Agriculture and
Agri-Food Canada

Agriculture et
Agroalimentaire Canada

BETTER FARMING
BETTER AIR

*A scientific analysis of farming practice
and greenhouse gases in Canada*

Canada

Agriculture and
Agri-Food Canada

Agriculture et
Agroalimentaire Canada

BETTER FARMING
BETTER AIR

*A scientific analysis of farming practice
and greenhouse gases in Canada*

MARCH 2008

Scientific Editors:
H.H. Janzen, R.L. Desjardins, P. Rochette, M. Boehm and D. Worth

Canada

For additional copies of this publication or to request an alternate format, please contact:

Publications Section
Agriculture and Agri-Food Canada
Sir John Carling Building
930 Carling Avenue
Ottawa, Ontario K1A 0C5

Telephone: (613) 759-6610
Fax: (613) 759-6783
E-mail: publications@agr.gc.ca

Electronic version available at http://www.agr.gc.ca/nlwis-snite/

Library and Archives Canada Cataloguing in Publication

Janzen, H. Henry, 1956-
Better Farming, Better Air: A scientific analysis of farming practice and greenhouse gases in Canada / H. Henry Janzen.

Issued also in French under title: Une agriculture efficace pour un air plus sain: une analyse scientifique des liens entre les pratiques agricoles et les gaz à effet de serre au Canada.

ISBN 978-0-662-47494-4
Cat. no.: A52-83/2008E
AAFC No. 10530E

1. Greenhouse gas mitigation--Canada. 2. Carbon dioxide mitigation--Canada. 3. Sustainable agriculture--Canada. 4. Agriculture--Environmental aspects--Canada. 5. Agricultural industries--Environmental aspects--Canada. 6. Agriculture and state--Environmental aspects--Canada. I. Canada. Agriculture and Agri-Food Canada II. Title. III. Title: Scientific analysis of farming practice and greenhouse gases in Canada.

HC120.E5J36 2008 363.738'7460971 C2008-980015-X

PRINTED IN CANADA IMPRIMÉ AU CANADA

100% post-consumer content

FOREWORD

As Assistant Deputy Minister, Agriculture and Agri-Food Canada (AAFC) Research Branch I am proud to present you with this book: *Better Farming Better Air.* It is the result of a collective work initiated in response to a commitment by AAFC to Treasury Board in 2001 under the Results-Based Management and Accountability Framework (RMAF) as part of the Model Farm program. *Better Farming Better Air* summarizes our understanding of Greenhouse Gas (GHG) fluxes on Canadian farms. It describes the contribution of agriculture to Canadian GHG emissions and agriculture's role in mitigating GHG emissions.

The composition of air is a complex phenomenon which can be influenced by human activities. As a provider of food and as a driver of our economy, agriculture is one of the human activities on which we can act in order to ensure better-quality air, thereby contributing to the well-being of future generations of Canadians. By studying the complex processes by which agriculture impacts on our air, AAFC scientists contribute to improving our understanding of the system. They use this understanding in the development of improved agricultural practices. *Better Farming Better Air* presents world-class research which describes the state of our knowledge in relation to agricultural practices; provides examples of how agriculture can contribute to improving air quality; and outlines our substantial achievements reached in recent years.

This book is a valuable addition to the collection of information on the environment that we are proud to make available to the agriculture sector, policy makers and Canadians in general.

Marc Fortin
Assistant Deputy Minister
Research Branch

PREFACE

A phrase taken from the concluding paragraph of this outstanding book sums up perfectly the spirit of the publication: we must restore the vision of "seeing our farmlands not as resources to be spent, but as a home in which we live, whether we reside there or not." This statement is precisely in accord with what eminent American ecologist, forester and environmentalist Aldo Leopold wrote. He said, "We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect."

Indeed, the adoption of agriculture-management practices based on ecological principles must be an integral component of any solution to the environmental problems of the modern era. This is important not only to meet the food demands of the world's 6.5 billion inhabitants (expected to grow to nine billion by 2050), but also to offset emissions from fossil-fuel combustion. Agriculture, managed ecologically, can sequester carbon in soils and trees, denature contaminants through phyto-remediation and microbial processes, filter pollutants from natural waters through the soil as a biomembrane and produce biomass needed for modern biofuels (ethanol, biodiesel).

The intent of the Model Farm Program, the origin of this book, was to improve the accuracy of estimates of greenhouse gas (GHG) emissions from Canadian farms and agriculture, and to identify ways to reduce emissions from farms. The theme is in accord with the Kyoto protocol, ratified by Canada in 2002, for the emission period 2008–2012 and beyond. Three specific objectives of the Model Farm Program were: to improve scientific understanding of emissions from Canadian farms, to verify the inventory of Canadian emissions for international commitments and to devise a method for holistic analysis of GHG emissions from entire farming systems. Reliable data are essential to the sustainable management of agricultural soils. Only through long-term planning, based on solid data, can agriculture hope to meet society's numerous and emerging demands.

Assessing emissions in terms of CO_2 (carbon dioxide) equivalent involves obtaining credible estimates of all GHGs: CO_2, CH_4 (methane) and N_2O (nitrous oxide) from diverse soils and management scenarios (e.g., tillage and other farm operations, livestock, nitrogenous fertilizers). Scientific models, specifically developed to predict emissions from Canadian farms, need to be validated against direct measurements under diverse land uses and management practices. The Model Farm Program project team, comprising world-class professionals, has meticulously developed a methodology and model that can be used in other countries. The model's merits are numerous:

- Based on an ecosystem approach and a holistic view
- Identifies win-win solutions
- Considers the role of biofuels
- Involves diverse farming systems
- Addresses all GHGs and not just CO_2
- Based on a positive approach of using agriculture as a solution to the issue of global warming

Better Farming, Better Air is an outstanding reference for diverse stakeholders, including agricultural researchers, policy makers, environmentalists, and the general public. It is prepared in a simple and reader-friendly format. It delivers a strong message about how farm management affects our air and how the adoption of prudent land-use and management practices can alleviate global environmental stresses of the 21st century.

RATTAN LAL

Professor of Soil Science
The Ohio State University
Columbus, OH 43210 USA

Acknowledgements

The findings presented were funded, in part, by the Model Farm Program of Agriculture and Agri-Food Canada (AAFC). We thank those who established this program and the many administrators and collaborators who supported and guided these efforts. In particular, we acknowledge our indebtedness to innumerable collaborators—researchers from outside AAFC, producers, industry specialists, and concerned members of the general public—who encouraged and helped steer the research. Earlier versions of this book were reviewed by Richard Asselin, Con Campbell, Henry Hengeveld, Barry Grace, Chang Liang, Alex Milton, Claudel Lemieux, Leslie Cramer and Sheila Torgunrud, who graciously provided many perceptive and corrective comments. Rattan Lal kindly agreed to draft the preface of this book, for which we owe him gratitude. Most of all, we thank the technicians, clerical staff, layout artists, plot personnel, livestock herders, local managers and many others who worked diligently and quietly behind the scenes. They performed much of the work described in this document and we do not always thank them enough.

THE EDITORS

Authors

Agriculture and Agri-Food Canada recognizes the significant contributions made by the following authors of this book (lead authors of one or more sections are identified by an asterisk): D. Angers *, K.A. Beauchemin, C. Benchaar, S. Bittman, M.A. Bolinder, M. Boehm*, S. Claveau, R.L. Desjardins*, C.F. Drury, J.A. Dyer, S. Gameda, B. Grant, E. Gregorich*, L.J. Gregorich, H.H. Janzen*, R.L. Lemke*, D.I. Massé*, L. Masse, T.A. McAllister, B. McConkey, S.M. McGinn*, N.K. Newlands*, E. Pattey*, R.L. Raddatz, P. Rochette*, E.G. Smith*, W. Smith, F. Tremblay, A.J. VandenBygaart, D. Worth, X. Vergé and B. Zebarth.

To make this publication readable for a wide audience, many of the references originally cited by authors have been removed and replaced with a sampling of general sources at the end of each section. This does not minimize our indebtedness to many unmentioned scientists whose insights and findings reside in these pages.

CONTENTS

Summary 2
Introduction 14

The Gases

Carbon Dioxide 20
Nitrous oxide 34
Methane 50

The Amounts

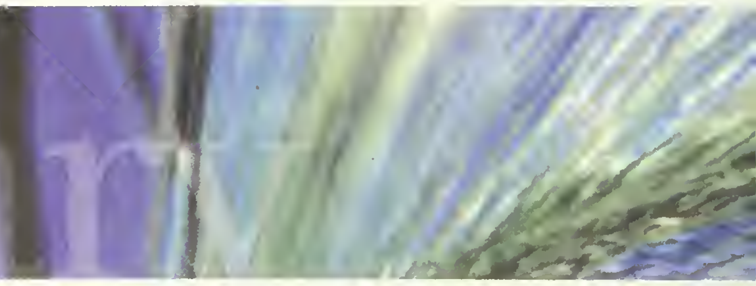
Measuring Ebbs and Flows 70
The Emissions we Produce 78
Reckoning the Total Budget 90

The Bigger Picture

A Holistic View 98
Finding Win-Win Solutions 108

The Future

The Promise of Biofuels 114
Rejuvenating the Air 124
What Could Happen 134
A Vision Restored 142



Summary

OUR CHANGING AIR

WE BARELY NOTICE THE AIR ABOUT US—invisible and silent, it seeps among and through all living things, enshrouding the earth in its fluid continuity. Yet unseen to us in air's apparent placidness are torrents of activity: gaseous molecules of all kinds flitting about, reacting, recombining, breathed in and out by plants and animals, chased endlessly about by the warmth of the sun.

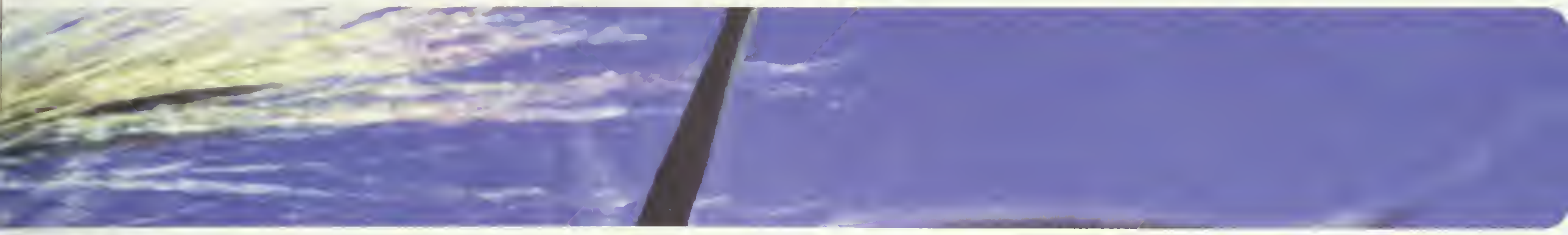
Through these ceaseless flows, the air keeps us all alive. It gives us food; for the carbon that fuels us comes from air, invested with energy from the sun. It provides the oxygen we inhale to burn the food we eat. It yields the proteins we need, for the nitrogen therein comes ultimately from air. We and all life on Earth are sustained by the gases that circulate among us in what we call air.

There is yet another reason we depend on air: it keeps us warm. Some of the gases in our atmosphere—carbon dioxide, methane, and nitrous oxide, among them—prevent the Earth's heat from escaping quickly back into space. Without these *greenhouse gases*, or GHGs, our planet would not be the oasis it has been for aeons now in the cold expanse of space.

But the air today is not as once it was. Humans occupy this planet in increasing numbers—our population has doubled in just 40 years—and we have devised more powerful means to rearrange our world, changing our air. Foremost is an increasing concentration of carbon dioxide: 280 parts per million (ppm) just centuries ago, but now surging past 380 ppm, mostly from burning fossil fuels and clearing tropical forests. Concentrations of other GHGs—nitrous oxide and methane—have increased too. So scientists increasingly worry: if these trends continue, will we bring about climate change, unpleasant and irreversible?

The role of farms

Farms—their fields and pastures, soils and animals—are tied closely to the changing air. They are important sources of GHGs: CH_4 (methane) from the breath and excreta of livestock; N_2O (nitrous oxide) from nitrogen in soils and manure; and CO_2 (carbon dioxide) from fuel burned in tractors and barns. Beyond that, farms also store carbon, mostly in their soils. When managed poorly, this carbon can be lost to air as CO_2, as it has been in the past. But if managed better, some carbon lost can be regained, actually *removing* CO_2 from the air. Because farms are so connected to the air, what farmers do—how they manage their land and livestock—affects profoundly the air that surrounds us all. Although few of us see much of what happens on farms, farmers' choices influence us all, often to our benefit.



Our intention is to show, briefly, how farmers' actions affect our air and how their future choices can help relieve some of the environmental stresses building globally.

The Gases

To see how better farming can lead to better air, we need to review the processes whereby GHGs—CO_2, N_2O, and CH_4—are exchanged with the air. Though these processes are often interwoven, we first consider each gas separately for clarity.

Carbon dioxide

Nature uses carbon to store energy. In the air, carbon exists mostly as CO_2; through photosynthesis, green plants invest the sun's energy in this CO_2, building from it first sugars and then other energy-rich forms. Plant materials are then eaten by other organisms—microbes, cows, and humans, among others—who, in effect, burn the material back to CO_2, using the solar energy it contains to live and grow. Some of the energy-rich carbon materials can be stored for thousands or millions of years before being converted back to CO_2. For example, soils contain vast amounts of carbon held in organic matter (humus), and the carbon in fossil fuels such as coal, oil and natural gas is solar energy trapped by plants aeons ago. Farms and other ecosystems can be likened to batteries; building carbon stocks is like charging the battery and losing carbon like discharging it.

On Canadian farms, carbon is stored mostly in the organic matter of soils. Changes in amounts stored depend on the rate of carbon coming in as plant litter, compared to the rate of carbon lost through decay. If rate of carbon input exceeds rate of loss, carbon accumulates; if rate of carbon added is less than rate of loss, carbon is depleted.

Historically, when lands were first cropped, large amounts of carbon were lost because cultivation accelerated decay and removal of harvests meant less carbon was returned to soil. But today, farmers can rebuild some of the lost carbon through improved practices: using no-till methods, planting more perennial hay or pasture crops, avoiding summer fallow (lands left unplanted), adding nutrients and manures to increase yields, restoring grasslands and using better grazing techniques. By increasing the amount of carbon stored in soils, these practices not only remove CO_2 from the air, but also make soils more productive and resilient for use by future generations. Some practices, such as no-till farming, also decrease CO_2 emissions by reducing the use of fossil fuel.

Methane

Sometimes, when carbon-containing materials decay without sufficient oxygen, microbes produce CH_4 instead of CO_2. On Canadian farms, this occurs mainly in two places. First, CH_4 is produced inside the rumen (fore-stomach) of ruminant animals such as cattle and sheep through a bacterial process called *enteric fermentation*. This process, the biggest source of CH_4 from Canadian farms, is important because it enables livestock to convert otherwise indigestible materials such as grass and hay into usable energy. Second, CH_4 is released from manure storage sites, especially when manure is stored wet or as a slurry, because water prevents entry of oxygen during decay.

Scientists have long studied CH_4 emissions from ruminants because such emissions mean the animal has not efficiently utilized the energy content of the feed to produce meat or milk. Through research, scientists have found effective ways of reducing these emissions. One way is to alter the diets of livestock: using high-grain rations, adding fats or oils to rations, and using anti-microbial agents called ionophores, which reduce emissions at least for a time. Feeding cattle higher-quality forage—replacing grass hay with alfalfa, for example—can also reduce emissions of CH_4 per unit of animal product. Scientists are also experimenting with compounds such as tannins, naturally present in some forages, as a way of suppressing CH_4. Various other agents, including yeasts, organic acids, halogenated compounds such as chloroform, and possible vaccines are also being investigated, although in some cases their effectiveness in reducing emissions has not been widely confirmed.

Beyond these *direct* methods, CH_4 emissions can be reduced *indirectly* by choosing practices that enhance productivity: extending lactation periods of dairy cows, using more efficient breeds, improving reproductive performance and increasing rates of gain in beef animals so they reach the market sooner. These practices, while they may not reduce emissions per animal per day, can lower the amount of CH_4 emitted per kilogram of milk or meat produced.

Research has shown also that CH_4 from manures can be reduced. Practices sometimes effective include: aerating manure, storing manure at low temperatures (below ground, for example), removing manure from storage more frequently, using bedding material to improve aeration and composting manure (although the overall effectiveness of this practice may vary, in part because of possible emissions of N_2O). Another way to reduce emissions from manures is to remove CH_4 using biological filters or, even better, to trap the CH_4 and burn it as fuel, thereby offsetting fossil fuel otherwise needed.

Nitrous oxide

Nitrous oxide is an important GHG emitted from Canadian farms, accounting for about half the warming effect of agricultural emissions. This gas, familiar to us as laughing gas, is produced in nature by microbes as they process nitrogen in soils.

All soils emit some N_2O, but farm soils often produce more than others because of the nitrogen added to soil in fertilizer, manures and other amendments. Without these additions to replace the nitrogen removed from farms in harvested grain, milk, meat, and other products, crop yields would soon decline. But as the amount of added nitrogen increases, so do potential losses into the environment, including losses of nitrogen to the air as N_2O. Typically, scientists assume that about 1% of the nitrogen added to farm fields is emitted as N_2O, though this can vary widely with soil water content (hence oxygen availability), hilliness of the land and soil clay content.

Aside from the N_2O released directly from soils, farms can also give rise to *indirect emissions*—N_2O produced elsewhere from nitrogen leached from fields or emitted into the air as ammonia gas. This nitrogen, once lost from the farm, can find its way into adjacent environments where it can be converted and emitted as N_2O. Although not produced on farms, this N_2O is from nitrogen used on the farm; hence, it must be counted as farm-derived N_2O.

Since N_2O is produced mostly from excess available nitrogen in soils, one way to suppress emissions of this gas is to apply fertilizer judiciously: adding just enough, at the right place and time, to meet crop demands, but avoiding excess amounts left over. This aim, long a goal of scientists, becomes ever more important in light of the high cost of fertilizers and environmental damage caused by nitrogen leaking from farms. Fertilizer can be used more efficiently by: adjusting fertilizer rates to coincide with plant needs; placing fertilizer near plant roots (but not too deep in the soil); applying fertilizer several times each year, rather than only once; and using slow-release forms. Similarly, using manure efficiently can also help limit N_2O emissions—not only because less is released from the manure, but also because less fertilizer now needs to be used. Perhaps the most fundamental way of reducing N_2O from manures is to alter feeding rations so that less nitrogen is excreted in urine and feces in the first place.

Other practices that can sometimes reduce N_2O emissions from farms include: greater use of legumes as a nitrogen source; use of cover crops (sown between successive crops) to remove excess available nitrogen; avoiding use of summer fallow (leaving the land unplanted, with no crop nitrogen uptake, for a season); and adjusting tillage intensity (sometimes, but not always, no-till practices can reduce emissions).

Most methods of reducing N_2O emissions depend on improving the efficiency of nitrogen use on farms. Progress toward this aim has many other benefits: it makes farms more profitable because fertilizer is expensive; it saves on fossil fuel use (and hence CO_2 emissions) because producing nitrogen fertilizer is energy-intensive; and it lessens the amounts of nitrates, ammonia and other nitrogen pollutants entering the environment. Despite much progress, the nitrogen cycle on farms is still quite leaky; stemming these leaks remains a research priority, both to reduce N_2O emissions and for many other urgent reasons.

The Amounts

How and why scientists measure emissions

We measure GHG emissions from farms in part to honor international commitments; for example, Canada needs to provide reliable annual estimates of emissions from all important sources, including farms. But emissions are also measured for scientific reasons: if you cannot measure emissions precisely, how can you know which of various practices best reduces emissions? And without good estimates of emissions, how can you understand the underlying principles of GHG formation and release?

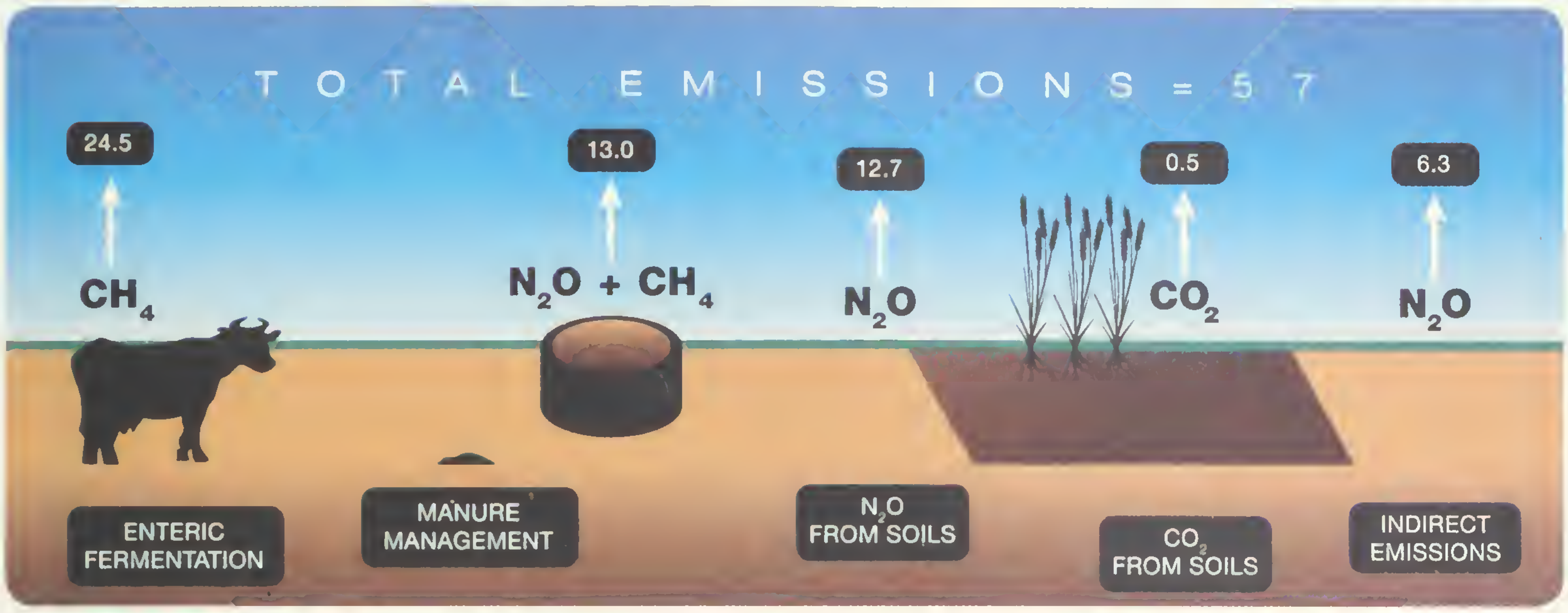
But measuring emissions of GHGs from farms is not easy; emissions come from many places on the farm: soils, animals of all kinds and machinery. Sometimes the gases seep slowly into the air; other times they spew in sporadic gusts. To capture these emissions, scientists have had to devise a host of methods: small chambers placed on soils or large chambers housing cows; instrumented towers downwind of fields or instrumented aircraft flying over farming regions; methods that require patient analysis of carbon change in soils over tens of years, or measurements of CO_2 in air, several times a second; analysis of air in tubes buried in the soil, or from tubes hung high in the air on balloons. No method is perfect, but each has its role. By pooling results from all methods, scientists obtain reasonably good estimates of emissions and the factors that control them. This understanding is then usually captured in *models*—sets of mathematical equations that can predict GHG emissions for any set of conditions. Such models are already widely used, but research continues to make them even more robust and reliable.

The emissions we produce

Agriculture emits (and sometimes removes) all three GHGs: CO_2, CH_4, and N_2O (see Figure 1). These gases differ, though, in their ability to trap heat; tonne for tonne, CH_4 is more than 20 times as effective at trapping heat as CO_2, and N_2O is about 300 times as effective as CO_2. To compare the emissions of these gases on equal terms, therefore, we usually speak of CO_2 equivalents (for example, N_2O has 298 CO_2 equivalents).

FIGURE 1

Sources of GHG Emissions from Canadian Agriculture in 2005, Excluding CO_2 Emissions Associated with Energy Use. Mt CO_2e

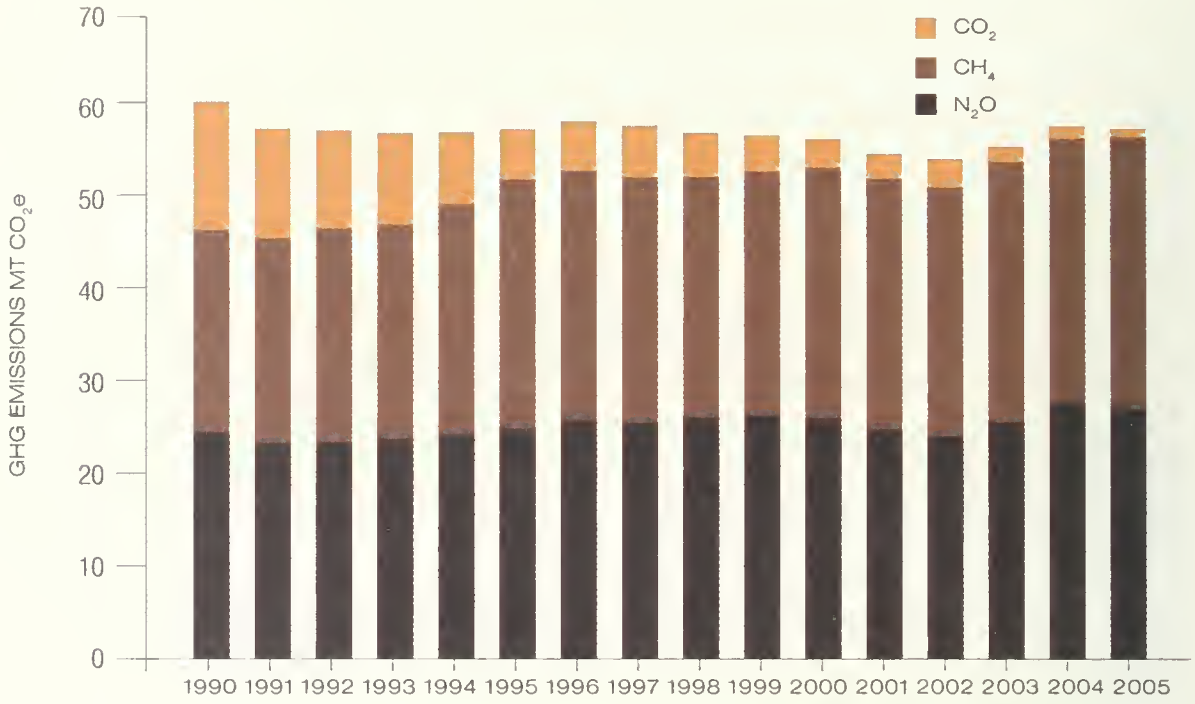


In 2005, Canada produced 747 million tonnes of CO_2 equivalents (Mt CO_2e) from all sources, mostly as CO_2 from energy use. Agriculture accounted for about 8% of these emissions, largely as CH_4 and N_2O in roughly equal proportion. (This value does not include emissions from energy use; if these are counted, then agriculture accounts for roughly 10% of Canada's emissions). As mentioned, farm soils *remove* substantial CO_2 from the air when soils gain carbon under improved practices (about 10 Mt CO_2e were removed in 2005), but because these removals are almost exactly balanced by carbon losses from recently cultivated forestlands, the net exchange of CO_2 between agricultural land and air is small.

The annual total GHG emissions from farms in Canada have stayed reasonably constant from 1990 to 2005, falling by 6% (see Figure 2). But this stability hides trends in the individual gases. Methane emissions, for example, have increased by 24% because of larger animal herds (the beef cattle population increased by 30%). Nitrous oxide emissions have risen by 14%, mostly from higher fertilizer use and more manure produced. Emissions of CO_2 from cultivated croplands have fallen, however, so that total annual emissions have declined slightly.

FIGURE 2

Carbon Dioxide, Methane and Nitrous Oxide Emissions From Canadian Agriculture, 1990 to 2005



These estimates may not be perfectly accurate; all carry some uncertainty, in particular those for N_2O. But they provide a reliable view of general trends and their uncertainty may slowly shrink with further research and gradually improving methods.

What will happen to GHG emissions in coming years? With growing demand for food and other products, livestock numbers and nitrogen additions may rise further, perhaps increasing CH_4 and N_2O emissions, unless new ways can be found to suppress them. Soil carbon gains (CO_2 removals from the air), which have offset past increases in CH_4 and N_2O emissions, may continue for some years, but not indefinitely; eventually, soil carbon approaches a maximum, typically a few decades after introducing new practices. Even with good practices, therefore, it is hard to foresee farm GHG emissions falling appreciably over time. More important than reducing total emissions, however, may be finding ways to reduce emissions per unit of product. In the last 15 years, for example, dairy farmers have reduced CH_4 emissions per kilogram of milk by about 13%, and similar trends are occurring with beef and pork.

Reckoning the total budget

Farming practices affect the climate not only through emitted GHGs, but also by the way they affect the colour of the land. In general, the whiter the landscape, the more of the sun's radiation is reflected back into space. A snow-covered field, for example, will reflect more radiation (and absorb less heat) than a dark forest with snow beneath the canopy. Cropping practices can also affect the timing of thunderstorms and severe weather by affecting water vapour release from plant pores (transpiration). And air temperature and precipitation can be influenced by practices such as summer fallow and irrigation. These examples show that the effects of farming practices on climate cannot be judged solely by the amounts of GHG emitted; other factors need also to be considered.

The Bigger Picture

A holistic view

An ecosystem, short for *ecological system*, is a community of organisms within its environment and all the interactions among them. The ecosystem, then, is more than the sum of its parts; it encompasses the fluid coherency of the whole system. This means that studying ecosystems is not an easy task, for many different disciplines are needed and they need to be applied over long spans of time, since ecosystems often change only gradually. But the approach allows us to see living systems as a whole; it lets us see the forest *and* the trees.

At first the ecosystem concept was applied mostly to landscapes untouched by humans. But farms also can be viewed as ecosystems; they are complex assemblages of organisms, interacting with each other and their environment. Seeing farms this way has several benefits: it forces us to take a *holistic* view; and it allows us better to study farms alongside natural systems, such as forests, wetlands and lakes.

The ecosystem approach may be especially useful in studying GHG emissions. We might even argue that this is the *only* way to study them, for GHG fluxes emanate from myriad processes, all interwoven and entangled. The emissions of one gas depend on emissions of another. For example, some practices may increase soil carbon, thereby withdrawing CO_2 from the air. But if those practices require more fertilizer, then will N_2O emissions be affected, and what will be the *net* effect? A new feeding practice may effectively suppress CH_4 emissions from cows; but how does that feed now influence the emission of GHGs from manure produced, and what are the GHG emissions on fields where the feed is grown? Even more complicated are the spillover effects of any new practice. For example, if land once cropped is planted to grass, will the crop displaced merely be grown elsewhere? And what will be the emissions there? These few examples illustrate that GHG emissions can be properly understood only from a broad ecosystem perspective and the effectiveness of proposed practices can be gauged only by looking at all the gases across space and across time.

Given this complexity, how can we study all the intertwined processes that emit GHGs from farms? The only practical way is to build mathematical models, equations that describe in mathematical language what we know about the system. Building such models, whether they be simple or highly sophisticated, forces us to include and connect all the many processes involved. Further, models offer a way of storing and updating what we know. As new findings emerge, they can be reflected in refined models. What's more, building models helps us recognize our ignorance, pointing scientists to those areas most in need of further study.

Scientists in Agriculture and Agri-Food Canada are now building such models for simulating GHG emissions from whole farms. One such model, a simple GHG calculator that predicts emissions for a single year, is now available for use by scientists, producers, policy makers and other users. Work is also underway to build more sophisticated *dynamic* models, which will simulate changes in emissions over time.

Greenhouse gas emissions are just the first focal point of such ecosystem models; they are merely a convenient, topical starting point. With time, other environmental issues may also be considered: biodiversity, water quality, food quality, alternative energy sources, ammonia emissions and other queries still beyond our view. Once the underlying processes of carbon, nutrient and energy flows are inscribed in an ecosystem model, it can be retuned and redirected to illuminate these and other pressing societal questions.

Ecosystem Services

Like all ecosystems, farms provide many benefits, many *ecosystem services*. Some of these services are obvious: farms give us food, fibre and now even fuel. But some, equally important, are more subtle: farms act as environmental filters, cleaning air and water, removing wastes; they offer habitat to us and other creatures; they provide livelihood for rural families; they give us all places to play; and they uplift our spirits with aesthetic appeal.

When enumerating the ecosystem services of farms, those who study climate change often think first of reducing GHG emissions. This indeed is an important function, especially since farms can *remove* CO_2 from air. But it is only one service among many and may not even rank as the highest priority. Few GHG-mitigating practices will be adopted if they do not also serve some other function, such as reduced cost, enhanced conservation or expanded biodiversity. Scientists therefore look especially for those practices that can reduce GHGs *and* enhance other ecosystem services. One such *win-win* opportunity is no-till farming. In some cases, it not only reduces GHG emissions, but it can also cut costs, conserve soils by preventing erosion, offer nesting habitats through improved ground cover and improve air quality by avoiding dust storms. Indeed, the widespread adoption of no-till farming likely stems more from these benefits than from its effectiveness in reducing GHGs.

No-till is a rare case, however. Often, a gain in one service demands a sacrifice in another. Indeed, even no-till farming may exact a cost somewhere along the way. Choosing practices therefore often involves trade-offs, looking for *big-win/small loss* opportunities. For example, are we willing to incur small yield losses (small loss) to achieve substantial GHG mitigation (big win)? Or small increases in CH_4 emission to achieve large increases in milk yield? Or a slight increase in ammonia emission to drastically reduce N_2O emission? Add to this mix all the other ecosystem services and the decisions grow even more dizzying.

Clearly, choosing best practices depends on a holistic approach, examining all ecosystem services, deciding how to value them and opting for the best of any number of trade-offs. Such an approach requires the counsel of more than scientists. The decisions belong to society as a whole and need to be instructed by all who live and depend on these farmlands.

Studying GHGs may help us reduce emissions, but that may not be its biggest reward. Critically, GHGs tell us also how well an ecosystem is performing. Eruptions of N_2O, for example, signal that the nitrogen cycle may be uncoupled; high CH_4 emissions may show that feeds are not efficiently used; excess CO_2 emissions may point to depleting carbon stores or unwise use of energy. Our farms and our planet may be on the threshold of tumultuous changes: changes in climate, water availability, energy use and global food demands, to name a few. In light of these coming changes, we need ways to see how our ecosystems are holding up, ways of taking their pulse. Measuring the GHGs is one method for doing that; they can direct us to better farming and better air.

The Future

The promise of biofuels

Farms, and what society expects from them, are in a constant state of change. One recent impetus has been a surging interest in growing biofuels. Humans have long used biomass for energy, burning wood or crop residues as fuel, for example. Today, new technologies and the escalating cost of fossil fuels have spawned interest in a range of other fuels produced from farm crops. Most advanced is the production of ethanol from corn or wheat. In Canada, once processing plants under construction are completed, grain ethanol will provide about 2% of motor gasoline consumption. Less advanced, but perhaps with more long-term potential, is the making of ethanol from cellulosic biomass—switchgrass, woody biomass, or crop residues. Other possible biofuels include biodiesel, made from soybean or canola oils; biogas (CH_4) from digested manures or other organic materials, or biocombustibles—biomass from trees, grasses or crop residues burned to generate heat, steam or electricity.

These biofuel crops may help reduce GHG emissions. Burning biofuel still releases CO_2, but it is from carbon recently absorbed from the air by the growing crop, so the CO_2 is *recycled*, rather than *added* to the air as it is when fossil fuels are burned. But some GHGs may be emitted when biofuels are produced (N_2O, for example, may be emitted when corn is grown). These emissions need to be subtracted when estimating the net benefit of burning biofuel.

Other factors come into play when analyzing the overall benefits of biofuel. For example, will the increased removal of harvested carbon affect soil quality, which depends on plant litter to replenish organic matter? Will land used for biofuel displace crops that will then be grown elsewhere, perhaps with higher environmental impacts? These and other questions emphasize the need for a holistic perspective in evaluating the system-wide effects of proposed practices.

Rejuvenating the air

There is emerging consensus among scientists that impending climate change is a serious challenge meriting a concerted global response. But crafting policies to meet this challenge is not easy, in part because we do not know exactly the magnitude of changes coming and how fast they will appear. Global efforts to combat climate change began in 1979, with the First World Climate Conference in Geneva. These were bolstered in 1988 with the establishment of the Intergovernmental Panel on Climate Change (IPCC), which delivered its first assessment report in 1990. (Its fourth report appeared in 2007).

The first IPCC report led to an international climate change agreement, the United Nations Convention on Climate Change, adopted by 192 countries. The agreement aims to stabilize GHG concentrations at levels below those that would cause dangerous climate change. Underlying this goal is the *precautionary principle*, the idea that we cannot afford to wait for complete certainty before acting to prevent irreversible damage that may await us in the future. Continued international negotiations culminated in the Kyoto Protocol, which aims to reduce annual GHG emissions between 2008 and 2012 to 5% below those in 1990. Countries could meet their individual commitments in two ways: by reducing emissions or by generating biological carbon sinks (increasing stores of carbon in trees or soils).

Canada ratified the Kyoto Protocol in 2002, with far-reaching effects on farms. An important effect has been increased interest in storing soil carbon, seen as an important element of Canada's commitment to reduce overall emissions.

What could happen

The world of our grandchildren, living 50 years from now, will likely look different than it does today. One important change coming may be in climate. Climate models project gradual warming in coming decades, and temperature increases in Canada, because of its high latitude, may be more pronounced than the global average. Precipitation may also be affected, though estimates are more uncertain than those for temperature. Because agriculture is so sensitive to climate, these changes may alter how we farm our lands and how the land behaves; they may influence the crops we grow, the way we house our livestock, the resilience of our soils, the pests we need to control. Any coming changes may affect the amounts of GHG emitted, requiring new ways to mitigate them. Thus, we must not only avoid emissions where we can, but also be prepared to adapt to changes that may happen.

Change, however, will not be limited to climate; indeed other stresses may be even more transformative. With the global population growing, reaching perhaps 9 billion by 2050, there will come greater demands for food from limited land, growing thirst for water from dwindling reserves, increased need for energy from depleting stocks and higher demand for space among competing interests. These impending pressures require sober, long-term vision to find ways of reducing GHG emissions and still meet the many other ecosystem services we expect from farms.

A vision restored—dreams of future solutions

As we have seen, scientists have made important advances recently in understanding GHG emissions from farms and in finding ways to reduce them. But the solutions are not yet all in place, especially in light of impending stresses. So scientists will continue to look for answers to these questions and to new questions still unseen. They might seek alternative energy sources and find ways to use energy more efficiently on farms: using biological nitrogen fixation more effectively, for example, or recycling nutrients from farms more efficiently, including the nutrients from the food we eat.

Whatever our responses, an underlying approach may be to reconnect consumers to the land. This would remind us that what happens on farmlands profoundly affects all, and, in turn, that how we consumers behave profoundly affects the land. Such an emerging way of thinking, enlightened by the ecosystem approach, would prompt scientists to seek solutions not only in their laboratories and field experiments, but also in the lessons of history, in the perceptiveness of art, and in the wisdom of those who farm the lands.

