Eco-efficiency of Alternative Cropping Systems Managed in an Agricultural Watershed

by

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ABSTRACT

The eco-efficiency index (EEI) framework has been used to determine economically and environmentally optimal nitrogen (N) fertilizer application rates for some pollutants (such as greenhouse gas emissions) for selected agricultural production systems. However, previous EEI applications have not examined N application rates linked to nitrate-N loss from crop production. The research gap is surprising given the importance of nutrient N in crop production and concerns with nitrate-N in groundwater systems. Eco-efficiency of crop production systems are increased for farm management practices which generate higher economic returns and lower negative environmental impacts and, therefore are considered more eco-efficient. Data for the analysis were generated using the SWAT biophysical simulation modeling. The cropping systems evaluated in this study included: i) corn-based cropping systems involving corn-corn-alfalfa-alfalfa-alfalfa (CCAAA), and CCCAA rotations; ii) potato-based cropping systems involving potato-corn-barley-potato-corn (PCBPC) and PBWPC; and iii) vegetable-horticulture cropping system involving potato-winter wheat-potato-carrot-corn (PWRC) all managed under conventional tillage (CT) and no-till (NT) systems. Estimated eco-efficient N fertilizer rates were substantially lower than current NMP-recommended rates (NMP N rates) and the maximum economic rate nitrogen fertilization (MERN). However, the actual amounts depended on the crop and rotation system. CCAAA-CT was the most eco-efficient rotation choice among the corn-based cropping systems considered. Similarly, PCBPC-CT was the most eco-efficient choice among the potato-based production systems. In addition, when the NMP-recommended N rate was replaced by the EE N rate for the vegetable horticulture cropping system, the eco-efficient cropping system shifted from a rotation involving CT to a NT system. Eco-efficient N fertilization rates that explicitly simultaneously considers economic and environmental dimensions of cropping system performance will require substantial trade-offs between farm returns and reduction in nitrate pollution.

Keywords: Eco-efficiency, agricultural sustainability, nitrogen fertilizer, nitrate-N pollution,

JEL classification codes: Q57, Q12, Q14

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1. INTRODUCTION

Nitrogen is a major nutrient in crop production, but is also a major environmentally-sensitive agricultural production. Inefficiency in N fertilizer use can result not only in significant economic losses, but also has negative environmental impacts. Nutrient N loss from field crop production, particularly nitrate-N leaching into groundwater systems, is a function of nitrogen fertilizer rate (Yiridoe and Weersink 1998).

Traditional recommended crop nutrient application rates often consider crop yield goals (or, more accurately, the value of the marginal product of crop outputs) relative to the unit cost of N fertilizer input, with uniform or fixed rates sometimes applied to the entire field. In intensive agricultural regions such as in Canada, the US and the EU, such N application rates may be adjusted by taking into consideration carry-over effects of previous crops in rotation systems. On the other hand, studies suggest that farmers tend to apply N fertilizer in excess of crop nutrient requirements (Sheriff 2005; Rajsic and Weersink 2008). Variable application rates using precision agriculture technologies tend to account for spatial differences in soil fertility within a field. However, both traditional recommended fertilizer application rates and variable rate technologies rarely explicitly consider simultaneously economic and (potential) environmental impacts of cropping production systems.

Increasing N fertilizer application rates generally increases crop yields (and farm economic returns) up to a threshold yield level beyond which additional fertilizer input does not improve crop yields (Schmidt et al. 2002). The negative environmental impacts from N fertilizer use in agriculture include nitrate-N leaching, resulting in pollution of both surface and groundwater systems (Moerman and Briggins 1994; Trattrie 2004; Janmaat 2007; Fuller et al

2010). In addition, agriculture is the largest source of N_2O emissions in intensive agricultural regions (Kim and Dale, 2008; Yiridoe and Chen 2013). Furthermore, over 30% of non-renewable energy consumption in corn production, for example, is associated with N fertilizer input production and use (Kim and Dale 2008). Thus, improving N fertilizer use-efficiency for field crops is desired.

The eco-efficiency index (EEI) framework has been used to determine economically and environmentally optimal nitrogen (N) fertilizer application rates, linked to greenhouse gas emissions from selected crop production systems (e.g., Kim and Dale 2008). However, previous EEI applications have not examined nitrogen fertilizer application rates (NARs) linked to nitrate-N pollution from crop production. The research gap is surprising given the importance of nutrient N in crop production, and concerns with nitrate-N in groundwater systems. EEI analysis allows for integrating environmental quality objectives of society as whole with a farmer's private economic objective, into a single index.

Eco-efficiency index (EEI) is the ratio of economic to environmental/ecological efficiency or impacts of a production system or process (Gómez-Limón et al. 2012). Eco-efficiency of agricultural systems can be enhanced by choice of crops and farming practices (such as rotation sequence) which reduce negative environmental impacts while at the same time maintaining or increasing farm returns (Del Grosso et al. 2000). Thus, agricultural production systems with higher EEIs are considered more economically and environmentally sustainable.

Studies have noted that existing nutrient management plan (NMP)-recommended N fertilizer rates for Nova Scotia (and other parts of Atlantic Canada) reflect recommendations from field trials for other regions of Canada (e.g., Belanger et al 2001; Huffman et al 2008). In addition, estimated maximum economic rates of N (MERNs) fertilization tend to differ from

NMP-recommended N rates for selected locations in Canada (e.g.,Yiridoe and Weersink 1998, Rajsic and Weersink 2008). However, previous research have not examined how NMP-recommended N rates and/or MERNs compare with NARs determined by taking into consideration both economic and (potential) environmental dimensions of cropping system performance.

