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Review

Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada

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Abstract

Agricultural soils can constitute either a net source or sink of the three principal greenhouse gases, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). We compiled the most up-to-date information available on the contribution of agricultural soils to atmospheric levels of these gases and evaluated the mitigation potential of various management practices in eastern Canada and northeastern USA. Conversion of native ecosystems to arable cropping resulted in a loss of ~22% of the original soil organic carbon (C)—a release of about 123 Tg C to the atmosphere; drainage and cultivation of organic soils resulted in an additional release of about 15 Tg C. Management practices that enhance C storage in soil include fertilization and legume- and forage-based rotations. Adopting no-till did not always increase soil C. This apparent absence of no-till effects on C storage was attributed to the type and depth of tillage, soil climatic conditions, the quantity and quality of residue C inputs, and soil fauna. Emission of N_2O from soil increased linearly with the amount of mineral nitrogen (N) fertilizer applied ($0.0119\ \mathrm{kg}\ N_2O\text{-}N\ \mathrm{kg}\ N^{-1}$). Application of solid manure resulted in substantially lower N_2O emission ($0.99\ \mathrm{kg}\ N_2O\text{-}N\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) than application of liquid manure ($2.83\ \mathrm{kg}\ N_2O\text{-}N\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) or mineral fertilizer ($2.82\ \mathrm{kg}\ N_2O\text{-}N\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$). Systems containing legumes produced lower annual N_2O emission than fertilized annual crops, suggesting that alfalfa (*Medicago sativa* L.) and other legume forage crops be considered different from other crops when deriving national inventories of greenhouse gases from agricultural systems. Plowing manure or crop stubble into the soil in the autumn led to higher levels of N_2O production ($2.41\ \mathrm{kg}\ N_2O\text{-}N\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$) than if residues were left on the soil surface ($1.19\ \mathrm{kg}\ N_2O\text{-}N\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$). Elevated N_2O emission during freeze/thaw periods in winter and spring, suggests that annual N_2O emission based only on growing-season measurements would be underestimated. Although measurements of CH_4 fluxes are scant, it appears that agricultural soils in eastern Canada are a weak sink of CH_4, and that this sink may be diminished through manuring. Although the influence of agricultural management on soil C storage and emission of greenhouse gases is significant, management practices often appear to involve offsets or tradeoffs, e.g., a particular practice may increase soil C storage but also increase emission of N_2O. In addition, because of high variability, adequate spatial and temporal sampling are needed for

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accurate estimates of greenhouse gas flux and soil C stock. Therefore a full accounting of greenhouse gas contributions of agricultural soils is imperative for determining the true mitigation potential of management practices.

Keywords: Greenhouse gases; Soil carbon; Nitrous oxide; Carbon dioxide; Methane; Agricultural management practices; Mitigation

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Contents

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1. Introduction

Rising atmospheric levels of the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) have caused an increase in radiative forcing of the earth's atmosphere. Agriculture plays an important role in the global flux of these gases. In Canada, agriculture accounts for about 8% of total greenhouse gas emission from all sectors (Environment Canada, 2002). Since agroecosystems are usually intensively managed, agricultural practices may offer a way to curb agricultural emission, in turn partially mitigating the enhanced greenhouse effect.

Agricultural soils can constitute either a net source or sink of greenhouse gases. The ways that these soils are managed can influence the flux of greenhouse gases by changing one or more of the following: the soil climate (i.e., temperature and water content), the physical/chemical environment of the soil, and the amount and chemical composition of organic residues applied to soil. Changes in these variables control the rate and extent of microbial processes, which in turn control the stabilization of C in soil and affect the production of greenhouse gases. These gases can play different roles in the metabolism of micro-organisms, serving as metabolic and stoichiometric products or as growth substrates (Conrad, 1996). Changes in the soil physical environment affect the aeration and diffusion of these gases.

Net CO_2 emission from Canadian agricultural soils are currently considered small (Environment Canada, 2002). However, the potential exists to increase soil C by increasing organic matter content (Janzen et al., 1998; VandenBygaart et al., 2004), thereby converting these soils to a net CO_2 sink. Management practices that can improve soil C content (usually the same as those suggested to enhance soil quality) are generally well known (Dick and Gregorich, 2003). In eastern Canada, management practices used to enhance soil C storage vary with cropping system. For example, in corn (*Zea mays* L.)/soybean (*Glycine max* (L.) Merrill) cropping systems, reduced tillage and improved crop yield may increase soil C content even though the potential has not been well quantified (VandenBygaart et al., 2003). The potential to increase soil C in dairy-based production systems, which are common in eastern Canada, has not been studied in detail. Opportunities exist to increase soil organic C in these systems by increasing forage production or improving manure management.

Nitrous oxide emission from soils is derived from nitrification and denitrification processes. In cool, temperate regions N_2O emission comprises the majority of greenhouse gas emission associated with crop production (Robertson et al., 2000). Climatic factors that regulate N_2O emission include temperature, precipitation and freezing and thawing regimes (Burton and Beauchamp, 1994). Many management factors, including tillage, legume cropping, crop residue management, and type and rate of mineral N fertilizer application, also contribute to N_2O emission. Manure is an important source of N_2O emission; an estimated 45% of agricultural N_2O emission in Canada originates from collection, storage, and application of animal manure (Desjardins and Riznek, 2000), creating significant potential for greenhouse gas mitigation through better manure management practices.

Most of the CH_4 produced in the agriculture sector is associated with animal production. Well-aerated arable land is usually a sink for atmospheric CH_4, because soil methanotrophs use CH_4 as a source of energy and C (Topp and Pattey, 1997). Methane is produced in soil by the decomposition of organic matter and reduction of CO_2 under highly anaerobic environments, such as localized areas that are poorly drained. In forest and grassland soils, N fertility has been shown to substantially decrease net CH_4 consumption (Mosier et al., 1991; Castro et al., 1994). Therefore any management system that involves large N inputs into the soil may have a significant effect on soil production/consumption of CH_4. As well, soil structural degradation, particularly through compaction, which is a common problem in poorly drained soil with fine texture in eastern Canada, can adversely affect CH_4 consumption (Hansen et al., 1993; Ball et al., 1999).

Measurement of greenhouse gas emission from soil is made at small (e.g., soil chamber) or large scales (e.g., tower), and the net balance of C storage in soil is usually derived from long-term field experiments and/or simulation modeling. However, because of the very large spatial and temporal variability of greenhouse gas emission and sinks, estimating regional fluxes for the purposes of accounting and reporting must rely on modeling and scaling up smaller-scale measurements taken in plots or fields.

The objective of this review was to assemble available information on the contribution of agricultural soils to CO_2, N_2O, and CH_4 emission, and to identify and quantify the mitigation potential of management practices in farming systems in eastern Canada and northeastern USA. Recent compendia of published Canadian studies evaluated the influence of agricultural management on soil C (VandenBygaart et al., 2003) and N_2O fluxes from farming systems (Helgason et al., in press). In this review we extract key observations from these compendia and collate new, additional data on N_2O as well as CH_4 from studies in eastern Canada. We interpret these data and draw some general conclusions about the influence of agricultural management on these greenhouse gases. From the reviews by VandenBygaart et al. (2003) and Helgason et al. (in press) it can be concluded that in Canada there are regional differences in the effects of management on soil C and N_2O fluxes which are related to climate and soil type. In this review we explore possible mechanisms and reasons for those regional differences. We also highlight important principles related to over- or under-estimating the mitigation potential of management practices.

2. Current land use

The climate of eastern Canada can be characterized as cool and temperate. Agricultural production is carried out in three main ecological areas in this region: the Boreal Shield, Mixed Wood Plains, and

Table 1
Key climatic, vegetative and pedological characteristics of ecoregions in eastern Canada

Ecoregion	Precipitation range (mm)	MAT (°C)	Winter temperature range (°C)	Summer temperature range (°C)	Native vegetation	Soil types[a]
Mixed Wood Plains	700–1000	4.5–8	−7 to −2.5	16–18	Mixed forest, deciduous forest, mosses, lichens	Gleysolic, Humo-Ferric Podzols, Dystric Brunisols, some Fibrisols, Melanic Brunisols, Gray Brown Luvisols
Boreal shield	800–1600	0–5.5	−11 to −4	11.5–14	White spruce, balsam fir, paper birch, aspen, black spruce, tamarack, evergreen shrubs, dwarf kalmia, mosses, deciduous shrubs, mixed ericaceous shrubs, lichens,	Humo-Ferric Podzols, Ferro-humic Podzols, Dystric Brunisols, Mesisols, Luvisols, Brunisols, Gleysols, Fibrisols, Gleyed Podzols
Atlantic maritime	900–1500	3–6.5	−8 to −1.5	14–15.5	Coniferous forests, mixed deciduous, heath	Podzols, Dystric Brunisols, Gleysols, Humo-Ferric Podzols, Ferro-Humic Podzols, Gray Luvisols, Mesisols, Humisols, Fibrisols, Regosols, Ortstein Podzols, Organic Mesisols, Gleyed Podzols

[a] ACECSS, 1998.

Atlantic Maritime ecozones (Ecological Stratification Working Group, 1995). Table 1 summarizes some key characteristics of these ecozones. The existing land use of the Boreal Shield ecozone consists mainly of mining, forestry, hydropower, recreation, and tourism, along with commercial and subsistence hunting, trapping, and fishing. Agriculture in this ecozone is limited to small areas where soil suitability and microclimate are favorable. The Mixed Wood Plains ecozone borders the lower Great Lakes and St. Lawrence River and is the most densely populated region in Canada. Most of the deciduous vegetation has been cleared for agriculture, urban areas, and highways. Agricultural land is mainly used for cash cropping, pasture, dairy and livestock production, and some vegetable and fruit production. The Atlantic Maritime ecozone covers all of the provinces of New Brunswick, Nova Scotia, and Prince Edward Island. Forestry, agriculture, and mining are the main land-use activities, with the coastal communities supporting large fisheries. The lowland soils support dairy and livestock operations, some cereal cash-cropping, along with fruit and vegetable production.

