-1}) for winter wheat production, under alternative nitrate –N leaching restrictions and management options.

	Restriction on Nitrates[a]	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC
	PBWPC-CT[b]			PWRC-CT			PBWPC-NT			PWRC-NT		
0%[c]	21.13	-10.52	14.64	21.57	41.80	18.83	21.18	-25.72	13.37	23.84	24.79	26.49
MCL[d]	24.08	28.75	12.17	28.60	**141.77**	**10.96**	24.22	-155.34	11.21	28.69	-52.89	13.48
25%	28.14	72.70	9.58	28.26	137.97	11.20	28.57	54.92	8.83	29.17	120.27	12.88
50%	36.45	136.12	5.98	37.13	216.06	6.93	37.25	116.27	5.55	37.23	197.17	7.17
75%	46.05	179.77	3.29	48.20	276.07	4.19	47.21	158.30	3.05	48.03	255.48	4.03
90%	52.43	196.46	1.98	55.89	303.40	2.98	53.81	174.26	1.83	55.82	281.55	2.74
100%	56.95	203.62	1.21	61.45	329.71	2.29	58.46	181.04	1.10	61.57	295.22	2.04
110%	61.67	207.63	0.50	67.37	318.00	1.68	63.31	184.73	0.43	67.75	305.91	1.44
MERN[e]	65.43	208.55	0.00	91.18	347.91	0.00	66.81	185.47	0.00	89.67	320.15	0.00

[a] Groundwater nitrate-N leached from associated N fertilization levels (0%, 25%, 50%, 75%, 90%, 100% and 110% of NMP recommended N rate) (kg N ha^{-1} yr^{-1}).

[b] CT denotes conventional tillage and NT denotes no-till systems.

[c] denotes percentage level of NMP recommended N rate.

[d] MCL denotes Health Canada maximum contaminant limit for N in drinking water.

[e] MERN denotes maximum economic rate of nitrogen.

Table 5.11. Gross Margins ($ ha^{-1}) and Marginal Abatement Costs ($ ha^{-1}) for potato production, under alternative nitrate –N leaching restrictions and management options.

	Restriction on Nitrates[a]	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC
	PBWPC-CT[b]			PCBPC-CT			PWRC-CT		
0%[c]	18.14	2840.76	875.26	21.33	2445.61	705.43	18.55	4477.84	731.71
MCL[d]	21.95	5092.49	399.29	21.25	2445.61	716.53	19.99	5378.61	535.37
25%	30.74	7056.94	121.44	36.35	6523.92	92.55	32.36	8191.38	88.19
50%	51.01	8147.69	21.08	59.01	7416.26	14.05	53.89	8979.18	12.64
75%	78.96	8418.39	3.71	89.31	7598.76	1.95	83.16	9133.34	1.60
90%	99.41	8463.06	1.13	111.15	7620.80	0.38	104.44	9149.83	0.23
100%	114.58	8473.93	0.39	127.25	n.c.[f]	n.c.	120.16	n.c.	n.c
110%	130.98	8476.81	0.01	144.56	n.c.	n.c.	137.13	n.c.	n.c
	PBWPC-NT			PCBPC-NT			PWRC-NT		
0%	18.23	2802.23	871.01	21.58	2417.33	698.13	22.73	3837.64	1343.07
MCL	22.11	**6973.62**	**395.36**	21.43	4307.60	718.05	20.34	5727.91	8624.30
25%	30.93	7042.29	121.08	36.75	6507.10	92.09	33.98	8227.81	103.13
50%	51.32	8135.90	20.99	59.56	7402.37	14.02	53.87	8975.69	10.85
75%	79.39	8406.46	3.68	90.03	7585.61	1.95	82.40	9088.71	0.87
90%	99.92	8450.95	1.12	111.98	7607.79	0.38	103.66	n.c	n.c.
100%	115.14	8461.73	0.38	128.14	n.c.	n.c.	119.56	n.c.	n.c.
110%	131.60	8464.54	0.00	145.52	n.c.	n.c.	136.84	n.c.	n.c.

[a] Groundwater nitrate-N leached from associated N fertilization levels (0%, 25%, 50%, 75%, 90%, 100% and 110% of NMP recommended N rate) (kg N ha^{-1} yr^{-1}).

[b] CT denotes conventional tillage and NT denotes no-till systems.

[c] denotes percentage level of NMP recommended N rate.

[d] MCL denotes Health Canada maximum contaminant limit for N in drinking water.

[f] The notation n.c. implies that the groundwater nitrate-N restriction was a redundant constraint.

Table 5.12. Gross Margins (\$ ha^{-1}) and Marginal Abatement Costs (\$ ha^{-1}) for carrot production, under alternative nitrate –N leaching restrictions and management options.

	Restriction on Nitrates[a]	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC
	PWRC-CT[b]			PWRC-NT		
0%[c]	22.41	14944.09	755.54	22.40	15851.29	806.46
MCL[d]	22.89	**14944.09**	**680.62**	22.91	14851.72	718.70
25%	36.48	18006.60	43.11	36.52	17978.18	40.33
50%	51.74	18220.42	2.26	51.81	18170.72	1.78
MERN[e]	55.00	18225.67	1.07	53.82	18173.55	1.08
75%	68.69	n.c.[f]	n.c.	68.77	n.c.	n.c.
90%	79.66	n.c.	n.c.	79.75	n.c.	n.c.
100%	87.32	n.c.	n.c.	87.41	n.c.	n.c.
110%	95.24	n.c.	n.c.	95.33	n.c.	n.c.

[a] Groundwater nitrate-N leached from associated N fertilization levels (0%, 25%, 50%, 75%, 90%, 100% and 110% of NMP recommended N rate) (kg N ha^{-1} yr^{-1}).

[b] CT denotes conventional tillage and NT denotes no-till systems.

[c] denotes percentage level of NMP recommended N rate.

[d] MCL denotes Health Canada maximum contaminant limit for N in drinking water.

[e] MERN denotes maximum economic rate of nitrogen fertilization.

[f] n.c. implies that the groundwater nitrate-N restriction was a non-binding constraint.

In general, NT systems were more cost effective among the alternative abatement strategies for corn production that CT systems, across the nitrate-N pollution restriction range considered, $\bar{V}_{ik}$ > MCL > $\bar{V}_{ik}$ (Table 5.8). PWRC-NT generated the highest farm returns and relatively low abatement cost for nitrate-N leached levels from N fertilization levels above 75% of the recommended rate and therefore, the preferred cost effective abatement strategy. On the other hand, for N pollution regulations, below this threshold (for nitrate-N leaching levels associated with below 75% of NMP recommended N rate), CCCAA-NT was the cost effective abatement strategy for corn management (Table 5.8).

Among alternative pollution control cropping systems for barley, NT systems generally resulted in lower abatement cost than CT systems. At more stringent pollution restrictions below MCL = 10mg L^{-1} yr^{-1}, PBWPC-NT generated the highest abatement cost (\$16 ha^{-1}), and a negative farm returns of (\$-52 ha^{-1}) (Table 5.9). The cost effective option with further relaxing in the pollution regulation was PCBPC-CT. PBWPC-NT management was cost effective for barley production for restrictions in N pollution, $\bar{V}_{ik} >$ 47.23 kg N ha^{-1} yr^{-1} (Table 5.9).

As with the results for barley, the least cost effective pollution control cropping system for winter wheat production at $\bar{V}_{ik} <$ MCL = 10 mg L^{-1} yr^{-1} was PBWPC-NT (Table 5.10). However unlike barley, the preferred cost effective option at $\bar{V}_{ik} >$ MCL = 10 mg L^{-1} yr^{-1} was PWRC-CT (Table 5.10). Among the winter wheat production options, rotation system effect on abatement cost was generally higher than effects due to tillage type.

For potato production, a dramatic decrease in abatement cost is observed for groundwater nitrate-N regulation levels associated with 0% to 75% N fertilization rates (Table 5.11). A similar trend was observed for carrot production (Table 5.12). The cost effective abatement strategy for carrot production was PWRC-CT, across all pollution regulation levels. The same cropping system (PWRC-CT) was cost effective pollution reduction strategy for potato production except at $\bar{V}_{ik}$ = 30.93 kg N ha^{-1} yr^{-1} where PWRC-NT was the preferred abatement system.

As with the ANOVA results (presented in chapter three), although alfalfa yields does not significantly respond to nitrogen, slight increases in alfalfa yields are observed when N fertilizer rate increased from 0% to 25% of the recommended N fertilization rate. Further increase in N fertilization beyond this rate resulted in a plateau alfalfa yields. Consistent with the yield results, less stringent nitrate regulations beyond MCL = 10 mg L^{-1} yr^{-1}, become redundant.

5.5.2.3 Cost effectiveness of pollution abatement under whole-farm scenarios

In this section, trade-offs were assessed by comparing farm returns and marginal abatement costs averaged for all the crops in each rotation system.

For corn-based cropping systems, the nitrate-N abatement strategies to meet the MCL = 10 mg L^{-1} yr^{-1} varied depending on the rotation system. The cropping system with the highest farm returns was CCCAA-NT. The same cropping system also resulted in the lowest marginal abatement cost, (Table 5.13).

As with the findings for corn-based cropping systems, the cropping system with the lowest marginal abatement cost, (PWBPC-NT) also generated the highest farm returns at MCL =10 mg L^{-1} yr^{-1}. Similarly, for the vegetable-horticulture systems, PWRC-CT was the cost-effective abatement system (Table 5.14).

As the pollution restriction was varied, CCAAA-NT consistently generated highest farm returns. The same cropping system (i.e., CCAAA-NT) also generated the lowest MACs at all levels of groundwater nitrate-N pollution limits (Figure 5.7). Thus CCAAA-NT was the most cost effective system among the corn-based cropping systems (Table 5.13; Figure 5.7).

In general, NT systems tended to generate higher farm returns for corn-based and potato-based systems at all groundwater nitrate-N pollution limits. NT systems also generated the lowest marginal abatement cost across all groundwater nitrate-N pollution limits for both corn-based and potato-based systems. For vegetable-horticulture systems, systems under NT management generated the highest abatement cost at more stringent nitrate-N leaching restrictions, while system under CT management generated the lowest marginal abatement cost. For both corn-based and potato based systems, tillage system had a dramatic effect on farm returns as the rotation system.

Table 5.13. Whole-farm analysis of Gross Margins (\$ ha^{-1}) and Marginal Abatement Costs (\$ ha^{-1}) for selected cropping systems under varying levels of nitrate-N pollution restrictions.

