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The fate of nitrogen in agroecosystems: An illustration using Canadian estimates

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Abstract

Agroecosystems rely on inputs of nitrogen (N) to sustain productivity. But added N can leak into adjacent environments, affecting the health of other ecosystems and their inhabitants. Worries about global warming have cast further attention on the N cycle in farmlands because farms are a main source of N_2O, and because carbon sequestration, proposed to help reduce CO_2 loads, requires a build-up of N. Our objective was to estimate, as an illustrative example, the net N balance of Canadian agroecosystems in 1996 and then infer some hypotheses about the routes of N loss, their magnitude, and ways of reducing them. We defined agroecosystems as all agricultural lands in Canada including soil to 1 m depth and all biota, except humans. Only net flows of N across those boundaries were counted in our balance – all others represent internal cycling. Based on our estimates, about 2.35 Tg N entered Canadian agroecosystems from biological fixation, fertilizers, and atmospheric deposition (excluding re-deposited NH_3). In the same year, about 1.03 Tg N were exported in crop products and 0.19 Tg were exported in animals and animal products. Consequently, N inputs exceed exports in products by about 1.13 Tg, a surplus that is either accumulating in agroecosystems or lost to the environment. Because potential soil organic matter gains can account for only a small part of the surplus N, most is probably lost to air or groundwater. Our finding, that N losses amount to almost half of N added, concurs with field experiments that show crop recovery of added N in a given year is often not more than 60%. Better management may reduce the fraction lost somewhat but, because N in ecosystems eventually cycles back to N_2, substantive gains in efficiency may not come easily. As well as trying to reduce losses, research might also focus on steering losses directly to N_2, away from more harmful intermediates. If some of the ‘missing N’ can be assimilated into organic matter, agricultural soils in Canada may need little added N to achieve C sequestration targets.

Introduction

The world’s population has more than doubled in the past half-century, and is still growing at an annual rate of 1.2% (United Nations 2001). To meet the burgeoning demand for food, more and more nitrogen (N) has been added to farmlands; globally, supplemental N added by humans now exceeds N from all ‘natural’ sources (Vitousek et al. 1997a,b). The added N has supported astonishing increases in food production; without it, crop yields would soon diminish as soil N reserves dwindled. But the infusion of N is not without risk – almost inevitably, some N ‘leaks’ away from farmlands, leaching into groundwater, or diffusing into the air (Kinzig and Socolow 1994). The ‘leaked’ N can pose problems: eutrophication of surface water, increased concentrations of greenhouse gases, contamination of drinking water, forest dieback, reduced biodiversity of native ecosystems, and more (Socolow 1999). Managing N therefore involves a delicate balance: adding enough to maintain yields and soil N but minimizing surpluses that ‘leak’ to air and water.

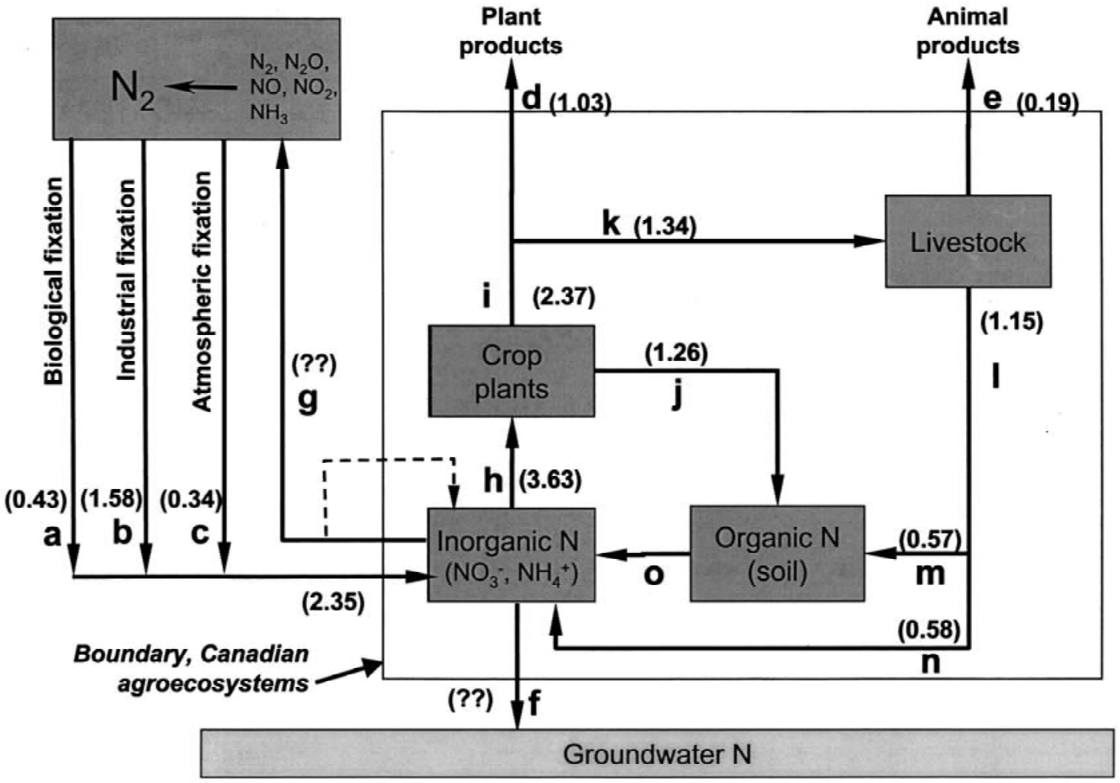

Figure 1. Conceptual view of the main nitrogen flows within agroecosystems and exchanges with other ecosystems. The net gain of N by agroecosystems can be calculated as follows: N gain = inputs – outputs; = (a + b + c) – (d + e + f + g), where: a = biological fixation; b = industrial fixation (fertilizer inputs); c = atmospheric fixation (by thunderstorms plus deposition of N from sources outside agroecosystems); d = N removal in plant products; e = N removal in animal products; f = N leached to groundwater; and g = N lost as N_2, N_2O, NO, NO_2, and NH_3. (For NH_3, only N not re-deposited on agricultural land is considered 'lost'.) This equation assumes inputs from imported feed and seed are negligible. Internal flows are as follows: h = total plant N uptake; i = N removed from fields in products for export, products for livestock feed, residues for livestock feed or bedding, and residues for export; j = N returned to the land in plant parts (crop residues and grain used for seed); k = N in plant parts used for livestock (feed and bedding); l = N from livestock not exported (primarily animal feces and urine); m = N in insoluble organic compounds from livestock; n = N in soluble compounds from livestock (primarily ammonia and precursors of ammonia); o = N mineralized from organic matter (if soil organic matter is at steady state, then o = j + m). Values in parentheses are our estimates of flows in 1996 (Tg N).

What is the N balance of agroecosystems? The question has long been relevant because N losses affect farm profits. But it is especially pertinent now that many countries have set targets for reducing greenhouse gas emissions. The extent to which agriculture helps meet these targets is tied to the N cycle in several ways. First, nitrous oxide (N_2O) accounts for a large share of agriculture's greenhouse gas emissions; in Canada, for example, N_2O accounts for about two thirds of the agricultural greenhouse gas emissions, expressed as CO_2 equivalents (Janzen et al. 1999). But these estimates are still uncertain, and to derive better values, we will need to know more accurately how much N flows through agroecosystems and how much N is available for loss. Second, to find ways of reducing emissions of N_2O and other N gases we need to understand current flows and accumulations of N; and, thirdly, agricultural soils have been proposed as important sinks of carbon (Bruce et al. 1999), but increases in soil C depend on concurrent increases in N – the two elements are both constituents of organic matter – so that increased C storage cannot occur without a net imbalance of N.