The purpose of this study was to explicitly determine eco-efficient nitrogen fertilizer application rates (NARs) associated with reducing groundwater-N leaching loss for alternative cropping systems assumed to be managed in a rural agricultural watershed. In addition, trade-offs between farm returns and groundwater-N pollution reduction are compared for the cropping systems considered. In a whole-farm scenario analysis, differences in economic importance among crops in a given rotation were investigated (using weights) to assess their effects on overall trends in eco-efficiency of cropping system performance. The cropping system characteristics investigated reflect important nutrient management planning attributes, including crop choice and rotation sequence, N fertilizer rate, and tillage type.

2. RELATED STUDIES

2.1 Eco-efficiency Index: Evolution and Applications

The eco-efficiency index (EEI) framework has been used to assess trade-offs between agricultural production and various environmental impacts (Brussaard et al 2010; Park et al 2010). The EEI approach integrates measures of economic performance and the associated environmental or ecological performance of agricultural production systems into a single dimensionless (aggregate) index.

Schaltegger and Sturm (1990) proposed the EEI framework as a method for linking business (financial) performance and sustainable development. Schmidheiny (1992) later applied (and helped popularize) the technique as a tool for simultaneously assessing business performance and and environmental impacts. The World Business Council of Sustainable Development (WBCSD) has also endorsed the technique as a useful analytical tool (WBCSD, 2000). The EEI approach has been widely used around the world to understand business decision issues, such as optimizing resource use efficiency while minimizing pollution production (Schmidheiny 1992; Jollands et al 2004).

The EEI is a system sustainability performance index, and considers both environmental and economic dimensions of sustainability (Figure 1). However, as illustrated in Figure 1, eco-efficiency does not capture social performance attributes of such production systems (International Council on Metals and the Environment 2001). Another limitation of eco-efficiency (EE) analysis is that the resulting single dimensionless index compromises details about the components or attributes of the production system, thereby complicating interpretation of system performance and comparisons. Another analytical challenge in some EEI applications relates to choice weights and aggregation criteria for constituents of the index (Roberts and Swinton 1996; Jollands et al 2003; Jollands et al 2004).

Recent applications of the EEI method in agriculture include comparison of managerial and program eco-efficiency of a sample of olive farmers (Gómez-Limón et al. 2012), and evaluation of the effects of economically and environmentally optimal nitrogen fertilization rate on greenhouse gas emissions and returns from corn production (Kim and Dale 2008). Reith and Guidry (2003) also applied eco-efficiency analysis to a 600-acre experimental farm in south-central Louisiana. The objective was to determine and recommend crop management strategies with potential for continuous improvement farm environmental quality and risks. Van Passel and Nevens (2007), on the hand, applied eco-efficiency modeling to assess dairy farm sustainability, using the Flemish dairy sector as a case study. Important linkages between partial agricultural productivity measures, eco-efficiency indexes and overall sustainability were also evaluated. In this study, the EEI framework is applied to an agricultural watershed to determine EE NARs, and trade-offs between crop yields (and farm returns), and the associated nitrate-N leached into groundwater systems.

2.2 *Eco-efficiency Modeling*

Eco-efficiency index (EEI) is generally expressed as a ratio of a measure of economic impact to environmental or ecological impacts (e.g., Park et al 2010; Van Meensel et al 2010; Brussaard et al 2010; Huppes and Ishikawa 2005). EEI is sometimes expressed mathematically as a ratio of a measure of "economic value creation" to "environmental impact" (Schaltegger et al 2003):

$$\text{EEI}=\frac{\text{Added economic value}}{\text{Ecological or environmental impact}} \quad (1)$$

Kim and Dale (2008) applied EEI modeling to investigate the effects of N fertilizer application on greenhouse gas (GHG) emissions from grain corn cropping system, for 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 various counties. Kim and Dale (2008) measured economic value added in terms of economic returns to N fertilizer application, while environmental impact was estimated as greenhouse gas emissions:

$$\text{EEI}=\frac{\text{Economic Return to Nutrient-N Rate}/(Y_0 \times P_{corn})}{\text{Greenhouse Gas Emissions}} \quad (2)$$

3. RESEACH METHODS

3.1 Agricultural Watershed and Cropping Systems

Crop yield and $NO_3^- - N$ data for the various cropping systems studied were assumed to be managed in the Thomas Brook watershed (TBW) using the SWAT biophysical simulation model calibrated and validated for TBW conditions. Nitrate-N leaching measurements reflected nitrates transported through the root zone into groundwater systems. An integrated watershed-scale management can be an economically efficient strategy to protect agriculture-induced water quality at the source, compared with treating contaminated water systems (Job 1996), and therefore has become a priority for sustainable water quality management in the Annapolis Valley region, and other parts of Canada (Timmer et al 2007, Stuart et al. 2010).

The Thomas Brook watershed (TBW) forms part of the larger Cornwallis River watershed, near the small town of Berwick, in Kings County, Nova Scotia (Figure 2). The Annapolis Valley accounts for about 19% of total agricultural land in the province (Statistics Canada 2007). Grain crops and potatoes, along with apples and strawberries are major products grown in the region (Gauthier et al 2009; Sinclair et al 2009). TBW covers about 760 ha of the 26,000 ha Cornwallis River watershed (Jamieson et al. 2003). Thomas Brook originates from the North Mountain, and discharges into the Cornwallis River, north of the town of Berwick (Gauthier et al 2009).

