

Scenario Modeling Potential Eco-Efficiency Gains from a Transition to Organic Agriculture: Life Cycle Perspectives on Canadian Canola, Corn, Soy, and Wheat Production

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Abstract We used Life Cycle Assessment to scenario model the potential reductions in cumulative energy demand (both fossil and renewable) and global warming, acidifying, and ozone-depleting emissions associated with a hypothetical national transition from conventional to organic production of four major field crops [canola (*Brassica rapa*), corn (*Zea mays*), soy (*Glycine max*), and wheat (*Triticum aestivum*)] in Canada. Models of these systems were constructed using a combination of census data, published values, and the requirements for organic production described in the Canadian National Organic Standards in order to be broadly representative of the similarities and differences that characterize these disparate production technologies. Our results indicate that organic crop production would consume, on average, 39% as much energy and generate 77% of the global warming emissions, 17% of the ozone-depleting emissions, and 96% of the acidifying emissions associated with current national production of these crops. These differences were almost exclusively due to the differences in fertilizers used in conventional and organic farming and were most strongly influenced by the higher cumulative energy demand and emissions associated with producing conventional nitrogen fertilizers compared to the green manure production used for biological nitrogen fixation in organic agriculture. Overall, we estimate that a total transition to organic production of these crops in Canada would reduce national energy consumption by 0.8%, global warming emissions by 0.6%, and acidifying emissions by 1.0% but

have a negligible influence on reducing ozone-depleting emissions.

Keywords Life cycle assessment · Organic · Conventional · Efficiency · Nitrogen · Green manure · Agriculture

Introduction

Modern agriculture largely owes its successes to an abundant supply of inexpensive fossil fuels, which are prerequisite to synthetic fertilizer production, suppressing insect damage and weed competition through pesticide/herbicide production and application and supplying mechanical advantage in the form of farm machinery and irrigation (Pimentel and others 2005). However, energy-intensive agriculture has been implicated in a broad range of proximate, ecological impacts, including water pollution (Carpenter and others 1998), soil erosion (Gerhardt 1997), pesticide toxicity (Carvalho 2006), and selection for pest resistance (Carvalho 2006; Fournier 1999). Moreover, the finite nature of fossil fuel reserves as well as the macro-scale environmental impacts of extracting and consuming the fossil energy that underpins intensive agriculture are of increasing concern (Pimentel and others 2005) and merit closer attention.

Organic agriculture has been promoted as a means to reduce many of the negative impacts associated with conventional food production (Pimentel and others 2005; Stolze and others 2000). In a broad sense, organic farmers strive to sustain agricultural production while minimizing external inputs (synthetic fertilizers and pesticides in particular) in favor of resources found on or near the farm. These resources generally include biologically fixed

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nitrogen, mineral-bearing rocks, and biological pest control. Fallowing, intercropping, use of buffer zones, and integrated production of both plants and animals are common as well (El-Hage Scialabba and Hattam 2002). Organic production practices have also been criticized as inefficient relative to conventional production technologies due to lower yields (Offerman and Nieberg 2000), although some large-scale reviews examining comparative yields in conventional and organic agriculture strongly challenge this critique (Badgley and others 2007; Stanhill 1990).

Improving the sustainability of agricultural production systems requires the promotion of farm practices that provide high-quality, affordable food in sufficient quantity while ensuring appropriate economic returns and minimizing negative environmental effects. Although numerous researchers have described the local-scale ecological benefits of organic versus conventional farming as well as reduced fossil energy dependency (as summarized in Stolze and others 2000), many of the broader, macroscale environmental implications of these alternative production technologies, including their comparative emission intensities of globally problematic compounds, have historically received considerably less attention. However, rising awareness of energy security issues and broad-scale anthropogenic perturbations of biogeochemical cycles such as ozone depletion, acid precipitation, and climate change has spurred interest in understanding the comparative eco-efficiency (i.e., the resource and emissions intensity per unit service) of conventional and organic food production strategies, and research in this area is increasing.

In a 12-year study of energy use, energy output, and energy-use efficiency in conventional and organic crop rotations and crop production systems in Canada, Hoepfner and others (2006) found that energy use was 50% lower with organic compared to conventional management. Although energy output was 30% lower per hectare with organic management, overall energy efficiency (output energy/input energy) was highest in the organic rotations. Similarly, Pimentel and others (2005) found that industrial energy use in organic cropping systems was 28–32% less than in conventional rotations for a 25-year trial in the United States. Smolik and others (1995) compared the relative sustainability of alternative (organic), conventional, and reduced-till farming systems in South Dakota. Productivity relative to total energy consumption (including fuel, fertilizers, and pesticides) was two to six times higher in the alternative systems than in the conventional and reduced-till systems.

Whereas energy use is often a good proxy for fuel combustion-related emissions intensity, other accounting methodologies are available to accurately describe a wider suite of the macroscale environmental dimensions of industrial activity. This is particularly valuable in the context of crop production, where field-level greenhouse

gas and acidifying emissions related to nitrogen fertilizers typically exceed those associated with crop input production (i.e., fertilizers, seed, and pesticides) and fuel use (Williams and others 2006).

Life Cycle Assessment (LCA) is an ISO-standardized biophysical accounting framework used to inventory the material and energy inputs and emissions associated with each stage of a product life cycle and to express these in terms of their quantitative contributions to a specified suite of environmental impact categories (Guinee and others 2001). Such analyses facilitate the identification of life-cycle stages that contribute disproportionately to specific areas of environmental concern, as well as comparisons of environmental performance between competing production technologies. Because LCA impact assessment methods require discrete, quantifiable relationships between the inputs and emissions of product/service systems and their environmental impact potentials, the tool is not well suited to accounting for contributions to local-scale environmental degradation (e.g., biodiversity loss) that results from multiple, synergistic influences or context-specific biogeochemical conditions (Pelletier and others 2007). Rather, it is best suited to evaluating how product/service systems contribute to broader-scale environmental change through resource appropriation and globally problematic chemical emissions.