The best answers may emerge from a vision restored; from seeing our farmlands not as resources to be spent, but as a home in which we all live, whether we reside there or not.

Introduction

OUR CHANGING CLIMATE

The air about us is changing. Its concentration of CO_2 (carbon dioxide), once 280 parts per million (ppm), is now pushing past 380 ppm and is rising quickly (Figure 3). These changes, we know now with certainty, are mostly the result of human activities; they bear our fingerprint.

Each year, we emit into the air about 9 billion tonnes of carbon, primarily from burning oil, gas and coal (Figure 4), but also from the burning of forests, mostly in the tropics. So every year the concentration of CO_2 is about 2 ppm higher than it was the year before. And there is no sign that these increases will slow; for the next few decades, at least, we will depend on the burning of fossil fuels to power our societies.

The changes to our air are not directly noticeable to us. Carbon dioxide is colourless, odourless, and not at all toxic at present levels—indeed, growing plants depend on this gas. Still, the rapidly rising concentrations are worrisome, because CO_2 is a greenhouse gas (GHG): its presence in the atmosphere helps slow the escape of heat back into space. In many ways, this is a good thing; without the greenhouse effect, our planet would be a cold and lifeless place (Figure 5). But if the concentration of CO_2 continues to increase—perhaps doubling by the end of the century—the world may warm appreciably. Already, there are signs that global temperatures have increased and models predict more warming in the future.

Why does this matter? If the climate warms, the sea will rise, because warmer water expands and because land ice will melt, increasing the amount of water in the oceans. Many people live on the ocean's edge, so even small rises—much less than one metre—would inundate vast areas now populated. A warming climate may change rainfall patterns and severe weather events may become more common. As Figure 6 explains, climate change may affect a host of basic human needs: food production, human health, biodiversity and access to water for starters. Not all of these effects would be unpleasant, but many could be. Much uncertainty still remains, but that uncertainty is itself a worry, since it makes preparing for the future more difficult.

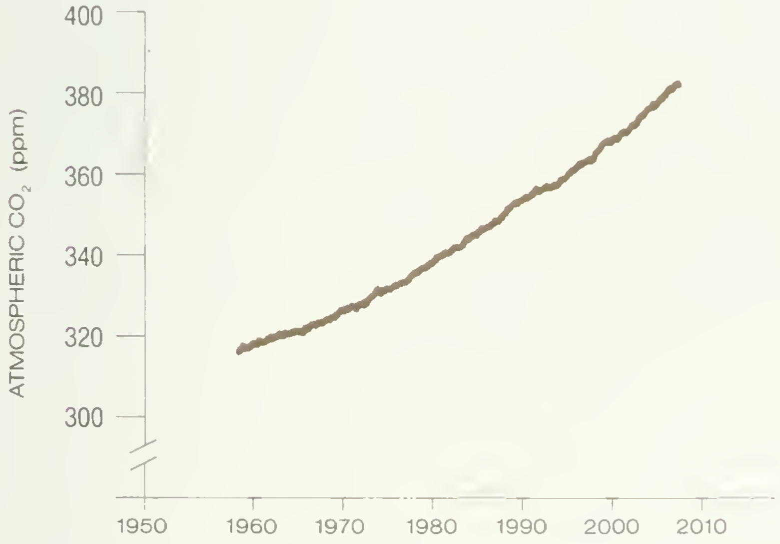
Carbon dioxide is not the only greenhouse gas; methane (CH_4) and nitrous oxide (N_2O), among other gases, also trap heat. And their concentrations too have risen, adding to the effect of increasing CO_2.

How agriculture is involved

Agriculture is closely tied to GHGs, three in particular: CO_2, N_2O, and CH_4. Historically, large amounts of CO_2 were released when forests were burned and grasslands ploughed to clear lands for farming. Even today, farming is a significant source of GHGs, accounting for about 10 to 12% of global emissions. (This does not include emissions from land-use change, which releases additional amounts.)

FIGURE 3

INCREASES IN ATMOSPHERIC CO_2 CONCENTRATIONS (CONCENTRATIONS OF ATMOSPHERIC CO_2 MEASURED AT MAUNA LOA, HAWAII.)



Source: C. D. Keeling, S. C. Piper, R. B. Bacastow, M. Wahlen, T. P. Whorf, M. Heimann, and H. A. Meijer, Exchanges of atmospheric CO_2 and $^{13}CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000. I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages, 2001. Data available online at: http://scrippsco2.ucsd.edu/data/data.html, accessed November 14, 2007

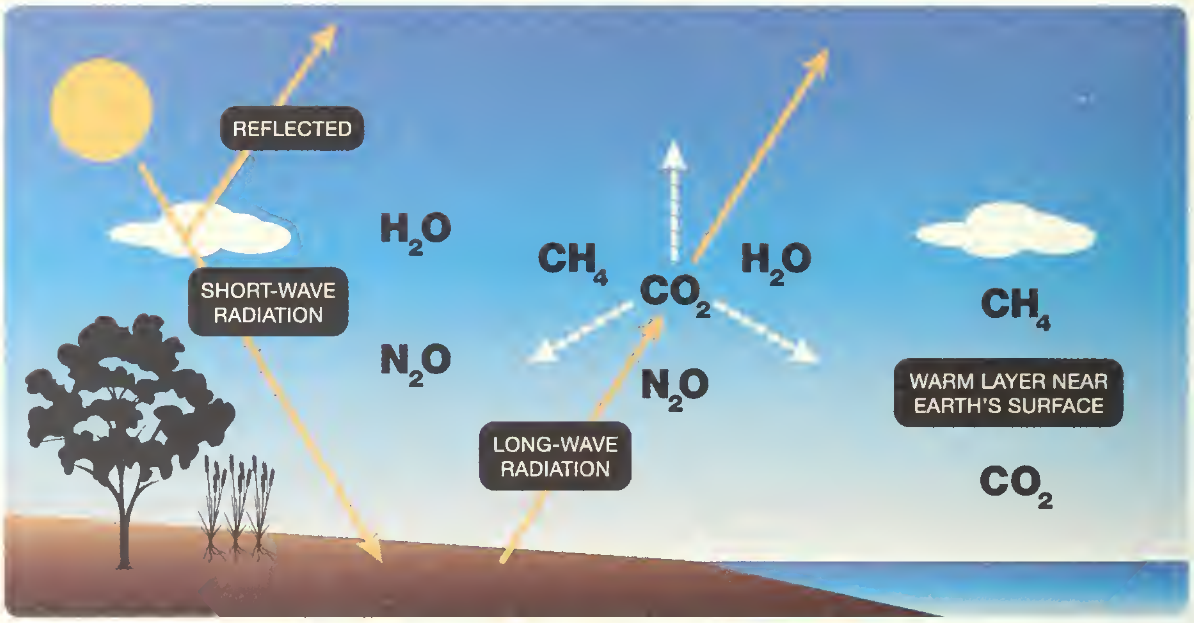
FIGURE 4

ANNUAL EMISSIONS OF CO_2 FROM FOSSIL-FUEL BURNING, CEMENT MANUFACTURE, AND GAS FLARING (1 Pg = 1000 Mt).

Source: Marland, G., T.A. Boden, and R. J. Andres. 2007. Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy: Oak Ridge, Tenn., U.S.A.

FIGURE 5

THE GREENHOUSE EFFECT



The earth continually receives radiation from the sun, part of which (about 30%), is directly reflected back into space by clouds, other material in the atmosphere and the Earth's surface, especially where it is covered by snow or other light-colored material. The rest, about the energy equivalent of several light bulbs per square metre, is absorbed by the Earth. The Earth, having been warmed, emits radiation back into space, but this radiation does not pass easily through the atmosphere. Some of the gases in air—termed greenhouse gases (GHGs)—absorb and re-emit the Earth's radiation, creating a layer of warmth next to the Earth's surface. The greenhouse effect, therefore, arises because of the difference between the sun's radiation, called ***short-wave radiation****, which passes through the GHGs, and the Earth's radiation, called* ***long-wave radiation****, which does not. The two forms of radiation differ because of the temperature of their sources—the sun is much hotter, so its radiation has a shorter wavelength visible to our eyes; the Earth's radiation is more like the warmth we feel emanating from a hot-water radiator.*

The greenhouse effect is essential to life on earth; without its warming effect, the Earth would be cold and inhospitable. Increasing concentrations of the GHGs, however, could lead to an ***enhanced*** *greenhouse effect, causing some unpleasant changes to our climate.*

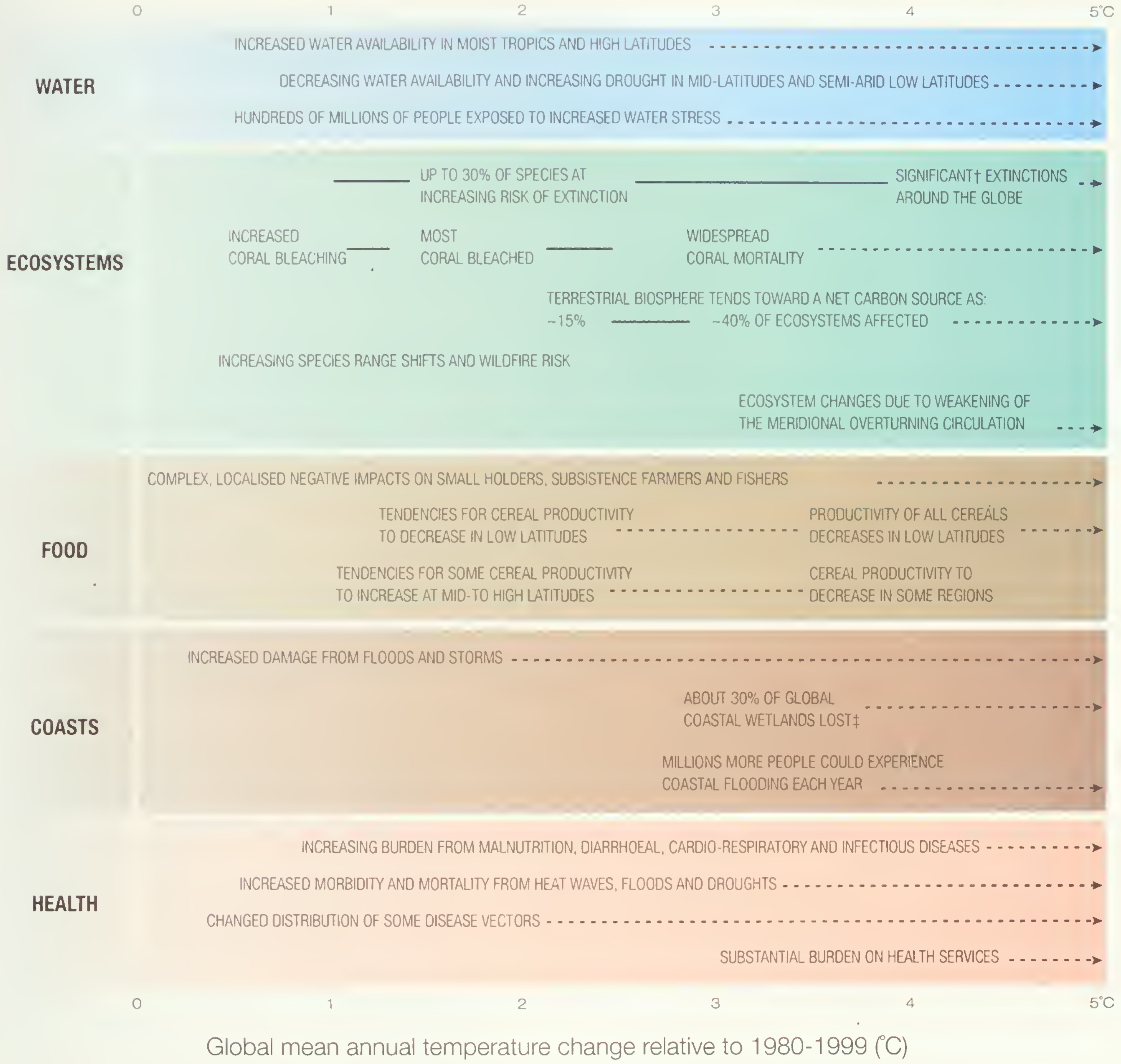
In agriculture, unlike other sectors, most GHG emissions occur as CH_4 and N_2O, two very potent GHGs. As Table 1 shows, agriculture is the main *anthropogenic*, or human-derived, source of these GHGs. Methane is emitted mostly from ruminant livestock, such as cattle and sheep, and N_2O comes mostly from the action of soil microbes as they process nitrogen, especially in soils with high amounts of added nitrogen from fertilizer or manure.

FIGURE 6

POSSIBLE GLOBAL IMPACTS

These are examples of what could happen as a result of varying levels of surface temperature increase in the 21st century.

Source: IPCC, Working Group II 2007 Summary for Policymakers Available online at http://www.ipcc.ch/SPM13apr07.pdf, accessed November 14, 2007.



†Significant is defined here as more than 40%

‡Based on average rate of sea level rise of 4.2mm/year from 2000 to 2080.

TABLE 1

THE MAIN GHGs EMITTED OR ABSORBED BY FARMS

A gas's global warming potential indicates how effectively the gas warms the atmosphere. For example, a kilogram of CH_4 is 25 times more powerful than a kilogram of CO_2 in warming the air. The estimates for global warming potentials keep evolving as scientists learn more. The estimates shown here were reported by the Intergovernmental Panel on Climate Change in 2007.

	CHEMICAL SYMBOL	PRE-INDUSTRIAL CONCENTRATION	CONCENTRATION IN 2005	GLOBAL WARMING POTENTIAL	IMPORTANT HUMAN-DERIVED SOURCES
Carbon dioxide	CO_2	280 ppm	379 ppm	1	Fossil fuel burning; deforestation
Methane	CH_4	715 ppb	1774 ppb	25	Agriculture; fossil fuel use
Nitrous oxide	N_2O	270 ppb	319 ppb	298	Agriculture

Agriculture, however, also has an important role in *decreasing* the concentration of GHGs in the atmosphere. When farmlands were first settled, they lost a great deal of the carbon stored in their soils; the Canadian Prairies, for example, lost to the air as much as 30% or more of the carbon stored in their organic matter (humus) within decades of initial ploughing. As our chapter on carbon explains, we now know that with improved agricultural practices, we can rebuild the carbon stored, thereby extracting CO_2 from the air. Every tonne of new carbon stored in soil is a tonne less carbon in the air. This process, called *carbon sequestration*, is seen by many countries—including Canada—as one way to reduce net overall emissions of GHGs.

Given the prominence of agriculture as both a *source* and potential *sink*—or absorber—of GHGs, much research has been undertaken recently to understand both processes. The immediate aim of these activities is to help meet Canadian targets for reduced emissions of GHGs. At present, improvements in farming practices alone can play only a small part in the overall challenge. But they serve as an example of one response that, when joined by small responses from other sectors of society, can add up to robust reductions.

GHGs are our bellwethers

There is another benefit to all this research—one often overlooked. GHGs emitted in excess tell us something about how efficiently an ecological system—for our purposes, a farm—is performing. If the land is emitting large amounts of N_2O we may conclude that nitrogen, an expensive commodity and potential pollutant, is not being used wisely. If livestock are releasing excess amounts of CH_4, we know that feed energy is not being used optimally. If soils are losing carbon, we know that solar energy stored as soil organic matter is not being prudently invested.

Put simply, GHGs are signals that indicate how well our ecosystems perform and that point us toward more efficient methods for farming land and livestock. This benefit, not always seen, already merits devoted study of GHGs, even apart from goals of meeting reduction targets.

Our aim for this publication is to review recent findings about GHG emissions from farms in Canada. Much of what we present is from research carried out over the past five years under the Model Farm Program of Agriculture and Agri-Food Canada. We have bolstered this information freely with results from other Canadian and international scientists. We seek not only to show how better farming practices can reduce GHG emissions, but also how the emerging science of GHG reduction can help steer us toward better farming practices.

The science stories we tell here are of interest to those in farming communities and to all citizens. As the freely circulating GHGs demonstrate, we are all connected; the gases do not honor the boundaries between farms and forests, between farmland and city centres, or between those living today and generations unborn.

Carbon Dioxide

MANAGING CARBON IN AGRICULTURAL SYSTEMS

As Charles Darwin concluded his seminal work, *The Origin of Species*, he reflected on the intricacies of life on Earth and the variety of forms that have arisen through natural selection. “There is *grandeur* in such a view of life,” he said. Had Darwin been a biochemist, he would undoubtedly have marveled at the simplicity and beauty of the chemical thread that connects all living things and ties them firmly to their surroundings—a thread spun from carbon atoms.

Carbon is a chemical element found in all living organisms. Bonded to itself, it forms chains and rings that create the backbone of biochemically important compounds, from sugars to the hereditary molecule DNA. This chapter describes the flow of carbon through agricultural systems and pays particular attention to its presence in soils. To begin this discussion, it is helpful to place agriculture in the context of the global carbon cycle and to understand the role of carbon in climate change and energy transfer.

The carbon cycle on a global scale

All of the carbon present in the global carbon cycle today was present at the formation of our solar system. The fourth-most abundant element on Earth, carbon moves through a major biogeochemical cycle, through living organisms on its way to or from the air, through the Earth’s interior and surface lands and through the oceans and other waters. Carbon atoms reside in certain chemical forms for thousands of years and in others for mere hours.

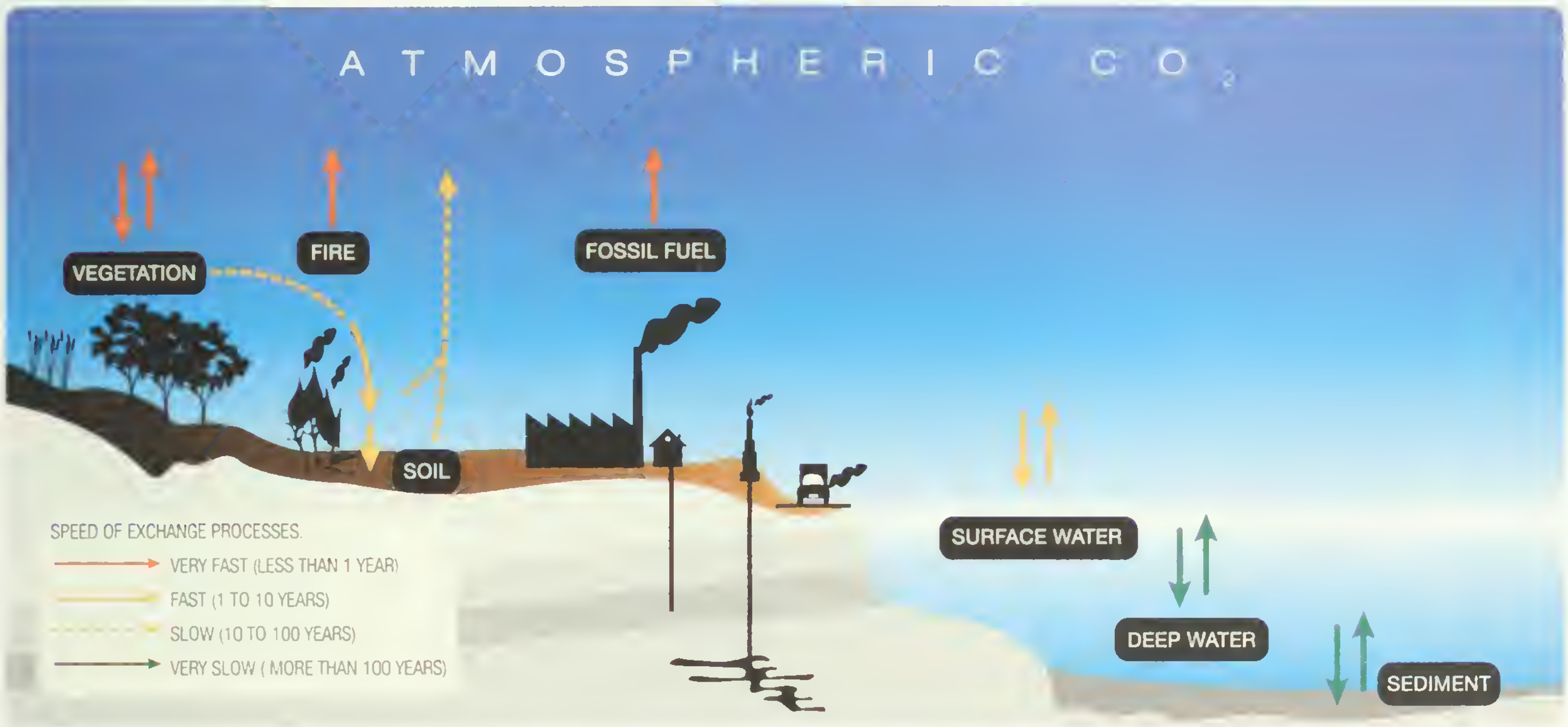
In the nonliving environment, carbon exists in a number of forms:

- CO_2 in the atmosphere and water
- Carbonates, such as calcium carbonate, found in limestone and coral
- Fossil fuel deposits, such as coal, petroleum and natural gas, formed from the tissues of organisms that lived in the distant past
- Organic matter in soils

Carbon enters the living organisms through photosynthesis. Plants, known as primary producers, absorb CO_2 into their leaves from the atmosphere and use energy from the sun to fix the carbon into sugars. These sugars provide energy for the plant and become basic building blocks of plant tissue. Carbon moves through the food chain when herbivores eat the plants and other creatures eat the herbivores. In this way, carbon comes to be found in all living tissues.

FIGURE 7

THE GLOBAL CARBON CYCLE



Source The Third Assessment of the Intergovernmental Panel on Climate Change, 2001

FIGURE 8

PHOTOSYNTHESIS AND RESPIRATION

PHOTOSYNTHESIS:

CO_2 + LIGHT+ H_2O -------------→ $CH_2O + O_2$

Photosynthesis transforms solar energy into chemical energy. Carbon dioxide from the atmosphere is combined with light from the sun and water taken up by plant roots. This reaction forms in plant compounds such as carbohydrates while releasing oxygen to the atmosphere.

RESPIRATION.

$CH_2O + O_2$ ------------→ $CO_2 + H_2O$ + ENERGY

Respiration allows organisms to use the energy manufactured during photosynthesis. The carbon in plant compounds is combined with oxygen. This reaction releases carbon as CO_2 and releases water and some energy as heat.

Carbon returns to the atmosphere or water through the cellular respiration of living organisms. During this process, sugar is *burned* in the presence of oxygen. This generates CO_2, which is released by the organism as a waste gas into the surrounding air. An important example of such respiration is *decomposition* or *decay*, whereby the tissues of once-living organisms are consumed by microbes, releasing the carbon they once held. Similar combustion chemistry takes place during forest fires or when humans burn fossil fuels to supply their energy needs. All of these actions release CO_2 into the atmosphere. Some carbon is also released as CH_4 when decay happens in the absence of enough oxygen to produce CO_2.

METHANE DYNAMICS IN AGRICULTURAL SOILS

Agricultural soils emit large amounts of N_2O and can be either a source or a sink for atmospheric CO_2. They can also produce or consume CH_4, but in much smaller quantities.

Methane is the main constituent of natural gas and its oxidation releases considerable amounts of energy. Some soil bacteria called methanotrophs can metabolize CH_4 as a source of energy and carbon when conditions are well aerated. In soils on farms being drained to eliminate excess water, this reaction occurs in most of the agricultural land during the growing season, but at very low rates. Indeed, approximately 100 hectares of land are required to oxidize the quantity of CH_4 produced by one lactating dairy cow.

Other soil bacteria, or methanogens, produce CH_4 during anaerobic decomposition of organic substrates. Their activity in water-logged portions of the farm such as ditches or near leaky manure storage structures can result in small net CH_4 emissions.

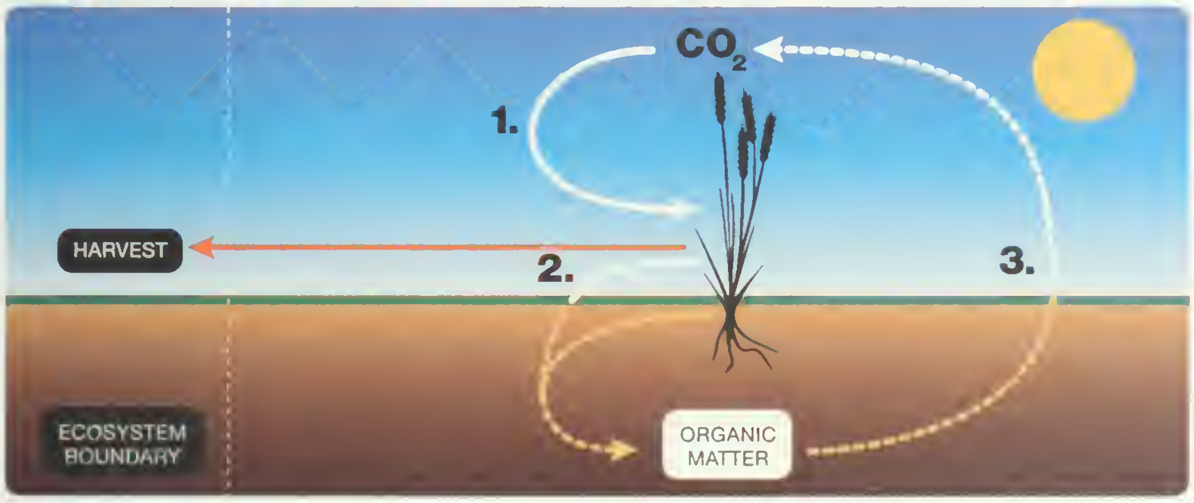
The carbon cycle on the farm

As in natural ecosystems, plants in agroecosystems absorb, or *fix*, carbon through photosynthesis. Some of this carbon is returned to the atmosphere in the form of CO_2 through cellular respiration. Some is removed from the system through harvesting. The remainder remains in the soil in the roots of plants or is incorporated into the soil in the form of aboveground crop residues.

As microbes decompose these residues, part of the carbon is returned to the atmosphere as CO_2, some is incorporated into the microbes and the rest becomes soil organic matter. In farming systems that include animals, carbon may be removed from the system in the form of animal forage and feed and subsequently in animal products such as meat—and then returned to the soil in manure. Animals also respire, emitting CO_2 directly into the atmosphere.

FIGURE 9

The Carbon Cycle in an Agricultural Ecosystem



Soil carbon is dynamic. Changes in the amount of carbon stored in soil organic matter depend on the relative rates of carbon input from plant litter and carbon emitted as CO_2 via decomposition. If carbon inputs are greater than carbon loss, then the amount stored increases; if carbon input is less then carbon loss, the amount of carbon stored decreases. To increase stored carbon, practices must either: 1) increase plant yield (photosynthesis); 2) increase the proportion of fixed carbon added to soil; or 3) slow the rate of organic matter decomposition.

Carbon's importance to climate change

Since the beginning of industrialization—about 150 years ago—the amount of carbon in the atmosphere has risen by more than 30%, from 280 to 380 ppm. Between 1970 and 2004, global CO_2 emissions increased by 70%, making it the most important *anthropogenic*—man made—of the greenhouse gases. This increase has resulted mostly from the growing use of fossil fuels for energy and, to a lesser extent, from changes in land use, such as deforestation to make room for agriculture and settlements.

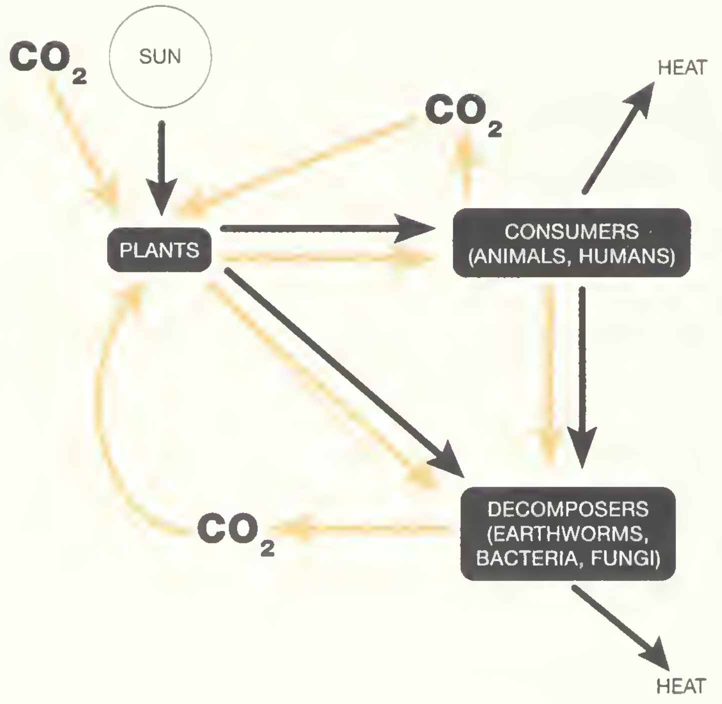
Rising atmospheric levels of CO_2 have raised fears of disruptive changes in climate, prompting scientists and policy makers to look for ways to slow down the rate of increase. This concern begs a more comprehensive understanding of how carbon cycles through the Earth's ecosystems, including agroecosystems and how this flow is tied to energy.

Carbon as energy currency

Virtually all of the energy used by living systems can be traced back to the sun. Photosynthesis ultimately traps light energy from the sun in the bonds that hold sugar molecules together. Thus, the energy in all organic compounds resides in their constituent chemical bonds and flows through ecosystems in the form of these bonds. During fuel combustion this energy is released as heat, which humans use to heat their buildings, power the pistons in their car engines and drive turbines to generate electricity. As cells respire, the combustion of sugars inside cells releases energy. That energy is either captured in the molecule adenosine triphosphate (ATP) or lost as heat. It is ATP that drives most of the energy-requiring reactions at the cellular level, moving the body's muscles and synthesizing complex chemical compounds.

FIGURE 10

CARBON AND ENERGY FLOWS THROUGH AN ECOSYSTEM



Energy

In photosynthesis, plants transform radiant energy from the sun into chemical energy, which is stored in the plant. This energy is passed from organism to organism through the food chain. Plants are consumed by animals and humans, who either use the energy—to move, eat and think—or lose the energy as heat. Decomposers, such as earthworms, bacteria and fungi, eat dead organic matter from plants and waste from consumers and use the energy or lose it as heat. All the energy in ecosystems comes from the sun and is eventually lost as heat. Energy is not recycled through the ecosystem.

Carbon

In photosynthesis, plants take up carbon in the form of CO_2 *from the atmosphere. Plants use this carbon to make sugars and starches that then become the plants' leaves and fruits. As plants are consumed by other organisms, carbon is passed on. Each time carbon is passed to another organism some of it is lost to the atmosphere as* CO_2*, where it can be used again by growing plants. All the carbon in the ecosystem comes from the atmosphere and will ultimately be returned to the atmosphere. Carbon is recycled through the ecosystem.*

UNDERSTANDING ENERGY UNITS

The amount of energy held in the food we eat is often referred to as calories. A calorie is simply a unit for measuring energy. Technically speaking, it is the amount of heat needed to raise the temperature of one millilitre of water by one degree Celsius. The calorie as a unit of energy has been replaced by the "joule" in the scientific community. One calorie is equivalent to about four joules, and the kilojoule (kJ) is 1000 joules.

Some of the energy held in organic compounds remains stored in ecosystems for years, even millennia. It can be stored either in plant materials, such as wood, or in soil organic matter—called *humus*—which is derived from the decaying tissues of dead organisms. The more carbon stored in an ecosystem, the more energy it holds. A very small proportion of organic matter becomes trapped over long periods of time in deposits of fossil carbon, such as coal, oil and natural gas. Humans harvest these deposits, called fossil fuels, and burn them to meet energy needs—in effect releasing solar energy that has been trapped underground for millions of years.

Globally, plants remove about 120 billion tonnes of carbon from the atmosphere each year. Averaged over the Earth's total land area, this translates to about eight tonnes of carbon per hectare (roughly the size of a football field). About half of this carbon is used by the plants themselves for their own energy requirements, leaving about 60 billion tonnes (four tonnes per hectare) to be stored in plant tissue. This storage value is termed *net primary production* (NPP). The amount of carbon stored at any given site is influenced by many factors, including climate and plant type. For example, the NPP in a tropical rainforest is much higher than that in a desert. All this carbon is either eaten by animals, burned by fire, or returned as plant litter to soil where it eventually decays.

The energy content of plant material ranges from 15 to 20 kilojoules per gram. Plants with higher carbon content contain more energy. Important plant compounds with a very high carbon content, and thus a high energy content, are lipids, lignin and proteins.

TABLE 2

THE ENERGY CONTENT OF SOME SUBSTANCES

MATERIAL	ENERGY CONTENT ($kJ^{1} g^{-1}$)
Cellulose	18
Starch	17
Lipid	39
Terrestrial plants (whole)	19
Terrestrial plants (seeds)	22
Insects	24
Wood (oak)	21
Peat	20
Forest humus	21
Soil organic matter	20
Charcoal	34
Coal	29-34
Crude oil	42
Diesel	48
Natural gas	38-50
Biodiesel	38
Methane	55
Ethane	52
Uranium-235	77,000,000
Nuclear fusion (^{2}He-^{3}He)	300,000,000

Sources: Energy Content of Biofuel. Available online at. http://en.wikipedia.org/wiki/Energy_content_of_biofuel. Accessed Nov. 12, 2007.

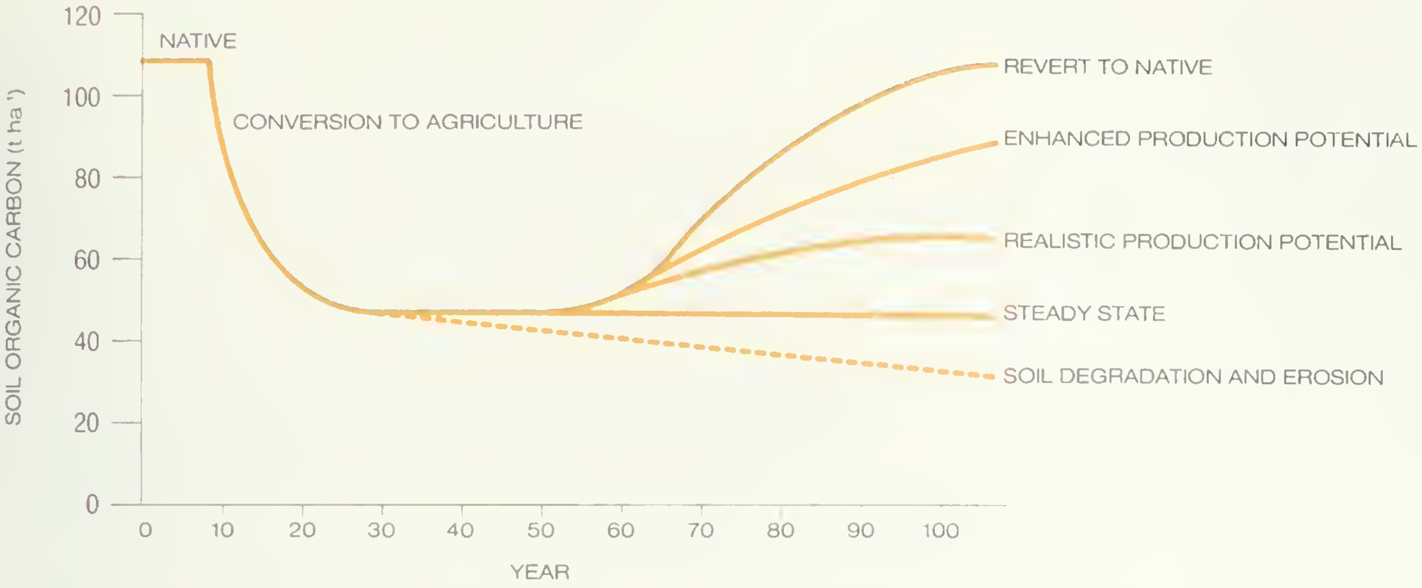
Discharging soil battery

Soils can hold a lot of carbon. For example, in a field of corn, the amount of carbon present in the top 60 centimetres of soil may be 10 times the amount held in the above-ground vegetation. Soil carbon represents a high reserve of energy in the soil. In effect, soil is much like a battery that can be depleted of its energy in some ways and recharged in others.

In an untouched native ecosystem, the soil has been charged up over the millennia, allowing soil carbon levels to reach maximum capacity, or equilibrium level. Any disturbance of this equilibrium results in a loss of carbon and thus a loss of energy. Cultivation and erosion are what most deplete soil carbon and discharge energy from the soil battery.

FIGURE 11

The Effects of Cultivation on Soil Carbon



Changes in soil carbon content occur whenever there is change in land-use or management practice. When virgin native land in Canada was first broken and cultivated, about one third of the carbon content was lost within 20 to 30 years. There is potential in Canadian agricultural systems to gain back some of the carbon lost by using improved practices such as no-till and by planting crops, such as legumes, that build soil organic matter levels. Even more carbon gain can be realized through alternative farming practices such as incorporating perennials into cropping systems.

Farmers ploughed the Canadian Prairies for the first time about 100 years ago. Within a few decades, these rich grassland soils had lost 30 percent or more of the total carbon they had stored. This loss of carbon happened in a number of ways:

- Crop plants often contributed less carbon below ground than the native plants they replaced.
- As crops were harvested, carbon was removed from the system. This meant less plant carbon was returned to the soil every year.
- Tillage disrupted stable, protected organic matter in the soil and, along with short-term cropping, often created temperature and moisture conditions in the soil that hastened the decay of carbon-laden organic matter.
- Cultivated soils are more prone to the loss of carbon-rich topsoil via wind, water and tillage erosion.

Cultivation makes soils more susceptible to erosion—the physical movement of soil particles by wind or water. Erosion redistributes soil, removing it from some areas and depositing it in others. Some fields lose 75% of soil organic matter once they have been cultivated.

Severe erosion can strip away surface soil, causing subsequent tillage to mix the now thinner surface soil with subsoil, which is lower in organic matter. This mixing has the effect of diluting the organic matter in the surface soil. Meanwhile, the organic matter eroded from one area is transported to another area, creating a thicker, organic-matter-rich deposit there. Thus, erosion changes both the lateral and vertical distribution of organic matter—and thus of carbon and energy—in the landscape. Reduced levels of organic matter constrain plant growth, and therefore net primary production, which further reduces the amount of dead plant tissue returned to the soil. Soils with less soil organic matter are more susceptible to erosion. The downward spiral continues and the soil is further degraded.

Recharging the soil battery

Soil organic matter levels rise when the input of carbon into the soil (recharging the battery) exceeds the output (discharging the battery). The balance can be swung in this direction by:

- adding more carbon to the soil through increased crop production or by returning to the soil more of plant residue remaining after harvest, or
- decreasing the rate of decomposition of plant residues and organic matter in the soil.

The amount of soil carbon that potentially can be stored—and the rate at which it can be added to the soil—depend on many local factors, including climate, topography, soil properties such as clay content, and cropping history. For example, soils with a history of excessive loss of carbon may have more potential for future gains.

