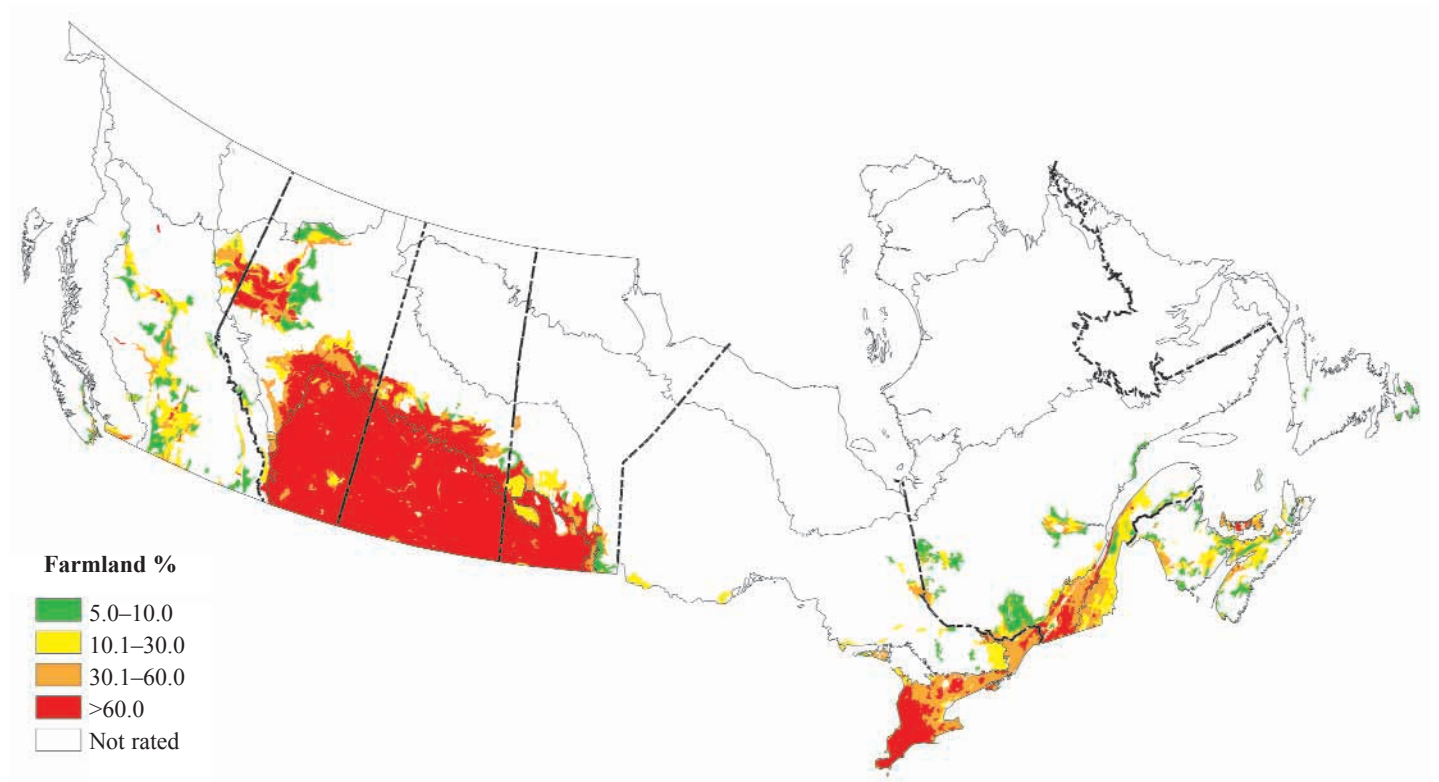


## 2. Canadian agriculture and greenhouse gases

Canadian agriculture is diverse, with a variety of crops and livestock in a range of climates and soils. Emissions of greenhouse gases are also highly variable, changing with type of farming operation and even within individual farms. To estimate the emission of greenhouse gases from Canadian farms, therefore, we have to first consider briefly the nature of farming in Canada.

### A glance at Canadian agriculture

The Canadian landmass has been classified into 15 ecological zones (ecozones) based on soil and climate. Most of Canada's land is forested, and only about 5% is suitable for farming, mainly in two ecozones—the Prairies and the Mixed Wood Plains of the St. Lawrence River (Fig. 1). The Prairies alone account for about 80% of Canada's 68 million hectares of farmland. Two-thirds of all farmland is used for crops and “improved” pastures (those that are seeded, drained, fertilized, or weeded);



**Figure 1**

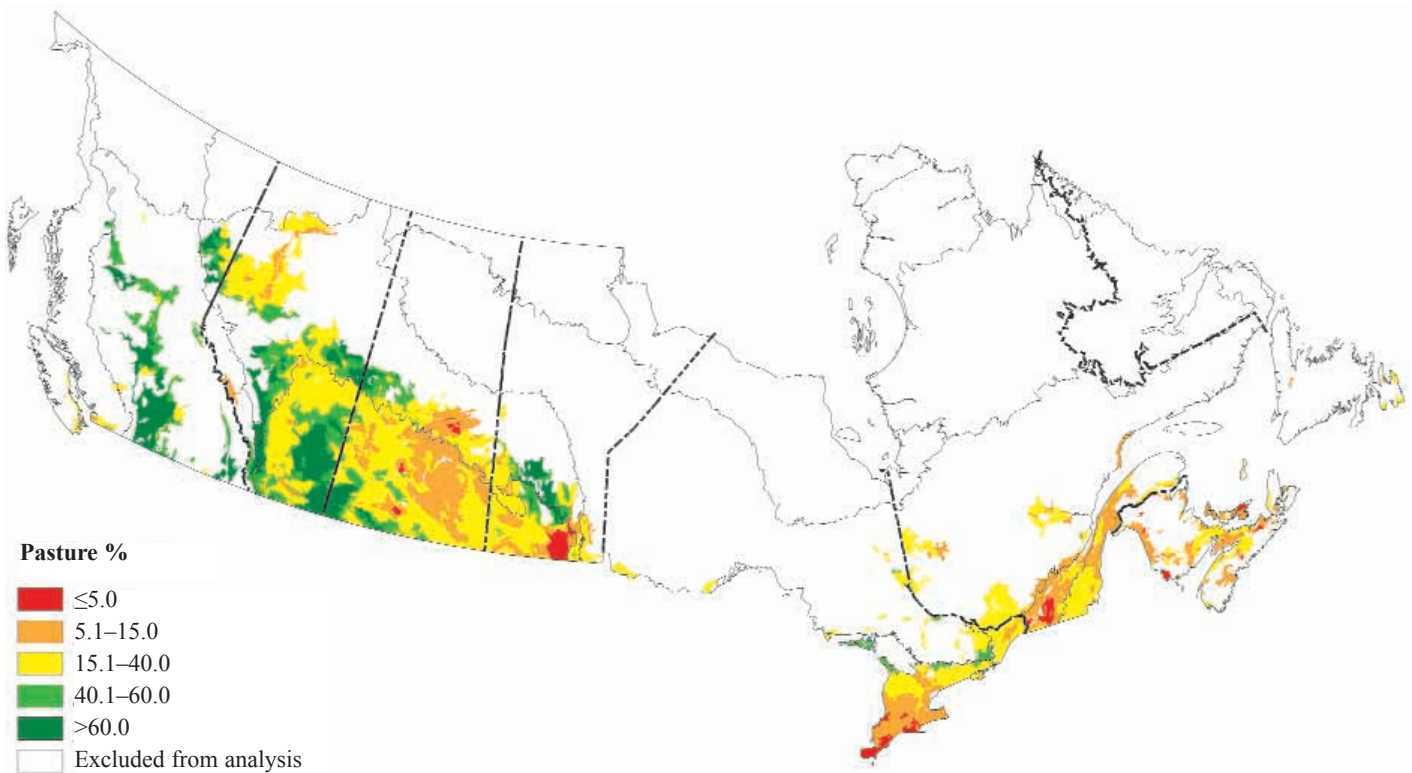
Farmland as a proportion of land area in various parts of Canada in 1996. (F. Wang and D.B. Gleig, AAFC)

the rest is occupied by “unimproved” pastures (largely native grasslands), buildings, barnyards, bush, sloughs, and marshes. The various types of pasture together account for about 30% of farmland (Fig. 2).

The relative areas devoted to annual crops and animal husbandry vary widely across the country. For example, large areas of the Prairies are used almost exclusively for cropland (Fig. 3), whereas small pockets of concentrated livestock production exist in areas of British Columbia and the southern regions of Alberta, Ontario, and Quebec (Fig. 4).

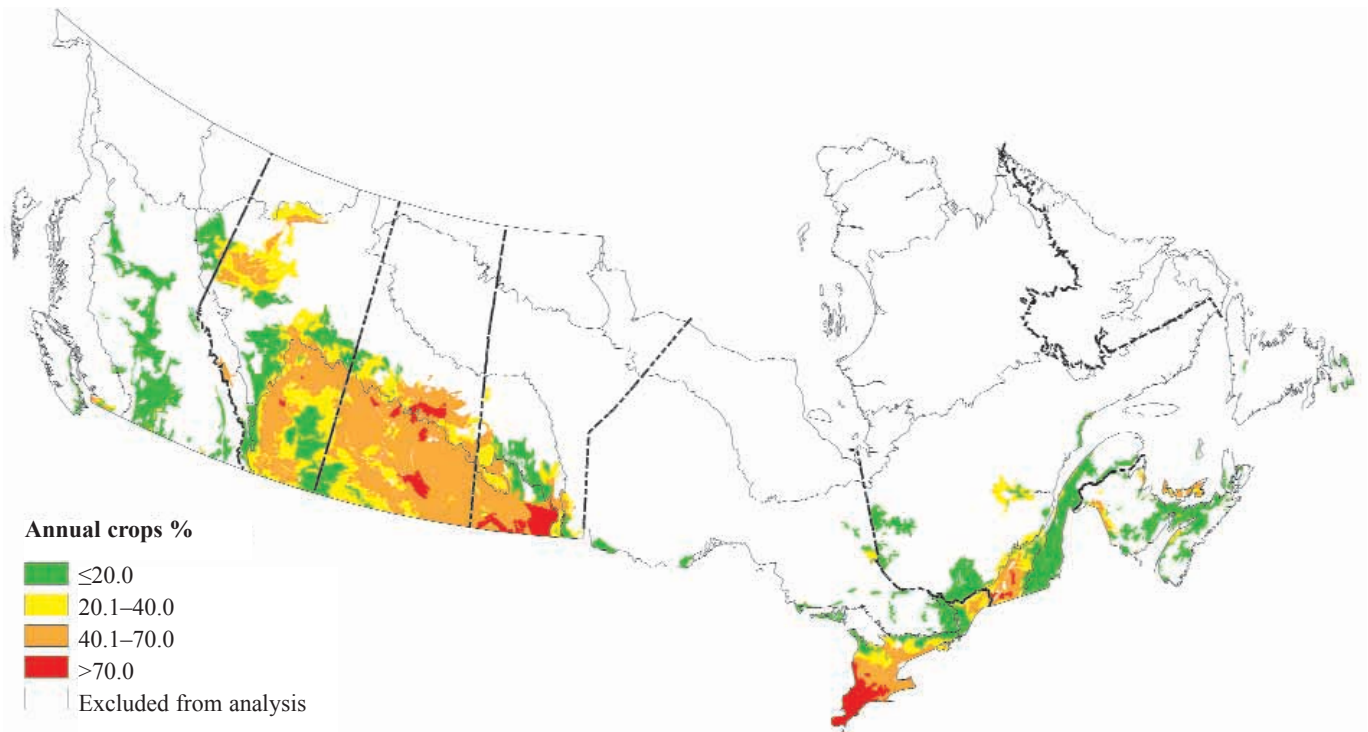
Although all ecosystems share common nutrient pathways, agriculture has unique features when compared to other land uses such as forestry. Farmlands, particularly those devoted to annual

crops, are intensively managed. Moreover, the time cycle for agricultural crops is short, often annual. As a result, agriculture can respond quickly to climatic, economic, and policy events by changing land use and cropping systems, and there can be large shifts in just a few years (Table 1). Finally, agricultural ecosystems are quite “open,” involving continual transfer of material in (e.g., fuel, fertilizers, and pesticides) and material out (e.g., crop yields and animal products). Unlike forests, which gradually increase their store of wood, farmlands rarely accumulate vegetation over the long term. Because of these unique features, studying and estimating greenhouse gas emissions from farms differs from that in other ecosystems.



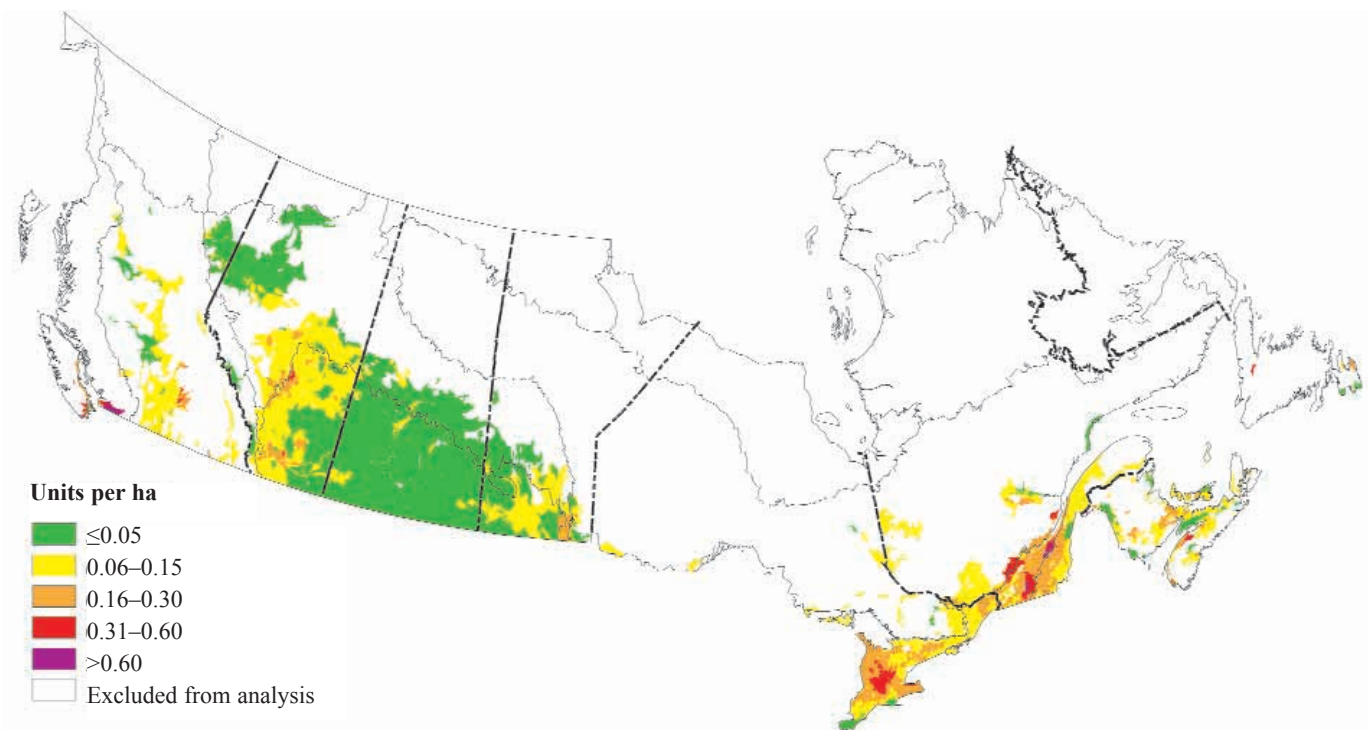
**Figure 2**

Pasture (improved and unimproved) as a proportion of farmland in 1996. (F. Wang and D.B. Gleig, AAFC)



**Figure 3**

Annual crops as a proportion of farmland in 1996. (F. Wang and D.B. Gleig, AAFC)



**Figure 4**

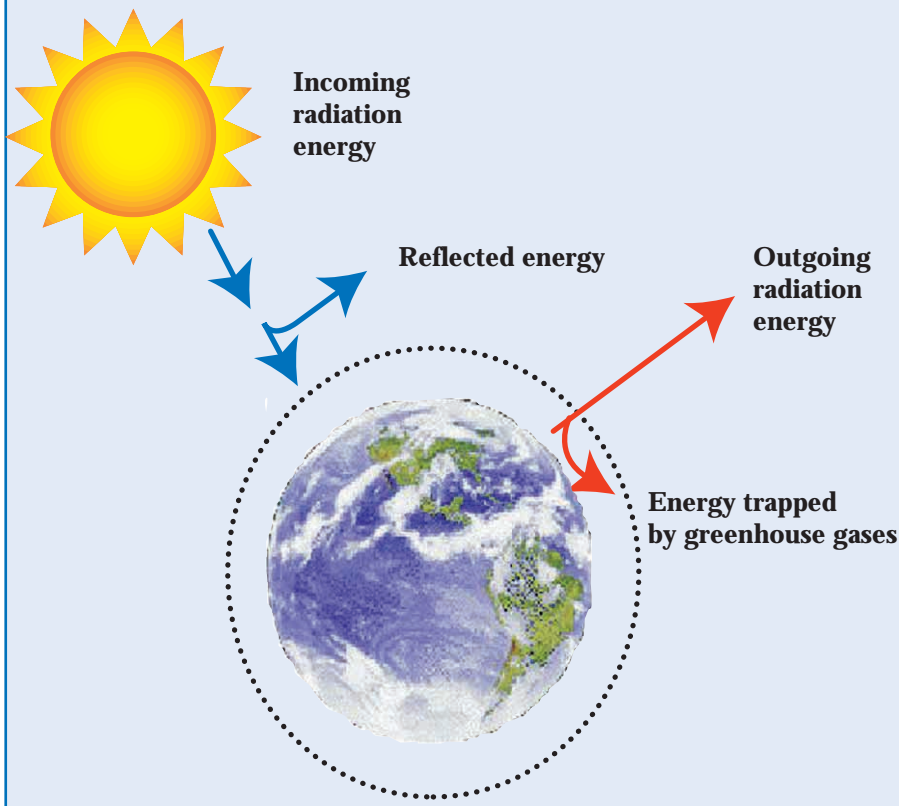
Distribution of livestock in Canada in 1996. One animal unit is the quantity of livestock that produces manure containing 170 kg of N per year. For example, approximately 2 dairy cows are equivalent to 1 animal unit. (F. Wang and D.B. Gleig, AAFC)

**Table 1** The area of farmland in Canada occupied by annual crops (million ha)

	1981	1986	1991	1996
Total farmland	65.9	67.9	67.7	68.0
Croplands	31.0	33.2	33.5	35.0
Summer fallow	9.7	8.5	7.9	6.3
Improved pasture	4.4	3.6	4.1	4.4
Nonimproved pasture	20.8	22.6	22.2	22.3

### The “greenhouse effect”

Short-wavelength radiation emitted from the sun is absorbed by the earth and re-radiated at longer wavelengths. Carbon dioxide, CH<sub>4</sub>, and N<sub>2</sub>O account for 90% of this “greenhouse effect.” In the long term, incoming radiation is balanced by outgoing radiation. Because of the greenhouse effect, the average surface temperature of the Earth is about 15°C, instead of -18°C.



## The greenhouse effect

The earth is warmed by the sun’s radiation (including visible light) that strikes it. The earth, in turn, radiates energy back into outer space, but this outgoing radiation differs from that of the sun: it has a longer wavelength and is invisible to the human eye. Furthermore, some of this outgoing, long-wave radiation is absorbed by various gases in the air, thereby warming the atmosphere. This warming is referred to as the “greenhouse effect” (though the warming effect inside glasshouses is really quite different!). The warming from the greenhouse effect is highly beneficial; without it, the average temperature on our planet would be about 33°C colder, making the earth inhospitable.

The gases causing the warming of the atmosphere are known as “greenhouse gases.” The most important are water vapor, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and CFCs. Foremost among these is water vapor because it is a powerful absorber of long-wave radiation and is present in relatively high concentration. This gas, however, is already present in high enough concentration in the lower atmosphere that further increases in its concentration would have minimal effect on temperature.

Much of the current concern about greenhouse gases has arisen from the recent recognition that the concentration of other greenhouse gases—CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and CFCs—has been increasing steadily since the industrial revolution, almost certainly because of human activity. By 1992, CO<sub>2</sub> had increased by 30%, CH<sub>4</sub> by 145%, and N<sub>2</sub>O by 15%. Current rates of increase are 0.5% per year for CO<sub>2</sub>, 0.6% for CH<sub>4</sub>, and 0.3% for N<sub>2</sub>O. The CFCs were not even

present in the atmosphere until a few decades ago. If the current rates of increase continue, many scientists expect significant impact on the world's climate. For example, the Intergovernmental Panel on Climate Change predicts that the doubling of the CO<sub>2</sub> concentration, likely to happen in the 21<sup>st</sup> century, would increase average global temperatures by 1 to 3°C—a rate of warming unprecedented in the last 10 000 years. As well, the enhanced greenhouse effect could amplify climate variability.

In short, greenhouse gases have a desirable effect, as they warm the atmosphere and create favorable conditions for biological activity. Further increases in these gases, however, may lead to an “enhanced greenhouse effect” with uncertain, possibly disruptive, consequences.