	Restriction on Nitrates[a]	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC	Restriction on Nitrates	Gross Margin	MAC
(a) CORN-BASED CROPPING SYSTEMS												
	CCAAA-CT[b]			CCCAA-CT			CCAAA-NT			CCCAA-NT		
0%[c]	29.42	464.48	42.76	27.01	228.23	44.55	30.33	473.69	34.97	24.92	264.65	34.20
MCL[d]	23.01	60.14	58.52	20.89	37.99	41.01	23.92	-78.46	43.12	24.80	**102.51**	**32.61**
25%	34.39	580.34	20.80	30.10	409.47	21.39	35.95	603.18	15.38	32.49	453.49	16.96
50%	40.12	659.92	11.28	38.78	544.27	11.08	42.56	683.81	8.98	42.28	587.15	9.77
75%	46.61	712.14	5.34	50.21	634.08	5.24	50.16	736.55	4.77	54.27	678.89	5.23
90%	50.86	730.55	2.72	58.40	666.56	2.81	55.20	755.77	2.72	62.53	714.61	3.17
100%	53.84	737.45	1.24	64.41	679.31	1.47	58.76	763.46	1.50	68.48	730.43	1.98
110%	56.95	n.c.[e]	n.c.	70.86	684.96	0.31	62.47	767.05	0.69	74.78	739.85	0.71
MERN[f]	33.59	763.12	4.35	54.38	703.46	0.00	39.74	773.01	11.87	58.94	746.33	6.49
(b) POTATO-BASED CROPPING SYSTEMS												
	PBWPC-CT			PCBPC-CT			PBWPC-NT			PCBPC-NT		
0%	20.61	1328.93	454.07	23.23	797.11	296.21	19.69	1056.04	364.20	22.44	825.57	292.21
MCL	23.20	2050.92	168.93	22.63	858.24	296.84	25.29	**2713.40**	**167.10**	25.15	1573.42	297.05
25%	27.47	2825.98	59.65	32.15	2541.30	45.81	29.23	2835.35	57.79	35.68	2574.21	44.68
50%	40.15	3329.91	15.38	48.15	2988.92	11.39	43.42	3340.37	14.26	53.76	3022.97	10.49
75%	56.73	3490.39	5.97	68.92	3130.39	4.55	62.24	3500.48	5.10	76.69	3164.83	3.69
90%	68.55	3532.16	3.86	83.68	3169.63	2.99	75.76	3541.86	3.08	92.77	3204.23	2.17
100%	77.21	3549.36	2.95	94.47	3186.39	2.30	85.70	3558.76	2.21	104.46	3221.11	1.49
110%	86.01	3561.08	2.32	104.88	3198.46	1.89	94.72	3570.24	1.62	114.33	3233.60	1.11
MERN	87.46	3595.96	0.90	106.73	3219.58	1.04	97.05	3602.18	0.33	118.88	3256.28	0.24

[a] Groundwater nitrate-N leached from associated N fertilization levels (0%, 25%, 50%, 75%, 90%, 100% and 110% of NMP recommended N rate) (kg N ha^{-1} yr^{-1}).

[b] CT denotes conventional tillage and NT denotes no-till systems.

[c] denotes percentage level of NMP recommended N rate.

[d] MCL denotes Health Canada maximum contaminant limit.

[e] n.c. implies that the groundwater nitrate-N restriction was a redundant constraint.

[f] MERN denotes maximum economic rate of nitrogen fertilization.

Table 5.14. Whole-farm analysis of Gross Margins (\$ ha^{-1}) and Marginal Abatement Costs (\$ ha^{-1}) for vegetable-horticulture-based cropping systems under varying nitrate–N pollution restrictions.

	Restriction on Nitrates[a]	Average Gross Margin	Average MAC	Restriction on Nitrates	Average Gross Margin	Average MAC
		PWRC-CT[b]			PWRC-NT	
MCL[c]	21.22	**5158.57**	**316.29**	24.21	5188.52	2347.29
0%	21.53	4787.14	391.47	20.71	4876.92	555.89
25%	29.07	6580.74	47.02	30.21	6606.12	48.27
50%	42.17	6917.69	14.21	43.11	6928.01	12.08
75%	58.40	7031.41	8.07	59.53	7030.77	6.64
90%	69.63	7072.19	6.37	71.07	7068.83	5.25
100%	77.75	7096.94	5.50	79.48	7088.72	4.53
110%	86.37	7109.77	4.75	88.44	7108.69	3.91
MERN[d]	84.62	7223.30	0.53	86.96	7222.54	0.55

[a] Groundwater nitrate-N leached from associated N fertilization levels (0%, 25%, 50%, 75%, 90%, 100% and 110% of NMP recommended N rate) (kg N ha^{-1} yr^{-1}).

[b] CT denotes conventional tillage and NT denotes no-till systems.

[c] denotes percentage level of NMP recommended N rate.

[d] MCL denotes Health Canada maximum contaminant limit.

[e] MERN denotes maximum economic rate of nitrogen.

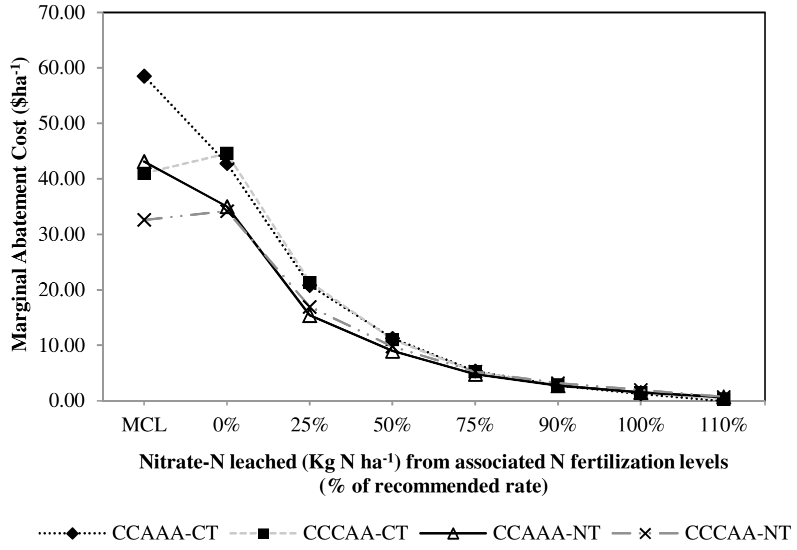

Figure 5.7: Marginal Abatement Cost for alternative corn-based cropping system.

5.6 Summary and Conclusion

Trade-offs between farm profitability and improvements in agriculture-induced water quality is important for agricultural watershed management. In this study eco-efficiency index method was used to evaluate a set of crops in selected cropping systems assumed to be managed in the Thomas Brook watershed. In addition, trade-offs between reductions in gross margins associated with incremental changes in water quality improvements were investigated, with and without restrictions or regulations on nitrate-N pollution. The crops considered in the analysis reflect high value and other economically important crops commonly grown in the Annapolis Valley region of Nova Scotia.

Without regulations on nitrate-N pollution, whole-farm analysis of farm returns suggests that CCAAA under CT generated the highest gross margins for corn-based cropping systems. The same cropping system was the preferred for producing corn among the corn cropping system based on EEI analysis. In addition, for growing potato, the potato-based cropping system with the highest EEI was PCBPC under NT, while PWRC under NT generated the highest EEI among carrots cropping system for managing carrots.

In the optimization analysis with nitrate-N pollution regulations, gross margins and abatement costs were estimated by varying the stringency of the policy regulation above and below the Health Canada MCL of 10 mg L^{-1} yr^{-1}. The most cost-effective cropping systems that met the Health Canada maximum contaminant limit (MCL) (of 10mg L^{-1}) on nitrate-N in drinking water were consistent with the cost-effective cropping systems without regulations on nitrate-N pollution for vegetable-horticulture-based and potato-based cropping systems. For grain corn-cropping systems, cost-effectiveness of pollution control cropping system shifted from one cropping system to another as a result of the MCL (of 10 mg L^{-1} yr^{-1}) regulation.

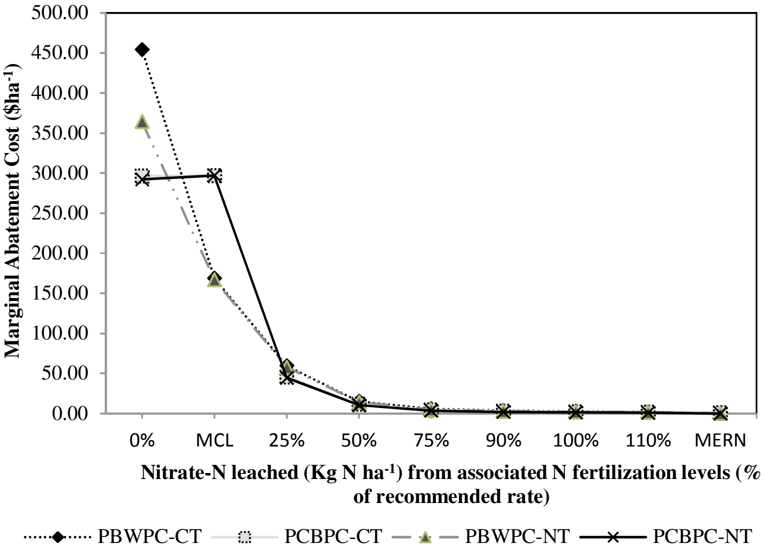

Figure 5.8: Marginal Abatement Cost for alternative potato-based cropping system.

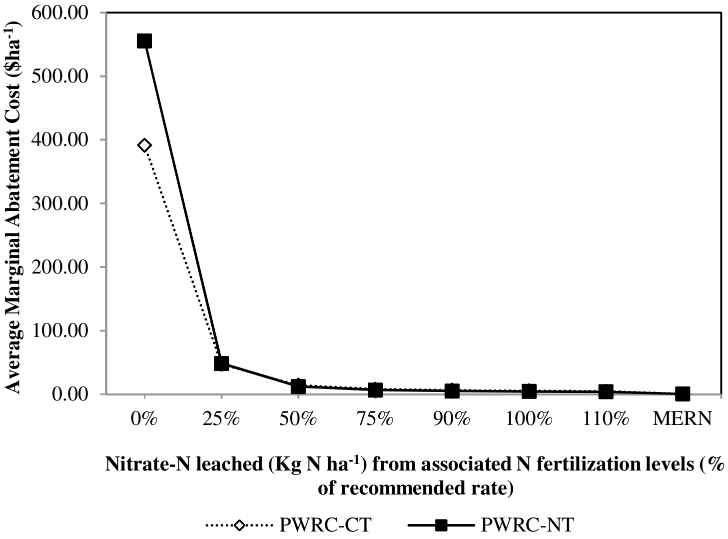

Figure 5.9: Marginal Abatement Cost for alternative vegetable-horticulture-based cropping system.

In summary the cost-effective choice of cropping system for nitrate-N pollution control depended on the stringency of the nitrate-N leached regulation level. The differences in MACs were not substantial among cropping systems at higher nitrate-N leached restrictions (i.e., less stringent nitrate-N pollution levels) (Figure 5.7 to 5.9). This implies that at less stringent nitrate-N pollution levels, extensive management choices (crop rotation and tillage systems) were not as important as the intensive management choice (i.e., N fertilizer/manure level e.g., MERN) for a particular crop. The findings in this study are generally consistent with Yiridoe and Weersink (1998) and Swinton and Clark (1994) who noted that, under stringent agricultural pollution regulations, there tend to be substitution for less N intensive cropping systems.

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CHAPTER 6 : SUMMARY AND CONCLUSIONS

6.1 Background

Groundwater nitrate-N pollution poses a threat to human health and is of heightened concerned in Atlantic Canada. There are also reported concerns with sediment transport from farm fields into water systems. An important problem for farmers involves determining ‘optimal’ crop choice and rotation management, and the associated level of N fertilizer application rates to crops.

In central and western Canada, guidelines for recommended nutrient rates to crops are commonly based on actual field trials. Agronomic studies during recent decades have further investigated potential savings from reduction in N fertilization due to residual nutrients from previous crops and management regimes. However, similar field trials have not been conducted for Atlantic Canada conditions. Nutrient application guidelines for the Maritimes reflect knowledge from field studies in Central Canada.

In this study, the economic problem was to provide policy analysts, and farmers with crop and site relevant information regarding how farmers could cost effectively adjust current crop management systems to control agricultural non-point source pollutants. The research problem was to integrate biophysical modeling with economic optimization analysis for various cropping systems. The main purpose of this study was to evaluate the effect of alternative cropping systems on farm net returns, and nitrate and sediment yields in the Thomas Brook Watershed. Cropping systems were defined as a combination of crop type, tillage type, crop rotation patterns, and nutrient N application rates.

6.2 Summary of Major Results

A summary of the main findings of the study are presented in this section according to the specific research objectives.