3. Carbon dioxide

3.1. Contribution of CO_2 resulting from conversion to cropland

In eastern Canada the conversion of native ecosystems to cropland often resulted in a loss of soil organic C due to increased mineralization and lower C inputs (Carter et al., 1998). However, in some cases this conversion resulted in greater soil C storage due to improved fertility or drainage of soils, on which primary production was previously limited under native conditions (Ellert and Gregorich, 1996). The total loss of soil C as CO_2 due to conversion of native ecosystems to agricultural cropland in eastern Canada was estimated using mean soil C by Great Group (ACECSS, 1998) from those soil pedons designated as agricultural from the Canadian National Soils Database (MacDonald and Valentine, 1992). We assumed that losses of C due to erosion were minimal and that pedon soil C levels would represent near-steady-state levels after conversion to cropland, since soil C following conversion of native ecosystem to agriculture has, for the most part, stabilized in Canadian soils (Janzen et al., 1998). Conversion of native ecosystems to cropland on mineral soils in eastern Canada has caused a mean loss of 22 ± 10% of the initial soil C levels (VandenBygaart et al., 2003). Assuming that this loss occurred in each of the Great Groups in eastern Canada, we estimated the net loss of C due to conversion of native land to agriculture as:

$$\mathrm{SC}_{\mathrm{loss}} = \sum_{1}^{n} \{[(\mathrm{SC}_{\mathrm{ag}} \times 1/0.78) - \mathrm{SC}_{\mathrm{ag}}] \times A\} \qquad (1)$$

where $\mathrm{SC}_{\mathrm{loss}}$ is the total loss of soil C for eastern Canada over time (t), n the number of great group areas of eastern Canada, $\mathrm{SC}_{\mathrm{ag}}$ the average soil C (Mg ha^{-1}) for the great group derived from the Soil Organic Carbon Database of Canada (Lacelle, 1997), and A the area (ha) of the great group in eastern Canada. This calculation yields a net C loss of 123 Tg C (1 Tg = 10^{12} g), or 450 Tg CO_2 equivalent due to conversion of native land to agriculture. This value is much smaller than the estimated 1.3 Pg (1 Pg = 10^{15} g) loss of C due to this type of conversion in western Canada (Janzen et al., 1998).

Drainage and cultivation of organic soils (Histosols; FAO, 1998) result in surface subsidence due to improved conditions for oxidation (Irwin, 1977). Drained organic soils that are brought under cultivation lose C at a rate of ~10 Mg ha^{-1} year^{-1} in a cool, temperate climate (Ogle et al., 2003) such as in eastern Canada. About two-thirds of Canada's 30,000 ha of cultivated organic soils are found in eastern Canada (Environment Canada, 2002). Assuming that most organic soils have been cultivated for 50–100 years, the historical loss of C ranged from 10 to 20 Tg C.

3.2. *Management practices and soil organic C*

It is generally acknowledged that minimizing soil disturbance promotes soil C storage (Paustian et al., 1997; West and Post, 2002). In western Canada the rate of storage under no-till was estimated at 0.32 ± 0.15 Mg C ha^{-1} year^{-1} (VandenBygaart et al., 2003), consistent with other assessments from the literature (Paustian et al., 1997; West and Post, 2002). In contrast, the rate of soil C storage was near zero in eastern Canada (−0.07 ± 0.27 Mg C ha^{-1} year^{-1}). In eastern Canadian soils, there is evidence suggesting that the gain of soil C in the top 10 cm under no-till is offset by an accumulation of soil organic C at lower depths under moldboard plowing (Angers et al., 1997; Yang and Kay, 2001; Deen and Kataki, 2003; VandenBygaart and Kay, 2004).

The apparent absence of no-till effects on C storage in eastern Canada can be attributed to several factors, including type and depth of tillage, soil climatic conditions, residue quality, residue inputs, and soil fauna. Tillage in eastern Canada is usually deeper (e.g., moldboard plow to 15–30 cm) than in western Canada (e.g., chisel plow to 10 cm). The cool, moist soils of eastern Canada are often poorly drained and aeration can be limiting at depth, reducing decomposition of buried residues (Angers et al., 1997). Moisture levels at the soil surface (where residues are concentrated in no-till systems) in eastern Canada are higher for longer periods of time during the year than in the drier Prairie soils, favoring greater decomposition of crop residues on the soil surface. Corn-based cropping systems are common in eastern Canada, whereas wheat-based systems are predominant in western Canada; cereal plants have higher lignin contents (16–24%) than corn (11–16%), and higher lignin content slows decomposition of organic matter (Stevenson, 1994). Tillage effects on crop yield (i.e., residue C inputs) can differ between corn-based and wheat-based systems. In corn-based systems, yield effects in no-till and moldboard plow systems are often variable in eastern Canada, with some studies showing negative or little effect of no-till on grain yield (Ball-Coelho et al., 1998). In western Canada, significant yield advantages have been achieved with no-till in wheat-based systems (Larney et al., 1994; Arshad et al., 2002). In eastern Canadian soils, decomposition of crop residues left on the surface is facilitated particularly by earthworms (*Lumbricus terrestris* L.), whereas in the western Canadian soils, where there are relatively few surface-feeding earthworms (Clapperton et al., 1997), more residue remains on the soil surface and decomposition is limited by dryness in the summer and coldness in the winter.

Few studies have assessed the effects of crops and crop rotations on soil C in eastern Canada. Continuous monoculture with annual crops usually results in lower soil C content relative to that under perennial crops (Elustondo et al., 1990; Carter et al., 1998; Gregorich et al., 2001). Rotations involving perennial crops can

Table 2
Default IPCC factors and corresponding Canadian-specific factors for soil C change following land-use conversion to long-term cultivation, tillage, and inputs for cropped mineral soils in eastern Canada[a]

Factor	Level/type	IPCC factor	Error[b]	Eastern Canada	Error
Land use	Long-term cultivated	0.71	±0.09	0.78	±0.08
Tillage	Full	1.00		1.00	
	Reduced	1.09	±0.07	n/a[c]	
	No-till	1.16	±0.05	0.96	±0.04
Input	Low	0.91	±0.07	n/a[c]	
	Medium	1.00		1.00	
	High input without manure	1.11	±0.11	1.04[d]	±0.02
	High input with manure	1.38	±0.11	1.16[d]	±0.12

[a] It is assumed that IPCC GPG for "temperate wet" reflects these conditions in eastern Canada.

[b] Error is 2 S.D. from the mean.

[c] n/a denotes insufficient data or not applicable.

[d] There are insufficient data to derive a coefficient for eastern Canada—these values are for all of Canada.

also result in greater soil C than continuous annual cropping. For example, Angers et al. (1999) found that at the end of 10 year, potato (*Solanum tuberosum* L.) rotations with a high frequency of perennial forages led to greater soil C content than continuous potato. Gregorich et al. (2001) determined that after 35 years, legume-based cropping systems had 20 Mg ha^{-1} greater C than corn monoculture. Much of the greater C storage in the legume system was found deeper in the soil profile (beneath the plow layer) and due presumably to the quantity and quality of root inputs. The type of crop used in rotation also seems to be a factor. In Prince Edward Island, 2-year potato rotation with Italian ryegrass (*Lolium multiflorum* Lam.) generally maintained soil C, whereas soil C declined under 2-year potato rotation with red clover (*Trifolium pratense* L.) or barley (*Hordeum vulgare* L.) (Carter et al., 2003). Similarly, Yang and Kay (2001) found that soil organic C under corn with rotation of soybean + winter wheat (*Triticum aestivum* L.) or barley + barley (underseeded with red clover) was 2–9 Mg ha^{-1} greater than for other corn-based rotations.

Improved crop nutrition through addition of N fertilizer to soils of eastern Canada can positively affect soil C. An Ontario clay loam soil receiving 130 kg N ha^{-1} year^{-1} for 32 years had 8 Mg ha^{-1} more C than that found in an un-fertilized soil in a corn-based system (Gregorich et al., 1996). High rate of N fertilization for 6 years resulted in an 18% increase in soil C in a Québec sandy clay loam soil under continuous corn (Liang and Mackenzie, 1992). However, Bélanger et al. (1999) could not detect any relationship between soil organic C and fertilizer application or crop yield in a permanent grass sward in New Brunswick, even after 35 years of fertilizer application. When studies from across Canada were considered ($n = 36$), N-fertilized soils gained soil organic C at a rate of 230 ± 130 kg ha^{-1} year^{-1} relative to un-fertilized soils (VandenBygaart et al., 2003). This corresponds to a "high input without manure" coefficient for Canada of 1.04 ± 0.02 (Table 2), which is lower than the default value of 1.11 suggested by the Intergovernmental Panel on Climate Change (IPCC).

Higher C levels occur in soils with manure amendments than those without. The increase is often linearly related to the quantity of manure added (N'Dayegamiye and Cote, 1989). From 18 studies across Canada, soil C was 28 ± 21% higher in soils receiving manure than those that did not (VandenBygaart et al., 2003). This yielded a factor for C change in manured systems (i.e., "high input with manure") of 1.16 ± 0.12 (Table 2). Most studies assessing the impact of manure on soil C have involved solid cattle manure, whereas the effects of other types of manure (e.g., liquid hog manure) have not been studied in detail.

3.3. Comparison of IPCC default factors with region-specific factors

The IPCC's Good Practice Guidance for the Land Use, Land-Use Change and Forestry (LULUCF) sector (IPCC, 2004) describes a procedure for determining changes in soil C based on country-specific databases for soil distribution, soil C stocks, land use, and management. A country selects one of three tiers of methodologies based on the quality and quantity of data available for a given parcel of land. For those countries lacking adequate databases and information (i.e., Tier 1), the IPCC (2004) describes default parameters and reference C stocks from which a change in soil C can be determined. These parameters are used in a simple model that calculates the expected change in soil C stock with a change in management from a reference. The Tier 2 consists of soil C stock changes derived by extrapolation from long-term experiments for various climate and soil types from within the country. Also, reference C stocks can be derived from soil surveys and mapping activities.

Since Canada has adequate representation of data for the effects of tillage and fertilizer management on soil C in cropland, factors can be derived for assessing eastern Canada's potential to enhance soil C levels. Using results from the review of VandenBygaart et al. (2003), management and input factors of relative change in soil C were derived with a measure of uncertainty similar to that compiled by the IPCC. Table 2 shows the matrix of factors across the country, along with a measure of relative confidence in the coefficients. The default values derived by the IPCC method are also given in Table 2. A comparison can be made between IPCC default input factors and our Canadian-specific factors for various management conditions. Our estimate for a land-use conversion factor to long-term cultivation is 0.78 ± 0.08 (i.e., 22% loss of C due to conversion of native land to agriculture) and is similar to the IPCC default factor of 0.71 (Table 2) assuming "temperate wet" represents climatic conditions in eastern Canada.