Agriculture accounts for about 54% of land use in the TBW, with the remaining 46% consisting of riparian, forest and residential land uses. Land use within the lower two-thirds of the watershed consists primarily of pasture and cropland (Figure 3). Although a variety of soil types exist in the watershed, the predominant soil types are reddish brown sandy loams (Cann et al 1965; Ahmad et al. 2011).

The cropping systems considered in this study included: i) two corn-based cropping systems consisting of corn-corn-alfalfa-alfalfa-alfalfa (CCAAA), and corn-corn-corn-alfalfa-

alfalfa (CCCAA); ii) two potato-based cropping systems consisting of potato-corn-barley-potato-corn (PCBPC) and potato-barley-winter wheat-potato-corn (PBWPC); and iii) a vegetable-horticulture cropping system involving potato-winter wheat-carrots-corn (PWRC). All five rotation systems were managed under conventional tillage and no-till. NARs were varied from 0 to 175% of existing NMP- recommended N fertilizer rates (Table 1).

3.2 Empirical Modeling

The EEI modeling and application in this study is consistent with the framework by Kim and Dale (2008):

$$EEI = \frac{\left\{\left[\left(Y_N - Y_0\right)p - \left(w \times X_N\right) + A_c\right] / \left(Y_0 \times p\right)\right\}_{ik}}{\left\{\exp\left(\frac{V_N - V_0}{V_0}\right)\right\}_{ik}} \qquad (3)$$

where EEI denotes eco-efficiency index;

Y_N represents average crop yield (t ha^{-1}), generated from N fertilizer rate *N* applied (*N* varied from 0% to 175% of NMP-recommended N rate);

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

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

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

X_N (kg ha^{-1}) denotes N fertilizer level applied (from 0% to 175% of recommended NMP rate);

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

V_N is nitrate-N leached (kg N ha^{-1}) from crop production for fertilizer applied at various rates (from 0% to 175% of recommended NMP rate);

V_0 is nitrate-N leaching from crop production associated with no N fertilizer application; and

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

The numerator in equation 3 represents the difference in economic returns for a given crop in a cropping system, using a particular N fertilizer rate (e.g., 25% of recommended NMP rate) compared with zero N fertilization rate. The denominator is an estimate of the difference in $NO_3^- - N$ leached from managing a crop with N fertilizer applied at a given rate compared with level of nitrate-N leaching with no fertilizer applied. The model (equation 3) was used to identify eco-efficient N fertilizer rates for individual crops, and the resulting eco-efficiency index for alternative cropping systems relative to the MERN and existing NMP recommended N rates. Eco-efficiencies of the cropping systems were then compared and used to assess trade-offs between nitrate-N pollution reduction and farm returns (measured in terms of gross margins).

In Atlantic Canada, potatoes and carrots are considered high valued crops, compared with grains, forages and other field crops. Consequently, in this study, different weights were assigned to such high value crops relative to other crops in the rotation system, to investigate their effect on trends in eco-efficiency performance.

Environmental impacts for the eco-efficiency index were estimated using an exponential functional form for nitrate-N leaching. This implies that as pollution rate increases, eco-efficiency reduces by more than a proportionate level (Kim and Dale 2008). Alternative cropping systems generate different eco-efficiency levels. Cropping systems with high EEI are preferred. Sensitivity analysis can be conducted with eco-efficiency index models to determine the effect of changes in specific economic variables (e.g., 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).

Average yields for crops when N fertilizer was applied at alternative rates ranging from 0% to 175% of existing NMP rates were determined using crop response functions, estimated as part of a larger research initiative for crops assumed to be grown in the watershed. Similarly, NO_3^- – N leaching at 0% to 175% of existing NMP rates were determined using the nitrate-N leaching response functions estimated. Data on crop inputs (fertilizer and manure) were obtained from local farm input retailers. Output prices for grain crops were obtained from Co-op Atlantic Canada, while output prices for potatoes, carrots and alfalfa hay were obtained from Nova Scotia Department of Agriculture statistical databases (Table 2). Fertilizer/manure application costs were obtained from farm enterprise budgets developed for the study.

4. RESULTS AND DISCUSSIONS

4.1 Eco-Efficient N fertilizer rates

For this analysis, NARs for different crops that generate the highest EEI represented the eco-efficient N fertilizer rate (EE N rate). In general, EE N rates were substantially lower compared with current NMP-recommended N fertilizer rates (NMP N rates), and the MERNs for each crop (Table 3 and Table 4). The only exception was for alfalfa, area extension specialists generally recommend moderate N fertilizer levels ((i.e., 46 kg ha^{-1}) during the initial stages for forage establishment. In addition, overall, the eco-efficient N fertilizer rates were similar for a given crop, regardless of rotation system and tillage type. For example, the eco-efficient N fertilizer rate was 90 kg ha^{-1} for grain corn, except for grain corn in PCBPC (at45 kg ha^{-1}). Similarly, the EE N rate was 46 kg ha^{-1} for barley, 57 kg ha^{-1} for winter wheat, 37.5 kg ha^{-1} for potatoes, 0 kg ha^{-1} for alfalfa, and 17 kg ha^{-1} for carrots (Table 3).