Our objective is to derive a net N accounting of an agricultural region, using Canadian agroecosystems as an illustrative example. From these findings, we hope to infer some hypotheses about the nature of N losses, opportunities for reducing them, and links to environmental questions. Though our estimates are for Canadian farmland, the approach used and questions

Table 1. Areas of agricultural land in Canada, by region or province, and N fertilizer use in 1996[a].

Region or province	Area of agricultural land (million ha)				Fertilizer use[b]	Average rate[c]
	All land	Cropped land	Improved pasture	Summer fallow	Tg N	kg N ha^{-1}
Atlantic	1.12	0.42	0.06	0.00	0.026	54.2
Quebec	3.46	1.74	0.20	0.01	0.088	45.6
Ontario	5.62	3.54	0.35	0.02	0.174	44.7
Manitoba	7.73	4.70	0.36	0.32	0.312	61.8
Sask.	26.57	14.40	1.23	4.43	0.518	33.1
Alberta	21.03	9.55	1.91	1.44	0.431	37.6
BC	2.53	0.57	0.24	0.04	0.027	33.4
Total or average	**68.05**	**34.92**	**4.35**	**6.26**	**1.576**	**40.1**

[a] In this table and throughout the paper, we use SI units for N pools and flows: 1 Pg = 10^{15} g, 1 Tg = 10^{12} g = million tonne, 1 Gg = 10^{9} g = 1000 tonne, 1 Mg = 10^{6} g = 1 tonne.
[b] Fertilizer consumption data are from Statistics Canada (for the year ending in June 30, 1996).
[c] Average rate = N applied/(area of cropland + area of improved pasture).

emerging from it may also apply to other scales and regions.

Approach

Review of nitrogen cycle

The N cycle in agroecosystems is complex, involving flows among biota, soil, atmosphere, and hydrosphere (Figure 1). At the heart of the cycle is the internal exchange of N between plants and soil. Plants absorb nitrate or ammonium from the soil solution and synthesize proteins. Some of this protein N is returned to the soil directly in crop residues. Another portion is fed to livestock and, since animals retain only a small fraction of N consumed (Bouwman and Booij 1998), most of the N in feeds is excreted and often returned to the soil as manure. Consequently, much of the N absorbed by plants cycles internally, returning to the soil either directly, as plant litter, or indirectly, as animal manure.

But the N cycle in agroecosystems is not closed – N is drawn away in harvested grains, other plant products, and livestock products. Indeed, farming systems are often configured to export as much protein (hence N) as possible. As well, N may leak unintentionally into groundwater, as nitrate, or into the air, mostly as N_2 but also as N_2O, NO, NO_2, and NH_3. Because of these N removals, the amount of N stored in agroecosystems will soon be depleted unless losses are replaced from outside sources.

The original source of all supplemental N is the atmosphere, an almost infinite reservoir of N. But virtually all of it occurs as N_2 which, because of its triple bond, is inaccessible to all but a few biota. 'Fixation' to plant-available NH_3 occurs in three ways: biological fixation by selected soil microorganisms (notably *Rhizobia*, in symbioses with legumes); industrial fixation (fertilizer manufacture); and atmospheric fixation (largely from thunderstorms).

Calculation of net nitrogen balance

Based on this simplified cycle, the net N gain of an ecosystem can be calculated as the difference between inputs and exports:

$$N_g = (I_{biol} + I_{ind} + I_{atm}) - (E_{plant} + E_{anim} + E_{leach} + E_{gas}) \qquad (1)$$

where: N_g = net N gain (Tg N yr^{-1}), I_{biol}, I_{ind}, I_{atm} = N inputs from biological, industrial, and atmospheric fixation, respectively (Tg N yr^{-1}), E_{plant}, E_{anim}, E_{leach}, E_{gas} = N export via plant products, animal products, leaching, and gaseous emission, respectively (Tg N yr^{-1}).

This calculation depends on strictly-defined boundaries. We define our system as all agricultural land in Canada (Table 1), including the soil to a depth of 1 m, and all biota residing in or on that land (excluding humans). Defining the system this way means that:

1. N absorbed by plants, harvested, and eventually returned to the soil is neither a loss nor a gain. For example, N added in manure or seed from Canadian farms is not an input – it has never left the system.

2. Although all gaseous N emissions escape the ecosystem briefly, only the *net* losses need to be counted in the balance. With NH_3, for example, only the portion not eventually re-deposited on agricultural lands needs to be considered.
3. Soil N removed from a site by erosion but deposited elsewhere on agricultural land is not counted as lost. Wind and water erosion can remove large amounts of N from localized areas, but much of this N may be re-deposited elsewhere in the watershed (Martz and de Jong 1987). Only the fraction (often small) lost to the upper atmosphere or, via streams, into lakes and oceans is counted as lost.
4. Organic amendments are counted as N inputs only if they originate outside agricultural lands.

Defining a system with large area simplifies the calculation of N balances. Gains and losses of N significant on the small scale can be ignored because they involve internal transfer of N. For example, if we define a system to be a single farm, then manure from a neighboring farm is an input; in our approach, the same manure merely represents re-cycling.

Sources and assumptions

We estimated the N flows and budget for Canadian agroecosystems in 1996, the year of a recent agricultural census in Canada. Where possible, to reflect Canadian climate and farming systems, we used coefficients and assumptions based on research conducted in Canada.

Nitrogen inputs

Additions of N in commercial fertilizer were based on amounts used for the year ending on June 30, 1996, as reported by Agriculture and Agri-Food Canada (2000). Conversion of N_2 to ammonia by biological fixation was determined from estimates of the total N uptake of leguminous crops (Appendix 1), multiplied by the fraction of plant N derived from the atmosphere, as estimated from the literature. Nitrogen inputs from atmospheric fixation and other atmospheric sources were calculated by assuming a uniform rate of deposition on all agricultural land in Canada.

Crop production, N uptake, and N disposition

The N uptake of all major crops in Canada was estimated from annual production data using the following equation:

$$\text{N uptake} = (Y_p {}^*N_p) + (Y_a {}^*N_a) + (Y_r {}^*N_r) \quad (2)$$

where: Y_p, Y_a, Y_r = dry matter yield of product, above-ground residue, and roots, respectively (Tg), N_p, N_a, N_r = N concentration of product, above-ground residue, and roots, respectively (g g^{-1} dry matter).

In Equation 2, ‘product’ refers to the plant part of primary economic value (e.g., grain, tuber) for which yields are usually well-documented. Yields of ‘product’ were converted to a dry matter basis, using estimates of moisture contents partly based on literature values. Where the ‘product’ is below-ground (e.g., potatoes, sugar beets), the yield of ‘roots’ refers to below-ground dry matter other than the ‘product’. Hay crops are reported as ‘Tame hay (alfalfa & mix)’ and ‘Tame hay (other)’; because production data did not differentiate between these two categories, we estimated production of each from area data, assuming that yields per ha were the same. Annual production on ‘Tame/seeded pasture’ and on ‘Natural land for pasture’, the amount removed by grazing, was estimated as 1.5 and 0.6 Mg dry matter ha^{-1}, respectively (Walter Willms, personal communication).