Objective 1: To investigate the effects of alternative cropping systems on crop and pollutant (nitrate and sediment) yields.

The Soil and Water Assessment Tool (SWAT) model was adapted for Thomas Brook watershed (TBW). The SWAT model was then validated with pollution and crop data from Thomas Brook Watershed. The model was then used to simulate crop yield, sediment load and $NO_3^- - N$ leached for representative corn-based, potato-based and vegetable horticulture cropping systems. Five crop rotation systems were evaluated each at seven fertilizer application levels and two tillage systems (conventional tillage and no-till).

ANOVA models were developed and used to statistically assess the main and interaction effects of the various cropping systems (i.e., tillage type, rotation sequence, and N fertilizer application rates) on crop yields and water pollution. Results indicated that tillage system did not significantly ($p > 0.05$) affect crop yields and $NO_3^- - N$ leached but significantly affected ($p < 0.05$) sediment load. No-till (NT) system significantly reduced sediment load. The choice of cropping sequence in a rotation significantly affected crop and pollutant yields. Crop yields and $NO_3^- - N$ leached levels were influenced by nitrogen rates, as expected.

Results suggests that, depending on the crop choice and preceding crops in a rotation, recommended/existing nutrient N could be adjusted to substantially reduce $NO_3^- - N$ leached without significant effects on crop yields.

Objective 2: To estimate input-output relationships for selected cropping systems.

Crop yield and associated nitrate-N pollution production response to N-fertilization were estimated for corn, potato, alfalfa, barley, winter wheat and carrots for the various cropping systems considered in this study using the SWAT-simulated data for the TBW. The estimated response functions were then used to determine the Maximum Economic Rate of Nitrogen (MERN) for each crop and rotation system. The analysis also allowed for determining trade-offs between crop yields reductions and associated improvements in water quality (measured in terms of changes in $NO_3^-{-}N$ leached reduction).

Among the various mathematical functional forms considered, the Mitscherlich-Baule (M-B) model best described potato, carrot and alfalfa yield response to N fertilization. By comparison, the quadratic functional form best described corn, winter wheat and barley yield response to N fertilization. $NO_3^-{-}N$ pollution response to N fertilization was best described by the quadratic functional form. For a given crop, estimated regression coefficients were different, depending on rotation and tillage type. This finding is consistent with agronomic arguments for basing fertilization rates on precision agriculture technologies and residual nutrient levels from prior crop management regimes.

Estimated MERNs for the crops considered also depended on previous crops managed in the rotation sequence. The analyses for the representative cropping systems suggest that famers in the study area tend to over-apply nutrient N to carrots, potatoes and alfalfa for all the rotations considered. On the other hand, there were contrasting findings especially for grains (i.e., corn, barley, and winter wheat), due to the properties of mathematical models considered. In general, the trade-off/frontier analysis suggest that reducing N fertilizer rate from Nutrient Management Plan recommended rates resulted in lower crop yields, in order to improve water quality (measure in terms of reduction in $NO_3^- - N$ leached level).

Objective 3: To develop a farm optimization model, and use the model to evaluate trade-offs in terms of loss in farm revenue associated with incremental reductions in nitrate-N pollution for various cropping systems. Specifically, marginal abatement costs (MAC) of reducing nitrate-N pollution were evaluated for selected cropping systems in the Thomas Brook Watershed using SWAT simulated data.

Crop yield and nitrate-N pollution response functions estimated allowed for estimation of farm enterprise budgets, eco-efficiency index, and MAC curves for alternative cropping systems considered.

Whole-farm analysis with and without nitrate-N leached regulation suggest that crop rotation sequence can be used to reduce nitrate-N pollution without substantially decreasing farm returns. There were contrasting findings on the effect of tillage system on nitrate-N pollution reduction, suggesting that tillage system, used alone, may not significantly reduce nitrate-N pollution, compared with the impacts from changes to crop rotation system.

Whole-farm analysis of farm returns and nitrate-N pollution suggest that CCAAA under CT was the preferred cropping system for grain corn, under a scenario with no regulations on nitrate-N pollution. For vegetable-horticulture cropping systems, PWRC-CT was the preferred cropping system with the highest farm returns and lowest MAC, while PBWPC-NT was the preferred choice among potato-based cropping systems.

Eco-efficiency analysis assuming no restrictions on nitrate-N pollution suggest that the CCAAA under CT management resulted in the highest eco-efficiency index (EEI) for corn production. The potato (carrot) production system with the highest EEI was PCBPC (PWRC) under NT.

On-farm pollution abatement cropping system choice generally depended on crop type, crop rotation, and tillage system. The cost effective cropping system that also met the Health Canada MCL (of 10 mg L^{-1} yr^{-1}) restriction was consistent with the findings under a scenario without restrictions on nitrate-N leached for vegetable horticulture-based and potato-based cropping systems.

6.3 Contributions of the Study

The main contributions of this research are summarized under three categories: pedagogical, methodological, and empirical contributions.

6.3.1 Pedagogical Contributions

This study consolidated the literature on mathematical functional forms commonly used in the literature to estimate response functions. For example, most of the applied economics literature on the estimation of the Mitscherlish-Baule functional form is not readily available in usable form. The properties and details of how to estimate the Mitscherlish-Baule functional form were consolidated in this study.

6.3.2 Methodological Contributions

Although there are applications of the SWAT model to watersheds in Atlantic Canada, there are no previous studies that integrated SWAT biophysical modelling with economic optimization modelling for agricultural conditions in Atlantic Canada. This study is a first attempt at such integrated biophysical-economic modelling for an agricultural watershed in Atlantic Canada.

6.3.3 Empirical Contributions

SWAT model parameters were adjusted to generate model outputs that reasonably represent the watershed conditions for the representative alternative cropping systems studied. The actual SWAT parameters that were adjusted, and magnitude of the adjustments, are reported in this study, and available for use in future related studies.

A major empirical contribution of this study involves the estimation of response functions for various crops and nitrate-N pollution for Atlantic Canada conditions. The response functions were estimated not only for individual crops, but also accounted for the effect of previous crops in a rotation sequence. Crop and pollution response functions that were previously not available for Atlantic Canada are now provided for specific crops managed in TBW. This study also provides empirical estimates of MERNs and trade-offs between farm profitability and water quality for TBW. This information can be adapted and scaled up to the larger Cornwallis River Watershed in the Annapolis Valley of Nova Scotia.

6.4 Recommendations for Further Research

As an extension of this study, it will be important for further studies to consider split application of N fertilizer to compare the effects of a single versus split application of N fertilizer rates on crop yields and nitrate-N leached.

Also further research can investigate the effect of time (i.e., annual differences in crop yields and pollutant yields) under different cropping systems. Field trials on specific locations in the watershed for specific crops of interest with different cropping systems will be important and help generate field data to further refine calibration and validation of the SWAT model for future economic analysis.

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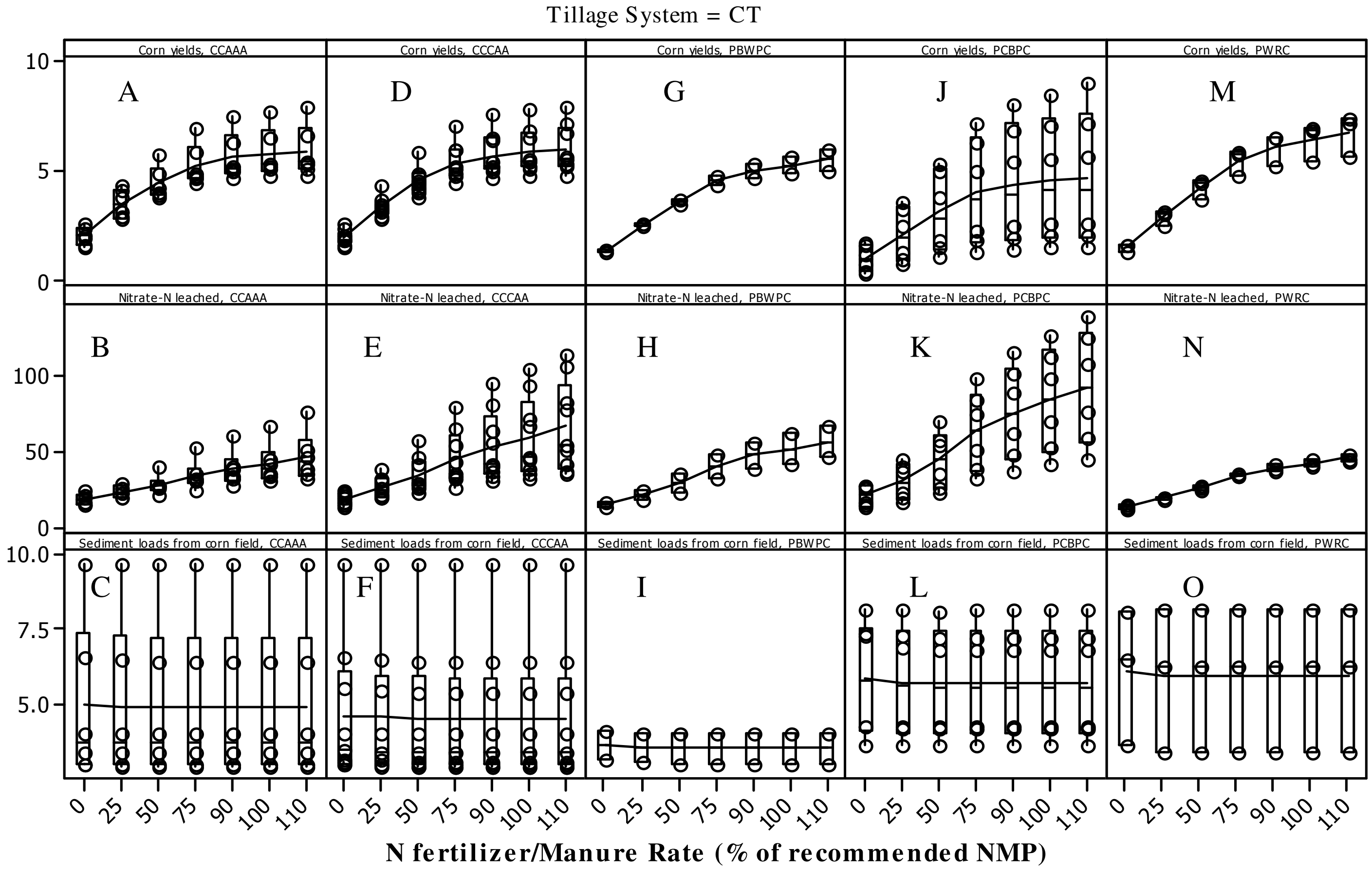
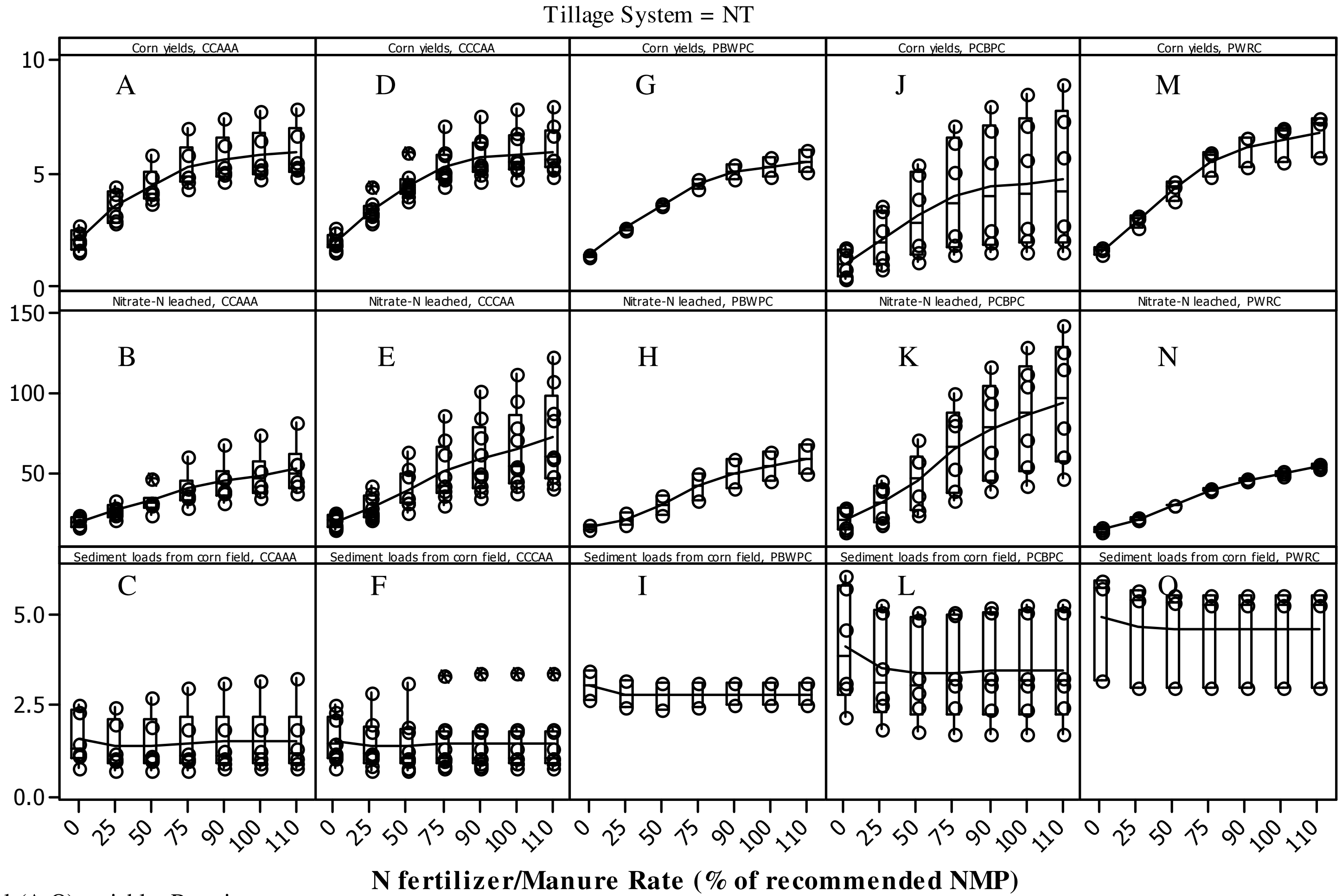
Appendix 1a: Box plots of corn yields, and associated nitrate leached and sediment loads from corn fields for different rotation systems under conventional tillage management.