With the exception of grain corn in PCBPC, the eco-efficient N rates for the three grain crops (i.e., corn, winter wheat and barley) were about 50% lower than the recommended NMP rates, and up to 70% lower than the MERNs (Table 3). In addition, the EE N rates for potatoes and carrots were up to 75% less than the recommended NMP rates and the MERNs (Table 3). The findings suggest that improving nitrate-N in groundwater systems will require substantial trade-offs in terms of reduction in crop yields and (ultimately) farm revenues.

Trade-off analyses using the NMP N fertilizer rate as a reference suggest that compared with the recommended NMP N rate, the eco-efficient N fertilizer rate resulted in nitrate-N leaching reduction ranging from 34% 64%, depending on the crop considered (Table 4). The water quality improvements will require corresponding reductions in corn yields ranging between 25% to 50% (and the associated farm returns). Similarly, at the eco-efficient N fertilizer rate, nitrate-N leaching reduction from potato production ranged from 55% to 73%, but also resulted in potato yield declines between 3% and 15% (Table 4). For carrot production, switching to the eco-efficient N fertilizer rate resulted in a decrease nitrate-N leaching by about 58%, but reduced carrot yields by about 1%.

4.2 Eco-efficient cropping system: individual crop production

The various crop rotation systems managed under CT and NT were assessed to identify the eco-efficient rotation choice for individual crops. For example, four cropping systems were evaluated for both grain corn and potatoes, while two vegetable-horticulture cropping systems were assessed for carrot production. In an initial analysis, all crops in a given rotation system were considered equally important, and assigned equal weights. In a further analysis, traditional high value crops (i.e. carrots and potatoes) were assigned higher weights (of 0.6), while the remaining crops in the rotation were assigned lower weights (i.e., 0.4). Thus, in CCAAA, for example, grain corn (alfalfa) was assigned 0.6 (0.4). Similarly, potatoes was considered high valued crop in all potato-based cropping systems, while carrots was the high valued crop in the vegetable horticulture systems.

In general, relative weights did not affect the eco-efficient choice of rotation system for a given crop. However, a higher weight (of 0.6) assigned to the economically important crop (i.e., grain corn, potatoes, and carrots) increased the EEI for grain corn-based cropping systems, and vegetable-horticulture cropping systems. In contrast, the EEI for potato-based cropping systems decreased (Figure 4).

4.3 Eco-efficient cropping system: Whole-farm analysis

Assessing eco-efficient cropping systems at the eco-efficient N fertilizer rate in a whole-farm scenario suggests that among the grain corn-based cropping systems, two years of corn (CCAAA-CT) was the most eco-efficient cropping system regardless of relative weights to the crops (Figure 4). In addition, PCBPC-CT was the most eco-efficient cropping system among the potato production systems, and PWRC-NT was the most eco-efficient cropping system among the vegetable-horticulture cropping systems (Figure 4).

The choice of eco-efficient cropping system depended on the reference NAR considered (i.e., MERN versus NMP N rate). For example, among the potato-based cropping systems, the eco-efficient choice of rotation system shifted from PBWPC-CT to PCBPC-CT when the reference NAR changed from the NMP N rate to the MERN (Figures 5 and 6; and Table 5). On the other hand, the eco-efficient choice of rotation system under CT using the NMP N rate, was replaced by a NT management when the NMP N rate was replaced by the MERN (Table 5).

5. SUMMARY

In this study, the usefulness of the eco-efficiency index was tested in a study to explicitly determine the eco-efficient nitrogen fertilization rates which minimized nitrate-N leaching impacts while at the same time optimizing farm economic returns. The eco-efficiency index mode model developed was applied to crop production in the Thomas Brook watershed, in Nova Scotia, Canada. Data for the analysis were generated using the SWAT biophysical simulation modeling.

For a given cropping system, the eco-efficient N fertilization rates were substantially lower compared with the maximum economic rate of N (MERN) fertilizer applied, and existing provincial nutrient management plan (NMP) recommended rates. Thus, nitrate-N pollution improvements from the cropping systems considered will require substantial trade-offs in terms of reduced crop yields and, ultimately, farm returns. In addition, the choice of eco-efficient rotation system for a given crop depended on the reference nitrogen fertilizer application rate (NAR) considered (i.e., MERN versus NMP N rate). For example, for potato-based cropping systems the eco-efficient choice of rotation system shifted from PBWPC-CT to PCBPC-CT when the reference NAR changed from the NMP N rate to the MERN.

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Table 1. Cropping systems studied

Crop	Rotation system[a]	Tillage type	N fertilizer rates (%)[b]
Grain corn-based cropping systems	CCCAA	CT	175%, 150%, 125%, 110%, 100%, 90%, 75%, 50%, 25% and 0% of recommended N rates.
	CCCAA	NT	
	CCAAA	CT	
	CCAAA	NT	
Potato-based cropping systems	PCBPC	CT	
	PCBPC	NT	
	PBWPC	CT	
	PBWPC	NT	
Vegetable-horticulture systems	PWRC	CT	
	PWRC	NT	

[a] Crops are denoted by A= alfalfa; B= barley; C= corn; P= potato; W= winter wheat; and R= carrot.

[b] Crop nutrient N applications rates considered included 175%, 150%, 125%, 110%, 100%, 90%, 75%, 50%, 25% and 0% of rates recommended in nutrient management plans for the study region.

Table 2. Output prices and fertilizer/manure and application cost

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 local farm input suppliers.

[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).