The various agricultural practices that contribute to higher levels of soil carbon can be grouped into the following strategies:

- Reduced tillage
- Intensified cropping systems
- Improved crop nutrition
- Organic amendments of soil
- Greater use of perennial crops
- Improved grassland management

Reduced Tillage

Since farming began, tillage has been used to kill weeds, prepare soils for planting and bury crop residues. In recent decades, the development of new herbicides and advances in the design of seeding implements have made it possible to greatly reduce tillage in many farming systems. *No-till*, or *zero tillage*, the most extreme reduced-tillage system, involves complete elimination of tillage apart from the seeding operation.

Tillage is a critical factor in the overall condition of soils. It alters the soil's water storage properties, which affects crop production and the rate at which organic matter decomposes; it ruptures soil aggregates, which exposes new organic matter to decomposition; it mixes plant residues into the soil, which alters the soil profile and it enhances contact between soil and plant residues.

Clearly, to eliminate tillage is to alter the distribution of carbon in the soil profile. In no-till systems, carbon tends to accumulate near the soil surface and is moved only gradually into deeper layers by natural processes such as earthworm activity. No-till systems also affect the amount of carbon stored because organic matter often decomposes more slowly in no-till soils; contact between soil and plant residues is reduced, isolating plant litter near the surface and leaving aggregates that protect organic matter undisturbed.

Since soil disturbance tends to stimulate soil carbon losses through enhanced decomposition and erosion, the elimination of tillage often results in soil carbon gain, but not always. The amount and rate at which soil-carbon content increases when tillage is eliminated varies with climatic conditions, soil type and the soil's initial carbon content. Elimination of tillage usually has a greater impact on soils with depleted reserves of soil carbon. Soil carbon tends to accumulate most rapidly in less-humid conditions. This is because, in drier areas, no-till has greater potential to conserve moisture and enhance crop yields. Higher crop yields leave more plant litter near the soil surface, which slows decomposition and increases soil carbon in the surface soil layer. Evidence shows that eliminating tillage *may* increase soil carbon reserves, but may not *guarantee* higher soil carbon reserves; the amount of carbon that accumulates depends on location and other management factors.

Intensive cropping

Summer fallow, the practice of leaving the soil unplanted for a growing season, was once widely used in western Canada to replenish soil moisture, control weeds and increase nutrients in the soil. However, summer fallow results in losses of soil carbon; because no crop residue is produced in the fallow year, carbon inputs decline. Summer fallow also creates conditions such as higher moisture content and temperature that favor faster decomposition of organic matter already in the soil. Thus, eliminating summer fallow can significantly increase carbon reserves in soil.

Improved farming practices, notably the development of reduced-tillage systems, have allowed farmers in many parts of western Canada to eliminate summer fallow. This change, along with the reduction in tillage, has been largely responsible for the net storage of carbon in the western provinces since 1990.

Improved crop nutrition

Any practice that increases crop yields adds carbon to the soil, provided that the increased residues produced are returned to the land. Thus, applying fertilizers to nutrient-deficient soils to increase yields often increases soil carbon. This effect is not always measurable since carbon increases can be small relative to the carbon already present. Furthermore, many agricultural soils in Canada are already fertilized at or near optimal levels, so additional carbon gains from adding more fertilizer may be insignificant.

Organic amendments

Farmers have known for millennia that spreading animal manure on a field can improve soil fertility. Manure is rich in organic matter and nutrients and applying it to land usually results in a build up of organic carbon and energy in soil. Applying manure to soil can also indirectly build soil carbon content by increasing crop yields, thereby providing more carbon input to the soil, or by improving soil structure and further protecting soil organic carbon from decomposition. These effects can be considered as true gains in soil carbon, as they either increase net primary productivity or decrease carbon decomposition.

On a global scale, however, recycling of plant carbon through animal manure may not truly increase soil carbon storage. There are really only two ways of storing more carbon: increasing inputs of photosynthesized carbon or slowing decomposition (or a combination of the two). Adding manure accomplishes neither, except to the extent that it increases yield by providing nutrients or improving soil structure. The carbon applied in manure is merely recycled plant carbon and does not represent additional carbon extracted from the atmosphere.

Greater use of perennial crops

As with manure application, the beneficial effects of perennial forage crops on soil quality and fertility have been known for a long time. Today, extensive use of perennial crops is recognized as one of the most effective ways to increase soil carbon. Perennial forages, such as alfalfa, clover, timothy grass and bluegrass, promote the accumulation of soil carbon, because they:

- grow over a longer season than most annual crops, and thus fix more atmospheric carbon;
- transfer a large proportion of their fixed carbon to the roots—up to three times their above-ground production—which may be more important for soil carbon formation; and
- maintain and increase soil structural stability through their extensive roots and because of the absence of tillage during their growth, thereby reducing carbon decomposition.

Improved grassland management

Most of Canada's farmland was once under grass, but conversion of grassland to cropland resulted in large losses of soil carbon. Re-establishing grasses on these lands could replenish soil carbon, perhaps eventually restoring carbon reserves to pre-cultivation levels. When this practice is used on what are often referred to as *set-aside lands*, there may be large gains of soil carbon. However, because this method involves taking land out of crop production, it is probably suited only to marginal lands.

Canada currently has about 28 million hectares of grazing land. Management of these lands—altering the amount and type of vegetation, the amount of residues returned, and the redistribution of soil carbon via livestock activity and erosion—can affect soil carbon reserves. Potential rates of soil carbon gains from improved grazing practices are probably highest on lands that have been degraded. However, rates of accrual have not been extensively documented.

Measuring carbon

It is difficult to estimate the effectiveness of soil recharging practices because changes tend to occur in tiny increments—typically by a fraction of a tonne of carbon per hectare per year. Meanwhile, carbon already present in the soil can amount to 100 tonnes per hectare or more; against such a background it can take years to make definitive measurements. Many of the proposed soil charging practices have not been studied for long enough in sufficient locales to establish with certainty how effective they are. However, some initial estimates are available from measurements in long-term experiments and from running simulation models.

Removing carbon from the atmosphere and locking it up in soils—officially known as *carbon sequestration*—is promoted as a strategy to mitigate climate change. The essence of this strategy is that soil is transformed from being a source that emits carbon into a reservoir that removes CO_2 from the air, often referred to as a *carbon sink*. Although using soil as a carbon sink has potential for reducing atmospheric CO_2 and curbing climate change, the strategy cannot be used indefinitely. Over several decades in a field where agricultural practices have been improved, the rate of carbon gain will gradually diminish, eventually approaching zero. As organic matter accumulates, its decomposition also increases, until eventually carbon losses equal carbon inputs. This is when a field's soil reaches a new equilibrium. Therefore, sequestration of carbon in soil is a temporary measure for extracting carbon from the atmosphere. Furthermore, the carbon stored as soil organic matter may be vulnerable to losses if the climate warms or if carbon-saving management practices are interrupted. For example, carbon gains in soil following elimination of tillage can be rapidly lost when the soil is once again ploughed.

TABLE 5

SOME AGRICULTURAL PRACTICES TO STORE CARBON IN SOIL, THE TOTAL AREA OF LAND AFFECTED AND THE POTENTIAL RATES OF CARBON GAIN OVER 20 YEARS

PRACTICE	AREA (10^6 ha)	RATES (t C ha^{-1} y^{-1})	CONFIDENCE HIGH, MEDIUM, LOW
Cropland			
1. Reduce tillage	4-6	0.0 to 0.4	M
2. Eliminate summer fallow	3	0.0 to 0.5	H
3. Include more forages in rotations	4	0.0 to 0.5	M
4. Increase residue return by increasing yields (e.g., nutrient amendment, irrigation, better varieties) or avoiding removal or burning	5	0.0 to 0.3	M
5. Restore permanent grass or woodland	1	0.2 to 1.0	H
6. Use organic residues (e.g., manures, biosolids, crop residues) more efficiently, especially to restore depleted soil	1	0.1-0.5	H
Grazing land			
1. Improved grazing practices (e.g., changes in grazing intensity or frequency)	10	0.0 to 0.1	L
2. Increase productivity (e.g., nutrients amendment, irrigation, new species)	1	0.0 to 0.3	M

The critical importance of soil organic matter

Soil fertility and plant nutrition

In addition to carbon and energy, soil organic matter also contains large quantities of the critical plant nutrients phosphorus, sulphur and nitrogen. Nitrogen is the most important plant nutrient. In fact, a lack of it is the key limiting factor for productivity in natural and agricultural ecosystems. Practices that promote the accumulation of soil organic matter and soil carbon also increase the potential supply of nitrogen as 99% of it is contained in organic matter.

Soil organic matter also contributes to fertility through its influence on the *cation exchange capacity* (CEC) of soils—the soil's ability to hold onto positive ions, such as the nutrient potassium and some micronutrients. In fine-textured soils the CEC is largely controlled by clay content, but in some sandy soils almost all CEC can be attributed to soil organic matter.

Physical condition of the soil

Soil organic matter affects the physical properties of soil, stabilizing its structure and holding its particles together in small clumps called *aggregates*. In doing this, organic matter helps prevent soil erosion by water, wind and tillage. By holding soil particles together, soil organic matter also helps to create pore space in the soil, permitting the circulation of air and water and encouraging the proliferation of living organisms, including plants.

Continuous or repeated incorporation of fresh plant material into soil is a good way to maintain its structural stability. Fresh plant material and other organic residues accelerate microbial growth in the soil, generating more compounds that glue soil particles together. These binding agents include microbial gum, humic substances, lipids and microbial structures such as filamentous fungal hyphae. Improved aggregation protects the decomposing organic matter from further decomposition through a feedback mechanism. If organic matter is not replenished regularly, or if soil is disturbed by heavy rainfall or intensive tillage, the aggregates can be broken, exposing their interiors and accelerating the decomposition of organic matter and binding agents. Without organic matter, sandy soils would look like beach sand and many other soils would feel like concrete.

Soil organic matter also improves the water-holding capacity of soils. This feature is particularly critical in sandy soil, which would otherwise be able to hold little water for plant use.

Good soils contribute to great farming

In short, a soil that has more organic matter, and hence carbon, is usually a better soil, which means conserving or enhancing soil organic matter has benefits far beyond concerns about climate change mitigation. Replenishing soil carbon reserves—an issue that was the subject of intensive research for decades before climate change issues came to prominence—is simply good agricultural practice.

FURTHER READING

Janzen, H.H. 2005. Soil carbon: A measure of ecosystem response in a changing world? *Canadian Journal of Soil Science* 85: 467–480.

Jenkinson, D.S. 1981. The fate of plant and animal residues in soil. Pp. 505–561. In: D.J. Greenland and M.H.B. Hayes (ed.) *The chemistry of soil processes.* John Wiley & Sons Ltd.: New York.

Smith, P. et al. 2007. Agriculture. Pp. 497-540. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds). Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press: Cambridge, United Kingdom and New York.

Swift, M.J., O.W. Heal, and J.M. Anderson. 1979. Decomposition in terrestrial ecosystems. University of California Press: Berkeley, CA.

Energy Content of Biofuel. Available online at: http://en.wikipedia.org/wiki/Energy_content_of_biofuel. Accessed Nov. 12, 2007.

Nitrous oxide

PLUGGING LEAKS TO THE ENVIRONMENT

PLANTS ARE IMMERSED IN A SEA OF NITROGEN—78% of the air is nitrogen gas—yet this nutrient is the one most often lacking in plants and, therefore, limiting their growth. That is because nearly all the nitrogen in air is dinitrogen (N_2), two nitrogen atoms bound together by a sturdy triple chemical bond. Only when this bond is broken, can plants use the nitrogen.

In nature, the breaking apart of dinitrogen to create *reactive nitrogen* occurs mostly by the activity of select bacteria through a process known as dinitrogen-fixation. One such group of bacteria, known as Rhizobia, reside in nodules attached to the roots of legumes such as alfalfa, beans and peas. Once *fixed*, the nitrogen reformulated by these bacteria can be used by plants. When the plants decay, they release their nitrogen into the soil for use by other plants. Alternatively, the plants may be consumed by animals, which return nitrogen to the soil when animals' bodies decay or via animals' wastes. Livestock, for example, obtain their nitrogen from protein they consume in feeds and then excrete most of the nitrogen through their urine and feces, returning it to the soil to be reused by plants.

The advent of synthetic fertilizers

About a century ago, humans learned how to fix nitrogen industrially, using intense heat and pressure through a process known as the Haber-Bosch process. This discovery revolutionized agriculture, making vast amounts of reactive nitrogen available and launching more intensive and productive farming methods. About 40% of the nitrogen in protein now consumed by humans worldwide is fixed industrially.

Unfortunately, the reactive nitrogen so essential for crop production is unstable. The nitrogen cycle is therefore leaky—nitrate and soluble organic nitrogen leach out of the soil profile, and gases (dinitrogen, ammonia, N_2O, nitric oxide and others) seep into the air. Such losses are especially prevalent in agricultural systems that use a great deal of nitrogen to maintain productivity and replace nitrogen lost in harvested materials.

Leaks cause damage

Many of the nitrogen forms lost through these leaks can cause environmental damage. Nitric oxide and N_2O, for example, can accelerate the breakdown of the ozone layer in the stratosphere, a process that lets in an increasing amount of

harmful ultraviolet radiation. Nitrate in excess concentrations can make water unsafe to drink, leading to methaemoglobemia or blue-baby syndrome in infants; nitrate can also lead to algal blooms in standing water. Ammonia, when deposited back onto land or water as a gas or in rain can acidify soils, affect water quality, cause forests to die back and change the plant population in natural ecosystems by making them more vulnerable to invasive species.

In this chapter we focus specifically on N_2O, because it is a greenhouse gas (GHG), and a very potent one at that. It is about 300 times as powerful as CO_2. Nitrous oxide emissions can emanate directly from farm soils and stored manure. These are often referred to as *direct* emissions. But nitrogen is also lost from agricultural systems in other forms, via leaching or volatilization. This nitrogen can be a source of N_2O emissions produced at sites outside the boundaries of the farm. These N_2O emissions, often referred to as *indirect* or *off-site* emissions, must also be included in the overall accounting of N_2O emissions originating from agricultural sources.

Although emissions of N_2O represent only a small proportion of nitrogen lost from farms, they account for about 50% of the warming from gases emitted from agriculture. Finding ways of suppressing N_2O releases, therefore, is critical if we are to reduce the effects of farming on global warming.

How N_2O is formed

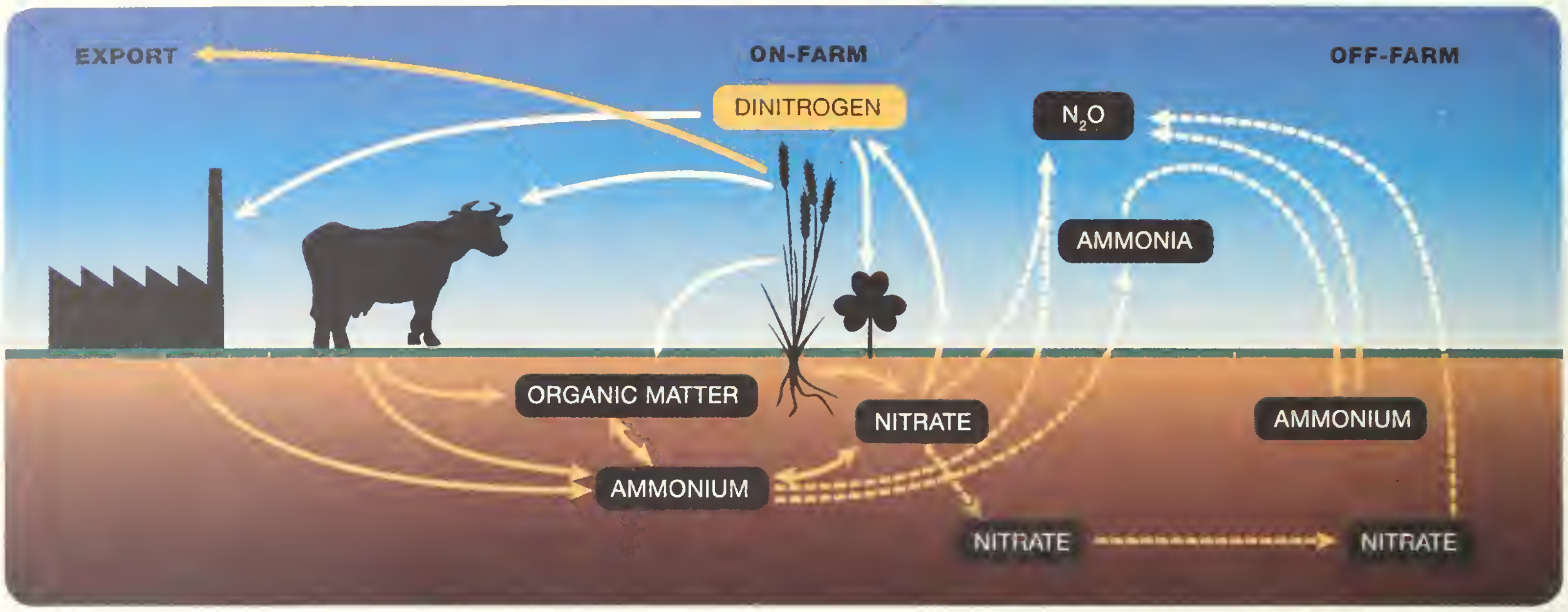
The nitrogen cycle

Nitrous oxide is released as a product or byproduct when microorganisms convert nitrogen from one form to another in the soil. To understand these emissions, we must review the processes whereby nitrogen flows through the soil.

Nitrogen can enter the soil in both organic and inorganic forms. Organic forms include plant litter, animal manures and other materials derived from plant or animal products. When these organic materials enter the soil they are gradually decomposed by soil fungi and bacteria, which release the nitrogen as ammonia, which, when dissolved in the soil water, becomes ammonium. Ammonium can be taken up by plants, but is usually converted quickly to nitrate by soil microbes in aerated soils (soils high in oxygen).

FIGURE 12

CONCEPTUAL VIEW OF THE NITROGEN CYCLE ON CANADIAN FARMS.



Nitrous oxide can be produced at many points in the cycle.

Thus, nitrogen typically flows from organic nitrogen to ammonium to nitrate, which accumulates in soil and is readily taken up by plants again. In some conditions, especially when soils are poorly aerated (low in oxygen), the nitrate can be *reduced* to dinitrogen gas through a process called denitrification. This process renders the nitrogen unavailable to plants.

In agricultural lands, soil nitrogen is often supplemented with industrially fixed nitrogen, applied as fertilizer. Once in the soil, this nitrogen behaves no differently than nitrogen from organic sources. Though forms vary, most fertilizers contain nitrogen as ammonia, ammonium, nitrate or urea. The first three enter directly through the processes already described; urea, a nitrogen form similar to that in urine, is quickly converted to ammonia in soil and then enters the same cycles. One important difference from incorporating nitrogen in organic form, however, is that applying fertilizer typically adds instantly a large pulse of reactive nitrogen that is immediately available to plants and microorganisms. Since plants cannot take up all of this nitrogen immediately, it remains in solute or gaseous forms and often produces more N_2O emissions.

In addition to fixation of N_2 by bacteria, nitrogen is also added to soils from the atmosphere, either as gas or particulates or in precipitation. Small amounts of this nitrogen are fixed by lightning, but most comes from ammonia or other forms of nitrogen released from such sources as feedlots. Thus, the rate at which nitrogen is deposited on soils varies depending on the proximity of a given field to sources of gaseous nitrogen. In Canada, deposition of atmospheric nitrogen is usually quite small compared to amounts from other sources.

Whatever the source of nitrogen, once it takes the form of ammonium or nitrate, it is readily absorbed by plants. If the plant is a farm crop, much of that nitrogen is exported in harvested product—grains, forage or animal products. This export is by far the largest loss of nitrogen from a soil-plant system. It will be consumed by humans or animals, excreted and mineralized back into an inorganic form. Each time a molecule of nitrogen is converted to an inorganic form it is susceptible to loss in gaseous forms such as nitric oxide, N_2O, ammonia and particularly dinitrogen. Thus, perhaps after many transformations, nearly all of the nitrogen that entered soils from the atmosphere will be returned to the atmosphere, thereby closing the nitrogen cycle.

In summary, a soil nitrogen molecule has an eventful existence. Some nitrogen is incorporated into soil organic matter that will have a very slow turnover (decades to centuries), but most of it is continually being transferred or cycled between organic and inorganic forms. This cycling of nitrogen between organic and inorganic forms may occur many times before the nitrogen is lost from the farm system through leaching, gaseous exchange or crop removal.

Processes of N_2O formation

Nitrous oxide can be released from various phases of the nitrogen cycle through a multitude of biological processes. Although many processes in soils can produce N_2O, most soil-emitted N_2O is thought to derive from two processes—nitrification and denitrification. Broadly stated, nitrifiers oxidize ammonium to nitrate. The amount of N_2O produced per unit of ammonium nitrified is usually small, but cumulative losses can be important on an annual basis. Denitrifiers transform nitrate to N_2O and/or dinitrogen. The amount of N_2O produced per unit of nitrate denitrified can be quite large and denitrification is a major pathway for N_2O emission from agricultural soils.

Delving Deeper

Nitrification is carried out by both autotrophs and heterotrophs, but the latter group is thought to be a minor contributor in agricultural systems. Autotrophic nitrification occurs in two stages, each stage conducted by separate groups of bacteria. The oxidation of NH_4^+ to nitrite (NO_2^-), typically represented as $NH_4^+ \rightarrow NH_2OH \rightarrow HNO \rightarrow NO_2^-$, is followed by the oxidation of NO_2^- to NO_3, which is completed in a single step.

Denitrification can be defined as the dissimilatory reduction of ionic nitrogen oxides to gaseous products by essentially aerobic bacteria under conditions of oxygen deficiency. The reaction sequence is usually represented as: $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$. Most denitrifying bacteria possess all the reductase enzyme complexes necessary to reduce NO_3- to dinitrogen, but some are not equipped with N_2O reductase and N_2O is the terminal product.

Even the broad categories of *nitrifier* and *denitrifier* are not clear cut as, for example, some nitrifiers can also denitrify (nitrifier-denitrification). In some situations nitrifier-denitrification can be an important contributor to soil-emitted N_2O. In addition, N_2O might also be generated by dissimilatory reduction of NO_3^- to NH_4^+ (DNRA) and other unidentified biochemical pathways, but the contribution from these pathways is likely negligible in Canadian agricultural soils.

Indirect N_2O emissions

Nitrogen can be lost from farms in many of its forms. Predominantly, it is lost in the forms of N_2O and dinitrogen via denitrification, nitrate via leaching, and ammonia via volatilization. Dinitrogen usually represents the largest loss, but it is not an environmental concern since nitrogen simply returns to the atmosphere as an inert gas. Leached nitrate and volatilized ammonia, on the other hand, are significant sources of N_2O via processes occurring off-site.

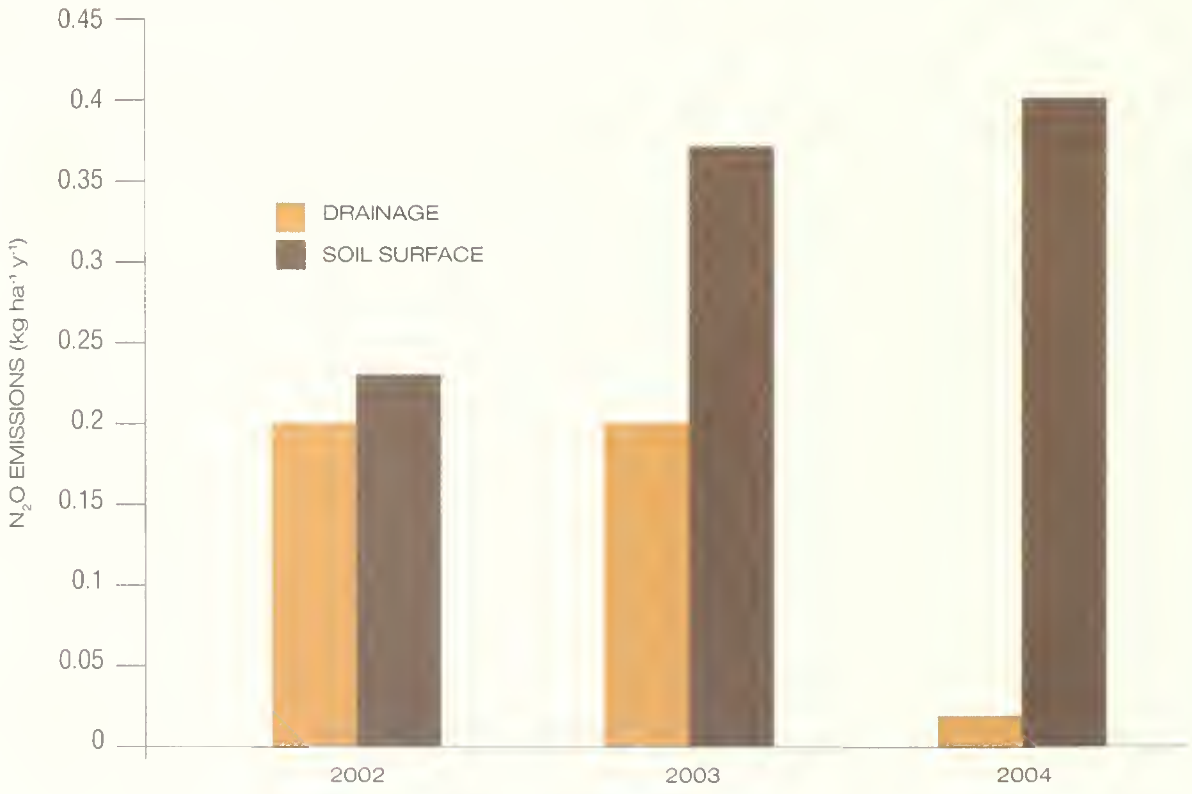
Nitrate leaching

Soils are negatively charged and therefore attract positively charged ions such as ammonium, K^+, and Ca^{++}. Nitrate, conversely, is negatively charged and will remain dissolved in soil water. If, under excess precipitation or irrigation, soil water flows through the soil and into groundwater below, the nitrate is carried with it; in other words, it is lost via leaching and ends up in groundwater or streams. Most nitrate loss from tile drains occurs in the late fall and early spring (between cropping seasons).

Though it is difficult to determine the exact amount, a fraction of the nitrate leached from farm fields can be further converted downstream to N_2O. This N_2O could be either from out-gassing when drainage water leaves agricultural fields or from denitrification if conditions are favourable.

FIGURE 13

N_2O DEGASSED FROM DRAINAGE WATER



Some of the N_2O that is produced in agricultural soils can dissolve in soil water and escape the field through drainage tiles. In this example, the amounts of N_2O degassed from the drainage water can be as large as soil-surface N_2O emissions.

Source: Dave Burton, Nova Scotia Agricultural College, Truro, NS

How much nitrogen is lost by leaching from Canadian farmlands? Estimates of average losses vary widely, with values as low as 2 kilograms of nitrogen per hectare per year in arid Canadian Prairies and as high as 30 kilograms of nitrogen per hectare per year in humid regions, the central provinces falling somewhere in between. Indirect loss of N_2O associated with nitrate leaching in Canada contributes approximately 9% of total N_2O emissions from agricultural sources.

Ammonia volatilization

Ammonia is released from ammonium dissolved in water. Thus, small amounts of ammonia can be generated wherever ammonium exists in solution: from soils, growing plants, even the breath of animals. Not surprisingly, most of the ammonia released from farms comes from highly concentrated sources: the urine of livestock, which contains high concentrations of urea, quickly hydrolyzed to ammonium; animal manures, which contain urine, but also ammonium from decomposing feces and bedding materials; ammonium-based fertilizers; and crop residues, which release ammonium when they decay.

The amount of ammonia released from farms may range from negligible traces to concentrated plumes that can be detected by smell. The most prominent factors affecting amounts emitted include: the concentration of ammonium in solution, which influences the strength of the ammonia source; the pH of the solution, which determines the relative abundance of ammonia and ammonium; and the degree of contact of the solution with the atmosphere, which affects how easily the ammonia will be emitted into the atmosphere.

Much of the ammonia transported in the atmosphere is eventually absorbed in a gaseous state by the ground or dissolved in precipitation. This is pertinent to the study of GHG emissions in that re-deposited ammonia is subject to nitrification and denitrification, which can release N_2O. We estimate that this indirect source of N_2O contributes approximately 9% of national agricultural sources of N_2O.

Factors that control the formation of N_2O

The amount of N_2O emitted from soils is determined by the rate at which N_2O is produced and the proportion of the N_2O produced that is actually released from the soil surface. These two factors are controlled at the cellular level according to the supply of raw materials and prevailing environmental conditions. Of course, mineral nitrogen is a key factor controlling nitrification and denitrification by soil microbes but denitrifiers also require a source of easily decomposable organic matter. For this reason, high N_2O emission rates may not be observed following application of mineral nitrogen in soils with low organic matter contents.

Water content

Because soil-water content strongly influences the amount of oxygen present, as well as the availability of nutrients, microbial activity and even soil temperature, it is considered the primary factor controlling N_2O emissions in soils. As seasonal precipitation levels vary considerably across the Canadian agricultural zone, so too does the magnitude of soil-emitted N_2O. For example, N_2O emissions in the semiarid to subhumid prairies tend to be much lower than emissions for the more humid areas in eastern Canada. This is not surprising as soil aeration is a strong regulator of N_2O emissions and soil aeration is affected significantly by soil water.

Precipitation patterns can also affect seasonal N_2O emission patterns. Deep snow packs insulate the soil, keeping temperatures near the surface hovering near or just below freezing. This allows low levels of microbial activity to continue through the winter, causing substantial over-winter emissions of N_2O in some cases. By contrast, in the arid and relatively snow free Prairies, soil temperatures near the surface can drop to -20 °C, leading to negligible emissions. Also, less snow in winter means soils dry more quickly in spring, which results in a relatively small *spring burst* of N_2O emissions.

Soil type, landscape and climate

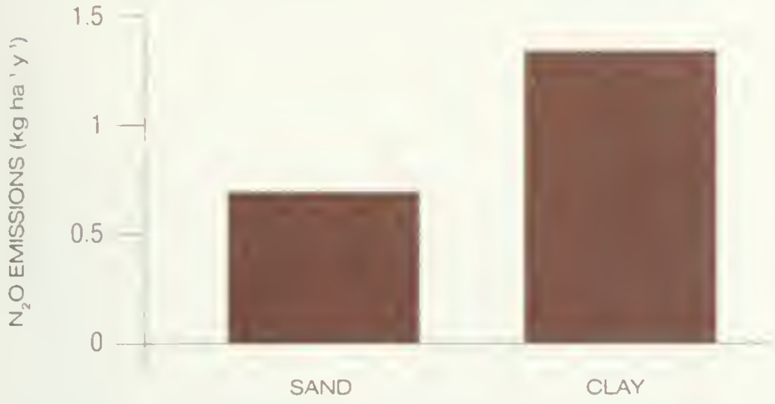
In general, N_2O emissions from agricultural soils in Canada can be characterized by low but reasonably consistent emissions with interspersed episodes of much higher emissions. In the drier regions of the country these emissions likely arise largely from nitrification and their magnitude is related to total nitrogen turnover. In more humid regions, emissions likely result from a combination of nitrification and denitrification. Bursts of N_2O emissions are generally triggered by high soil-water contents after rainfall, irrigation or snow melt, largely from denitrification.

Soil water content—and hence N_2O emissions—also varies according to such factors as soil texture, drainage and slope position. In some instances, scientists found that drainage and soil texture could explain up to 86% of annual differences in denitrification. As the amount of clay particles increases in soils, water infiltration slows down and soil water content increases. Accordingly, some scientists have reported N_2O emissions that were on average twice as high on clay as on loamy and sandy soils.

Water is not distributed equally over the landscape as it drains from higher grounds and collects in depression areas. Thus N_2O emissions are higher from moist depressional areas than from the dry upslope areas.

FIGURE 14

CUMULATIVE N_2O EMISSIONS FROM SANDY AND CLAY SOILS NEAR QUÉBEC CITY

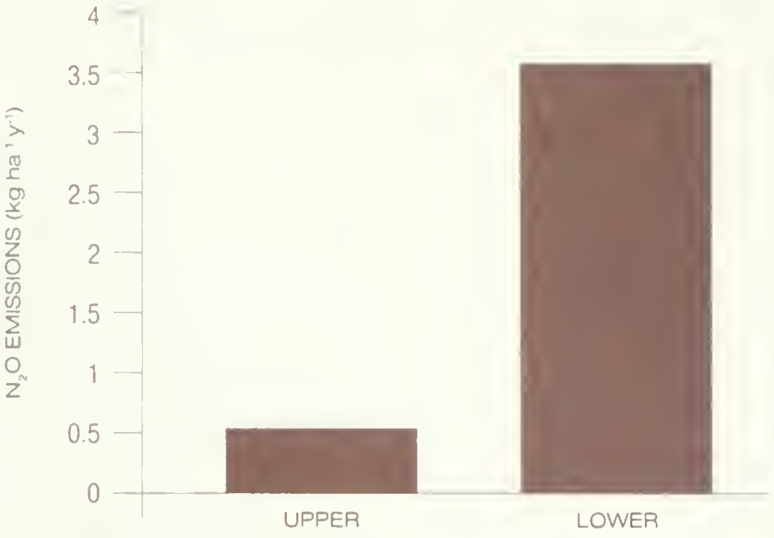


Soils with more fine particles (clay) usually emit more N_2O than sandy soils. Clay materials slow down water infiltration and result in poorly aerated, wetter soils. These conditions favour denitrification and high N_2O production rates.

Source P Rochette, AAFC Quebec City QC

FIGURE 15

CUMULATIVE N_2O EMISSIONS (MARCH-OCTOBER) FROM UPPER AND LOWER (DEPRESSION) POSITIONS OF A SLOPE NEAR MUNDARE, ALBERTA



Both slope positions were seeded to spring wheat and were fertilized with 60 kilograms of nitrogen. Wetter conditions in the lower portions of the landscape resulted in poorly-aerated conditions and higher N_2O emissions.

Source R Lemke, AAFC, Saskatoon, SK

Minimizing N_2O emissions from agricultural soils

We saw in earlier sections of this chapter that N_2O production in soils is a function of two principal factors: the quantity of soil mineral nitrogen available for the reactions of nitrification and denitrification, and the level of soil aeration, which will determine if denitrification, the most important source of N_2O, is favoured.

The following sections outline a few ideas for managing agricultural soils to minimize N_2O emissions.

Nitrogen Management

In natural environments, nitrogen is often the nutrient limiting plant growth. The nitrogen available in the soil of these ecosystems comes mostly from the decomposition of soil organic matter and plant residues (fallen leaves, dead roots, dead trees) and is quickly absorbed by plant roots when it becomes available. The mineral nitrogen content of these soils is usually low. Consequently, the N_2O emissions are very small.

In agricultural fields, the situation is different. All agricultural crops contain nitrogen. For example, there are approximately 10 kg of nitrogen in each tonne of corn or wheat. When crops are harvested, large quantities of nitrogen leave the field and must be replaced to maintain soil fertility. In other words, fertilization of agricultural soils is an essential component of most cropping systems and fertilizer nitrogen is one of the largest causes of N_2O emissions.

Why is this the case? Plant roots and denitrifying microorganisms consume nitrogen in the same forms: ammonium and nitrate. Therefore, fertilizer cannot be made available to the plant roots without also being available to N_2O-producing microorganisms. Completely eliminating the N_2O emissions from agricultural soils is thus not a realistic objective. Our goal is rather to reduce them by ensuring that as much of the applied nitrogen as possible is absorbed by the crops and not transformed by the microorganisms.

How can we achieve this? Managing the following farming inputs may help.

Mineral fertilizers

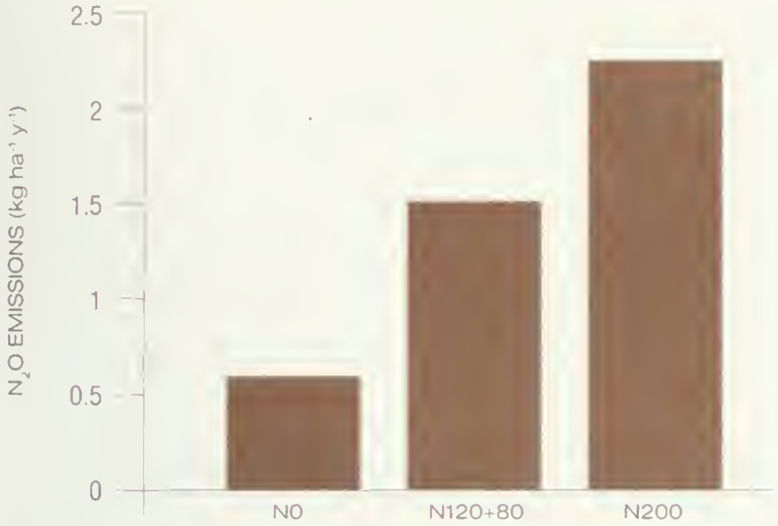
If we are to reduce N_2O emissions by managing how fertilizers are applied, it makes sense to keep a key strategy in mind: apply only the amount of fertilizer that plants need—and apply it at the correct time so that plants can absorb it immediately rather than leave it to microorganisms.

Nitrogen for crops comes from two sources: fertilizers (mineral and organic) and crop residues. Fertilizers should fill the difference between the plants' nitrogen requirements and the nitrogen released by the decomposition of crop residues. For example, if legumes have been planted in the previous growing season, 25 to 100 kilograms of nitrogen per hectare will be released gradually by decomposition over the growing season. Such releases must be factored into the overall nitrogen fertilizer requirements of any given crop.

During the first weeks after planting, young seedlings take up relatively little nitrogen. During the period of rapid growth they take up a great deal. Once mature, they take up none at all. Therefore, rather than apply one season's nitrogen fertilizer at seeding time, the application could be split; a portion could be applied at seeding time with the balance applied when the crop is growing rapidly. It is impossible to synchronize fertilization and plant growth perfectly, but it is certainly worth considering split applications to lower soil mineral nitrogen early in the season and N_2O emissions. This practice is not effective for all regions in Canada. For example, on the semiarid prairies, the potential reduction in N_2O emissions would likely not justify the energy used for this additional field operation.

FIGURE 16

CUMULATIVE N_2O EMISSIONS FROM A POTATO FIELD IN FREDERICTON, NEW BRUNSWICK



Experimental plots receiving no nitrogen fertilizer (N0) were compared to plots receiving 200 kg of nitrogen per hectare at planting (N200) or 120 kg of nitrogen per hectare at planting and 80 kg of nitrogen per hectare at final hilling (N120+80). Application of nitrogen fertilizers increased emissions by increasing soil mineral nitrogen availability to soil microbes. However, splitting total fertilizer requirements in two applications lowered soil nitrogen levels and N_2O emissions.

Source: D. Burton, Nova Scotia Agricultural College, Truro, NS

The form and the mode of fertilizer application can also influence the efficiency with which crops use nitrogen and thus affect the amounts of N_2O produced. It is important to make fertilizers easily accessible to plant roots. Therefore, surface application is not recommended as the most effective way to encourage plants to use nitrogen. Placing the fertilizer in bands near the seed row usually improves nitrogen uptake by the crop, but depth of application may be an important consideration. In a study on a clay loam soil in southwestern Ontario, banding nitrogen fertilizer at a depth of 2 cm decreased N_2O emissions by 25% compared to banding at a depth of 10 cm. One explanation for higher N_2O emissions is that soils more frequently become anaerobic at depth due to wetter soil conditions. Therefore, denitrification was favored.