## Commitments to reduce emissions

Concern about the enhanced greenhouse effect has prompted international action to reduce emissions. A first agreement, intended to stabilize emissions at 1990 levels by 2000, was signed in 1992 at the Earth Summit in Rio de Janeiro. A more binding agreement was reached at Kyoto, Japan in 1997. This protocol was aimed at reducing emissions from participating countries to at least 5% below 1990 levels, by 2008 to 2012. This treaty will come into effect, however, only when ratified by at least 55 countries representing 55% of total greenhouse gas emissions from developed countries.

### The Intergovernmental Panel on Climate Change

In 1988, the World Meteorological Organisation and the United Nations Environment Program created the Intergovernmental Panel on Climate Change (IPCC). The IPCC evaluates research and policy options and publishes reports on climate change and the risk of global warming.

The latest synthesis report, based on 1995 science, includes the following conclusions:

- The balance of evidence from observed changes suggests a discernible human influence on global climate
- Human-induced climate change represents an important additional stress, particularly to the many ecological and socioeconomic systems already affected by pollution, and unsustainable management practices
- Significant reduction in net greenhouse gas emissions are technically possible and can be economically feasible . . . in all sectors including . . . agriculture

The assessment report now being planned will provide the major science input to the future evolution of the UN Framework Convention on Climate Change and the Kyoto protocol.

### The Kyoto protocol

At Kyoto, developed countries agreed to reduce their combined emissions of greenhouse gases by 5.2% from 1990 levels. This target will be realized through national reductions of 8% by Switzerland, many Central and East European states, and the European Union; reductions of 7% by the United States; and reductions of 6% by Canada, Hungary, Japan, and Poland. Russia, New Zealand, and Ukraine are to stabilize their emissions, while Norway may increase emissions by 1%, Australia by up to 8%, and Iceland by 10%.

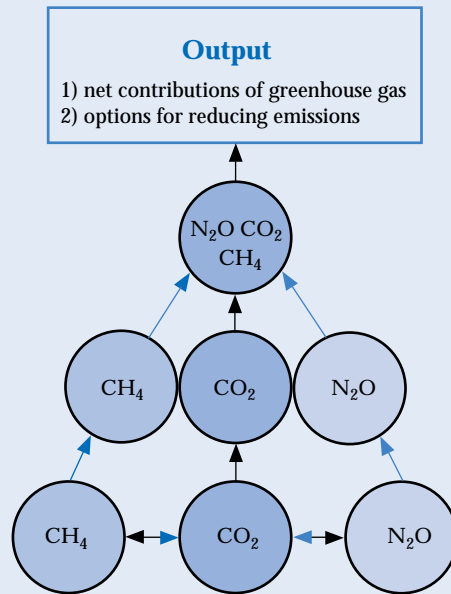
The protocol aims to lower overall emissions from a group of six greenhouse gases by 2008–2012, calculated as an average over these 5 years. Cuts in the three most important gases—CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O—will be measured against a base year of 1990. Cuts in the three long-lived industrial gases—hydrofluorocarbon, perfluorocarbon, and sulfur hexafluoride—will be measured against either a 1990 or a 1995 base year, depending on what year is most beneficial.

## Greenhouse gas research methodology

The sources and patterns of emission of carbon dioxide, methane, and nitrous oxide are complex. Laboratory and experimental plot studies are needed to improve our understanding of biological processes. Then the emissions must be assessed over whole fields and groups of fields, to account for soil, landscape, and management variations. Finally, interactions between these three greenhouse gases must be considered, regional and climatic variations taken into account, and the global effect integrated over complete ecosystems and all of Canada.

### Research Approach

Level	Objectives
Integration	<ul style="list-style-type: none"> <li>temporal/spatial scaling up</li> <li>model validation</li> <li>interaction of gases</li> </ul>
Ecosystem	<ul style="list-style-type: none"> <li>net balances for greenhouse gases</li> <li>feasibility of practices for reducing emissions</li> </ul>
Process	<ul style="list-style-type: none"> <li>identification of sources/sinks</li> <li>characterization of rate-determining factors</li> </ul>



In the Kyoto protocol, Canada agreed to reduce its emissions to 94% of 1990 levels by 2008 to 2012. But Canada's emissions are already well above 1990 levels. Based on increases from 1990 to 1997 and assuming a "business as usual" scenario thereafter, one estimate suggests that Canada will need to reduce its emissions by about 21%. Consequently, a widespread effort involving all sectors of our economy will be required to meet Canada's commitments.

In 1992, Agriculture and Agri-Food Canada initiated a research program to estimate emissions of greenhouse gases from Canadian agriculture and to devise

ways of reducing these emissions. Findings from this effort, some of which are summarized in this report, may help Canada meet its reduction target.

## Estimates of emission

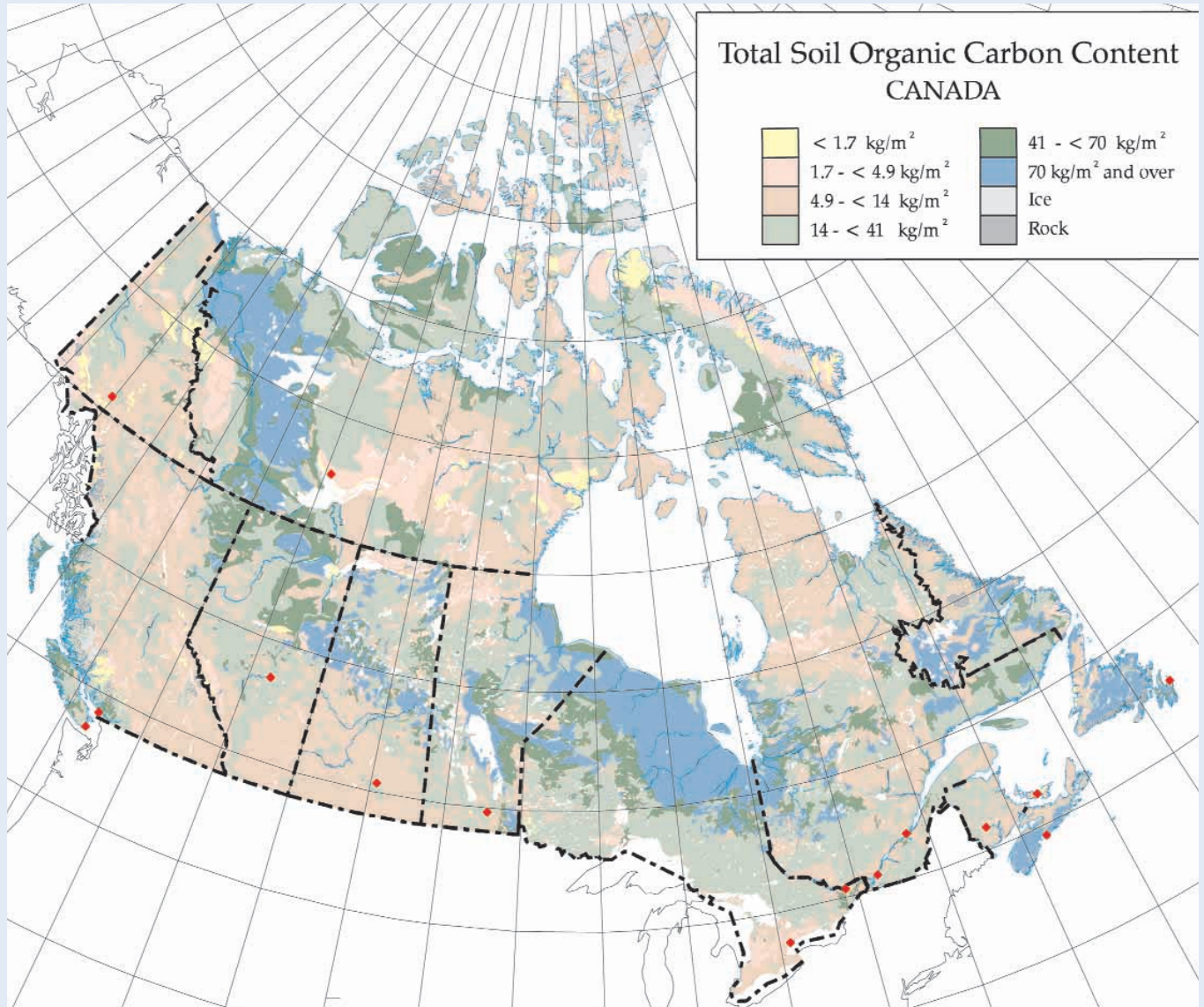
### Carbon dioxide

#### The global carbon cycle

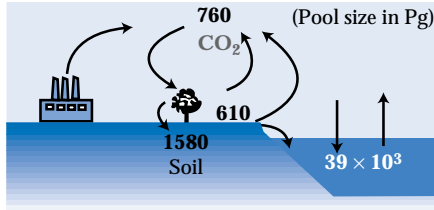
There are about 40 000 petagrams (Pg) of C in global circulation (Fig. 5). Most C is in the oceans but large pools also occur in soils, vegetation, and the atmosphere. Of these three pools, the atmosphere is the smallest but most active. The CO<sub>2</sub> in the air is continually being removed by plants through photosynthesis and being absorbed into the oceans. At the same time, however, CO<sub>2</sub> in the air is being replenished by release from plants, soils, and oceans. Thus, though C is always cycling, the concentration of atmospheric CO<sub>2</sub> has remained constant from year to year. Analysis of air bubbles trapped in old glaciers and shells buried in ocean sediments reveals that the atmospheric concentration of CO<sub>2</sub> had stayed at about 270 parts per million by volume (ppmv) for about 10 000 years.

## Soil carbon map of Canada

The Canadian Soil Organic Carbon Database, consisting of over 15 000 soil landscape polygons, contains information describing the soil landscape and carbon content of each polygon. The total carbon in the first metre of all Canadian soils is 260 Pg (billion tonnes), which represents 13% of the world's total organic carbon. However, most of the carbon is in the northern wetlands and permafrost. Only about 10 Pg (billion tonnes) or 4% of the carbon is contained in the soil of agricultural ecosystems.



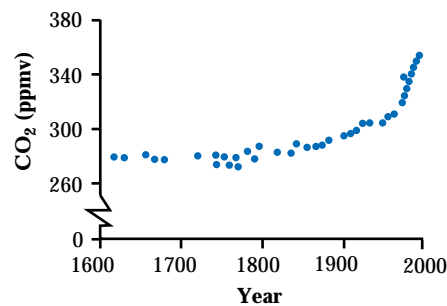
(C. Tarnocai, AAFC)



**Figure 5**

**A simplified view of the global carbon cycle.**

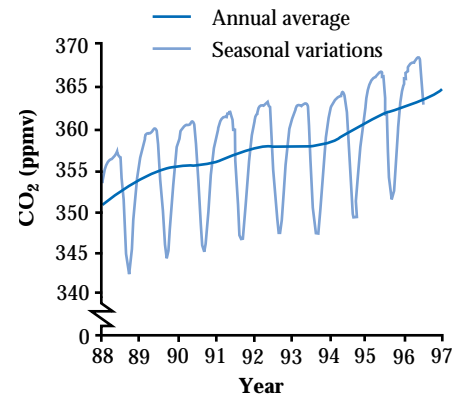
That changed with the advent of the Industrial Revolution. Since then, the demand for energy has resulted in ever-increasing amounts of fossil fuels being extracted from deep reserves and converted to atmospheric CO<sub>2</sub>. This process, in effect, withdraws C from an inactive pool and emits it into the atmosphere as CO<sub>2</sub>. Other activities have also favored increases in atmospheric CO<sub>2</sub>: removal of forests has resulted in vegetative C being converted to CO<sub>2</sub>, and the cultivation of previously undisturbed soils has resulted in soil C being converted to CO<sub>2</sub>. Because of these processes, the emissions of CO<sub>2</sub> into the atmosphere now exceed the withdrawals, resulting in the gradual buildup of CO<sub>2</sub> (Fig. 6)



**Figure 6**

**Long-term atmospheric CO<sub>2</sub> concentrations as determined from ice core data (before 1950) and atmospheric measurements (after 1950).**

In 1995, fossil fuel combustion alone released 23.5 Pg (billion tonnes) of CO<sub>2</sub> into the atmosphere. The natural C cycle can absorb some of this increased CO<sub>2</sub> emission: some is absorbed by oceans, some by increased photosynthesis in plants. Nevertheless, the total amount of CO<sub>2</sub> in the atmosphere is still increasing by about 11.7 Pg (billion tonnes) of CO<sub>2</sub> every year. These increases are readily apparent in weekly measurements of atmospheric CO<sub>2</sub> at Alert, NWT, which, despite seasonal variations reflecting plant growth, show a clear, undeniable upward trend (Fig. 7).



**Figure 7**

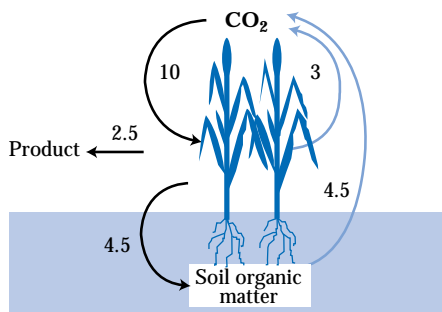
**Seasonal variations of CO<sub>2</sub> concentrations measured at Alert, NWT. Most land and, therefore, vegetation on the earth is in the Northern Hemisphere. This vegetation draws heavily on the atmospheric CO<sub>2</sub> pool in summer but returns the CO<sub>2</sub> as the vegetation dies in winter.**

## Carbon cycles in agricultural ecosystems

The carbon cycle in cropped land is quite simple, at least in principle (Fig. 8). Carbon dioxide is absorbed from the atmosphere by plant leaves and is transformed, via photosynthesis, into C-containing compounds such as sugars, carbohydrates, cellulose, and lignin.

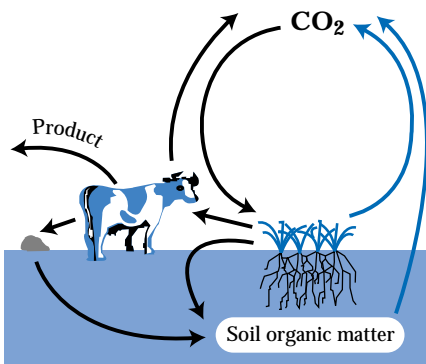


Some of this material is used by the plant for its own energy and converted back to  $\text{CO}_2$ . Of the C remaining in the plant, a portion is removed during harvest (e.g., in grain) and the rest is returned to the soil. This residue, including roots, becomes part of the soil organic matter. Microorganisms in the soil, in turn, decompose the soil organic matter, releasing  $\text{CO}_2$  back into the atmosphere and closing the loop. This cycle is essentially the same in all cropping systems, but rates vary depending on climate, soil, and crop type.



**Figure 8**  
Conceptual C cycle for corn (values are estimates of annual flows of C in Mg/ha).

Where present, livestock add another component to the carbon cycle (Fig. 9). Instead of being exported, much of the harvested plant material is fed to animals or used as bedding. Some of this C is released by the animals to the atmosphere as  $\text{CO}_2$ , some is removed as animal products, but much is returned to the soil as manure. Consequently, livestock-based systems often retain higher proportions of C on the farms. In many ways, this cycle does not differ from that in crops grown for human food. But the  $\text{CO}_2$  and wastes from human consumption of crops are often released far from the farm and therefore are not usually thought of as part of the agricultural C cycle.



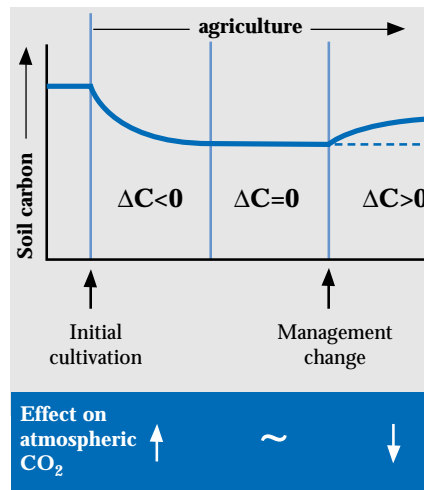
**Figure 9**  
Conceptual C cycle of a livestock-based cropping system.

In systems that have remained largely unchanged for several decades, the amount of C entering the soil as plant residues is usually balanced by the amount of C converted to  $\text{CO}_2$  by microbial activity. Consequently, though C is continually added to the soil, the amount of C stored in the soil may not change measurably. For example, in the corn system illustrated (see Fig. 8), residue inputs of 4.5 Mg (tonne) C per hectare are exactly balanced by microbial production of  $\text{CO}_2$  from the soil, so that there is no change in the amount of C stored in the soil.

## Management effects on carbon cycle

A change in the way land is managed can disrupt the C cycle, affecting the amount of C stored. Perhaps the most drastic example was the initial cultivation of soils for farming. This event, which happened on many Canadian farmlands more than a century ago, resulted in high losses of soil C: many soils lost about 25% of the C originally present in the C-rich surface layer, releasing a lot of  $\text{CO}_2$  into the

atmosphere. There are several reasons for this loss. First, farming involves the harvest of C from the fields, and the removal of this C means less input of new C. As well, cultivation and growing annual crops often speed up the conversion of soil C to CO<sub>2</sub> by soil microbes. After soils have been cultivated for a few decades, however, losses of C usually slow down or cease entirely, and the level of soil C is again stable (Fig. 10).



**Figure 10**  
Theoretical changes in soil C as influenced by management.

The effect of the initial cultivation on the C cycle is largely past. Today we are interested more in how current practices or future modifications might affect the C cycle. By choosing their crops, tillage practices, fertilizer treatments, and other options, farmers can alter the C cycle, thereby changing the amount of C stored in the system.

## Measuring management effects on carbon cycle

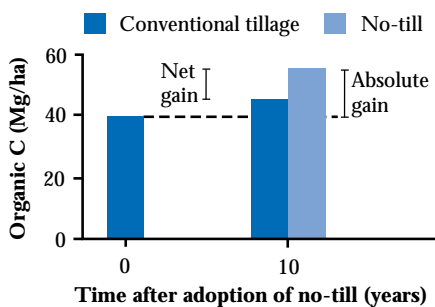
How do we determine the influences of farming practices on the C cycle? One way is to measure all the flows in the C cycle in a farm field (see Fig. 8). By subtracting the amounts of C leaving the field from the amounts entering, we can calculate the net change in C. Such measurements are useful in describing how management affects the C cycle, but they are time-consuming and are used only at selected research sites.

Another way is to measure the net exchange of CO<sub>2</sub> between vegetation and the atmosphere above it. Using sensors placed on towers, researchers can measure CO<sub>2</sub> transfer above the crop continuously for months or even years, allowing them to calculate CO<sub>2</sub> exchange over an entire field. This approach, using towers, aircraft, and other variations, provides an average of net CO<sub>2</sub> emissions from larger areas, thereby overcoming the natural variations that occur across a field. The main disadvantage of this method is cost and the difficulty of integrating over long periods.

A third method, and that most widely used, is to measure the change in the amount of stored C after a number of years. In farm fields (as opposed to forests), virtually all the C is stored in the soil organic matter. By measuring the amount of soil C once and then again several years later, scientists can tell whether the field has gained or lost C under certain practices (Fig. 11).

A common variation on this approach is to measure the change under one treatment relative to another. For example, if we are interested in the effect of tillage on C storage, we can maintain

two systems side by side—one tilled, the other not—and then measure the increase in stored C in the untilled plot by comparing it to that in the tilled plot. But measuring changes in soil C is not easy. Any increase may be small, say 3 tonnes C per hectare, compared to the amount initially there, say 60 tonnes C per hectare. This problem is further complicated by the natural variability of C in the field, which is often much greater than the difference we hope to measure. Accurate measurement of soil C change, therefore, requires careful sampling and analysis. Some researchers have focused on specific forms of soil C or on atomic markers (isotopes) to measure soil C changes more precisely.



**Figure 11**

**Estimating soil C gain after adoption of no-till.**

To estimate the effects of management on the C cycle over large regions, we have to rely on models. These models may be simple equations or highly complex computer programs that take into account many variables such as weather, soil type, and farming practices to predict C processes on the farm. Whatever their complexity, these models need to be checked against actual measurements to ensure that they are reliable. By using measurements from specific locations, researchers can verify

## Tower-based flux measurements

Tower-based long-term measurements of CO<sub>2</sub>, water vapor, and energy exchange from many ecosystems are now available for North America and Europe. Scientists make these measurements to

- collect critical new information to help define the global CO<sub>2</sub> budget
- improve predictions of future concentrations of atmospheric CO<sub>2</sub>
- enhance understanding of CO<sub>2</sub> exchange between atmosphere and biosphere
- determine response of CO<sub>2</sub> fluxes to changes in environment and climate
- provide information on processes controlling CO<sub>2</sub> flux and net ecosystem productivity
- help calibrate and verify data for CO<sub>2</sub> flux models.



Tower-based system for measuring gas exchanges.

(S. McGinn and E. Pattey, AAFC)

## Twin Otter aircraft

The Twin Otter aircraft (*see* photo), operated by the Flight Research Laboratory of the National Research Council, provides an excellent platform for investigating gas exchange near the surface. It is equipped with sophisticated turbulence and trace gas sensors. At a flying speed of 60 m/s and at altitudes of 30–100 m, the instruments record atmospheric data every 2 m. In flight, the measured net fluxes of a particular gas, such as CO<sub>2</sub>, water vapor, O<sub>3</sub>, CH<sub>4</sub>, and N<sub>2</sub>O, can be determined as the average product of vertical wind and the actual concentration of the gas. The flux value can be positive (indicating that more gas is released by the surface than is being absorbed), zero, or negative (meaning that more gas is being absorbed than is being released).