Yields of above-ground residues and roots were calculated from ‘product’ yields using estimates of dry matter allocation derived from harvest index and root:shoot ratios reported in the literature. For example, wheat grown in Canada typically has a harvest index [grain/(grain+above-ground residue)] of 0.40 (Nuttall et al. 1986; Campbell et al. 1992a,b; Tremblay and Vasseur 1994; Hay 1995) and a root/(above-ground biomass) ratio of about 0.18 (Campbell and De Jong 2001). Consequently, the dry matter allocation of wheat (grain:above-ground residue:root) was calculated to be 0.34:0.51:0.15. Thus, based on annual wheat production of 26.2 million Mg, estimated residue yield was 39.3 million Mg ($26.2 \times 0.51/0.34 = 39.3$) and root yield was 11.6 million Mg. For perennial crops, we assumed that all residues and roots are returned to the soil in the year the crop was discontinued (e.g., when hay crop was plowed), and in other years, 10% of above-ground residue N and 10% of root N is returned to the soil. Actual root-turnover may be higher than 10%, but we assumed that most of the N in decomposing root material was re-absorbed by the growing crop.

The N concentrations in most ‘products’ were based on analyses provided by the Canadian Grain Commission (2000). Concentrations in remaining ‘product’ and in above-ground residues and roots were estimated from literature or agricultural reports.

Table 2. Estimates of the nitrogen content of crop plants, crop products, products exported from agroecosystems, and residues applied to the soil in Canada in 1996 (for assumptions see Appendix 1).

Crop	Total plant	Product			Residue		
		Total[a]	Exported	Fed	Total[b]	Livestock	To soil
	Tg N						
Wheat	1.034	0.682	0.545	0.109	0.352	0.031	0.316
Oat	0.126	0.069	0.026	0.040	0.057	0.007	0.050
Barley	0.431	0.260	0.078	0.174	0.171	0.023	0.147
Rye	0.009	0.005	0.003	0.001	0.004	0.000	0.003
Flax	0.045	0.027	0.027	0.000	0.017	0.000	0.012
Canola	0.276	0.162	0.138	0.021	0.114	0.000	0.114
Corn (grain)	0.137	0.096	0.022	0.073	0.041	0.001	0.038
Soybean	0.157	0.125	0.048	0.075	0.032	0.000	0.032
Mixed grains	0.019	0.011	0.003	0.008	0.008	0.001	0.007
Peas, dry	0.078	0.038	0.030	0.006	0.040	0.007	0.033
Beans, dry field	0.003	0.002	0.002	0.000	0.001	0.000	0.001
Mustard seed	0.014	0.009	0.009	0.000	0.005	0.000	0.005
Lentils	0.024	0.015	0.015	0.000	0.009	0.001	0.008
Corn (silage)	0.027	0.021	0.000	0.021	0.006	0.000	0.006
Canary seed	0.013	0.006	0.006	0.000	0.007	0.001	0.006
Summerfallow	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tame hay (other)	0.314	0.161	0.008	0.153	0.153	0.000	0.153
T. hay (alfalfa&mix)	0.465	0.361	0.018	0.343	0.104	0.000	0.104
Potatoes	0.025	0.016	0.015	0.000	0.009	0.000	0.009
Forage for seed	0.005	0.002	0.002	0.001	0.002	0.000	0.002
Vegetables	0.026	0.011	0.011	0.000	0.014	0.000	0.014
Other[c]	0.024	0.008	0.006	0.002	0.015	0.000	0.012
Total cultivated	**3.249**	**2.090**	**1.013**	**1.027**	**1.159**	**0.072**	**1.073**
Pasture (nat. land)[d]	0.211	0.141	0.000	0.141	0.071	0.000	0.071
Pasture (seeded)	0.166	0.098	0.000	0.098	0.068	0.000	0.068
Total (incl. Pasture)	**3.626**	**2.328**	**1.013**	**1.266**	**1.298**	**0.072**	**1.211**

[a] 'Product (total)' includes: product N exported + product N fed to livestock + product N returned to soil (e.g., as seed). The latter is small and not presented in the table.

[b] 'Residue (total)' includes: residue N used for livestock (feed or bedding) + residue N returned to soil + residue N exported (e.g., for straw board). The latter estimate is small (total = 0.014 Tg N) and not presented in the table.

[c] 'Other' includes all crops for which estimated total N uptake was less than 0.01 Tg N: buckwheat, sunflower seed, safflower, tobacco, sugar beets, triticale, and 'other field crops'. Calculations were performed individually for each crop or category, and then summed. All legume crops, even where N uptake was less than 0.01 Tg, are shown explicitly in the table because these values are later used for calculating N fixation.

[d] Estimates of N uptake and allocation in 'natural land for pasture' are very uncertain.

Nitrogen export was then calculated using Equation 3:

$$\text{N export} = (Y_p\,{}^*N_p)(1 - F_{l,p} - F_{s,p}) + (Y_a\,{}^*N_a)(1 - F_{l,a} - F_{s,a}) \qquad (3)$$

where: $F_{l,p}$ = fraction of product used for livestock, $F_{s,p}$ = fraction of product returned to soil, $F_{l,a}$ = fraction of above-ground residue used for livestock, $F_{s,a}$ = fraction of above-ground residue returned to soil.

The fate of N in the products and above-ground residues (exported, fed to livestock, or added to soil) was estimated from export data (Canada Grains Council 1999), commodity reports (e.g., Ontario Corn Producers' Association 2000), and our judgement. We assumed that all roots, apart from those defined as 'product', were returned to the soil.

Livestock production, N content, and N disposition

Nitrogen exported in animal products was calculated from meat production data, using estimates of dressed weight/live weight ratios, whole-animal protein content, and proportion of animal N returned to agroecosystems. For example, total meat production in

Table 3. Estimates of the amounts of N removed from Canadian agroecosystems in livestock and livestock products in 1996.

	Production	N content (Gg N)	% retained[b]	N removed (Gg N)
Livestock for meat[a]	(Gg meat)			
Cattle	976.1	44.25	1	43.81
Calves	40.3	2.00	1	1.98
Mutton & lamb	10.7	0.53	1	0.53
Pig	1227.8	35.97	1	35.61
Chicken	746.5	31.52	1	31.20
Duck	7.0	0.32	1	0.32
Goose	0.9	0.04	1	0.04
Turkey	145.7	5.68	1	5.62
Horse	14.0	0.63	1	0.63
Sub-total	*3168.8*	*120.94*		*119.73*
Live Animals[a,c]	*(1000's)*			
Cattle	1.481	20.85	0	20.85
Calves	0.032	0.18	0	0.18
Mutton & lamb	0.045	0.05	0	0.05
Market pigs	2.011	4.77	0	4.77
Weaner pigs	0.767	0.32	0	0.32
Sub-total	*4.336*	*26.15*		*26.15*
Products				
Milk and cream[d]	7173×10^6 L	40.24	0	40.24
Eggs[e]	490 mill. doz.	5.88	0	5.88
Wool[f]	1750 Mg	0.19	0	0.19
Sub-total		*46.31*		*46.31*
Total		**193.41**		**192.20**

[a] Production and live export data for cattle, calves, mutton and lamb, chicken, and turkey are from Statistics Canada (as reported by Canada Grains Council 1999) and from FAO. N content was calculated as follows: N content = meat production / dressing proportion * protein content * 0.16 g N/g protein. Estimates of dressing proportion (0.48–0.78, depending on species) were based on Forrest et al. (1975) and Swatland (1994). Protein contents of whole animals (0.13–0.19 g/g, depending on species) were based on Ensminger and Olentine (1978).