Several researchers have used LCA to compare conventional and organic food production technologies. In an LCA of intensive, extensive, and organic grassland farming in southern Germany, Haas and others (2001) found that organic farms consumed less energy and generated lower greenhouse gas emissions. This was primarily due to foregoing the use of nitrogen fertilizer. The organic farms also scored better in terms of lower contributions to acidification and eutrophication. Mattsson (1999) reported trade-offs in environmental impacts between organic and conventional carrot production systems in Sweden. Organic production created higher acidification and eutrophication impacts due to the use of manure as fertilizer and it required more arable land. However, energy use was higher in the conventional system due to the production of pesticides and fertilizers, both of which also contributed to greater toxicity impacts. Similar analyses include comparisons of conventional and organic milk production in the Netherlands (Thomassen and others 2008), a hybrid input/out-LCA study of conventional and organic farming in Australia (Wood and others 2006), and an analysis of feed production systems for conventional and organic aquaculture (Pelletier and Tyedmers 2007).

Conventional canola, corn, soy, and wheat together accounted for 75% of both seeded area and production for all field crops (excluding hay) produced in Canada in 2005 and occupied 24.2 million hectares of the Canadian

agricultural landscape (Statistics Canada 2007). Given this scale of production, changes in production technologies that influence eco-efficiency might have non-trivial implications in terms of total resource use and emissions at the national level. This study used LCA to quantify the cumulative energy demand (both fossil and renewable) and greenhouse gas, ozone-depleting, and acidifying emissions associated with generic models of conventional and organic canola, corn, soy, and wheat production in Canada. The information derived subsequently informed an assessment of how the specific production strategies characteristic of conventional and organic farming differentially affect eco-efficiency and the magnitude of energy savings and emissions reductions potentially associated with a national transition to organic production of these crops.

Methods

Goal Definition and Scoping

The goal of this research was to generate generic life-cycle models of contemporary conventional and organic canola, corn, soy, and wheat production systems in Canada in order to predict the cradle-to-farm gate cumulative energy demand (both fossil and renewable) and greenhouse gas, ozone-depleting, and acidifying emissions associated with these distinct production technologies, as well as to assess the magnitude of energy use and emission reductions that might be achievable through a nationwide transition to organic production practices for these crops. The system boundaries encompassed all direct inputs and emissions associated with the use of farm machinery (i.e., fuel for field operations and crop drying), the production of fertilizers/soil amendments, seed, and pesticides, as well as field-level nitrous oxide and ammonia emissions from fertilizers and crop residues. Inputs and emissions associated with the production and maintenance of farm machinery and infrastructure as well as transportation of inputs were not included, nor were anticipated differences in soil carbon sequestration or methane production. Although each crop was modeled and analyzed independently, for the sake of calculating and assigning input costs of green manure nitrogen provision in the organic systems, corn–soy and wheat–canola rotations with green manure intercrops or cover crops were assumed. The functional unit was 1 kg of each crop produced, at the farm gate.

Life Cycle Inventory

The life cycle inventory (LCI) stage of an LCA involves collecting relevant data regarding the material and

energetic inputs and emissions associated with each stage of the product life cycle. Data for material inputs (fertilizer, fuel, seed, pesticides, etc.) and yields for the conventional production systems were derived from Canadian GHGenius reports (Levelton Engineering and (S&T)² 1999; (S&T)² 2003, 2005) and represent average contemporary Canadian conditions. Specific fertilizer mixes for N, P₂O₅, and K₂O were based on average fertilizer use in the major production regions for each crop (corn and soy in Ontario, canola and wheat in the western Prairies/Alberta) as reported in Korol (2002). Field-level nitrogen emissions and CO₂ emissions from urea fertilizers were calculated following IPCC Tier 1 Guidelines (IPCC 2006).

Comparable, broadly representative data were not available for organic agriculture in Canada. Hypothetical organic models were therefore designed to maximize comparability with the conventional systems while reflecting key similarities to and differences from conventional production technologies based on the Canadian Organic Production Systems Permitted Substances list (Canadian General Standards Board 2006) and broad trends identified through a literature review of comparative inputs and emissions in conventional and organic crop production. Key aspects of the modeled organic systems included the following:

- **Fertilizer Inputs:** Quantities of fertilizers (N, P₂O₅, K₂O) required in the organic systems were assumed to be equivalent to fertilizer inputs in the conventional systems on a per-hectare basis. Nitrogen inputs were assumed to be derived from the cultivation of sweet clover green manure intercrops or cover crops. Reported estimates of the fertilizer replacement value of sweet clover vary widely, with a high of 450 kg/ha, a more typical range of 40–225 kg/ha and an apparent mode of roughly 100–120 kg/ha, depending on seeding density, biomass yield, and seasonal factors (e.g., see Killpack and Buchholz 1993; Leikem and others 2007; Rehm and others 2002; Shelley 2004; State and Posner 1995). Given that nitrogen inputs to the conventional systems were 140 kg/ha for corn and 59, 7.9, and 65.6 kg/ha for canola, soy, and wheat, respectively, we assumed that a single sweet clover green manure intercrop or cover crop that did not displace productive land use was cultivated to satisfy nitrogen requirements for each corn–soy rotation, and similarly for each canola–wheat rotation. Individual crops were assigned the energy and seed input costs of green manure production weighted for their total share of nitrogen demand in the rotation. Input data for green manure production were 16.1 L of diesel and 45 kg of seed/ha based on long-term field trial data collected at Agriculture Canada research stations (Zentner, personal

communication). Finally, phosphate rock was assumed to replace conventional concentrated phosphorus fertilizers in the organic systems, and potash was assumed to supply potassium.

- Machinery use differs between conventional and organic systems, with conventional producers employing machinery more frequently for fertilizer and pesticide application and organic producers relying on increased tillage for weed control as well as green manure production. Consistent with field trial data reported in Hoepfner (2001), which were derived from long-term multiple-replicate trials at Agriculture Canada research stations, fuel inputs/hectare were assumed to be similar for organic and conventional production but were adjusted per unit mass produced to account for anticipated yield differences.
- Based on a global review of datasets examining comparative yields in established conventional and organic crop production systems (Badgley and others 2007), yield rates for organic canola, corn, soy, and wheat were assumed to be 90%, 95%, 100%, and 90% of conventional yields, respectively.
- Considerable uncertainty exists regarding comparative field-level nitrous oxide and ammonia emissions from nitrogen fertilizers in conventional and organic agriculture. Stolze and others (2000) reviewed existing literature and concluded that no significant differences can be identified. We therefore assumed identical emissions between organic and conventional systems on a per-hectare basis, but we adjusted per unit mass produced to account for yield differences.
- The organic systems did not employ pesticides.