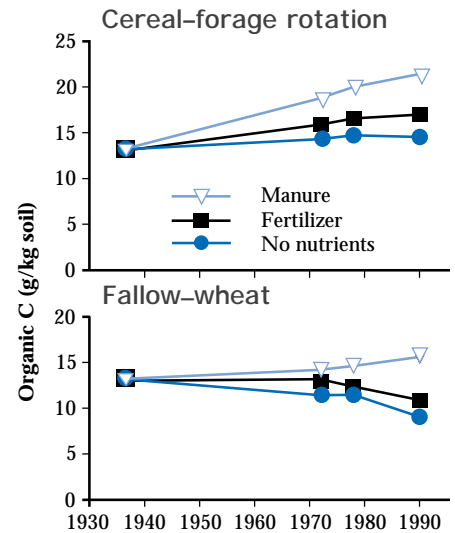
(J.I. MacPherson, NRC, and R.L. Desjardins, AAFC)

### Get a feel for magnitudes

Multiplier	Name	Other name	Abbreviation
$10^0$ gram			g
$10^3$ grams	kilogram		kg
$10^6$ grams	megagram	tonne	Mg
$10^9$ grams	gigagram	thousand tonnes	Gg
$10^{12}$ grams	teragram	million tonnes	Tg
$10^{15}$ grams	petagram	gigatonne or billion tonnes	Pg

100 m × 100 m = 1 hectare (ha).  
1 ha = 2.5 acres.

only increased crop yield but also provided direct addition of C.



**Figure 12**

Change in organic C in two cropping systems at Breton, Alta., as affected by nutrient application. (R.C. Izaurrealde, University of Alberta)

the models and present their predictions for large areas with some confidence.

### Examples of management effects on carbon cycle

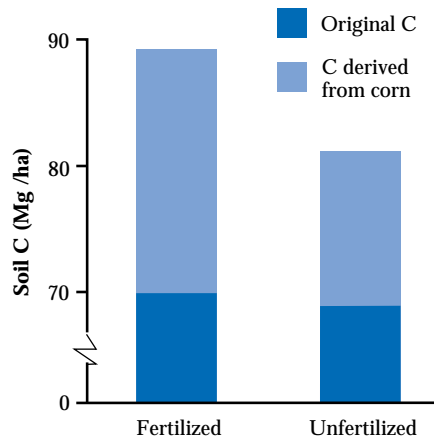
Scientists have measured the effect of management on the C cycle at numerous sites across Canada. Rather than attempt to summarize all these, we offer a few as examples of recent findings.

#### *Crop rotation in forest soil*

The Breton plots near Edmonton, Alta., are among the longest-running research sites in Canada. This experiment shows that an appropriate crop rotation, including legumes and cereal crops, can result in large increases in the C content of this soil, originally cleared from forest (Fig. 12). By comparison, soil under fallow-wheat showed no appreciable gains of C. Within each crop rotation, soil receiving fertilizer had higher gains of C than unfertilized soils, probably because of higher residue inputs with fertilization. Manure application increased soil C even more than fertilizer, because the manure not

#### *Fertilizer application to corn*

Application of fertilizer can increase soil C. At a long-term research site in Ontario, soil under fertilized corn had higher soil C than that under unfertilized corn after 32 years (Fig. 13). Using C isotopes to distinguish between C from corn and that from previous organic matter, the researchers also showed that the increase came entirely from the corn residue—fertilization had no effect on the organic matter that was there before corn was first planted. Adding fertilizer to this soil increased yields, thereby increasing the amount of residues returned to the soil. Where there is no yield response to fertilizer, there may be no increase in soil C.



**Figure 13**

**Soil C after 32 years of growing corn showing the proportion derived from corn and that remaining from previous organic matter. (E. Gregorich, AAFC)**

### Tillage

Historically, tillage was one of the main tools available to farmers for controlling weeds and preparing land for seeding. But with new herbicides and seeding equipment, intensive tillage is no longer always necessary. Some farmers have opted to eliminate tillage entirely, a practice referred to as “no-till” farming or “direct seeding.” This practice can lead to substantial increases in soil C. A partial survey of studies across Canada shows no-till can increase soil C by as much as 10 Mg (tonne) per hectare, when compared with tilled soil (Table 2). But such gains are not automatic. In some cases, researchers were not able to detect any effect of tillage on soil C. The inconsistency of the results is not surprising, because the response of soil C is affected by climate, soil properties, length of time under no-till, crop rotation, and many other factors. Some of the variability may simply reflect the

### Soil management

Some of the many techniques used by farmers include

- Conventional tillage: soils are routinely cultivated to eliminate weeds and prepare soil for seeding
- Reduced, minimum, or conservation tillage: tillage is reduced to keep residues on the surface
- No-till: seeds are planted directly without any prior tillage; weeds are controlled by chemicals
- Summer fallow: no seeding for one season; weeds are controlled by cultivation or by chemicals.

Definitions of tillage practices differ from region to region.

No-till can have several advantages. It requires less time and machinery. The organic residues left on top of the soil help to preserve moisture and protect it against erosion.



Use of no-till\* in Canada

	Area under no-till (%)	
	1991	1996
Atlantic	2	2
Quebec	3	4
Ontario	4	15
Manitoba	5	8
Saskatchewan	10	20
Alberta	3	9
British Columbia	5	9
Canada	7	14

\* No-till includes direct seeding into stubble or sod, or tillage of only the ridge of rows.

**Table 2** Examples of the effects of no-till on soil C in selected long-term studies in Canada

Location	Duration (years)	Cropping system	Soil C gain/loss* (Mg/ha)
Ontario	11	Corn	-0.9
Ontario	18	Corn–soybean	11.5
Saskatchewan	11	Wheat	1.8
Saskatchewan	11	Fallow–wheat	0.6

\*C in no-till - C in tilled.  
 Tilled treatments and depth of analysis vary among sites.  
 (C. Campbell, AAFC; C. Drury, AAFC; T. Vyn, University of Guelph)

difficulty of measuring soil C change precisely.

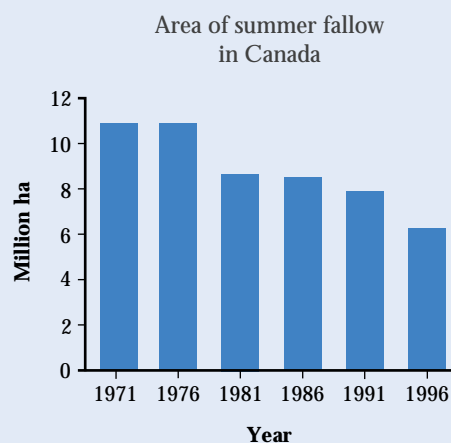
### Summer fallow

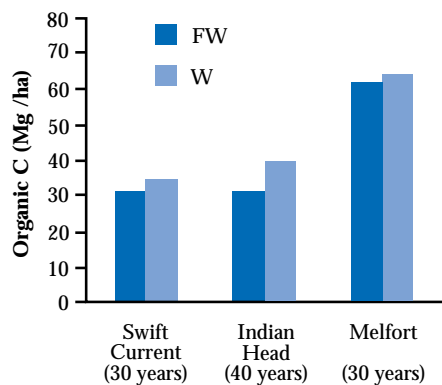
Summer fallow, the practice of leaving land unplanted for a whole year, was once widely practiced in western Canada because it helped control weeds, replenish soil moisture, and increase available nutrients in the soil. The area of fallow has declined recently but still occupies about 6 million hectares every year. Soils that are frequently under summer fallow usually have lower C content than those that are cropped annually. For example, long-term studies in Saskatchewan show that, after several decades, soil cropped to wheat every year have C contents several tonnes per hectare higher than those that are fallowed every second year (Fig. 14). Fallow has two negative effects on soil C: it hastens decomposition of soil C, and it reduces C inputs into the soil during the year when there is no crop.

### Summer fallow in Canada

The major development that allowed agriculture in the climatically restricted prairies occurred by accident. In the spring of 1885, the farm horses of Indian Head, Sask., were conscripted for the army that was suppressing the Rebellion. By the time the horses were released, it was too late to plant. However, the land was worked during the summer and produced an excellent crop the next year, while drought caused an almost complete crop failure everywhere else. Experiments at the Dominion Experimental Station at Indian Head, established soon after, led to the system of summer fallowing being developed that turned Palliser’s Triangle into the bread-basket of Canada. (Palliser’s Triangle is the dry southwestern area of Alberta and Saskatchewan, named after this early explorer.) With modern methods of weed control, fertilization, and planting, summer fallow is no longer as essential as it once was.

Fields not cropped for a year still require weed control, either mechanical or chemical. The bare soil is directly exposed to wind and sun, enhancing erosion and organic matter decomposition. Without a crop, little organic residue is returned to the soil. Use of summer fallow depends on soil moisture and expected crop income. It is expected that summer fallowing will continue to decrease and stabilize at about 4.5 million hectares by about 2050.





**Figure 14**

**Organic C in surface soil of fertilized fallow–wheat (FW) and continuous wheat (W) in long-term sites in Saskatchewan. (C. Campbell, AAFC)**

### *Grass on previously cultivated land*

One of the fastest ways to increase soil C is to return cultivated land to vegetation like that under “native” conditions. A study at Lethbridge, Alta., compared the C cycle in four treatments: native grasses, crested wheat grass (a common, introduced grass), continuous wheat (wheat planted annually), and fallow–wheat (wheat planted only every second year). These plots were started on land that had been under fallow–wheat for many decades. Using the C budget method described earlier, researchers showed that the grass plots were gaining large amounts of C (Table 3). The fallow–wheat plots, on the other hand, were losing C whereas the continuous wheat plots were neither losing nor gaining C.

### *Manure application to silage corn*

Animal manure is widely used as a nutrient source for crops. In a study at St-Lambert, Que., regular manure application increased the amount of C stored in the soil after 10 years

(Table 4). Part of this increase came from the direct addition of C in the manure. This C represents a recycling of the C from plant materials used to feed and bed the animals. But the manure, by providing plant nutrients and improving soil aggregation and porosity, also increased crop growth and the amount of C returned to the soil as residues. Thus, using manure not only results in efficient recycling of plant C but also promotes soil C gains by increasing plant photosynthesis.

These few examples, along with numerous similar studies across Canada, show clearly that the choice of farming practice can affect the C cycle and influence the net exchange of CO<sub>2</sub> from farms.

**Table 3 Carbon balance on plots seeded to grass or wheat in Lethbridge**

	Crested wheatgrass	Native grasses	Continuous wheat	Wheat–fallow
	g/m <sup>2</sup>			
Net primary production	423	315	291	215
Harvested matter	-101	-66	-76	-58
Carbon input in the soils	322	249	215	157
Carbon loss from the soils (organic matter decay)	-191	-196	-207	-178
Net soil carbon gain (loss)	131	53	8	-21

(B.H. Ellert, AAFC)

**Table 4 Carbon inputs, soil carbon storage, and soil physical properties of a silty clay loam in Quebec following 10 years of biennial applications of solid dairy cattle manure**

Manure application rate (t/ha/2 y)	C added by manure (kg/ha/y)	C added by crop (kg/ha/y)	Soil C storage (kg /ha)	Aggregate size (mm)	Porosity (%)
0	0	350	4969	1.3	51
20	870	380	6078	1.6	52
40	1740	430	6459	1.5	54
60	2610	480	7080	1.7	55
80	3480	530	7505	1.7	56
100	4350	600	7708	1.8	56

(A. N'Dayegamyie, MAPAQ, Qc and D. Angers, AAFC)

## Energy use

Most cropping systems depend on external energy sources. Much of this energy comes from the burning of fossil fuels, which releases CO<sub>2</sub> into the

atmosphere. We must consider this CO<sub>2</sub>, which is part of the C cycle on farms, if we want to look at the overall effect of agriculture on the atmosphere.

The main use of fuel on Canadian farms is to power the machinery for tillage, planting, harvesting, and other field operations. Additional amounts are also used for transportation, irrigation, drying of crops, heating of buildings, and equipment used in livestock operations.

Aside from that used directly on the farms, agriculture also depends on energy for the manufacture and transport of inputs. For example, manufacturing pesticides, buildings, and farm machinery uses energy. But the largest off-farm use of energy is for making and transporting fertilizer, notably that containing nitrogen. The resulting release of CO<sub>2</sub> varies depending on fertilizer form (Table 5). But, on average, producing and transporting 1 kg of fertilizer N releases about 1 kg of C (or 3.7 kg CO<sub>2</sub>) into the atmosphere. In

**Table 5 C released as CO<sub>2</sub> from manufacturing and transporting fertilizers**

Fertilizer	kg C per kg of nutrient (N,P,K)
Anhydrous ammonia	0.8
Urea	1.2
Ammonium nitrate	1.1
Ammonium sulfate	1.0
Urea–ammonium nitrate	1.1
Monoammonium phosphate (N + P)	1.2
Potassium (K <sub>2</sub> O)	0.2

(E. Coxworth, Saskatoon, Sask.)



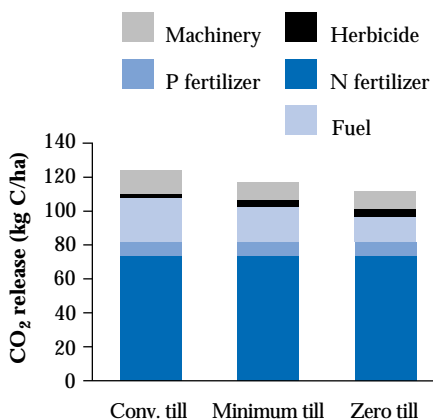
national estimates of emissions, researchers usually assign these indirect uses of energy to other sectors (e.g., manufacturing). But they still relate to farming and offer a means of reducing CO<sub>2</sub> emissions from farms.

The rate of CO<sub>2</sub> emission from energy use on Canadian farmland varies widely, depending on how intensive the farming operation is. For example, farms producing livestock on grassland may require relatively little external energy. By comparison, farms with high inputs of fertilizer, intensive tillage, and irrigation may generate high amounts of CO<sub>2</sub> from using energy.

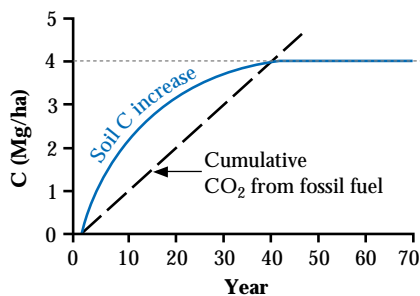
A typical farming system on cropland may release C from energy use at a rate of roughly 100 kg C per hectare per year. For example, an analysis of farming systems at Indian Head, Sask., showed that the total C emission from direct and indirect use of energy ranged from about 100 to 115 kg C per hectare per year, depending on tillage intensity (Fig. 15). The largest sources of this CO<sub>2</sub> were the manufacture and transport of fertilizer and the on-farm use of fuel.

The net effect of a farming system on atmospheric CO<sub>2</sub> is the increase in soil C minus the amount of C released from energy use. Thus, a farm that emits CO<sub>2</sub> from fuel use at a rate of 100 kg C per hectare per year will have a net benefit on atmospheric CO<sub>2</sub> only if the rate of soil C gain exceeds 100 kg C per hectare per year. For example, suppose a field gains 4 Mg (tonnes) C per hectare over several decades in response to better management and that soil C then stabilizes at that new, higher level. The net benefit to the atmosphere will be the difference between the soil C gain and cumulative CO<sub>2</sub> release from energy use (Fig. 16). If CO<sub>2</sub> from energy use is 100

kg C per hectare per year, then the CO<sub>2</sub> release would be equal to the soil C gain after about 40 years. Thereafter, the field would again be a net emitter of CO<sub>2</sub>, unless some further soil C gains are made.



**Figure 15**  
Sources of CO<sub>2</sub> from spring wheat at Indian Head, Sask., as affected by tillage. (E. Coxworth, Saskatoon, Sask.)



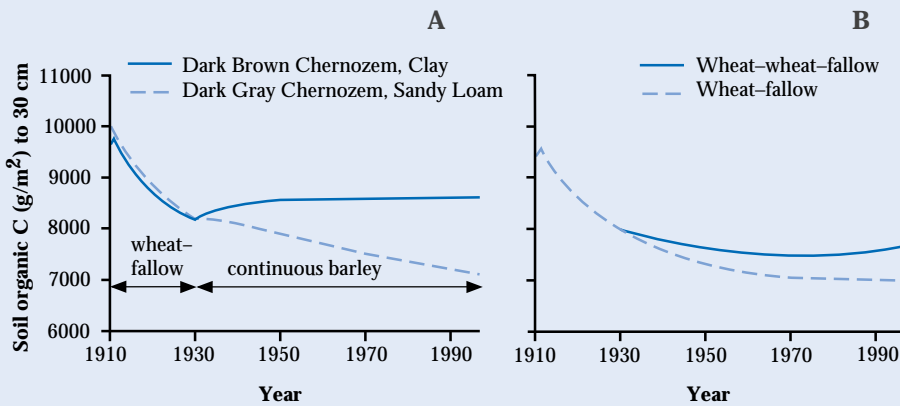
**Figure 16**  
Conceptual illustration of soil C gain and cumulative CO<sub>2</sub> from fossil fuels in an agroecosystem.

## Modeling soil carbon content

The site-specific model Century makes use of simplified relationships of the soil–plant–climate interactions to describe the dynamics of soil carbon and nitrogen in grasslands, crops, forests, and savannas. It accounts for several agricultural management practices including planting, applying fertilizer, tilling, grazing, and adding organic matter. It simulates above- and below-ground plant production as a function of soil temperature and availability of water and nutrients. Century predictions of the change in soil carbon in Saskatchewan are shown for two cases:

- A) two soil types and a change from wheat–fallow rotation to continuous barley in 1930
- B) one soil type, Dark Brown Chernozem clay loam, but two different rotations after 1930.

Century predictions for different soils and crop rotations



(W. Smith, Ottawa, Ont.)

because soil properties and management practices vary across the country. Measuring the change directly would require enormous effort, so our estimates rely on mathematical models.

In a recent study, a detailed model (“Century”) was used to predict changes in C content of Canadian agricultural soils, based on climate and soils data from across Canada. Information about farming practices was taken from recent Statistics Canada data. The study considered the predominant agricultural systems in Canada but did not include all possible variations. Some of the factors not included were a) biomass burning, a practice no longer widely used; b) soil erosion, which moves C around the landscape; c) manure addition; d) minor crops such as potatoes and annual legumes; and d) minimum tillage, which is intermediate between “conventional” and no-till. Future analyses may include some of these factors.

The model predictions agree with historical observations: soil C declines rapidly after initial cultivation, but the rate of decline diminishes gradually over time as soils approach a new “steady-state” at which they no longer lose C (Fig. 17). According to the model, current rates of C loss are negligible. The model predicts, further, that agricultural soils will begin regaining some of the lost C in the future, as farmers adopt improved practices such as no-till and reduced summer fallow (Table 6). According to the model, the agricultural soils were losing C at a rate of about 3 Tg (million tonnes) of C per year in 1970 but could be gaining C at a rate of 0.4 Tg of C per year by 2010. Predicted rates of soil C change differ among regions, reflecting variable adoption of improved practices and differences in soil properties. For

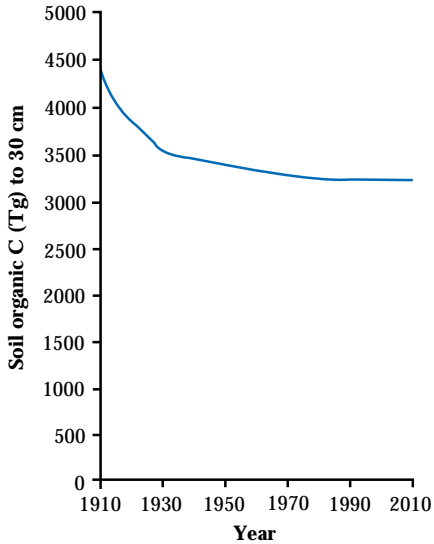
## Estimates of carbon dioxide emissions in Canada

Scientists calculate the net emissions of CO<sub>2</sub> from Canadian agriculture by estimating the annual change in stored C and adding CO<sub>2</sub> release from fossil fuel (see Fig. 8). Most of the C stored in agroecosystems occurs in soil, so they can estimate the change in storage from the gain or loss of soil C.

### Estimate of soil C change

Estimating soil C change for all the agricultural area of Canada is difficult,

example, the model suggests that rates of gain are highest in Saskatchewan and lowest in Alberta.



**Figure 17**

Long-term predictions of soil C change based on the Century model, assuming only a gradual adoption of no-till. (W. Smith, Ottawa, Ont.)

All these predicted rates of change are low compared to the total amount of stored C. For example, a C gain of 0.4 Tg/y amounts to a rate of <0.01 Mg (tonnes) of C per hectare per year, when averaged across all cultivated soils in Canada. This value is very small compared to the total C content of soils, which is commonly about 60–100 Mg (tonnes) C per hectare.