[b] Authors' estimate of the proportion of the total N content of the animal that is returned to agroecosystems in feeds and soil amendments.

[c] Except for weaner pigs, N export = number of animals * dressed weight/dressing proportion * protein content * N concentration of protein. Dressed weights were estimated from averages for animals slaughtered in Canada (Statistics Canada, as reported by Canada Grains Council – Statistical Handbook 99). N export in weaner pigs was calculated in the same way, except that animal weights were assumed to be 20 kg.

[d] N export = volume of milk * 3.3 kg protein/hl * 0.17 g N/g protein. Volume from 1999 Canada Year Book.

[e] N export = number eggs * 6.25 g protein/egg * 0.16 g N/g protein. Production data from 1999 Canada Year Book (data for 1997).

[f] N export = Mg wool * 0.11 Mg N/Mg wool. Production data for 1996 from FAO. http://apps.fao.org/; estimate of N concentration in wool from Fillery (2001).

1996 from cattle was 0.976 Tg. Assuming the dressed weight/live weight ratio was 0.60, the animal has an average protein content of 17%, and 1% of total animal N content was returned to agroecosystems:

$$\text{N removal} = [0.976\ \text{Tg meat} \times 1\ \text{Tg live animal}/0.60\ \text{Tg carcass} \times 0.17\ \text{Tg protein}/\text{Tg animal} \times 0.16\ \text{Tg N}/\text{Tg protein}]\,(1 - 0.01) = 0.044\ \text{Tg N}$$

Estimates of N removal in live animals were calculated from the number of animals exported, estimates of animal weight based on carcass weight of those slaughtered in Canada (or 20 kg weights for weaner pigs), and estimates of live animal protein content. Nitrogen exported in milk, eggs, and wool was calculated from production data and estimates of N concentrations obtained from the literature.

The N added to soil as manure or other livestock by-products was calculated as the difference between N used for livestock (feed and bedding) and N exported.

Leaching and gaseous losses

The amount of N lost to groundwater and atmosphere can be estimated only roughly. These N losses were calculated by multiplying the input of soluble N (fertilizer, soluble manure-N, atmospheric deposition) by the possible fraction lost, based on a literature review and our judgement. We assumed, further, that a fraction of N mineralized from organic matter was lost via both mechanisms.

Estimates of annual N flows

Crop N uptake and disposition

According to our estimates, agricultural crops in Canada assimilated 3.63 Tg of N in 1996 (Table 2). Four crops accounted for about two-thirds of the N uptake – wheat (29%), tame hay (21%), barley (12%), and canola (8%). Pastures accounted for an additional 10%.

Of the N taken up by crop plants, about two thirds was recovered in ‘product’, the plant part of primary economic value. About half of the N in products was removed from agroecosystems; most of the remainder was fed to livestock (Table 2).

Livestock N consumption and disposition

About 0.15 Tg N was exported from Canadian agroecosystems in animals used for meat (Table 3). Of this, 18% was exported in live animals. A further 0.05 Tg N was removed in animal products other than meat, most of it in milk.

About 1.25 Tg N of plant N was used in 1996 for livestock feed (Table 2). Consequently, if N removed in livestock products is 0.19 Tg (Table 3) and the amount of N stored in livestock biomass is constant from year to year, then about 85% of the N used as feed is retained in feces, urine, and other by-products. This value is reasonably consistent with studies that show livestock may excrete about 80% of ingested N (ECETOC 1994; McGinn and Janzen 1998). The N use efficiency (livestock N production/livestock N intake) in Canada is therefore about 15%, somewhat higher than the global average of about 10% (Bouwman and Booij 1998; Van der Hoek 1998), though the methods of calculation may not be directly comparable. In addition to N in products used for feed, 0.07 Tg N in crop residues was also routed through livestock, primarily as bedding.

Most of the plant N used for feed but not exported in livestock products is excreted as urine and feces. In general, each of these forms account for about half of the N excreted (Rodhe et al. 1997), though the distribution varies with factors such as nutrition and animal species (Smits et al. 1997; Webb 2001). Nitrogen in urine consists largely of urea and related soluble compounds, readily hydrolyzed to ammonia; N in feces is largely in insoluble organic forms (Sommer and Hutchings 1997; Bussink and Oenema 1998). We assumed that, of the livestock-N retained in agroecosystems, half is in soluble forms readily converted to ammonia, the rest is in organic forms only slowly mineralized to soluble forms. Thus, a total of about 1.15 Tg N are retained annually, of which 0.57 enters the soil organic matter, and 0.58 Tg is already in soluble form, primarily as ammonia and its precursors. The N in livestock by-products, therefore, if it were all conserved, is equivalent to about a third of annual crop N uptake.

Industrial fixation

Commercial fertilizers applied to Canadian farmlands contained about 1.58 Tg N, of which 40% was applied as urea and 33% as anhydrous ammonia [Agriculture and Agri-Food Canada (2000), for fertilizers sold in the 1995/96 crop year]. About 80% of this fertilizer was applied in the prairie provinces – Manitoba, Saskatchewan, and Alberta (Table 1). The average fertilizer N rate, assuming it is all applied on cropland and ‘improved’ pasture, is 40 kg N ha^{-1}, a rate well below that of some other industrialized countries (FAO 2000).

Biological fixation

Annual symbiotic fixation of N on Canadian farmlands can be calculated from estimates of legume N yields and the fraction of their N derived from the air (Table 4). Based on this approach, we suggest that about 0.43 Tg of N is fixed each year, mostly in association with alfalfa (60% of total), soybean (15%), and peas (11%). This value is lower than other recent estimates: Gleig and MacDonald (1998) suggested that alfalfa and soybean alone contributed about 0.43 Tg N annually, and Chambers et al. (2001) estimated N inputs from symbiotic fixation of 0.77 Tg N for 1996. Our estimate, therefore, may be conservative.

Atmospheric fixation

Farmlands receive inputs of N directly from the atmosphere. Some of this deposited N is fixed from N_2 during thunderstorms. Though important over geological time scales, inputs of N from this atmospheric fixation are small on an annual scale – globally, about 3 Tg of N is fixed annually (Kinzig and Socolow 1994; Galloway et al. 1995; Schlesinger 1997; Galloway 1998), amounting to less than 0.1 kg N ha^{-1} yr^{-1} if the N is deposited uniformly.

In addition to the N fixed by lightning, however, the atmosphere also contains NH_3 and other reactive N gases released from the biosphere via natural processes or human activity. This N can be washed from the atmosphere into soil via precipitation (‘wet deposition’) or it can be deposited in gaseous or particulate forms (‘dry deposition’). Typically, lands not adjacent to anthropogenic emissions receive about 5 kg N ha^{-1} yr^{-1} or less from the atmosphere (Woodmansee 1978; Nyborg et al. 1995; Holland et al. 1999; Smil 1999; NAtChem 2000).

Total inputs on some farmlands may be much higher. For example, lands immediately downwind of livestock operations may receive as much as 50 kg N ha^{-1} yr^{-1} or more by dry deposition of ammonia (Goulding et al. 1998; Pitcairn et al. 1998). But most of this N originates from nearby farms, so it is not a net input, merely re-cycling of agricultural N.