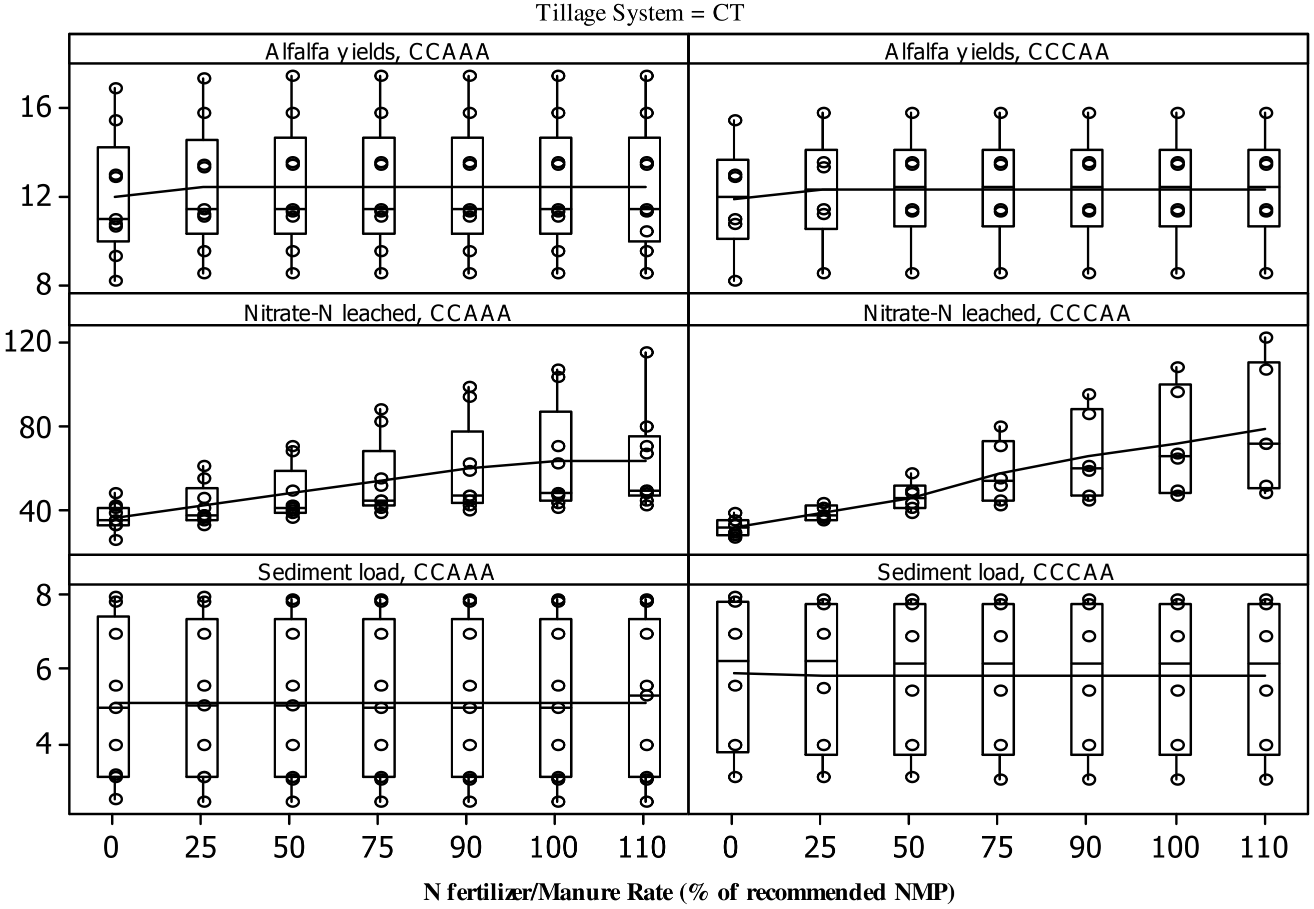
Panel (A-O) variable: Rotation sequence

Appendix 1b: Box plots of corn yields, and associated nitrate leached and sediment loads from corn fields for different rotation systems under no-till management.



Panel (A-O) variable: Rotation sequence

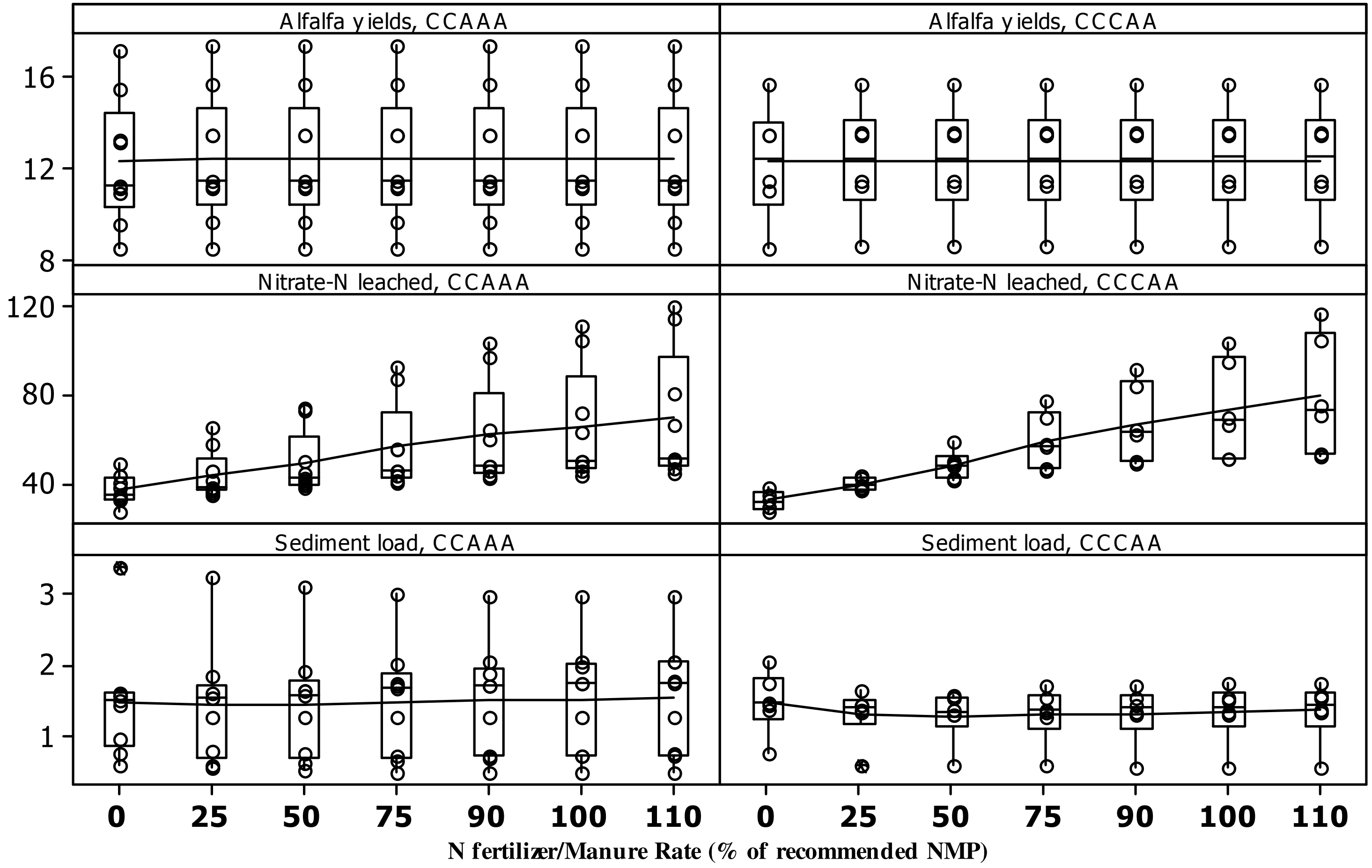
Appendix 1c: Box plots of alfalfa yields, and associated nitrate leached and sediment loads from alfalfa fields for different rotation systems under conventional tillage management.