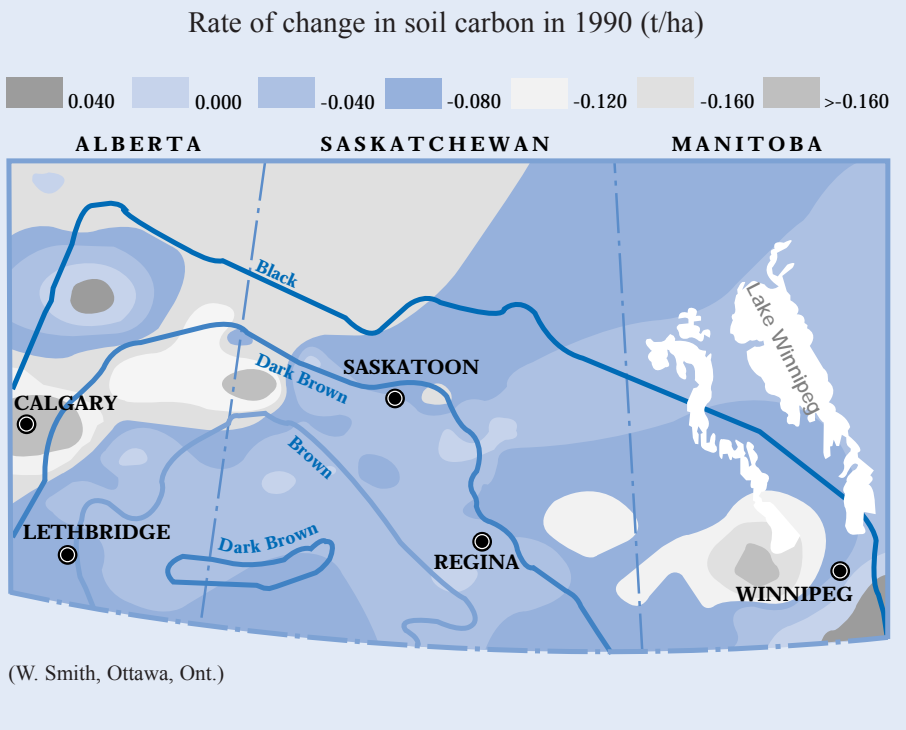
The Century model predictions represent our current best estimates of soil C change across the country. But these estimates rely on several simplifying assumptions and have not yet been fully tested for all conditions across Canada. For example, compared to some actual data on the change in soil carbon under no-till, the predicted changes appear to

### Rate of change of carbon in Canadian agricultural soils, 1990

Agriculture’s largest store of carbon is in its soils, where dead plants have accumulated over the centuries. Cultivating the soil, however, has greatly affected this store of carbon, reducing it by about 15–35%. Agriculture and Agri-Food Canada’s research program confirmed that, in many cases, farmers have been able to reduce or even reverse the C loss with good management.

The Century model (a site-specific computer simulation of the dynamics of soil organic matter) was used to estimate the rate of change of carbon in Canadian soils for the year 1990. Soil, crop coverage, tillage, and crop rotation data were obtained for 1229 soil landscape of Canada polygons. Century runs were carried out on 15% of the polygons. For each sampled polygon Century was run for one to five types of crop rotations under conventional tillage. It was also run for no-till practices for polygons for which no-till represented 5% or more of the agricultural area.

The map shows carbon change in agricultural soils on the Prairies during 1990. The estimated average carbon loss corresponds to about 40 kg/ha/y, which is much smaller than the amount that can be measured.



**Table 6 Soil organic C change in Canadian crop lands<sup>1</sup> as estimated using the Century model**

	1970	1981	1986	1991	1996
Average C change (kg/ha/y)	-67	-51	-48	-35	-11
Total C change (Tg/y)	-2.7	-2.1	-2.0	-1.4	-0.5

<sup>1</sup> Pastures are not included.

<sup>2</sup> Since 1910, there has been a 24% reduction of soil organic C (1053 Tg C) in cultivated soils. Total C in first metre of agricultural soils in Canada is 10 000 Tg. (W. Smith, Ottawa, Ont.)

**Table 7 Estimated CO<sub>2</sub> emissions from fossil fuel use in Canadian agriculture**

	1981	1986	1991	1996
	(Tg CO <sub>2</sub> )			
Direct use				
Fuel used on farm	9.5	7.7	8.1	9.5
Indirect uses				
Fertilizer manufacture, transport & application	4.4	5.5	5.1	6.6
Machinery manufacture & repair	4.8	4.8	4.8	4.8
Building construction (steel & cement manufacture)	2.5	2.2	2.3	2.2
Pesticide manufacture	0.2	0.3	0.3	0.3
Electricity generation	1.8	1.9	2.1	2.4
Total indirect fossil CO <sub>2</sub>	13.7	14.7	14.6	16.3

(R.L. Desjardins, AAFC; E. Coxworth, Saskatoon, Sask.)

be low by as much as 50%. With further research and as the reliability of the models improves, the estimates may be adjusted.

### *Emissions from the use of fossil fuel*

The other major source of CO<sub>2</sub> in agriculture, aside from the biological C cycle, is burning of fossil fuel. Direct fuel use on Canadian farms releases about 10 Tg (million tonnes) of CO<sub>2</sub> annually (Table 7). Indirect sources, associated with the production or transport of inputs, emit additional CO<sub>2</sub>. Of these, manufacture and transport of fertilizer is the most important.

Emissions from this source have increased steadily because of increased rates of fertilizer application. The manufacture of farm machinery, construction of buildings, and generation of electricity also emit large amounts of CO<sub>2</sub>. Altogether, CO<sub>2</sub> emissions from indirect sources amounted to about 16 Tg (million tonnes) of CO<sub>2</sub> in 1996.

Direct and indirect use of fossil fuels on Canadian farms, therefore, amounted to about 26 Tg (million tonnes) of CO<sub>2</sub> (7 Tg C) in 1996. In calculating national inventories, however, researchers count only the CO<sub>2</sub> produced from stationary combustion (about 3 Tg CO<sub>2</sub> in 1996) in estimates for agriculture; the remainder they include in emissions from manufacturing, construction, and transportation sectors.

### *Total emissions*

Total emissions of CO<sub>2</sub> from Canadian agricultural activity are the sum of net soil C loss, emissions from direct use of fossil fuel, and emissions from indirect uses of fossil fuel (Table 8). These estimates suggest that, in 1996, agricultural activity released about 28 Tg of CO<sub>2</sub> into the atmosphere, slightly less

than in 1981. Projections to the year 2010 suggest that total emissions will not change appreciably from those in 1996. Scientists predict that emissions from soils are likely to decline and become negative (that is, soils will gain C) but, at the same time, emissions from indirect sources may increase, offsetting these benefits. These estimates, however, assume a “business-as-usual” scenario and do not yet take into account any benefits that might occur from concerted efforts to reduce emissions.

## Methane

Methane is perhaps most familiar to us as the main component of natural gas. Though present in the atmosphere at very low concentrations (about 2 ppmv), it is a comparatively powerful greenhouse gas: one kilogram of CH<sub>4</sub> has 21 times the warming effect of the same amount of CO<sub>2</sub>, when calculated over a 100-year period. This effect arises not only from the CH<sub>4</sub> itself but also from other indirect effects, including the CO<sub>2</sub> to which it eventually converts.

The concentration of CH<sub>4</sub> in the atmosphere, which had been increasing at a rate of 1.1%, is now increasing at about 0.6% per year. Globally, agriculture is a prominent source of CH<sub>4</sub>, accounting for about two-thirds of human-induced emissions.

Most of the CH<sub>4</sub> emitted from agriculture is produced by the microbial breakdown of plant material. Normally, when oxygen supply is adequate, most of the C in decomposing plant material converts to CO<sub>2</sub>. But, in the absence of oxygen, decomposition is incomplete and C is released as CH<sub>4</sub> instead. In agricultural systems, such conditions occur in the digestive system of ruminant

**Table 8** Estimated CO<sub>2</sub> emissions from Canadian agriculture from direct and indirect sources

	1981	1986	1991	1996
	(Tg CO <sub>2</sub> )			
Direct emissions				
Soils	7.7	7.3	5.1	1.8
Fuel used on farm	9.5	7.7	8.1	9.5
Total direct emissions	17.2	15.0	13.2	11.3
Indirect emissions	13.7	14.7	14.6	16.3
Total emissions attributable to agriculture	30.9	29.7	27.8	27.6

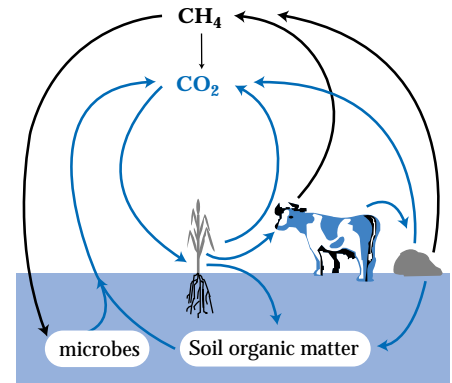
(R.L. Desjardins, AAFC)

livestock (e.g., cattle) and in water-logged soils (e.g., rice paddies). Incomplete burning of fuel or organic wastes also produces small amounts of CH<sub>4</sub>. Methane and CO<sub>2</sub>, therefore, are somewhat complementary: C not converted to CH<sub>4</sub> is largely released as CO<sub>2</sub>.

The CH<sub>4</sub> emitted into the atmosphere has a lifetime of, on average, about 12 years. Chemical reactions in the atmosphere convert most CH<sub>4</sub> to CO<sub>2</sub>. Microorganisms living in the soil convert probably less than 10% of CH<sub>4</sub> released into the atmosphere to CO<sub>2</sub>.

## Methane emission by livestock

All animals produce  $\text{CH}_4$  when they digest feed. But emission is especially high from cattle, sheep, goats, and other ruminants. These animals have a rumen, or “fore-stomach,” where microbial fermentation partially digests feed. Because of this process, ruminants can efficiently digest fibrous feeds. But, since the fermentation occurs under restricted oxygen supply, some C in the feed, often about 5–10%, is released as  $\text{CH}_4$  rather than as  $\text{CO}_2$  (Fig. 18). Nonruminant animals, such as pigs and poultry, also emit some  $\text{CH}_4$  during digestion, but the amounts released are almost negligible by comparison (Table 9).



**Figure 18**

**$\text{CO}_2$  and  $\text{CH}_4$  flow in a livestock-based agroecosystem.**

### Measuring methane emission

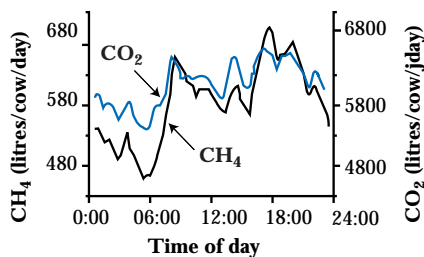
We can measure the amount of  $\text{CH}_4$  emitted by livestock in a number of ways. One method is to place the animal in an enclosed chamber and measure  $\text{CH}_4$  accumulating in the airspace. This approach permits accurate analysis, but estimates may be distorted because the animal is removed from its normal environment. Recently, therefore,

**Table 9** Estimated  $\text{CH}_4$  emissions from livestock and manure in 1991

	Number of animals (Millions)	Mass of manure (Tg)	Methane from manure (Gg)	Methane from livestock (Gg)	Total methane (Gg)
Dairy cattle	2	17	70	190	260
Beef cattle	11	98	10	558	568
Pigs	10	19	102	15	117
Poultry	103	3	8	N/A	8
Sheep/lambs	1	0.4	0.2	8	8
Total livestock	127	137	190	771	961

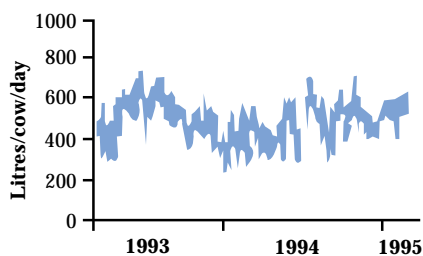
(R.L. Desjardins, AAFC)

researchers have measured CH<sub>4</sub> emission from cattle in their natural setting. They measured the CH<sub>4</sub> concentration in air emitted from vents in a dairy barn and calculated the emission from all cows in the barn, including the manure they produced. Using this approach, they were able to estimate not only the average rate of CH<sub>4</sub> production per animal (about 550 litres per cow per day) but also the daily and seasonal fluctuations in emission rates (Figs. 19 and 20). For example, highest emissions usually occurred immediately after each feeding.



**Figure 19**

Diurnal pattern of CO<sub>2</sub> and CH<sub>4</sub> emitted by dairy cows. (H. Jackson and R. Kinsman, AAFC)



**Figure 20**

Average monthly emission of CH<sub>4</sub> from a dairy barn in Ottawa. (H. Jackson and R. Kinsman, AAFC)

### Emissions from dairy cows

A complete barn, with a handling system for liquid manure, was instrumented to monitor CO<sub>2</sub> and CH<sub>4</sub> emissions from 118 dairy cows and their manure. Experiments such as this help to determine the amount of greenhouse gases emitted from cattle. The rate at which feed energy is converted to CH<sub>4</sub> is based on the quantity and quality of feed. Dairy cows emit much more CH<sub>4</sub> per year than other cattle.



Cows unknowingly participating in an experiment to measure greenhouse gas at the Central Experimental Farm in Ottawa, Ont.

(H. Jackson and R. Kinsman, AAFC)

Measuring CH<sub>4</sub> from cattle on pastures poses more difficult problems. But researchers now have a new technique, based on the use of a chemical marker, to measure directly CH<sub>4</sub> emission from grazing animals. This method, used in a grazing study in Manitoba, showed that emission rates were about 0.7 litre per kilogram body weight per day (0.5 g CH<sub>4</sub> per kilogram body weight per day).

### Factors affecting methane emission

Many factors influence the rate of CH<sub>4</sub> emission from ruminants. They are reasonably well known because CH<sub>4</sub> loss represents incomplete use of feed energy.

## Measuring methane emissions from grazing animals

Scientists can measure  $\text{CH}_4$  produced from grazing cattle by using sulfur hexafluoride ( $\text{SF}_6$ ) as a tracer gas. Capsules that gradually release  $\text{SF}_6$  at a constant rate are placed in the animals rumen. Then, by comparing the ratio of the concentrations of  $\text{CH}_4$  and  $\text{SF}_6$  expired by the animal, the researchers can calculate the  $\text{CH}_4$  produced.



Steer equipped to measure  $\text{CH}_4$  production using a tracer gas.

(P. McCaughey, AAFC)

forage plant, degree of chopping or grinding, the amount of grain in the diet, and the addition of oils. For example,  $\text{CH}_4$  emission may be lower from legume rather than grass forage, from ensiled rather than dried feeds, and from highly concentrated rather than high-roughage diets.

Another important factor is the amount of feed intake. When intake of feed is increased above maintenance levels, the amount of  $\text{CH}_4$  emitted per animal increases, but the efficiency of feed usage also increases. Consequently,  $\text{CH}_4$  emission per unit of product (e.g., milk or beef) is usually reduced at higher levels of feed intake. For this reason, it is often better to assess  $\text{CH}_4$  emission per unit of product rather than per animal or unit of feed.

For animals on pasture, the  $\text{CH}_4$  production may be affected by the grazing regime. In a Manitoba study, halving the number of beef cattle per hectare increased  $\text{CH}_4$  emission per animal but reduced the emission per hectare. Overall,  $\text{CH}_4$  emission per kilogram of weight gain (about 150 g  $\text{CH}_4$  per kilogram of gain) was unaffected by grazing practice.

As much as 15% of the gross energy in feed may be lost through  $\text{CH}_4$  emission. As a result, researchers studied the factors affecting  $\text{CH}_4$  emission long before the environmental concerns about  $\text{CH}_4$  became prominent.

One important factor affecting the rate of  $\text{CH}_4$  emission is the quality of the feed. In general, diets that increase the rate of digestion reduce  $\text{CH}_4$  emissions, because the feed does not stay in the rumen as long. Thus, several characteristics of the feed can affect  $\text{CH}_4$  emission: the amount of roughage in the diet, preservation method, growth stage of

The animal itself—its breed, weight, rate of growth, and whether it is producing milk—affects  $\text{CH}_4$  emission. The environment may also affect  $\text{CH}_4$  emission. For example, some research suggests that emissions may increase at lower temperatures. Because of the large number of factors that influence  $\text{CH}_4$  release from livestock, it may be possible to reduce emissions by changing management practices.



## Estimates of methane emission from livestock

Direct emission of CH<sub>4</sub> from Canadian farm animals can be estimated by multiplying the number of animals by an average emission rate per animal. In 1991, direct emission of CH<sub>4</sub> from Canadian farm animals was about 771 Gg (thousand tonnes) (see Table 9). Of this, beef cattle accounted for 72% and dairy cattle for 25%. By comparison, direct emissions from other livestock were almost negligible.

## Emission of methane from manure

Methane is emitted not only from the animals themselves but also from the C they excrete (see Fig. 18). Manure, like other organic materials, is decomposed by microorganisms. If the decomposition occurs under well-aerated conditions, most of the C is released as CO<sub>2</sub>. When oxygen is deficient, however, a lot of CH<sub>4</sub> may be produced instead.

The ratio of CO<sub>2</sub> to CH<sub>4</sub> produced depends on how the manure is managed. Much of the CH<sub>4</sub> from manure is produced during storage. When manure is stockpiled, inadequate aeration inside the pile may lead to CH<sub>4</sub> production. Even higher amounts of CH<sub>4</sub> may be released from manure stored in liquid form because of limited aeration. Thus pig manure, commonly stored as a slurry, may emit high amounts of CH<sub>4</sub>. Once manure is applied to the land, it produces little additional CH<sub>4</sub> because of adequate exposure to air.

Using estimates of manure produced and CH<sub>4</sub> emission rates, it is possible to estimate the amount of CH<sub>4</sub> emitted from manure in Canada (see Table 9). According to this

calculation, emission from manure accounts for about 20% of the total CH<sub>4</sub> emitted by livestock (manure + direct emission). In particular, these estimates point to pig manure as an important source of CH<sub>4</sub>, both because of large numbers of animals and because of the way the manure is stored.

## Methane emission and absorption by soils

Soils can either release CH<sub>4</sub> or absorb it, depending largely on moisture content. When organic materials decompose in submerged or water-laden soils, the water reduces the oxygen supply causing the release of large amounts of CH<sub>4</sub>. Globally, for example, rice paddies are an important source of atmospheric CH<sub>4</sub>. In the agricultural soils of Canada, however, CH<sub>4</sub> emission is probably confined to localized wetland areas and perhaps to brief periods when low-lying soils are submerged during snowmelt or after high precipitation. Most soils have enough aeration that they do not produce CH<sub>4</sub>; in fact, microorganisms in the soils convert CH<sub>4</sub> to CO<sub>2</sub> so that the soils “absorb” CH<sub>4</sub>. The amount absorbed depends to some extent on management practices. For example, CH<sub>4</sub> absorption is usually higher under grassland than in tilled soils and is suppressed by applying N fertilizers.

Although CH<sub>4</sub> absorption by soils is an important mechanism in the global CH<sub>4</sub> cycle, the amounts absorbed by Canadian agricultural soils are probably small compared to total emissions from farms (Table 10). Researchers estimate net absorption of CH<sub>4</sub> by agricultural soils in Canada to be about 12 Gg (thousand tonnes) per year. Even large increases in amount of CH<sub>4</sub> absorption by soils would offset only a small

proportion of current emissions from livestock and manure.

## Other sources of methane

Fossil fuels used in agriculture release small amounts of CH<sub>4</sub> by volatilization and combustion. This emission amounts to about 1 Gg (thousand tonnes) of CH<sub>4</sub> per year (*see* Table 10). Some CH<sub>4</sub> is emitted from the burning of crop residues, but amounts are small and will diminish further because this practice is becoming obsolete.

## Estimates of net emission from all sources

Virtually all the CH<sub>4</sub> emission on Canadian farms is from livestock (*see* Table 10). According to current estimates, about 1 Tg (million tonnes) of

CH<sub>4</sub> was emitted from Canadian farms in 1996. Of this amount, about 80% came directly from livestock, the remainder from livestock manure.

Changes in emissions from year to year reflect differences in livestock numbers, which fluctuate depending on costs of feeds, market prices for the products, and export markets. If livestock numbers increase as expected, CH<sub>4</sub> emissions may further increase unless farmers adopt new methods that reduce emissions per animal.

## Nitrous oxide

Nitrous oxide is familiar to us as an anesthetic. It occurs naturally in the atmosphere at very low concentrations (about 0.3 ppmv), but the concentration is now increasing at a rate of about 0.3% per year. Much of this increase comes from agriculture, which accounts for up to 70% of the N<sub>2</sub>O emissions from human activity.

The increase poses two potential threats. First, N<sub>2</sub>O is a potent greenhouse gas with a long lifetime in the atmosphere (about 120 years). Its warming potential is about 310 times that of CO<sub>2</sub> over 100 years. Second, N<sub>2</sub>O released is eventually converted in the upper atmosphere to nitric oxide (NO), a gas that breaks down O<sub>3</sub>. Ozone in the upper atmosphere filters out UV radiation from the sun, so its depletion results in higher doses of harmful UV radiation reaching the earth's surface. Higher N<sub>2</sub>O levels, therefore, not only contribute to the greenhouse effect but may also increase indirectly the intensity of UV radiation.