Life Cycle Impact Assessment

Impact assessment, which is the third stage of an LCA, involves calculating the potential environmental burdens associated with specific life-cycle activities by quantitatively expressing all inputs and emissions tabulated in the LCI according to their contributions to a suite of specified environmental impact categories (Pennington and others 2004). Numerous environmental impact categories have been developed for use in LCA (Pelletier and others 2007) and should be chosen according to the specific goals of the study at hand. Because the purpose of the present study was to compare contributions to macroscale environmental concerns between conventional and organic production systems, the impact categories considered were cumulative energy demand (in MJ), global warming potential (as CO₂ equiv.), ozone-depletion potential (as CFC-11 equiv.), and acidification potential (as SO₂ equiv.). Cumulative energy demand (including both fossil and renewable sources) was quantified following the Cumulative Energy Demand

method v 1.03 (VDI 1997). Global warming, acidification, and ozone-depletion potentials were calculated according to the CML 2 Baseline 2000 method (CML 2001). All impact assessment calculations were carried out using the SimaPro 7.0 LCA software package from PRé Consultants (PRé 2006). Proximate ecological impacts such as ecotoxicity effects from pesticide use and potential eutrophication impacts were not addressed.

In order to identify life-cycle “hot spots,” relative contributions to each impact category associated with fuel inputs to machinery, fertilizer production, nutrient emissions, and other inputs (pesticides, seed, sulfur) were evaluated for each crop system, as were the proportional contributions of nitrogen, phosphorus, and potassium inputs to overall impacts for each crop. The impacts associated with the production of 1 kg of average conventional nitrogen, phosphorus, and potassium fertilizers [based on Canadian fertilizer mixes as per Korol (2002)] as well as phosphate rock and potash were also calculated using average European process models from the EcoInvent database (EcoInvent 2007) that were modified to reflect the Canadian electricity mix. The impacts of green manure nitrogen production were calculated assuming a conservative yield of 110 kg N/ha. Finally, 2005 Canadian national crop production statistics for canola, corn, soy, and wheat (Statistics Canada 2007) were used to estimate the total potential energy savings and emission reductions associated with a hypothetical nationwide transition from conventional to organic production of these crops in Canada. In light of the conflicting claims regarding yield potentials in conventional and organic crop production, a sensitivity analysis was carried out to determine the yield levels for the organic crops at which contributions to the impact categories considered would be equivalent to those of conventional crops.

Results

Life Cycle Inventory Results

Table 1 reports the LCI data and data sources that informed our generic models of the inputs and emissions associated with the cradle-to-farm gate production of conventional and organic canola, corn, soy, and wheat in Canada.

Life Cycle Impact Assessment Results

Table 2 reports total cradle-to-farm gate life-cycle impact assessment results for the cumulative energy demand and global warming, ozone-depleting, and acidifying emissions associated with the production of 1 kg of conventional and organic canola, corn, soy, and wheat in Canada. Due to the

Table 1 Cradle-to-farm gate LCI data for the production of 1 kg of conventional and organic canola, corn, soy, and wheat in Canada

	Canola		Corn		Soy		Wheat	
	Con. ^a	Org.	Con. ^b	Org.	Con. ^c	Org.	Con. ^d	Org.
Inputs								
N ^e (g)	46.1		19.5		3.3		24.4	
P ₂ O ₅ ^f (g)	50.4	56.0	6.3	6.6	30.7	30.7	28.1	31.2
K ₂ O ^g (g)	12.0	13.4	3.8	4.0	53.5	53.5		
Sulfur (g)	8.0	8.9			1.7	1.7		
Pesticides ^h (g)	1.4		0.4		0.5		1.6	
Diesel (mL)	35.2	39.1	6.6	7.0	14.2	14.2	10.8	12.0
Diesel for GM ⁱ (mL)		6.6		2.2		0.4		3.5
Gasoline (mL)					4.5	4.5		
Natural gas (cm ³)			181.7	191.3	6.3	6.3		
LPG (mL)					1.4	1.4		
Electricity ^j (kJ)					7.0	7.0		
Seed ^k (g)	5.2	5.8	2.6	2.7	45.0	45.0	46.0	51.1
Seed for GM ^l (g)		18.4		6.2		1.0		9.8
Fertilizer emissions^m								
N ₂ O (g)	1.2	1.3	0.6	0.6	0.3	0.3	0.7	0.8
NH ₃ (g)	9.7	10.8	3.0	3.2	2.9	2.9	4.9	5.4
NO _x (g)	0.9	1.0	0.4	0.4	0.1	0.1	0.5	0.6
CO ₂ from urea (g)	15.6		8.7		1.5		8.2	
Yield (kg/ha)	1288	1159	7180	6821	2380	2380	2690	2421

^a Data from (S&T)² Consultants (2005)

^b Data from Levelton Engineering and (S&T)² Consultants (1999)

^c Data from (S&T)² Consultants (2005)

^d Data from (S&T)² Consultants (2003)

^e For conventional, assumes any manure N is ultimately derived from synthetic N and is modeled based on a regional fertilizer mix for dominant production region of each crop (Korol 2002)

^f For conventional, modeled based on P₂O₅ content of regional P fertilizer mix for dominant production region of each crop (Korol 2002); for organic, modeled based on P₂O₅ content of phosphate rock

^g For conventional, modeled based on K₂O content of regional K mix for dominant production region of each crop (Korol 2002); for organic, modeled on K₂O content of potash (IFIA 2007)

^h Active ingredients

ⁱ Diesel for green manure calculated based on average fuel inputs of 16.1 l/ha as per data collected at Agriculture Canada research stations (Zentner, personal communication) and is apportioned to each crop based on its share of nitrogen demand in the assumed corn–soy and canola–wheat rotations

^j Based on electricity mix in dominant production region for each crop

^k Modeled as if derived from same production system

^l Seed input for sweet clover green manure is 45 kg/ha, based on data collected at Agriculture Canada research stations (Zentner, personal communication.) and is apportioned to each crop based on its share of nitrogen demand in the assumed corn–soy and canola–wheat rotations

^m Calculated following IPCC Tier 1 Guidelines employing all default values as listed and assuming a 90%/10% NH₃/NO_x split for volatilization (IPCC 2006)

assumed lower yield rates for canola (90% of conventional yields), corn (95%) and wheat (90%) in the organic crop models (soy yields were assumed to be equivalent), with inputs and emissions per hectare held constant, the predicted impacts associated with fuel inputs to machinery and field-level emissions from nitrogen fertilizers were correspondingly slightly higher per kilogram of crop produced for organic compared to conventional production (Fig. 1).