If fertilizer application occurs under conditions of imperfect aeration (very wet or compacted soils), the ammonium form is preferable because in the short run it reduces the risks of denitrification, the major source of N_2O. Conversely, in well-aerated soil, the nitrate form will generate less N_2O than the ammonium form.

As the name implies, slow-release fertilizers release nitrogen slowly over time—at a rate that better matches crop uptake. This avoids large accumulations of mineral nitrogen in the soil and minimizes the potential for N_2O production. Other substances, when added to the soil, can inhibit nitrification, maintain the applied nitrogen in the ammonium form longer and result in low N_2O emissions.

Manure Nitrogen

Farm animals' feed is often rich in proteins. The ammonia released as they digest these proteins is toxic to the animal and is quickly excreted in their urine as urea or ureic acid. What happens to this nitrogen depends on the conditions found in the various manure storage structures. Oxygen being required for nitrification, most mineral nitrogen will remain as ammonium if stored in absence of oxygen. Such conditions are found in liquid storage systems and no or very little N_2O is produced and emitted from liquid manure tanks and lagoons. The situation is very different in more aerated environments such as in solid manure. In manure piles, N_2O is produced during nitrification of ammonium and even more is formed when a fraction of the product of nitrification—nitrate—is later denitrified if conditions become anaerobic.

Manure treatment can also influence N_2O emissions during manure storage. For example, while static composting does not increase N_2O emissions compared to standard solid manure piles, composting with frequent turning of the compost pile can increase emissions 10-fold. This dramatic effect on N_2O emissions is the result of bringing nitrates produced in aerated outer parts of the pile to locations inside the pile where oxygen is limited and denitrification occurs.

Animal excretions contain large amounts of nitrogen that can be used to fertilize crops. Manure nitrogen, when applied to soils, increases N_2O emissions in a way similar to mineral fertilizers. Therefore, precautions recommended for increasing the uptake of synthetic nitrogen by crops also apply to manure nitrogen. Efficient use of manure nitrogen not only allows for appreciable savings in mineral fertilizers for the farmer but also results in important reductions in N_2O emissions as less synthetic fertilizers needs to be applied.

Legume crops

Legume crops such as soybean and alfalfa can fix nitrogen present in the atmosphere with help from bacteria in their roots called Rhizobium. These microbes can convert atmospheric dinitrogen into ammonium that plants can use. Until recently, it was believed that this nitrogen fixing was accompanied by a significant release of N_2O but recent studies no longer support this.

Legume crop residues returned to the soil after harvest are relatively rich in nitrogen; their decomposition does stimulate more N_2O production than the residues of non-nitrogen fixing plants. However, the production of N_2O associated with the legume crops is usually small compared to emissions generated by crops requiring nitrogen fertilizers.

Cover crops

Nitrogen uptake by plants is an important sink for soil nitrogen. When crops are absent, mineral nitrogen can accumulate and be lost to the environment in several forms, including N_2O. Perennial crops have a long growing season and little soil nitrogen accumulates in these systems. In annual crops, however, little nitrogen uptake occurs early in the season and after maturity or harvest. The accumulation of mineral nitrogen released by the decomposition of soil organic matter and crop residues during these periods can result in important N_2O emissions. Cover crops planted after the harvest of annual crops take up free soil nitrogen, avoiding its accumulation in the soil and thereby reducing N_2O losses. Cover crops may not be a good option for the drier regions of the country, where soil-water conservation is of utmost importance.

However, crop management is important to the efficiency of this practice. The nitrogen stored in the cover crop's tissues must be released into the soil at a time when crops will take it up. Therefore, it may make sense to delay ploughing the cover crop into the soil until the following spring.

Soil aeration

As we have seen, N_2O is produced in much greater quantity in soils that do not contain much oxygen. These include soils that have a high water content and soils that are compacted. Soils poor in organic matter also have properties that tend to decrease aeration as they have fewer tunnels formed by roots, earthworms and insects. These soils also tend to be more susceptible to compaction.

Soil management practices can minimize the release of N_2O by their impact on soil water content, soil organic matter content and soil compaction. These general principles, as seen below, can guide us in choosing management practices that ensure enough soil water for an optimal crop growth while maintaining an adequate soil aeration that limits denitrification rates and N_2O production.

Soil tillage

Traditionally, the preparation of the seedbed and the control of weeds in agricultural fields were carried out by vigorous soil tillage. In Eastern Canada, mouldboard plough followed by harrow passes incorporates the residues of the previous crop and loosens the surface soil layer in preparation for planting. In row crops, weed control during the growing season is often accomplished by periodic passes of adapted harrows. Because of a drier environment on the Canadian Prairies, preparation of the seedbed was traditionally carried out by successive passes with a field cultivator and/or harrows.

Aggressive soil tillage requires time, energy and resources, contributes to the destruction of soil structure and leaves the soil surface more vulnerable to erosion. Reduced or no tillage is an alternative approach that avoids these problems. It consists of a limited use of soil tillage implements; the crops are often sown through the crop residues left on the soil surface after the previous year's harvest. Compared to conventional tillage, no tillage results in several important differences, which can influence the production and the emission of N_2O.

Under no tillage, the crop residues, fertilizers and the organic amendments are left close to the surface rather than incorporated into the soil. Their decompos-

ition and the transformations of mineral nitrogen are thus done under different temperature and moisture conditions. The absence of soil mixing also makes the soil denser and the presence of plant residues on the surface reduces evaporation and increases soil water content. This reduces soil aeration, which often increases denitrification rates and the potential for N_2O production. However, this influence of no tillage on denitrification and N_2O production is mostly observed under wetter climates and particularly in clay soils. In Canada, it seems that, generally, no tillage increases N_2O emissions in the humid east whereas it reduces them in the semiarid Prairies.

Irrigation and drainage

We have seen how important water content is for soil aeration; it is easy to understand how drainage and irrigation influence aeration. Heavy irrigation obstructs soil aeration, whereas less abundant but more frequent irrigation avoids excessive soil water content resulting in lower N_2O emissions. Similarly, slow drainage of excess water in agricultural soils results in poor aeration, which leads to denitrification and N_2O production. Good soil structure that allows water to enter rapidly and artificial drainage that ensures adequate conditions for crop growth also help to avoid large N_2O emissions.

Summer fallow

Crop growth in the southern Canadian Prairies is limited by low rainfall. To mitigate this problem, summer fallowing has been practiced since the first settlers broke the land some 100 years ago. This practice consists of leaving the soil free of vegetation for one complete growing season. During the fallow years, the absence of plants reduces evaporation and replenishes soil water reserves to ensure a satisfactory harvest during the following crop year. Under summer fallow, the soil is thus wetter but it is also warmer because of its direct exposure to solar radiation. These conditions favour the biological decomposition of soil organic matter and the accumulation of mineralized nitrogen that, in the absence of crop uptake, can stimulate microbial transformations into N_2O.

Indeed, it was shown that N_2O emissions from soils under summer fallow are of similar magnitude to emissions from cropped soils receiving nitrogen fertilizers. Recently, the adoption of reduced or no tillage made it possible to increase the crop water-use efficiency and to reduce the need for summer fallow. The shift from summer fallow systems to continuous cropping with no tillage has made it possible to increase agricultural production without increasing overall N_2O production.

Reducing indirect emissions

The preceding practices can help reduce *direct* emissions of N_2O. Reducing *indirect* emissions—those emitted away from farmlands but from nitrogen originally from farms—involves finding ways to reduce leaching and volatilization. Because losses by these mechanisms have high economic and environmental costs, many studies have been conducted to seek ways of reducing them.

Minimizing fertilizer use

As Table 4 shows, a wide range of practices has been advocated, grouped under two broad approaches. To reduce losses from agricultural fields, the most basic approach involves applying just enough nitrogen to satisfy crop needs, but no more. This aim is simple in principle, but challenging to implement because of the biological complexity and variability of the nitrogen cycle on farms. For example, the amounts of nitrogen available to crops depends not only on the amounts applied, but also on the rate at which organic nitrogen already present mineralizes—a process hard to predict. Further, the amounts of nitrogen needed by plants and the timing of these requirements is unpredictable, depending on weather and other factors that affect plant growth.

TABLE 4

POSSIBLE APPROACHES FOR MINIMIZING AGRICULTURAL NITROGEN LOSSES VIA LEACHING AND AMMONIA VOLATILIZATION

APPROACH	EXAMPLES OF SPECIFIC PRACTICES
Minimizing losses from soils	
Avoid applying excess nitrogen	Improved recommendations based on soil analyses, or nitrogen budget calculations
	Applying nitrogen at variable rates to reflect plant needs (precision farming)
	Adopting more efficient methods of nitrogen delivery to plants (e.g., banding)
Synchronize nitrogen additions with plant needs	Improved timing of manure and fertilizer applications
	Improved timing of residue incorporation
	Improved fertilizer forms (e.g., slow release forms)
	Use of cover crops
	Avoiding fallow
Minimizing losses from livestock	
Conserve manure nitrogen during storage	Physical covers for manure stores
	Chemical amendments (e.g., acidifying agents)
	Careful composting practices
Prevent post-application losses	Improved placement of manure nitrogen (e.g., banding)
	Timely incorporation of manure

To minimize losses, the nitrogen needs to be made available not only in the right amounts, but also at the right times. This can be achieved by applying nitrogen just prior to plant uptake (e.g., avoiding fall fertilization of spring-seeded crops), by using controlled-release fertilizers or by ploughing under nitrogen-rich residues so that mineralization is synchronized with the plants' nitrogen demands. Often, nitrogen losses can be reduced by methods such as *banding* that place nitrogen in close contact with soil and near roots. Losses between crops can be minimized to some extent by planting cover crops and avoiding the use of summer fallow, a practice that favours accumulation of soil nitrate when no plants are present to absorb it.

Managing livestock

Livestock systems also are an important source of nitrogen losses, notably as ammonia from excreted urea compounds. Typically, about 50% of the feed nitrogen consumed by cattle, for example, is excreted in urine. The most fundamental approach to suppress these losses is to minimize nitrogen excreted by adjusting the amount and nature of protein in animal diets. In the rumen of cattle, protein is normally broken down into ammonia, which is then used by rumen microbes to synthesize microbial protein, the major source of protein for the ruminant animal. If too much rumen-degradable protein is fed, or if a lack of energy (carbohydrates) limits bacterial growth, unused ammonia is absorbed from the rumen into the blood and is excreted in urine.

Dietary protein can be reduced without constraining animal production by improving the balance between rumen-degraded intake protein and rumen-fermentable organic matter. This maximizes the microbial protein supply. Another way of reducing nitrogen excretion is to supply amino acids to the small intestine by feeding *undegradable intake protein* (also referred to as by-pass or protected protein). A diet where total crude protein is reduced and specific amino acids are added to meet dietary requirements has proven effective in reducing total nitrogen excretion in poultry and swine.

However, in ruminant livestock (cattle), amino acids in feed must be protected from degradation in the rumen. Some protein sources consist of a relatively high percentage of undegradable intake protein. Care is needed to ensure that the proportion of undegradable intake feed is not excessive since excess nitrogen is excreted in the urine. Ideally, the diet should optimise rumen-degradable intake protein while not over feeding undegradable protein—that is, not exceeding growth and maintenance requirements. Such practices, however, still require further research to ensure that they do not jeopardize yields of meat and milk products.

Volatile ammonia losses of nitrogen from manure stores can be effectively controlled by installing physical barriers, applying chemical amendments (e.g., acidifying agents, absorbents), and by adjusting conditions during either storage or composting. Post-application losses of nitrogen from manures can be minimized using methods similar to those described for other nitrogen sources; particularly important is the timely and effective soil incorporation of manures to prevent ammonia volatilization.

The best approaches for reducing losses will vary among regions and even among farms in the same region. Many studies have shown, however, that the recovery of applied nitrogen in crops is sometimes not much more than 50%, suggesting there is still considerable room to reduce both N application and indirect N_2O emissions.

Other benefits and costs of reducing N_2O emissions

Methods for reducing emissions of N_2O may have numerous corollary benefits; indeed, these methods are generally adopted not so much to suppress N_2O emissions, but to reduce nitrogen inputs and thereby reduce farming costs. Other benefits include reducing nitrate leaching, improving air quality (e.g., by reducing aerosols formed from ammonia), improving odour control and reducing energy used to manufacture and apply nitrogen fertilizers. (This, of course, reduces emission of CO_2.)

However, these practices have potential drawbacks. Some involve investments in infrastructure or equipment; others, especially those aimed at reducing application rates, may carry the risk of lower crop yields. Many can conflict with other environmental objectives. For example, effective incorporation of manures may require intensive tillage that jeopardizes soil quality and is energy intensive; and avoiding losses of ammonia from manures may simply defer nitrogen losses or increase losses via other forms (e.g., N_2O). Thus, prospective practices for reducing indirect N_2O emissions can be effectively evaluated only in light of other agricultural and environmental goals.

Despite the widespread advantages of avoiding nitrogen losses—and despite abundant research devoted to reducing losses—the nitrogen cycle on farms is still leaky, and these leaks still lead to significant (though poorly quantified) N_2O emissions. Stemming these leaks remains a prominent research objective, both to improve productivity and to avoid environmental damage. Given the complexity of the nitrogen cycle and the sporadic progress to date, future improvements in efficiency are likely to be incremental—but worthy of the effort.

FURTHER READING

Beauchamp, E.G. 1997. Nitrous oxide emission from agricultural soils. *Canadian Journal of Soil Science* 77[2]:113–123.

Erisman, J.W., A. Bleeker, J. Galloway, and M.S. Sutton. 2007. Reduced nitrogen in ecology and the environment. *Environmental Pollution* 150:140-149.

Freney, J.R. 1997. Emission of nitrous oxide from soils used for agriculture. *Nutrient Cycling in Agroecosystems* 49[1/3]:1-6.

Mosier, A.R., et al. 1998. Assessing and mitigating N_2O emissions from agricultural soils. *Climatic Change* 40[1]:7-38.

Methane

METHANE FROM LIVESTOCK AND METHODS TO REDUCE EMISSIONS

Methane is a colourless, odourless gas, familiar to us as the main constituent of the natural gas we use to heat our homes. It is produced in nature wherever plant material decays without enough oxygen to form CO_2. On Canadian farms, these conditions occur in two main places: in the fore-stomachs (rumens) of ruminant animals (cattle and sheep), where feeds are digested in oxygen-free conditions and in manure storage sites where high water content limits the entry of oxygen.

Worldwide, animal agriculture is the largest source of atmospheric CH_4 produced through human activity; an estimated 1.3 billion cattle account for 21% of total anthropogenic CH_4 emissions. In Canada, CH_4 from ruminant animals is by far the largest source, producing about eight times the CH_4 that emanates from manure. We will refer to CH_4 produced in ruminants as enteric CH_4. The first portion of this chapter discusses *enteric* CH_4, while the second portion discusses CH_4 from manure.

Methane from ruminant livestock

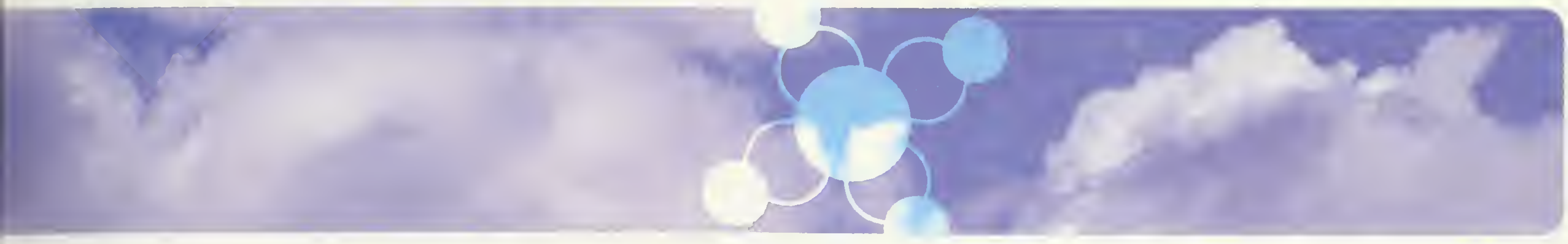
Cattle farming in Canada

Canada's 16 million cattle represent roughly 1.4% of the global population of cattle. Most of Canada's cattle, especially beef cattle, reside in Alberta and Saskatchewan, while most dairy cattle reside in Québec and Ontario. There are many regional influences that account for the distribution of cattle and how they are managed in Canada; many of these influences are related to resources and to the history of the industry.

The vast grassland and parkland regions of western Canada are conducive for grazing cattle for a large part of the year. An ample supply of barley grain in those regions also enables farmers to manage their cattle on feedlots, a practice more common in Alberta than in Saskatchewan or Manitoba.

Farming meat and milk

The beef production cycle in Canada has three components. In the *cow-calf* component, calves born in late winter/early spring are kept on pasture throughout the summer and weaned in the late fall. During the *backgrounding* period, steer calves (males) and non-replacement heifers (females that will not be kept as cows) are moved from pasture to a feedlot and fed a high-forage diet for up to 100 days. Finally, during the finishing period, cattle are shifted, over two to four weeks, to a high-grain diet. Cattle are offered a high-grain diet when they reach a weight of roughly 380 kg. For the next 130 days they gain about 1.4 kg per



day and are then slaughtered. In some operations, the backgrounding period is extended throughout the winter and the cattle are reintroduced to pasture in the following spring. These *stocker* or *yearling* cattle typically undergo a short finishing period of less than 80 days and are marketed in late fall or early winter.

Typically, farmers allow dairy cows to lactate (produce milk), for about 305 days and then cease milk production for approximately 60 days. Just less than half a dairy herd consists of non-lactating stock; this includes dry cows and replacement heifers. (Young females begin lactating at about 24 to 28 months, once they have given birth.)

When lactating, dairy cows require a high-energy diet that consists of 40–60% forage, supplemented with grain, protein sources, minerals and vitamins. The feed intake for dairy cattle is generally greater than for beef cattle, because dairy cattle require a great deal of energy to produce milk (typically averages 30 to 35 litres of milk per day). Unlike many countries, Canada typically houses its dairy cows in open or closed barns, which means the cows do not experience extensive grazing periods.

The confinement of dairy cows in barns, and beef cattle in feedlots, means that their feed can be managed to a high degree and their diets adjusted to reduce CH_4 production. In grazing systems, fewer options exist for producers to adjust their cattle's diet composition. In those systems, producers' main strategy is to improve the quality and availability of forage through pasture management.

How cows produce enteric methane

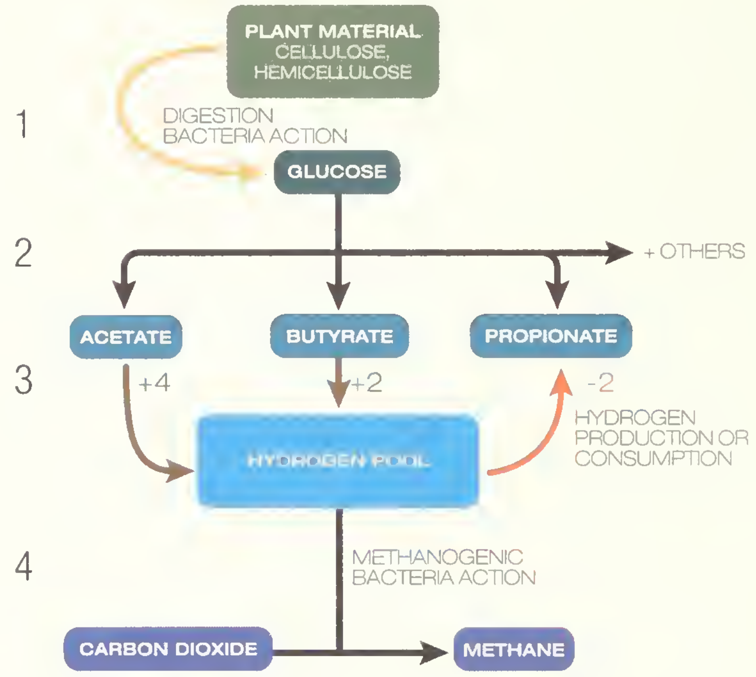
Cattle, being ruminants, are able to digest forages, which consist mostly of cellulose and hemicellulose. Although they can thrive on forages alone, grains, which contain starch, are also fed to cattle in some operations.

To convert carbohydrates into usable energy, bacteria in the rumen break down plant compounds into volatile fatty acids (VFAs). VFAs are the major energy source for cattle, the most abundant VFAs being acetate, propionate and butyrate. Different types of animal feeds produce different proportions of VFAs. For example, a diet that consists of 90% grain—as opposed to a forage diet or lower-grain diet—produces an increase in the proportion of acetate and a decrease in the proportion of propionate. This is important because VFAs have a critical role to play in the generation of hydrogen in the rumen. Hydrogen is important in the production of enteric CH_4. The formation of acetate generates twice the amount of hydrogen as does the formation of butyrate, whereas the formation of propionate actually *uses* hydrogen. The accumulation of hydrogen in the rumen has a negative impact on the function of bacteria, thereby interfering with the digestion of carbohydrates. Consequently, it makes sense to ensure that hydrogen does not accumulate in the rumen.

Meanwhile, a group of bacteria known as methanogens (CH_4-producing bacteria) plays a role in converting hydrogen and CO_2 found in the rumen into CH_4 and water. Therefore, restricting the hydrogen available in the rumen for methanogenic bacteria will limit the formation of enteric CH_4. One way to do this is to shift the fermentation process to form propionate or butyrate rather than acetate. This reduces the available hydrogen required for the formation of enteric CH_4 by methanogenic bacteria.

FIGURE 17

PRODUCTION OF CH_4 IN THE RUMEN



Cattle are able to utilize forages, which are composed of cellulose and hemicellulose material, as an energy source for maintenance, growth and milk production. These materials are digested to form glucose (1) and other simple sugars in the rumen (stomach), which are then converted to various types of volatile fatty acids (2). Increasing the proportion of propionate produced in the rumen (3) through dietary changes decreases the amount of hydrogen available to methanogenic bacteria (4) for the formation of CH_4. The production of propionate is a strategy that decreases enteric CH_4 emission.

Most of the enteric CH_4 produced by cattle originates in the rumen through the process described above. However, fermentation can also occur in the intestine of the animal. One of the published studies on ruminal versus intestinal production of CH_4 indicates that although 13% of CH_4 is produced in the intestine, about 89% of it is absorbed across the intestinal wall into the blood stream. Likewise, about 95% of CH_4 generated in the rumen is absorbed into the blood stream. Methane in the blood is transferred to the lungs where the animal breathes it out. As a result, 99% of CH_4 emission is lost via the nostrils and mouth and only 1% of the total CH_4 emission of the ruminant is lost through the rectum.

Reducing enteric methane emissions

There are two main approaches by which CH_4 emissions from beef and dairy cattle can be reduced. One method is to reduce CH_4 per unit of feed energy consumed by modifying the diets and using other management options. A second method is to reduce enteric CH_4 through the use of more efficient animals; this can reduce emissions per unit of meat or milk produced so that fewer animals are required to grow or produce the same amount of product.

Note however, that increased animal productivity in itself does not lead to a decrease in CH_4 emissions unless total production is fixed. An example is a supply management system that limits the total amount of product produced—similar to the way milk production is managed within the Canadian dairy sector. Table 5 offers an overview of these practices and their expected CH_4 reduction. The elements of Table 5 are explained in detail in the following paragraphs.

Method 1: reducing CH_4 emissions through diet and other management options

Higher-grain diets control CH_4

Feeding high-grain diets to ruminants—in which more than 90% of the animal's dietary dry matter is composed of grain—lowers the proportion of feed energy converted to CH_4 in the cow's rumen. However, feeding grain to cattle—grain that could be otherwise fed directly to humans—does not exploit ruminants' unique ability to convert cellulose feeds, unsuitable for human consumption, into high-quality protein sources such as milk and meat.

Feeding a high-grain diet to ruminants causes a change in rumen fermentation—it results in a decrease in the proportion of acetate produced and an increase in the proportion of propionate produced. Formation of acetate in the rumen promotes CH_4 production, whereas propionate production is associated with a decline in CH_4. It is also possible that higher acidity of the rumen is an important factor in lowering enteric CH_4 production. Fermentation acids produced may lower the pH in the rumen to a level that inhibits the growth of methanogenic bacteria.

TABLE 5

Possible Mitigation Practices for Reducing CH_4 Emissions

MITIGATION METHOD	REDUCTION IN CH_4 (%)	COMMENT
Reducing CH_4 emissions per unit of feed energy consumed through diet and other options		
Higher grain diets	10-100	High certainty
Composition of grains	5-10	High certainty
Fats and oilseeds	5-25	High certainty
Ionophores	0-15	Level dependent, transient
Forage and pasture quality	5-25	Moderate certainty
Forage species	10-25	Moderate certainty
Condensed tannins	0-15	Depends on source and level
Propionate precursors	0-75	Dose dependent response
Yeast	0-5	Depends on strain
Methane vaccine	Unknown	Experimental
Breeding for reduced methane production	Unknown	Theoretical
Reducing CH_4 emissions through more efficient animals, reducing emissions per unit of product		
Animal breeding to increase efficiency	5-25	Experimental
Reformulating diets to improve rate of gain or milk production	10	High certainty
Extended lactation of dairy cows to reduce replacement animals	10	Experimental
Lifetime management of beef cattle	10-20	High certainty
Better reproductive performance	Unknown	Experimental
Breeding for increased productivity	10-25	High certainty

Source: S. McGinn, AAFC, Lethbridge, AB

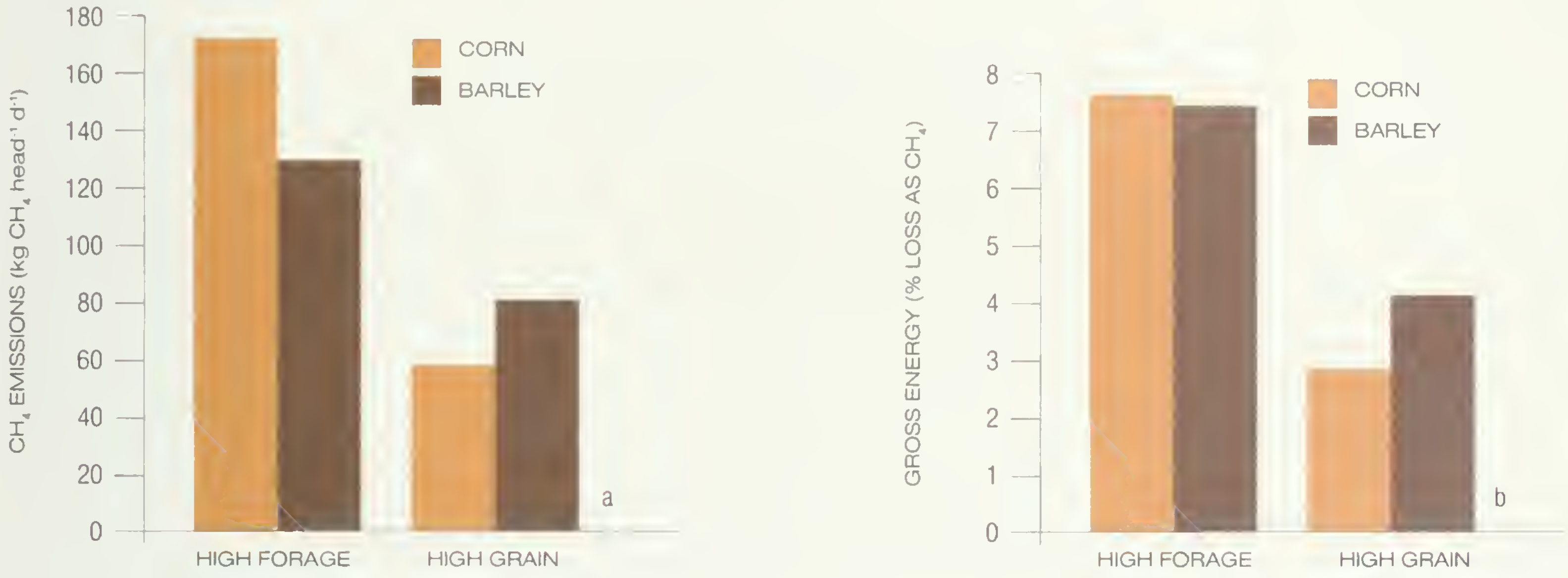
However, while increased use of grains reduces CH_4 emissions, grain production increases the production and transportation of chemical nitrogen fertilizer. Increased use of chemical fertilizers results in increases of N_2O (released from the fertilizers themselves) and CO_2, which is released by the fossil fuels used to produce and transport fertilizers. The question that remains is whether increased grain feeding reduces or increases total GHG from the livestock industry. The answer to this question is not yet available.

Composition of grains—not all grains are equal

As the graph below indicates, the extent to which high-grain diets lower CH_4 emissions depends on the type of grain. Greater reductions are achieved with corn than with barley. Methane emissions of feedlot cattle fed a backgrounding diet of 70% forage dropped by 38% when a barley-based feedlot finishing diet was fed—and by 64% when a corn-based finishing diet was fed. This difference may be due to a partial shift in the site of digestion from the rumen to the intestines, as corn is typically less extensively digested in the rumen than is barley. In addition, barley contains more cellulose and hemicellulose than corn. These structural carbohydrates ferment at slower rates than starch and sugars, resulting in higher proportions of acetate and lower proportions of propionate.

FIGURE 18

EXAMPLE OF DIETARY IMPACT ON CH_4 EMISSION



The emissions are expressed as (a) grams of CH_4 per head per day, and (b) percent of energy contained in the feed that is lost as CH_4. Using (b) to calculate the amount of CH_4 lost from an animal is more accurate since it reflects knowledge of the diet that controls CH_4 losses.

Source: Beauchemin and McGinn (2005)

Fats and oilseeds

Feeding fats offers much potential for lowering CH_4 emissions—and is a logical mitigation strategy. Fats such as oils, oilseeds and animal fats are already used in commercial ruminant feed production to increase the energy density of dry matter and reduce the amount of fermentation required to obtain the same level of energy from the feed. Supplementing the diet with fat reduces CH_4 emissions mainly by inhibiting the growth of rumen protozoa; many CH_4-producing bacteria are physically associated with protozoa so decreasing protozoal numbers decreases methanogens as well. Further, adding fats to a diet replaces some of the carbohydrates, which would otherwise be digested in the rumen and contribute to CH_4 production. For lipids rich in unsaturated fatty acids (mainly plant-derived fats), the transformation or *biohydrogenation* of fatty acids that occurs in the rumen is a process that competes for hydrogen.

As Table 6 shows, studies have examined the effect on CH_4 emissions of supplementing forage-based diets with fat sources. All types of fat sources (supplying between 3.3 and 5.3% of the animal's energy intake) reduced CH_4 emissions. Sources of long-chain unsaturated fatty acids (sunflower oil and seeds, canola oil) were most effective in reducing emissions, with 21-27% less methane per unit of gross energy intake. Tallow, a source of saturated fat, was slightly less effective, at 17% reduction. (The effectiveness of long-chain fatty acids in suppressing enteric CH_4 is inversely proportional to degree of saturation of the fatty acids. Medium-chain fatty acids are also effective at reducing CH_4 emissions, but these fat sources—such as coconut oil and genetically modified canola oil—are often cost-prohibitive for livestock producers.)

TABLE 6

Impact of Adding Supplemental Fat Sources to High Forage Diets (75% forage, DM basis) Fed to Growing Cattle

SOURCE	LEVEL OF ADDED FAT (% OF DM INTAKE)	DM INTAKE	DIGESTIBILITY OF DM IN THE DIGESTIVE TRACT	CH_4 (% OF GEI)
		Percentage change from control diet without added fat		
Sunflower oil	3.3	-1.4	0.7	-21.3[a]
	5.3	-1.5	-6.1	-21.5[a]
Sunflower seeds	3.3	-10.5[a]	-6.6[a]	-26.7[a]
Canola oil	4.6	-9.9[a]	-14.7[a]	-20.6
Tallow	3.3	-4.1	-1.2	-17.1[a]

a = different from control ($P < 0.15$).
DM = dry matter; GEI = gross energy intake

Sources . Results of three studies conducted at the Lethbridge Research Centre by S. McGinn and K. Beauchemin.

Although adding fat to the diet reduces CH_4, it can also reduce feed intake and fibre digestibility. The net result can be a decrease in the total intake of digestible energy despite an increase in the energy *density* of the diet. Such was the case when sunflower seeds, canola or tallow were provided at high inclusion rates in a study. Long-chain fatty acids inhibit the fibre-digesting bacteria in the rumen; thus, some decrease in fibre digestion is inevitable. Use of supplementary fats can increase the energy intake of cattle if the negative effects on fibre digestion and intake are minimized by feeding a higher proportion of grain in the diet, or by limiting the total fat content of the diet to 6–7% of the dietary dry matter.

Ionophores

Ionophores such as monensin are antimicrobials that are typically used in Canadian commercial beef and dairy cattle diets to modulate feed intake, control bloat and improve feed efficiency. Monensin decreases the proportion of acetate and increases the proportion of propionate in the rumen—an effect that decreases CH_4 output. Sometimes, monensin can also cause a decrease in rumen protozoa. This is important, as a direct relationship has been established between rumen protozoa numbers and CH_4 formation. Rumen protozoa are estimated to provide a habitat for up to 20% of ruminal methanogens while methanogens living on and within protozoa are thought to be responsible for an estimated 37% of CH_4 emissions from ruminants.

In studies with beef cattle fed a 75% forage diet, CH_4 emissions decreased by 9% with the addition of monensin to the diet at 33 mg/kg for a period of 21 days. This reduction in CH_4 is within the range (slight to 25%) reported previously. However, several studies have reported that the effects of monensin on CH_4 emissions are short lived. For example, scientists have reported that the CH_4 suppression effect of monensin was lost after four to six weeks of feeding. This, combined with increased public pressure to reduce the use of antimicrobials in animal agriculture, would suggest that monensin is not a long-term solution to enteric CH_4 abatement in Canada.

Forage and pasture quality

Improved forage quality typically results in greater CH_4 output per day, especially when cattle are provided with free-choice access to feed. High-quality forages have a faster passage rate from the rumen, which leads to greater feed intake and more fermentable substrate in the rumen. This results in greater daily enteric CH_4 production. However, the amount of CH_4 produced per unit of energy consumed or per unit of product typically increases as the quality of forages decreases.

Forage species

Methane emission is lower from animals fed legume forages compared to those fed grasses, but this relationship is also influenced by the maturity of the forage consumed. Scientists have estimated a 21% decrease in CH_4 production per unit of digestible energy when alfalfa hay replaces timothy hay. Legumes produce less CH_4 because they possess a lower proportion of structural carbohydrates and therefore the feed passes more quickly through the rumen. This leads to a higher proportion of propionate in the rumen, which reduces enteric CH_4.

Condensed tannins

Tannins are phenolic compounds found in some plants. Several laboratory studies have shown that the use of forages containing condensed tannins and tannin extracts reduce CH_4 emissions. These *in vitro* studies prompted scientists in New Zealand to conduct a series of studies in which tannin-rich forages were fed to sheep and dairy cows. When conventional forages, such as perennial ryegrass, were replaced with tannin-rich forages, CH_4 emissions decreased. However, it is not clear whether the CH_4 reduction was a direct effect of the tannins or a result of improved forage quality. Forages that have high levels of condensed tannins may suppress CH_4 production through a reduction in fibre digestibility in a manner similar to the addition of fats and oilseeds to the diet.

The use of tannins has potential as a CH_4 abatement strategy, but further research is needed to determine the optimum level and source of tannin to avoid potentially negative effects on animal productivity. Studies in Europe and Australia have shown that although feeding tannins to some ruminants (sheep and dairy cattle) will depress CH_4 production, this procedure may have a negative impact on productivity, making this approach questionable at present.

Propionate precursors

Fumarate and malate are organic acids that act as hydrogen sinks in the rumen. They have the potential to decrease CH_4 emissions by increasing the formation of propionate, if added to feed in sufficient proportion. An addition of up to 2% of the diet as fumaric acid had no effects on CH_4 emissions of cattle. In a recent study in Ireland, 3% malate added to the diet of lactating cows resulted in a very small reduction in CH_4 emissions. In the U.K., a much higher inclusion rate, in which fumaric acid made up 10% of the diet of sheep, reduced CH_4 emissions by 40–75%, the higher amount when the fumaric acid was encapsulated with fat to slow its rate of availability in the rumen. Unfortunately, these organic acids are expensive, which means feeding high levels to reduce CH_4 is uneconomical and impractical at present.

Yeast

Yeast cultures of *Saccharomyces cerevisiae* are widely used in ruminant diets in Canada to improve the rumen function of cattle. Products vary in the strain of *S. cerevisiae* used and the number and viability of yeast cells present. Laboratory studies suggest that some live yeast strains can stimulate the use of hydrogen by acetate-forming strains of ruminal bacteria, thereby enhancing the formation of acetate without forming CH_4.

Some commercially available yeast products can cause a 3% decrease in the amount of feed energy converted to CH_4. With strain selection, it is possible that yeast products could be developed based on their anti-methanogenic effects. However, at present, available strains of yeast likely have only minor, if any, effects on CH_4.

Methane vaccine and antibody therapy

Australian scientists have looked at the possibility of developing a vaccine against methanogens and protozoa in an effort to lower ruminal CH_4 production. Canadian scientists have also generated IgY antibodies against methanogens and examined their impact on CH_4 production *in vitro*. In some instances this approach has reduced *in vitro* CH_4 production, but the technology has yet to be evaluated in animals. Both technologies remain strictly at the experimental level and have yet to be demonstrated as a viable means of lowering CH_4 production.

Breeding for reduced CH_4 production

Methane production in humans is heritable, but so far there has been no attempt to breed cattle for reduced CH_4 production. Selecting animals for a single non-production related trait could lower the production efficiency of cattle and, for that reason, is not likely to be undertaken.

Method 2: reducing CH_4 through more efficient animals, reducing emissions per unit of product

Animal breeding to increase efficiency

Methane production is highly dependent on the quantity of feed consumed, which means reducing the amount of feed required to produce one unit of meat or milk is one way to reduce emissions. Scientists in Canada and Australia have recently bred and selected beef cattle based on residual, or net, feed intake (RFI), which is a measure of feed efficiency. Cattle with low RFI eat less than expected for their weight and growth rate and are therefore more efficient than cattle with high RFI. A recent Australian study reported that efficient cattle produced 6.7% less CH_4 per kilogram of gain than less efficient cattle. In Canada, a similar breeding program showed that low RFI cattle consumed less feed per kilogram of gain. This was associated with reduced daily CH_4 emissions. When all cattle were fed the same amount, the low RFI cattle produced 28% less CH_4 than the high RFI cattle, indicating that low RFI cattle may be more metabolically efficient.

Reformulating diets

Improved diets can enhance the way cattle utilize their feed and nutrients and, as a result, reduce CH_4 emissions. Improved diets can be achieved by better characterizing the nutrient profiles of feeds, improving models used to formulate rations and by gaining a better understanding of the nutrient requirements of cattle.