Most N<sub>2</sub>O from agriculture is produced in the soil. To understand the origins of the N<sub>2</sub>O and the factors that affect its emission, it is helpful to review the overall N cycle on farms.

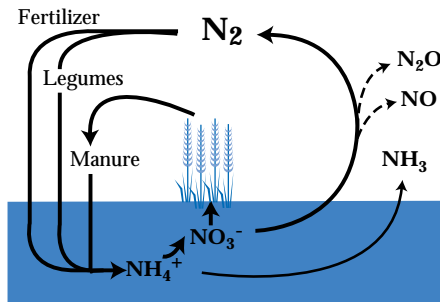
Table 10 Estimated total CH<sub>4</sub> emissions

	1981	1986	1991	1996
Livestock	849	748	771	879
Manure	208	192	190	208
Soils	-12	-12	-12	-12
Fuels	1	1	1	1
Total (Gg CH <sub>4</sub> )	1046	929	951	1076
Total (Tg CO <sub>2</sub> equivalents)	22	20	20	23

(R.L. Desjardins, AAFC)

## Nitrogen cycle

In terrestrial ecosystems, there are three main pools of N—soil, plants, and atmosphere (Fig. 21). The largest of these is the atmosphere; in the column of air above a hectare of land there are about 76 million kg of N, roughly a million times the amount that plants on that hectare use in a year. Virtually all this N, however, occurs as  $N_2$ , a gas that is almost inert and not directly available to plants.



**Figure 21**

Conceptual N cycle in an agroecosystem.

Despite living in a sea of gaseous N, plants obtain most of the N they need through their roots, by absorbing nitrate ( $NO_3^-$ ) and ammonium ( $NH_4^+$ ) dissolved in soil water. When the plants later die, the N in the plant litter is returned to the soil, where it becomes part of the soil organic matter. Soil microorganisms, in turn, gradually decompose this organic matter, releasing  $NH_4^+$ , which may be further converted to  $NO_3^-$ . These forms are then available again for plant uptake, completing the cycle. In “natural” systems, this cycle between soil and plants can continue almost indefinitely, with only very small inputs of N from the air via lightning or specialized soil bacteria.

In farmlands the N cycle is more complicated, as grain and other products remove large amounts of N from the field. In fact, cropping systems are often designed specifically to maximize the amount of N (as protein) in the plant parts that farmers harvest and remove. In high-yielding wheat, for example, harvesting the grain removes more than 100 kg N per hectare from the field every year. Consequently, to continue the cycle and to maintain crop growth, inputs from outside must replace the lost N.

The main source of new N is the air. There are two ways of converting the otherwise inert  $N_2$  into a form available to plants. One is the industrial approach, which uses energy from fossil fuel to convert  $N_2$  into “chemical” fertilizer. The other is a biological approach, which uses legumes such as alfalfa, clover, beans, and peas to “fix”  $N_2$ . These crops have nodules on their roots, containing bacteria that convert  $N_2$  into plant-available form. The plants absorb this N and, when they die and decompose, release it back into the soil as  $NH_4^+$ .

The N from fertilizers and legumes has allowed large increases in food production, but, if they are to feed the growing population, producers will need even larger amounts of N. Already, the global additions of N from these sources exceed inputs from “natural” sources (mainly fixation by lightning and bacteria not associated with agricultural crops). Although this injection of N sustains food production, it exerts pressure on the N cycle and often results in losses or “leaks” of N into the environment (see Fig. 21). Large portions of applied N—as much as 50% in extreme cases—may leach into the groundwater. As well, N enters the air in

various gaseous forms: ammonia (NH<sub>3</sub>), nitric oxide (NO), N<sub>2</sub>, and N<sub>2</sub>O. Most of these “leaks” occur from the pool of plant-available N (NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>). Consequently, losses are highest when producers add these forms in amounts greater than the plants can use or at a time when plants are not growing.

### Nitrous oxide formation

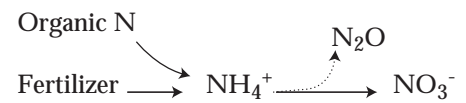
Nitrous oxide can originate from two places in the N cycle: during nitrification (converting NH<sub>4</sub><sup>+</sup> to NO<sub>3</sub><sup>-</sup>), and during denitrification (converting NO<sub>3</sub><sup>-</sup> to gaseous N<sub>2</sub>). Both processes are carried out by bacteria living in the soil.

#### Nitrification

Most N enters the soil either as NH<sub>4</sub><sup>+</sup> or in a form that converts to NH<sub>4</sub><sup>+</sup>. For example, the N in crop residues occurs largely in organic forms (like protein) which, when decomposed, release NH<sub>4</sub><sup>+</sup>.

Similarly, most of the N fertilizers used in Canada contain N as NH<sub>4</sub><sup>+</sup>, or in a form (like urea), which converts to NH<sub>4</sub><sup>+</sup> soon after application. Most of the N applied to soil, therefore, passes through the nitrification process.

During nitrification, most of the N is released as nitrate (NO<sub>3</sub><sup>-</sup>), but a small proportion of the N (usually less than 1%) may be emitted as N<sub>2</sub>O (Table 11):



In general, the more NH<sub>4</sub><sup>+</sup> applied, the more nitrification occurs, and the greater is the potential for N<sub>2</sub>O release. But the proportion of N released as N<sub>2</sub>O is not fixed; under conditions of good aeration and high NH<sub>4</sub><sup>+</sup>, for example, less of the N will appear as N<sub>2</sub>O than when oxygen or NH<sub>4</sub><sup>+</sup> concentrations are low. As a result, the amount of N<sub>2</sub>O released from nitrification may not correspond directly to the amount of N entering the process.

#### Denitrification

When movement of oxygen into soil is restricted, nitrate (NO<sub>3</sub><sup>-</sup>) can be converted into nitrogen gas (N<sub>2</sub>) in the process called denitrification. Deprived of oxygen in air, some bacteria use NO<sub>3</sub><sup>-</sup> instead, thereby releasing N<sub>2</sub>. As for nitrification, however, a small proportion of the denitrified NO<sub>3</sub><sup>-</sup> may be released as N<sub>2</sub>O:

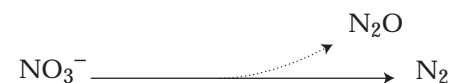


Table 11 Estimates of proportion of N released as N<sub>2</sub>O from various fertilizers as estimated in laboratory studies

Synthetic fertilizer	Amount of N fertilizer evolved as N <sub>2</sub> O (%)
Urea	0.3
Ammonium sulfate ((NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> )	0.1
Ammonium nitrate (NH <sub>4</sub> NO <sub>3</sub> )	0.3
Anhydrous ammonia	1.6
Nitrogen solution	0.3
Calcium nitrate (Ca(NO <sub>3</sub> ) <sub>2</sub> )	0.2

(Adapted from a review by E.G. Beauchamp and G.W. Thurtell, University of Guelph)

Three main factors control the rate of denitrification: the supply of oxygen, the concentration of  $\text{NO}_3^-$ , and the amount of available C (used by bacteria as an energy source). Highest rates of denitrification occur when all three factors are present: low oxygen, high  $\text{NO}_3^-$ , and high available C. The absence of any one of these three may reduce denitrification to negligible rates. Because it occurs only in the absence of oxygen, denitrification is most intense in water-logged soils. Some denitrification may also occur inside the root nodules of legumes.

The amount of  $\text{N}_2\text{O}$  release, however, depends not only on the rate of denitrification but also on the ratio of  $\text{N}_2\text{O}$  to  $\text{N}_2$  produced. This ratio is highly variable and tends to be lower under conditions favoring high rates of denitrification.

Often, we think only of the denitrification that occurs on farm fields. But N that is lost from the soil may also convert to  $\text{N}_2$  or  $\text{N}_2\text{O}$ . For example, the  $\text{NO}_3^-$  that leaches from the soil eventually finds its way into the groundwater or into sediments of streams and lakes. Once there it can undergo denitrification. Consequently, the amount of  $\text{N}_2\text{O}$  produced from farm practices may be much higher than that which is emitted directly from the soil.

Of the two processes, denitrification is probably more important than nitrification as a source of  $\text{N}_2\text{O}$  in Canadian farms. Emissions of  $\text{N}_2\text{O}$  from denitrification may be several times higher than those from nitrification, but it is difficult to distinguish between the two sources, and their relative importance varies widely from place to place.

## Management practices affecting nitrous oxide emission

Because of larger N inputs and disrupted N cycling, agricultural soils often have higher rates of  $\text{N}_2\text{O}$  emission than comparable soils under “natural” vegetation. For example, a fertilized barley field near Quebec City had  $\text{N}_2\text{O}$  emissions as high as 7 kg N per hectare per year, compared to negligible amounts (0.04 kg N per hectare) in a nearby forest soil. But the rate of  $\text{N}_2\text{O}$  emission is highly sensitive to conditions in the soil; under many conditions there may be no emission; in others there may be large bursts of  $\text{N}_2\text{O}$ . By their effects on soil conditions, therefore, farming practices can greatly affect  $\text{N}_2\text{O}$  emission.

### Form of fertilizer applied

In Canada, producers use a variety of commercial fertilizers to supplement soil N (see Table 11). Of these, urea and anhydrous ammonia (pressurized ammonia gas) are the most common, together accounting for almost 75% of the N applied. Most forms include N either as  $\text{NH}_4^+$  or in a form that quickly changes to  $\text{NH}_4^+$  after application. For example, anhydrous ammonia becomes  $\text{NH}_4^+$  immediately upon reacting with water in the soil, and urea is converted by soil enzymes to  $\text{NH}_4^+$  and  $\text{CO}_2$

within days of being applied. As a result, most of the N in fertilizers passes through the nitrification process (conversion to  $\text{NO}_3^-$ ) with the potential for some to be lost as  $\text{N}_2\text{O}$ .

During their initial reactions, fertilizers may affect pH, soluble C content, and other properties of soil in their immediate vicinity. These effects vary with fertilizer form so that  $\text{N}_2\text{O}$  formation during nitrification may vary among fertilizers. Indeed, some research suggests that there may be large differences in  $\text{N}_2\text{O}$  emission among fertilizer forms. Highest emissions may occur from anhydrous ammonia, and lowest from calcium nitrate, presumably because the N in the latter does not undergo nitrification.

Nitrous oxide emissions from various fertilizer formulations were compared in a study at Elora, Ont. Equivalent amounts of N were applied to turfgrass in one of several forms: ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ), urea ( $\text{CO}(\text{NH}_2)_2$ ), and slow-release urea. There was little  $\text{N}_2\text{O}$  emission from the slow-release urea, probably because its gradual N release coincided with plant N uptake, preventing the accumulation of  $\text{NH}_4^+$  or  $\text{NO}_3^-$ . The other two sources showed significant  $\text{N}_2\text{O}$  emission, with slightly higher values from ammonium nitrate than from urea.

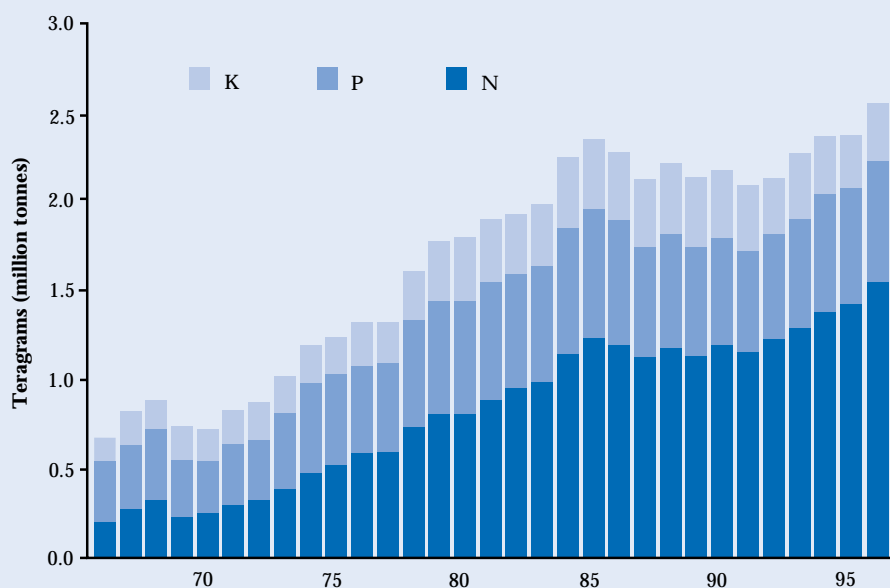
The physical form and placement of fertilizers may also influence  $\text{N}_2\text{O}$  emissions. For example, results of a laboratory study suggest that emissions may be higher from large granules than from fine particles mixed into the soil. The finer fertilizer is more widely dispersed in the soil and, presumably, has less effect on the pH immediately next to individual particles. Banding fertilizer, similarly, concentrates the N in

### Fertilizer consumption in Canada

From 1930 to 1960, the world production of nitrogen, phosphate, and potash was about equal. Since 1960, the use of all three nutrients has greatly increased but that of nitrogen fertilizers has increased faster than that of phosphate and potash. Canada uses about 2% of the world fertilizers.

Much like the global trend, there has been a large increase in fertilizer use in Canada since the 1960s. Most of this increase is in nitrogen fertilizer and occurred in the Prairies. In eastern Canada, fertilizer usage has stabilized or even decreased in the last decade. Compared to other developed countries, Canada has a low rate of fertilizer use per hectare.

Fertilizer consumption in Canada from 1966 to 1996



## Selecting the fertilizer

Selecting a fertilizer is a question of convenience and cost.

Convenience factors include the following:

- concentration of nutrient
- machinery, training, and maintenance requirements
- safety
- ease of transportation and application
- secondary effect on soil acidity
- possibility of combining with other operations (irrigation, spraying, seeding).

Economic factors include the following:

- cost relative to other formulations
- value of the crop
- efficiency of use by crop.



## Nitrogen requirements of crops

Nitrogen is the nutrient needed most to ensure growth of nonleguminous crops, such as corn or wheat. Although leguminous crops, such as alfalfa and soybeans, derive some nitrogen from the soil, most comes from biological fixation. Other sources of nitrogen include synthetic fertilizers and manure. Residues of alfalfa following ploughing or chemical burndown may also supply the succeeding crop with significant quantities of nitrogen.

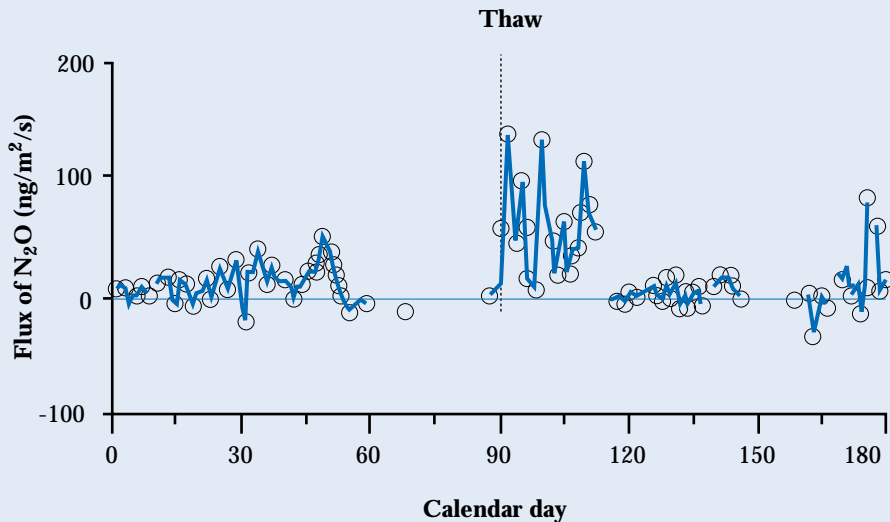
The optimum rate of application for fertilizer or manure depends on the crop's need for added nitrogen, the anticipated yield, and the availability of nitrogen from previous manure application or leguminous crop residue. Soils differ significantly in their ability to furnish nitrogen to crops. Although data on historical response to nitrogen are generally used to predict the amount of nitrogen required, soil tests can also be used.

Yields of nonleguminous crops may be increased by as much as 50% by adding manure or nitrogen fertilizer. But the amount should not exceed that which will return the most profit. Maximum profit usually occurs at about 95% of maximum yield. When applied at the rate for maximum profit, the nitrogen will be used efficiently, yet as economically as possible.

(E. Beauchamp, University of Guelph, Guelph, Ont.)



Nitrous oxide emissions measured at Elora (using a tower-based flux-measuring system) from a corn field. Bursts of N<sub>2</sub>O emissions occur just after spring thaw and following fertilizer application.



(C. Wagner-Riddle and G. Thurtell, University of Guelph, Guelph, Ont.)

localized areas and may therefore also affect N<sub>2</sub>O emission.

Although these and other data suggest that how a fertilizer is formulated and where it is placed may affect N<sub>2</sub>O emission, this effect has not yet been fully defined. Because N<sub>2</sub>O emissions also depend on other factors such as rate of application, soil properties, timing of precipitation, and crop rotation, the effect of fertilizer formulation may not always be the same.

### *Manure management*

Of the N consumed by livestock in feed, as much as 78% is excreted in urine and feces. In 1 year, for example, a dairy cow

may excrete as much as 100 kg N or more. Consequently, animal manure contains large amounts of N; in Canada, the N excreted each year by livestock may approach the amount of N applied as fertilizer.

Some N in manures is lost to the atmosphere as NH<sub>3</sub>, either immediately or during storage, but most is returned to the land. The N content of manures varies depending on animal, rations, and bedding material but is typically about 2% of dry weight. This N occurs largely in two forms: NH<sub>4</sub><sup>+</sup> and organic N. The former is immediately available to plants and behaves in the soil like NH<sub>4</sub><sup>+</sup> from fertilizer. The organic N, however, acts more like a slow-release form, gradually being converted to NH<sub>4</sub><sup>+</sup> by the action of soil microorganisms.

The N applied in manure is susceptible to loss as N<sub>2</sub>O. Because a large part of the N occurs as NH<sub>4</sub><sup>+</sup>, some N<sub>2</sub>O may be formed during nitrification to NO<sub>3</sub><sup>-</sup>. Denitrification may produce much higher amounts, because manure is a source not only of N but also of available C. Applying high concentrations of N and available C together favors denitrification. In extreme cases, where soils have received excessive rates of manure for many years in succession, N<sub>2</sub>O emissions may be as high as 50 kg N per hectare per year, though emissions are usually much lower.

The amount of N<sub>2</sub>O emitted from manured soils depends on method and rate of application, type of manure, and soil properties. One study suggests that liquid manure applied in bands may produce more N<sub>2</sub>O than manure applied uniformly on the soil surface. Placing the manure in bands concentrates the N and C, creating conditions more favorable for denitrification.



Manure management may also have indirect effects on N<sub>2</sub>O emission. A large portion of N excreted from livestock, as much as 50%, may be released into the atmosphere as ammonia (NH<sub>3</sub>) gas. This NH<sub>3</sub> is eventually deposited onto soil or water, where it reverts to NH<sub>4</sub><sup>+</sup> and can be lost as N<sub>2</sub>O like N applied directly.

### *Crop residue input and soil management*

Crop residues (e.g., straw, roots) and other plant materials return much N annually to the soil. In many cases, this N is merely a recycling of N absorbed earlier from the soil. But legumes, which can capture N<sub>2</sub> from the air, can actually add new N to the soil. Sometimes crops grown solely for the purpose of capturing N are ploughed back into the soil as “green manures.”

The amount of N<sub>2</sub>O produced from added plant materials depends on the rate of N release. Some residues, such as wheat straw and corn stover, have a low N concentration, commonly less than 0.5%. When these materials decompose, they release little N; in fact, sometimes they even result in the withdrawal of NH<sub>4</sub><sup>+</sup> or NO<sub>3</sub><sup>-</sup> from the soil because the microbes need extra N to decompose the residue. In contrast, N-rich materials such as legume residues or green manures can quickly release large amounts of NH<sub>4</sub><sup>+</sup> (later converted to NO<sub>3</sub><sup>-</sup>) during decomposition. Like animal manure, these materials also provide a ready source of available C, favoring the release of N<sub>2</sub>O from denitrification. For example, alfalfa residues may release 2–4 kg N<sub>2</sub>O-N per hectare and soybean residues 0.3–2 kg N<sub>2</sub>O-N per hectare per year.

The way in which farmers manage crop residues may also influence N<sub>2</sub>O

emission. Tillage may be the most important tool for managing residues. Normally, tillage mixes crop residues into the soil, but in no-till or other “minimum tillage” systems the residues remain on the soil, altering decomposition patterns. Some studies suggest that no-till techniques may increase N<sub>2</sub>O emission; others conclude that no-till can reduce emissions (Table 12). How tillage affects N<sub>2</sub>O emission, it seems, depends on soil, cropping system, climate, and other factors. Aside from their effect on residue placement, tillage practices also influence soil moisture, temperature, and aeration, all of which affect N<sub>2</sub>O production.

Soils, even without recent additions of

### *Injecting liquid manure*

Injecting liquid manure into the soil prevents rapid loss of nitrogen compounds into the air and minimizes release of unpleasant odors. If the soil is loosened-up at the same time, deep soil fissures will be broken, and the liquid will not drain directly into the drainage tiles. Because manure tankers are very heavy and will compact moist soil, such as occurs in early spring, it is often difficult to find appropriate times to apply liquid manure.