Our estimates for some factors differ from those using the IPCC. For example, the no-till factor for eastern Canada is 0.96, but 1.16 from the IPCC (2004). This discrepancy reflects the lack of noticeable C increase in soil converted to no-till in eastern Canada (Angers et al., 1997; Yang and Kay, 2001; Deen and Kataki, 2003; VandenBygaart and Kay, 2004). The large discrepancy could also indicate that, with further data, the default IPCC factors could be further refined by subdividing the general temperature classes, similar to the recent addition of moisture sub-classes in the latest good practice guide of LULUCF (IPCC, 2004). Thus, countries with moist and cool climates could adopt a no-tillage factor of 0.96 if the country-level data was lacking for this practice. This supports the use of the tier structure of the guidelines since it appears that the no-tillage factor for Canada should be much lower than that proposed for moist, temperate conditions, and as such Canada would, at a minimum, be reporting at the Tier II level for a change in soil C due to no-tillage.

4. Nitrous oxide

We have summarized N_2O emission data from agricultural soils in eastern Canada to identify potential mitigation practices. Most of the emission values presented in Tables 3–8 are from studies in which weekly or bi-weekly measurements were made from March/April to November using chamber-based techniques. The important N sources (e.g., mineral N fertilizers, manures, and legume crops), agricultural management practices (e.g., no-tillage), and natural climatic events (e.g., winter and spring thaw) that result in N_2O production and emission from agricultural soils (IPCC, 1997) have been documented for eastern Canada. However, there is only indirect information on N_2O emission associated with decomposition of crop residues. Spatial coverage of the entire region of eastern Canada is incomplete, with measurements obtained only from Ontario and Québec. This is a significant gap in information, since N_2O emission is highly sensitive to local interactions among soil, cropping, and climate conditions. For example, we have no data assessing the mild and wet conditions of the Atlantic Maritime ecozone on N_2O emission in highly fertilized potato fields and during the frequent winter freeze/thaw cycles.

4.1. Winter/spring and freeze/thaw

In eastern Canada N_2O emission can be significant outside the growing season, sometimes exceeding that during the growing season (Wagner-Riddle et al., 1997). Laboratory incubation studies indicate that freeze/thaw cycles can lyse a substantial proportion of microbial cells, resulting in release of C and nutrients into surrounding soil (Ivarson and Sowden, 1970).

Table 3
N_2O-N emission during winter/spring thaw events under different cropping systems

Location	Year	Cropping /management system	Soil Texture	Fall N applied (kg N ha^{-1})	Emission (kg N_2O-N ha^{-1})	Reference
Fall incorporation of organic matter						
Guelph, Ont.	1994	Fallow	Silt loam	Manure (90)	4.84	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1994	Alfalfa	Silt loam	Crop residue N	3.79	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1994	Corn	Silt loam	Crop residue N	1.33	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1995	Corn	Silt loam	Crop residue N	0.92	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1996	Wheat	Loam	Crop residue N	1.16	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1996	Wheat	Loam	Manure (75) + crop residue N	3.16	Wagner-Riddle and Thurtell (1998)
Mean ± S.D.					2.41 ± 1.79	
Annual stubble						
Guelph, Ont.	1994	Fallow	Silt loam	0	2.63	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1994	Corn	Silt loam	0	1.67	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1995	Barley	Silt loam	0	0.83	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1995	Soybean	Silt loam	0	0.20	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1995	Canola	Silt loam	0	0.59	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1995	Corn	Silt loam	0	0.52	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1996	Barley	Silt loam	0	0.90	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1996	Soybean	Silt loam	0	1.20	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1996	Canola	Silt loam	0	2.34	Wagner-Riddle and Thurtell (1998)
Ottawa, Ont.	1996	Corn	Clay loam	0	1.06	Grant and Pattey (1999)
Mean ± S.D.					1.19 ± 0.79	
Perennial crops						
Guelph, Ont.	1994	Turfgrass	Silt loam	0	0.21	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1995	Turfgrass	Silt loam	0	0.03	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1996	Turfgrass	Silt loam	0	0.08	Wagner-Riddle and Thurtell (1998)
Guelph, Ont.	1997	Turfgrass	Loam	0	0.00	Maggiotto and Wagner-Riddle (2001)
Guelph, Ont.	1997	Turfgrass	Loam	50	0.63	Maggiotto and Wagner-Riddle (2001)
Guelph, Ont.	1997	Turfgrass	Loam	50	1.02	Maggiotto and Wagner-Riddle (2001)
Guelph, Ont.	1997	Turfgrass	Loam	50	0.07	Maggiotto and Wagner-Riddle (2001)
Mean ± S.D.					0.29 ± 0.39	
All winter/spring thaw						
Mean ± S.D.					1.18 ± 1.24	

Accordingly, field research has indicated that substantial N release can occur during spring thaw in seasonally cold ecosystems (Wang and Bettany, 1993). Furthermore, during thaw events in the winter and spring, saturation of the soil can restrict aeration, favoring the denitrification of soil mineral N and production of N_2O.

A review of field studies shows that N_2O emission during winter/spring thaw is usually greater in annual (1.19 ± 0.79 kg N_2O-N ha^{-1} $year^{-1}$) than in perennial (0.29 ± 0.39 kg N_2O-N ha^{-1} $year^{-1}$) cropping systems (Table 3). This is likely because there is less inorganic N in soils under perennial crops due to the longer period of active growth and the associated uptake of nutrients, and also to the slower decay of above-ground residues and roots after harvest.

Incorporation of manure or stubble residue by tillage in the autumn can lead to higher N_2O emission (2.41 kg N_2O-N ha^{-1} $year^{-1}$) than if residues are left on the soil surface (1.19 kg N_2O-N ha^{-1} $year^{-1}$) (Table 3), consistent with the observation that decomposition of organic residues can occur when temperatures are near freezing (Chantigny et al., 2002). Decomposition of this organic matter supplies inorganic N for nitrification and denitrification and may lead to the development of anoxic microsites

Table 4
N_2O-N emission from soils under moldboard plow (MP) and no-till (NT)

Location	Year	Cropping system	Soil texture	N applied (kg N ha^{-1})	Emission MP (kg N_2O-N ha^{-1} $year^{-1}$)	Emission NT (kg N_2O-N ha^{-1} $year^{-1}$)	Reference
Québec, Que.	2001	Barley	Loamy sand	60	1.24	1.23	Rochette et al. (2003)[c]
Québec, Que.	2001	Barley	Clay	60	20.62	44.24	Rochette et al. (2003)[c]
Québec, Que.	2002	Barley	Loamy sand	60	0.93	1.52	Rochette et al. (2003)[c]
Québec, Que.	2002	Barley	Clay	60	6.12	12.12	Rochette et al. (2003)[c]
Québec, Que.	2003	Barley	Loamy sand	60	0.81	0.61	Rochette et al. (2003)[c]
Québec, Que.	2003	Barley	Clay	60	12.16	38.92	Rochette et al. (2003)[c]
Ottawa, Ont.	2002	Soybean	Sandy loam	0	1.51	1.15	Gregorich et al. (2004)[c]
Ottawa, Ont.	2002	Corn	Sandy loam	190	0.71	1.06	Gregorich et al. (2004)[c]
Ottawa, Ont.	2003	Soybean	Sandy loam	0	0.42	0.29	Gregorich et al. (2004)[c]
Ottawa, Ont.	2003	Corn	Sandy loam	190	0.37	0.27	Gregorich et al. (2004)[c]
Montreal, Que.	1994	Corn + Soybean	Heavy clay	180	2.1	1.8	MacKenzie et al. (1998)
Montreal, Que.	1994	Corn + Soybean	Silt clay loam	180	3.5	2.2	MacKenzie et al. (1998)
Montréal, Que.	2003	Soybean	Loamy sand	0	0.9	1.44	Rochette et al. (2003)[c]
Woodslee, Ont.	2003	Corn	Clay loam	155	1.29	0.96	Kaharabata et al. (2003)
Woodslee, Ont.	2004	Corn	Clay loam	155	1.07	1.04	Kaharabata et al. (2003)
Mean ± S.D.[a]					3.58 ± 5.63	7.26 ± 14.26	
Mean ± S.D.[b]					1.67 ± 3.21	1.88 ± 4.63	

[a] Mean of raw data.
[b] Mean of log-transformed (to the base 10) data.
[c] Unpublished data.

(Paul and Beauchamp, 1989; Beauchamp, 1997). Chamber techniques are not well-suited for gas flux measurement on snow-covered or flooded soils and cumulative N_2O emission reported in the literature usually pertains only to the snow-free season. Consequently, the lack of emission estimates during winter and spring likely underestimates annual N_2O emission.

4.2. No tillage

Reporting a change in N_2O emission with adoption of no-till is not mandatory under the original Kyoto agreement. However, recent additions to the agreement at the Conference of Parties 7 held in Marrakech, Morocco, in November 2001 require that N_2O emission be reported if the country elects to adopt C sink offset by no-till.

Table 4 summarizes field studies from eastern Canada comparing N_2O emission under no-till and conventional tillage (i.e., moldboard plowing). Nitrous oxide emission was lower for no-till soils in more than half the studies, but the distribution of differences between no-till and plowed soils was strongly skewed due to some very high values. As a result, annual N_2O emission was higher for no-till than plowed soils by an average of 3.7 kg N ha^{-1} (0.21 kg N ha^{-1}, if log-transformed data were used). This result contrasts with the response to tillage observed in the Prairies of western Canada, where N_2O emission under no-till was less than that under conventional tillage (Helgason et al., in press). That the greatest positive effects in eastern Canada were measured in fine-textured soils (Table 4) suggests that a significant part of the effect of no-till on increased N_2O emission may be linked to its direct impact on soil density and water content, and its indirect impact on oxygen levels, gas diffusion, and aeration. This effect is likely less important under the much drier climate in the western Canadian Prairies. Thus the effect of no-till on N_2O emission appears to be governed by an interaction between soil and climate factors that affect soil aeration.