Panel variable: Rotation sequence

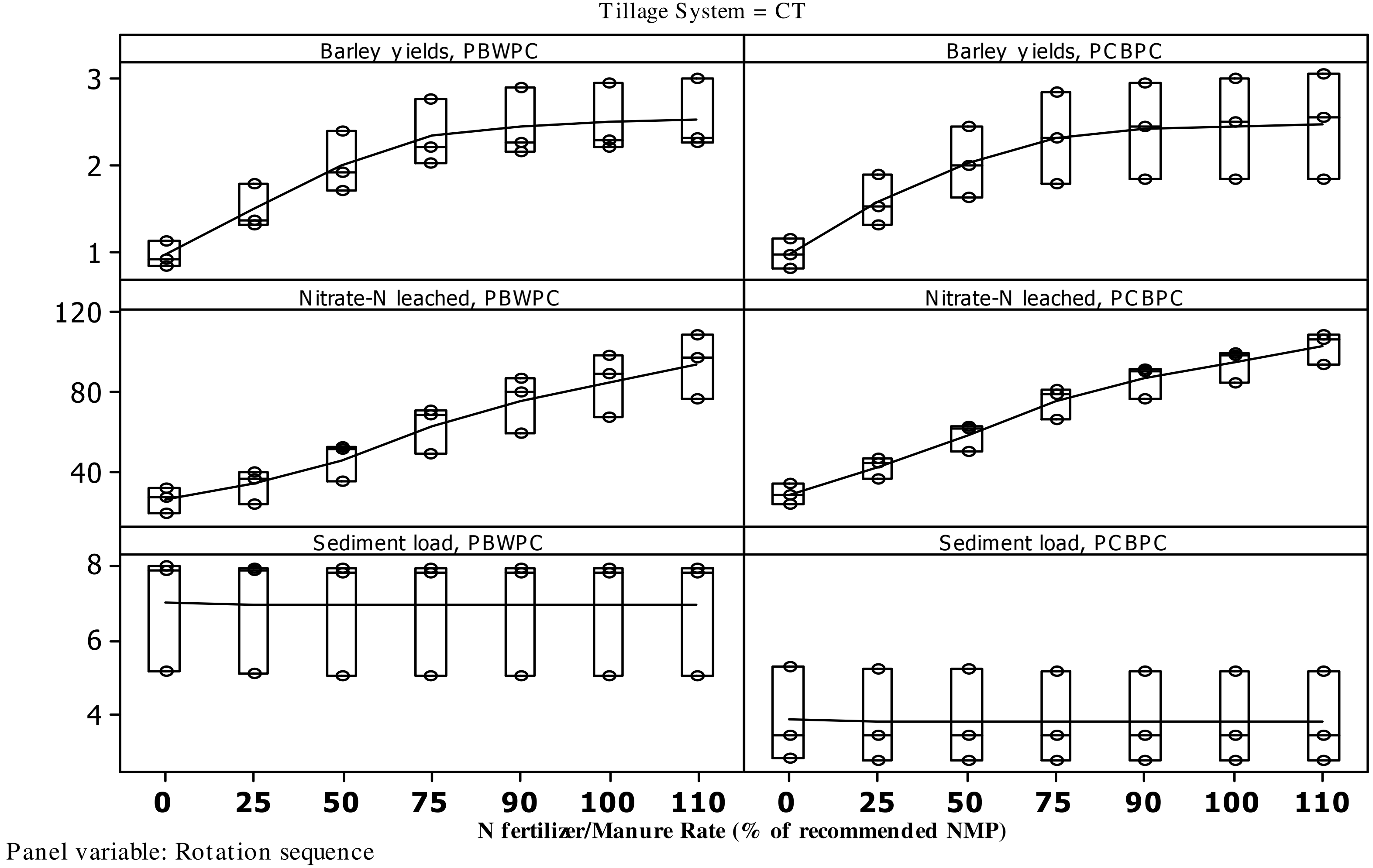
Appendix 1d: Box plots of alfalfa yields, and associated nitrate leached and sediment loads from alfalfa fields for different rotation systems under no-till management

Tillage System = NT

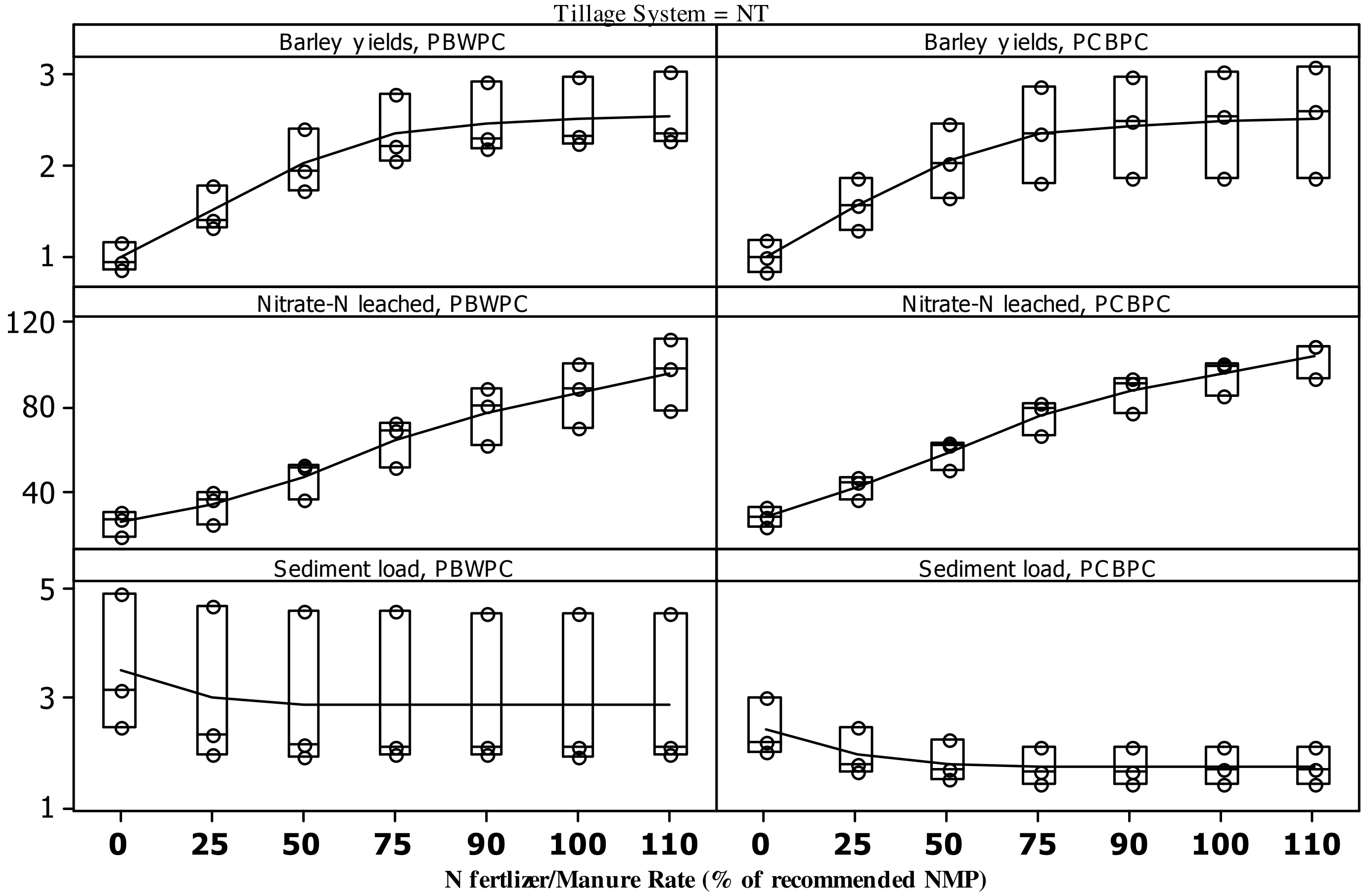


Panel variable: Rotation sequence

Appendix 1e: Box plots of barley yields, and associated nitrate leached and sediment loads from barley fields for different rotation systems under conventional tillage management.

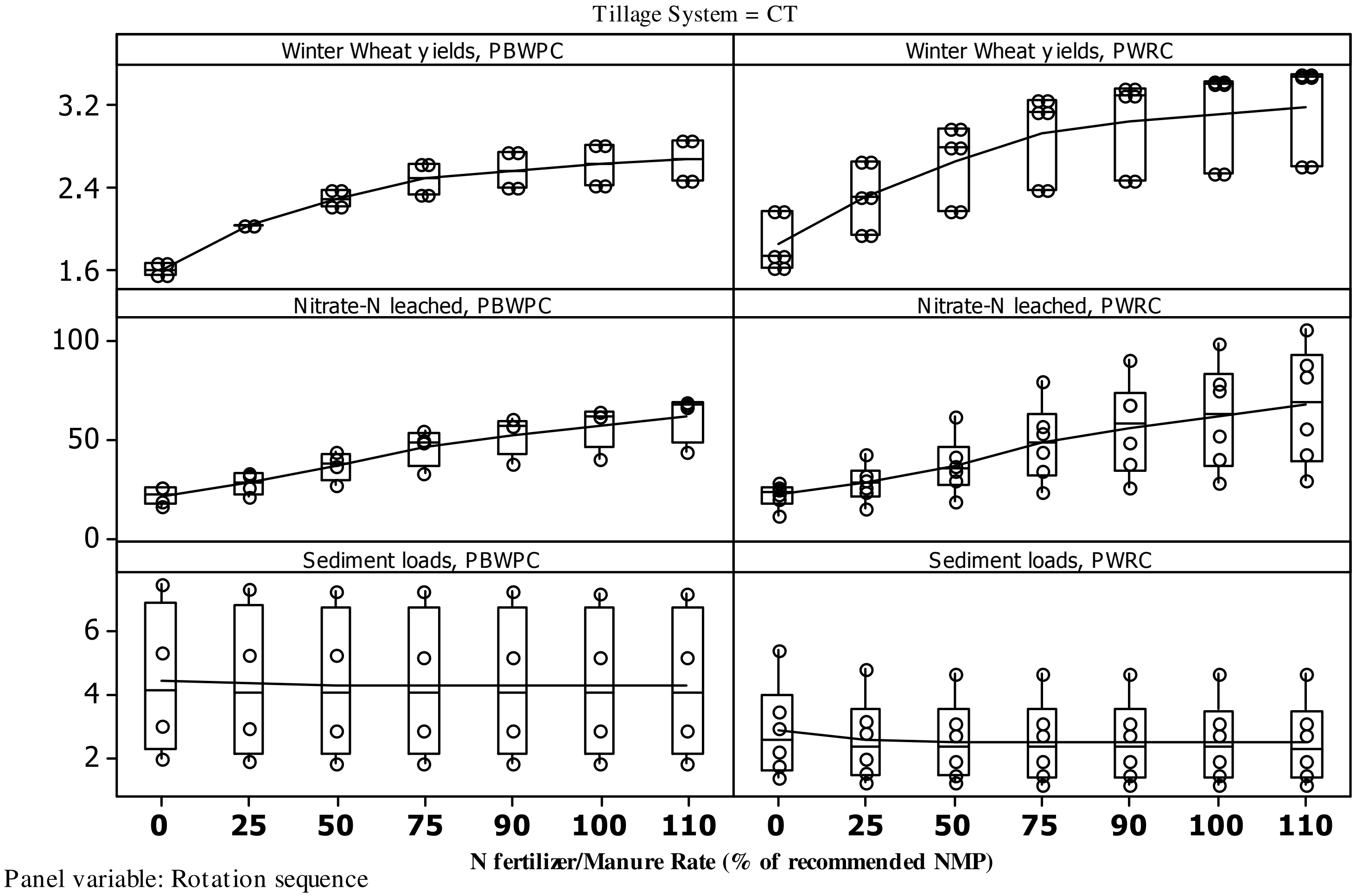


Appendix 1f: Box plots of barley yields, and associated nitrate leached and sediment loads from barley fields for different rotation systems under no-till management.