**Table 12 Comparison of N<sub>2</sub>O emissions in central Alberta as affected by tillage**

	1993–94	1994–95
	N (kg/ha)	
Till / with fertilizer	1.7	2.5
Till / no fertilizer	0.6	2.4
No-till / with fertilizer	1.7	0.9
No-till / no fertilizer	0.6	0.4

(R. Lemke, University of Alberta)

residues or other N, can emit N<sub>2</sub>O from their decomposing organic matter. Organic soils, because of their rich organic N reserves, may release particularly high amounts of N<sub>2</sub>O—about 5 kg N per hectare per year. Similarly, soils that are left unplanted for a year (a practice known as summer fallow) may emit significant amounts of N<sub>2</sub>O. Soil microbes gradually break down the organic N in these soils into NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>, and because there are no growing plants to remove this N, it accumulates and is highly susceptible to loss via denitrification.

### *Amount and timing of nitrogen application*

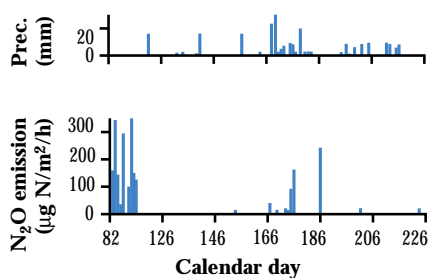
Often, N<sub>2</sub>O emission is assumed to be directly proportional to the amount of N applied. But a better measure may be the amount unused by the crop. Matching the NH<sub>4</sub><sup>+</sup> or NO<sub>3</sub><sup>-</sup> released into the soil precisely to their uptake by plants prevents these N forms from accumulating in the soil, and N<sub>2</sub>O losses

will be minimal. Such ideal synchrony, however, rarely occurs. Often NH<sub>4</sub><sup>+</sup>, and particularly NO<sub>3</sub><sup>-</sup>, accumulate in excess of the plants' capacity to absorb them, resulting in high potential for N loss via leaching or denitrification. This situation is especially true if the NO<sub>3</sub><sup>-</sup> accumulates after harvest, because then it is vulnerable over the fall, winter, and, especially, the following spring, when denitrification is particularly intense. Consequently, matching the amount and time of N application with plant N uptake pattern is an important management tool to minimize N<sub>2</sub>O emissions.

### *Nature of nitrous oxide emission*

Nitrous oxide emissions are usually sporadic. Unlike CO<sub>2</sub>, which is released from soil almost continuously, N<sub>2</sub>O is often emitted in bursts or “flushes.” Under Canadian conditions, the most important of these flushes may occur in early spring, as the snow melts. At a site in central Alberta, for example, most of the N<sub>2</sub>O emitted in the entire year occurred during 10 days at the end of March (Fig. 22). These bursts of N<sub>2</sub>O emission at snowmelt may reflect favorable conditions for denitrification and N<sub>2</sub>O formation: high moisture content (oxygen deficiency), adequate NO<sub>3</sub><sup>-</sup> and available C, and favorable temperature. Or the N<sub>2</sub>O flush may reflect the abrupt release of N<sub>2</sub>O that was previously trapped under a layer of frozen soil or ice. Although the spring flush is often the largest, additional bursts of N<sub>2</sub>O follow heavy rains that result in water-logging of soils, especially in low-lying areas. As well, N<sub>2</sub>O may erupt immediately after fertilizer is applied because of the sudden availability of N.

Emission of  $N_2O$  is sporadic not only over time but also across space. This variability stems, in part, from the differences in N and moisture (hence oxygen) content across the landscape. At any time, there may be minimal release of  $N_2O$  from most areas in a field, but high emissions from small “hot spots” where conditions are ideal for  $N_2O$  production.



**Figure 22**

Seasonal pattern of precipitation and  $N_2O$  emissions from a fertilized wheat field at Ellerslie, Alta., 1993. (R. Lemke, University of Alberta)

A further complication is that much of the  $N_2O$  is often produced in deeper soil layers. The release of this N depends on its rate of diffusion to the soil surface, which is controlled by soil porosity and the presence of ice or water at the surface. The trapped  $N_2O$  may also be dissolved in soil water or be further converted to  $N_2$  or to  $NO_3^-$  by microbes, so that the  $N_2O$  formed at depth is not all released to the atmosphere. Consequently,  $N_2O$  emission from soils depends not only on how fast it forms but also on how fast it diffuses or converts to other N forms.

### Nitrous oxide emissions in the winter

Eastern Canada, where soils can be covered with snow for up to 5 months, has a relatively short growing season. We once thought that  $N_2O$  emissions during winter were minor and of little importance in the annual N-budget. But we now know that significant losses of nitrogen as  $N_2O$  occur from under the snow cover. In certain cases, soils release substantial amounts of  $N_2O$  during the winter. Freeze-thaw cycles also affect the  $N_2O$  emissions from soils. These cycles induce physical and biological changes to the soil; they disrupt soil structure and stimulate denitrification leading to more  $N_2O$  production.



(E. van Bochove, AAFC)

Until recently, we thought little  $N_2O$  would form over winter because of low soil temperatures. But this idea may not hold true where snow insulates the soil. In parts of eastern Canada, for example, snow blankets the soil thickly for up to 5 months per year, keeping soil temperature above or near freezing. As a result,  $N_2O$  can be produced all winter and be released through the porous snow. At a site near Quebec City, a fertilized barley field, ploughed the previous fall, released up to 5 kg N per hectare during the winter and spring, equivalent to 5–10% of the fertilizer N applied. The

same field released only 2 kg N during the growing season.

Because of the sporadic and unpredictable pattern of N<sub>2</sub>O release, estimating amounts of emission is difficult. Hence, current estimates of N<sub>2</sub>O emission are probably less reliable than those for the other greenhouse gases.

### Estimates of national nitrous oxide emission

Given our limited understanding of N<sub>2</sub>O formation and release, we can estimate only tentatively N<sub>2</sub>O emissions from Canadian farms. Current estimates rely on simple equations, developed by the International Panel on Climate Change (IPCC), that calculate N<sub>2</sub>O release from three sources: direct emissions from soils,

direct emissions from livestock production, and indirect emissions from farms.

Direct emissions from soils include N<sub>2</sub>O derived from fertilizer, land-applied manure, legumes, and crop residues. Researchers calculated emissions from the total N content of these sources, based on national statistics, assuming that a specified proportion of the N was released as N<sub>2</sub>O (about 1%, depending on source). They also included estimates of N<sub>2</sub>O release from organic soils, though these amounts are small. Based on this calculation, they estimated direct emissions of N<sub>2</sub>O from agricultural soils in Canada in 1996 to be 70 Gg (thousand tonnes) of N<sub>2</sub>O (Table 13). When averaged over the area of cultivated land in Canada, this amount equates to about 1 kg N per hectare per year. The estimated emission rates, however, vary widely among regions (Fig. 23 a,b).

The scientists calculated direct emissions from livestock by estimating the amount of N in manure and assuming that a specified portion of that N was emitted as N<sub>2</sub>O. They assumed the fraction of N converted to N<sub>2</sub>O to be 2% for grazed animals and 0.1–2% for other livestock, depending on waste management. Using this approach, they estimated direct emissions from livestock to be 24.5 Gg (thousand tonnes) of N<sub>2</sub>O in 1996 (*see* Table 13).

They also calculated indirect emissions from estimates of atmospheric N (e.g., NH<sub>3</sub>) deposited on the soil, N leached from farm fields, and N produced from human sewage. According to these calculations, leached N is the most important, accounting for more than 80% of the roughly 38 Gg (thousand tonnes) of N<sub>2</sub>O released from indirect sources in 1996 (*see* Table 13). This estimate

**Table 13** Estimates of direct and indirect sources of N<sub>2</sub>O emissions from Canadian agriculture in 1996

Province	Direct emissions from soils	Direct emissions from manure	Indirect emissions	Total N <sub>2</sub> O emissions
(Gg N <sub>2</sub> O)				
Atlantic	0.9	0.5	1.0	2.4
Quebec	5.7	2.4	4.0	12.1
Ontario	13.1	3.7	6.0	22.8
Manitoba	10.6	2.3	5.7	18.6
Sask.	19.1	4.5	9.2	32.8
Alberta	18.4	9.6	10.8	38.8
B.C.	1.9	1.5	1.5	4.9
Canada	69.7	24.5	38.2	132

(R.L. Desjardins, AAFC)

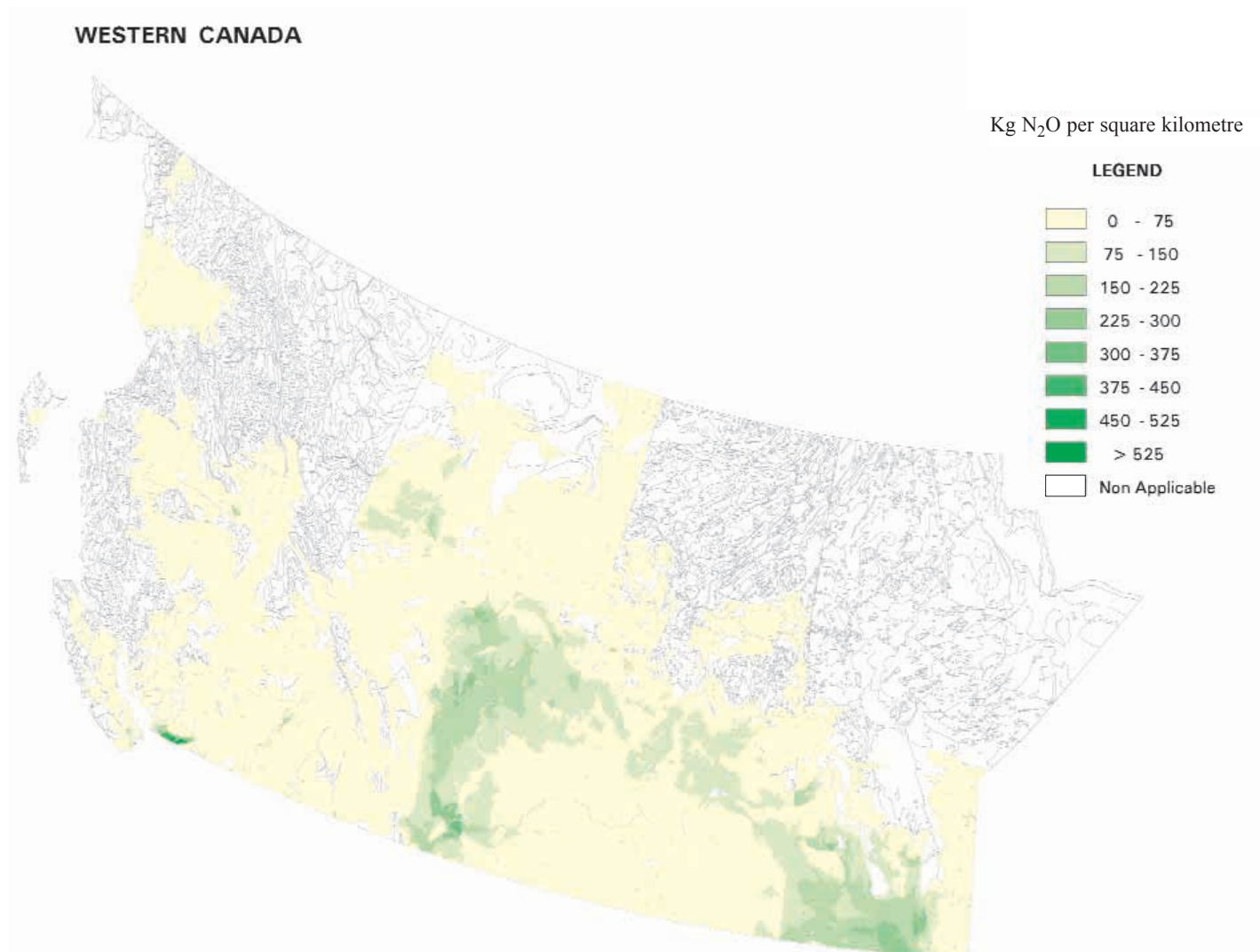
assumed that 30% of the N applied as fertilizer or manure leached into the groundwater.

Based on the IPCC approach, total emissions of N<sub>2</sub>O from agriculture in Canada in 1996 were about 132 Gg (thousand tonnes) of N<sub>2</sub>O (see Table 13). Of this, direct emissions from soils accounted for about half.

The trend in N<sub>2</sub>O emissions over time may be as important as the total amount. Current estimates suggest that N<sub>2</sub>O emissions have increased steadily since 1981, increasing by 20% from 1991 to 1996 alone. Much of the increase resulted from higher N inputs as fertilizers and animal manure. With increases in livestock numbers and higher crop yields expected in the future, N<sub>2</sub>O emissions may climb still further unless producers make improvements in N management.

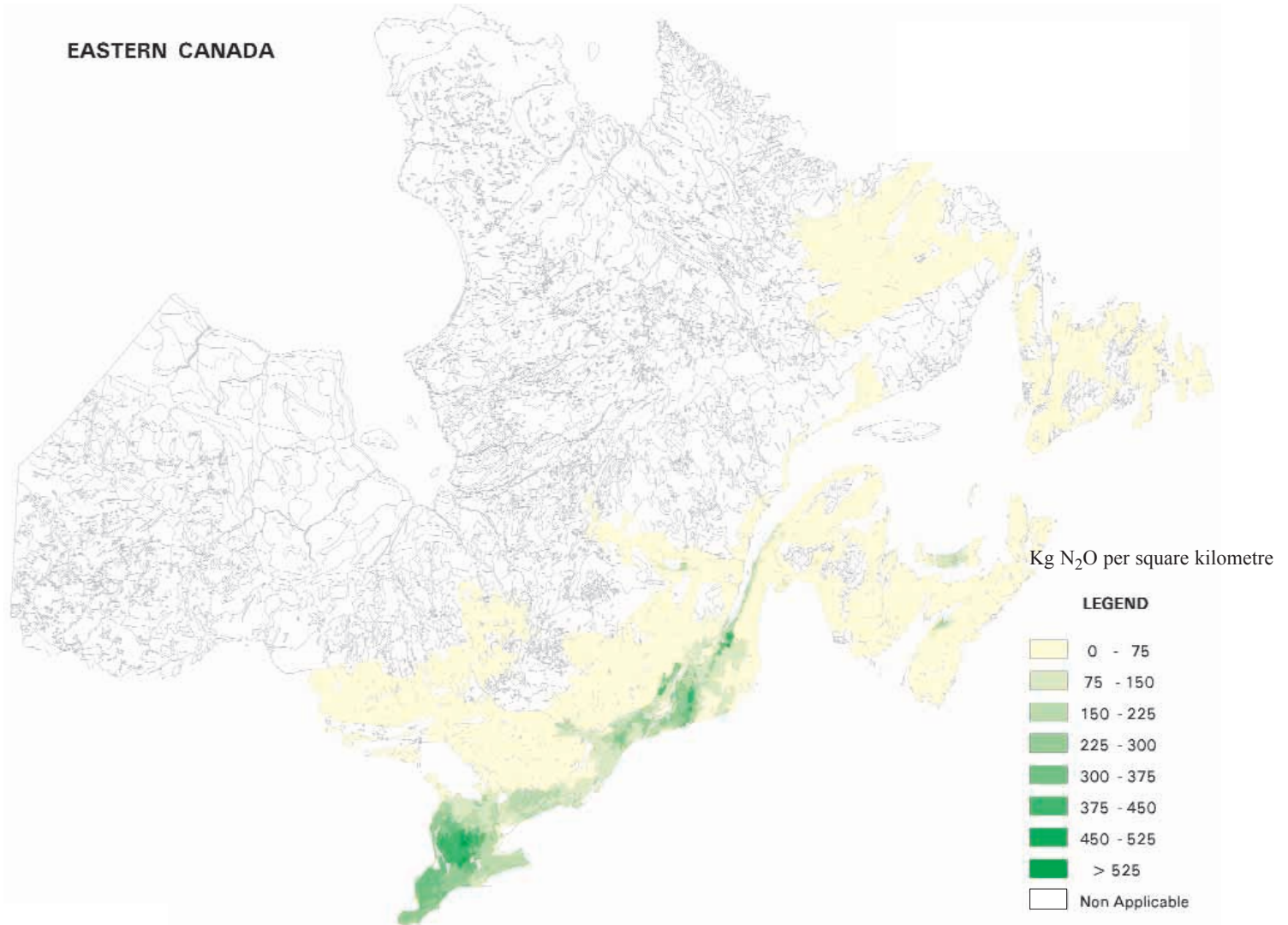
### Figure 23a

Estimated direct N<sub>2</sub>O emissions from agricultural sources in western Canada for 1991.



**Figure 23b**

Estimated direct N<sub>2</sub>O emissions from agricultural sources in eastern Canada in 1991.



### *Combined effect of the three greenhouse gases*

The three gases (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) differ in their warming effects. To compare their relative effects, therefore, their emissions are usually expressed as “CO<sub>2</sub> equivalents.” One kilogram of N<sub>2</sub>O has the warming effect of about 310 kg of CO<sub>2</sub> (when considered over 100 years), so it represents 310 CO<sub>2</sub>

equivalents. Similarly, 1 kg of CH<sub>4</sub> represents 21 CO<sub>2</sub> equivalents.

According to best estimates, using the approaches described for each gas, Canadian agriculture had emissions of 67 Tg (million tonnes) of CO<sub>2</sub> equivalents in 1996 (Table 14). Of this

amount, about two-thirds was as N<sub>2</sub>O and about one-third as CH<sub>4</sub>. By comparison, net emissions as CO<sub>2</sub> were almost negligible.

The estimates of CO<sub>2</sub> emission, however, exclude most of the CO<sub>2</sub> from fossil fuels used to produce inputs, power farm machinery, and transport products. These sources, which are included in inventories for transport and manufacturing sectors, emitted about 25 Tg (million tonnes) of CO<sub>2</sub> in 1996.

The emission of greenhouse gases from Canadian agriculture are increasing, according to current estimates (see Table 14). By 2010, emissions may be about 9% higher than those in 1996, unless producers adopt better management practices. These projected increases stem largely from predicted increases in livestock numbers and N inputs as fertilizer and manure. Emissions of CO<sub>2</sub> are expected to decline, but not nearly fast enough to compensate for predicted increases in the other gases.

Future emissions will depend on changes in farming practices that are hard to predict. Livestock numbers, crops that are grown, fertilization patterns, and manure management techniques can all change quickly, throwing off our current best projections.

### Uncertainties in current estimates

Current estimates of greenhouse gas emission are not without uncertainty. We face many possible pitfalls in calculating emissions for ecosystems as extensive and diverse as Canada's farmlands. We still do not even understand all the processes that affect emissions. And so we admit that each estimate is subject to potential error. Of the three gases, N<sub>2</sub>O has the highest degree of uncertainty

### Global warming potential

Global warming potentials (GWPs) are a simple way to compare the potency of various greenhouse gases. They help policy makers compare the effects of reducing CO<sub>2</sub> emissions relative to another greenhouse gas for a specific time horizon. For example, a small reduction in N<sub>2</sub>O can be just as if not more effective than a larger reduction in CO<sub>2</sub> emissions.

The heat-trapping potential of a gas depends not only on its capacity to absorb and re-emit radiation but also on how long the effect lasts. Gas molecules gradually dissociate or react with other atmospheric compounds to form new molecules, with different radiative properties. For example, CH<sub>4</sub> has an average residence time of about 12 years, N<sub>2</sub>O 120 years, and CO<sub>2</sub> 200 years. Over a 20-year period, CH<sub>4</sub> has 56 times the radiative impact of CO<sub>2</sub>. However, as time proceeds some of the CH<sub>4</sub> molecules are broken down into CO<sub>2</sub> and H<sub>2</sub>O. Therefore, over a 100-year period, CH<sub>4</sub> has a global warming potential of 21 times that of CO<sub>2</sub>.

Global warming potentials are presented for 20-, 100-, and 500-year time horizons. In *The Health of Our Air*, we use the 100-year GWPs recommended by IPCC. Calculations of warming potential are continually refined, so these numbers are subject to revision as understanding improves.

#### Relative global warming potential (CO<sub>2</sub> equivalents per unit mass of gas)

Gas	Time horizon		
	20 y	100 y	500 y
CO <sub>2</sub>	1	1	1
CH <sub>4</sub>	56	21	6.5
N <sub>2</sub> O	280	310	170

(Fig. 24). Estimates for this gas could be off by 50% or more. Despite their uncertainty, these values are the first comprehensive estimates of greenhouse gas emission from Canadian agriculture and provide a reference point for showing trends.

Though valuable as a first approximation, the estimates will likely change as we learn more. Ongoing research will teach us more about the processes leading to

## Agri-environmental indicators

An agri-environmental indicator is a measure of change, or the risk of change, in environmental resources used or affected by agriculture. Although the indicators are national in scope, regional variations are taken into account. Six indicators are being developed, each of which has several components as follows:

*Farm resource management:*  
tracks farmers' use of environmentally sustainable management practices, by measuring soil residue cover and management of agricultural land, fertilizers, pesticides, and manure.

*Soil degradation risk:*  
measures progress in reducing the vulnerability of agricultural soils to degradation and identifies soils still at high risk of erosion, salinization, compaction, or loss of organic matter.