Mean N_2O emission was strongly influenced by high fluxes measured in a clay soil in Québec. Using raw data, mean annual N_2O emission was

3.58 kg N_2O-N ha^{-1} for plowed soils and 7.26 kg N_2O-N ha^{-1} for no-till soils. If log-transformed data were used, the mean annual N_2O emission would be 1.67 kg N_2O-N ha^{-1} for plowed soils and 1.88 kg N_2O-N ha^{-1} for no-till soils (Table 4). The high spatial and temporal variability of no-till on N_2O emission suggests that extrapolation of site-specific measurements to broad regional scales should be done with caution. This variability also underscores the need for developing a reliable, accurate predictive model that could integrate the complex interactions between biotic and abiotic factors governing N_2O emission.

Relatively high N_2O emission from no-till soils would offset part of the mitigation benefit of increased soil C storage. Here we estimated that no-till would have a relatively small influence on net greenhouse gas emission at most of the sites shown in Table 4. Yet this summary also suggests that, when certain conditions exist, no-till can cause a large increase in N_2O emission. Considering that 1 kg N_2O-N has a global warming potential equivalent to 133 kg CO_2-C and that little or no increase in soil C stocks might occur under no-till in eastern Canada, adoption of no-till on soils with N_2O hot spots would negate any mitigation potential. These results highlight the importance of a full assessment of all greenhouse gas emission on the basis of net global warming potential.

4.3. Nitrogen fertilizers

In Canada, estimates of N_2O emission associated with the agricultural use of mineral N fertilizers accounts for about 15–20% of total anthropogenic emission (Desjardins and Riznek, 2000). In Ontario and Québec, relatively large areas are cropped to corn (1.5 Mha; Statistics Canada, 2001). The relatively high rate of fertilizer N applied to corn (~150 kg N ha^{-1}) suggests there is potential for mitigating N_2O emission through improved fertilizer N management.

Emission of N_2O associated with application of N fertilizers is extremely variable (Table 5). Some emission values observed in eastern Canada are among the highest reported in the literature (up to 45 kg N_2O-N ha^{-1} year^{-1}); they occurred consistently over three years on a clay soil amended with 60 kg N ha^{-1} (Rochette et al., 2003). With these data included, the rates of N_2O emission for the region were found to be log-normally distributed. Mean annual N_2O emission using raw data was 5.03 and 2.82 kg N_2O-N ha^{-1} year^{-1} if log-transformed data were used (Table 5). This latter emission rate would be similar to that obtained if the extremely high emission rates from the clay soil were omitted (3.03 kg N_2O-N ha^{-1} year^{-1}). An argument could be made to include such values in a mean estimate of N_2O-N loss. Even in highly fertilized fields, rates of N_2O emission are spatially variable and log-normally distributed due to hotspots driven by the distribution of anaerobic microsites and C availability. The occurrence of high emission in clay soils managed with no-till and moderate levels of inorganic N fertilization suggests the importance of factors other than N application rate on N_2O fluxes (e.g., oxygen and carbon).

Fig. 1 shows the relationship of N_2O-N emission as a function of applied N in annual cropped systems. The highest values from the clay soil in Québec were not included, because factors other than application of N fertilizer probably played a key role for the high N_2O production at that site. The best linear fit of the data was:

$$N_2O\text{-N} = 0.822 + 0.0119 \times \text{N fertilizer rate},$$

$$R^2 = 0.43$$

This relationship indicates that, on average about 1.19% of applied N is released as N_2O. This value matches or is very close to the IPCC coefficient (1.25%, Bouwman, 1996) and to the estimates reported by Bouwman and Boumans (2002) (0.9%,

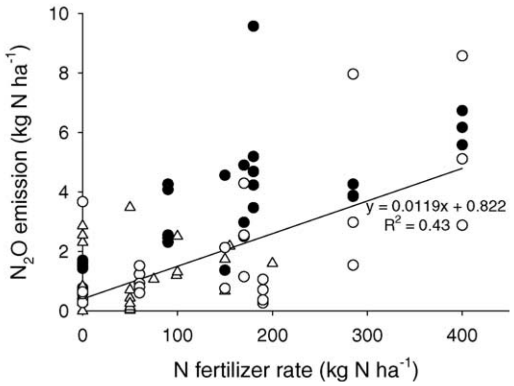

Fig. 1. Relationship between N fertilizer application rate and N_2O emission from soils in eastern Canada. Symbols indicate soil textural class: (●) clay; (△) loam, silt- and clay-loam; (○) sandy loam, loamy sand.

Table 5
N_2O-N emission from soils receiving inorganic N fertilizer

Location	Year	Cropping system	Soil texture	N applied (kg N ha^{-1})	Tillage	N emitted (kg N_2O-N ha^{-1} $year^{-1}$)	Emitted N to applied N (kg N_2O-N kg^{-1} N)[a]	Reference
Annual crops with $N = 0$								
Ottawa, Ont.	1993	Corn	Loam	0	MP	0.3	–	Lessard et al. (1996)
Ottawa, Ont.	1994	Corn	Loam	0	MP	0.83	–	Rochette et al. (1999)
Montréal, Que.	1994	Corn	Clay	0	MP	1.63	–	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	0	MP	1.54	–	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	0	MP	1.7	–	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Clay loam	0	MP	2.86	–	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay loam	0	MP	2.31	–	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay loam	0	MP	2.55	–	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Clay	0	MP	1.43	–	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	0	MP	0.77	–	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	0	MP	0.64	–	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Sandy loam	0	MP	3.67	–	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Sandy loam	0	MP	0.58	–	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Sandy loam	0	MP	0.64	–	MacKenzie et al. (1998)
Mean ± S.D.						1.53 ± 1.00		
Annual crops with $N > 0$ kg ha^{-1}								
Québec, Que.	2001	Barley	Loamy sand	60	MP	1.24	0.021	Rochette et al. (2003)[d]
Québec, Que.	2001	Barley	Loamy sand	60	NT	1.23	0.021	Rochette et al. (2003)[d]
Québec, Que.	2001	Barley	Clay	60	MP	20.62	0.344	Rochette et al. (2003)[d]
Québec, Que.	2001	Barley	Clay	60	NT	44.24	0.737	Rochette et al. (2003)[d]
Québec, Que.	2002	Barley	Loamy sand	60	MP	0.93	0.016	Rochette et al. (2003)[d]
Québec, Que.	2002	Barley	Loamy sand	60	NT	1.52	0.025	Rochette et al. (2003)[d]
Québec, Que.	2002	Barley	Clay	60	MP	6.12	0.102	Rochette et al. (2003)[d]
Québec, Que.	2002	Barley	Clay	60	NT	12.12	0.202	Rochette et al. (2003)[d]
Québec, Que.	2003	Barley	Loamy sand	60	MP	0.81	0.014	Rochette et al. (2003)[d]
Québec, Que.	2003	Barley	Loamy sand	60	NT	0.61	0.010	Rochette et al. (2003)[d]
Québec, Que.	2003	Barley	Clay	60	MP	12.16	0.203	Rochette et al. (2003)[d]
Québec, Que.	2003	Barley	Clay	60	NT	38.92	0.649	Rochette et al. (2003)[d]
Guelph, Ont.	1994	Barley	Silt loam	75	MP	1.07	0.014	Wagner-Riddle et al. (1997)
Montréal, Que.	1994	Corn	Clay	90	MP + NT	2.45	0.027	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	90	MP + NT	2.31	0.026	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	90	MP + NT	2.55	0.028	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Clay	90	MP + NT	4.08	0.045	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	90	MP + NT	2.31	0.026	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	90	MP + NT	4.26	0.047	MacKenzie et al. (1998)
Ottawa, Ont.	1998	Corn	Clay loam	99	MP	1.20	0.012	Grant and Pattey (2003)
Guelph, Ont.	1994	Canola	Silt loam	100	MP	1.31	0.013	Wagner-Riddle et al. (1997)
Guelph, Ont.	1994	Corn	Silt loam	100	MP	2.51	0.025	Wagner-Riddle et al. (1997)
Québec, Que.	1997	Corn	Loam	150	MP	0.67	0.004	Rochette et al. (2000)
Québec, Que.	1999	Corn	Loam	150	MP	1.74	0.012	Rochette et al. (2004b)
Québec, Que.	2002	Corn	Clay	150	MP	1.37	0.009	Rochette et al. (2002)[d]
Québec, Que.	2002	Corn	Sandy loam	150	MP	2.13	0.014	Rochette et al. (2002)[d]
Québec, Que.	2003	Corn	Clay	150	MP	4.56	0.030	Rochette et al. (2002)[d]
Québec, Que.	2003	Corn	Sandy loam	150	MP	0.76	0.005	Rochette et al. (2002)[d]
Ottawa, Ont.	1998	Corn	clay loam	155	MP	2.18	0.014	Grant and Pattey (2003)
Montréal, Que.	1994	Corn	Clay	170	MP + NT	4.9	0.029	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	170	MP + NT	2.5	0.015	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	170	MP + NT	2.98	0.018	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Sandy loam	170	MP + NT	4.29	0.025	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Sandy loam	170	MP + NT	1.15	0.007	MacKenzie et al. (1998)

Table 5 (*Continued*)