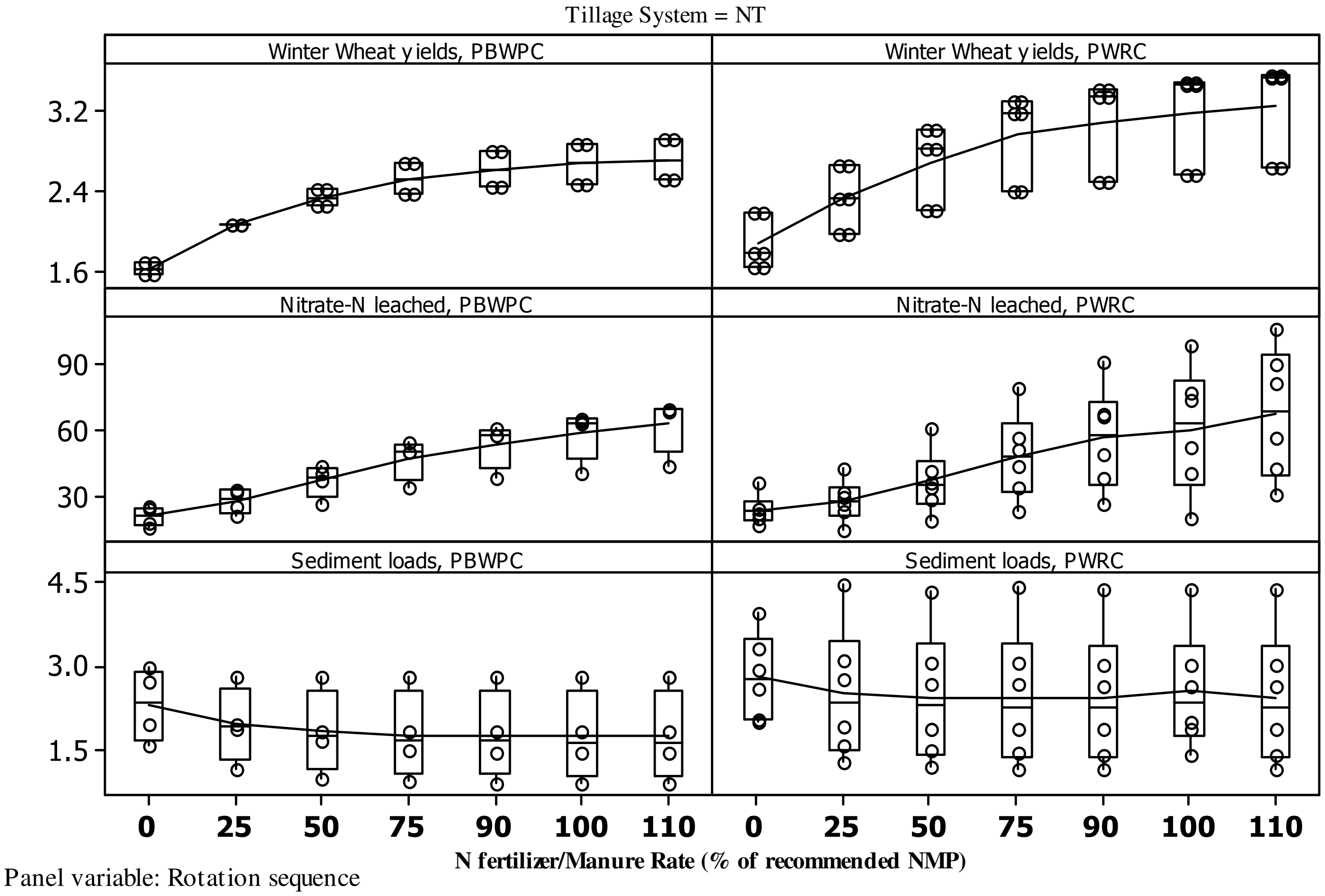


Panel variable: Rotation sequence

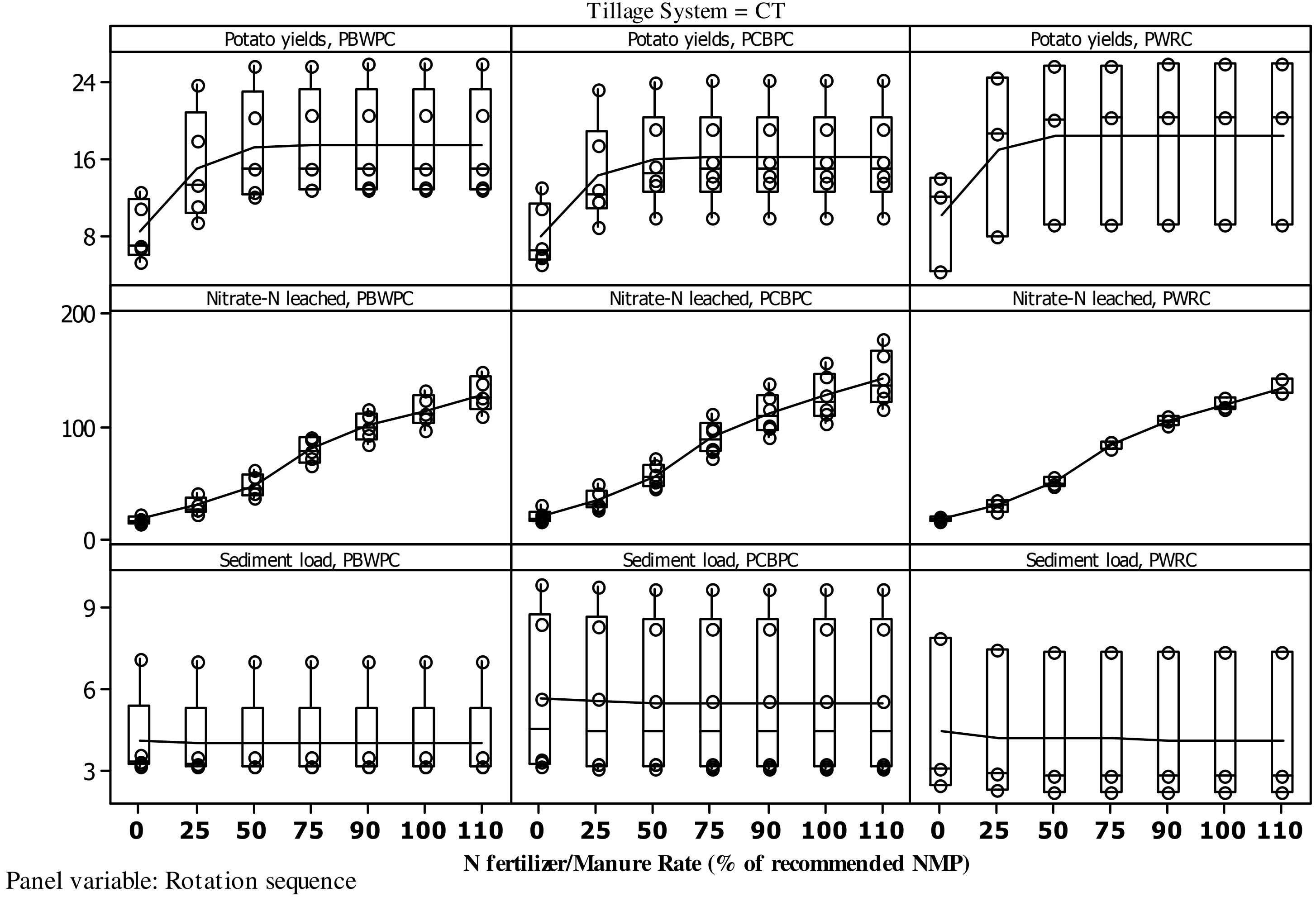
Appendix 1g: Box plots of winter wheat yields, and associated nitrate leached and sediment loads from winter wheat fields for different rotation systems under conventional tillage management.



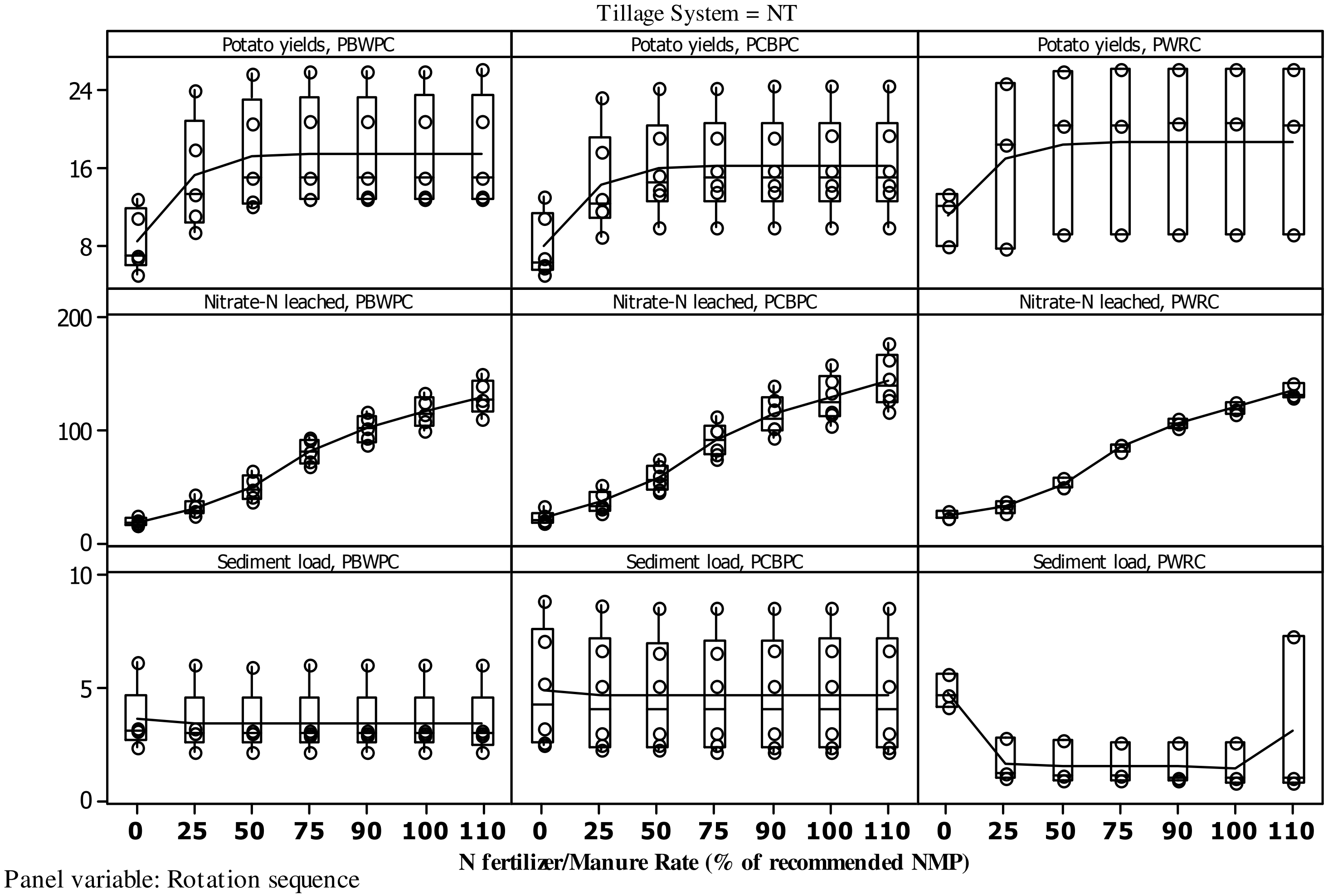
Appendix 1h: Box plots of winter wheat yields, and associated nitrate leached and sediment loads from winter wheat fields for different rotation systems under no-till management.