Extending lactation of dairy cows

Scientists in many parts of the world are examining the feasibility of calving dairy cows every second year, rather than once yearly, and extending lactation across two seasons. Total milk production by the herd is expected to remain the same with extended lactations. This approach would have the benefits of reducing the number of days the cow is not lactating over her lifetime and lowering the production costs associated with mating, calving, animal health and cow replacement. Such practices would also improve animal well-being by reducing the metabolic stress associated with calving. In a recent study in Victoria, Australia, 400-day lactations were found to reduce the total farm feed budget by 10% compared to traditional 305-day lactations, because fewer heifers were maintained. (There was a reduced need for replacement of mature cows.)

Lifetime management of beef cattle

To increase the productivity of beef cattle is to enable them to reach an acceptable slaughter weight at a younger age, which can have a major impact on lifetime CH_4 emissions. Scientists have calculated that reducing the age of steers at slaughter from 30 to 25 months resulted in a 16.5% reduction in lifetime CH_4 emissions and a 12% reduction in emissions per kilogram of carcass. (Carcasses reduced from 400 to 380 kilograms). It is also possible to reduce CH_4 emissions per unit of product by increasing carcass weights at slaughter, which lowers the number of animals required to produce the same amount of meat.

Better reproductive performance

Better reproduction of cattle can reduce the total amount of CH_4 per herd by reducing the total number of replacement stock. Scientists have estimated that improvements in fertility could reduce overall CH_4 emissions by 10% and by as much as 24% in regions where fertility was particularly low. In New Zealand, an increase in the incidence of twinning in ewes has resulted in substantial reductions in CH_4 emission; fewer ewes are producing the same lamb crop. This approach is particularly attractive as it offers obvious economic incentives quite apart from potential reductions in GHG emissions.

Breeding for increased animal productivity can reduce enteric CH_4 because it leads to less feed per animal per unit of product. However, increased productivity, especially in the dairy sector, is often accompanied by reduced cow fertility. Reduced fertility will increase the overall CH_4 emission on the farm due to the increased numbers of replacement animals.

Agricultural management practice

The agricultural strategies that lower enteric CH_4 emissions not only reduce GHGs in the atmosphere, but also promise to significantly increase the efficiency with which cattle convert plant material into milk and meat. A 20% reduction in enteric CH_4 in Canada would translate to a 9% decline in GHG emissions from agriculture and a 0.7% decline in Canada's total GHG emissions. Meanwhile, this 20% reduction would improve the competitiveness of Canada's livestock sector by increasing the weight gain of growing beef cattle by 75 grams per day and milk production in dairy cattle by one litre per day—a boon to farmers.

Although research has shown that CH_4 reductions are achievable by changing the diet of cattle, there is a financial cost to implementing these strategies. Further research on finding cost-effective strategies is required. It is also important that mitigation strategies be assessed from a life-cycle perspective because a reduction in greenhouse emissions at one point may lead to increases in emissions at other points along the production continuum.

One thing is certain with respect to the benefits of reducing enteric CH_4 emissions from cattle: it increases the energy efficiency of meat and milk production. Many of these dietary strategies are relatively easy to implement on farm. Some of these also lower the cost of producing meat and milk. The introduction of carbon-offset trading programs may encourage producers to adopt other mitigation strategies that are not, at present, economically viable. Importantly, reducing CH_4 emissions makes cattle husbandry a more environmentally friendly industry.

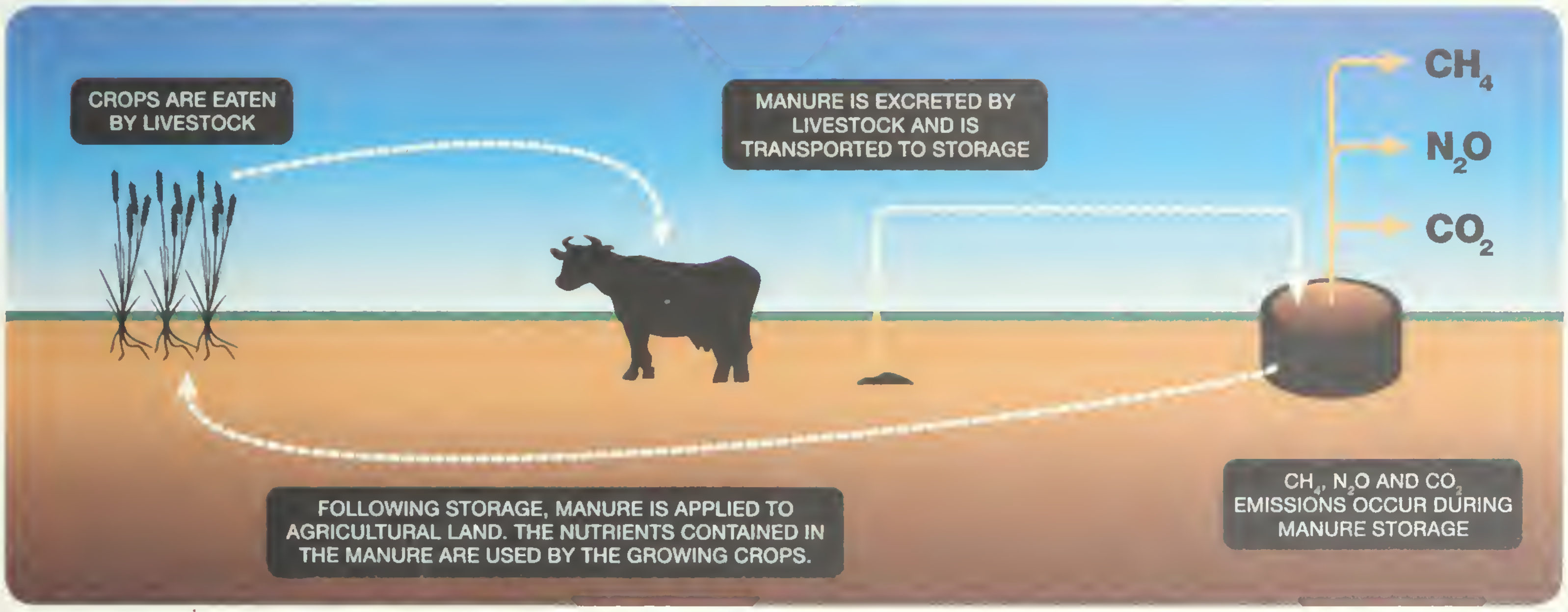
Methane from manures

Manure production in Canada

There are far more livestock in Canada than there are people. In 2007, Canadian farms had about 16 million cattle, 15 million hogs, 130 million poultry and additional millions of other animals. These herds produce considerable excrement: more than 200 million tonnes on an annual basis, with about 70% from beef cattle. As Figure 19 shows, most of this manure is applied to farmland as a fertilizer. But before it is applied to crops it accumulates, lingering in barns, manure piles, lagoons and tanks. While there, microbes decompose and digest it, decaying the nutrient-rich substrate and releasing considerable amounts of GHGs.

FIGURE 19

MANURE IS AN ESSENTIAL COMPONENT OF MODERN FARMING SYSTEMS



Nutrients absorbed by crops are fed to livestock, which then excrete a portion of these nutrients in manure. Although manure represents a disposal liability to the farmer, it also represents a resource, as it contains valuable nutrients which can be applied to fields to grow the following year's crop. The cycling of nutrients from crop to animal to manure to crop again allows farmers to dispose of manure while providing nutrients to the soil.

Manure is stored according to animal type and intended use of the manure. With grazing animals, urine and feces are deposited onto the pastures or paddocks, where they remain. The trend with swine and larger dairy operations is to use very small amounts of bedding and to add cleaning and milkhouse wastewaters to the manure and store it as a liquid in tanks or lagoons. Most other livestock systems refrain from adding water and store manure as a solid. This solid manure usually contains appreciable amounts of bedding—straw wood chips, or other organic materials added to keep animals warm and dry. Some farmers now compost manure or add it to anaerobic *digesters*, which produce energy by burning the CH_4 from the manure. These methods are not new, but their prominence is growing, in part because they can sometimes help reduce GHG emissions and also because they can provide energy for use on the farm. These biotechnologies substantially reduce manure pathogens and odours, thereby improving conditions for nearby residents.

Manures produce the most CH_4 when they are stored as slurry or in other mostly liquid forms. When they are stored as solids, oxygen diffuses into the manure, reducing the formation of CH_4 as it is oxidized to CO_2 and H_2O. The amount of CH_4 produced depends not only on the way manure is handled and stored, but also on the type of animal and diet composition.

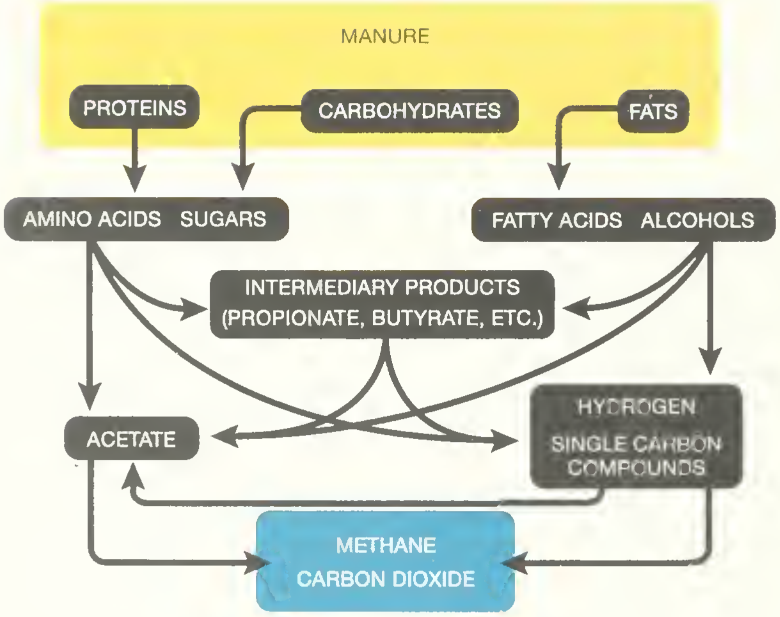
How manure produces CH_4

Methane emissions from manure are the end product of organic matter decomposition under anaerobic—or oxygen free—conditions. Methanogenic bacteria consume organic matter for their growth and emit gases, including CH_4. This gas is therefore a by-product of bacterial activities. The transformation of organic matter into CH_4 is performed by a series of different types of bacteria, which sequentially decompose organic matter to CH_4 and CO_2 as follows:

Manure components that are too large to pass through the bacterial cell membrane are reduced in size by the process of hydrolysis, which occurs outside of the bacterial cell. The enzyme used to break down large manure components is produced by the bacteria themselves. The resulting sugars, alcohols and acids go through a series of reactions that produce several types of molecules, including other types of volatile fatty acids, hydrogen and simple organic components. The final stage ends with the production of CH_4 and CO_2. The whole process can be divided into six parallel or series reactions presented in Figure 20.

FIGURE 20

THE CONVERSION OF ORGANIC MATERIAL IN MANURE TO CH_4 AND CO_2



Livestock manure contains organic compounds such as proteins, carbohydrates and fats. These compounds are too large to permeate a bacterial cell membrane. Extra-cellular enzymes produced by fermentative bacteria break down these molecules into small soluble compounds such as amino acids, sugars and fatty acids that can diffuse across the cell membrane of fermentative bacteria. The sugars and amino acids are transformed into acetate, propionate, butyrate, hydrogen and CO_2 *by the same fermentative bacteria. Hydrogen-producing acetogenic bacteria oxidize propionate and butyrate into acetic acid, hydrogen and* CO_2*. Finally, acetoclastic methanogens transform the acetic acid into* CH_4 *and* CO_2*, and hydrogen utilizing methanogenic bacteria reduce* CO_2 *to* CH_4*.*

Manure naturally contains all of the bacteria required to produce CH_4. However, the rate of CH_4 emission from manure depends on the density of active methanogens and their activity level. There are many factors that can influence the density and activity of methanogenic bacteria, including the following:

- Absence of oxygen—CH_4 is only produced under strict anaerobic conditions.
- Temperature—bacterial activity, and therefore the efficiency of CH_4 production, reaches a maximum at approximately 60-65 °C.
- Animal species
- The quality and quantity of feed given to the animal
- Age and gender of the animal
- Manure collection method
- Manure storage period
- Storage management practices such as manure removal frequency, amount of residual manure left in the structure after removal and amount of foreign material (straw or sawdust bedding) incorporated into the manure.
- Manure characteristics such as acidity (pH) and compounds such as ammonia and Volatile Fatty Acids (VFA), which inhibit the development of anaerobic bacteria at high concentrations, decreasing CH_4 emissions.

Because of the wide range of environmental conditions and management practices that affect CH_4 emissions from manure management systems, it is difficult to compare the rate of emissions among regions, manure management systems and animal types. Long-term monitoring of CH_4 emissions from manure storage systems and laboratory-scale studies that adequately simulate farm conditions are necessary to evaluate the impact of individual environmental factors and manure management practices on CH_4 emissions.

MEASURING CH_4 EMISSIONS FROM MANURE – AN EXAMPLE FROM DAIRY SYSTEMS IN EASTERN CANADA

To evaluate the influence of manure storage temperature, manure storage duration, manure composition and management practices on CH_4 emissions from dairy cattle manure, scientists carried out a study on two representative commercial dairy farms in eastern Canada.

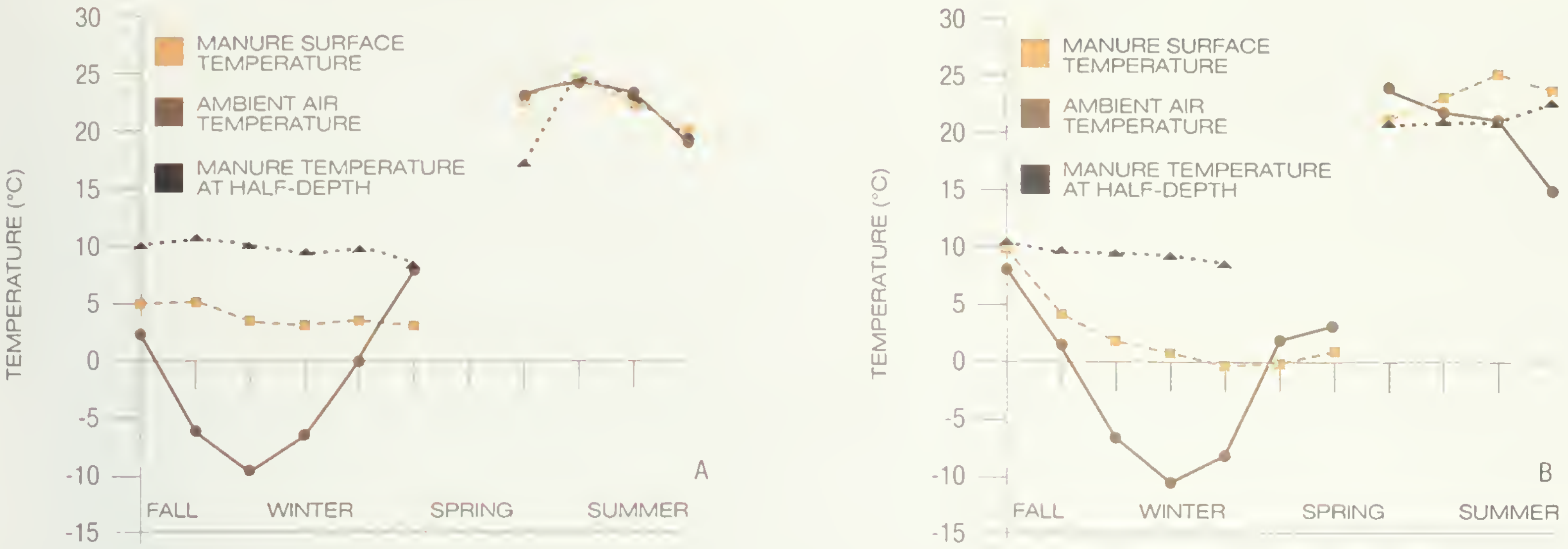
Most of the difference between the two farms (A and B) was in their animal feeding practices. On Farm A, lactating cows were fed a concentrated ration mainly composed of corn and alfalfa silage, soy bean, crushed corn, barley and mineral supplements. The dairy cows receiving this diet produced a great deal of milk—approximately 10,300 kg per year. On Farm B, cows received a diet rich in hay, composed of timothy, alfalfa, crushed corn and commercial dietary supplements. Dairy cows on Farm B had average milk production of 8,200 kg per year.

Because of Farm A's feeding practices, the manure from Farm A had a higher concentration of soluble organic compounds, which can be readily degraded into CH_4. Therefore, based on manure composition, the potential to produce CH_4 was greater in the manure from Farm A.

Methanogenic activity increases with temperature. At Farms A and B, manure temperature was measured over a one-year period (average monthly temperature is presented in Figure 21). During fall and winter, air temperature decreased to approximately -10 °C. However, bacterial activity in the manure created heat and kept its surface temperature above 0 °C. In summer, manure temperatures rose rapidly at both farms and reached an average of 20°C. The rapid increase was mainly due to the shallow depth of manure in the storage facilities after manure removal in the spring. Because of the high manure temperatures during the summer period, CH_4 emission potential was at its highest.

FIGURE 21

AMBIENT AND MANURE TEMPERATURE AT FARMS A AND B



During winter, the addition of fresh manure and bacterial activity generates heat and maintains the manure well above ambient air temperature. In spring and summer, manure and ambient air temperature are approximately the same. These elevated temperatures correspond with the potential for the highest CH_4 emissions. Here, average monthly temperature at the surface and half-depth of the manure tank on Farm A and Farm B are compared to ambient air temperature.

Source: D. Massé, AAFC, Lennoxville, QC

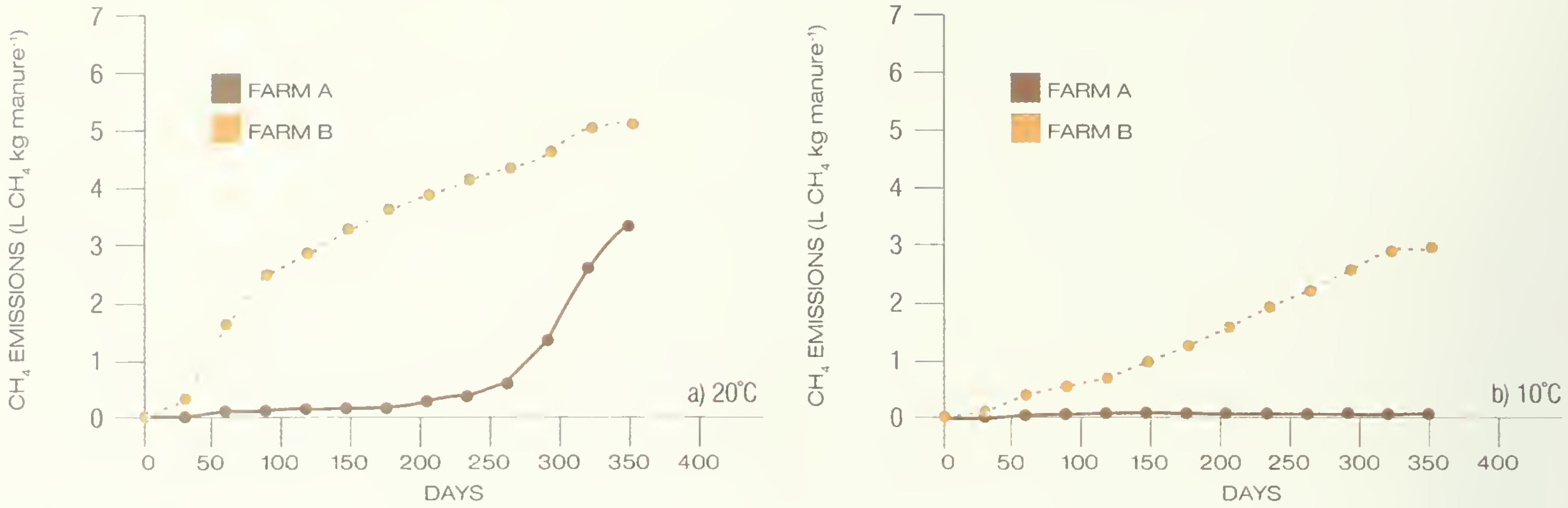
METHANE EMISSION FACTORS WITH RESPECT TO STORAGE DURATION, MANURE TEMPERATURE AND STORAGE MANAGEMENT PRACTICES

Manure slurries collected on Farms A and B were stored in eight 220-litre miniature storage structures. The containers were placed in two controlled-environment chambers maintained at 10°C and 20°C, respectively, to simulate average seasonal temperatures in commercial manure storage facilities. A tube inserted into the headspace of each barrel was equipped with a gas sampling port. Biogas production was measured daily over a 350-day period.

Figure 22 shows cumulative CH_4 production over the 350-day storage period for both farms at both storage temperatures. Total CH_4 production depended on storage duration, manure temperature and manure characteristics. At 10°C, there was no apparent methanogenic activity in the manure from Farm A over the whole study period. At 20°C, manure from Farm A started producing methane after about 250 days. Because this delay in CH_4 production is longer than the storage period between field applications on commercial farms, CH_4 emissions from the manure stored on Farm A is expected to be relatively small.

FIGURE 22

CUMULATIVE CH_4 PRODUCTION ACCORDING TO TIME, TEMPERATURE AND TYPE OF MANURE



Source: D. Massé, AAFC, Lennoxville, QC

Manure from Farm B produced CH_4 at both temperatures. Methanogenic activity occurred immediately after storage at 20°C and remained high for 120 days. At 10°C, methanogenic activity also occurred immediately after storage, but at a substantially lower rate than at 20°C. Manure from Farm B produced more CH_4 than Farm A at both temperatures. Possible explanations are:

A significant quantity of manure (more than 60-cm high) was left at the bottom of the Farm B storage structure after manure was removed for application to the land. Residual manure contained important populations of microorganisms already adapted to the storage temperature and the physico-chemical composition of the manure. These microorganisms readily produced CH_4.

On Farm A, the 250-day delay in methanogenic activity at 20°C could be due to either a low population of methanogens in the manure or the presence of inhibitory substances such as cleaning and disinfecting agents.

Manure compounds that could inhibit methanogenic activity when present in high levels, such as ammonia or VFAs, were higher in the manure from Farm A than in manure from Farm B. Scientists also reported higher CH_4 production in diluted as opposed to more concentrated manure.

Reducing CH_4 emissions from manure storage

Discouraging bacteria

Although it is difficult to completely eliminate CH_4 emissions from manure, many techniques can be applied on farms to reduce emissions. Since CH_4 emissions from manure are produced by bacteria, the best way to mitigate emissions is to diminish their activity. One method is to lower the temperature of the manure. During winter, manure should be removed frequently from barn buildings so that it will cool rapidly outside. During summer, the use of below ground storage tanks would help to maintain lower manure temperatures and result in lower CH_4 emissions.

A second way to reduce methanogenic bacterial activity is to ensure that manure does not remain long under anaerobic conditions. This can be accomplished by reducing the amount of time manure is stored; manure should be applied to the land as frequently as possible, for instance following each cut of hay. Once manure is applied to fields—and sufficiently aerated—CH_4 emissions cease.

A third option is to ensure that a minimal amount of manure remains in a storage tank once it is emptied. This practice can dramatically reduce the number of bacteria well adapted to the specific tank environment—and thus cut down on the CH_4 produced when fresh manure is placed in the tank.

Composting manures

Composting solid manure can reduce CH_4 emissions while simultaneously reducing odour emissions. However, some composting technologies may negatively affect air and water quality because they produce N_2O and ammonia emissions and also leach nitrate. For environmental and economical reasons, it is important that composting technology be carefully selected to minimize these nitrogen losses.

Utilizing CH_4

There is also the option of treating—or using—CH_4 after it is produced. By covering a manure storage tank with a flexible membrane, the biogas is trapped and prevented from entering the atmosphere (Figure 23). The trapped gas can then be treated in several ways to reduce the concentration of CH_4.

Biogas combustion

The simplest option is to burn, or flare, the biogas produced by the manure, which converts the CH_4 to CO_2, a much less potent GHG. However, if the gas is flared, the potential energy contained in the CH_4 is lost to the atmosphere as heat. Instead of burning the CH_4 in an open flame, it can instead be burned in a furnace to create heat (Figure 24) or used to power an electric generator. Both the heat and the electrical energy can be used on-farm. This is a more complex GHG mitigation method, but has the dual benefit of decreasing GHG emissions, while reducing costs for the farmer because of a decreased need for fossil fuels.

FIGURE 23

Covered Manure Storage Tank

Covering a manure storage tank with a flexible membrane prevents the biogas from entering the atmosphere and allows the gas to be treated prior to release. Here, a covered manure storage facility in Eastern Canada is shown.

Photo credit: D. Massé, AAFC, Lennoxville, QC

FIGURE 24

Anaerobic Digestion of Manure

Manure is removed from the livestock buildings and is pumped directly into the bioreactor (1), where the manure is digested anaerobically. Gas flow from the bioreactor is monitored in the control room (2), which passes a regulated flow of biogas to the furnace or electrical generator (3). If the furnace or electrical generator is not operational, a flare tower (4) burns the biogas. Finally, the treated manure is stored in the long-term storage tank, shown in the foreground.

Photo credit: D. Massé, AAFC, Lennoxville, QC

FIGURE 25

BIOFILTRATION OF BIOGAS

Biofiltration of biogas emitted during the decomposition of manure is one method of reducing CH_4 emissions. Manure gases are drawn into the biofilter where bacteria consume CH_4 as a fuel and emit CO_2 and water as waste products. This portable biofilter is shown installed at the exhaust of a covered manure storage facility in Eastern Canada.

Photo credit D Masse, AAFC Lennoxville, QC

Biofiltration

One further option to remove CH_4 is biofiltration, a natural bacterial process that converts CH_4 to CO_2 and H_2O. Using this technique, biogas is passed through a substance containing CH_4 consuming bacteria (Figure 25). Instead of producing CH_4 as a waste product, these bacteria feed on CH_4. Biofiltration technology is used for controlling odours and has the potential to reduce CH_4 emissions by up to 80%.

These are examples of mitigation practices that have the potential to reduce CH_4 emissions from manure. In most cases, mitigation practices not only reduce CH_4 emissions, but also have other benefits such as improved air quality through reduced odour emissions and reduced fossil fuel consumption through the creation of green energy.

FURTHER READING

Beauchemin, K.A. and S.M. McGinn. 2005. Methane emissions from feedlot cattle fed barley or corn diets. *Journal of Animal Science* 83:653–661.

Benchaar, C., C. Pomar and J. Chiquette. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: a modelling approach. *Canadian Journal of Animal Science* 81:563–574.

Kebreab, E., K. Clark, C. Wagner-Riddle, and J. France. 2006. Methane and nitrous oxide emissions from animal agriculture: a review. *Canadian Journal of Animal Science* 86:135-158.

Massé, D.I., F. Croteau, N.K. Patni and L. Massé. 2003. Methane emissions from dairy cow and swine manure slurries stored at 10°C and 15°C. *Canadian Biosystems Engineering* 45:6.1- 6.4

McAllister, T.A., E.K. Okine, G.W. Mathison, and K.-J. Cheng. 1996. Dietary, environmental and microbiological aspects of methane production in ruminants. *Canadian Journal of Animal Science* 76:231–243.

Measuring Ebbs and Flows

HOW AND WHY SCIENTISTS QUANTIFY GHG EXCHANGE

Scientists need to measure GHG emissions on farms to identify and understand their source, to quantify the amounts produced and to find better ways of reducing them. They also need to measure more than one gas at a time, because management practices that reduce the emissions of one gas can sometimes increase the emissions of another. For example, applying less nitrogen fertilizer reduces emissions of N_2O but eventually affects crop yield and reduces the quantity of carbon stored in the soil as organic matter.

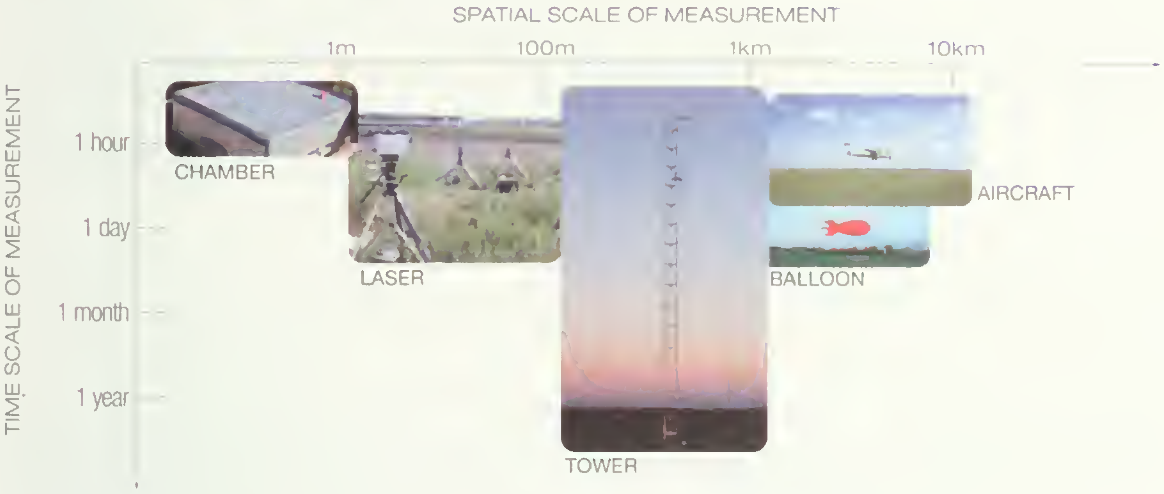
But measuring GHG emissions is not easy; the amounts measured depend on where the sensors are located and what the conditions are like there. Nitrous oxide, for example, is released in sporadic puffs, scattered across fields. And emissions vary throughout the year; while there may be next to none emitted for weeks or months, suddenly large emissions may occur in a single day, spread unevenly over the field. This is particularly the case during spring thaw in Eastern Canada when up to 40% of the N_2O emissions are estimated to occur. Meanwhile, net release of CO_2 from soil organic matter happens more gradually—so slowly that in many cases it can be measured only by comparing the change in soil carbon over many years. Methane emissions are probably the easiest to measure. However, CH_4 emissions from manure storage vary with air temperature while emissions from cattle vary with the feeding schedule.

A perfect solution would be to measure GHG emissions from an entire farm, field or region. Such a method would measure them year-round for many years and would in no way disturb the crops or animals from which the emissions originate. Unfortunately, no such methods exist, so scientists must make do with an array of techniques, each useful but none without weaknesses. As shown in Figure 26, by using several methods, scientists can measure GHG emissions over a wide range of scales. They can then assemble the data they need to develop and test models, which, in turn, can be used to obtain emission estimates for farms, fields and regions.

Whatever methods are used, the data collected apply only to the places and times where the measurements are made. For example, CH_4 is only ever measured from a few barns and N_2O and CO_2 from a few fields. To calculate emissions at either a provincial or national scale scientists use models—equations that describe in mathematical language what we know about how GHGs are produced.

FIGURE 26

The Principal Measurement Techniques



A variety of measurement techniques are used to estimate GHG emissions from Canadian agriculture. Each measurement technique is appropriate over a specific time and area, represented by the size of the photograph in this figure. By combining measurement techniques that cover different time frames and areas, scientists can estimate GHG emissions from areas smaller than one square metre to several square kilometres and from time frames of a few minutes to several years.

Source and Photo Credits. R Desjardins, E Pattey, AAFC, Ottawa, ON and P.-L Lizotte, McGill University Montreal, PQ

Models, discussed in more detail below, estimate the amounts of GHGs produced on a farm, in a region or across a country based on the area of land in question, how many animals live there, how farmers are managing their lands and the particular soil and climatic conditions. Models used to estimate GHG emissions have improved a great deal in recent years and they will continue to change as scientists learn more about how GHGs are produced and how farm practices affect GHG emissions. We may find, for example, that our estimate of GHGs from farms in 2005 is different in 2008 than it was in 2006 because we have used new research findings to improve our models.

How GHG measurements are taken

Measuring GHG exchange at the soil surface

The simplest way to measure GHGs seeping from the soil is to place an enclosure (or chamber) on the soil, trapping the air beneath, and repeatedly measure the GHG in the trapped air. For example, if the soil is releasing N_2O, the concentration will gradually increase in the chamber; the more rapid the increase in N_2O, the more N_2O is being produced. If the soil is absorbing CH_4, a decrease in CH_4 will be observed in the chamber over time.

This method, still the most widely used, has several advantages: it is relatively inexpensive and it can be used for comparing multiple practices at the same time. For example, it can be used to compare N_2O from side-by-side research plots ploughed in different ways or receiving different forms of fertilizer. However, the chambers have shortcomings: they can be used only for short periods of time—an hour at most; they measure the gas emissions only from the small area covered by the chamber; they sometimes disturb the soil surface, affecting the measurements; and they cannot be used easily where fields are under water or snow. Small networks, based on chamber measurements, have been established for GHG measurements. These have provided valuable information for model development.

Measuring GHG exchange from agricultural fields

Another way to measure GHGs is to sample the air above a field using sensors mounted on towers (see Figure 27). This approach is predicated on the fact that if a source is emitting a gas, the concentration is greatest near the source. Air moving upward from the soil will contain more GHGs, while air moving downward from the atmosphere will have a lower concentration. By measuring about 20 times per second the vertical wind speed and GHG concentrations at a point above an agricultural field, scientists can calculate how much GHG is released or absorbed by the field. GHG emissions can also be estimated by measuring the difference in gas concentration between two different heights above a field. In both cases, the higher the sensors are from the ground, the larger the area they detect.

This approach has important advantages over the chamber method: it estimates overall emissions from a large area and it allows continuous measurement over long periods, even through winter and early spring—critical periods for N_2O emissions. However, this approach is unreliable when the air is not moving, which frequently occurs at night. Many techniques have been developed to fill these gaps in the data.

Measuring CH_4 and CO_2 from cattle

Unlike soils, animals do not always cooperate placidly with those who try to measure the gases they emit, so scientists have had to devise some inventive methods. One way is to use barns as giant chambers. By mounting sensors in vents, scientists can measure the CH_4 entering and leaving a barn and make accurate calculations without disturbing the animals. As Figure 28 shows, such a system has been used with good results in a dairy barn at the Dairy and Swine Research and Development Centre in Lennoxville, Québec. By altering what the cows are fed or how they are handled on different measurement days, scientists can learn how these practices affect CH_4 emissions and, from these findings, recommend ways of reducing emissions.

FIGURE 27

TOWER-BASED MEASUREMENT

Tower-based GHG measurement techniques are becoming more common. They provide continuous measurements at the scale of a field. Here, N_2O emissions are being measured above a wheat crop. The tower on the left collects air samples at two separate heights. The air samples are sent to an analyzer that measures the difference in the N_2O concentration. On the right-hand tower, an anemometer measures vertical and horizontal wind speeds. By combining the N_2O concentration measurements with the wind-speed measurements, N_2O emissions can be calculated.

Photo Credit: E. Pattey, AAFC, Ottawa, ON

FIGURE 28

MEASURING CH_4 EMISSIONS IN BARNS

From the outside, the dairy barn at the Dairy and Swine Research and Development Centre in Lennoxville Québec, does not look unusual. However, inside is sophisticated equipment to measure CH_4 emissions from animals. By monitoring CH_4 concentrations and air flow at the fan inlet and outlet of the barn, the amount of CH_4 produced by the dairy cows can be accurately estimated.

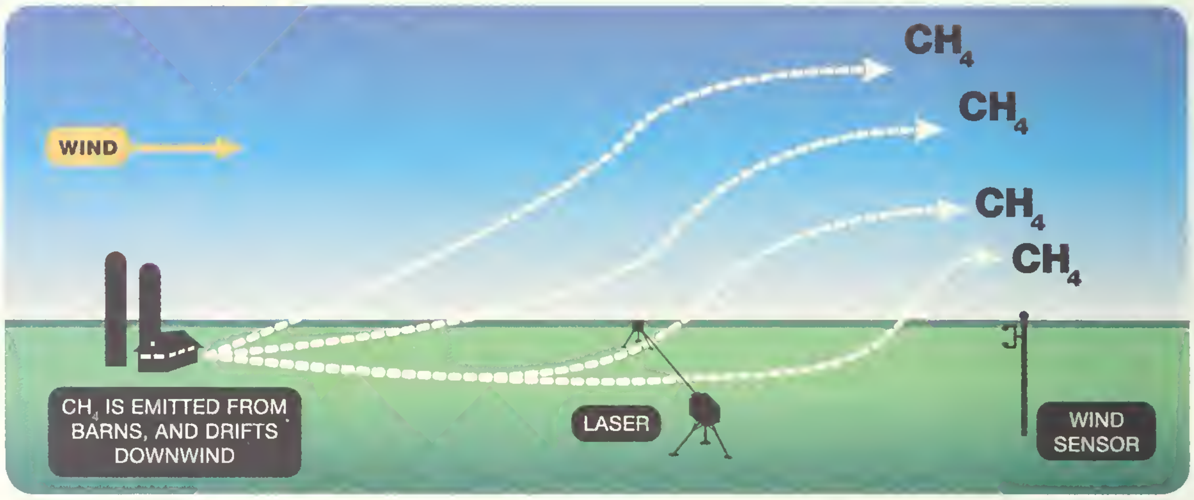
Photo Credit: D. Massé, AAFC, Lennoxville, QC

It is possible to place one or two animals inside smaller chambers—*instrumented rooms*—for more meticulous measurements of CH_4 emissions. Scientists can measure precisely and swiftly the impact of several different types of feed or feed additives; but the animals need to be trained and handled carefully so that anxiety does not bias the results.

Recently, even more advanced ways of measuring CH_4 emissions have been developed. Highly sensitive laser instruments sample the air downwind of CH_4 sources and count the number of CH_4 molecules crossing a cross-section of the plume downwind of an animal herd, a barn or a manure storage tank (see Figure 29). Combining the CH_4 concentration measurements with wind flow information, CH_4 emissions are estimated using a computer model. This determines the relationship between CH_4 emission and concentration anywhere in the plume. The method is ideal in that it yields measurements without the animals even being aware of the process. However, like most measurement techniques that rely on the wind speed to transport the GHG, it is inaccurate under light wind conditions.

FIGURE 29

Measuring CH_4 in Plumes of Air



Methane emitted from animals in a barn is transported downwind in the air. By measuring the CH_4 concentration using lasers, as well as wind flow, scientists can estimate CH_4 emissions from the barn.

Measuring CO_2 exchange

Carbon dioxide is the most abundant GHG worldwide, mostly because of its release from burning fossil fuels such as gasoline, diesel and coal. In agriculture, large quantities of CO_2 are fixed by photosynthesis to produce biomass. However, an almost equal amount of CO_2 is released to the atmosphere by plant and soil respiration. For example, in one year, the corn on one hectare of land might fix by photosynthesis 30 tonnes of CO_2, but roughly the same amount is released to the air by respiration (on- or off-site) and the decay of plant residues and organic matter in soil.

Measuring the *net* exchange of CO_2 in the soil reservoir—the difference between the absorption and emission of CO_2—is not easy and requires continuous, year-round measurements. Therefore, scientists usually use a simpler approach: first, they measure the amount of carbon stored in the soil; some years later, they return to the same spot to measure it again. If the amount has increased, the field has absorbed more CO_2 than it has released; if the amount has declined, the field has released more than it absorbed.