Specifically, fuel-related impacts were, on average, 8% higher for organic production of canola, corn, and wheat across impact categories, whereas fertilizer-related field emissions were 7% higher (only applies to global warming and acidifying emissions). Conversely, averaged across the three crops and all impact categories, impacts related to both fertilizer and seed/pesticide production (Other) for the conventional systems were 845% and 380% of those for

Table 2 Cradle-to-farm gate life-cycle impact assessment data for the cumulative energy demand and global warming, ozone-depleting, and acidifying emissions associated with the production of 1 kg of conventional and organic canola, corn, soy, and wheat in Canada

	Canola		Corn		Soy		Wheat		Ave. Δ in Org./Conv.
	Con.	Org.	Con.	Org.	Con.	Org.	Con.	Org.	
Cumulative energy demand (MJ/kg)	5.2	2.2 (42%)	2.4	1.3 (54%)	2.3	1.5 (65%)	2.7	0.8 (30%)	48%
Global warming potential (g CO ₂ equiv./kg)	696.3	541.0 (78%)	330.1	256.3 (78%)	247.6	190.3 (77%)	382.2	290.6 (76%)	77%
Ozone-depletion potential (μ g CFC-11 equiv./kg)	27.6	4.3 (16%)	15.1	6.6 (44%)	10.4	5.0 (48%)	15.2	0.8 (5%)	28%
Acidification potential (g SO ₂ equiv./kg)	20.2	19.8 (98%)	5.6	5.4 (96%)	7.2	5.7 (79%)	10.2	9.7 (95%)	92%
Ave. Δ in Org./Conv.		59%		68%		67%		52%	

Note: Values in parentheses are the relative magnitudes of impacts in organic systems relative to conventional systems

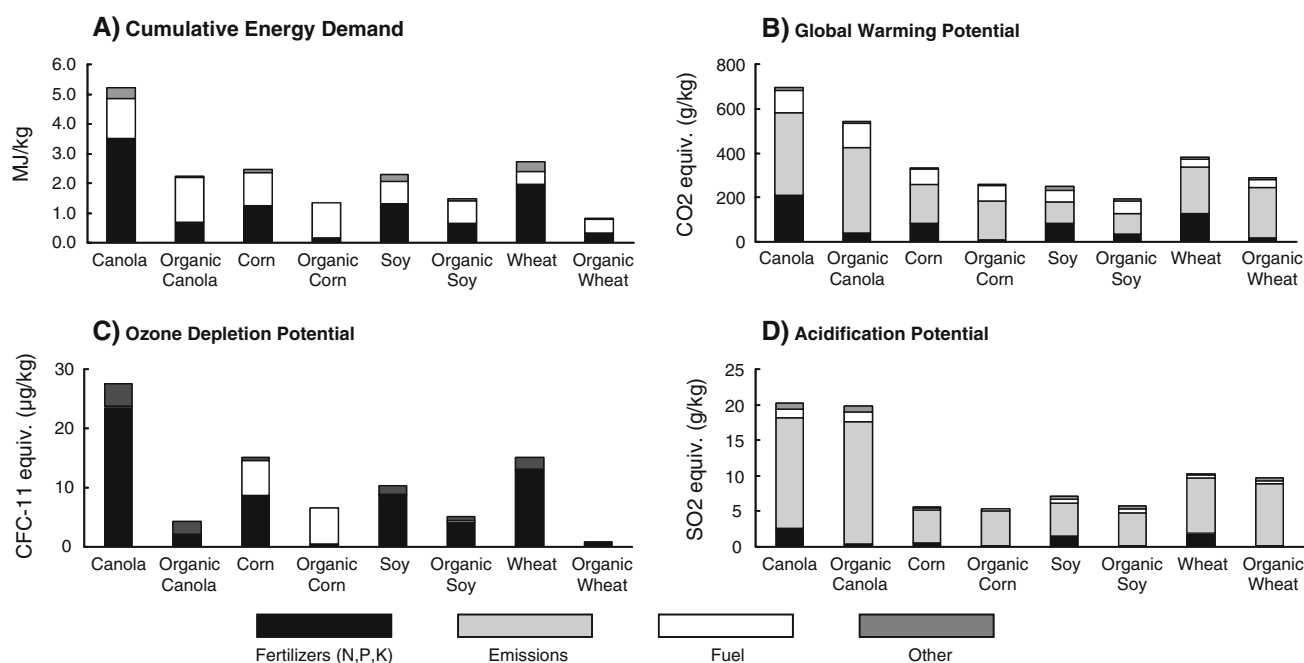


Fig. 1 Cradle-to-farm gate cumulative energy demand and global warming, ozone-depleting, and acidifying emissions associated with the production of 1 kg of conventional and organic canola, corn, soy, and wheat in Canada. “Fertilizers” refers to the production of N, P,

and K inputs. “Emissions” refers to field-level emissions of N compounds and CO₂ associated with fertilizer use. “Fuel” refers to all energy inputs to farm machinery and crop drying. “Other” refers to production of all other field level inputs (seed, pesticides, sulfur)

the organic systems (Fig. 1). For soy production, where yields were equivalent, only fertilizer- and seed/pesticides/sulfur (Other)-related impacts differed, with the organic crop generating, on average, 37% and 53% of the impacts of the conventional crop for these respective inputs.