Table 3: Comparison of Eco-efficient N (EE N) Rate with NMP Rate and MERN (kg ha^{-1})*

Crop	Crop rotation	NMP N rate (kg ha^{-1})	EE N rate (kg ha^{-1})	% change from NMP N to EE N	Conventional Tillage		No Till	
					MERN (kg ha^{-1})	% change from MERN to EE N	MERN (kg ha^{-1})	% change from MERN to EE N
Corn	CCAAA	180	90	-50	212.11	-57.57	217.63	-58.65
	CCCAA	180	90	-50	208.22	-56.78	221.03	-59.28
	PBWPC	180	90	-50	352.47	-74.47	343.90	-73.83
	PCBPC	180	45	-75	275.09	-83.64	278.54	-83.84
	PWRC	180	90	-50	421.19	-78.63	424.84	-78.82
Barley	PBWPC	92	46	-50	94.82	-51.49	93.53	-50.82
	PCBPC	92	46	-50	88.48	-48.01	86.49	-46.81
Winter wheat	PBWPC	114	57	-50	134.12	-57.50	133.31	-57.24
	PWRC	114	57	-50	165.83	-65.63	160.68	-64.527
Potato	PBWPC	150	37	-75	137.22	-72.67	137.10	-72.65
	PCBPC	150	37	-75	123.03	-69.52	123.13	-69.545
	PWRC	150	37	-75	118.72	-68.41	109.26	-65.68
Alfalfa	CCAAA	42	0	-100	0.00	0.00	0.00	0.00
	CCCAA	42	0	-100	0.00	0.00	0.00	0.00
Carrot	PWRC	68	17	-75	37.40	-54.55	36.11	-54.55

Notes:

N fertilization rates are denoted by: i) EE N rate: eco-efficient nitrogen application rate; ii) NMP N rate: nutrient management plan (NMP)-recommended N rate; and iii) MERN: maximum economic rate of nitrogen fertilization.

Table 4: Trade-off between crop yields and nitrate-N leaching

Crop	Crop rotation	Crop yield at NMP N rate (tonnes ha^{-1})	Crop yield at EE N rate (tonnes ha^{-1})	% change	Nitrate-N leached at NMP N rate (kg ha^{-1})	Nitrate-N leached at EE N rate (kg ha^{-1})	% change
Corn	CCAAA	5.76	4.50	-21.84	42.29	27.99	-33.82
	CCCAA	5.85	4.54	-22.29	59.55	33.82	-43.21
	PBWPC	5.27	3.60	-31.58	51.53	29.19	-43.34
	PCBPC	4.55	2.16	-52.52	83.42	30.64	-63.27
	PWRC	6.41	4.27	-33.42	42.08	25.91	-38.43
Barley	PBWPC	2.50	1.99	-20.49	48.42	33.09	-31.66
	PCBPC	2.47	2.019	-18.50	51.03	33.45	-34.45
Winter wheat	PBWPC	2.66	2.32	-12.87	56.95	36.45	-36.00
	PWRC	3.16	2.67	-15.61	61.45	37.13	-39.57
Potato	PBWPC	17.47	15.12	-13.44	114.58	51.01	-55.48
	PCBPC	16.12	14.27	-11.44	127.25	36.35	-71.43
	PWRC	18.54	16.92	-8.74	120.16	32.36	-73.07
Alfalfa	CCAAA	12.43	12.27	-1.22	61.55	36.48	-40.72
	CCCAA	12.33	12.25	-0.72	71.70	31.84	-55.59
Carrot	PWRC	25.50	25.19	-1.21	87.32	36.48	-58.22

Table 5: Eco-efficient cropping systems at NMP, MERN and EE N rates *

Cropping systems	NMP N rate	MERN	EE N rate
Corn-based cropping systems	CCAAA-CT	CCAAA-CT	CCAAA-CT
Potato-based cropping systems	PBWPC-CT	PCBPC-CT	PCBPC-CT
Vegetable-horticulture systems	PWRC-CT	PWRC-NT	PWRC-NT

Notes:
N fertilization rates are denoted by: i) EE N rate: eco-efficient nitrogen application rate; ii) NMP N rate: nutrient management plan (NMP)-recommended N rate; and iii) MERN: maximum economic rate of nitrogen fertilization.

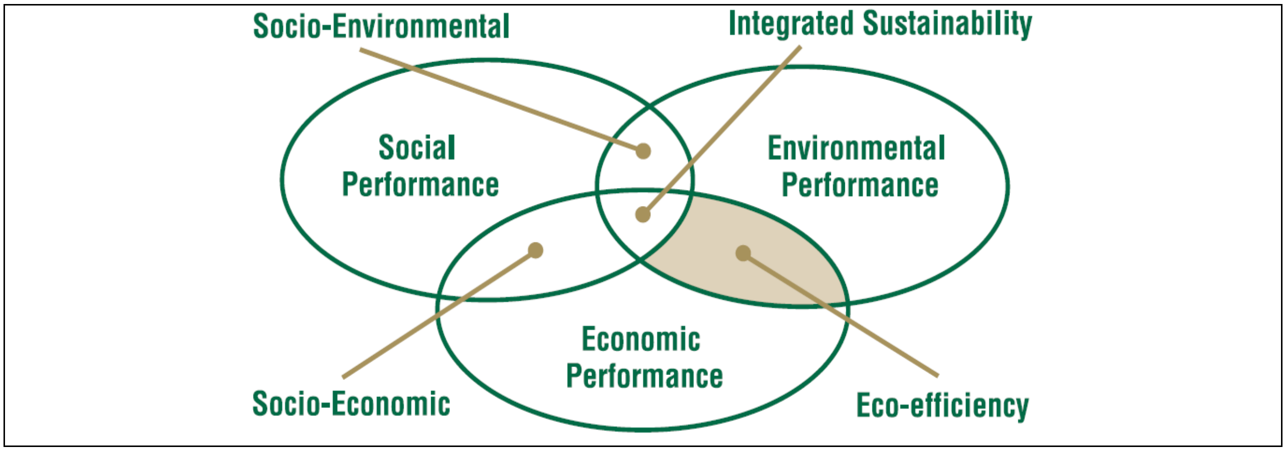

Figure 1: Sustainable development dimensions and inter-relationships among social performance, environmental performance and economic performance

Source: International Council on Metals and the Environment (2001).