*Water contamination risk:*  
assesses progress in reducing the risk of water contamination by nutrients used in agriculture and identifies the areas at risk of contamination.

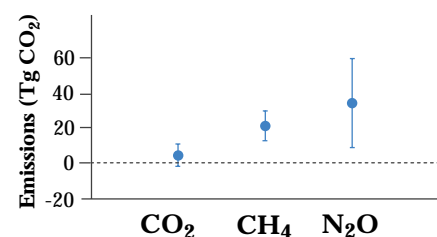
(T. McRae, AAFC)

*Agroecosystem greenhouse gas balance:*  
estimates trends in the net emission of CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>.

*Agroecosystem biodiversity change:*  
monitors biodiversity in agricultural ecosystems by measuring changes in habitat availability.

*Input use efficiency:*  
measures the efficiency of fertilizers, energy, and irrigation water used by farmers to track possible effects on the environment.

emission and allow us to build better models. As well, new techniques that simultaneously measure all three gases over large areas will allow us to evaluate better the models' reliability. We can therefore expect more definitive estimates in the future, but we need not wait for their arrival before trying to reduce actual emissions.



**Figure 24**  
Estimates of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions in CO<sub>2</sub> equivalents from Canadian agriculture, showing relative uncertainty for each gas.

**Table 14** Estimates of total greenhouse gas emissions from Canada's agroecosystems

	1981	1986	1991	1996	2000*	2005*	2010*
	(Tg CO <sub>2</sub> equivalents)						
CO <sub>2</sub>	9	7	5	3	1	0	0
CH <sub>4</sub>	22	20	20	23	23	24	25
N <sub>2</sub> O	32	33	34	41	43	45	48
Total	63	60	59	67	67	69	73

\* Predicted using a scenario of medium growth from Canadian Regional Agricultural Model (CRAM) to 2007. All 2010 data follow a best-fit trend using data from 1993 to 2007 from the CRAM. All fertilizer data were predicted using a best-fit trend from 1981, 1986, 1991, and 1996 Census data. All sheep, chicken, and turkey populations were predicted using a best-fit trend from Census data.

(R.L. Desjardins, AAFC)



## Techniques to minimize emission of greenhouse gases

Agriculture is a net emitter of greenhouse gases. Furthermore, current predictions point to increased emissions unless some changes are made to farming practices. Fortunately, farmers can adopt several measures to reduce emissions. Some of these would be expensive, but some can be used with little cost or even at higher profit. Widespread use of such practices could reduce emissions of all three greenhouse gases and, for CO<sub>2</sub>, even make farms net absorbers.

## Reducing carbon dioxide emissions

Farming means managing carbon. On every hectare of farmland, many tonnes (Mg) of C are removed from the air every year and changed to organic materials through photosynthesis (see Figs. 8, 9). At the same time, decomposing organic matter and the burning of fossil fuels releases roughly equivalent amounts of CO<sub>2</sub> back into the air. By their choice of farming practices, farmers can manage this cycle, altering it to reduce net emissions of CO<sub>2</sub>.

There are two main ways of reducing emissions: one is to increase the amount of C stored in soil; the other is to burn less fuel. Several practices are already available to achieve each of these.

## Population of hogs in Canada

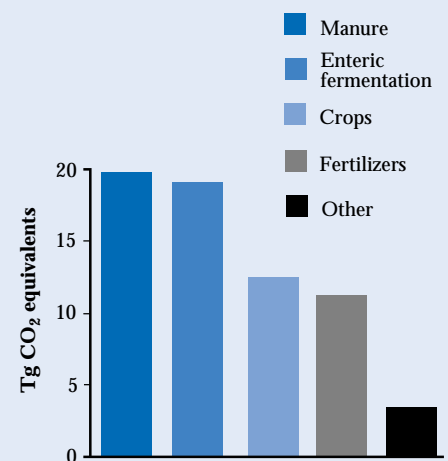
Future greenhouse gas emissions depend on economic trend. For example, the Canadian Regional Agricultural Model (CRAM) estimates that, by 2010, the hog population in Canada will be about 14 million. This population is an increase of 36% over that recorded in 1990. This increase may cause N<sub>2</sub>O and CH<sub>4</sub> emissions from manure to greatly increase. Hogs produce the second highest amount of manure per 1000 kg of live animal per day, which is equivalent to 10 kg CH<sub>4</sub> per animal per year. Therefore, the CH<sub>4</sub> emissions from hog manure, in 2010, is expected to be about 143 Gg (thousand tonnes) of CH<sub>4</sub>, which is 25 Gg higher than 1996 emissions from hogs.



## Greenhouse gas emissions from agriculture

Agriculture contributed about 10% of Canadian anthropogenic greenhouse gas emissions in 1996. Using the global warming potentials, the major sources of emissions of all the gases were converted into CO<sub>2</sub> equivalents. From agriculture, the major sources are manure, enteric fermentation, crops, and fertilizers.

(R.L. Desjardins, AAFC)



## Measuring greenhouse gases over farms

Scientists are now looking at ways of measuring greenhouse gas emissions from entire farms. One way is to use instruments mounted on a tethered balloon, filled with helium, to measure changes in greenhouse gases over time at various heights above the farm.

(E. Pattey, AAFC)



## Increasing soil carbon

In soils that have been managed in the same way for many years, the C content is reasonably constant. A change in management, however, can result in losses or gains of C. To increase soil C, we can do one of two things: increase the amount of C added to the soil, or slow the rate at which soil C is decomposed (decayed) back to CO<sub>2</sub> (see Figs. 8, 9).

### *Adding organic matter*

Atmospheric CO<sub>2</sub> enters the soil by way of photosynthesis. This process traps CO<sub>2</sub> in organic forms, a portion of which is added to the soil as residues (including roots). The only direct way to increase C additions, therefore, is to use practices that favor higher photosynthesis; in other words, practices that increase plant yield. Farmers can achieve such increases by using higher yielding crops and varieties, by improving crop nutrition (using fertilizers and manures), or by reducing water stress (by irrigation, water conservation, or drainage). Actions that improve soil quality also promote higher yields. Perhaps most important is to use cropping systems that keep actively growing (and photosynthesizing) plants on the land as long as possible.

But increased photosynthesis helps build soil C only if at least some of the additional trapped C is returned to the soil. The more of the plant removed from the field as grain or other products, the less the increase in soil C. Thus, using cropping practices that keep all residues in the field and planting crops (like forage grasses) that store much of their C in roots can achieve soil C gains. Often, animals help recycle the C back into soil. In many livestock-based systems, a large part of the plant yield is returned to the soil as manure, and only

## Conservation tillage

Conservation tillage prior to potato planting in Prince Edward Island. Minimum tillage in corn in Ontario and wheat in Saskatchewan.



a small portion is actually exported from the field or pasture.

### *Reducing decay rate*

The other way to build soil C is to slow the rate of organic matter decay in the soil. One method of doing that is to make conditions less favorable for soil microbes. For example, residues on the soil surface keep soils cooler, slowing decay. Similarly, maintaining growing plants on the surface as long as possible slows decay, because plants dry out the soil and cool it by shading.

Decay rate can also be slowed by shielding the organic matter from soil microbes. Soils are usually granulated, with organic materials protected inside the granules (or aggregates). Breaking these aggregates open by intensive tillage exposes that organic matter to soil microbes. As a result, practices that minimize soil disturbance tend to preserve soil C.

Another way to shield organic materials is to place them where conditions are not favorable for decay. For example, they can be kept on the surface where they tend to stay dry, or placed deep in the profile, where soil is cool (although this approach would require intensive tillage).

### *Practices that increase soil carbon*

Much can now be done to promote soil C gain, either by adding more C or slowing decay (or both). The following methods are often effective, though the amount of C gain depends on climate and soil type:

*Reduce tillage* : Tillage was once necessary to control weeds and prepare soil for planting. But now weeds can be controlled with herbicides, and new

seeding equipment can place seeds directly into untilled soil. As a result, intensive tillage is no longer necessary, and a growing number of farmers have eliminated tillage entirely, using no-till or “direct-seeding” practices. These practices protect C inside aggregates and keep residues on the surface where they decay more slowly and cool the soil beneath them. No-till and other “reduced tillage” practices also prevent erosion, thereby preserving soil quality and maintaining future photosynthesis. No-till, already used on about 14% of cropland in 1996, could be adopted on a large proportion of Canada’s cropland.

*Apply more nutrients* : Where soils do not have enough nutrients, adding fertilizers, animal manure, or green manure increases yields, leading to higher inputs of C. Manures may also improve the physical condition or “tilth” of the soil, further increasing yields and residue additions.

*Grow more perennial forage crops* : Perennial crops can trap more CO<sub>2</sub> than annual crops because they continue growing for more months of the year. Because they dry out the soil more and there is no tillage, decay rates may also be slower. Many perennial crops, like grasses, have extensive root systems that place much C below-ground.

*Remove land permanently from cultivation* : Probably the most effective way of increasing soil C is to allow the land to revert to its original vegetation, whether grasses or trees. Because there is little or no removal of C in products, virtually all the C trapped by photosynthesis is returned to the soil or stored in the wood. In theory, such “set-aside” lands would eventually regain all the C lost since cultivation began. However, this option means a loss in

## Trees on agricultural land as a carbon reservoir

Farmers have long planted trees as shelterbelts and for other environmental reasons. Since “afforestation”—the practice of planting trees on previously untreed land—is explicitly recognized as a legitimate carbon offset under the Kyoto protocol, we need to know how much C can be stored in such trees and at what rate.

Prairie Farm Rehabilitation Administration (PFRA) Shelterbelt Centre at Indian Head, Sask., has determined the quantities and rates of C stored in prairie shelterbelts. Typical shelterbelt trees contained from 162 to 544 kg C, with poplar trees having the most. Shrub shelterbelts contained as much as 52 tonnes C per kilometre.



(J. Kort, AAFC)

productivity so it is probably only feasible on marginal lands. The practice may also be applicable in small areas of cultivated land planted to shelterbelts or grassed waterways for control of wind and water erosion.

*Eliminate summer fallow* : Leaving land unplanted for a growing season (summer fallow) helps control weeds and replenish soil moisture. But it results in soil C loss because, during the fallow year, no new residue is added and the soil remains warm and moist, which hastens decay. A shift to continuous

cropping (growing a crop every year) therefore favors increases in soil C. The area of summer fallow has declined in recent years, but it still occupies about 6 million hectares every year. Eliminating summer fallow may not be practical in very dry regions, such as parts of the southern prairies.

*Use cover crops* : Where the growing season is long enough, a winter cover crop can be sown after the main crop has been harvested. This practice can add more residues to the soil and prevent erosion.

*Avoid burning of residues* : When residues are burned, almost all their C is returned to the atmosphere as CO<sub>2</sub>, which reduces the amount of C added to the soil.

*Use higher yielding crops or varieties* : Crops or crop varieties that have more efficient photosynthesis often produce more residues, which increases soil C. But because plant breeders choose varieties based on marketable yield (e.g., grain yield), residue and root yields of new varieties may not increase as much as the yield of harvested product.

*Improve water management* : Water is often the limiting factor to crop growth. In the dry southern prairies, yields can be increased by irrigating or by trapping and storing water more effectively (e.g., using crop residue or windbreaks to trap snow). In parts of central and eastern Canada, conversely, crop growth may be limited by excess water in poorly drained soils. In these conditions crop growth and C additions to soil can be increased by drainage.

*Restore wetlands* : Some low-lying areas in farmlands have been drained to allow crops to grow. Re-submerging these soils would cut off oxygen supply, preventing

decay. These restored wetlands or “sloughs” could gain a lot of C quickly, though the small area of potential wetlands would limit CO<sub>2</sub> removal.

*Integrate livestock into cropping systems :*

Feeding crops to livestock results in effective recycling of C if the manure is managed well. Thus, although large amounts of C may be removed from the field as forage or silage, much of this C can be eventually returned as manure. The manure also promotes crop growth and photosynthesis, favoring further soil C inputs.

*Improve grazing management :* The way a grassland is grazed can affect the C cycle in several ways. It influences the proportion of the plant “harvested” by the animal, the redistribution of C in manure, the condition of the soil (via hoof action), and the species composition. Because of these many effects, the relationship between soil C and grazing regime is still unclear. Overgrazing, however, can result in large losses of C via erosion. Reducing the number of animals per hectare on such lands will likely increase the amount of C stored.

Many studies across Canada have shown that these practices can increase soil C. The amount of potential gain, however, is still unclear and will vary depending on the initial soil C content, soil properties, climate, and other factors. The extent to which farmers adopt these practices also influences the amount of C gain. That will depend on crop prices, costs of production, and other factors that fluctuate from year to year.

Despite the uncertainty, some estimates suggest that agricultural soils in Canada could gain as much as several million

tonnes of C per year if these C-conserving practices were widely adopted. Such a gain would result in a net removal of CO<sub>2</sub> from the atmosphere. With time, however, the rate of C gain would decline because it becomes harder to add additional C as the C content of soil goes up.

## Storing carbon in plant material

Although the soil is the main storehouse of C in farm ecosystems, plant material can store additional C. One way to store more plant C is to grow trees on farmland, either as shelterbelts (which also control erosion) or as woodlots alongside farmsteads. The net benefit of this practice for atmospheric CO<sub>2</sub> depends on the area of land devoted to trees, their rate of growth, and the fate of the wood. If the wood is burned, for example, there is little long-term benefit unless its use reduces dependence on other fuels.

Another way of storing plant C is to convert crop residues into products with a long lifetime. One approach is to construct fiberboard (wood-like panels) from cereal straws. These materials are

used for construction and, whereas much of the C in straw returned to soil would normally decay back to CO<sub>2</sub>, the C in these construction materials remains trapped for a long time.

## Reducing fossil fuel use

Farms rely on energy from fossil fuels to power machinery, heat buildings, dry harvested crops, and transport goods. Energy is also used to supply materials employed on the farm, such as fertilizers, pesticides, machinery, and buildings. Most of these emissions are not attributed to agriculture in the national inventory of greenhouse gases. Even so, using less fuel on farms would reduce Canada's total CO<sub>2</sub> emissions.

The amount of fuel used on the farm and in the supply of farm inputs can be reduced in the following ways:

*Reduce tillage* : It takes a lot of energy to lift and turn soil during tillage. Reducing or stopping tillage can, therefore, save on fossil fuel use. One Ontario study showed diesel fuel use reduced from 30 litres per hectare for conventional tillage to only 4 litres per hectare in a modified no-till system. A study on the Prairies, which considered both direct and indirect use of fuel, showed that reducing tillage decreased emissions from direct fuel use by about 40% (see Fig. 15). Emissions for pesticide inputs were slightly higher under reduced tillage and emissions from fertilizer were unchanged. When all the direct and indirect factors were counted, emissions from no-till were 92% of those in conventional tillage, and emissions from minimum tillage were intermediate.

### Storing carbon in strawboard

Strawboard made from crop residues can store C and may help mitigate greenhouse gas emissions. At the end of their lifetime, the boards could be burned in power plants, replacing fossil fuel, resulting in a true reduction in CO<sub>2</sub> emissions.

One example is the industrial Isobord plant in Elie, Man. It expects to use 180 000 tonnes of wheat straw per year, which is equivalent to sequestering 267 000 tonnes of CO<sub>2</sub> per year. The plant at Elie has already sold 80% of its first 5 years' production.



*Use fertilizer more efficiently* : Making and transporting fertilizer is energy-intensive. For each kilogram of fertilizer N used, about 1 kg of C is released into the atmosphere as CO<sub>2</sub>. Consequently, methods of applying fertilizer that produce high yields from less fertilizer can reduce CO<sub>2</sub> emissions. Possible approaches include placing fertilizer more effectively (e.g., banding); applying only as much as is needed, based on soil tests; and using variable rates of application on a field to reflect differences in soil fertility (“precision farming”).

*Grow legumes* : Legumes can often get much of the N they need from the air. When they die and decompose, they also release N into the soil. Careful use of legumes in cropping systems, therefore, can reduce the amount of N fertilizer needed, and thereby lower CO<sub>2</sub> emissions. For example, in a study at Melfort, Sask., introducing pea into the crop rotation reduced CO<sub>2</sub> emissions from fossil fuel by about 28% (Table 15).

*Use manure more efficiently* : Animal manure contains many nutrients. These nutrients, however, are not always used efficiently, in part because of the high cost of transporting the heavy, bulky manures. Avoiding excessive application rates of manure in localized areas would not only prevent harmful loss of nutrients to the environment but also save on fertilizer use, thereby reducing CO<sub>2</sub> emissions.

*Increase energy use efficiency* : Additional opportunities for reducing energy use include drying crops in the field wherever possible, using more efficient irrigation systems, and insulating farm buildings. As well, many of the energy conservation measures advocated for urban areas also apply to the farm.

**Table 15 Impact of planting a legume on C emissions in a Saskatchewan cropping system**

Rotation (legume or no legume)	CO <sub>2</sub> emissions (kg C/ha/y)
Pea–Barley–Wheat	82
Barley–Barley–Wheat	114

(E. Coxworth, Saskatoon, Sask.)

An entirely different way of reducing emissions from fossil fuels is to grow crops that provide an alternate energy source. This “biofuel” can displace fossil use, thereby indirectly reducing CO<sub>2</sub> emission. Instead of extracting C from deep within the earth and burning it to CO<sub>2</sub>, biofuel production simply recycles the C originally removed from the atmosphere by photosynthesis.

The most efficient way of using crop materials for fuel is to burn them directly. Although this approach is used in some parts of the world, it is not always practical in Canada, where the fuel may have to be transported great distances.

An alternative is to ferment crops, producing ethanol and mixing it, at proportions of about 10%, with gasoline. This mixture can be used in most gasoline engines and reduces the amount of CO<sub>2</sub> produced from fossil fuel. The net savings in fossil fuel use, however, depend on the amount of fuel used to grow the crop in the first place.

The materials most easily converted into ethanol are those with high starch content. Thus cereal grains, such as corn and wheat, are preferred for ethanol production. One study suggests that, if the CO<sub>2</sub> emitted in crop production are

## Ethanol as a fuel

In 1997, Canadians used about 40 million litres of ethanol and 34 billion litres of gasoline, so ethanol represents about 0.1% of total gasoline sales in Canada. Ethanol has a lower energy content than gasoline. But when carefully blended at less than 10%, mileage is not affected.

Ethanol is a liquid alcohol produced by fermenting either starch materials (corn, wheat, barley) or cellulosics (agricultural residues, wood, wood wastes). Much of the CO<sub>2</sub> released when biomass is converted to ethanol and burned in car engines is recaptured when new vegetation is grown, thus offsetting the greenhouse gas effect. Net lifecycle CO<sub>2</sub> emissions from burning 10% ethanol-blended gasoline have shown about 3% reduction when compared to regular unleaded gasoline. Recent developments in the ethanol industry are expected to increase Canadian production from wheat and corn to about 350 million litres by 2000.



(M. Stumborg, AAFC)

tonnes) per year. If Canadian ethanol production reaches the expected 265 million litres by the end of 1999, reductions in net CO<sub>2</sub> emission will be increased by the same proportion.

Though ethanol is most easily made from high-starch materials, new methods now also make it possible to make ethanol from fibrous matter, such as crop residues, forages, and crop wastes. An excess of about 2 Tg (million tonnes) of straw and chaff may be produced every year, beyond the amount needed for animal bedding and preventing soil erosion. If all this amount were used, it would produce about 500 million litres of ethanol and replace about 0.5 Tg (million tonnes) of fossil fuel CO<sub>2</sub> (equivalent to 2% of the emissions from fossil fuel used in agriculture). The process could also be used to produce ethanol from perennial grasses grown on marginal lands.

Still another way to reduce reliance on fossil fuel is to produce fuel for diesel engines ("biodiesel") from oilseed crops such as canola, flax, soybean, and sunflower. Although technically feasible, producing biodiesel is still much more expensive than producing fossil fuel.

taken into account, use of corn-ethanol reduces CO<sub>2</sub> emissions by about 40%, relative to the emissions from the gasoline it replaces. If the emissions of other greenhouse gases are also taken into account, then use of ethanol from corn or wheat reduces the global warming potential by 25–30%. In Canada, about 30 million litres of ethanol are currently produced annually from wheat and corn, reducing CO<sub>2</sub> emissions by about 33 Gg (thousand



## Current status of methods to reduce carbon dioxide emissions

The C cycle is central to farming systems. Methods to reduce CO<sub>2</sub> emissions rely mainly on managing that cycle more efficiently: recycling as much organic C as possible, minimizing disruption of soil, optimizing use of the sun's energy (via photosynthesis), and relying less on off-farm energy.

Because they promote efficiency, many of these methods also help sustain land resources and may even be profitable. As a result, they are being adopted for reasons quite apart from their benefits to atmospheric CO<sub>2</sub>. For example, most farms in Canada now use less tillage than a generation ago, and an increasing proportion now use no-till practices. Similarly, the area of land devoted to summer fallow has fallen from about 11 million hectares in 1971 to about 6 million hectares in 1996. The use of these and other C-conserving approaches will likely continue to increase in coming decades.

The two general approaches—storing more C and relying less on fossil fuel—reduce CO<sub>2</sub> emissions over somewhat different periods. Storing C in soils has highest benefits early, in the first few years or decades, but net removal of CO<sub>2</sub> declines with time because it gets harder and harder to add additional C as soil C accumulates. Carbon dioxide savings from reduced fossil fuel, on the other hand, may seem rather small in the short term but can be significant when viewed over many decades. The net removal of atmospheric CO<sub>2</sub> from soil C gains is finite; that from reduced fossil fuel can continue indefinitely.