Location	Year	Cropping system	Soil texture	N applied (kg N ha^{-1})	Tillage	N emitted (kg N_2O-N ha^{-1} year^{-1})	Emitted N to applied N (kg N_2O-N kg^{-1} N)[a]	Reference
Montréal, Que.	1996	Corn	Sandy loam	170	MP + NT	2.55	0.015	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Clay	180	MP + NT	3.47	0.019	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	180	MP + NT	4.23	0.024	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	180	MP + NT	4.68	0.026	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Clay	180	MP + NT	4.69	0.026	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	180	MP + NT	5.19	0.029	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	180	MP + NT	9.57	0.053	MacKenzie et al. (1998)
Ottawa, Ont.	2002	Corn	Sandy-loam	190	NT	1.06	0.006	Gregorich et al. (2004)[d]
Ottawa, Ont.	2002	Corn	Sandy-loam	190	MP	0.71	0.004	Gregorich et al. (2004)[d]
Ottawa, Ont.	2003	Corn	Sandy-loam	190	NT	0.27	0.001	Gregorich et al. (2004)[d]
Ottawa, Ont.	2003	Corn	Sandy-loam	190	MP	0.37	0.002	Gregorich et al. (2004)[d]
Ottawa, Ont.	1994	Corn	Loam	200	MP	1.6	0.008	Rochette et al. (2002)[d]
Montréal, Que.	1994	Corn	Clay	285	MP + NT	3.88	0.014	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	285	MP + NT	3.85	0.014	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	285	MP + NT	4.26	0.015	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Sandy loam	285	MP + NT	7.96	0.028	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Sandy loam	285	MP + NT	1.54	0.005	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Sandy loam	285	MP + NT	2.98	0.010	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Clay	400	MP + NT	6.73	0.017	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Clay	400	MP + NT	5.58	0.014	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Clay	400	MP + NT	6.17	0.015	MacKenzie et al. (1998)
Montréal, Que.	1994	Corn	Sandy loam	400	MP + NT	8.57	0.021	MacKenzie et al. (1998)
Montréal, Que.	1995	Corn	Sandy loam	400	MP + NT	2.88	0.007	MacKenzie et al. (1998)
Montréal, Que.	1996	Corn	Sandy loam	400	MP + NT	5.11	0.013	MacKenzie et al. (1998)
Mean ± S.D.[b]						5.03 ± 7.82	0.05 ± 0.13	
Mean ± S.D.[c]						2.82 ± 2.78		
Perennial crops with $N = 0$								
Québec, Que.	2001	Timothy	Loamy sand	0		0.38		Rochette et al. (2004a)
Québec, Que.	2002	Timothy	Sand loam	0		0.28		Rochette et al. (2004a)
Québec, Que.	2002	Timothy	Clay	0		0.36		Rochette et al. (2004a)
Guelph, Ont.	1995	Turfgrass	Loam	0		0		Maggiotto et al. (2000)
Guelph, Ont.	1996	Turfgrass	Loam	0		−0.03		Maggiotto et al. (2000)
Guelph, Ont.	1997	Turfgrass	Loam	0		−0.06		Maggiotto et al. (2000)
Mean ± S.D.						0.16 ± 0.21		
Perennial crops with $N > 0$ kg ha^{-1}								
Guelph, Ont.	1995	Turfgrass	Loam	50		0.03	0.001	Maggiotto et al. (2000)
Guelph, Ont.	1995	Turfgrass	Loam	50		0.02	0.000	Maggiotto et al. (2000)
Guelph, Ont.	1995	Turfgrass	Loam	50		0.05	0.001	Maggiotto et al. (2000)
Guelph, Ont.	1996	Turfgrass	Loam	50		0.44	0.009	Maggiotto et al. (2000)
Guelph, Ont.	1996	Turfgrass	Loam	50		0.14	0.003	Maggiotto et al. (2000)
Guelph, Ont.	1996	Turfgrass	Loam	50		3.48	0.070	Maggiotto et al. (2000)
Guelph, Ont.	1997	Turfgrass	Loam	50		0.43	0.009	Maggiotto et al. (2000)
Guelph, Ont.	1997	Turfgrass	Loam	50		0.71	0.014	Maggiotto et al. (2000)
Guelph, Ont.	1997	Turfgrass	Loam	50		0.26	0.005	Maggiotto et al. (2000)
Mean ± S.D.						0.62 ± 1.10	0.012 ± 0.022	
All crops with $N > 0$ kg ha^{-1}								
Mean ± S.D.						2.67 ± 2.22	0.017 ± 0.011	

[a] Includes background levels of N_2O emission.

[b] Mean of raw data

[c] Mean of log-transformed (to the base 10) values.

[d] Unpublished data.

2002) in a review of international studies and by Helgason et al. (in press) (1.19%, 2004) for Canadian systems.

There are inherent differences between perennial and annual cropping systems that affect soil environmental conditions and N cycling. The longer growth period with tighter N cycling in perennial cropping affects soil water content, temperature and available mineral N content, all of which govern N_2O production in soil. To assess the impact of these differences on N_2O emission, we separated perennial and annual cropping systems (Table 5). Mean N_2O emission in annual cropping systems (2.82 kg N_2O-N ha^{-1} $year^{-1}$; mean of log-transformed data) was greater than in perennial cropping systems (0.62 kg N_2O-N ha^{-1} $year^{-1}$). The lower values in perennial systems were mostly due to low background emission (as estimated from unfertilized cropping systems) rather than lower N_2O-N production per unit of applied fertilizer N.

4.4. Crop residues

The IPCC procedure for estimating greenhouse gas emission from agricultural soils includes decomposition of crop residues as a significant source of N_2O. It has been estimated that crop residues account for nearly 15% of the total N_2O emission from agriculture in Canada (Desjardins and Riznek, 2000). However, no field study specifically aimed at quantifying the contribution of crop residue decomposition to N_2O emission has been undertaken in eastern Canada. A first approximation can be obtained by considering studies with annual crops receiving no N input, either from symbiotic fixation or from inorganic or organic amendments (Table 5). A summary of these studies shows emission ranging from 0.3 to 3.7 kg N_2O-N ha^{-1} $year^{-1}$, with a mean value of 1.53 kg N_2O-N ha^{-1} $year^{-1}$. Unfertilized perennial-cropped soils, with little or no residue input, have much lower (nearly zero) emission of N_2O (0.16 kg N_2O-N ha^{-1} $year^{-1}$; Table 5). The low N_2O-N emission in perennial-crop systems suggests that the N cycle is tightly coupled to plant growth and N uptake, and that little N is available for soil denitrification. Also, the large and sudden input of plant residues following harvest of annual crops can generate C substrates and mineral N that can promote and sustain nitrification, denitrification and N_2O production. Since annual-cropped systems are moldboard plowed and perennial-cropped systems are not, the difference in N_2O-N emission could be related to acceleration of N mineralization associated with tillage providing more nitrate for denitrifiers or ammonium for nitrifier N_2O production.

4.5. Manure

Manure management is an important component of agricultural production in eastern Canada because of the prevalence of intensive dairy livestock and hog operations. Most of this manure is applied to soils and accounts for about 10% of total agricultural N_2O emission (Desjardins and Riznek, 2000). Emission of N_2O in manured soils is variable (Table 6). Most of the difference observed between studies is likely due to soil type and climate, as well as the type and composition of manure since all measurements were in the same crop (corn).

Several factors may be responsible for greater N_2O emission following application of liquid manure (2.83 kg N_2O-N ha^{-1} $year^{-1}$) than that following solid manure (0.99 kg N_2O-N ha^{-1} $year^{-1}$; Table 6). Application of liquid manure results in higher soil moisture, lower oxygen availability, and a relatively large amount of labile C, all of which promote denitrification. Application of total N can be much higher for solid than for liquid manure, but much of the N in solid manure is unavailable (i.e., in organic compounds) in the short term for denitrification. With time the organic N in solid manure would be mineralized and could eventually become available for denitrification. The lower N_2O emission following application of solid manure may result from the uptake of available N by growing plants, which precludes a large build-up of mineral N. Furthermore, short measurement periods (i.e., one year) following application of solid manure may not fully account for the total manure-induced emission of N_2O; hence a full accounting of N_2O from solid manure for a period of several years may be needed to explain the slower release of available N.

The similarity of N_2O emission from soils amended with mineral fertilizer and liquid manure (Tables 5 and 6) agrees with the observation that NH_4-N constitutes a large fraction (50–70%) of liquid manure N. Liquid manure also contains labile soluble organic C that can

Table 6
N_2O-N emission from soils receiving solid and liquid manure

Location	Year	Cropping system	Soil texture	N applied (kg N ha^{-1})	Tillage	N emitted (kg N_2O-N ha^{-1} $year^{-1}$)	Emitted N to applied N (kg N_2O-N kg^{-1} N)	Reference
Liquid manure								
Québec, Que.	1997	Corn	Loam	252	MIN	3.37	0.013	Rochette et al. (2000)
Québec, Que.	1997	Corn	Loam	126	MIN	1.25	0.010	Rochette et al. (2000)
Québec, Que.	1999	Corn	Loam	186	MIN	3.23	0.017	Rochette et al. (2004b)
Québec, Que.	1999	Corn	Loam	219	MIN	5.99	0.027	Rochette et al. (2004b)
Québec, Que.	2002	Corn	Clay	150	MP	1.25	0.008	Rochette et al. (2003)[a]
Québec, Que.	2002	Corn	Clay	150	MP	1.04	0.007	Rochette et al. (2003)[a]
Québec, Que.	2002	Corn	Sandy loam	150	MP	2.12	0.014	Rochette et al. (2003)[a]
Québec, Que.	2002	Corn	Sandy loam	150	MP	3.27	0.022	Rochette et al. (2003)[a]
Québec, Que.	2003	Corn	Clay	150	MP	6.06	0.040	Rochette et al. (2003)[a]
Québec, Que.	2003	Corn	Clay	150	MP	3.96	0.026	Rochette et al. (2003)[a]
Québec, Que.	2003	Corn	Sandy loam	150	MP	1.09	0.007	Rochette et al. (2003)[a]
Québec, Que.	2003	Corn	Sandy loam	150	MP	1.38	0.009	Rochette et al. (2003)[a]
Mean ± S.D.						2.83 ± 1.81	0.017 ± 0.010	
Solid manure								
Ottawa, Ont.	1993	Corn	Loam	170	MP	0.7	0.004	Lessard et al. (1996)
Ottawa, Ont.	1993	Corn	Loam	339	MP	1	0.003	Lessard et al. (1996)
Ottawa, Ont.	1994	Corn	Loam	513	MP	1.47	0.003	Rochette et al. (1994)[a]
Ottawa, Ont.	1994	Corn	Loam	486	MP	0.77	0.002	Rochette et al. (1994)[a]
Mean ± S.D.						0.99 ± 0.35	0.003 ± 0.001	
All manure								
Mean ± S.D.						2.37 ± 1.77	0.013 ± 0.011	

MIN: minimum tillage; MP: moldboard plow; NT: no-tillage.

[a] Unpublished data.

stimulate N_2O production where C availability limits denitrification. In soils with low C content, liquid manure has often resulted in greater N_2O emission than mineral fertilizer (Rochette et al., 2000). The similarity in N_2O emission from soils receiving liquid manure and mineral fertilizer suggests that available C was probably not limited in soils where mineral N was applied.