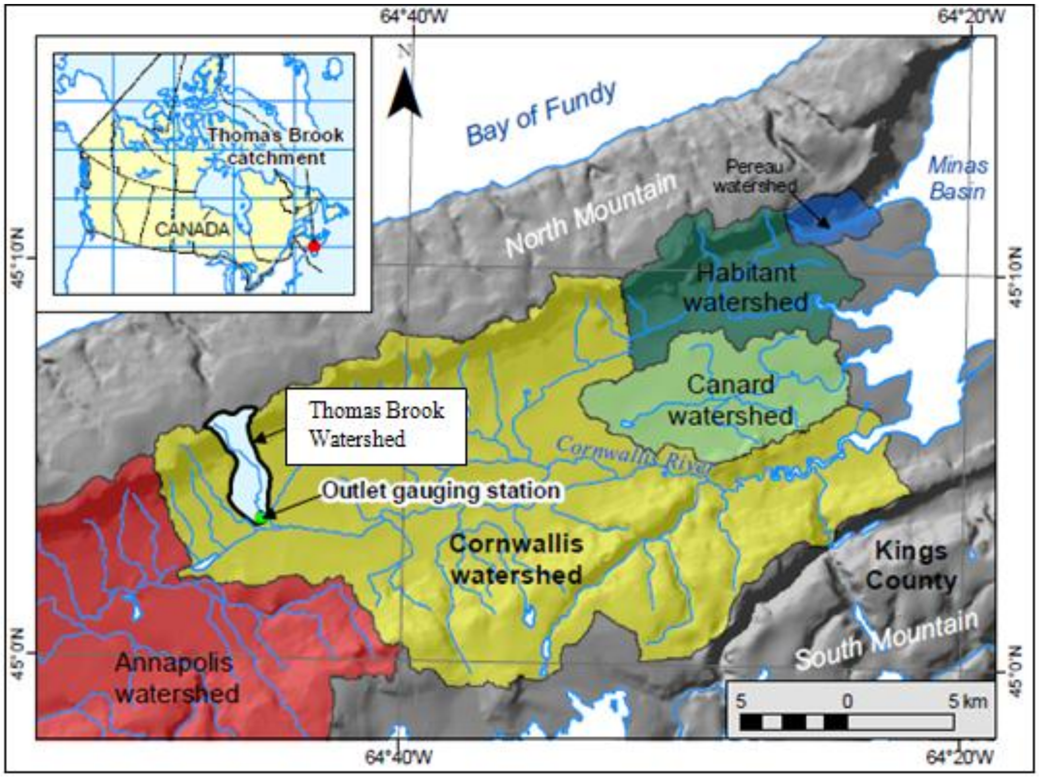

Figure 2: Location of the Thomas Brook watershed, in Annapolis Valley, Nova Scotia. Source: Gauthier et al (2009).