## Reducing methane emissions

Methane, like CO<sub>2</sub>, is part of the C cycle in farm ecosystems. It is released during decay of organic material when a shortage of oxygen prevents organic C from being completely converted to CO<sub>2</sub>. Although both CH<sub>4</sub> and CO<sub>2</sub> are greenhouse gases, CH<sub>4</sub> has a much higher warming potential, so release of C as CO<sub>2</sub> is preferred.

Most CH<sub>4</sub> from Canada's farms comes from the livestock industry, either directly from the animals or from the manure they produce. A number of methods have been proposed to reduce emissions from these sources, some of which are already in use.

## Reducing methane emissions from animals

Much of the CH<sub>4</sub> produced on farms is from ruminants—livestock such as cattle and sheep that have a rumen for digestion of feed. Specific practices that can reduce emissions from these animals include the following:

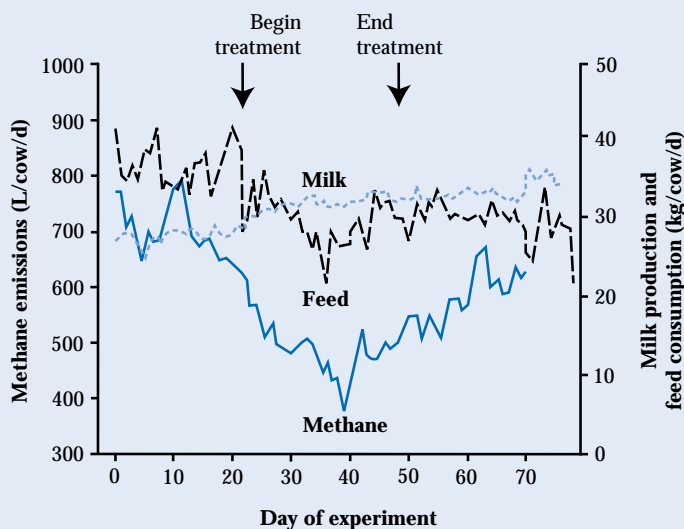
### *Change rations to reduce digestion time:*

Most CH<sub>4</sub> is released from the rumen, where feed is fermented in the absence of oxygen. The longer the feed remains in the rumen, the more C is converted to CH<sub>4</sub>. As a result, any practice that speeds the passage of feed through the rumen will reduce CH<sub>4</sub> production. One study with steers showed that, when scientists increased the passage rate of matter through the rumen by 63%, CH<sub>4</sub> emission fell by 29%. The passage of feed through the rumen can be hastened by

- using easily digestible feeds grains, legumes, and silage

## Effect of feed additives on methane emissions from dairy cows

Scientists at AAFC measured CH<sub>4</sub> emissions from dairy cows in a barn over 3 years with an automatic gas sampling system. In one trial, 95 to 100 cows were fed a total mixed ration (TMR) consisting of concentrate and ensiled forage (35:65 on a dry matter basis) and produced an average of 26.8 kg of milk per cow per day. After a control period, monensin was added to the ration. There was an immediate decrease in CH<sub>4</sub> emissions. At the same time milk production increased and daily feed consumption decreased, indicating an increased efficiency in feed usage. The effects of feeding monensin lasted 2 months after it was removed from the ration. There was, however, indication that rumen bacteria became resistant to monensin when a second feeding trial was conducted 5 months later. The use of monensin in dairy feeds is under consideration by regulatory authorities but has not yet been approved. This feed additive has been used in beef cattle since 1975. These results show that feeding additives can significantly decrease CH<sub>4</sub> emissions by dairy cows. However, further work is needed to resolve rumen microbial resistance and to develop a rotational system of feed additives to overcome this possibility.



(H. Jackson and F. Sauer, AAFC)

- harvesting forages at an earlier, more succulent growth stage
- chopping the feed to increase surface area
- minimizing use of fibrous grasses and hays
- feeding concentrated supplements as required.

*Add edible oils* : Adding canola, coconut, or other oils to the diet may reduce CH<sub>4</sub> production by inhibiting the activity of CH<sub>4</sub>-producing bacteria. Though quite effective, this practice may not always be economical.

*Use ionophores* : Ionophores are feed additives that inhibit the formation of CH<sub>4</sub> by rumen bacteria. Already widely used in beef production, they can reduce CH<sub>4</sub> emission. However, some evidence suggests that rumen microbes can adapt to a given ionophore, lessening its effect over time. For long-term effectiveness, it may be necessary to use a rotation of different ionophores.

*Alter the type of bacteria in the rumen* : In the future it may be possible to introduce into the rumen genetically modified bacteria that produce less CH<sub>4</sub>. Though research efforts are promising, such inoculants are not yet commercially available.

*Improve production efficiency* : Any practice that increases the productivity per animal will reduce CH<sub>4</sub> emissions because fewer animals are needed to achieve the same output. For example, giving animals more feed may increase CH<sub>4</sub> production per animal but reduce the amount of CH<sub>4</sub> emitted per litre of milk or per kilogram of beef. Any other practice that promotes efficiency will likewise reduce CH<sub>4</sub> emission per unit of product.

Many of these practices are already practical and economical. When used together, they can lower loss of energy through CH<sub>4</sub> release from about 5–8% of the gross feed energy to as low as 2 or 3%. Because they increase feeding efficiency, these practices also often have economic benefits. Consequently, they are already widely used on many farms,

especially in dairy herds and beef feedlots.

## Reducing methane emissions from manures

Most of the  $\text{CH}_4$  from manure is produced during storage. When the manure is stored as liquid or in poorly aerated piles, lack of oxygen prevents complete decomposition to  $\text{CO}_2$ , resulting in the release of  $\text{CH}_4$ . Most ways of reducing emission, therefore, involve slowing the rate of decomposition, providing better aeration, or reducing the length of storage. Specific methods include the following:

*Use solid- rather than liquid-manure handling systems* : Oxygen supply is usually better in solid manure, which encourages  $\text{CO}_2$  to form rather than  $\text{CH}_4$ .

*Apply manure to land as soon as possible* : The longer manure is left in feedlots, in stockpiles, or in slurry tanks and lagoons, the more  $\text{CH}_4$  will be emitted. Frequent applications to the land can therefore reduce emissions. Unfortunately, storing the manure is sometimes unavoidable because the land is frozen, too wet, or planted to crops.

*Minimize amount of bedding in manure* : Manure with less bedding, such as straw, contains less C that can be converted to  $\text{CH}_4$ .

*Keep storage tanks cool* : Lowering the temperature of tanks, by insulating or placing them below-ground, slows decomposition, thereby reducing emission of  $\text{CH}_4$ .

*Burn methane as fuel* : Methane is a very effective fuel; indeed, it is the main

## Cattle management systems

Producers feed and manage their cattle in different ways during different stages of the production cycle. The amount of greenhouse gas emitted depends on the system used and the stage in the cycle. Management systems can be compared in terms of net emissions; for example, grams of  $\text{CH}_4$  emitted per kilogram of milk or beef produced. Feeding cattle grain instead of forage reduces  $\text{CH}_4$  emissions. But feed type is only one factor to be considered in selecting a management system. For example, the use of forages in a feeding system encourages land to be used for perennial forage, rather than for annual crop production which results in greater soil C losses. Manure management and its greenhouse gas emissions must also be considered when determining an optimum management system.



(P. Strankman, Canadian Cattlemen's Association and K. Wittenberg, University of Manitoba)

## Improved manure storage can reduce greenhouse gas emissions

Traditionally, manure is stored during summer and winter and is applied to the field in early fall or spring. Summer is usually the season of highest gas production because warm temperatures enhance microbial activity in stored manure. Anaerobic storage favors  $\text{CH}_4$  production, whereas aerobic storage produces  $\text{CO}_2$  and  $\text{N}_2\text{O}$ .

Scientists measured greenhouse gas emissions from beef and dairy manure each stored in three ways: compost, slurry, and stockpile. Methane and  $\text{N}_2\text{O}$  emissions, expressed in  $\text{CO}_2$  equivalents, were always smaller for compost than for the other storage methods. For dairy manure, slurry emitted 1.9 times more greenhouse gas than the compost. Stockpiled manure emitted 1.5 times more greenhouse gas than the compost. Methane was the dominant gas in both the slurry and the stockpile. Nitrous oxide represented most of the compost emissions and a significant portion of the stockpile emissions.

For beef manure, emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  were much lower than from dairy manure. Emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  were 1.3 times higher from stockpiled beef manure than from compost and 4–6 times higher from slurry than from compost.

These results indicate that aerobic storage such as composting may limit the greenhouse gas emissions. On the other hand, creating fully anaerobic conditions during storage promotes emission of  $\text{CH}_4$  that could be collected and used as a fuel.



Bins in which the manure was stored either as slurry, stockpiled, or for composting. A large enclosure was installed over each bin, and the gas emissions were monitored for a given time.

(E. Pattey, AAFC)

constituent of natural gas. In some countries,  $\text{CH}_4$  from stockpiled manure is already collected and burned. In Canada, this approach may not yet be widely practical or economical but is receiving growing interest. Burning  $\text{CH}_4$  converts it to  $\text{CO}_2$ , which has a much lower warming potential.

*Avoid landfilling manure* : Although most manure in Canada is applied to land, small amounts are still disposed of in landfills. Because decomposition in landfills is usually oxygen-starved, large amounts of  $\text{CH}_4$  can be emitted from this practice. Furthermore, placing it in landfills wastes valuable nutrients in the manure.

*Aerate manure during composting* : To make it easier to transport, manure is sometimes composted before applying it to the land. The amount of  $\text{CH}_4$  released during composting can be reduced by aerating the stockpiled manure, either by turning it frequently or by providing a ventilation system inside the pile. Aeration encourages complete decomposition to  $\text{CO}_2$  rather than release of C as  $\text{CH}_4$ .

These methods can reduce, to some extent, the  $\text{CH}_4$  emitted from animal manure. Because of high densities of livestock in some areas, and the high cost of handling and transportation, managing manure still remains a challenge. Other ways to reduce emissions may still be needed.

## Reducing nitrous oxide emissions

Much of the  $N_2O$  emitted from farmland is produced when excess  $NO_3^-$  in soil undergoes denitrification, either on farmland or after it is leached away. Farmers can reduce these emissions by preventing build-up of  $NO_3^-$  or avoiding soil conditions that favor denitrification. Some  $N_2O$  is also emitted when  $NH_4^+$  is converted to  $NO_3^-$  (nitrification). Adding less  $NH_4^+$  or slowing the rate of nitrification can reduce emissions from this source. The best way to reduce  $N_2O$  losses is to manage the N cycle more efficiently, thereby avoiding the buildup of excessive  $NH_4^+$  or  $NO_3^-$ .

Specific ways of reducing  $N_2O$  emission vary for farming systems across Canada, but examples include the following:

### *Match fertilizer additions to plant needs :*

The best way to reduce  $N_2O$  emission may be to apply just enough N so that crops can reach maximum yield without leaving behind any available N. A perfect match is rarely achievable, but the synchrony can often be improved by basing fertilizer rates on soil tests and estimates of N release from residues and organic matter. In fields where fertility needs vary, applying N at different rates across the landscape (“precision farming”) may also improve the match between amount applied and the amount taken up by crops.

### *Avoid excessive manure application :*

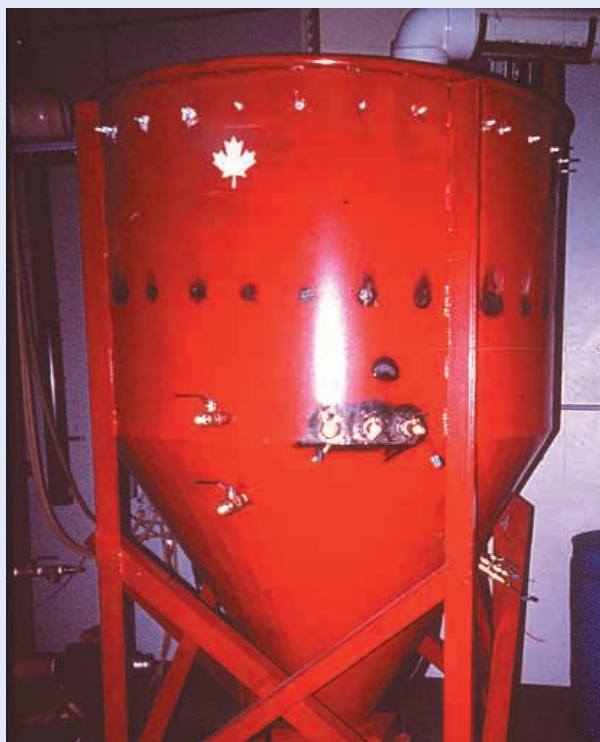
Heavily manured land can emit a lot of  $N_2O$  because the manure adds N and available C, both of which promote denitrification. Moreover, manure is often applied to land as a means of disposal, so that rates can be excessive. Applying the manure at rates that just supply plant demands can greatly reduce  $N_2O$  emissions from this source.

## New technology of manure treatment

Scientists have introduced a new manure treatment process based on the use of anaerobic microorganisms in sequencing batch bioreactors (ASBR). Trials performed in the laboratory showed that the ASBR technology is very stable and versatile and works well at low temperatures (between 10 and 20°C). Furthermore, the bioreactors need to be fed only once a week, during regular manure removal.

The airtight reservoir needed to maintain anaerobic conditions in the bioreactor completely eliminates any emissions of greenhouse gas during treatment and storage. The biogas can be recovered and used for energy on the farm.

The technology also has other interesting benefits. It deodorizes and stabilizes the swine manure slurry leading to the degradation of most of the 150 odor-causing substances in the manure. Furthermore, this technology increases the availability of nitrogen and phosphorus to crops and reduces the need for chemical fertilizers.



Anaerobic sequencing batch bioreactor.

(D. Massé and F. Croteau, AAFC)

### *Optimize timing of nitrogen application :*

When the N is applied is as important as the rate of addition. Ideally, farmers should apply N just prior to the time of maximum uptake by the crop. Wherever possible, they should avoid applying fertilizer and manure in fall. Similarly, they should time the plough-down of N-rich crops, like legumes, so that N release from the residues coincides with subsequent crop demands.

*Improve soil aeration* : Denitrification, and hence  $N_2O$  emission, is favored by the low oxygen levels that usually occur in saturated soil. As a result, farmers can reduce emission of  $N_2O$  by managing soil water—draining soils prone to water-logging, avoiding over-application of irrigation water, and using tillage practices that improve soil structure.

*Use improved fertilizer formulations* : Some research suggests that certain forms of fertilizer emit more  $N_2O$  than others. Highest emissions may occur from anhydrous ammonia; lowest from forms containing  $NO_3^-$ . This finding suggests that, by selecting appropriate fertilizers, farmers could reduce  $N_2O$  release. However, the differences among forms of fertilizer have not yet been widely verified in Canada. Another option is to use slow-release fertilizers, such as sulfur-coated urea. These forms release available N gradually; they feed the crop yet prevent available N from accumulating. Though effective in reducing  $N_2O$  emissions, slow-release forms may only be economical for high-value crops.

*Use appropriate fertilizer placement* : Placing fertilizer in close proximity to crop roots can improve the efficiency of nutrient use, allowing the farmer to achieve high yields with lower rates of application. On the other hand, placing the fertilizer too deep in the soil, or concentrating forms like urea in bands, may increase  $N_2O$  emissions.

*Use nitrification inhibitors* : Certain chemicals, applied with fertilizers or manures, inhibit the formation of  $NO_3^-$  from  $NH_4^+$ . Their use may suppress  $N_2O$  formation in several ways: it reduces  $N_2O$  formation during nitrification, it prevents denitrification of

accumulated  $NO_3^-$ , and, because  $NH_4^+$  does not leach easily, it prevents loss of N into groundwater where denitrification could occur.

*Use cover crops* : Where the growing season is long enough, farmers can sow crops after harvest to extract excess soil  $NO_3^-$ , which prevents it from leaching or converting to  $N_2O$ .

*Lime acid soils* : Because it is favored by acidity,  $N_2O$  emission can be suppressed by applying neutralizing lime to acid soils.

*Reduce tillage intensity* : Though results are still inconsistent, some studies in Canada suggest that  $N_2O$  emission may be lower in no-till than in conventional tillage. If confirmed, this observation may point to no-till as a method of reducing emissions, at least in some soils.

These practices can help reduce  $N_2O$  emissions in many settings. Because  $N_2O$  fluxes are so sporadic, however, all these practices cannot yet be recommended with confidence across Canadian soils and cropping systems. But those that improve the efficiency of N use are often already justified for reasons quite apart from reduced  $N_2O$  emission. Fertilizers account for about 9% of production costs on farms, and any method that reduces N losses has economic benefits.

## Putting it all together

For simplicity, we often discuss methods of reducing emissions for each gas separately. But the C and N cycles are tightly interwoven; a change in farming practice that reduces emission of one gas almost always affects another. Whether or not a new practice helps alleviate the greenhouse effect depends on the net effect on emission of all gases and the relative warming potential of each. A few examples may help to illustrate some of the complex interactions.

One of the ways to reduce CO<sub>2</sub> emissions is to farm more intensively: to eliminate summer fallow, to use higher-yielding varieties, and to aim for higher productivity. Such practices can increase stored C by producing higher amounts of residue that become soil organic matter. At the same time, however, the new, more-intensive system may require higher inputs, including fertilizers, to maximize yields. And those higher inputs of fertilizer may increase N<sub>2</sub>O emissions. The overall effect of the new practice must therefore take into account the change in soil C, the CO<sub>2</sub> cost of making the added inputs, and any increase in N<sub>2</sub>O emission. Because N<sub>2</sub>O is such a potent greenhouse gas, a small increase in emission rate (say 1 kg N per hectare per year), will offset a comparatively high rate of soil C accumulation (~130 kg C per hectare per year).

The evaluation becomes even more complex if we include animals. Suppose, for example, we opt to allocate greater land area to producing forages. This effect would have pronounced benefits for storing soil C. Furthermore, it would reduce fertilizer requirements (and N<sub>2</sub>O emissions from that fertilizer), because nutrients are effectively recycled back to

the soil as manure. On the other hand, much of the C in that system would be fed to animals, and a portion would be released as CH<sub>4</sub>. Furthermore, some CH<sub>4</sub> and N<sub>2</sub>O would be produced from manure. Thus, with one management change, we have affected emission of all three gases, sometimes both negatively and positively. And to know the net effect of the practice, we must consider all three and their relative warming potentials.

We cannot yet grasp all the interactions among gases, nor are our models sophisticated enough to predict them. At present, however, it may be sufficient to recognize that all are part of a complex web, and any attempt to reduce emissions of one may affect the others. Often, the net effect may still be overwhelmingly positive; for example, it may be that the increased soil C from a livestock-based system more than offsets any increase in CH<sub>4</sub> emission. Indeed, sometimes the effects may even be mutually positive; no-till, for example may increase soil C, reduce CO<sub>2</sub> from fossil fuel, and perhaps even reduce N<sub>2</sub>O emissions. Similarly, more efficient use of manures, can almost certainly reduce N<sub>2</sub>O and CH<sub>4</sub> emissions, while reducing CO<sub>2</sub> costs of fertilizer manufacture.

A final consideration is that the various practices aimed at reducing greenhouse gas emissions may work over different periods. For example, efforts to increase soil C gains may show largest response in the short term, say one or several decades, but rates of C gain may diminish thereafter because each new increment of C becomes harder and harder to achieve. In comparison, efforts to reduce CH<sub>4</sub> emission from ruminants, N<sub>2</sub>O emission from soils, or CO<sub>2</sub> emission from fossil fuels may have only small effects in the short term but

achieve highest effect over many decades because the benefits accrue indefinitely.

### *Other effects of practices that reduce greenhouse gas emissions*

We cannot judge the attractiveness of various management practices solely on how well they reduce greenhouse gas emissions. Other factors that come into play include their practical feasibility, economic cost, effect on soil quality, and influence on the whole environment (Table 16). When all these factors are considered together, many of the proposed practices have favorable ratings across the spectrum. For example, reducing tillage intensity has either favorable or neutral effects on all

the criteria (though, clearly, these tentative ratings will vary for different areas of the country). Some practices, such as using nitrification inhibitors, have numerous benefits but their use may be limited by cost. Most of the proposed methods of reducing greenhouse gas emissions have favorable effects on soil quality and adjacent environments.

Many of these other considerations are as important as any benefits to the atmosphere. The adoption of proposed practices will be driven at least as much by these factors as by the desire to reduce greenhouse gas emissions.

**Table 16 Projected effects of various agricultural practices that affect greenhouse gas emissions**

Practice	Effect on GHG emission			Other considerations			
	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	Feasibility	Economics	Soil quality	Environment
Reduced tillage intensity	++	0	?	+++	+	++	++
Reduced summer fallow area	+++	+	-	++	-	++	+
Improved manure management	0	+	++	++	--	+	++
Improved feeding rations	-	++	0	+	++	0	0
Improved drainage/irrigation	+	+	++	+	+	+	-

+ beneficial      0 no effect      - detrimental  
number of + or - signs indicate magnitude of effect