Such measurements sound simple, but they must be made carefully. Changes in soil carbon happen gradually, changing at a rate of perhaps 0.2 tonnes per hectare per year. Meanwhile, the amount of carbon in soil is high, sometimes as high as 100 tonnes per hectare. Therefore, changes can be measured only after many years, often decades. Experiments must be carefully designed to take into account the variability in soil carbon in one location versus another.

For a long time, year-round continuous measurements of GHG exchange were considered almost impossible to obtain. However, a global network of CO_2 towers has been established at approximately 462 sites. The equivalent of about 2,750 years of data have already been collected. This excellent data set is now being used to quantify the net carbon budget for most major ecosystems.

Night-time GHGs from whole farms

Helium-filled balloons have long been used to probe the atmosphere. Now scientists are using them to measure GHG emissions on a regional scale. At night when the lower atmosphere is stable, GHGs emitted from agricultural sources are contained and cannot escape above the lower 50 to 100 metres of the atmosphere—the *nocturnal boundary layer*—essentially an enclosed chamber of air over a region. Several times a night, meteorological and GHG measurements are made in this chamber from a tethered blimp. This enables calculation of the GHG released from a whole farm during the night.

Aircraft measurements of GHG emissions from whole regions

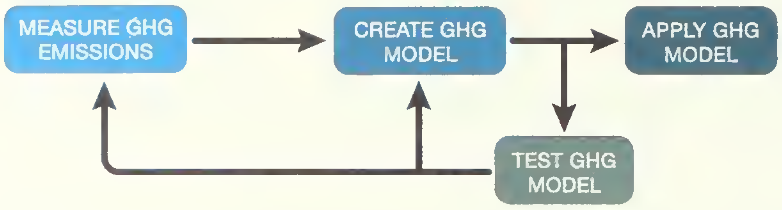
To obtain GHG emissions for a region, fast-response instruments are mounted on aircraft. Flying at about 50 metres above agricultural land at 180 km/h, the aircraft measures GHG emissions over entire regions by calculating the difference in the concentration of upward and downward moving air for the gas of interest. Data collected by such aircraft, one of which is available in Canada, are especially useful to test the accuracy of simulation models and GHG emissions estimates, such as regional and national CH_4 and N_2O inventory estimates. Since aircraft are expensive and can measure GHG emissions only over short periods, they are often used in combination with towers, which measure GHGs around the clock. In this way, the aircraft can expand the "view" of the tower from 1 square km to 100 square km.

Simulation models for estimating GHG emissions

Scientists will never be able to make sufficient measurements over a long enough period of time to capture GHG emissions from all farms. Therefore, estimates must rely on mathematical equations—or models—which are based on available measurements. Models are an attempt to describe in mathematical language how scientists understand the real world. Because our understanding is still incomplete, any model is always an over-simplification of the real world. As Figure 30 shows, if we are to make reasonable estimates with models, we need to use flux measurements to build models and continuously test the models against our observations.

FIGURE 30

THE DEVELOPMENT OF MODELS



GHG model development occurs alongside experimental measurements. Initially, GHG emission measurements give scientists the knowledge they need to create a GHG model. When the model is tested under conditions somewhat different from those under which it was originally designed, shortcomings are sometimes revealed. This process can inspire new research questions. To address any shortcomings that appear, and to resolve research questions, further model refinements and GHG emissions measurements are often required.

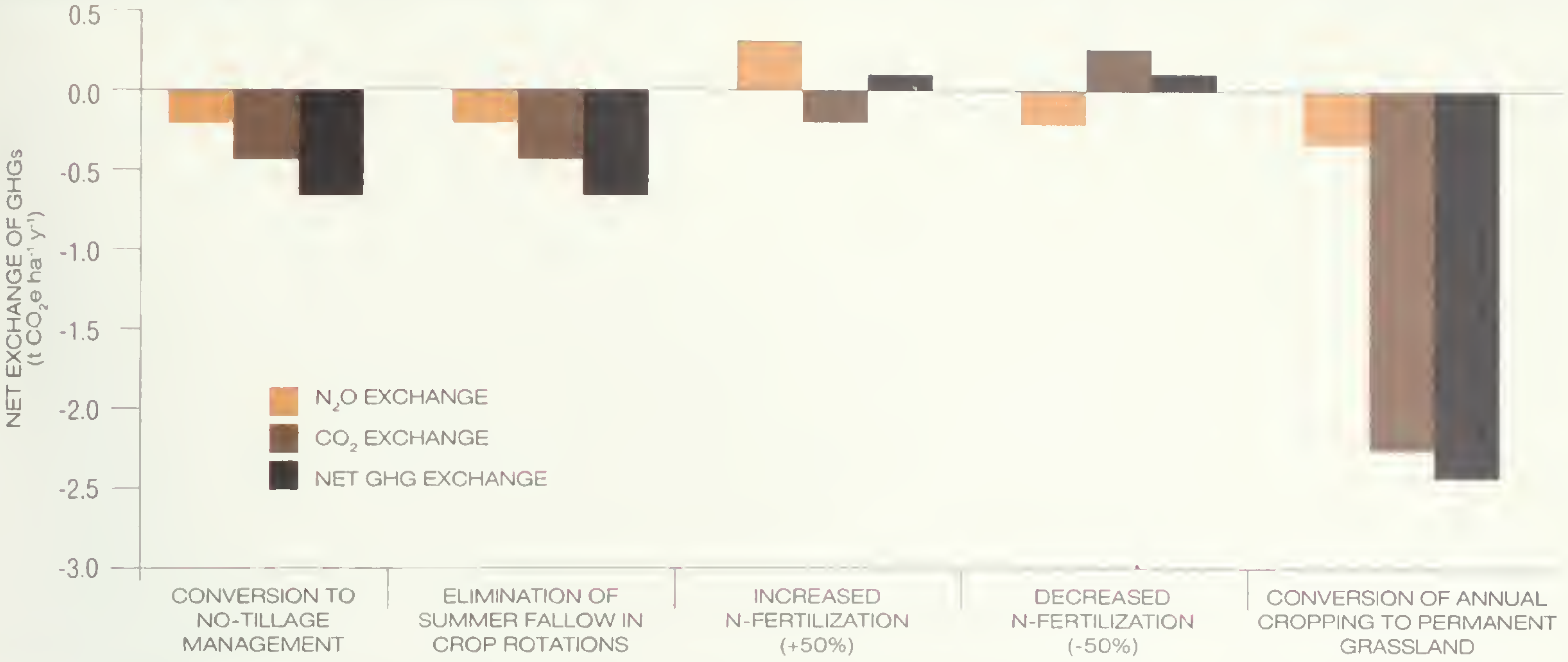
The models for emission estimates vary widely in complexity. Some approaches use simple arithmetic. For example, the amount of N_2O emitted from a field can be estimated by assuming that a certain percentage of all nitrogen added to soil as fertilizer, manure and crop residue is released as N_2O. The Intergovernmental Panel on Climate Change has recommended a value of 1.25%. However, this percentage has been modified based on measurements made in Canada to account for such factors as soil moisture and topography. Thus, to estimate emissions in Canada, scientists sum up all nitrogen added to a field and multiply by a series of emission factors representing several processes. Such approaches, based on observations from many years, are called *empirical* models.

Models can be highly complex, residing in sophisticated computer code developed over many years of study. These *process-based* models try to describe each of the processes that lead to GHG emissions and try to capture all factors influencing those processes. Figure 31 shows results obtained with such a model for Canadian conditions. While the adoption of no-tillage, the elimination of summer fallow and conversion of lands to permanent grasslands all reduced both CO_2 and N_2O emissions, it is possible for a management practice that reduces CO_2 emissions to actually increase net GHG emissions due to increased N_2O emissions associated with that practice. Such is the case when a crop is fertilized with nitrogen above the recommended levels. In this situation, depicted in Figure 31, carbon sequestration will increase, however the CO_2 sequestered will be less than the increase in N_2O emissions caused by the increased fertilizer. Therefore, the net GHG emissions will increase when a crop is over-fertilized, despite the increased carbon sequestration.

Over the long term, most scientists aim to use process-based models. However, in the short term, scientists are often forced to use simpler empirical models, which require less data and understanding.

FIGURE 31

RESULTS FROM PROCESS-BASED MODELS



When evaluating management practices for their effectiveness in reducing GHG emissions it is necessary to determine more than just CO_2 *emissions. Two process-based models were used to investigate the impact that several changes in farm management practices had on both* N_2O *and* CO_2 *emissions across Canada.*

Source B. Grant and W Smith, AAFC, Ottawa, ON

Building better models remains an important aim of scientists in GHG research. Such models can give us better estimates of the amounts of GHG produced, and, more importantly, help us to project in advance, which practices might best reduce emissions. There is a further benefit of building these models: they point to our ignorance, showing where our understanding is weakest, and where we most need further study to expand our knowledge.

FURTHER READING

Baldocchi, D.D. 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. *Global Change Biology* 9:479–492.

Desjardins, R.L., J.I. MacPherson and P.H. Schuepp. 2000. Aircraft-based flux sampling strategies. Pp. 3573–3588. In: R.A. Meyers (ed.) *Encyclopedia of Analytical Chemistry*. John Wiley & Sons Ltd.: Chichester.

McGinn, S.M. 2006. Measuring greenhouse gas emissions from point sources in agriculture. *Canadian Journal of Soil Science* 86:355–371.

Pattey, E., et al. 2006. Towards standards for measuring greenhouse gas flux from agricultural fields using instrumented towers. *Canadian Journal of Soil Science* 86: 373–400.

Rochette, P. and G.L. Hutchinson. 2005. Measurement of soil respiration in situ: Chamber techniques. Pp. 247–286 in M.K. Viney, (ed). Micrometeorology in agricultural systems. ASA, CSSA, SSSA, Madison, WI. *Agronomy Monograph* 47: 584 pp.

The Amounts

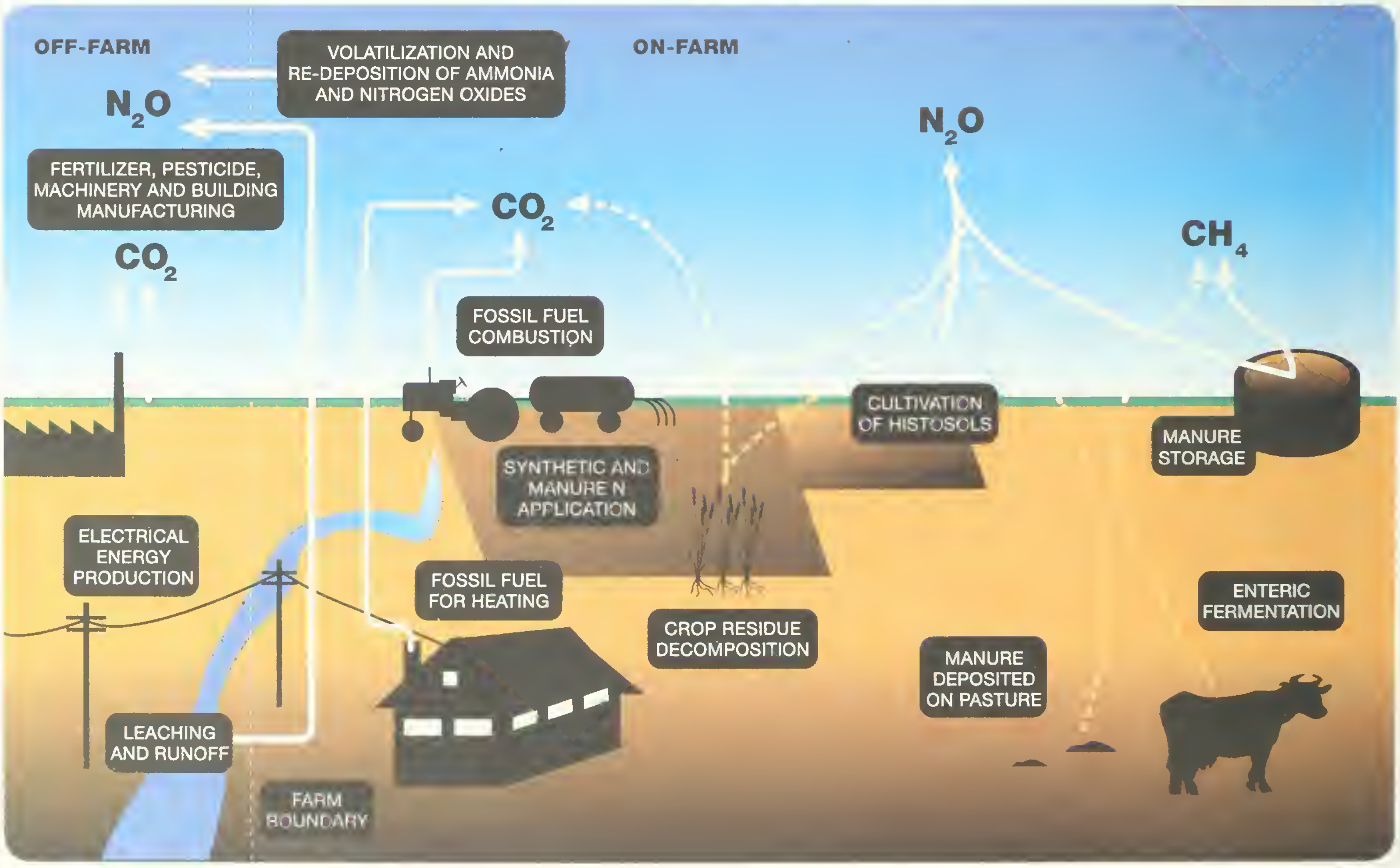
The Emissions we Produce

ESTIMATES OF GREENHOUSE GAS EMISSIONS FROM CANADIAN AGRICULTURE

As earlier chapters have explained, agriculture is a significant source of three GHGs: CO_2, CH_4 and N_2O. Figure 32 shows that for each GHG there are multiple sources, both on farms and off farms. In responding to international agreements such as the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC), and to track progress in addressing climate change, Canada elected to quantify and report annually its GHG emissions from all sources in a transparent and verifiable manner. This technical chapter presents GHG emission estimates from the Canadian agricultural sector for the period from 1990 to 2005.

FIGURE 32

ON- AND OFF-FARM SOURCES OF GHG EMISSIONS



Global warming potential

Greenhouse gases differ in their ability to trap heat in the atmosphere and therefore are not equal in their contribution to global warming. Global warming potential (GWP) allows us to assess how much a given mass of GHG is likely to contribute to global warming. The latest values are given in the introductory chapter. For reporting purposes, the GWP for N_2O and CH_4 are considered to be 310 and 21 times more powerful than CO_2 by mass over a 100-year period. By indexing each gas to CO_2 using the GWP, national GHG emissions are reported as million tonnes (Mt) of CO_2 equivalents, or Mt CO_2e. One Mt CO_2e is roughly equal to the CO_2 emissions that 220,000 mid-size cars produce when traveling over a distance of 20,000 km.

There are many on-farm and off-farm sources of GHG emissions. On-farm N_2O emissions are enhanced when nitrogen is added to the environment. This happens when synthetic fertilizer and manure are applied to the land, when manure is stored, when manure is excreted on pasture and when organic soils (histosols) are cultivated. Off-farm N_2O emissions occur when nitrogen is transported away from the farm before being converted to N_2O. This occurs in water by leaching and runoff and through the air by volatilization. Methane emission occurs on-farm when organic material is decomposed by methanogenic bacteria under oxygen-free conditions. This occurs during the digestive process in ruminants and during the storage of manure. Carbon dioxide emissions occur on-farm when crop residues and other organic matter decompose and when fossil fuels are burned to propel farm machinery and to heat farm buildings. Off-farm CO_2 emissions occur when fossil fuels are consumed to produce goods that are needed on-farm: fertilizer, pesticides, machinery, building construction material and electrical energy.

[illegible]

Calculation methodology

The methodology to calculate emissions from the Canadian agricultural sector varies by gas depending on our level of knowledge of each. Soil CO_2 emissions are calculated by incorporating the results from a process-based model to estimate net CO_2 exchange between the plant-soil and the atmosphere. However, because of a lack of adequate process-based models, CH_4 and N_2O emissions are calculated using empirical models developed by the Intergovernmental Panel on Climate Change and modified for Canadian conditions. These methods of calculation allow flexibility to incorporate Canadian conditions and research results, while allowing comparison with GHG emission inventories from other nations.

Equation 1: CO_2 emissions from the soil

Changes in either land use or land management can cause soil carbon content to remain constant or increase or decrease. If there is no change in land use or land management, and climatic conditions are relatively similar from year to year, soil carbon stocks will tend, over many years, to approach an equilibrium.

The basic equation used to estimate a change in soil carbon as the result of a land management change (LMC) is given as:

$\Delta C = F \times A$

where:

ΔC = Change in soil C stock, t C y^{-1}

F = Average annual change in soil organic carbon (SOC) from the LMC, t C $ha^{-1}y^{-1}$.

A = Area of the LMC, ha

As Figure 33 shows, the activity data—A in equation 1—are spatially referenced with respect to the boundaries of the National Ecological Framework, a hierarchical eco-stratification of all land in Canada. The eco-stratification provides a systematic basis for scaling the information from the smallest area for which soil information is available on a national scale to larger ecologically related areas (i.e., ecodistrict, ecoregion, ecozone). We estimated agricultural soil carbon change for Soil Landscapes of Canada (SLC). In Canada, there are 3,264 SLC units in which agricultural activities take place. The main source of national activity data is the Census of Agriculture, available from Statistics Canada for all farms every five years.

A large body of Canadian and international literature describes how management practices are known to influence soil carbon in cultivated cropland. To include such practices in the GHG inventory, a good understanding of soil carbon change expected for the LMC and the area of the LMC are required. The LMC selected were reduction in tillage intensity, reduction in summer fallow and conversion from annual to perennial crops. They are the three main strategies used in Canada during 1990-2005.

To estimate the average annual change in soil carbon due to LMC (F), a plant-soil organic matter model, CENTURY, was used to simulate carbon nutrient dynamics for Canadian croplands. This process model has been used widely to simulate SOC and has been tested and validated for Canadian conditions. Carbon factors (F) derived from model simulations were estimated as the difference in soil carbon stocks over time between two simulations: a *base* run representing general land management conditions (excluding specific changes in practices) and a *factor* run in which everything was held constant relative to the base except for the LMC of interest.

Carbon dioxide emissions from fossil fuel use

Many activities on farm and off farm, which rely on the use of fossil fuel, result in releases of CO_2 along with trace amounts of CH_4 and N_2O. A large percentage arises directly from farm field operations and indirectly from electricity production, heating fuel and the manufacture of fertilizer, pesticide and machinery. These emissions are very important as far as managing GHG emissions. However, for the UNFCCC and reporting purposes, they are attributed to the transportation and manufacturing sectors and are not included in the agricultural GHG inventory.

FIGURE 33

THE HIERARCHICAL ECO-STRATIFICATION OF ALL LAND IN CANADA

Canada has been subdivided into small spatial areas—called Soil Landscapes of Canada—that have similar soil and climatic conditions. By grouping estimates made at the small scale, scientists can estimate emissions at much larger scales, such as provincial or national.

Equation 2: N_2O emissions

Nitrous oxide emissions from soil and manure management systems for each nitrogen (N) source are calculated by multiplying the amount of N additions from various sources (e.g., synthetic fertilizer N, crop residue N, manure N, etc.) by a particular empirical emission factor for that source.

N_2O Emissions = N × EF

where:

N_2O emissions = Emissions from various N sources, kg N_2O–N y^{-1}

N = Amount of N by source, kg N

EF = Emission factor, kg N_2O–N kg N^{-1} y^{-1} for a particular source.

In Canada, the soil N_2O emission factors are primarily a function of soil moisture conditions. As Figure 34(a) shows, in drier climates such as the Prairie provinces, the emission factors are much lower than for Eastern Canada, where the climate is generally more humid. In British Columbia, the emission factors are moderate in the wet coastal areas and low in the dry interior areas. The N_2O emission factors are also dependent upon soil texture, tillage intensity, and landscape position, as well as soil moisture added during spring thaw and crop irrigation. Factors were derived for each SLC based on the climatic conditions.

Nitrous oxide emissions occurring from manure are a function of the manure storage system. As compared to CH_4 emissions, aerobic conditions tend to enhance N_2O emissions. Therefore, as Figure 34(b) shows, when manure is deposited onto pasture by grazing animals or stored as a solid, N_2O emissions are greater than for liquid manure.

Equation 3: CH_4 emissions

Methane emissions from enteric fermentation are calculated by multiplying animal population in each animal category by an empirical emission factor for that particular category.

CH_4 Emissions = n × EF

where:

CH_4 emissions = Emissions from a particular livestock class, kg CH_4 y^{-1},

n = Animal population for a particular livestock class,

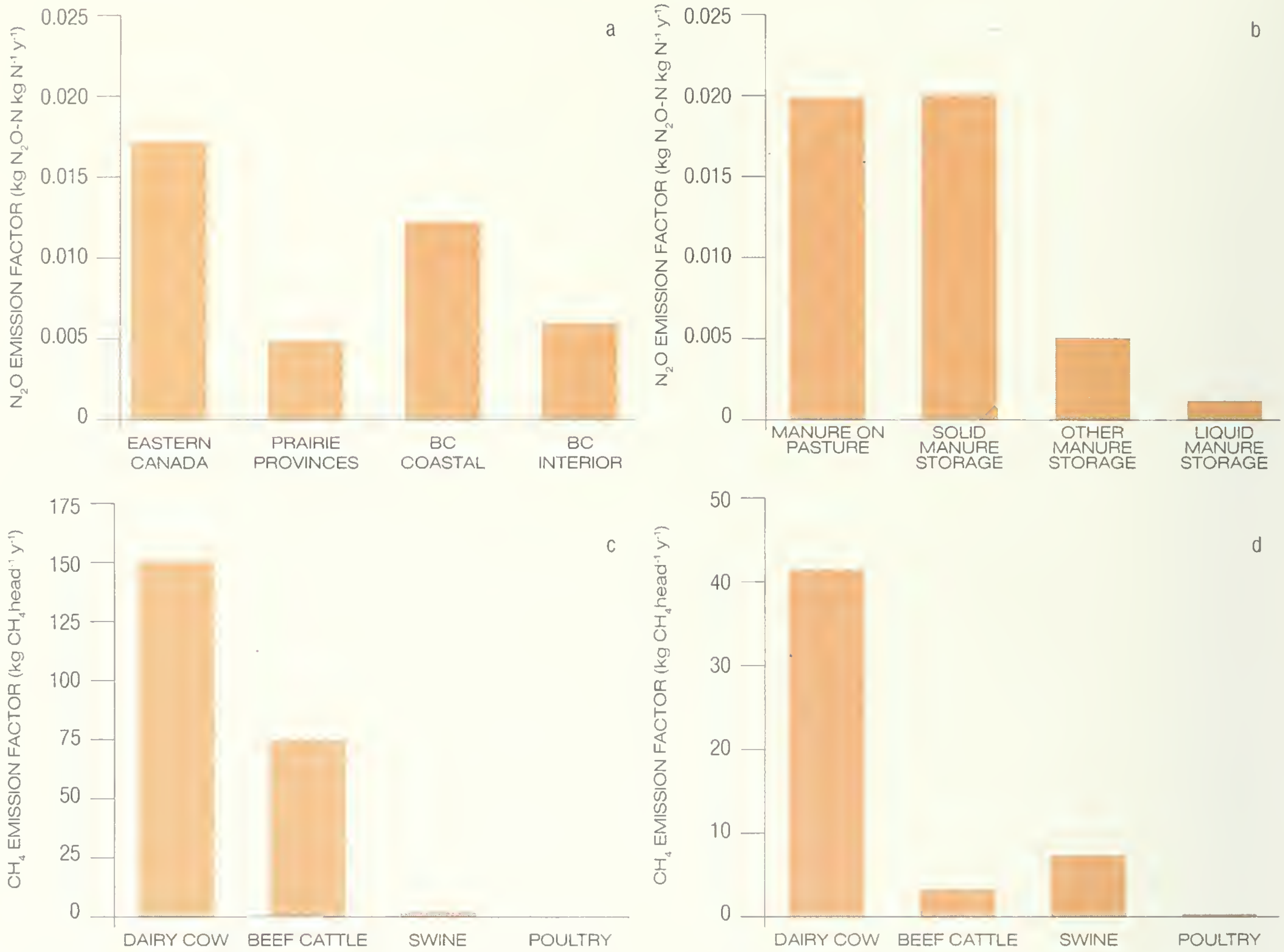
EF = Emission factor, kg CH_4 $animal^{-1}$ y^{-1} for a particular livestock class.

As Figure 34(c) shows, the emission factors are very different for various animal categories. They also vary with the diet and the activity level of the animal. More information is available in the chapter on methane emissions.

Emissions associated with manure management are estimated using a similar approach: animal population × emission factor. As Figure 34(d) shows, the emission factor is the largest for dairy cows. This is a function of the manure storage system employed (e.g., liquid storage creates greater emissions than solid storage), the amount of manure produced per animal and the temperature of the stored manure. The chapter on methane emissions offers more details.

FIGURE 54

GHG Emission Factors in Canada



Moisture enhances N_2O emissions from soils. As a result, N_2O emissions are higher per unit of area in the moist soils of the eastern provinces, and lower in the dry Prairie provinces. Emissions are variable in British Columbia, where moist soils occur on the west coast, but dry conditions prevail in the interior of the province (Panel a). Nitrous oxide emissions from manure are enhanced when manure decomposes under aerobic conditions. Therefore, emissions are greatest when manure is stored as a solid, or deposited on pasture by grazing animals, and smallest when the manure is stored as a liquid (Panel b).

The rate of GHG emissions is highly variable between animal categories and regions across the country. For instance, a dairy cow produces approximately 150 kg of CH_4 from enteric fermentation per year, whereas a beef cow, which is nearly as large as a dairy cow, produces only 70 kg per year (Panel c). Methane emissions from manure management vary depending on the storage type used. Dairy-cow and swine productions tend to store manure as a liquid, which promotes CH_4 emissions, whereas beef-industry manure tends to be stored as a solid, which restricts CH_4 emissions (Panel d).

Source: R. Desjardins and D. Worth, AAFC, Ottawa, ON

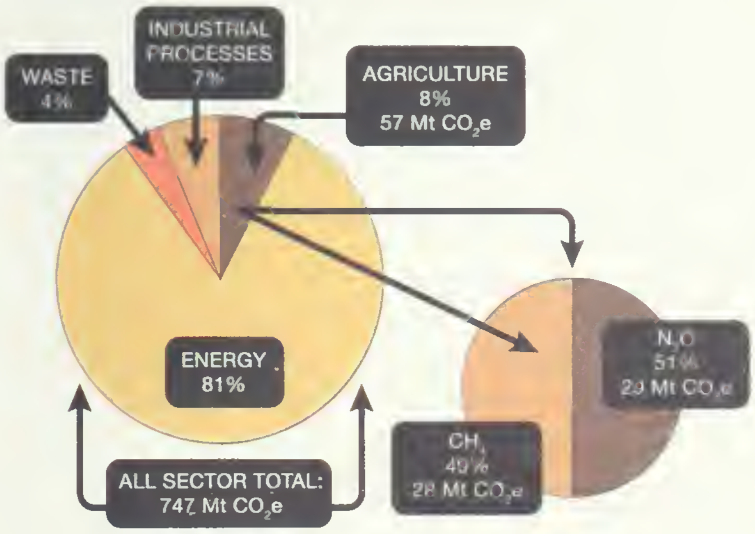
GHG emission estimates from Canadian agriculture, 1990 to 2005

The UNFCCC has stipulated that GHG emissions be calculated annually from 1990 onwards. With respect to the international agreements, most sectors are largely concerned with how current emissions compare with emissions in 1990. From 1990 to 2005, Canada's GHG emissions for all sectors increased by 25%. As Figure 35 shows, agriculture is responsible for approximately 8% of national GHG emissions if emissions associated with fossil fuel are not counted and 10% if they are included. Meanwhile, agriculture is increasing its emissions of N_2O and CH_4 at roughly the same rate as all other sectors and these gases continue to be the most significant GHGs in agriculture (Figure 36).

Carbon dioxide emissions and removals by soils are accounted for under the UNFCCC category of Land Use, Land Use Change and Forestry. The categories pertaining to agriculture include grasslands converted to croplands, croplands remaining croplands, forests converted to croplands, and grasslands remaining grasslands. As Figure 37 shows, since 1990, grasslands converted to croplands has been a relatively minor and decreasing *source* of CO_2, croplands remaining croplands has been a relatively major and increasing *sink* of CO_2, and forests converted to croplands has been a relatively major but decreasing *source* of CO_2. Canada has chosen to define grasslands as rangeland—unimproved pasture in regions where it would not revert to forest if unmanaged. Under this definition, grassland remaining grassland was assumed to be neither source nor sink of CO_2. On a net basis, these categories have gone from being a source of 14 Mt CO_2e in 1990 to being almost neutral in 2005.

FIGURE 35

ALL SECTOR AND AGRICULTURAL GHG EMISSIONS IN CANADA FOR 2005

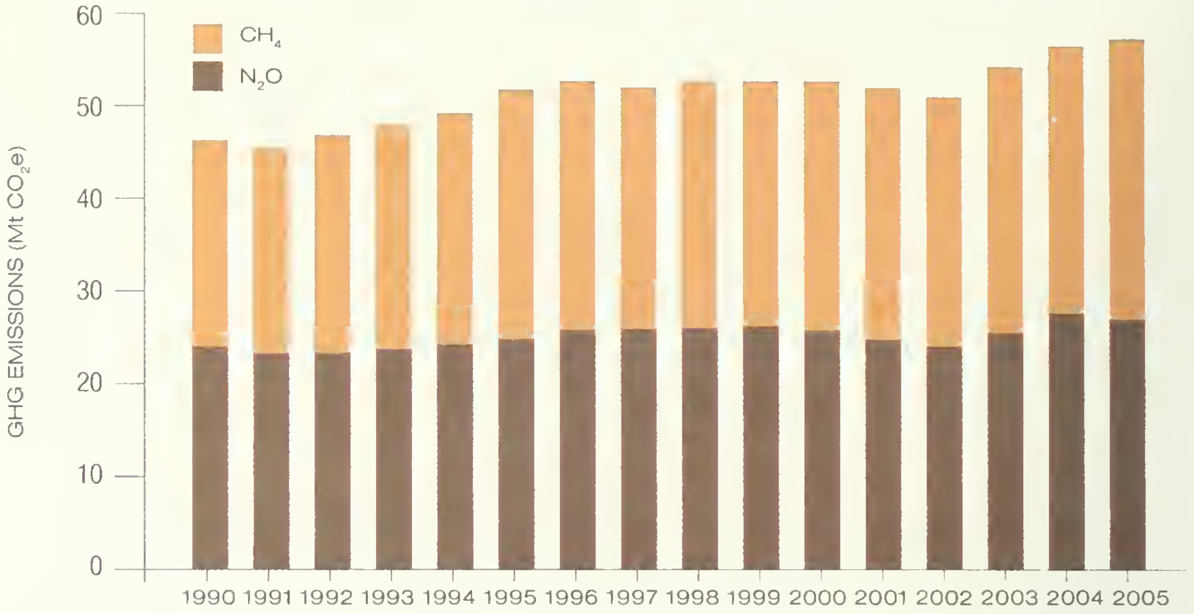


In 2005, Canada emitted 747 Mt CO_2e. Energy production was responsible for 81% of these emissions. Agriculture was responsible for a smaller, but significant, portion of national GHG emissions, approximately 8% or 57 Mt CO_2e. Emissions from Canadian agriculture are nearly evenly split between N_2O and CH_4. Emissions associated with fossil fuel use in agriculture accounted for an additional 2% of the national emissions, however these are counted in the transportation and manufacturing sectors.

Source: R. Desjardins and D. Worth, AAFC, Ottawa, ON

FIGURE 36

AGRICULTURAL N_2O AND CH_4 EMISSIONS IN CANADA, 1990–2005

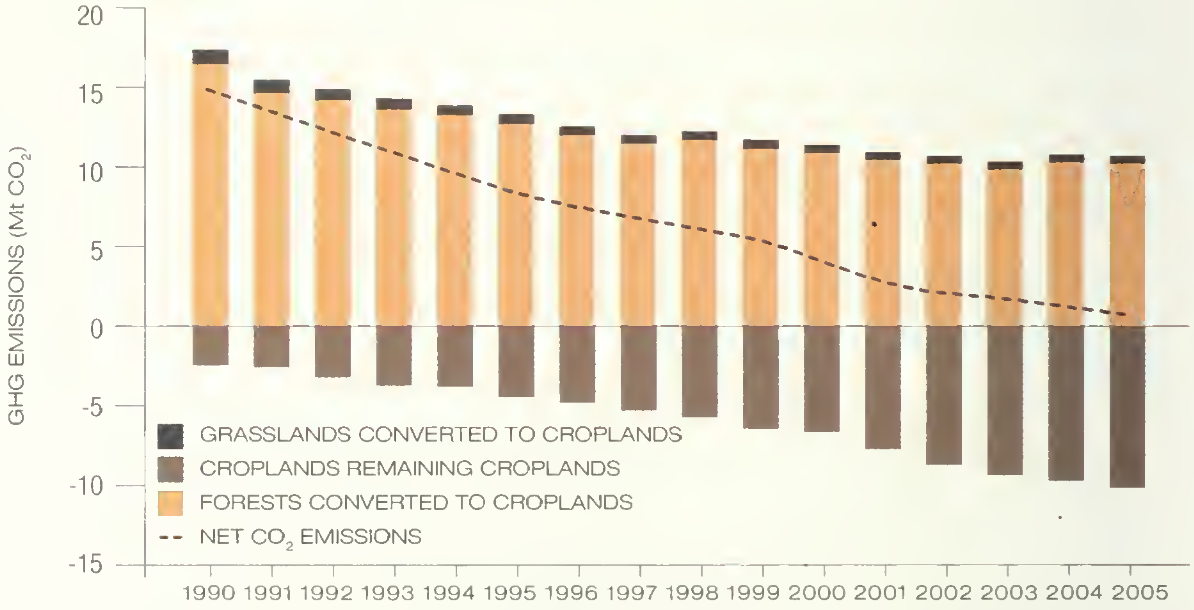


Nitrous oxide emissions from Canadian agriculture increased by 4 Mt CO_2e (or 14%) between 1990 and 2005 while CH_4 emissions increased by 7 Mt CO_2e (or 24%).

Source: R. Desjardins and D. Worth, AAFC, Ottawa, ON

FIGURE 37

CARBON DIOXIDE EMISSIONS FROM AGRICULTURE RELATED TO LAND USE, LAND USE CHANGE AND FORESTRY

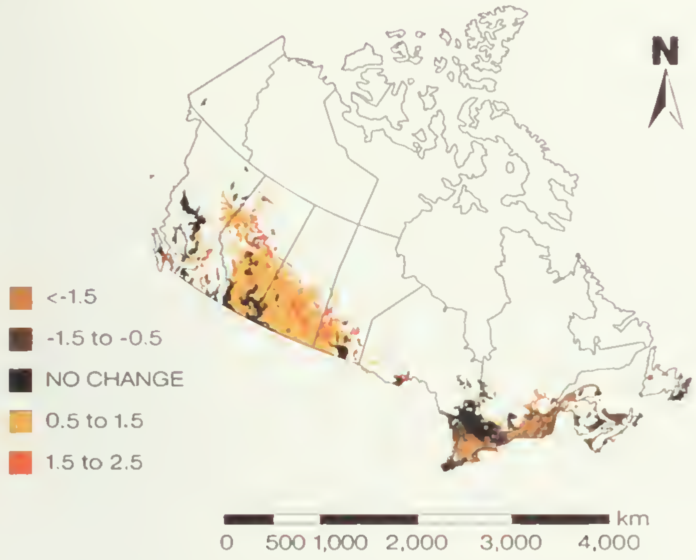


Net CO_2 emissions from agriculture related to Land Use, Land Use Change and Forestry decreased by almost 14 Mt CO_2 between 1990 and 2005. This is due to an increase in carbon sequestration in croplands and a decrease in CO_2 emissions caused by forests converted to croplands.

Source. B. McConkey, AAFC, Swift Current, SK

FIGURE 38

THE CHANGE IN SOIL ORGANIC CARBON CONTENT OF AGRICULTURAL SOILS IN CANADA 1990–2005, t ha^{-1}



Farmers have the ability to change the amount of organic carbon in their soils by adopting beneficial management practices such as reduced tillage, reduced summer fallow and the conversion of annual to perennial crops. In Canada, widespread adoption of such practices has led to an increase in soil organic carbon in croplands of the Prairie provinces. However, in many areas of Eastern Canada, there has been a decrease in soil organic carbon in croplands because of a shift from perennial to annual crops such as corn and soybean. This conversion emits more CO_2 even if it is accompanied by the adoption of beneficial management practices. In this map the change in soil organic carbon between 1990 and 2005 in the first 30cm in the soil is shown for all agricultural lands in Canada.

Source: B. McConkey, AAFC, Swift Current, SK

Figure 38 shows the net change in soil carbon stocks between 1990 and 2005 to a depth of 30 cm in Canadian agricultural lands for cropland remaining cropland. These show a substantial gain in soil carbon, particularly in the Prairie provinces, after the introduction of beneficial agricultural practices such as reduced summer fallow, increased use of conservation tillage and perennial crops.

Why have GHG emissions changed?

As Figure 36 shows, agricultural GHG emissions in the form of CH_4 and N_2O have increased by 19% since 1990. However, when CO_2 emissions from agricultural land use are included in the comparison, total net agricultural GHG emissions decreased by 6%. This is because of a large decrease in net soil CO_2 emissions driven by the increased adoption of beneficial agricultural practices. Specifically, a decrease in the occurrence of summer fallow in the Prairie provinces, an increase in conservation tillage—tillage that minimizes disruption of the soil—and an increase in perennial crops in the Prairie provinces have increased soil carbon content.

Minimum tillage and no-tillage practices often provide both economic and environmental benefits. As a result, the area under these practices in Canada has expanded from 30% of the cropland in 1990 to 70% of the cropland in 2005. An extensive discussion of beneficial agricultural practices is included in the carbon chapter.

Although soil organic carbon has been increasing in agricultural soils of the Prairie provinces, it is important to note that changes in farming practices can also increase the *emission* of soil carbon stocks as CO_2. This has been happening in Eastern Canada, especially Ontario and Quebec where the area of perennial forages has been decreasing in favour of growing annual crops such as corn and soybeans. In fact, some areas of Quebec and Ontario are as large a *source* of

CO_2 as parts of the Prairie provinces are a *sink*. It is also important to note that if the beneficial agricultural practices discussed above were stopped, carbon would be reemitted into the atmosphere, possibly at a faster rate than the rate at which it was sequestered. Changes in economics, government policies or the climate could bring about different agricultural practices and, therefore an increase or decrease of soil organic carbon.

Much of the decreased CO_2 emissions from soil has been offset by increases in CH_4 and N_2O emissions. From 1990 to 2005, CH_4 emissions from the Canadian agricultural sector increased by 24% due to larger populations of most animals. As Figure 39 shows, the Canadian beef cattle population, increased by 30%. Most of this expansion occurred in the Prairie provinces. Similarly, the swine, and poultry populations have increased by 31% and 23%, respectively. Only the dairy cow population decreased, by 29%. The net effect in Canada is that total CH_4 emissions have continued to increase.