The production of fertilizer was the dominant contributor to cumulative energy demand for conventionally produced crops (average of 62% across all crops), with fuel inputs contributing 30% and seed, pesticides, and sulfur (Other) contributing only 8% (Fig. 1). In contrast, fuel inputs were most important to cumulative energy demand

for organic production (average of 66% across all crops), with fertilizer production contributing 32%. The production of seed and sulfur (Other) contributed a nominal 2% in organic production, suggesting that avoidance of pesticide use resulted in a small but nontrivial energy savings. Fertilizer production was the dominant contributor to ozone-depleting emissions for both conventional (78%) and organic (57%) crops. A notable exception was the case of corn production, for which the use of natural gas for crop drying increased the contribution from fuel inputs to 39% and 93% of ozone-depleting emissions for conventional

and organic production, respectively. Field-level emissions associated with fertilizer use contributed the majority of global warming and acidifying emissions for all conventional and organic crops. Specifically, this accounted for (on average) 50% of global warming and 76% of acidifying emissions in the conventional systems and 66% of global warming and 88% of acidifying emissions in the organic systems. Fertilizer production was the second most important contributor to these impact categories for conventional production (31% and 15% of global warming and acidifying emissions, respectively), whereas fuel use was the second largest contributor to these impact categories in the organic systems (22% and 6%, respectively) (Fig. 1).

Overall, however, the organic crop production models generated consistently lower contributions to all impact categories considered (Table 2, Fig. 1). Averaged over the four crops, cumulative energy demand for organic production was 48% of that for conventional crop production, whereas global warming potential for the organic crops was 77%, ozone depletion potential was 28%, and acidification potential was 92% relative to the conventional crops (Table 2). Differences were greatest for canola and least for soy, which have the highest and lowest nitrogen requirements, respectively.

These differences were almost exclusively due to the varied life-cycle impacts associated with the production of

the fertilizers particular to conventional and organic farming. More specifically, they were most heavily influenced by the different nitrogen procurement strategies characteristic of conventional (using synthetic nitrogen fertilizers) and organic (using green manure cultivation) crop production, although differences in phosphorus fertilizer production for conventional and organic systems was the most important factor for acidifying emissions (Fig. 2).

For all conventionally produced crops other than soy (a legume requiring nominal nitrogen inputs), nitrogen fertilizer production was the dominant contributor to fertilizer-related cumulative energy demand (on average, 75% for canola, corn, and wheat production), global warming (72%), and ozone-depleting emissions (78%). Green manure nitrogen production was proportionally less important for these impact categories in the organic systems, contributing, on average, 52% to fertilizer-related cumulative energy demand for organic canola, corn, and wheat production, 64% to global warming, and 1% to ozone-depleting emissions. In contrast, green manure nitrogen production accounted for 78% of fertilizer-related acidifying emissions for these crops (Fig. 2). Phosphorus fertilizer was the major contributor to fertilizer-related acidifying emissions in the conventional production systems (average of 76% for all crops). In the organic systems,

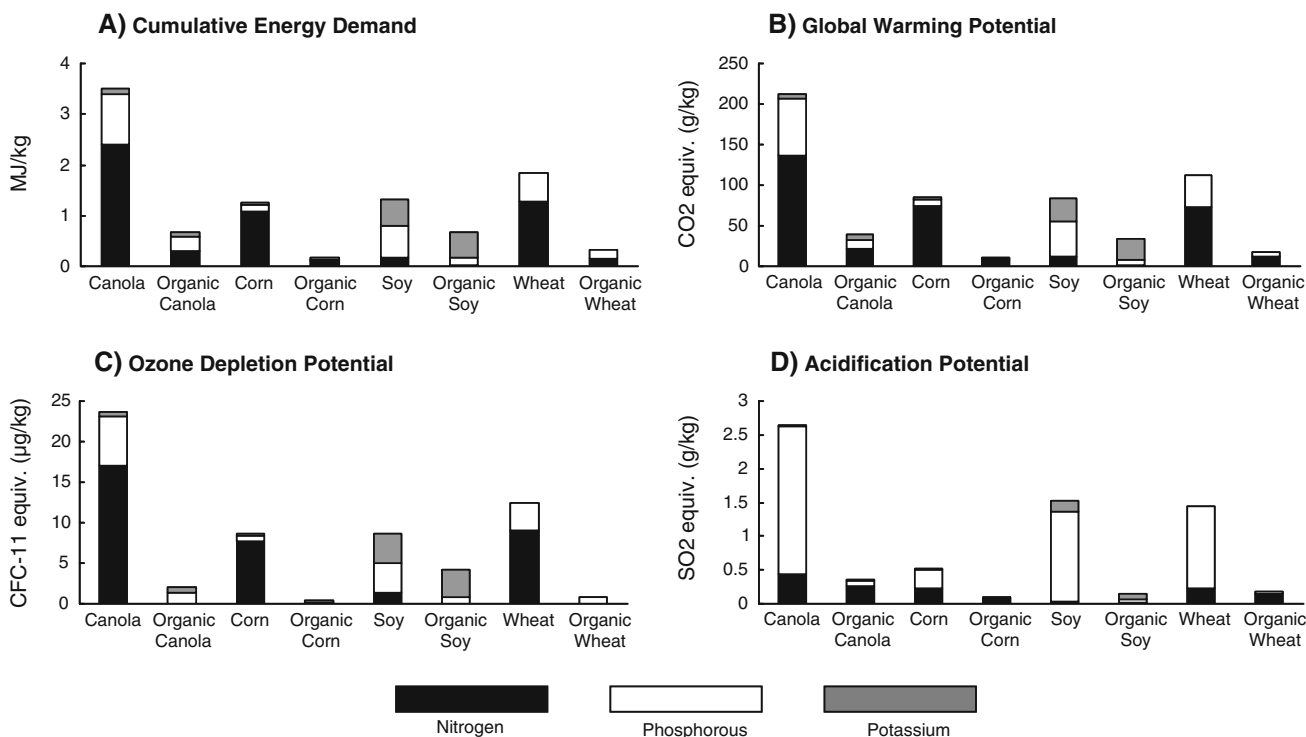


Fig. 2 Cumulative energy demand (A), global warming (B), ozone-depleting (C), and acidifying emissions (D) associated with fertilizer provision for the production of 1 kg of conventional (using average

N, P₂O₅, and K₂O fertilizers) and organic (using green manure N, rock phosphate, and potash) canola, corn, soy, and wheat in Canada

the use of phosphate rock contributed, on average, only 19% to acidifying emissions. The contributions from potassium fertilizer to fertilizer-related impacts were small for all impact categories for both conventional and organic production of all crops other than soy, for which potassium inputs were relatively high (Fig. 2). Overall, cumulative energy demand associated with fertilizer production in the organic systems was 25% of that in the conventional systems, whereas global warming, ozone-depleting, and acidifying emissions were 22%, 17%, and 14%, respectively (Fig. 2).