Recognizing that most Canadian farmlands are far removed from industrial N emissions, we assume that average deposition of N from atmospheric fixation and sources outside agroecosystems amounts to 5 kg N ha^{-1} yr^{-1}. On the 68 million ha of agricultural land in Canada, this rate of deposition yields an annual input of 0.34 Tg N.

Leaching losses

Globally, rates of leaching loss from farmlands may average about 10–15 kg N ha^{-1} yr^{-1} (Smil 1999). But losses vary widely, depending on amounts of surplus nitrate, climate (especially precipitation), and soil properties. One international survey (Frissel and Kolenbrander 1978; cited by Smil 1999) showed losses of about 10% of fertilizer N when application rates were less than 150 kg N ha^{-1} and about 20% when applied fertilizer rate exceeded 150 kg N ha^{-1}.

In Canada, too, leaching losses vary widely among regions. In the humid conditions of southern British Columbia, for example, leaching losses may exceed 100 kg N ha^{-1} yr^{-1} (Paul and Zebarth 1997a; Zebarth et al. 1998), and in Ontario, Goss and Goorahoo (1995) predicted leaching losses of 0–37 kg N ha^{-1} in a range of cropping systems. But on the prairies of western Canada, where most of the fertilizer is applied (Table 1), leaching may be minimal because potential evapotranspiration exceeds precipitation by a wide margin (Reynolds et al. 1995; Macdonald 2000a; Fairchild et al. 2000). Significant losses may occur under irrigation (Chang and Janzen 1996) or from fallow fields (Campbell et al. 1984). Under some conditions, N fertilization may even *reduce* leaching, because of improved root growth (Campbell et al. 1993, 1995).

Because of the diversity of Canadian cropping systems and only sporadic measurements of nitrate leaching (often focusing on areas where high losses are expected), only order-of-magnitude estimates of leaching losses are possible. As a crude first estimate, we assume that leaching removes:

1. 10% of the N added in immediately soluble forms: fertilizer N, atmospheric N, and immediately-available manure-N.
2. 10% of mineralized N, based on findings that leached nitrate originates not only from fertilizers but also from organic matter (Izaurralde et al. 1995; Jenkinson 2001). If organic matter N is reasonably constant, then: N mineralization $\approx$ N added in crop residue + organic N in manure (Figure 1).

Estimated this way, leaching losses from Canadian agriculture might amount to about 0.43 Tg N yr^{-1}. This may be an overestimate, since large areas of land, notably the native grasslands used as pasture, may have negligible leaching (Woodmansee 1978).

Table 4. Estimate of annual symbiotic nitrogen fixation in Canadian agroecosystems.

Crop	Area[a] *(1000 ha)*	Total N uptake *(Tg N)*	NDFA[b]	N fixed *Tg N*	N fixed *kg N/ha*
Soybean	877	0.157	0.40	0.063	72
Peas, dry	536	0.078	0.60	0.047	87
Beans, dry field	94	0.003	0.40	0.001	12
Lentils	303	0.024	0.65	0.016	52
Tame hay (other)	2613	0.314	0.10	0.031	12
T. hay (alfalfa&mix)	3598	0.465	0.55	0.256	71
Forage for seed	184	0.005	0.20	0.001	5
Other field crops	30	0.003	0.05	0.000	5
Vegetables	128	0.026	0.05	0.001	10
Natural land for pasture	15612	0.211	0.02	0.004	0
Tame/seeded pasture	4349	0.166	0.05	0.008	2
Total				**0.429**	

[a] Harvested area from Statistics Canada 1996.

[b] NDFA = proportion of nitrogen derived from the atmosphere through biological N fixation. Values are authors' estimates, after consulting references, including the following: Androsoff et al. (1995); Biederbeck et al. (1996); Bremer and van Kessel (1990); Dashti et al. (1998); Hardarson et al. (1988); Heichel et al. (1984); Heichel and Henjum (1991); Hogh-Jensen and Schjoerring (1994); Kelner et al. (1997); Kerley and Jarvis (1999); Matus et al. (1997); Rennie and Dubetz (1984); Smith and Hume (1987); Stevenson et al. (1995); Stevenson and van Kessel (1996); van Kessel (1994); Vasilas et al. (1990); Walley et al. (1996); West and Wedin (1985).

Gaseous N losses

Transformations among inorganic N compounds can lead to gaseous emissions via various pathways. Of these, denitrification probably causes the largest losses, mostly as N_2 but also as N_2O and NO (Aulakh et al. 1992; Drury et al. 1992; Paul et al. 1993).

Denitrification rates are affected by nitrate concentration, oxygen availability (related to water content), and levels of available carbon (Beauchamp 1997). Furthermore, denitrification is very difficult to measure precisely (Aulakh et al. 1992). Consequently, estimated losses vary widely among sites (Aulakh et al. 1984; Curtin et al. 1994; Liang and MacKenzie 1994; Nyborg et al. 1995, 1997) and can be as high as 75 kg N ha^{-1} yr^{-1} in localized areas (Paul and Zebarth 1997a,b). Elliott and de Jong (1992) measured denitrification rates across a hummocky landscape in Saskatchewan, and estimated that losses of N in a canola–wheat–wheat–wheat–fallow cropping system would amount to 108 kg N ha^{-1} in 20 years (roughly 5 kg N ha^{-1} yr^{-1}).

In a global review, Smil (1999) suggested that, on average, about 10–15% of susceptible N might be lost via complete denitrification from agroecosystems (not including N_2O). For Canadian conditions, we suggest as a first estimate that about 10% of the soluble N entering agroecosystems as fertilizer, atmospheric inputs, and readily-available N in manure might be lost via denitrification. This value is comparable to that of Korsaeth and Eltun (2000) for Norway (7% of inorganic N applied), von Rheinbaben (1990) for the Netherlands (10% of N applied) and Zebarth et al. (1998) for BC, Canada (7% of total N applied as manure and fertilizer). We suggest, further, that 10% of the N mineralized from organic matter may be denitrified. Based on these assumptions, losses of N_2 (and N_2O) from denitrification amount to about 0.43 Tg, for an average rate across all farmlands of 6 kg N ha^{-1} yr^{-1}. In a review of global estimates, Barton et al. (1999) found that, on average, N losses from denitrification in agricultural soils averaged 13 kg N ha^{-1} yr^{-1} (3 kg N ha^{-1} yr^{-1} in unfertilized soils).

Some N may also be lost during nitrification, as N_2O or NO (e.g., Paul et al. 1993; Civerolo and Dickerson 1998; Wolf and Russow 2000). Although these losses have important environmental consequences, their effect on the net N balance may be small compared to that of other processes, perhaps amounting to less than 1% of added N (Skiba et al. 1997; Veldkamp and Keller 1997). Davidson and Kingerlee (1997) found a mean NO flux of 3.6 kg N ha^{-1} for cultivated temperate soils. An estimated 0.084 Tg N was also lost from Canadian farmlands as N_2O in 1996 (UNFCCC 2001), but much of that may have come from denitrification. We have assumed that gaseous N losses via nitrification will be small and already accounted for in our crude estimate of denitrification.