Nitrous oxide emissions in Canada increased by 14% between 1990 and 2005, primarily because of an increase in the use of synthetic nitrogen fertilizer and the increase in animal population. National synthetic nitrogen fertilizer sales increased from 1.20 Mt of nitrogen to 1.54 Mt of nitrogen from 1990 to 2005. The increase in nitrogen fertilizer use has occurred exclusively in the Prairie provinces; in all other provinces consumption decreased or maintained its level during this period. Meanwhile, larger animal populations have contributed to greater N_2O emissions because of greater manure production. Finally, emissions from crop residue nitrogen addition are directly related to crop production, which depends on weather conditions. For example, 2002—a year in which severe drought led to crop production 44% lower than in 2005—resulted in the lowest N_2O emission estimates from crop residue decomposition for the 1990 to 2005 period.

Uncertainty in GHG emission estimates

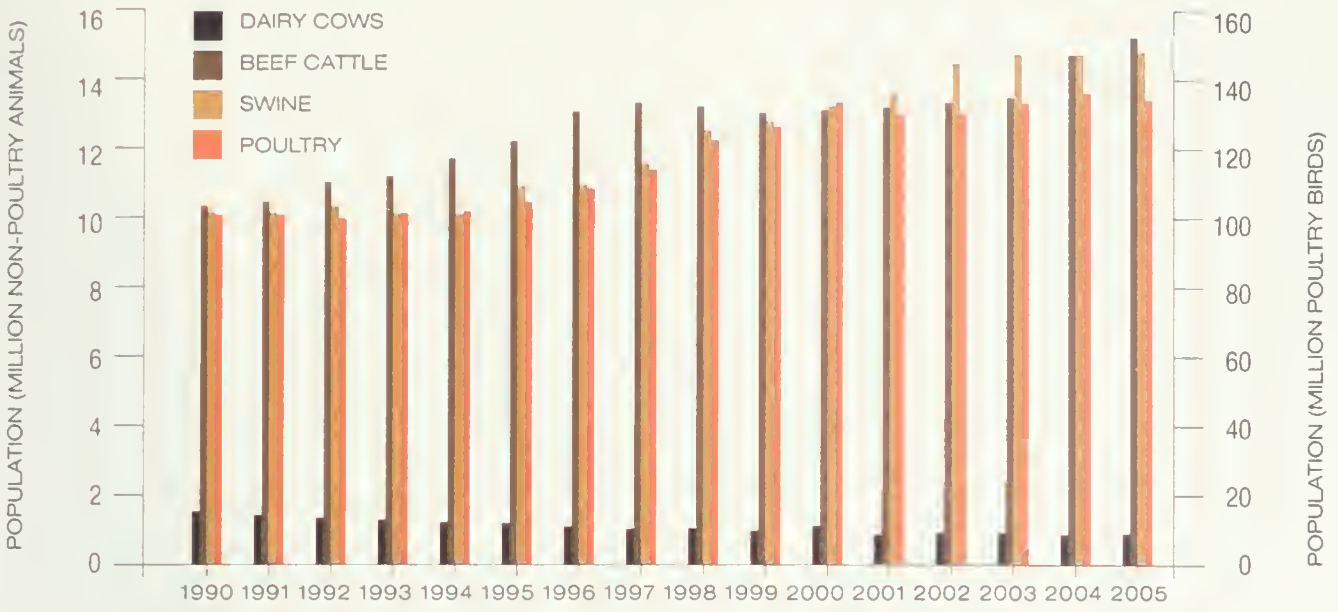
Farm management practices change quickly, climate varies year to year and precise agricultural data are difficult to collect. This makes estimating agricultural GHG emissions an uncertain practice. Experts have long believed that uncertainties in Canadian agricultural GHG emissions are largest for N_2O, followed by CH_4, the least uncertainty being associated with CO_2. However, analyses suggest these initial rankings may not adequately consider the uncertainty in agricultural activities. In particular, changes in soil carbon stocks appear more uncertain than CH_4 emissions because the uncertainty in land management change is greater than the uncertainty in the livestock population. Unfortunately, it is not possible to provide quantitative error estimates at this time.

GHG emission trends

Statistics Canada reports that between 1991 and 2006 the number of farms in Canada decreased from 280,043 to 229,373 and that the average farm size has increased from 242 hectares to 295 hectares. This trend is likely to continue.

FIGURE 39

DOMESTIC FARM ANIMAL POPULATION IN CANADA, 1990–2005



The population of farm animals in Canada is directly related to GHG emissions from Canadian agriculture. Canadian farm-animal populations increased substantially for most animal categories between 1990 and 2005. Beef cattle and swine increased by 30% and 31%, respectively, while poultry increased by 23%. Only the dairy-cow population decreased, by approximately 29%.

Source: R. Desjardins and D. Worth, AAFC, Ottawa, ON

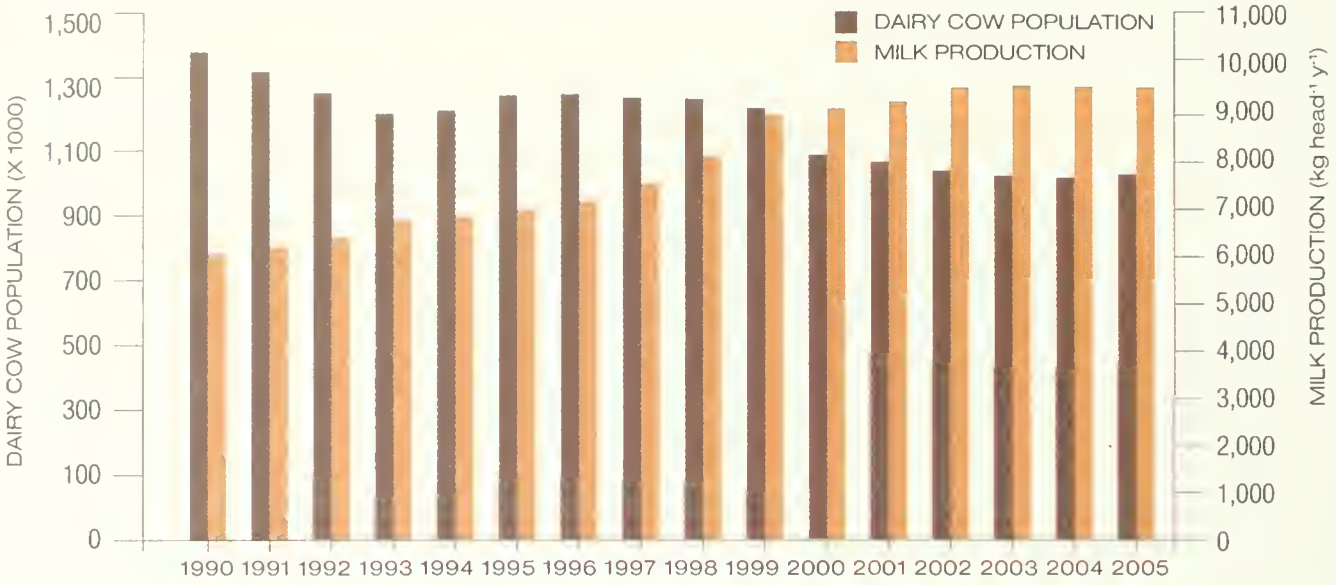
During the same period, crop production intensified and the number of animals destined for meat products also increased markedly. Consequently, between 1990 and 2005, N_2O, CH_4 and fossil fuel CO_2 emissions from Canadian agriculture have increased by 14%, 24% and 10% respectively. Because of improved management practices related to soil conservation, agricultural soils have gone from being a 14 Mt CO_2 source to being nearly neutral in that respect. It is likely that Canadian agricultural soils will become a net carbon sink in the near future. However, the sink is likely to be fairly small and the question of permanence must always be considered.

GHG emissions are unavoidable

Greenhouse gas emissions must be viewed as a necessary cost of food production as their emission is the inevitable result of growing crops and raising livestock. As the human population increases, so will the demand for food. Consequently, GHG emissions of CH_4 and N_2O are very likely to continue to increase as Canadian farms respond. Since GHG emissions constitute a loss of energy from the system, there will continue to be a search for more efficient practices that reduce these economic losses. Scientists have determined that increased efficiency in crop and animal production will lead to a small reduction in GHG emissions per unit of product—but that these reductions will have a relatively minor impact on total GHG emissions.

FIGURE 40A

Dairy-cow Populations and Milk Production in Canada

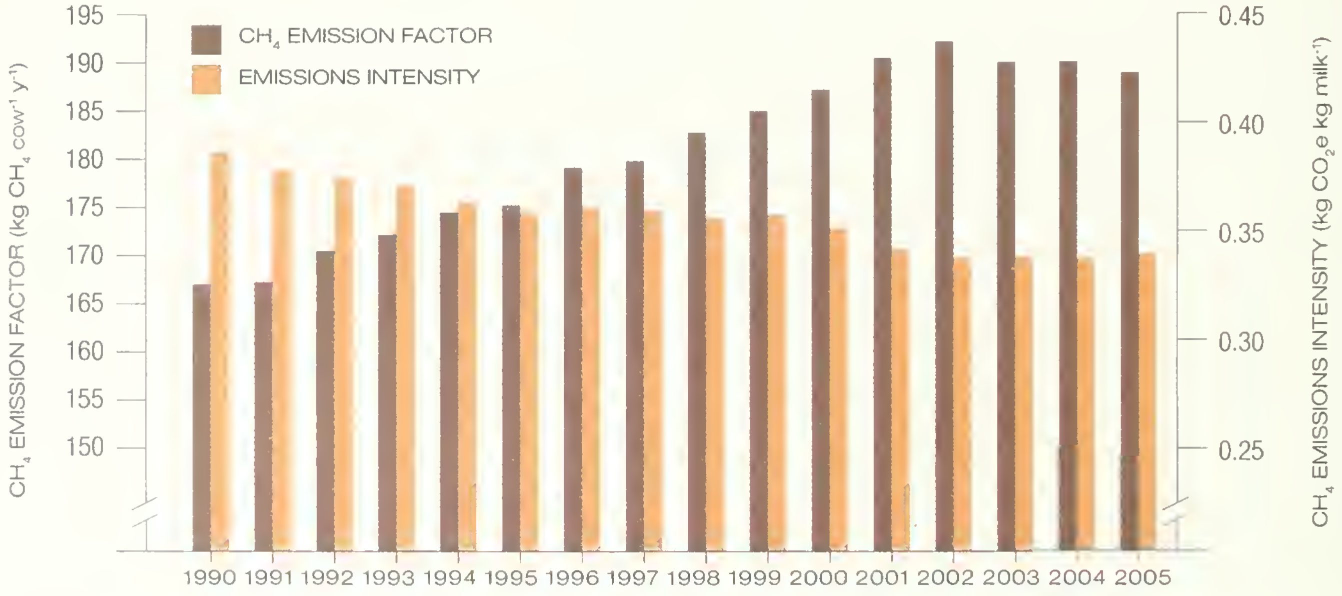


Although Canada's dairy-cow population decreased between 1990 and 2005, total milk production remained relatively constant as dairy cows became more productive (Panel A). The increase in productivity resulted in greater enteric CH_4 emissions per cow, however, when expressed per kg of milk produced, CH_4 emissions from enteric fermentation and manure management decreased by 13% (Panel B).

Source: R. Desjardins and X. Vergé, AAFC, Ottawa, ON

FIGURE 40B

Methane Emission Factor for Dairy Cows (enteric and manure) and CH_4 Emissions per kg of Milk



Source: R. Desjardins and X. Vergé, AAFC, Ottawa, ON

If we are to realize significant emission reductions, society must pursue alternatives for the types of food it consumes, the way in which it produces that food and the way in which it deals with agricultural wastes. For example, a decreased dependence on animal products for food would reduce emissions from enteric fermentation and manure management. Society must also pursue alternatives to the way it uses energy. The adoption of biofuels from biodiesel or biomass, or the large-scale adoption of biodigestion as a manure management technique could potentially displace a substantial amount of GHG emissions from fossil fuels. Conversely, a policy of increased corn and oilseed production for bioenergy along with reduced livestock production could promote the breaking of hayland and pasture and even the clearing of trees to increase land for production. At least in the short term, those actions would greatly increase GHG emissions from the decomposition of soil organic carbon.

Clearly, a holistic analysis across all agricultural activities is needed to assess optimal policies for reducing GHG emissions in the short and long terms.

A CONCRETE EXAMPLE

As shown in Figure 40, CH_4 emissions per liter of milk produced are decreasing. Improved dairy cattle breeding led to a 21% increase in milk production per head between 1990 and 2005—and a concurrent 29% decrease in the dairy cattle population. As a consequence of producing more milk per cow, CH_4 emissions per cow increased during the same period. However, the CH_4 increases have been smaller than the rate of increase in milk production. Therefore, GHG emissions in the form of CH_4 have decreased by about 13% per unit of milk produced.

FURTHER READING

Desjardins, R.L., et al. 2005. Greenhouse Gases. Pp. 142– 148 in Lefebvre, A., W. Eilers, and B. Chunn (eds.) *Environmental Sustainability of Canadian Agriculture: Agri-Environmental Indicator Report Series*, Report #2. Agriculture and Agri-Food Canada: Ottawa. Available online at: http://www.agr.gc.ca/env/naharp-pnarsa/index_e.php. Accessed October 23, 2007.

Environment Canada, 2007. *National Inventory Report: 1990–2005, Greenhouse gas sources and sinks in Canada.* Environment Canada, Greenhouse gas division.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: The Scientific Basis: Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: New York.

Statistics Canada. 2007. Total farm area, land tenure and land in crops, by province (1986–2006 Censuses of Agriculture). Available online at: http://www40.statcan.ca/l01/cst01/agrc25a.htm. Accessed October 23, 2007.

Smith, W., R.L. Desjardins and B. Grant. 2001. Estimated changes in soil carbon associated with agricultural practices in Canada. *Canadian Journal of Soil Science* 81: 221–227.

Reckoning the Total Budget

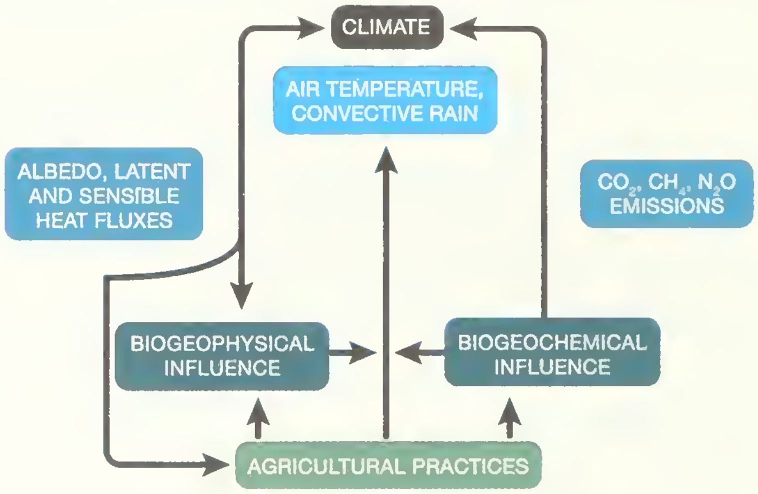
NON-GREENHOUSE GAS EFFECTS OF AGRICULTURE ON CLIMATE

Agricultural production is highly dependent on weather and climate. Without adequate rainfall and appropriate temperatures, crops fail and pastures become barren. Interestingly, the opposite is also true: weather and climate are influenced by agricultural practices. By managing croplands and pastures farmers influence a series of physical, chemical and biological interactions between the Earth's surface and the atmosphere that can affect air temperature and precipitation in many ways.

One reasonably well-accepted effect of agriculture on air temperature is agriculture's production of GHG emissions, which contributes to the anthropogenic (human caused) greenhouse effect. As Figure 41 shows, this is known as a *biogeochemical* effect of agriculture on climate. However, it is less well known that agriculture affects weather and climate by changing the Earth's albedo, that is, the fraction of solar radiation that strikes the Earth and is then reflected back into space. Albedo has a *biogeophysical* effect on weather and climate and is a key determinant of climate on the Earth.

FIGURE 41

BIOGEOPHYSICAL AND BIOGEOCHEMICAL IMPACTS ON CLIMATE



Agricultural practices have an impact on climate by influencing the energy exchange between crops and the atmosphere—a biogeophysical impact on climate. Agricultural practices can also influence climate by modifying the rate at which soils and plants exchange GHGs with the atmosphere—a biogeochemical impact on climate.

The importance of albedo

The albedo of a given surface, or land cover, affects the temperature of the surface and of the overlying air. Different land covers have different albedos. Land covers with a higher albedo—ice and snow—tend to have lower temperatures because they reflect back into space a high percentage (35-90%) of incoming radiation. Land covers with lower albedo—such as grasslands and forests—tend to have higher air temperature because they reflect back into space a smaller percentage (5-25%) of incoming radiation. Globally, the Earth's average albedo is about 30%.

A thorough understanding of the albedos of various land covers is important to our overall understanding of climate. For example, scientists previously assumed that the albedo of the boreal forest in winter was high, because of the presence of snow. In reality, satellite measurements have shown that snow cover only marginally increases the albedo of boreal forests because snow is "hidden" under the canopy. This error had been causing weather forecast models to underestimate daily winter temperatures over boreal regions by as much as 10ºC. The albedo of grasslands is sharply increased by snow cover. Thus, the difference in net radiation between grasslands and coniferous forests is largest in winter.

This is important because, contrary to popular belief, reforesting high latitude agricultural regions may actually *contribute* to global warming, rather than slow its progress. The dark canopy of Canadian, Scandinavian and Siberian forests absorb solar radiation that would otherwise be reflected back to space by snow if these regions were agricultural land.

Delving Deeper

The biogeochemical and biophysical effects of agriculture on climate are quantified in terms of the resulting energy received at the surface of the earth, measured in watts per square metre (Wm^{-2}). Values greater than zero—termed *positive radiative forcing*—indicate warming, while values less than zero—termed *negative radiative forcing*—indicate cooling.

By studying the relation between global temperature and natural changes in net radiative forcing, it has been estimated that the long term mean temperature increases by 0.4 to 0.7 °C for each increase of 1 Wm^{-2} of net radiative forcing. Figure 42 shows the global average radiative forcing estimates and their uncertainty in 2005 for anthropogenic CO_2, CH_4, N_2O and other radiative forcing components associated with aerosols, land use, ozone and variations in solar irradiance together with the range in estimates.

Variations in solar activity are considered natural forcing. Periods of high solar activity have been shown to be about 0.2 °C warmer globally than periods of low solar activity and warming is amplified near the Earth's poles.

The largest positive radiative forcing is associated with the increase of long- and short-lived GHGs in the atmosphere, which add up to +3.0 Wm^{-2}. The largest negative forcing is associated with the direct and indirect effect of aerosols in the air, which add up to -1.5 Wm^{-2}. The sum of all positive and negative anthropogenic forcings results in a net positive forcing of approximately +1.5 Wm^{-2}. Most of these forcings act at a global scale, except for surface albedo, which has more of a local effect. Natural forcings such as volcanic aerosols are not considered in Figure 42 because of their episodic nature. They tend to cause a temporary negative forcing.

Energy Budget and Air Temperature

Land use and land-cover changes affect climate through the surface energy budget. As Figure 43 shows, net radiation at the Earth's surface, Q_n, is determined by incoming short-wave solar radiation ($S\downarrow$) minus reflected short-wave solar radiation ($S\uparrow$), plus the difference between long-wave radiation emitted downward by the atmosphere ($L\downarrow$) and the long-wave radiation emitted by the Earth ($L\uparrow$):

$$Q_n = (S\downarrow - S\uparrow) + (L\downarrow - L\uparrow)$$

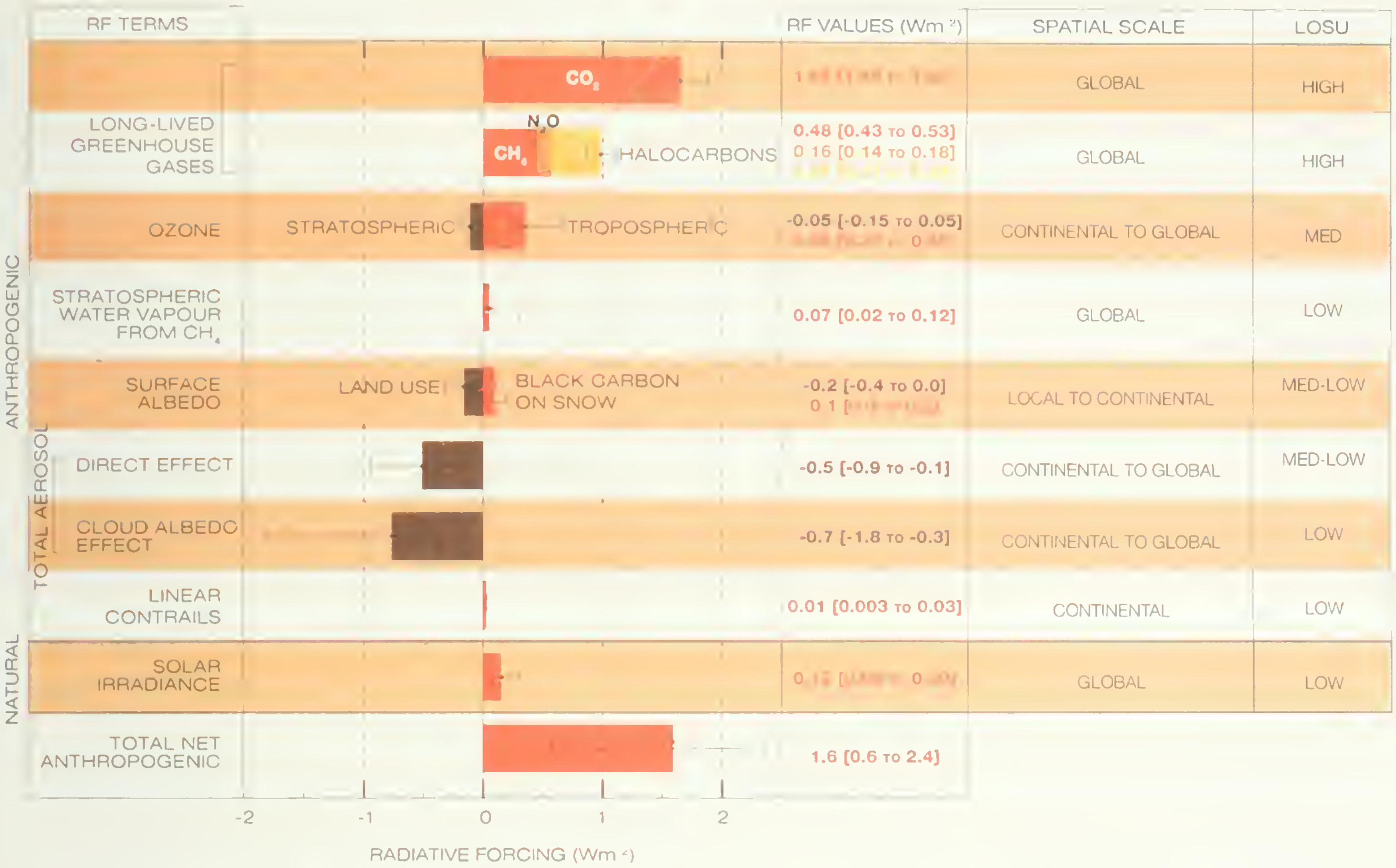
Net radiation is partitioned into energy used to heat the air, or the sensible heat flux (Q_H), energy used for evapotranspiration, or the latent heat flux(Q_L), as well as the heat conducted in or out of the soil (Q_G):

$$Q_n = Q_L + Q_H + Q_G$$

An increase in radiative forcing due to biogeochemical changes in the composition of the atmosphere results, primarily, from an increase in counter-radiation from the atmosphere, ($L\downarrow$), hence, the greenhouse analogy. The primary impact is on overnight, or minimum, temperatures when the short-wave radiation terms do not come into play in the net radiation budget of the Earth's surface. In contrast, biogeophysical effects such as changes to surface albedo and changes to vegetation and soil moisture have their greatest impact on the maximum daytime temperatures.

FIGURE 12

RADIATIVE FORCING COMPONENTS

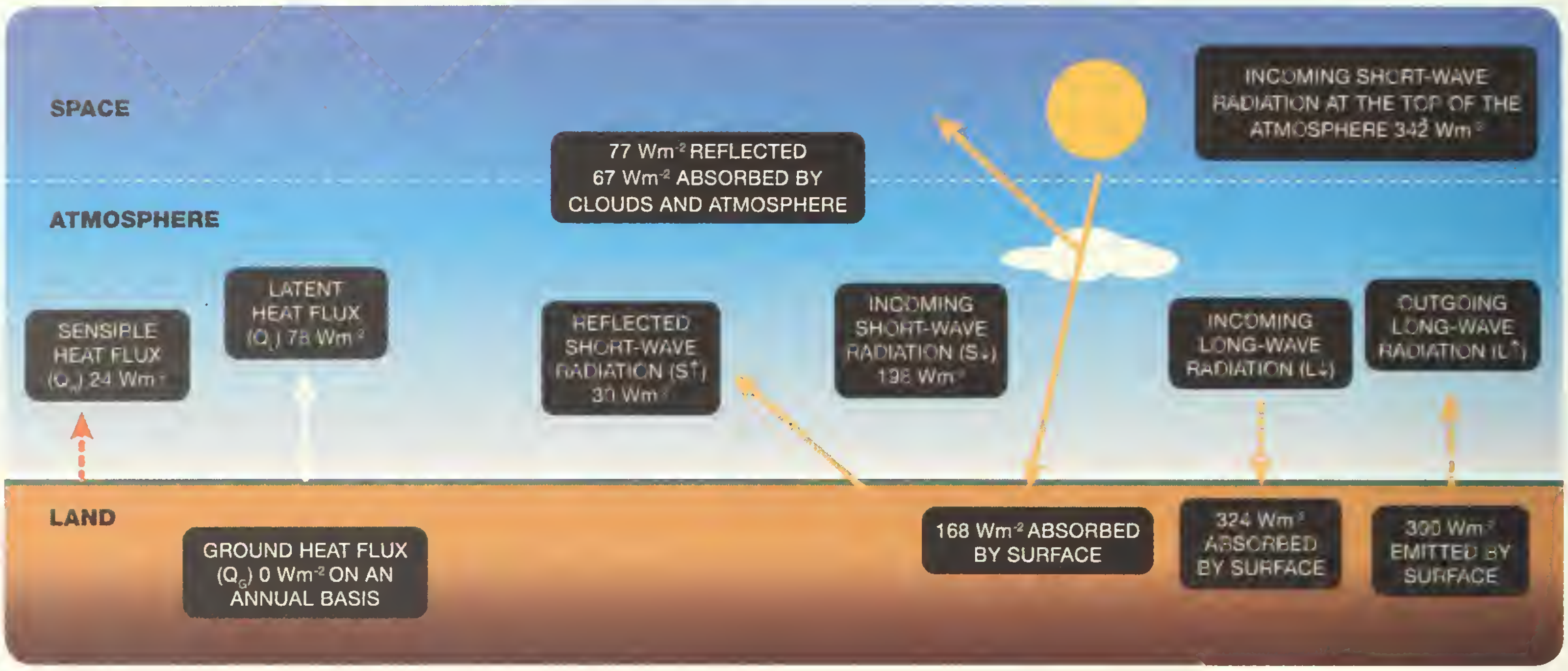


There are many anthropogenic contributions to radiative forcing (RF). The most significant contributions include the emission of GHGs such as CO_2, CH_4, N_2O and halocarbons (a solvent and refrigerant); changes in stratospheric and tropospheric ozone; changes in albedo through land-use change and deposition of black carbon on snow and from changes in aerosol concentration in the atmosphere. GHG emissions represent the largest anthropogenic climate forcing. There are also natural radiative forcings, including the slow change over time in the sun's intensity. This natural forcing is much smaller than the sum of anthropogenic forcings, which are estimated to be +1.6 Wm^{-2}, with a range in estimates from +0.6 to +2.4 Wm^{-2}. The emission of agricultural GHGs, a biogeochemical effect, and the change in albedo due to land converted to agriculture are relevant to this chapter. Also shown in this figure is the spatial scale of the forcing and the current level of scientific understanding (LOSU).

Source: IPCC AR4 WG1 Summary for Policy Makers. Available online at http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf, accessed January 25, 2008.

FIGURE 43

ENERGY EXCHANGE BETWEEN THE EARTH'S SURFACE AND THE ATMOSPHERE



Water vapour and energy are constantly being exchanged between the Earth's surface and the atmosphere. Radiant energy from the sun is reflected or converted into sensible heat-energy to heat the air, latent heat energy to evaporate water, transferred into the soil as ground heat or re-emitted to the atmosphere as long-wave radiation.

Source: The magnitude of Earth's annual and global mean energy budget is adapted from Kielhl and Trenberth. 1997. Bulletin of the American Meteorological Society.

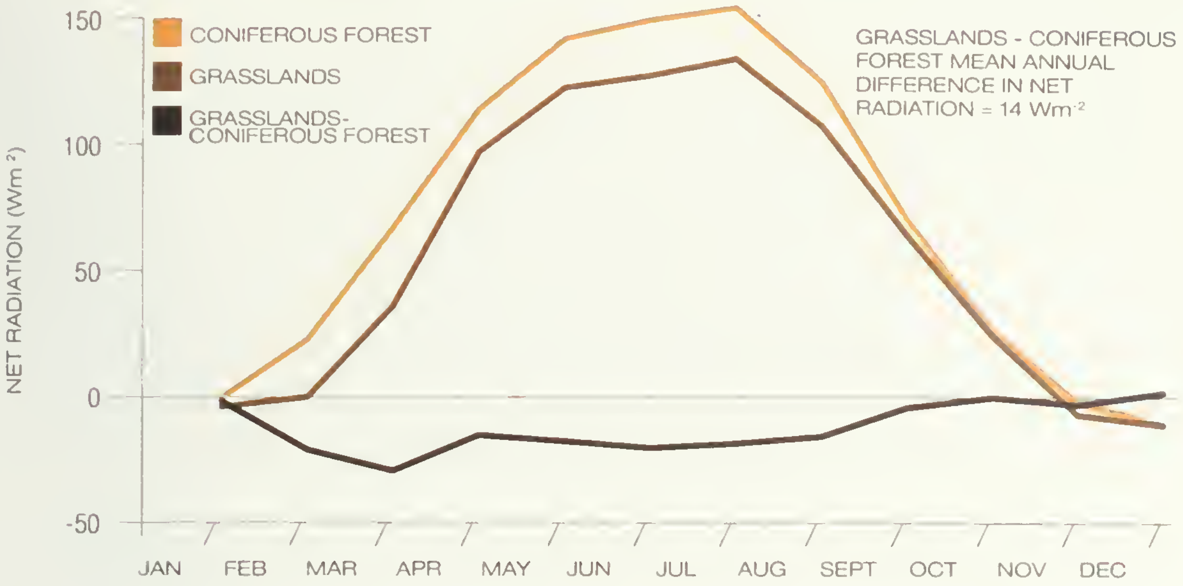
Agriculture can affect air temperature

The biogeophysical impact of agriculture on air temperature is a significant local and continental issue. Increasing human population and the need for food production to keep pace has resulted in conversion of vast areas of natural land to cropland and pasture. Over the last three centuries, cropland has increased more than five-fold and the area under pasture has increased more than six-fold. In recent years, increases in cropland and pasture have occurred largely at the expense of forests. This has altered the net global radiation budget of the Earth's surface.

At present, it is estimated that the practice of converting forested land to agricultural land has increased surface albedo, which results in an overall cooling of our climate by 0.1 °C. Another estimate is that were all forests replaced by grasslands, global climate would cool by more than 2 °C once the full impact of the land-cover change had come into play.

FIGURE 41

MEAN MONTHLY DIFFERENCE IN THE NET RADIATION BETWEEN CONIFEROUS FOREST AND GRASSLANDS.



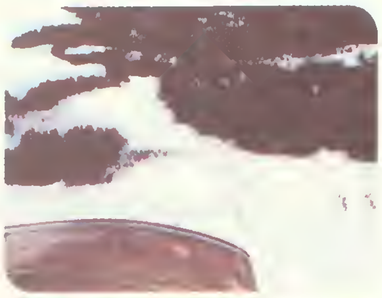
Coniferous forests keep their needles year round and are very efficient at absorbing solar radiation, even in the winter when agricultural grasslands will be buried with snow. The mean annual difference in net radiation between coniferous forest and grasslands is approximately 14 Wm^{2}. For comparison, the mean annual difference in net radiation between a coniferous forest and a deciduous forest is approximately 10 Wm^{2}.

Source: R. Desjardins and D. Worth, AAFC, Ottawa, ON

Crops can influence the timing of thunderstorms and severe weather

As a crop grows, it transpires, absorbing water from the soil and transferring it to the atmosphere. The rate of transpiration varies as the crop grows; that is, the proportion of sensible heat (energy used to heat the air) to the latent heat (energy used for evapotranspiration) changes. Scientists have shown that for the same amount of net radiation, the larger the evapotranspiration, the higher the potential for thunderstorms. For the Canadian Prairies, scientists have demonstrated how the widespread transformation of native mixed perennial grasses to annual field crops may have modified the seasonal pattern of thunderstorm days. They found that agriculture has decreased the potential for thunderstorms early and late in the growing season, but has enhanced the potential around the mid-point of the growing season when rapid leaf growth results in high transpiration.

Agriculture also affects the availability of water vapour, and thus the prevalence of rain, over portions of the globe. For the Canadian Prairies, in areas with normal summer rain, 20% of the moisture in the air originates from the crops. It follows that agricultural crops are an important source of water vapour for growing-season rain and that they play a role in the persistence of wet and dry periods.



Impact of GHG mitigation practices on air temperature

Changes in agricultural management practices can affect not only weather, but they can also reduce the rate of increase of atmospheric CO_2 by sequestering carbon in agricultural soils. Globally, it is estimated that agricultural soils could be a significant carbon sink over the next century.

This is possible because in the past, soil carbon stocks have been considerably depleted in Canada and around the world by various farming practices. Scientists believe that by adopting agricultural practices favourable to increasing the soil carbon stock, farmers in Canada could store in the soil every year the equivalent of the CO_2 emitted from 2.5 million mid-sized cars. With enhanced measures Canadian agricultural soil sinks could be made even more effective. See the earlier chapter on carbon for a full explanation of carbon sequestration in soils and the agricultural practices that best promote sequestration.

The reduction of summer fallow area in the prairies in recent years has been shown to promote carbon sequestration in agricultural soils. Therefore, we can say that the biogeochemical effect of reducing summer fallow had a cooling effect on air temperature. It is estimated that more intensive cropping between 1976 and 2000 in the Prairie provinces, where annual crops and forages have replaced summer fallow, has been associated with a decrease in the regional maximum air temperature of 1.7 °C per decade and an increase in precipitation of 10 mm per decade from June 15 to July 15.

This is most likely the case because sensible heat flux is greater over summer fallow than over cropped land, whereas latent heat flux is greater over cropped land than summer fallow. The latter effect adds moisture to the atmosphere. Therefore, conversion of land from summer fallow to crops tends to decrease air temperature and increase the water content of the air, resulting in greater precipitation.

The biogeochemical and biogeophysical impacts of a GHG mitigation strategy on climate are not all complementary. As stated in the discussion of albedo, planting trees on agricultural land in northern ecosystems—particularly coniferous trees— results in an increased air temperature through lower albedo, thus negating the beneficial climatic effect of the trees' ability to absorb CO_2 and store carbon. The point is, the biogeophysical effect of changing one hectare of land from wheat to forest in Canada, would be more significant to climate change than the biogeochemical effect of sequestering 60 tonnes of carbon on that hectare of land over the next 50 years.

Clearly, agricultural practices can affect weather and global climate through biogeochemical and biogeophysical forcing. For example, irrigation cools air temperature by as much as 5 °C locally and possibly 1 °C on a regional scale by enhancing cloud cover that reflects sunlight. A relatively recent trend toward less frequent ploughing of fields (reduced tillage) increases albedo and has a cooling effect comparable to the biogeochemical cooling from reported carbon sequestration. There are many other examples.

It is critical to consider the effects of a whole range of management practices in regions where production systems are vulnerable to weather variation. It is unlikely that non-GHG effects can completely counterbalance the increase in GHGs due to agricultural practices, but it is clear that their impact on climate must be taken into account.

FURTHER READING

Betts, R.A. 2000. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature.* 408:187–190.

Desjardins, R.L., M.V.K. Sivakumar, and C. de Kimpe (eds.). 2007. The contribution of agriculture to the state of climate. Special issue of *Agricultural and Forest Meteorology.* Elsevier: Oxford, U.K. pp. 88–324.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: The Scientific Basis: Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, New York. 881 pp.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007. The physical science basis. Summary for policy makers. Available online at: http://www.ipcc.ch/SPM2feb07.pdf. Accessed February 15, 2007.

Raddatz, R.L., 2005. Moisture recycling on the Canadian Prairies for summer drought and pluvials from 1997–2003. *Agricultural and Forest Meteorology* 131:13–26.

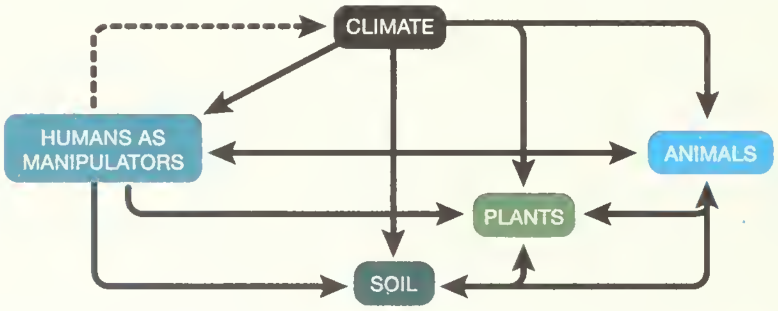
A Holistic View

EXPLORING THE ECOSYSTEM PERSPECTIVE

THE ECOSYSTEM—the word itself a contraction of 'ecological system'—is the fundamental unit of ecological study. First used in print in 1935 (although coined much earlier) the word stands for a community of organisms within a given environment and all of the interactions that occur between those organisms (see Figure 45).

FIGURE 45

COMPONENTS OF ECOSYSTEMS AND THEIR INTERACTIONS



Source: Adapted from Van Dyne, 1969

An ecosystem, therefore, includes not only the grasses, trees and mosses on the ground; not only the owls, ants and bison that feed upon them; but also the soils that support them and the air that wafts about them. When we speak of an ecosystem, we speak also about how each constituent affects the others—the fluid coherency of the whole.

How big is an ecosystem? The scale may vary, from a beehive to the global biosphere, though an ecosystem's size will most likely be measured in hectares or square kilometres. Whatever the scale, an ecosystem occupies a specific place, with a fixed address and defined boundaries. Ecosystems are always open systems; energy and matter are continually lost and continually replaced. As a result, a given ecosystem by its very nature is interdependent with others.

To understand an ecosystem is alarmingly complex, demanding expertise and knowledge from various fields—and a way of melding information so it can be clearly understood, explained and used. Another complicating factor is time; ecosystems cannot be studied without considering history. This is because living systems change; their activities and conditions at any given moment depend on what has happened in that place before. Despite this daunting complexity, viewing all life as part of an ecosystem has one great merit: it allows us—indeed, it forces us—to study life systems as a whole, sparing us from the distortion that results when we focus on components in isolation.