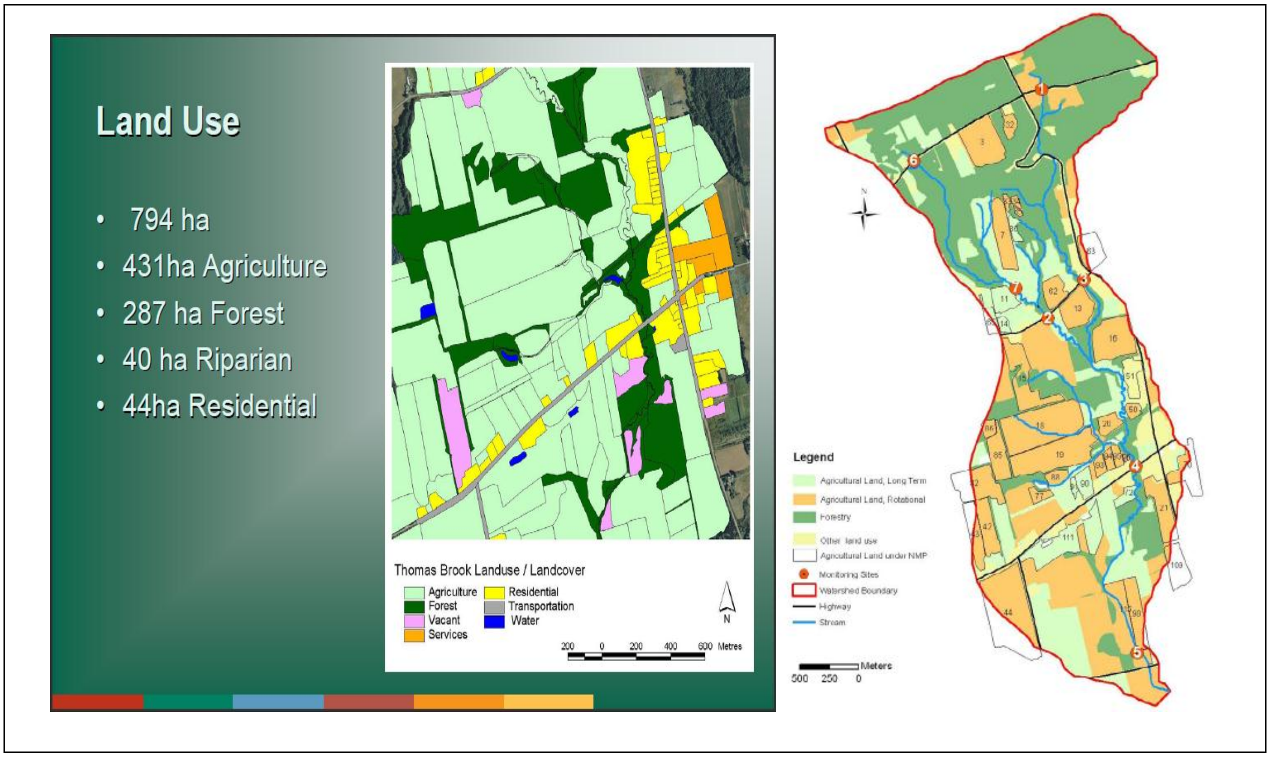

Figure 3: Land uses in Thomas Brook Watershed.
Source: Stuart et al. (2010).

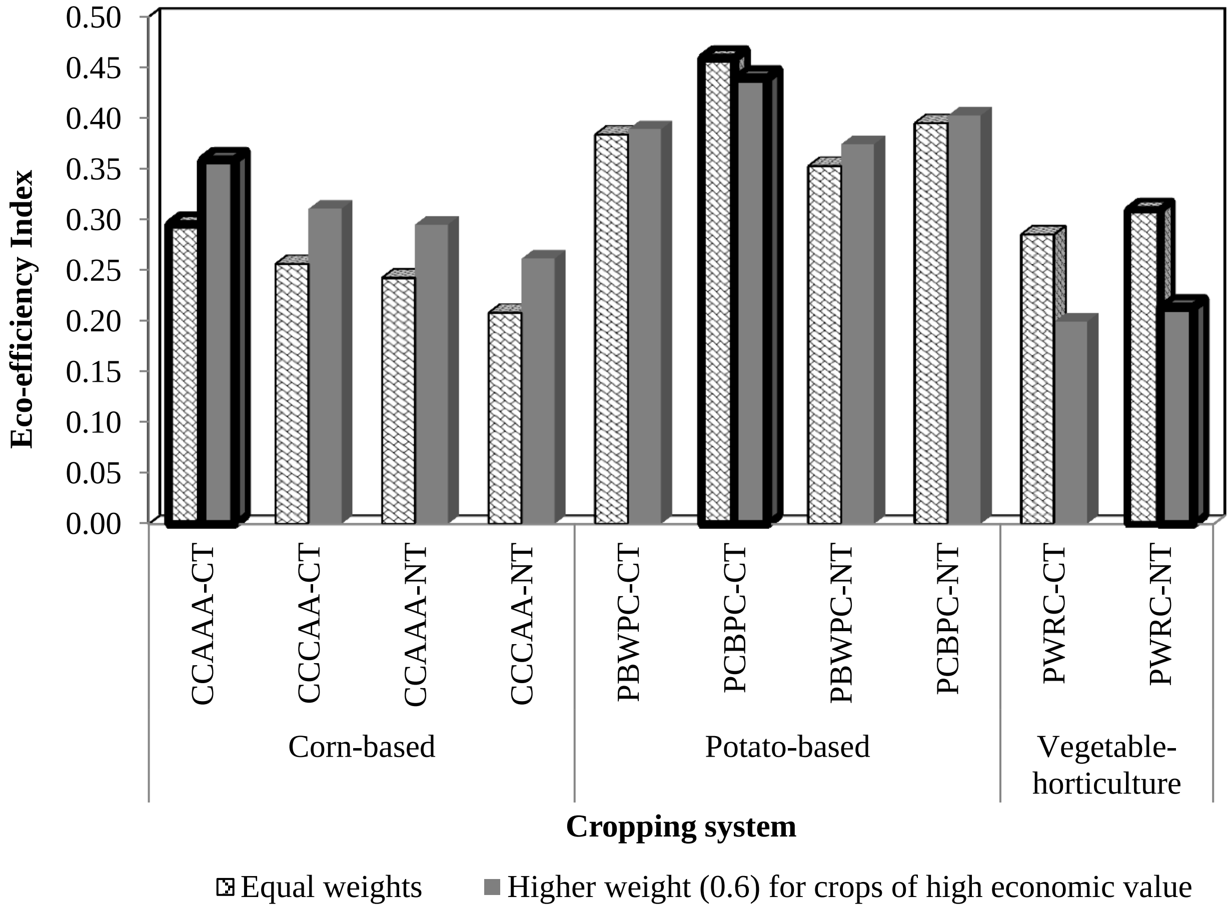

Figure 4: Whole-farm analysis and eco-efficiency EEI at eco-efficient nitrogen fertilization rate