The trend of a growing number of animal units per farm (Statistics Canada, 2001) could result in a greater proportion of manure being managed as liquid. As a consequence, N_2O emission following application of manure to soils will probably increase in the near future in eastern Canada. Thus, mitigation strategies should center on the judicious use of liquid manure. The N in liquid manure should be valued and credited as a crop nutrient so that reduced use of mineral N fertilizer could partially offset the potentially higher N_2O emission from soils receiving liquid manure.

4.6. *Legume cropping*

Symbiotic N fixation by legume crops contributes relatively large amounts of N to agricultural soils, and this flow of N in the plant-soil system can stimulate N_2O production from several processes. The IPCC N_2O inventory methodology is based on the assumption that N_2O is lost during biological N fixation and that further loss occurs when the plant residues are returned to the soil. Total N_2O emission from both sources estimated using the IPCC methodology can be as high as 7 kg N_2O-N ha^{-1} $year^{-1}$ (Rochette et al., 2004a). Legumes are widely grown in eastern Canada both as a perennial forage crop in dairy-based cropping systems and as soybean (1 Mha; Statistics Canada, 2001) in rotation with corn. Therefore, there is a need to assess the impact of these legumes on N_2O emission and the potential for mitigation through their management.

Cropping to soybean (i.e., an annual crop) in cash-crop system and alfalfa (i.e., a perennial crop) in a

Table 7
N_2O-N emission from soils cropped to legumes

Location	Year	Cropping system	Soil texture	Tillage	Emission (kg N_2O-N ha^{-1} $year^{-1}$)	Reference
Alfalfa						
Québec, Que.	2001	Alfalfa	Loamy sand		1.45	Rochette et al. (2004a)
Québec, Que.	2001	Alfalfa	Sandy loam		1.78	Rochette et al. (2004a)
Québec, Que.	2001	Alfalfa	Clay		2.26	Rochette et al. (2004a)
Québec, Que.	2002	Alfalfa	Sandy loam		1.12	Rochette et al. (2004a)
Québec, Que.	2002	Alfalfa	Clay		0.91	Rochette et al. (2004a)
Guelph, Ont.	1993	Alfalfa	Silt loam		3.75	Wagner-Riddle et al. (1997)
Guelph, Ont.	1994	Alfalfa	Silt loam		2.46	Wagner-Riddle et al. (1997)
Montréal, Que.	1994	Alfalfa	Silty clay loam		2.00	MacKenzie et al. (1998)
Montréal, Que.	1995	Alfalfa	Silty clay loam		2.83	MacKenzie et al. (1998)
Montréal, Que.	1996	Alfalfa	Silty clay loam		4.57	MacKenzie et al. (1998)
Mean ± S.D.					2.31 ± 1.15	
Soybean						
Québec, Que.	2001	Soybean	Loamy sand	MIN	0.46	Rochette et al. (2004a)
Québec, Que.	2001	Soybean	Sandy loam	MIN	1.37	Rochette et al. (2004a)
Québec, Que.	2001	Soybean	Clay	MIN	4.73	Rochette et al. (2004a)
Québec, Que.	2002	Soybean	Sandy loam	MIN	0.71	Rochette et al. (2004a)
Québec, Que.	2002	Soybean	Clay	MIN	1.65	Rochette et al. (2004a)
Guelph, Ont.	1994	Soybean	Silt loam	MP	1.61	Wagner-Riddle et al. (1997)
Montréal, Que.	1994	Soybean	Silty clay loam	MP+NT	2.19	MacKenzie et al. (1998)
Montréal, Que.	1995	Soybean	Silty clay loam	MP+NT	3.86	MacKenzie et al. (1998)
Montréal, Que.	1996	Soybean	Silty clay loam	MP+NT	3.71	MacKenzie et al. (1998)
Montréal, Que.	2003	Soybean	Loamy sand	MP	0.9	Rochette et al. (2003)[a]
Montréal, Que.	2003	Soybean	Loamy sand	NT	1.44	Rochette et al. (2003)[a]
Ottawa, Ont.	2002	Soybean	Sandy loam	NT	1.15	Gregorich et al. (2004)[a]
Ottawa, Ont.	2002	Soybean	Sandy loam	MP	1.51	Gregorich et al. (2004)[a]
Ottawa, Ont.	2003	Soybean	Sandy loam	NT	0.29	Gregorich et al. (2004)[a]
Ottawa, Ont.	2003	Soybean	Sandy loam	MP	0.42	Gregorich et al. (2004)[a]
Mean ± S.D.					1.73 ± 1.32	
All legumes						
Mean ± S.D.					2.11 ± 1.24	

MIN: minimum tillage; MP: moldboard plow; NT: no-tillage.

[a] Unpublished data.

livestock-based system is common in eastern Canada, and we analyzed these systems separately (Table 7). Annual N_2O-N emission was higher in alfalfa cropping systems than in soybean systems (2.31 versus 1.73 kg N ha^{-1}). The higher emission in alfalfa systems may have been the result of frequent cutting and harvesting of above-ground plant material on sources of N_2O in soil (Rochette et al., 2004a). This reasoning agrees with the observation that the dieback of alfalfa nodules occurs following harvest (Vance et al., 1979), which could contribute to N release from the root systems. Another source of N_2O loss in alfalfa may be litter fall during the growing season (estimated to be ~13 kg ha^{-1} $year^{-1}$; Tomm et al., 1995).

Rochette et al. (2004a) used the original (for soybeans) and an adapted (for alfalfa) IPCC method to calculate N_2O emission from typical legume crops in eastern Canada. Greater estimates for soybean (4.1 to 7.4 kg N ha^{-1} $year^{-1}$) than for alfalfa (1.8 to 5.2 kg N ha^{-1} $year^{-1}$) were due to the contribution of crop residues to N_2O emission in the annual cropping systems. These estimates for soybean and alfalfa were much greater than those measured in studies reported in Table 7, indicating that IPCC estimates may overestimate growing season N_2O emission in eastern Canada. Wagner-Riddle et al. (1997) measured high N_2O emission in the spring following plow-down of an alfalfa crop the previous autumn. Thus, total emission in an alfalfa cropping system is likely to be greater than that solely measured during the growing season. These results underscore the importance of processes that contribute to the production of N_2O following harvest and plow-down of N-rich crop residues. They also suggest that alfalfa and other legume forage crops are a significant source of N_2O but that the default IPCC coefficients may not be well adapted for conditions in eastern Canada.

4.7. *Indirect N_2O emission*

Agricultural systems can also make a significant contribution to N_2O by indirect emission. Indirect emission includes N_2O produced in non-agricultural systems (e.g., aquatic, forest) from N lost from agricultural systems via leaching, runoff, and volatilization. The IPCC method calculates this emission by estimating the amount of N lost from agricultural ecosystems and by assuming that a fixed fraction of this N will be emitted as N_2O outside the agriculture ecosystem boundaries. Indirect N_2O emission is relatively high in Canada, accounting for approximately 22% of all agricultural N_2O produced (Desjardins and Riznek, 2000). There are no estimates specific for eastern Canada, but several factors contribute to increased indirect emission in the region. For example, the combination of high application rate of mineral N fertilizers in corn and potato production with relatively abundant rainfall increases the risk of N loss through surface runoff and leaching. In addition, intensive hog and dairy operations also produce large volumes of manure, increasing the risk of ammonia volatilization and subsequent deposition in neighboring ecosystems.

5. Methane

Studies in cool temperate regions indicate that fertilization, tillage, and compaction can influence CH_4 flux (Hansen et al., 1993; Ball et al., 1999). Other research has shown that mineral N status plays a key role in methane uptake by soil (Chan and Parkin, 2001). Only a few field studies have been conducted in eastern Canada to determine CH_4 uptake, and most of these have involved manure amendment (Table 8).

Table 8
Annual CH_4-C fluxes in soils under different cropping and tillage systems

Location	Year	Tillage/cropping	Soil texture	Amendment N applied (kg N ha^{-1})	Annual CH_4 flux (kg CH_4-C ha^{-1})[a]	Reference
Québec, Que.	1997	MP silage corn	Loam	0	−0.70	Rochette and Côté (2000)
Québec, Que.	1997	MP silage corn	Loam	Pig slurry @126	−0.57	Rochette and Côté (2000)
Québec, Que.	1997	MP silage corn	Loam	Pig slurry @252	−0.14	Rochette and Côté (2000)
Ottawa, Ont.	1992	Forest	Loam	0	−0.64	Lessard et al. (1994)
Ottawa, Ont.	1992	MP grain corn	Loam	0	−0.04	Lessard et al. (1994)
Ottawa, Ont.	1993	MP grain corn	Loam	0	−0.09	Lessard et al. (1997)
Ottawa, Ont.	1993	MP grain corn	Loam	Solid manure @190	−0.05	Lessard et al. (1997)
Ottawa, Ont.	1993	MP grain corn	Loam	Solid manure @383	−0.04	Lessard et al. (1997)
Ottawa, Ont.	1994	MP grain corn	Loam	0	−0.14	Lessard et al. (1997)
Ottawa, Ont.	1994	MP grain corn	Loam	200	−0.11	Lessard et al. (1997)
Ottawa, Ont.	1994	MP grain corn	Loam	Solid manure @523	−0.08	Lessard et al. (1997)
Ottawa, Ont.	1994	MP grain corn	Loam	Solid manure @504	−0.07	Lessard et al. (1997)
Ottawa, Ont.	2002	NT soybean	Sandy-loam	0	−0.51	Gregorich and Rochette (2002)[b]
Ottawa, Ont.	2002	NT grain corn	Sandy-loam	190	−0.28	Gregorich and Rochette (2002)[b]
Ottawa, Ont.	2002	MP soybean	Sandy-loam	0	−0.21	Gregorich and Rochette (2002)[b]
Ottawa, Ont.	2002	MP grain corn	Sandy-loam	190	−0.25	Gregorich and Rochette (2002)[b]
Ottawa, Ont.	2003	NT soybean	Sandy-loam	0	+0.11	Gregorich and Rochette (2003)[b]
Ottawa, Ont.	2003	NT grain corn	Sandy-loam	190	−0.28	Gregorich and Rochette (2003)[b]
Ottawa, Ont.	2003	MP soybean	Sandy-loam	0	−0.55	Gregorich and Rochette (2003)[b]
Ottawa, Ont.	2003	MP grain corn	Sandy-loam	190	−1.08	Gregorich and Rochette (2003)[b]
Mean ± S.D.					−0.29 ± 0.30	

MP: moldboard plow; NT: no-tillage.