Another pathway of N loss is ammonia volatilization. A large proportion of soluble N excreted by livestock, as much as 50% or more, may be volatilized as ammonia, either immediately after excretion, during manure storage, or after land application (e.g., ECETOC 1994; Sommer and Hutchings 1997; McGinn and Janzen 1998; Smil 1999). But losses vary, depending on livestock and manure management (e.g., Paul et al. 1998). Ammonia losses may also occur from some fertilizers, especially urea (Terman 1979; Ouyang et al. 1998), from surface residues (Janzen and McGinn 1991), and from crop canopies (Schjoerring and Mattsson 2001).

But not all of the volatilized ammonia is lost from agroecosystems. Ammonia is readily absorbed by vegetation, soils, and surface water, so that a large proportion of volatilized ammonia may be re-deposited near the site of emission (Berendse et al. 1993; ECETOC 1994; Ferm 1998; Harper and Sharpe 1998; Pitcairn et al. 1998; Ping et al. 2000; Mosier 2001). For example, Asman (1998) estimated that up to 60% of ammonia emitted may be re-deposited within 2000 m of the source.

For a rough estimate of ammonia loss from agroecosystems in Canada, we assume that 30% of soluble manure-N and 5% of urea fertilizer-N is volatilized. (Volatile losses from surface-broadcast urea may be much higher, but urea is usually placed below the surface, almost eliminating NH_3 emissions [Hargrove 1988; Singh and Nye 1988]). We assume, further, that 70% of the volatilized N is deposited, eventually, on agricultural land in Canada. This fraction is similar to that of Zebarth et al. (1999), who proposed that 65% of ammonia volatilized from a 690 km^2 area was re-deposited within the same area. Based on these crude assumptions, we estimate that net loss of ammonia from agricultural land in Canada may be about 0.06 Tg N. This estimate is much lower than that of Kurvits and Marta (1998), partly because we assumed most of the volatilized N was re-deposited.

Total gaseous N losses from Canadian agroecosystems, based on our assumptions, amount to 0.49 Tg N in 1996. We present this value, however, more to illustrate the uncertainties in its derivation than as an attempt at a reliable estimate. At best, it should be viewed as an order-of-magnitude estimate.

N return in biosolids (sewage sludge)

Some of the N removed from agroecosystems in food products is returned in land-applied biosolids. According to Webber and Singh (1995), about 120 000 mg of municipal sludge (dry weight) is applied annually to farmland in Canada. If these biosolids have an N concentration of 35 g N kg^{-1} (Banerjee et al. 1997), then N additions are about 0.0042 Tg N yr^{-1}. Chambers et al. (2001) estimated that applied biosolids furnished about 0.0084 Tg N annually. Consequently, N inputs from biosolids are small compared to uncertainties in our budget, and we have not included them.

Overall nitrogen budget

Based on the preceding assumptions, the total addition of external N to Canadian agroecosystems in 1996 amounted to about 2.35 Tg N, of which about 67% was applied as commercial fertilizer (Table 5; Figure 1). Across the 68 million ha of agricultural land, these inputs average about 34 kg N ha^{-1} yr^{-1}.

About 1.23 Tg N yr^{-1} were removed from agroecosystems in plant and animal products (Table 5). Additional N was lost to the groundwater and atmosphere – about 0.92 Tg N yr^{-1} – though we have little faith in this value.

Inserting these estimates into Equation 1 yields a net N balance of about + 0.20 Tg N (Table 5), corresponding to an average rate of 3 kg N ha^{-1} yr^{-1}. This analysis suggests that the N cycle in Canadian agroecosystems is roughly in balance.

The net value, however, is dwarfed by the cumulative uncertainty of estimates used in its calculation (Table 5). Because of uncertainties in N flows, notably for leaching and gaseous losses, we cannot constrain the budget enough to give a precise estimate of net N gains or losses. And even extensive research may not soon reduce uncertainty by the orders-of-magnitude required.

A more definitive analysis, however, is possible by grouping those terms in Equation 1 with high uncertainty. Thus, we re-arrange Equation 1 to read:

$$(E_{leach}+E_{gas})+N_g=(I_{biol}+I_{ind}+I_{atm}) -(E_{plant}+E_{anim}) \qquad (4)$$

Now, if: M = N which is missing or unaccounted for, and presumed lost to atmosphere and groundwater, or stored in the system [= $(E_{leach} + E_{gas}) + N_g$], then:

$$M = (I_{biol} + I_{ind} + I_{atm}) - (E_{plant} + E_{anim}) \qquad (5)$$

Table 5. Apparent net N budget of agroecosystems in Canada.

Nitrogen flow	Estimated magnitude *($Tg\ N\ yr^{-1}$)*	Confidence[a]	Approximate range *($Tg\ N\ yr^{-1}$)*
Nitrogen Inputs			
• Biological fixation	0.43	M	0.30 to 0.56
• Industrial fixation	1.58	H	1.56 to 1.60
• Atmospheric fixation[b]	0.34	M	0.24 to 0.44
Total inputs	**2.35**		**2.10 to 2.60**
Nitrogen Losses			
• Plant products[c]	1.04	H	0.88 to 1.08
• Animal products	0.19	H	0.16 to 0.22
• Leached to groundwater	0.43	L	0.20 to 0.80
• Gaseous losses	0.49	L	0.30 to 0.90
Total losses	**2.15**		**1.54 to 3.10**

[a] L= low (± >30%); M = medium (± < 30%); H = high (± <15%); confidence values reflect authors' judgement, and are presented only as crude, qualitative indices of relative uncertainty.
[b] Includes volatile N deposition from non-agricultural sources.
[c] Includes a small amount of N (0.014 Tg N) exported as crop residues (e.g., strawboard).

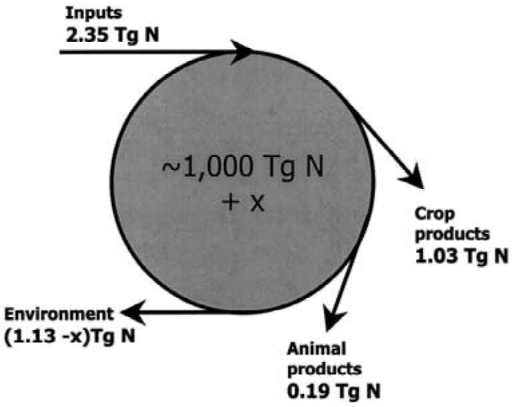

Figure 2. Estimates of the net exchanges of N between agroecosystems and the larger environment. All values indicating flows are expressed in units of Tg N yr^{-1}. The amount of N stored in agroecosystems (1000 Tg N) is estimated from the amount of C stored in the surface 1 m of soil organic matter (Dumanski et al. 1998), assuming an average C:N ratio of about 10.

From this equation emerges a simplified view of the N cycle in Canadian agroecosystems (Figure 2). Of the 2.35 Tg N entering the system each year, almost half (1.03 Tg N) is exported in plant products and 8% (0.19 Tg N) is exported in animal products. The remaining 48% (1.12 Tg N) is either released to adjacent environments or is accumulating in the agroecosystem itself.

That an amount equal to almost half of added N is either lost from or accumulating in agroecosystems is corroborated by studies of fertilizer N uptake by crops. Many experiments, employing ^{15}N or other techniques in a wide range of conditions, show that uptake by crops of applied N is often not more than 50–60% in the year of application, even with recommended application methods (e.g., Janzen et al. 1990; Grant et al. 1991; Aulakh et al. 1992; Malhi 1997; Malhi et al. 1996; Pradhan et al. 1998; Tran and Giroux 1998; Smil 1999; Tran and Tremblay 2000). If average uptake by crops of N added in a given year is only 60%, then an amount equal to 40% of N entering the system is, by definition, either lost or accumulating within the system. (Plant uptake of biologically fixed N, presumably, is much higher than 60%, but this source of N accounts for less than 20% of N inputs, according to our estimates.)