The large differences in the contributions of specific fertilizers to the life-cycle impacts of crop production were partially attributable to the varied application rates modeled for nitrogen, phosphorus, and potassium for each crop (Table 1). For example, canola receives high levels of nitrogen, whereas soy receives very little. However, the actual magnitude of impacts associated with the production of specific fertilizers played a still more important role (Table 4). For conventional fertilizers, the magnitude of cumulative energy demand as well as global warming and ozone-depleting emissions for nitrogen production was two to three times that of phosphorus production on a per-kilogram basis and approximately six times that of potassium production. In contrast, phosphorus production generated much higher acidifying emissions than either nitrogen (4 times higher) or potassium production (17 times higher), largely due to the production and use of sulfuric acid to concentrate the phosphates derived from phosphate rock (Table 4). These differences were more variable and of consistently lesser scale among the fertilizers used in organic production.

More interesting in the context of this study, however, is the difference in impacts associated with the specific fertilizers used to supply nitrogen, phosphorus, and potassium in the conventional and organic production systems, respectively. On a per-kilogram basis, the impacts associated with the modeled production of the average synthetic nitrogen fertilizer mix employed in Canada were

approximately five times higher than those of producing an equivalent amount of nitrogen through green manure cultivation. Similarly, the impacts of producing the typical Canadian conventional phosphorus fertilizer were, on average, six times higher than those associated with producing the phosphate rock used in organic agriculture. In contrast, the differences between the conventional potassium mix and the potash used for organic production were much smaller (Table 3). This is attributable to the fact that potash makes up the majority of the conventional potassium fertilizer mix used in Canada.

Given the large differences in cumulative energy demand and global warming, ozone-depleting, and acidifying emissions among conventional and organic corn, canola, soy, and wheat production in Canada, most of which are attributable to the fertilizer-related impacts characteristic of these different production technologies, it is worth considering the magnitude of energy savings and emissions reductions potentially achievable through a nationwide transition from conventional to organic production of these crops. Based on the differences in contributions to each impact category for conventional and organic production as predicted by our models (Table 2) and total 2005 Canadian production volumes for each of these crops (CANSIM 2007), we estimate that a complete transition to organic production would reduce cumulative energy demand by over 90 billion megajoules (Table 4) which is equivalent to the combustion energy of approximately 2.5 billion liters of diesel fuel and equals roughly 0.8% of Canada's total energy consumption in 2004 (Environment Canada 2006). Such a transition would similarly reduce greenhouse gas emissions by 4.8 million tonnes (Table 4)—approximately 0.6% of Canada's total greenhouse gas emissions and 8.7% of greenhouse gas emissions from agriculture in 2004 (Environment Canada 2006). The most recent estimate of Canadian emissions of ozone-depleting substances was 2000 tonnes of CFC-11 equiv. per year (Canadian Council of Ministers 2001), suggesting that a transition to organic crop production would have negligible impact in reducing

Table 3 Cumulative energy demand and global warming, ozone-depleting, and acidifying emissions associated with the production of 1 kg of N, P₂O₅, or K₂O in fertilizers used in conventional (average nitrogen, phosphorus, and potassium fertilizer mixes) and organic (green manure nitrogen, phosphate rock, and potash) crop production in Canada

Inputs/emissions	Con. N fertilizer	Green manure (N) ^a	Con. P fertilizer	Phosphate rock	Con. K fertilizer	Potash (K ₂ O)
Cumulative energy demand (MJ/kg)	52.7	6.7 (13%)	20.0	4.9 (25%)	9.6	9.2 (96%)
Global warming (kg CO ₂ equiv./kg)	3.2	0.5 (16%)	1.4	0.2 (14%)	0.5	0.5 (0%)
Ozone-depletion (μg CFC-11 equiv./kg)	374.0	0.4 (.1%)	121.0	24.4 (20%)	66.0	63.1 (96%)
Acidification (g SO ₂ equiv./kg)	10.3	5.8 (56%)	43.2	1.3 (3%)	2.6	1.7 (65%)

Note: Values in parentheses are the percentages of impacts generated by organic fertilizer relative to conventional fertilizer

^a Inputs and emissions for Green Manure (N) based on the fuel, nutrient and seed requirements for the cultivation of the 90.9 m² of sweet clover required to yield 1 kg of N, assuming a fertilizer replacement value of 110 kg N/ha

Table 4 Projected reductions in cradle-to-farm gate cumulative energy demand and global warming, ozone-depleting, and acidifying emissions associated with a total transition of Canadian canola, corn, soy, and wheat production from conventional to organic methods [based on total national production data for each crop in 2005 (CANSIM 2007) and differences in energy inputs and emissions for each crop as calculated in this study (Table 2)]

Production (tonnes)		Canola 9.11×10^6	Corn 9.27×10^6	Soy 3.53×10^6	Wheat 2.73×10^7	Total 4.92×10^7	% Δ
CED (MJ)	Con.	4.74×10^{10}	2.22×10^{10}	8.12×10^9	7.37×10^{10}	1.51×10^{11}	39
	Org.	2.00×10^{10}	1.21×10^{10}	5.29×10^9	2.18×10^{10}	5.92×10^{10}	
	Δ	2.74×10^{10}	1.01×10^{10}	2.83×10^9	5.19×10^{10}	9.18×10^{10}	
GWP (tonnes CO ₂ equiv.)	Con.	6.34×10^6	3.06×10^6	8.74×10^5	1.04×10^7	2.07×10^7	77
	Org.	4.93×10^6	2.37×10^6	6.72×10^5	7.93×10^6	1.59×10^7	
	Δ	1.41×10^6	6.90×10^5	2.02×10^5	2.47×10^6	4.80×10^6	
ODP (tonnes CFC-11 equiv.)	Con.	2.51×10^{-1}	1.40×10^{-1}	3.67×10^{-2}	4.15×10^{-1}	8.43×10^{-1}	17
	Org.	3.92×10^{-2}	6.12×10^{-2}	1.76×10^{-2}	2.18×10^{-2}	1.40×10^{-1}	
	Δ	2.12×10^{-1}	7.88×10^{-2}	1.91×10^{-2}	3.93×10^{-1}	7.03×10^{-1}	
AP (tonnes SO ₂ equiv.)	Con.	1.84×10^5	5.19×10^4	2.54×10^4	2.78×10^5	5.39×10^5	96
	Org.	1.80×10^5	5.01×10^4	2.01×10^4	2.65×10^5	5.15×10^5	
	Δ	4.00×10^3	1.80×10^3	5.30×10^3	1.30×10^4	2.40×10^4	