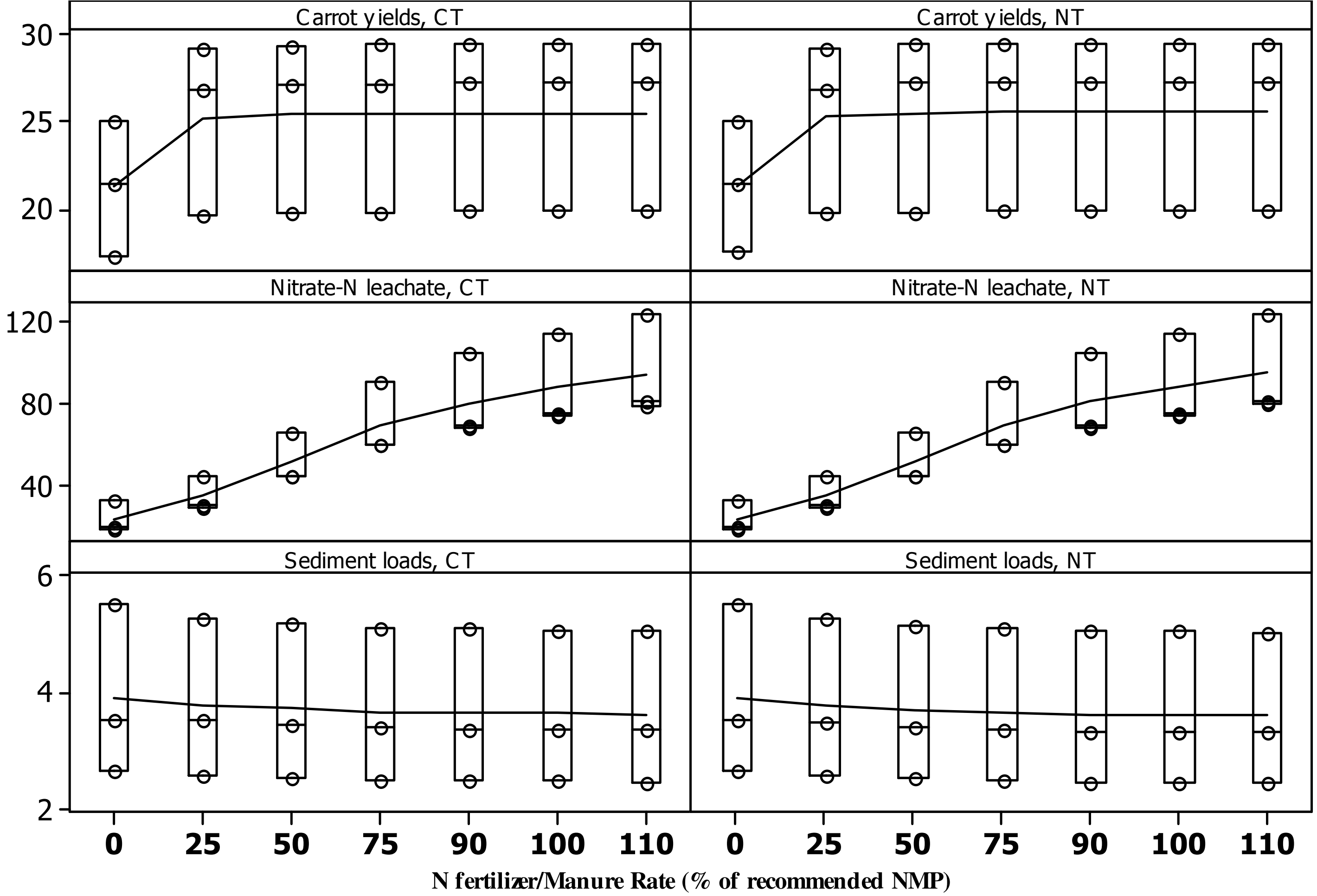
Appendix 1i: Box plots of potato yields, and associated nitrate leached and sediment loads from potato fields for different rotation systems under conventional tillage management.



Appendix 1j: Box plots of potato yields, and associated nitrate leached and sediment loads from potato fields for different rotation systems under no-till management.

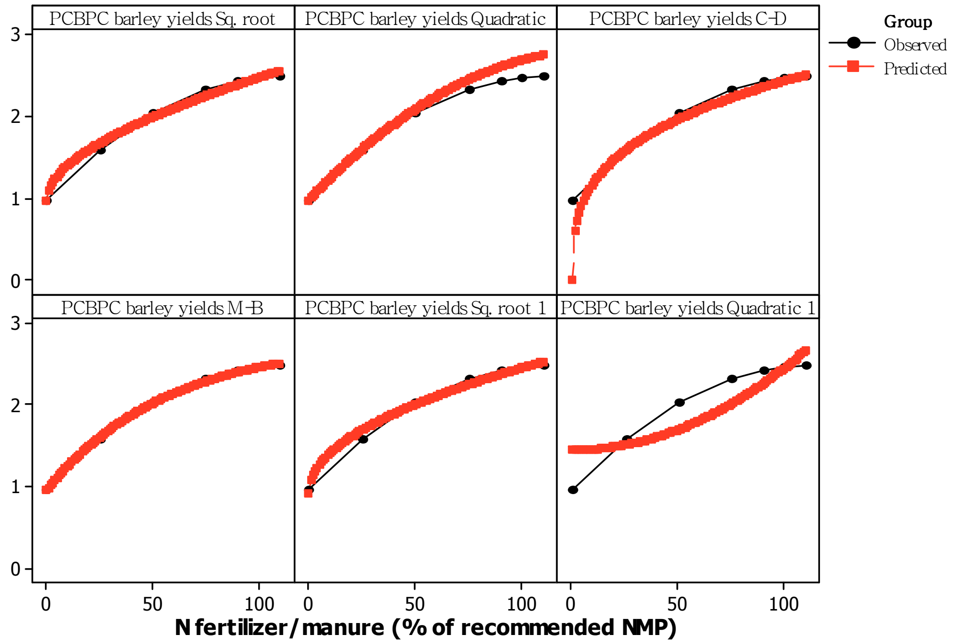


Appendix 1k: Box plots of carrot yields, and associated nitrate leached and sediment loads from carrot fields for PWRC rotation systems under both conventional and no-till management.

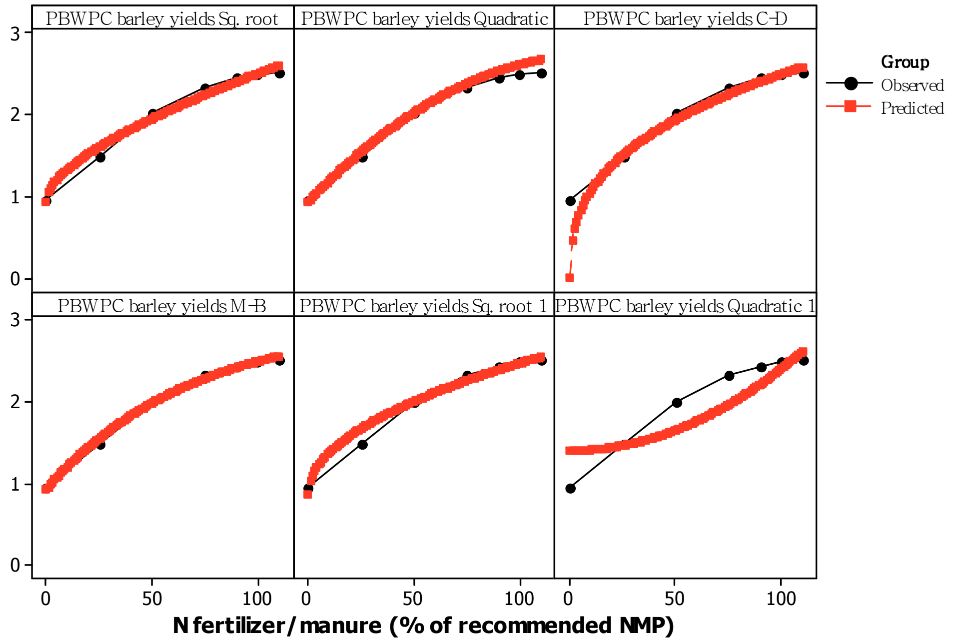


Panel variable: Tillage System

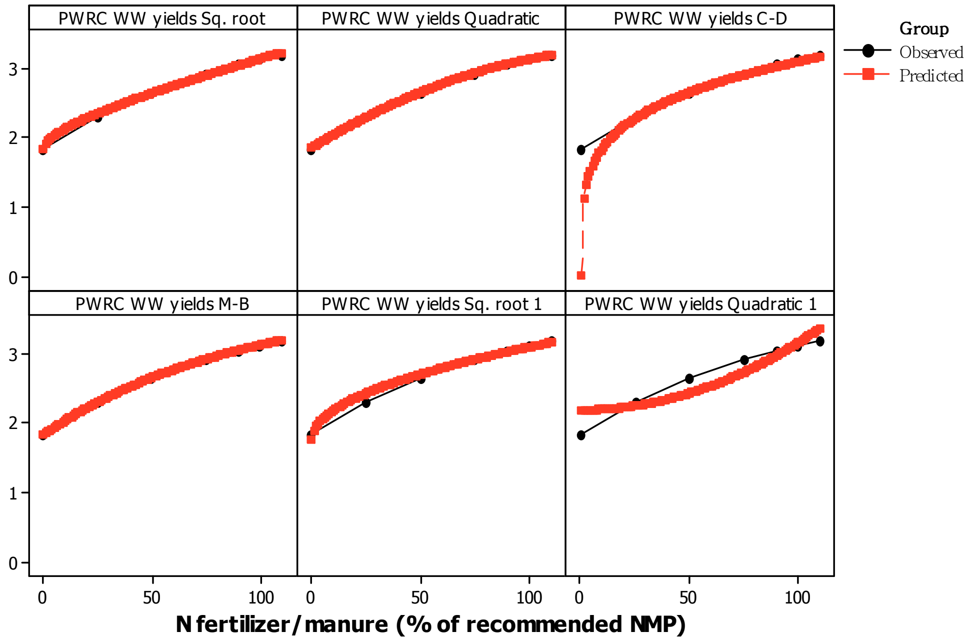
Appendix 2a: Scatter plots for alternative functional forms estimated for barley yield response to N fertilizer in PCBPC rotation under conventional tillage.



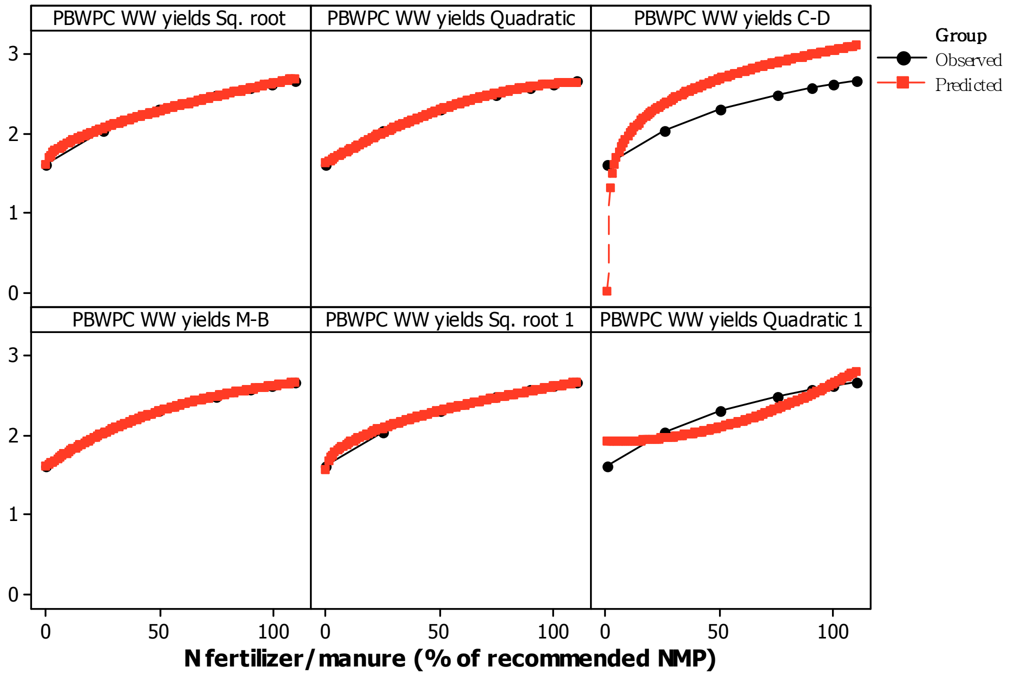
Appendix 2b: Scatter plots for alternative functional forms estimated for barley yield response to N fertilizer in PBWPC rotation under conventional tillage.