When averaged over the 68 million ha of farmland in Canada, the 'missing N' (1.1 Tg) accounts for an average of 17 kg N ha^{-1}; that is, over all farmland in Canada, the N input, on average, exceeds N export by about 17 kg N ha^{-1} yr^{-1}. (Using the uncertainty values presented in Table 5, we estimate a range of 10–23 kg N ha^{-1} yr^{-1}.) Our value is comparable to a recent estimate by OECD (2000) which, based on an alternate approach, proposed that farmlands in Canada had a net N excess of 13 kg N ha^{-1} yr^{-1}. Earlier, Parris (1998) presented an estimate of 9 kg N ha^{-1} yr^{-1} for Canada, based on the OECD approach. Not all of this surplus is necessarily lost to the environment; some of it may be accumulating in the ecosystem.

Our broad average, of course, hides enormous variability (MacDonald 2000b). In some localized areas, the N surplus may approach or even exceed 100 kg N ha^{-1} yr^{-1} (e.g., Barry et al. 1993; Zebarth et al. 1999).

Elsewhere, the N cycle may be virtually in balance or even in deficit. For example, a fallow-wheat system in semi-arid regions of the prairies may remove more N in harvested wheat than is added in fertilizer or from other sources.

Limitations and research needs

Any attempt at calculating the 'missing N' on such a large area inevitably involves oversimplifications, even errors. Acknowledged weaknesses in our evaluation include:

- Estimates of N uptake and export are calculated by multiplying several individual coefficients – N concentrations, plant dry matter allocation, fraction of products exported, and others – each of which include some uncertainty. Especially tenuous are estimates of N in crop residues (notably in roots) because they have not been widely measured, though this uncertainty affects estimates of internal N flow more than that of net exports.
- Calculating net N uptake and disposition in perennial crops such as forages was hampered by uncertainties about the duration of crops before plowdown and carry-over of N from one year to the next (especially in roots). Similarly, estimates of uptake, distribution, and turnover of N in pasture crops are tenuous.
- Estimates of N removal are sensitive to assumptions regarding the fate of plant N, whether exported, used for livestock, or returned to soil directly. Our relative allocations are only approximate, and could not always be rigorously confirmed with data.
- Our values for N_2 fixation are subject to errors, both in calculating plant N uptake and in estimating the fraction of N derived from N_2. Our estimate may be conservative, based on comparisons with others in the literature; if so, our estimate of 'missing N' would also be conservative.
- For clarity and simplicity, we have excluded some smaller N flows, including inputs from sedimentary nitrate, seed imports, and feed imports. Of these, the last may be most important. Including these imports would further increase our estimate of 'missing N', but their amounts are assumed to be less than the uncertainty of our estimates.
- Our estimates apply only to one year (1996), which is not necessarily representative of other time periods; extending the analysis over a decade or more (perhaps including predictive scenarios) would allow analysis of temporal trends.

In the face of these and other uncertainties, we sometimes relied on 'expert judgment' to decide on best coefficients and assumptions. As research continues and improved data sets emerge, we hope that some of our estimates will be supplanted and any distortions corrected.

Implications

Our analysis of the N cycle provides estimates of the key N flows in Canadian agroecosystems. More important than the values presented, however, may be the questions and research directions that surface from their calculation. Some of these questions can be partially answered using the data compiled; others await more rigorous, re-focused research.

What is the fate of the 'missing' N?

According to our estimates, N additions to Canadian farmlands exceed N harvest by almost 50%. By definition, this 'missing' N is either lost to adjacent environments or is accumulating within agroecosystems. Some of the N added may be immobilized in soil organic matter (e.g., Malhi et al. 1996). But a net accumulation can continue only as long as organic matter content is increasing. Over the long term, mineralization eventually balances immobilization so that there is no net storage of N (Jenkinson 1990).

Studies of carbon cycling suggest that agricultural soils in Canada, as a whole, were neither gaining nor losing appreciable organic matter in recent years (Anderson 1995; Janzen et al. 1997, 1998; Smith et al. 1997). Consequently, it is unlikely that agricultural soils were gaining C at a rate higher than 2 Tg C yr^{-1} in 1996. And if we assume that the N follows C in a ratio of 1:10, then gains of N can account for a very small fraction of the 'missing' N, perhaps 0.2 Tg, at most. Most of the 'missing' 1 Tg N is therefore apparently being lost to the air or groundwater.

Can we reduce N losses?

By changing management, can we funnel more of the added N into 'products', thereby reducing costs and pollution? In theory, if all losses could be eliminated, inputs of N could be reduced by close to 50% without jeopardizing productivity. But plugging the 'leaks' may not be easy because:

1. The key to eliminating losses is to synchronize plant-available N release with plant N uptake (Campbell et al. 1995). But perfect synchrony may be an unrealistic target. Even if inputs can be matched perfectly in time and space with plant N needs, release from organic matter is not so easily controlled. The main source of N loss, often, may not be the N added, but that mineralized from crop residues and soil organic matter (MacDonald et al. 1989; Jenkinson 2001).
2. Plants rarely reduce soluble N concentrations in soil to zero, so there is always at least some N susceptible to loss (especially on a variable landscape).
3. Some gaseous loss of N seems unavoidable. For example, nitrification is a significant source of N_2O and other gases. Since most N absorbed by plants is nitrified at least once, some loss seems inevitable.

In short, the N cycling through agroecosystems comes originally from atmospheric N_2, and eventually finds its way back to that same pool. Agroecosystems are deliberately maintained in a 'young' state of development (Kinzig and Socolow 1994; Odum 1969) and hence have open nutrient cycles. Is it possible to eliminate or drastically curtail losses in such an ecosystem?

Can we increase the proportion of N lost as N_2?

If some losses of N from agroecosystems are unavoidable, can a change in management reduce the proportion of N lost via deleterious intermediates such as N_2O? For example, management can control to some extent the ratio of N_2:N_2O from denitrification (Beauchamp 1997), though such practices may not all be practical. If the N we apply to farmlands eventually returns to N_2, then future research might focus on shifting the N losses toward N_2, avoiding damaging leaks via intermediates.

Can we store more N in our farmlands?

The farmlands of Canada contain roughly 1000 Tg N in the surface 1 m, based on an organic C content of 9.36 Pg (Dumanski et al. 1998) and a C:N ratio of about 10:1. About 150 Tg of N have been lost since cultivation began, assuming an organic C loss of 1.68 Pg (Dumanski et al. 1998) and a slight narrowing of the C:N ratio after cultivation (Ellert and Gregorich 1996). Consequently, past changes in organic N storage are large compared to annual losses of N via leaching and gaseous emissions (roughly 1 Tg yr^{-1}). Adopting practices that re-build organic matter could reduce these losses somewhat, but not indefinitely. Over the long term, N mineralization equilibrates with N inputs (Jenkinson 1990), and then further accumulation stops and losses to environment continue.

Do we need to add more N to support C sequestration?