CED: cumulative energy demand; GWP: global warming potential; ODP: ozone-depletion potential; AP: acidification potential

national emissions. Acidifying emissions would be reduced by 24.5 thousand tonnes of SO₂ equivalents (Table 4)—approximately 1% of Canada's estimated emissions in 2000 (Environment Canada 2007).

Due to the sensitivity of the reported results to assumptions regarding comparative yields between the conventional and organic systems, a sensitivity analysis was conducted to determine the yield levels for the organic crops at which the estimated impacts would be equivalent per unit yield to those predicted for the conventional systems (Table 5). To consume equivalent amounts of energy per unit yield, organic crop yields would have to drop to between 27% (wheat) and 65% (soy) of conventional yields. Similarly yields would have to range from 68% (wheat) to 77% (soy) to produce equivalent greenhouse gas emissions per unit yield and from 5% (wheat) to 48% (soy) for equivalent ozone-depleting emissions. In contrast, due to the much smaller difference in acidifying emissions

between the conventional and organic systems, yields would only need to dip from 79% (soy) to 91% (corn).

Discussion

To produce food crops at rates greater than those afforded by unmanaged ecosystems, intensive modern agriculture replaces or augments ecosystem goods and services with industrial inputs such as fossil fuels, pesticides, and synthetic fertilizers. However, it is clear that such increases in material and energy throughput result in both benefits (higher yields) and costs (local and nonlocal environmental impacts). It is thus of value to understand the environmental trade-offs associated with alternative production technologies that are characterized by variable resource and emissions intensities. More specifically, in an energy-constrained world increasingly compromised by anthropogenic perturbations of biogeochemical cycles directly attributable to unsustainable levels of material and energy consumption and waste production, the identification and promotion of more ecologically efficient production technologies must be prioritized (Hall and Klitgaard 2006; MEA 2005).

The results of this study suggest that organic crop production systems for canola, corn, soy, and wheat consume considerably less energy and produce lower greenhouse gas, ozone-depleting, and acidifying emissions relative to conventional systems. This result is driven almost exclusively by differences in the fertilizers characteristic of conventional and organic crop production and, in particular, the much lower impacts of green manure

Table 5 Estimated yield levels relative to yields achieved in conventional crop production at which organic production of canola, corn, soy, and wheat in Canada would generate equivalent impacts per kilogram of crop produced to those associated with conventional crop production

	Canola (%)	Corn (%)	Soy (%)	Wheat (%)
Cumulative energy demand	38	51	65	27
Global warming potential	70	74	77	68
Ozone-depletion potential	14	42	48	5
Acidification potential	88	91	79	86

nitrogen production in organic farming compared to conventional synthetic nitrogen fertilizer production. These findings are consistent with other LCA research, as well as numerous energy analyses of conventional and organic crop production (Ess and others 1994; Haas and others 2001; Mattsson 1999; Pimentel and others 2005; Smolik and others 1995).

This conclusion is not surprising considering that nitrogen fixation via plant/bacteria symbiosis is solar driven and, hence, essentially free, whereas the production of nitrogen fertilizer is a highly energy-intensive process (Bhat and others 1994). Moreover, the policy relevance of this distinction should not be overlooked. According to Smil (2001), 40% of the human population is at present fundamentally dependent on synthetic nitrogen use in agriculture, and Crews and Peoples (2004) questioned the life history strategy of a species that has become fundamentally dependent on the abundant and inexpensive availability of nonrenewable energy sources for the procurement of food. This issue is especially pertinent for developing nations, for which synthetic nitrogen fertilizers might become unaffordable due to rising energy costs and, more generally, for nations lacking in the natural gas reserves necessary for synthetic nitrogen production. It would appear that organic crop production offers substantial eco-efficiency gains with respect to energy use.

Although important, comparative energy intensity in agriculture must be considered in tandem with other eco-efficiency measures. Our analysis indicates that fertilizer production strongly influences the comparative eco-efficiency of conventional and organic crop production in all impact categories considered, with organic fertilizer procurement strategies resulting in consistently lower emission intensities per unit yield. However, we also found that field-level emissions related to nitrogen fertilizer use were the dominant contributor to overall greenhouse gas and acidifying emissions for both conventional and organic production. For this reason, despite the fact that fertilizer production for the organic systems had substantially lower associated emissions, much of this gain was overshadowed by the much larger field-level emissions from nitrogen fertilizer use, which, consistent with available literature (as reviewed by Stolze and others 2000), our models assumed were comparable between conventional and organic crops on a per-hectare basis. This is in agreement with Williams and others (2006), who described the importance of considering the nitrous oxide footprint of agriculture over the greenhouse gas emissions associated with fertilizer production and on-farm fuel use.

Given that field-level emissions are central to greenhouse gas and acidifying emission intensities in crop production and that they are notoriously variable within and between production systems because they are

influenced by a wide variety of factors, including climate, season, soil, fertilizer type, and management practices (Dobbie and others 1999), comparisons of these dimensions of eco-efficiency in conventional and organic production systems must therefore be approached with caution. Moreover, other factors such as soil carbon sequestration, which we did not consider in our analysis, might also have a strong influence on comparative greenhouse gas intensities. For example, Robertson and others (2000) compared the total greenhouse gas emissions associated with legume and fertilizer-based cropping systems and found that the global warming potential of conventional systems was almost three times higher than that of legume-based systems. However, conventional no-till systems were less emissions-intensive than were the legume-based systems due to greater soil carbon sequestration. Further research in this area should be prioritized, as this consideration might be a critical determinant of comparative greenhouse gas emissions in conventional and organic systems.