[a] Uptake (−); emission (+).

[b] Unpublished data.

With application of manure, net CH_4 uptake by soil is reduced relative to un-manured soil (Rochette and Côté, 2000). Available data suggest that in general, soil CH_4 emission from, and uptake by, cultivated soils play a minor role in atmospheric loading of greenhouse gases relative to other agricultural sources/sinks for CH_4 (Table 8; Lessard et al., 1997; Rochette and Côté, 2000). For example, assuming a mean CH_4-C consumption rate by arable land of 0.30 kg CH_4-C ha^{-1} $year^{-1}$ (Table 8), total annual uptake of CH_4 by the 10 Mha of agricultural land in eastern Canada would be approximately 3 Gg C $year^{-1}$, or 4% of the CH_4 produced by dairy cows in the same region (833,000 cows; Statistics Canada, 2001), at 90 kg CH_4-C cow^{-1} $year^{-1}$ (Desjardins and Riznek, 2000).

6. Accurate assessment of the potential for mitigation

Assessments such as this review rely on studies carried out by different researchers at different locations and different times. Hence the results depend on the methods used and the perspectives and objectives of the researchers. Adequate spatial and temporal sampling of greenhouse gas flux and soil C stock is crucial to an accurate, integrated assessment of potential for mitigation.

Adequate determination of the vertical distribution of soil C is needed to account accurately for any gain in soil C that might occur as a result of a change in tillage. The pedon soil database in eastern Canada (>600 profiles) indicates that soils in Ontario are usually plowed to a depth of about 15–20 cm in Ontario and as deep as 25–30 cm in Quebec. Some studies in eastern Canada have shown that moldboard plowed soils contain greater C content near the bottom of the plow layer compared to C content at the same depth under no-till (Angers et al., 1997; Deen and Kataki, 2003; Yang and Kay, 2001; VandenBygaart and Kay, 2004). This, combined with the fact that soil C is concentrated at the soil surface under no-till, suggests that comparisons of tillage systems based on depths shallower than the plow layer (e.g., 0–7.5 cm) would overestimate the potential for increased soil C under no-till.

Adequate characterization of N_2O emission relies on a good understanding of spatial variability at both the small (i.e., profile) and large (i.e., field) scales. Small-scale variability can cause inaccurate estimates, because N_2O emission is often localized as hotspots whose occurrence may be related to distribution of anaerobic microsites and C availability. By sampling a few very small areas (e.g., with chambers) for short periods of time (e.g., biweekly through the growing season), hotspots might be missed, leading to the probability that N_2O emission is underestimated. Similarly, at the regional scale, a particular field or site may exhibit high N_2O emission due to known (e.g., high clay content) or unknown (e.g., management history) factors. Including these data may result in the rates of N_2O emission for the region being log-normally distributed, making it difficult to develop a model that accurately simulates emission of N_2O.

Adequate temporal sampling of gases over the period when significant flux occurs is needed to accurately estimate the contribution of greenhouse gases to the atmosphere. Significant emission of N_2O is often produced outside the growing season, such as during the wet conditions in spring and autumn. In a study that spanned more than two calendar years, Wagner-Riddle et al. (1997) measured N_2O emission in March–April that made up 65% of the total annual emission. Since most of the studies reported in eastern Canada were conducted during the snow-free period, it is likely that the production of N_2O emission from soil was underestimated.

7. Conclusions

Research in eastern Canada has shown that, although gains may occur in some soils, adopting no-till does not always increase soil C. Hence, more research is needed to elucidate the interactions among soil texture, tillage systems, and climate that contribute to greater C storage in no-till systems. Planting more forages and legumes in rotation and increasing residue inputs from higher yields have been shown to increase soil C.

Tillage appears to affect N_2O production, although the results are inconsistent among studies. Mean annual N_2O emission across the region was higher for no-till soils than for moldboard-plowed soils. Therefore, converting plowed soils to no-till appears to have a limited mitigation potential in eastern Canada because higher N_2O emission could offset any gain in soil C. Practices such as increasing the frequency of soybean in annual crop rotations (e.g., corn-soybean) and avoiding incorporation of crop residues in the fall would likely reduce N_2O emission in the region. Greater N_2O emission was reported in systems involving application of liquid manure than with solid manure. In the future in eastern Canada, more manure will likely be applied in liquid than in solid form. Thus, mitigation strategies will need to value and credit the N in liquid manure as a crop nutrient, so that reduced use of mineral N fertilizer can partially offset the potentially higher N_2O emission from soils receiving liquid manure.

Only a few field studies have been conducted in eastern Canada to determine CH_4 uptake by agricultural soils. It appears that soils in the region are a weak sink of CH_4 and that this sink may be diminished by application of manure. Since research in other regions and other ecosystems has shown that N fertility can dramatically decrease net CH_4 uptake by soils, it seems important that research be conducted to determine whether, this occurs in eastern Canada.

Inadequate temporal and spatial measurements of soil C and greenhouse gas emission can lead to over- or under-estimation of the mitigation potential of management practices. Comparisons of tillage systems based on depths shallower than the plow layer would overestimate the mitigation potential for increased soil C under no-till because tilled soils in eastern Canada are deeply plowed and have relatively high levels of C near the bottom of the plowed layer, and because no-till soils have a high concentration of C at the surface. Significant quantity of N_2O is emitted outside the growing season and during thaw events in the winter and spring. Since most of the studies reported in eastern Canada were conducted during the snow-free period, it is likely that cumulative production of N_2O has been underestimated.

Many of the practices that result in higher N_2O emission can increase soil C stock. For example, planting legumes and increasing residue inputs through higher yield may enhance soil C levels but may also augment emission of N_2O. This higher N_2O emission would offset some gain in soil C storage, but modifying management to reduce N leakage from the soil-plant system could reduce N_2O emission. The best way to reduce N_2O emission is to avoid excess nitrate accumulation by matching the temporal and spatial patterns of N availability to plant needs. For example, banding fertilizer rather than broadcasting it, or splitting the total N application into two smaller applications, could achieve this. Therefore, the management practices used are important for mitigating the release of greenhouse gases from soils.

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References

Agriculture Canada Expert Committee on Soil Survey (ACECSS), 1998. The Canadian System of Soil Classification, Publ. 1646, 3rd ed. NRC Research Press, Ottawa, 187 pp..

Angers, D.A., Edwards, L.M., Sanderson, J.B., Bissonnette, N., 1999. Soil organic matter quality and aggregate stability under eight potato cropping sequences in a fine sandy loam of Prince Edward Island. Can. J. Soil Sci. 79, 411–417.

Angers, D.A., Bolinder, M.A., Carter, M.R., Gregorich, E.G., Drury, C.F., Liang, B.C., Voroney, R.P., Simard, R.R., Donald, R.G., Beyaert, R., Martel, J., 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Till. Res. 41, 191–201.

Arshad, M.A., Soon, Y.K., Azooz, R.H., 2002. Modified no-till and crop sequence effects on spring wheat production in northern Alberta. Canada Soil Till. Res. 65, 29–36.

Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2, and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Till. Res. 53, 29–39.

Ball-Coelho, B.R., Roy, R.C., Swanton, C.J., 1998. Tillage alters corn root distribution in coarse-textured soil. Soil Till. Res. 45, 237–249.

Beauchamp, E.G., 1997. Nitrous oxide emission from agricultural soils. Can. J. Soil Sci. 77, 113–123.

Bélanger, G., Richards, J.E., Angers, D.A., 1999. Long-term fertilization effects on soil carbon under permanent swards. Can. J. Soil Sci. 79, 99–102.

Bouwman, A.F., 1996. Direct emission of nitrous oxide from agricultural soils. Nutr. Cycl. Agroecosyst. 46, 53–70.

Bouwman, A.F., Boumans, L.J.M., 2002. Modelling global annual N_2O and NO emission from fertilizer fields. Global Biogeochem. Cycl. 16, 1080.

Burton, D.L., Beauchamp, E.G., 1994. Profile nitrous oxide and carbon dioxide concentrations in a soil subject to freezing. Soil Sci. Soc. Am. J. 58, 115–122.

Carter, M.R., Gregorich, E.G., Angers, D.A., Donald, R.G., Bolinder, M.A., 1998. Organic C and N storage, and organic fractions, in adjacent cultivated and forested soils of eastern Canada. Soil Till. Res. 47, 253–261.

Carter, M.R., Kunelius, H.T., Sanderson, J.B., Kimpinski, J., Platt, H.W., Bolinder, M.A., 2003. Trends in productivity parameters and soil health under long-term two-year potato rotations. Soil Till. Res. 72, 153–168.

Castro, M.S., Peterjohn, W.T., Melillo, J.M., Steudler, P.A., 1994. Effects of nitrogen on the fluxes of N_2O, CH_4, and CO_2 from soils in a Florida slash pine plantation. Can. J. For. Res. 24, 9–13.

Chan, A.S.K., Parkin, T.B., 2001. Methane oxidation and production activity in soils from natural and agricultural ecosystems. J. Environ. Qual. 30, 1896–1903.

Chantigny, M.H., Rochette, P., Angers, D.A., 2002. The fate of carbon and nitrogen from different organic residues in wet and cold soils. Soil Biol. Biochem. 34, 509–517.

Clapperton, M.J., Miller, J.J., Larney, F.J., Lindwall, C.W., 1997. Earthworm populations as affected by long-term tillage practices in southern Alberta. Canada Soil Biol. Biochem. 29, 631–633.

Conrad, R., 1996. Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). Microbiol. Rev. 60, 609–640.

Dick, W.A., Gregorich, E.G., 2003. Developing and maintaining soil organic matter levels. In: Schjønning, P., Elmholt, S., Christensen, B.T. (Eds.), Managing Soil Quality—Challenges in Modern Agriculture. CAB International Publishing, pp. 103–120.

Deen, W., Kataki, P.K., 2003. Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Till. Res. 74, 143–150.

Desjardins, R.L., Riznek, R., 2000. Agricultural greenhouse gas budget. In: McRae, T., Smith, C.A.S., Gregorich, L.J. (Eds.), Environmental Sustainability of Canadian Agriculture: Report of the Agri-environmental Indicator Project. Agriculture and Agri-Food Canada, Ottawa, Ont., pp. 133–140.