Management of soil to store additional C has been proposed as a means of mitigating atmospheric CO_2 increases (Paustian et al. 1997). According to one report (Anonymous 1999), Canadian farmlands might be able to store as much as 6.6 Tg C yr^{-1} from 2008 to 2012 with widespread adoption of C-conserving practices, though a lesser amount – say, 2–3 Tg C yr^{-1} – may be more readily achievable. Assuming a C:N ratio of 10 in accumulating organic matter, this C gain would require about 0.2–0.3 Tg N. Gains in organic matter occur disproportionately in decomposable fractions, with a wider C:N ratio (Janzen et al. 1998), so actual N requirements may be even less than 0.2–0.3 Tg N. This amount is much smaller than the $\sim$1 Tg N currently unaccounted for. Consequently, if the needed N can be immobilized from surplus N, no further additions would be needed to support the expected C sequestration (though better distribution of N within the system may be necessary).

Possible next steps

Our analysis suggests several research directions that may advance our understanding of nutrient cycles in farmlands. They include:

- Further refinement of the budget presented. Some of our coefficients, assumptions, and approaches are tenuous (perhaps misleading) and can be improved by including new research findings as they emerge.
- Examining regional differences to identify areas that may benefit most from improvements in N efficiency.
- Including other nutrients (e.g., C and P) in the same analysis.
- Using the N budget approach to improve estimates of N_2O emission. The IPCC protocol estimates N_2O emission based largely on inputs of N. An

Appendix 1. Data and assumptions used to estimate annual crop N uptake and disposition in Canadian agroecosystems.

Crop	Area	H_2O content	Relative DM allocation			Duration	N concentration			Plant N uptake	Product disposition			Residue disposition			Roots to soil
			Product	AG residue	Roots		Product	AG residue	Roots		Export	To l'stock	To soil	Export	To l'stock	To soil	
	mil. ha	*% w/w*				*yrs*	*g N/kg*			*Gg N*	Mg/Mg			*Mg/Mg*			*Mg/Mg*
Wheat	12.419	12	0.34	0.51	0.15	1	26	6	10	1034	0.80	0.16	0.04	0.02	0.13	0.85	1.00
Oat	2.045	12	0.33	0.47	0.20	1	18	6	10	126	0.38	0.58	0.04	0.00	0.20	0.80	1.00
Barley	5.241	12	0.38	0.47	0.15	1	19	7	10	431	0.30	0.67	0.03	0.00	0.20	0.80	1.00
Rye	0.192	12	0.34	0.51	0.15	1	18	6	10	9	0.65	0.30	0.05	0.00	0.15	0.85	1.00
Flax	0.592	8	0.26	0.60	0.15	1	35	7	10	45	0.98	0.00	0.02	0.40	0.00	0.60	1.00
Canola	3.531	9	0.26	0.60	0.15	1	35	8	10	276	0.85	0.13	0.02	0.00	0.00	1.00	1.00
Corn (grain)	1.132	15	0.47	0.38	0.15	1	15	5	7	137	0.23	0.76	0.01	0.05	0.05	0.90	1.00
Soybean	0.877	14	0.30	0.45	0.25	1	67	6	10	157	0.38	0.60	0.02	0.00	0.00	1.00	1.00
Mixed grains	0.294	12	0.33	0.47	0.20	1	22.3	6.3	10	19	0.30	0.68	0.02	0.01	0.16	0.83	1.00
Buckwheat	0.020	12	0.24	0.56	0.20	1	18	6	10	1	0.98	0.00	0.02	0.00	0.00	1.00	1.00
Peas, dry	0.536	13	0.29	0.51	0.20	1	37	18	10	78	0.80	0.15	0.05	0.00	0.20	0.80	1.00
Beans, dry field	0.094	13	0.46	0.34	0.20	1	42	10	10	3	0.95	0.00	0.05	0.00	0.10	0.90	1.00
Mustard seed	0.239	9	0.26	0.60	0.15	1	40	8	10	14	0.99	0.00	0.01	0.00	0.00	1.00	1.00
Sunflower seed	0.037	2	0.27	0.53	0.20	1	24	10	10	3	0.98	0.00	0.02	0.00	0.00	1.00	1.00
Lentils	0.303	13	0.28	0.52	0.20	1	44	10	10	24	0.95	0.00	0.05	0.00	0.10	0.90	1.00
Corn (silage)	0.191	70	0.72	0.08	0.20	1	13	13	7	27	0.00	1.00	0.00	0.00	0.00	1.00	1.00
Canary seed	0.249	12	0.20	0.60	0.20	1	25	7	10	13	0.98	0.00	0.02	0.00	0.30	0.70	1.00
Summerfallow	6.261	0	0.00	0.00	0.00	1	0	0	0	0	1.00	0.00	0.00	0.00	0.00	0.00	1.00
Tame hay (other)	2.613	13	0.18	0.12	0.70	5	16	16	10	314	0.05	0.95	0.00	0.00	0.00	1.00	1.00
T. hay (alfalfa & mix)	3.598	13	0.40	0.10	0.50	5	26	15	15	465	0.05	0.95	0.00	0.00	0.00	1.00	1.00
Safflower	0.002	2	0.27	0.53	0.20	1	24	10	10	0	0.98	0.00	0.02	0.00	0.00	1.00	1.00
Potatoes	0.150	75	0.68	0.23	0.10	1	15	20	10	25	0.95	0.00	0.05	0.00	0.00	1.00	1.00
Tobacco	0.029	20	0.64	0.16	0.20	1	20	10	10	2	0.98	0.00	0.02	0.00	0.00	1.00	1.00
Sugar beets	0.024	80	0.76	0.19	0.05	1	10	29	10	4	0.28	0.70	0.02	0.00	0.10	0.90	1.00
Triticale	0.026	12	0.32	0.48	0.20	1	22	6	10	2	0.70	0.28	0.02	0.00	0.20	0.80	1.00
Forage for seed	0.184	13	0.12	0.48	0.40	5	30	15	13	5	0.70	0.28	0.02	0.00	0.20	0.80	1.00
Vegetables	0.128	80	0.40	0.40	0.2 0	1	20	20	10	26	0.98	0.00	0.02	0.00	0.00	1.00	1.00
Other field crops	0.030	10	0.28	0.55	0.16	1	33.25	9.75	10	3	0.98	0.00	0.02	0.11	0.08	0.81	1.00
Total tree fruits & nuts	0.042	84	0.04	0.67	0.30	10	2	10	10	5	1.00	0.00	0.00	0.60	0.00	0.40	1.00
Berries & grapes	0.058	85	0.03	0.48	0.50	5	7	20	10	4	1.00	0.00	0.00	0.40	0.00	0.60	1.00
Total cultivated	**41.136**									**3249**							
Natural land for pasture	15.612	0	0.20	0.20	0.60	1000	15	15	15	211	0.00	1.00	0.00	0.00	0.00	1.00	1.00
Tame/seeded pasture	4.349	0	0.24	0.16	0.60	10	15	15	15	166	0.00	1.00	0.00	0.00	0.00	1.00	1.00
Total (incl. pasture)	**61.097**									**3626**							

[a] Agricultural land in Canada also includes an additional 0.022 million ha of nursery crops, 0.022 million ha of sod, and 6.914 million ha of ‘other land’.

improved approach might base estimates on *flows* of N rather than only on inputs. According to our estimates, soluble N released from mineralization of organic matter may exceed that added in fertilizers; yet current methods of estimating N_2O emissions do not directly consider mineralized N.

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