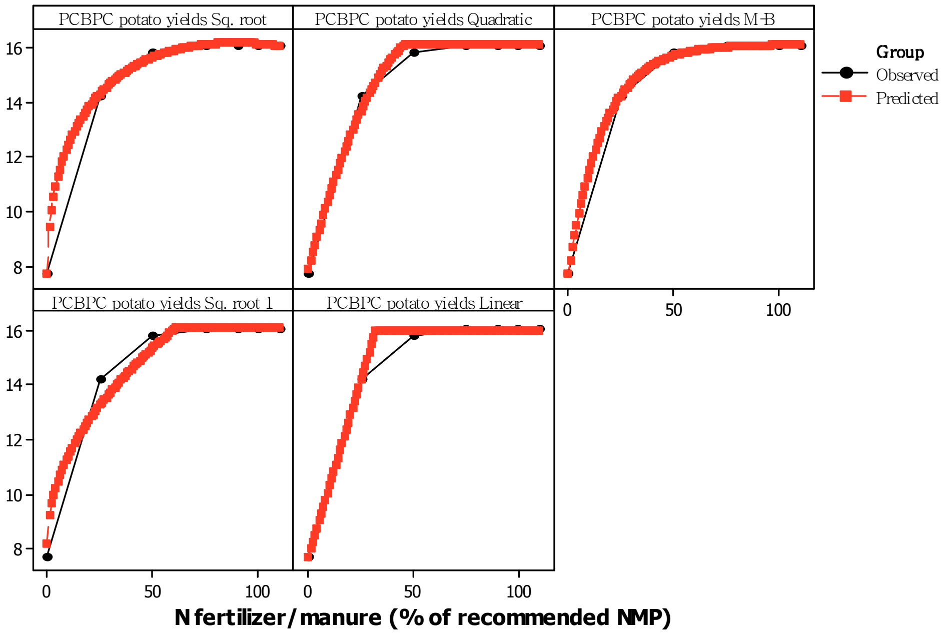
Appendix 2c: Scatter plots for alternative functional forms estimated for winter wheat yield response to N fertilizer in PWRC rotation under conventional tillage.



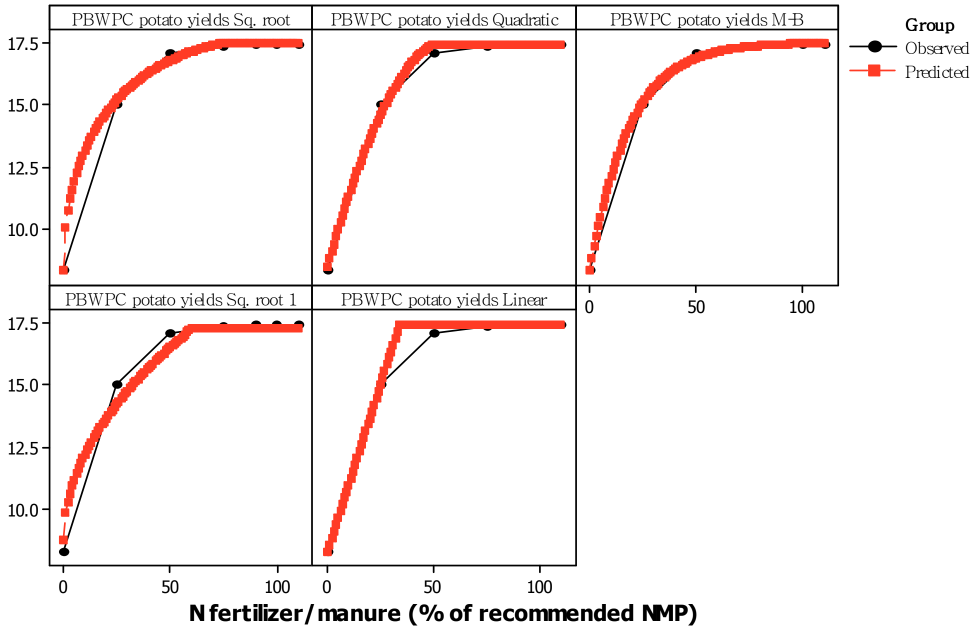
Appendix 2d: Scatter plots for alternative functional forms estimated for winter wheat yield response to N fertilizer in PBWPC rotation under conventional tillage.



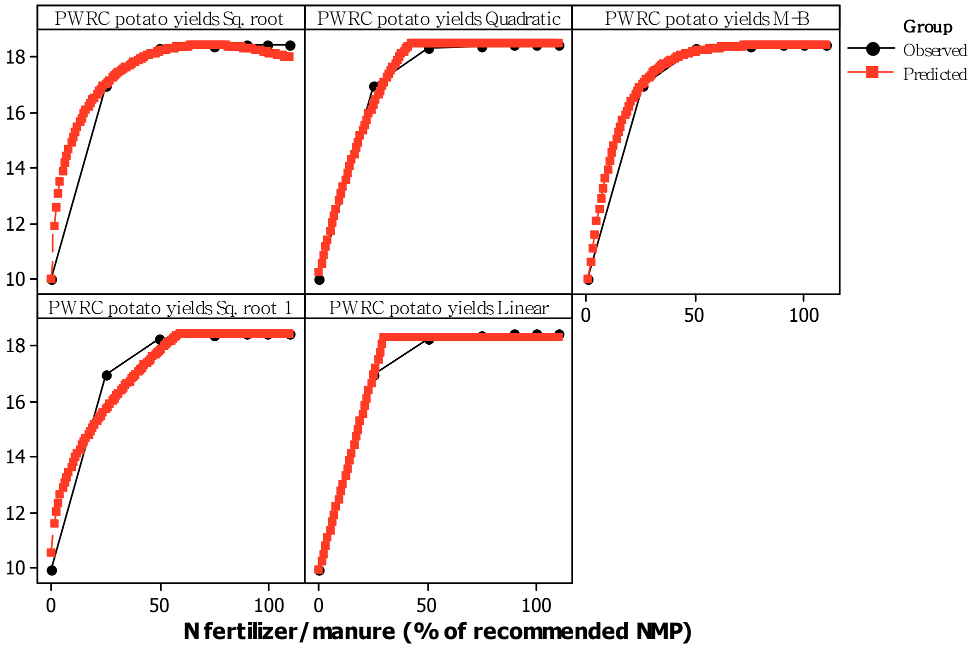
Appendix 2e: Scatter plots for alternative functional forms estimated for potato yield response to N fertilizer in PCBPC rotation under conventional tillage.



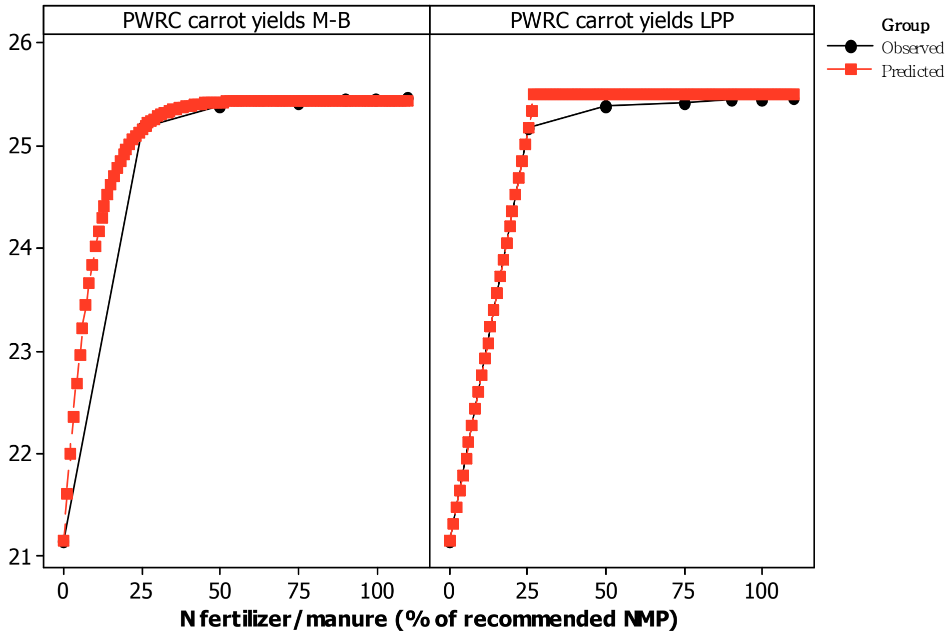
Appendix 2f: Scatter plots for alternative functional forms estimated for potato yield response to N fertilizer in PBWPC rotation under conventional tillage.



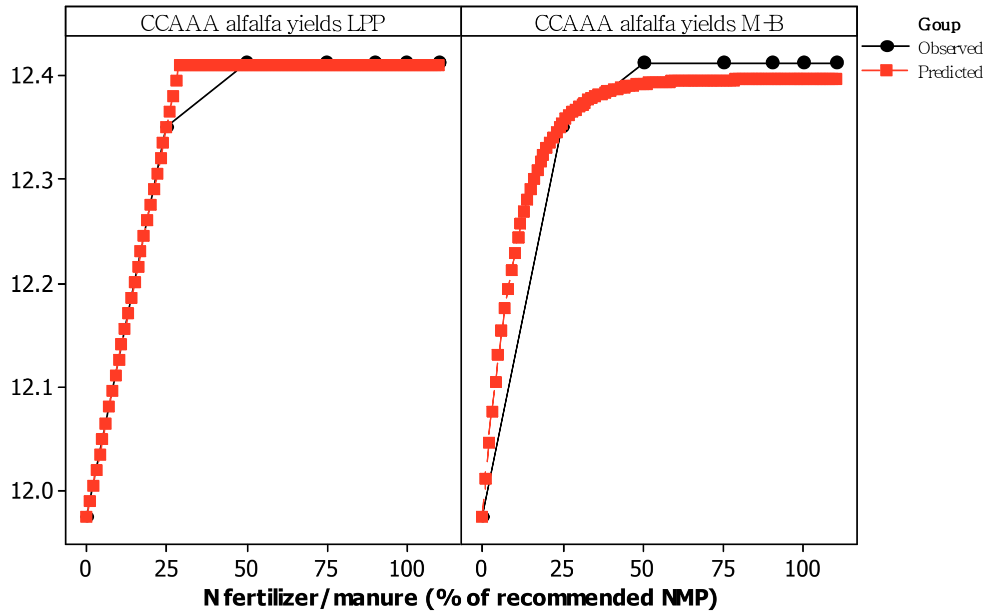
Appendix 2g: Scatter plots for alternative functional forms estimated for potato yield response to N fertilizer in PWRC rotation under conventional tillage.



Appendix 2h: Scatter plots for alternative functional forms estimated for carrot yield response to N fertilizer in PWRC rotation under conventional tillage.



Appendix 2i: Scatter plots for alternative functional forms estimated for alfalfa yield response to N fertilizer in CCAAA rotation under conventional tillage.



Appendix 2j: Scatter plots for alternative functional forms estimated for alfalfa yield response to N fertilizer in CCCAA rotation under conventional tillage.