One of the most common arguments against organic farming is that reduced yields per hectare and the necessity of devoting land to green manure rotations would require the cultivation of additional land at the expense of wild ecosystems. Given that 670 million hectares of land were dedicated to cereal production in 2000, each 10% decrease in yield would require an additional 6.7 million hectares of land to maintain productivity (MEA 2005). That said, any net loss in caloric production could easily be mitigated by allocating greater shares of crop production for direct human consumption rather than animal husbandry. Moreover, as evidenced by this study and others, the production and use of fertilizers and pesticides on conventionally managed croplands also have clear environmental costs. Weighing the relative merits of highly intensive, land-efficient production technologies versus lower intensity but less land-efficient practices demands a complex calculus indeed.

Several extensive published literature reviews suggest that for most crops, organic yields are very close to, equivalent to, or greater than yields of conventionally managed crops (Badgley and others 2007; Lockeretz and others 1980; Stanhill 1990). In a comparison of 26 commercial mixed-grain and livestock farms covering a range of soil types in the western Corn Belt, the mean yield for corn was 8.5% higher on conventional fields compared to fields grown without pesticides and conventional fertilizers, although the difference was not statistically significant. Yields tended to be higher for conventional fields under favorable conditions but lower under adverse conditions (Lockeretz and others 1980). Stanhill (1990) compared the productivity of organic and conventional systems in a wide range of environments, including the eastern US Corn Belt,

Switzerland, Germany, Finland, Sweden, Israel, and Australia. On average, yields in organic systems were within 10% of yields obtained in conventional systems. More recently, Badgley and others (2007) compared yields of organic versus conventional food production using a global dataset of 293 examples and estimated the average organic:conventional yield ratio of different food categories for the developed and the developing world. Generally, the average yield ratio was slightly <1.0 for studies in the developed world and >1.0 for studies in the developing world. These findings suggest that the predicted yields and associated energy use/emissions for conventional and organic crops employed in the present study are realistic. Moreover, as evidenced by our sensitivity analysis, yields in organic crop production would have to be substantially lower before cumulative energy demand and emissions intensity per unit yield would be equivalent to that predicted for conventionally produced crops.

Although our analysis suggests large differences in energy use and emissions intensity between conventional and organic crop production and despite the fact that the four crops considered account for three-quarters of field crop production (excluding hay) in Canada (Statistics Canada 2007), it would appear that a nationwide transition to organic production of these crops would have a relatively small influence on total energy use and emissions of greenhouse gases, ozone-depleting, and acidifying compounds at the national level. As a policy instrument for improving national eco-efficiency in terms of the impact categories considered in this study, there are therefore likely more effective leverage points than a wholesale transition to organic cropping practices. However, these gains must be considered in concert with other measures of socioeconomic and ecological integrity—an exercise far beyond the scope of this article.

Several important simplifying assumptions in our analysis should also be noted. For example, only industrial fertilizers and green manure were modeled as potential nutrient sources. In reality, manure might be an important nutrient source in both conventional and organic systems. However, because manure is simply a conduit for nutrients originally derived from either industrial sources or biological nitrogen fixation, we do not consider its exclusion from our analysis to be problematic. It could also be argued that inputs and emissions related to crop production are context dependent, regardless of whether the system is conventional or organic. For this reason, we believe that modeling average systems based on national production data provides a realistic and useful comparison of the tradeoffs associated with these competing production technologies.

Certainly, there are many more trade-offs associated with a conversion from conventional to organic agriculture than have been addressed in this study. However, ample literature is presently available regarding the numerous proximate environmental interactions characteristic of conventional versus organic farming technologies (Stolze and others 2000). What is clear from our work is that, given the important role of nutrient provision in the environmental performance of crop production and the varied life-cycle impacts associated with the production and use of different fertilizers (Brenttrup and others 2001), the identification and promotion of least-environmental-cost nutrient sources and efficient fertilizer use should be a research priority. It might be that combining elements of conventional and organic production (e.g., using pesticides to maintain high yields but relying on green manure as a nitrogen source) would actually optimize environmental performance according to the impact categories considered in this study, although a consideration of additional trade-offs such as toxicological impacts might again shift the balance in favor of organic production technologies. However, rather than a simple transition from conventional to organic nutrient procurements strategies, it should also be considered that the goal of achieving sustainable food production systems might be much better served by a transition away from many annual crops such as corn and soybeans, which are used predominantly for animal fodder, toward perennial cropping systems and crops for direct human consumption. Cox and others (2006) and Jordan and others (2007) suggested that such a transition would reduce problems frequently associated with annual crop production, including water degradation due to sedimentation and nutrient/pesticide runoff, groundwater depletion, soil erosion, and higher greenhouse gas emissions, while increasing biodiversity value and soil organic carbon sequestration.

Conclusions

Global grain production is expected to double by 2050 (Alexandratos 1999; Cassman 1999) to satisfy the demands of a growing population consuming increasing volumes of grain-fed meat and biofuels. How to achieve this objective as well as respond to the pressing needs of the estimated 3.7 billion currently malnourished people (Pimentel and Pimentel 2006) without further compromising the ecological integrity of agroecosystems and biogeochemical cycles is among the most pressing challenges of the 21st century. A transition to organic crop production practices might be instrumental in meeting this goal, although insufficient in isolation to substantially mitigate human-induced environmental perturbations.

Food is a fundamental human requirement. Although much of the material and energy throughput of contemporary society is nonessential and can be pared away as resource constraints require, we cannot change the basic human physiological requirement for a minimum amount and quality of food energy. What we can change is the efficiency of our food production systems, such that we satisfy human needs in ways that minimize environmental harms. Such considerations must necessarily be central to the development of a sustainable human society.

Our analysis underscores the importance of considering the broader, macroscale implications of conventional and organic crop production (and industrial activities generally), with particular reference to present and future constraints on fossil fuel availability and contributions to climate change, acid precipitation, ozone depletion, and other concerns. Certainly, ignoring the contributions of industrial agriculture to the disruption of the biogeochemical cycles that cumulatively provide the implicate order for biological productivity is, at best, a serious oversight.

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