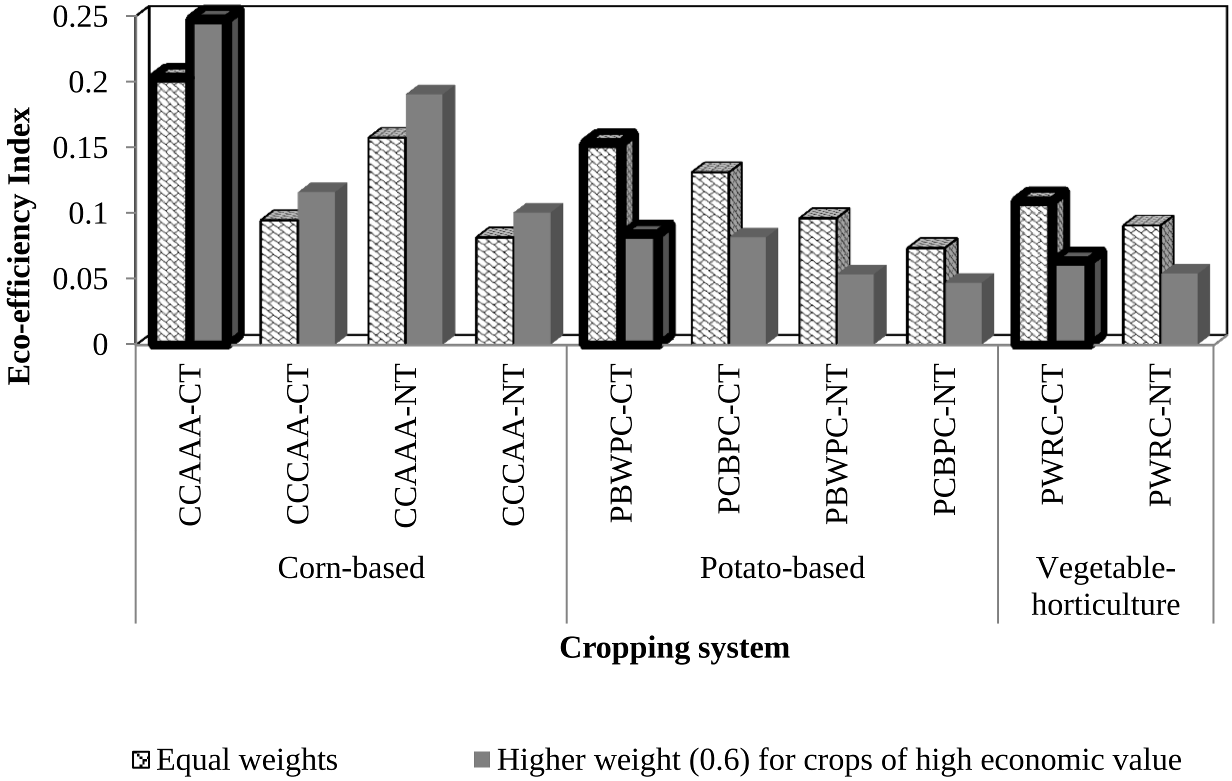

Figure 5: Eco-efficiency Index comparison at NMP-recommended N Rate: whole-farm analysis

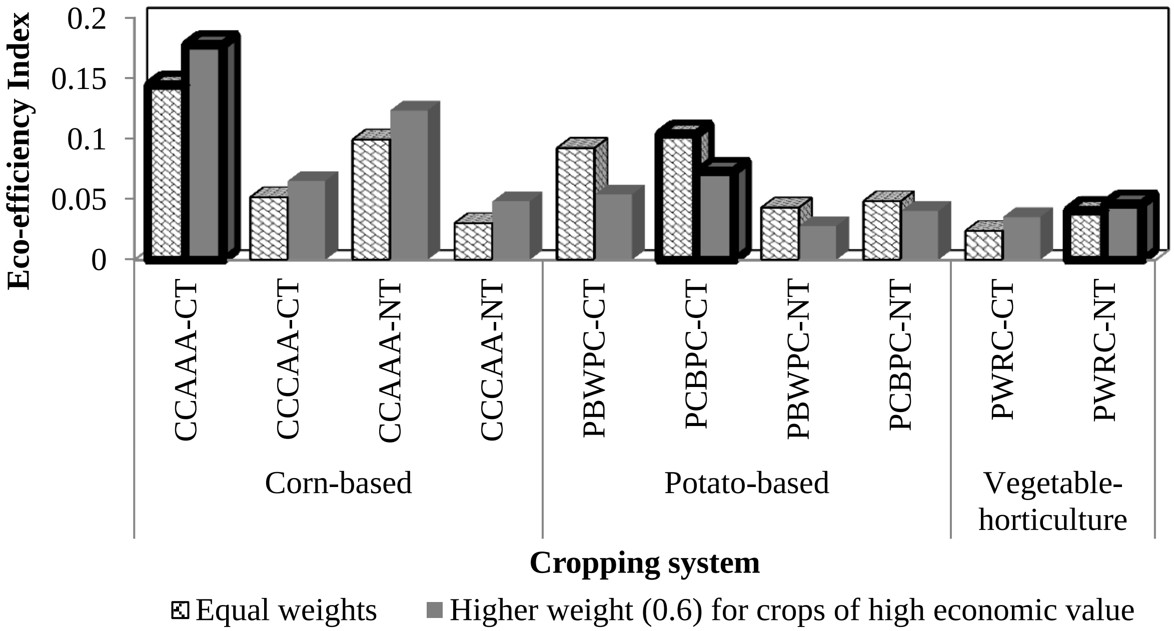

Figure 6: Eco-efficiency Index comparison at MERN: whole-farm analysis