Ecological Stratification Working Group, 1995. A National Ecological Framework for Canada. Agriculture and Agri-Food Canada, Research Branch, Centre for Land and Biological Resources Research, and Environment Canada, State of the Environment Directorate, Ecozone Analysis Branch, Ottawa/Hull. Report and national map at 1:7,500,000 scale.

Ellert, B.H., Gregorich, E.G., 1996. Storage of carbon and nitrogen in cultivated and adjacent forested soils of Ontario. Soil Sci. 161, 587–603.

Elustondo, J., Angers, D.A., Laverdière, M.R., N'dayegamiye, A., 1990. Influence de la culture de maïs et de la prairie sur l'agrégation et la matière organique de sept sols de Québec. Can. J. Soil Sci. 70, 395–403.

Environment Canada, 2002. Canada's Greenhouse Gas Inventory Fact Sheet 1- Overview: 1990-2000. Available online: http://www.ec.gc.ca/pdb/ghg/1990_00_factsheet/fs1_e.cfm - agriculture. Verified July 1, 2004.

Food and Agriculture Organization of the United Nations (FAO), 1998. World Reference Base for Soil Resources. World Soil Resources Report, vol. 84, Food and Agriculture Organization of the United Nations, Rome, pp. 98.

Grant, R., Pattey, E., 2003. Modelling variability in N_2O emission from fertilized agricultural fields. Soil Biol. Biochem. 35, 225–243.

Grant, R.F., Pattey, E., 1999. Mathematical modelling of nitrous oxide emission from an agricultural field during spring thaw. Global Biogeochem. Cycl. 13, 679–694.

Gregorich, E.G., Drury, C.F., Baldock, J.A., 2001. Changes in soil carbon under long-term maize in monoculture and legume-based rotation. Can. J. Soil Sci. 81, 21–31.

Gregorich, E.G., Ellert, B.H., Drury, C.F., Liang, B.C., 1996. Fertilization effects on soil organic matter turnover and corn residue C storage. Soil Soc. Am. J. 60, 472–476.

Hansen, S., Mæhlum, J.E., Bakken, L.R., 1993. N_2O and CH_4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biol. Biochem. 25, 621–630.

Helgason, B.L., Janzen, H.H., Chantigny, M.H., Drury, C., Ellert, B.H., Gregorich, E.G., Lemke, R.L., Pattey, E., Rochette, P., Wagner-Riddle, C., in press. Toward improved coefficients for predicting direct N_2O emission from soil in Canadian agroecosytems. Nutr. Cycl. Agroecosyst.

Intergovernmental Panel on Climate Change (IPCC), 2004. Good Practice Guidance For Land Use, Land-Use Change and Forestry (GPG LULUCF). IPCC National Greenhouse Gas Inventories Programme. http://www.ipcc-nggip.iges.or.jp/lulucf/gpglulucf_unedit.html Verified July 1, 2004.

Intergovernmental Panel on Climate Change (IPCC), 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual, 74 pp.

Irwin, R.W., 1977. Subsidence of cultivated organic soil in Ontario. J. Irrig. Drain. Div. 103, 197–205.

Ivarson, K.C., Sowden, F.J., 1970. Effects of soil action and storage of soil at freezing temperatures on the free amino acids, free sugar and respiratory activity of soil. Can. J. Soil Sci. 59, 191–198.

Janzen, H.H., Campbell, C.A., Gregorich, E.G., Ellert, B.H., 1998. Soil carbon dynamics in Canadian agroecosystems. In: Lal, R., Kimble, J., Follet, R., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. Advances in Soil Science. Lewis Publishers, CRC Press, Boca Raton, FL, pp. 57–80.

Kaharabata, S.K., Drury, C.F., Priesack, E., Desjardins, R.L., McKenney, D.J., Tan, C.S., Reynolds, D., 2003. Comparing measured and expert-N predicted N_2O emission from conventional and no till corn treatments. Nutr. Cycl. Agroecosyst. 66, 107–118.

Lacelle, B., 1997. Canada's soil organic carbon database. In: Lal, R.A., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 93–101.

Larney, F.J., Lindwall, C.W., Izaurralde, R.C., Moulin, A.P., 1994. Tillage systems for soil and water conservation. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, FL, pp. 305–328.

Lessard, R., Rochette, P., Topp, E., Desjardins, R.L., Beaumont, G., 1994. Methane and carbon dioxide fluxes from poorly drained adjacent cultivated and forest sites. Can. J. Soil Sci. 74, 139–146.

Lessard, R., Rochette, P., Gregorich, E.G., Desjardins, R.L., Pattey, E., 1997. CH_4 fluxes from a soil amended with dairy cattle manure and ammonium nitrate. Can. J. Soil Sci. 77, 179–186.

Lessard, R., Rochette, P., Gregorich, E.G., Pattey, E., Desjardins, R.L., 1996. N_2O fluxes from manure-amended soil under maize. J. Environ. Qual. 25, 1371–1377.

Liang, B.C., Mackenzie, A.F., 1992. Changes in soil organic carbon and nitrogen after six years of corn production. Soil Sci. 153, 307–313.

MacDonald, K.B., Valentine, K.W.G., 1992. CanSIS/NSDB: A General Description. Centre for Land and Biological Resources Research. Research Branch, Agriculture Canada, Ottawa. CLBRR Contribution Number 92-35, pp. 40.

MacKenzie, A.F., Fan, M.X., Cadrin, F., 1998. N_2O emission in three-years as affected by tillage, corn-soybean-alfalfa rotations, and N fertilization. J. Environ. Qual. 27, 698–703.

Maggiotto, S.R., Wagner-Riddle, C., 2001. Winter and spring thaw measurements of N_2O, NO and NO_x fluxes using a micrometeorological method. Water Air Soil Poll. Focus 1, 89–98.

Maggiotto, S.R., Webb, J.A., Wagner-Riddle, C., Thurtell, G.W., 2000. Nitrous and nitrogen oxide emission from turfgrass receiving different forms of nitrogen fertilizer. J. Environ. Qual. 29, 621–630.

Mosier, A., Schimel, D., Valentine, D., Bronson, K., Parton, W., 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. Nature 350, 330–332.

Ogle, S.M., Breidt, F.J., Eve, M.D., Paustian, K.P., 2003. Uncertainty in estimating land use and management impacts on soil organic carbon storage for U.S. agricultural lands between 1982 and 1997. Global Change Biol. 9, 1521–1542.

N'Dayegamiye, A.N., Cote, D., 1989. Effect of long-term pig slurry and solid cattle manure application on soil chemical and biological properties. Can. J. Soil Sci. 69, 39–47.

Paul, J.W., Beauchamp, E.G., 1989. Effect of carbon constituents on denitrification in soil. Can. J. Soil Sci. 69, 49–61.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long term Experiments in North America. CRC Press, Boca Raton, FL, pp. 15–49.

Robertson, G.P., Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 922–1925.

Rochette, P., Côté, D., 2000. CH_4 fluxes and soil CH_4 concentration following application of pig slurry for the 19th consecutive year. Can. J. Soil Sci. 80, 387–390.

Rochette, P., Van Bochove, E., Prévost, D., Angers, D.A., Côté, D., Bertrand, N., 2000. Soil carbon and nitrogen dynamics following application of pig slurry for the 19th consecutive year: II: N_2O fluxes and mineral nitrogen. Soil Sci. Soc. Am. J. 64, 1396–1403.

Rochette, P., Angers, D.A., Bélanger, G., Chantigny, M.H., Prévost, D., Lévesque, G., 2004a. Emission of N_2O from alfalfa and soybean crops in eastern Canada. Soil Sci. Soc. Am. J. 68, 493–506.

Rochette, P., Angers, D.A., Chantigny, M.H., Bertrand, N., 2004b. Carbon and nitrogen transformations and CO_2 and N_2O emission following fall and spring applications of pig slurry to an agricultural soil. Soil Sci. Soc. Am. J. 68, 1410–1420.

Statistics Canada, 2001. Canada Census of Agriculture. Data Tables. Catalogue No. 95F0301XIE. Available online: http://www.statcan.ca/english/freepub/95F0301XIE/tables.htm. Verified July 1, 2004.

Stevenson, F.J., 1994. Humus Chemistry, 2nd ed. Wiley, New York, 512 pp..

Tomm, G.O., Walley, F.L., van Kessel, C., Slinkard, A.E., 1995. Nitrogen cycling in an alfalfa and bromegrass sward via litterfall and harvest losses. Agron. J. 87, 1078–1085.

Topp, E., Pattey, E., 1997. Soils as sources and sinks for atmospheric methane. Can. J. Soil Sci. 77, 167–178.

Vance, C.P., Heichel, G.H., Barnes, D.K., Bryan, J.W., Johnson, L.E., 1979. Nitrogen fixation, nodule development, and vegetative re-growth of alfalfa (*Medicago sativa*) following harvest. Plant Physiol. 64, 1–8.

VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., 2003. Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. Can. J. Soil Sci. 83, 363–380.

VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., Stoklas, U.F., 2004. Uncertainty analysis of soil organic carbon stock change in Canadian cropland from 1991 to 2001. Global Change Biol. 10, 983–994.

VandenBygaart, A.J., Kay, B.D., 2004. Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. Soil Sci. Soc. Am. J. 68, 1394–1402.

Wagner-Riddle, C., Thurtell, G.W., 1998. Nitrous oxide emission from agricultural fields during winter and spring thaw as affected by management practices. Nutr. Cycl. Agroecosyst. 52, 151–163.

Wagner-Riddle, C., Thurtell, G.W., Kidd, G.K., Beauchamp, E.G., Sweetman, R., 1997. Estimates of nitrous oxide emission from agricultural fields over 28 months. Can. J. Soil Sci. 77, 135–144.

Wang, F.L., Bettany, J.R., 1993. Influence of freeze–thaw and flooding on the loss of soluble organic carbon and carbon dioxide from soil. J Environ. Qual. 22, 709–714.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.

Yang, X.M., Kay, B.D., 2001. Rotation and tillage effects on soil organic carbon sequestration in a Typic Hapludalf in southern Ontario. Soil Till. Res. 59, 107–114.