An expanded focus

Once, those who studied ecosystems looked for sites untouched by human hands; today, we admit that few such places remain. Humans are now part of most ecosystems, inextricably intertwined with other organisms and their interactions. In any case, if an ecosystem includes *all* organisms and their interactions, we are forced to admit that the definition must also include us. And in few places on the landscape is our influence more pervasive than on farmlands.

Farms are ecosystems

Farms are often viewed primarily as economic entities; a farm generates a livelihood for a farmer. From a broader ecological perspective, farms can also be seen as ecosystems, with numerous functions, only one of which is to generate income. This perspective has several advantages. First, it enforces a holistic view. Thus, cows cannot be divorced from crops, or land from barns, or air from fertilizers. Second, examining farms as ecosystems helps us take into account their interactions with the larger environment. Farms as ecosystems become part of the biospheric continuum, alongside forests and wetlands, grasslands and lakes, all studied using similar methods, with an eye to the energy and matter passing between them.

As ecosystems, however, farms have some distinguishing features: they are deliberately maintained at a young successional stage (as opposed to mature, long-standing vegetation). They are more open than other ecosystems; because of large removals of energy and matter in harvests, they depend on correspondingly large inputs to keep the system running.

Farms are remarkably diverse, reflecting the land and the people who live there. Farms encompass everything from sheep herded on sparse deserts to dairy cows grazed on lush pastures; from vast mechanized wheat lands to raspberries plucked from backyard bushes. Regardless of the farming activity, the same ecological processes undergird them all.

Compared to other ecosystems, farms are extensively manipulated. Farmers exert control over plants grown, nutrients applied, type and number of animals present, insects allowed to persist, amount of watering and drainage, and the degree to which the land is disturbed by tillage. Many of these decisions depend on short-term economic and social factors, which means that practices and conditions imposed on the farm ecosystem may change unpredictably and sporadically.

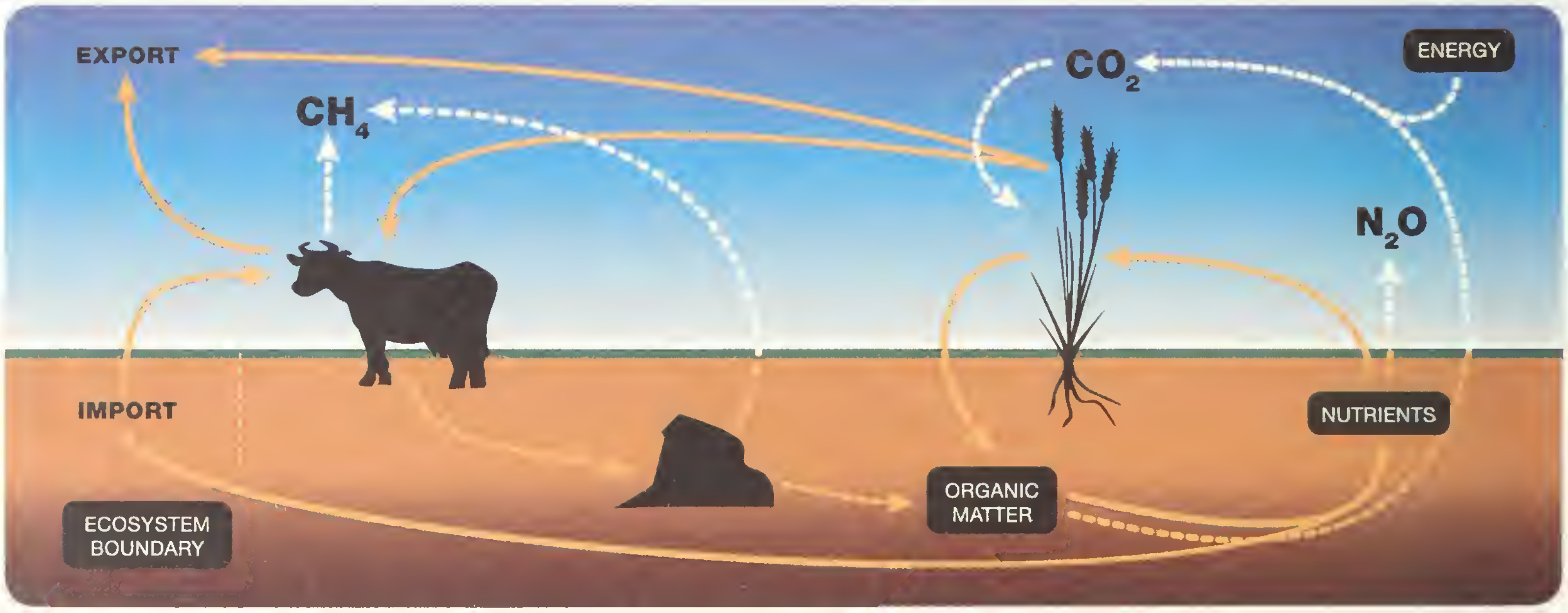
To view farms as ecosystems presents some challenges: farms are complex, highly dynamic and subject to the whims of human intervention. But to view them in this manner offers clear advantages: in particular, it helps us integrate all a farm's processes, capturing their net effects within the ecosystem and beyond, over the short and long term. Regarding an individual farm as an ecosystem also meshes nicely with the definition of ecosystems as fundamental ecological units. Farms, after all, are the basic unit over which the farmer exerts control, choosing practices and management options.

GHGs are part of our farms' ecosystems

Examining farms as ecosystems provides a unique vantage for studying GHG emissions. Indeed, it may be that GHG emissions can *only* be studied meaningfully from the ecosystem perspective. As Figure 46 shows, GHG fluxes emanate from myriad processes connecting all phases of the farming system. Consequently, efforts to reduce emissions of one gas from one source may have offsetting (or amplifying) effects elsewhere; the full effect can be judged only by assessing effects on *net* emissions. That is, they can be meaningfully quantified only by adopting an ecosystem approach.

FIGURE 46

THE INTERWOVEN FLOWS OF CARBON, NITROGEN AND ENERGY IN FARM ECOSYSTEMS



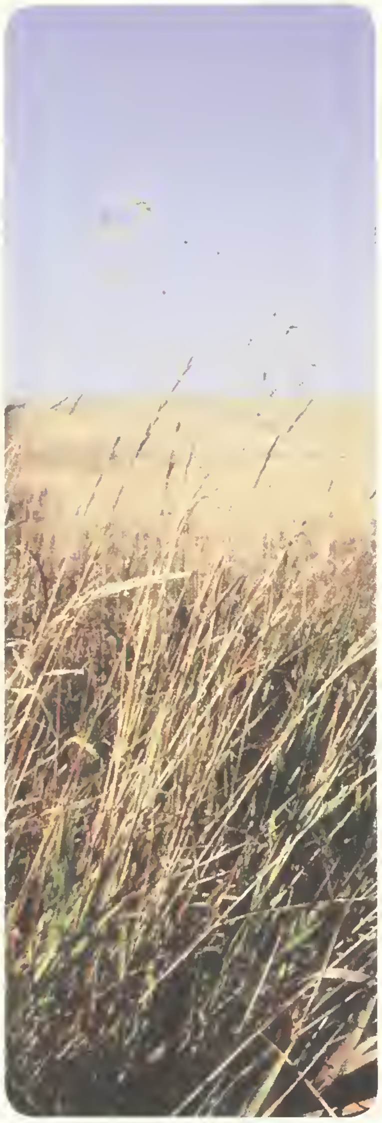
Consider some examples of the interplay among various fluxes on a farm. Perhaps the most prominent is the removal of atmospheric CO_2 by building soil carbon—called *soil sequestration*. Many studies throughout the world show that under some conditions the carbon content of soil can be increased by such practices as reduced tillage, which reduces soil disturbance, or by re-seeding lands to grass, which returns more plant carbon to the soil. Almost invariably, however, such practices alter *other* properties and processes. For example, reducing tillage may sometimes increase soil moisture, reducing aeration, thereby favouring the release of more N_2O. Or, in drier lands, adopting no-till might reduce emissions of N_2O. Either way, the net effect of the practice must consider not only the C sequestered, but any effects on emissions of N_2O, a potent GHG. There are other possible effects on the system as a whole. Reducing tillage intensity might lead to reduced fossil fuel use—and hence reduced CO_2 emissions—or might require temporary increases in the use of fertilizer, which increases emissions from associated energy use. Further complicating the question is the influence of time; responses in soil carbon and N_2O emission, CH_4 removal and energy CO_2 emission may have different temporal patterns. Some, such as carbon accumulation, are temporary; others, such as savings in energy-derived CO_2 emissions, persist indefinitely. Thus, a single practice has cascading influences on GHG emissions throughout the system. Only an ecosystem approach can hope to capture the full effect.

Similar arguments can be made for other examples. Opting for a new feeding practice may effectively reduce CH_4. But to know its full effect, we need also to ask: what emissions are associated with producing that new feed crop? How does the new feed affect emissions from manure produced, now with altered composition? How does the new feeding practice affect the number of livestock fed and their accompanying emissions?

Consider another practice, now widely studied: producing biofuel from farm crops. Ethanol or biodiesel extracted from farm crops effectively reduces fossil-derived CO_2 emissions. Though burning these biofuels still generates CO_2, it is from recently recycled atmospheric carbon and introduces no new CO_2 into the carbon cycle. But what emissions are associated with growing the crop from which the biofuel is made? And how much energy is required to transport, process and eventually deliver the feedstock and the final product?

Even more complicated are the possible spillover effects of these practices. For example, cultivated lands, when revegetated with grasses or trees, capture carbon in soil and remove CO_2 from the air. Similarly, growing biofuel crops reduces CO_2 emitted from burning of fossil fuels. But will the land removed from farming in one place be replaced by new lands elsewhere? And what are the emissions there?

GHG emissions can be effectively quantified and reduced only by considering all emissions from the farming system—in short, by viewing farms as ecosystems and counting all the processes there.



Models enforce an ecosystem view

Given the many agricultural processes that emit GHGs, the way they interact and the diversity of farms themselves, how can we estimate net emissions from these ecosystems? How can we capture all that we know and weave it together without getting entangled in details or lost in abstractions? Probably the only practicable approach is to build mathematical models. Such models might range from the crude to the complex—from *back-of-the-envelope* calculations scribbled by hand to dense software crafted by teams of scientists and programmers.

Models capture pertinent processes from entire ecosystems, meld them and estimate net fluxes of GHGs from the whole. It is not that models invariably get the right answer; often, equations are generalizations based on crude assumptions or even timid guesses. But models enforce an ecosystem view of emissions and, as such, enforce discipline; they tear off the blinkers that reductionist scientists are prone to wear.

Models offer other benefits as well. First, they provide a focal point and repository to capture and express research findings. In the absence of a model, the findings in an avalanche of papers on soil carbon sequestration and GHG fluxes in agricultural systems, for example, may soon lie neglected on dusty library shelves. To have enduring influence, findings must somehow connect to a growing understanding.

As the chapter on quantifying GHG exchange explains, models are a skeleton on which to hang findings; they provide a framework for growing understanding. In the case of GHG fluxes, as new data emerge, algorithms and assumptions can be adjusted and improved, slowly fleshing out our skeletal understanding. This benefit, of course, relies on discipline, the will to meticulously collect the accumulated findings in a database or other suitable form.

A further advantage of using models is that they point to areas of scientific ignorance, identifying those places where our understanding is dimmest and inquiry most needed. Without such reminders of the shadow areas, scientific research can sometimes focus too much on the areas we already know best.

Static and dynamic models

As noted in an earlier chapter, increasing efforts have been devoted to build models that predict GHG emissions from farms. Though few of these comprehensively consider all of the facets of a farming system, many have started at least to examine *systems*, rather than single components or processes.

The various models and approaches for such holistic efforts can be divided into two broad categories: static models and dynamic models. Static models predict cumulative net emissions for a given interval of time, typically one year or farming season. Dynamic models are more complex; they introduce time, looking into the future and the past and predicting how net emissions will change in response to a practice or external factor.

Consider the ecosystem response to adopting no-till practice. The static model, based on simple equations or coefficients, would predict the annual net change in soil carbon, along with an average annual emission of N_2O. The dynamic model would trace out the accumulation pattern of soil carbon over several decades, showing how the rate of accumulation changes with time, eventually approaching zero. A full-fledged dynamic model might also take into account coming changes in climate or other external factors. At present, there are few if any dynamic models capable of measuring net emissions of all GHGs from whole-farm ecosystems—though it remains a prominent research goal.

The static model

The following is an example of a static model to predict GHG emissions from farms. As of 2007, this model had been released by Agriculture and Agri-Food Canada and a new version *Holos* was being developed.

GHGFarm

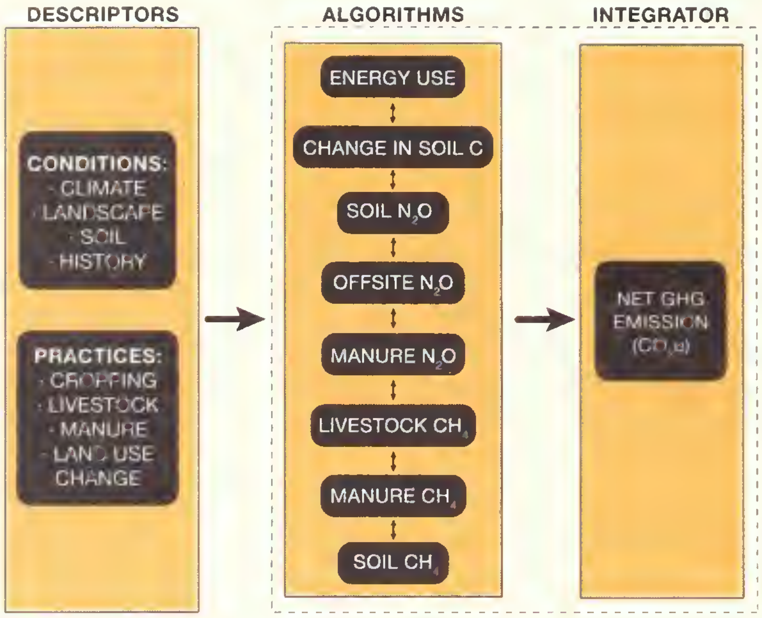
A simple model, GHGFarm, was developed to permit users to estimate net GHG emissions from Canadian farms. The model relies on two types of inputs, as shown in Figure 47:

- Management *practices* under the control of the farmer, including such variables as crop selection, fertilizer rates, tillage techniques, feeding practices and manure management systems
- Farm *conditions*, largely beyond management control, including such factors as soil type, temperature and precipitation.

The model estimates the effects of these variables on all three GHGs—CO_2, CH_4 and N_2O—using simple equations based on globally accepted algorithms, but modified to reflect Canadian conditions and practices based on recent research.

FIGURE 47

A SIMPLE MODEL FOR ESTIMATING NET WHOLE-FARM EMISSIONS



The user describes the farm by stating its conditions (those factors not controlled by the farmer) and the farm's practices (options controlled by the farmer). These inputs are then fed into equations or algorithms that estimate emissions from the various farm components. The outputs from these equations are integrated to yield a single estimate of overall net farm emissions.

The model has two potential applications. The first is to allow producers, policy makers, scientists and other users to estimate current net emissions from a given farm ecosystem (typically one commercial farm, or perhaps a small group of closely-linked farms). The second application—and a more useful one—is to allow users to explore possible opportunities for reducing emissions; it allows them to ask the *what if* questions. Thus, the current emissions are calculated as a baseline and various possible changes in practices are then compared alongside: What if we use a different feed or manage the manure differently? What if we reduce tillage intensity or take some land out of production? These options can then be examined together, comparing whole-farm net emissions as a criterion for choosing the optimal set.

The model does not operate without uncertainty; in many instances, the degree of uncertainty exceeds the difference between management options, which is obviously a barrier to choosing best options. However, the process of building the model and of applying it on real farms has been enlightening in understanding farms as ecosystems and ensuring that all facets and sources are considered in calculating net GHG emissions from farm ecosystems. Perhaps GHGFarm is best viewed as a tool for communication and education rather than for delivering defensible predictions.

The dynamic model

The following describes a proposed dynamic model to predict GHG emissions from farms.

The Virtual Farm

To reliably estimate the emission of GHGs from farms, one must consider that emissions of CO_2, CH_4 and N_2O all vary over time and are affected by the actions of humans and by nature. To see how emissions vary over time we need to understand how their constituents—namely carbon and nitrogen—are cycled through farm ecosystems.

As of 2008, a simple time-dependent model of a farm ecosystem for estimating net GHG emissions over time was in development at Agriculture and Agri-Food Canada. The ecosystem model consists of six main components: vegetation, shelterbelt, crop, soil, livestock and manure. The model assumes that emission losses can be attributed to three main contributions:

- farm management or activities (perturbed conditions),
- carbon and nitrogen flow in the ecosystem (un-perturbed conditions), and
- the interaction of the first two whereby they mediate changes in stored amounts of carbon and nitrogen within each ecosystem component.

Benefits beyond the farm

Developing ecosystem-based models for estimating net GHG emissions from farms will enhance our ability to mitigate climate change. But there are other benefits as well: estimating GHG emissions may provide a sensitive measure of ecosystem health—a way of taking the pulse of farms and other ecosystems. Almost invariably, high losses of carbon and nitrogen signal some ecological inefficiency in use of energy, carbon or nitrogen. For example, if N_2O spews too fast, the nitrogen cycle is probably disconnected. If CO_2 losses are too high, then soil carbon may be waning or energy is being used superfluously. If CH_4 is excessive, perhaps cows are not being fed efficiently and photosynthetic energy has not been fully exploited. Thus, GHGs are biomarkers—biosignals of ecosystem ill health—pointing to opportunities for better management to make them more robust, more efficient and more permanent. Such biosignals may be most useful in agricultural systems, which are so intensely manipulated and which are under increasing stress in the face of growing population demands.

The methods developed to study GHG emissions from ecosystems can also be applied to other environmental problems. Models that predict GHG emissions are built, by necessity, on the flows of energy, carbon and nitrogen through ecosystems. To predict GHG emissions from an ecosystem, a model must simulate the energy, carbon and nitrogen cycles in that ecosystem and connect them to the broader cycles in adjacent environments. These broader cycles are at the heart of other ecological concerns: water quality, food quality, alternative energy sources, and emissions of air pollutants such as ammonia. They also have a bearing on broader social issues, such as rural vitality, biodiversity and wildlife habitat.

There are likely issues still beyond our purview—perhaps years or decades in the future—that will depend on knowing better how energy, carbon and nutrients flow within and among ecosystems. Ecosystems are changing, perhaps at rates faster than our ability to understand. The primary benefits of modeling GHG emissions, therefore, may be not to reduce emissions of these gases *per se*, but instead to equip us with a better understanding of our fragile ecosystems, and from that solid footing in ecological processes engender far-sighted solutions to the ecological distresses that await us.

Reducing emissions may not be the final aim of ecosystem GHG models; that is, just a temporary, incremental goal. The GHGs are merely a sensitive and timely test case for an ecosystem modeling approach. The bigger prize, the long-term aim, will be to understand our ecosystems well enough, describe them succinctly enough, to help us speak with wisdom, insight and foresight about any of the environmental stresses still to come. And, given the pace and unpredictability of global change, such stresses are sure to come.

FURTHER READING

Evans, F. C. 1956. Ecosystem as the basic unit in ecology. *Science* 123:1127-1128.

Janzen, H.H., D.A. Angers, et al. 2006. A proposed approach to estimate and reduce net greenhouse gas emissions from whole farms. *Canadian Journal of Soil Science* 86:401–418.

O'Neill, R.V., and J.R. Kahn. 2000. Homo economus as a keystone species. *Bioscience*. 50:333–337.

Palmer, M.A., E.S. Bernhardt, et al. 2005. Ecological science and sustainability for the 21st century. *Frontiers in Ecology and Environment* 3:4–11.

Van Dyne, G.M. 1969. Implementing the Ecosystem Concept in Training in the Natural Resource Sciences. Pp. 327–367, in G.M. Van Dyne (ed.) *The Ecosystem concept in natural resource management*. Academic Press, NY.

Finding Win-Win Solutions

LINKS BETWEEN GHG MITIGATION AND OTHER ECOSYSTEM SERVICES

Ecosystem services—an emerging concept

Until recently, when ecologists wanted to study ecosystems they sought lands untouched by people and unspoiled by human presence. Humans were regarded by ecologists as an invasive species. To study how nature behaved, ecologists trekked to the quickly dwindling tracts of land deemed *natural*.

Today, ecologists increasingly accept that few unaffected terrestrial areas remain. For better or worse, humans are part of most ecosystems; indeed, often we are the *keystone*, or dominant species, controlling our environment and dictating which other species survive in our presence.

That perspective has led to the emergence of a new concept: *ecosystem services*. As one researcher has said, ecosystem services are “the conditions and processes through which natural ecosystems…sustain and fulfill human life.”[1] Ecosystem services include a host of natural functions: filtering impurities from water, removing excess CO_2 from air, keeping alive the diversity of life forms, for example. Although conceived originally to describe natural ecosystems, the ecosystem services concept can be applied also to agricultural lands, which are managed to maximize human benefit. Usually, these benefits are perceived to be what farms can sell: food, fibre and biofuel. Like all ecosystems, however, farms also provide important services that are not readily apparent. As Table 7 shows, farms act as environmental filters, as cleansing repositories for unwanted wastes, as habitat for wildlife and people, and as places of aesthetic respite. These more subtle ecosystem services also merit out attention.

An important ecosystem service of farms—one already discussed—is to help ameliorate GHG emissions. Though usually net *sources* of GHGs—notably of CH_4 and N_2O—farms can also be net *absorbers* of GHGs by absorbing CO_2 from the air and sequestering that carbon in soils and plants. With growing fears of unpleasant climate change, reducing GHGs from farms has become an increasingly urgent goal. But, when a farm’s potential ecosystem services are tallied and prioritized, reducing GHGs may not be a farmer’s main concern. Rarely will a GHG-reducing practice be adopted if it does not also favour other services. Consequently, finding and advocating GHG mitigation practices is merely a pleasant academic diversion if it ignores these other, often more urgent, ecosystem services.

---

[1] *Daily, G.C. 1997. Nature’s Services—Societal Dependence on Natural Ecosystems. Island Press: Washington D.C.*

TABLE 7

Partial List of Ecosystem Services Provided by Canadian Farms

PHYSICAL BENEFITS	SOCIAL BENEFITS	ENVIRONMENTAL BENEFITS
Food	Livelihood	Water filtering
Fibre	Living space	Air scrubbing
Fuel	Recreation	Waste repository
	Aesthetics	Wildlife habitat
		Gene preservation
		GHG mitigation

Finding win-win solutions

How do we acknowledge and accommodate other ecosystem services when choosing GHG-reducing options? The obvious solution is to seek win-win options—those practices that reduce GHG emissions *and* favor other services. One such practice is no-till farming. Many studies have shown that reduced tillage can increase soil carbon, at least for a time, thereby removing CO_2 from the air. Reduced tillage also reduces emissions from fossil fuel combustion. Meanwhile, no-till farming may contribute other ecosystem services unrelated to reducing GHGs: improved livelihood for farmers through reduced costs; preserved soil quality by holding soils in place; improved nesting habitats for migratory birds; and enhanced air quality by reducing dust from wind storms. Indeed, the wide acceptance of reduced tillage worldwide is probably mainly for these other benefits.

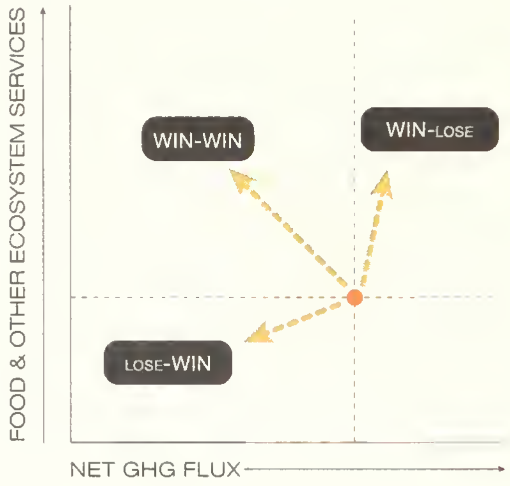
Such win-win opportunities are ideal GHG mitigation practices. In fact, they may be the only ones widely accepted. But few practices are purely win-win; few do not exact some sacrifice, some cost somewhere along the way. Even no-till farming may not have purely beneficial effects on all ecosystem services. For example, it might sometimes lead to higher leaching of pesticides, affecting water quality. In some areas it might limit yields, affecting food production.

Big win-small loss

As Figure 48 shows, the possible positive and negative effects imply the need for trade-offs—of making choices that will improve one ecosystem service while sacrificing another. The solution becomes one of seeking big-win/small-loss options. Are we willing to recommend a practice that effectively reduces GHG emissions (big-win), but exacts a small cost of reduced food yield (small-loss)? Conversely, would we advocate a practice that incurs slightly higher CH_4 emissions (small-loss) but dramatically improves the yield of milk (big-win)? If we include more than two ecosystem services the questions grow more complex. Suppose we include in our analysis of trade-offs also water quality, aesthetics, and wildlife habitat; how do we choose the best options now?

FIGURE 48

THE TRADEOFFS BETWEEN GHG EMISSIONS AND ECOSYSTEM SERVICES PROVIDED BY FARMS



A matrix showing the potential relationships between reducing GHGs and increasing food production. Ideally, we would opt for 'WIN-WIN' options. But would we be also willing to choose a lose-WIN option (small sacrifice in food production and large gain in GHG mitigation), or a 'WIN-lose' option (small sacrifice in GHG mitigation for a large gain in food production)? A new dimension is added with the addition of each new ecosystem service and the decisions grow ever more complex.

Source: Figure adapted from Janzen, 2007. (The concept of 'WIN-lose' was proposed by DeFries et al. 2004.)

Adding to the complexity are spillovers from one ecosystem to the next. A significant benefit to a service in one ecosystem might jeopardize services in another, perhaps far away. For example, seeding cultivated land to grass can drastically reduce GHG emissions by sequestering carbon and by reducing emissions from inputs. Where it is adopted, this practice is powerfully effective in reducing emissions, clearly advancing the service of buffering GHG emissions. But will the reduced output from that land be replaced by increased output elsewhere, perhaps causing a patch of forest somewhere to be burned, which would incur losses of ecosystem services there?

Choosing best practices involves more than identifying the practices that reduce emissions, or those that make immediate economic sense. We may need a more holistic approach, finding ways to understand and quantify the diverse services provided by farming ecosystems. And we may need to develop new ways to quantify success in reducing emissions. We might, for example, develop a method to compare practices on the basis of emissions per unit of output, rather than merely on the basis of emissions alone. Whatever our approach, we will need to understand all the services arising from agricultural systems and how they are interwoven via the myriad processes that comprise the ecosystem. Increasingly, scientists will aim to see farms as ecosystems, and policy makers will aim to find ways to value all the services they provide.

GHGs: bellwethers of ecosystem performance

Measuring and understanding GHG fluxes is important not only so we can find ways to reduce them, but also for judging how well an ecosystem is performing. Because GHGs are embedded and interwoven in the flows of carbon, nutrients and energy throughout ecosystems, GHGs may be a way of taking an ecosystem's pulse.

There seems little question that such bellwethers will be needed, for the biosphere is changing, perhaps at rates unprecedented. In coming decades, the Earth's temperature may be higher, precipitation less reliable and CO_2 more concentrated in the air. Other physical factors—aerosols in the atmosphere and the changing reflective properties of the landscape—also contribute to change, adding further to uncertainty.

Perhaps more potent than physical changes are changes that stem from social factors. These changes are driven by the burgeoning world population and our increasing capacity to reshape the land and sea and air around us. Although global population could almost level off by mid-century, it may increase by nearly 50% before then. This may pose further stresses on farmland as demands for food grow.

Perhaps more disconcerting than the prospect of increased demand is our dwindling resource base. There are few new productive lands left to cultivate, meaning higher yields will be expected of lands already in use. And, irrigation water, so important for past yield increases, may be diverted to other uses. Reserves of cheap energy are being exhausted and there may be other limitations that we cannot foresee. Increasing demands and dwindling resources lead, inevitably, to what E.O. Wilson calls a bottleneck.

Clearly, in the face of coming stresses, we will need markers to tell us how our ecosystems are performing. Are they holding up or are they winding down? Without reliable signals, how will we know? Addressing these questions may be the highest reward of studying GHGs. For GHGs are sensitive to flows of nutrients and energy in ecosystems. Excess releases of CO_2 tell us that carbon stocks in the soil may be depleting or that fossil energy is being wasted; high CH_4 emissions may indicate that solar energy stored in plant feeds is not being used efficiently; eruptions of N_2O may signal that nitrogen flows are uncoupled. By studying these fluxes we learn not only what the emissions are and how they contribute to climate change, but also something about how changes are affecting other ecosystem services: soil quality, water quality, biodiversity, aesthetics and others.

This perspective vaults us beyond mere inventories, mere counting of gigatonnes of emissions. It tells us whether or not our ecosystems are, in the end, permanent or sustainable. It helps us focus on the question, as phrased by Berrien Moore III in 2002: “And what now are the sky, land, and sea saying to us? And are we listening?”

FURTHER READING

Cohen, J.E. 2005. Human population grows up. *Scientific American* 293:48-54.

Daily, G.C.(ed.) 1997. Nature's Services–Societal Dependence on Natural Ecosystems Island Press, Washington D.C.

DeFries, R.S., J.A. Foley, and G.P. Asner. 2004. Land-use choices: balancing human needs and ecosystem function. *Frontiers in Ecology & Environment* 2:249-257.

FAO. 2003. World Agriculture: towards 2015/2030. Earthscan Publications Ltd., London.

Green, R.E., S.J. Cornell, J.P.W. Scharlemann, and A. Balmford. 2005. Farming and the fate of wild nature. *Science* 307:550-555.

Janzen, H.H. 2007. Greenhouse gases as clues to permanence of farmlands. *Conservation Biology* 21:668-674.

MEA. 2005. *Ecosystems and human well-being: Synthesis.* Island Press, Washington, D.C.

Smil, V. 2002. *The earth's biosphere: Evolution, dynamics, and change.* MIT Press, Cambridge, Massachusetts.

von Kaufmann, R.R., and H. Fitzhugh. 2004. The importance of livestock for the world's poor, pp. 137-159, In C. G. Scanes and J. A. Miranowski, eds. *Perspectives in world food and agriculture 2004.* Iowa State Press, Ames, Iowa.

Wilson, E.O. 2002. *The future of life.* Vintage Books, Random House Inc., New York, NY.

The Promise of Biofuels

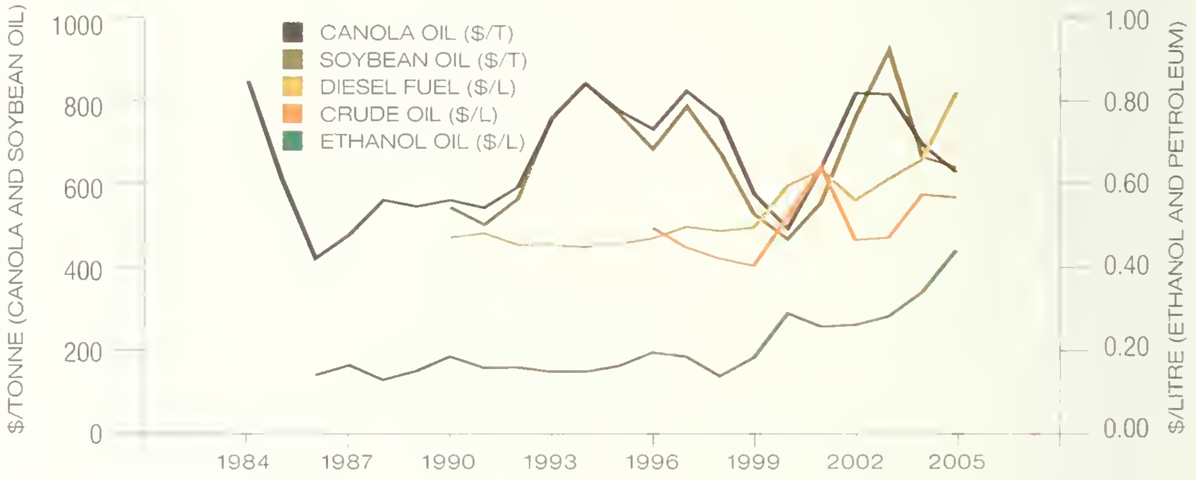
AN OPPORTUNITY AND A CHALLENGE

Toward the end of the 20th century, the world began to be increasingly concerned about declining energy supplies and the build up of CO_2 in our atmosphere. Energy demand was growing fast, which resulted in higher energy prices. Meanwhile, ethanol (ethyl alcohol) and biodiesel offered an alternative liquid fuel source, but at the time the cost of producing them exceeded the cost of comparable petroleum products.

More recently, the economics of producing bio-based fuels has improved. As Figure 49 shows, this is mostly due to higher petroleum prices and partly because the production of biofuels has been encouraged through tax breaks and subsidies.

FIGURE 49

PRICES FOR CANOLA AND SOYBEAN OIL, ETHANOL AND PETROLEUM PRODUCTS (1984–2005)



Source: Smith et al.

Another reason biofuel systems have become more interesting to producers and consumers is that, unlike fossil fuels such as petroleum and coal, biofuels are *renewable*. This means they can generate electrical, thermal or mechanical energy that at least matches the energy used to grow the living organisms and create the byproducts that make them up. Importantly, the plants used to produce liquid biofuels also pull CO_2 out of the air as they grow, which offsets a portion of the CO_2 produced when biofuels are burned for energy.

Canada's renewable energy record

Canada's annual primary energy supply is nearly 11 exajoules (*exa* denotes a factor of 10^{18}) and 17% of this is from renewable sources. The largest supply of renewable energy comes from water (hydroelectricity) at 11% and wood biomass at 6%.

Renewable bioenergy supplied from agricultural and forest wastes (with contributions from industrial, municipal solid waste and sewage biogas), energy crops, wind and solar sources are increasing in Canada. The pulp and paper and forest-product industries recycle half of their total energy use by converting biomass into electricity, steam and heat, while fuel-wood and gas from landfills are used to heat residential spaces. The use of biofuel in Canada's transportation sector is of special interest given that this sector contributes about 26% of the nation's CO_2 emissions in addition to reducing environmental air quality.

Agriculture plays a critical role

When we use biofuels in place of fossil fuels, we reduce net emissions of carbon into the atmosphere. The agricultural sector has a direct role in this replacement, as products grown on farms are the main ingredient of many bio-based energy systems, including ethanol (grains and cellulosic biomass), biodiesel (oilseeds), biogas (waste products), and heat energy and biogas (woody biomass).

TABLE 8

BIOFUELS AND THE PROCESSES FOR MAKING AND UTILIZING THEM

SOURCES	FEED SOURCE	PROCESS	PRODUCTS
Ethanol	Starch (grains, sugar)	Fermentation	Ethanol, Distillers Dry Grains
Biodiesel	Oils (animal and vegetable)	Trans-esterification	Biodiesel, Protein Meal, Glycerine
Biogas	Organic Material	Anerobic Digestion	CH_4, Heat
Cellulose	Wood, Straw	Hydrolysis and Fermentation	Ethanol
Woody Biomass	Wood	Combustion, Gasification	Electricity, Heat, Synthetic Gas

[illegible]

Biomass energy—plant material used for energy—has been used for thousands of years to cook food and provide heat. It provided a significant part of human energy needs prior to the industrial revolution. Since then, most energy requirements in the developed world have been provided by the combustion of readily available and inexpensive fossil fuels such as coal, oil and natural gas—but not without cost to the environment.

Biomass is still a predominant form of energy in much of the developing world, where it provides more than one third of primary energy consumption—although fossil energy consumption is growing. The International Energy Agency forecasts that by 2020, world demand for energy will have increased by 50% over 2006.

While direct combustion is the cheapest, simplest and most common method of obtaining energy from biomass, pyrolysis is a thermochemical process that converts biomass into bio-oil, charcoal or methanol by heating to about 1023 °C in the absence of air. Pyrolysis produces energy fuels with high fuel-to-feed ratios, making it an efficient process for converting biomass to crude oil for use in engines and turbines.

Scientists have estimated that in 2007 global forest and agricultural residues would make up about one thirteenth of the world's energy demand. Estimates for potential future contributions of biomass to global energy use range widely—the most generous estimates being four times that of the most modest. Estimates vary widely because two key variables—land availability and crop yield—are uncertain and open to interpretation. A more recent study has estimated the global potential of bioenergy production from agriculture and forestry residues and wastes at 76 to 96 exajoules per year by 2050. The key to achieving that level of bioenergy production is to optimize agricultural production systems so that food demand can be satisfied by using 50 to 75% of the cropland required in 1998 to achieve the same result, making the balance of land available for the production of energy crops.

Ethanol

Ethanol is the major source of bio-based energy. It is made by fermenting and distilling simple sugars. Sugars can be obtained from: sugar beets and sugar cane; converted starch from cereal grains; cellulose sources such as trees, grasses and crop residues; potatoes; and animal waste.

In Canada, ethanol production is from grains; either wheat in the west, or corn in the east. The process is as follows: the grain is milled to obtain the starch—the energy component of the grain—fermentation is used to produce the ethanol, and the product is distilled to remove water and impurities. The solid by-products have a high protein content and can be used in livestock feed. When Canadian processing plants currently under construction are completed, ethanol production will be enough to provide about 2.1% of motor gasoline consumption.

In the U.S., most of the ethanol production is from corn. About 15% of corn production is used for ethanol, but this biofuel represents only a small fraction (2.4%) of gasoline consumption. Projected increases for ethanol production are expected to supply about 5% of motor gasoline consumption.

In Brazil, ethanol production from sugar cane provides an astonishing 40% of the country's motor fuel. The production cost of ethanol from sugar cane has been comparable to the production cost of ethanol from corn in the U.S., but the cost advantage or disadvantage has depended on the price of the feedstock over time.

The efficiency of ethanol production depends on many factors: crop yield, energy inputs from fuel, amount of fertilizer used, pesticides, the genetics of the crop, specific cultivation practices and the proportion of energy that goes into co-products compared to what goes into the main biodiesel/ethanol products. For example, dry milling of corn is preferred over wet milling because it is more efficient.

Ethanol can also be obtained from cellulosic biomass such as switchgrass, or woody biomass such as fast-growing, short-rotation, hybrid poplar and willow trees. This technology offers the potential for low-cost ethanol production, but is currently at the pilot-plant stage. Many limitations must be overcome for it to be commercially viable.

CONVERTING CELLULOSE INTO FUEL

Sugars used to produce ethanol can be derived from sources other than corn or wheat grain. One promising option is to obtain sugars from cellulose, an abundant organic compound on Earth. Conversion of cellulose into sugars typically has three steps. The first step is pretreatment to increase the accessibility of the material to enzymes. The second step is enzymatic hydrolysis, which uses cellulose enzymes to increase the rate of biochemical reaction, and/or thermal hydrolysis, to convert cellulose into glucose. The third step is ethanol fermentation. The lignin in the plant fibre is used to generate steam as a heat source for distillation.

Biodiesel

Biodiesel is produced from animal fat or vegetable oil, such as soybean oil and recycled cooking oil, or animal waste fats extracted while food is being processed. The transformation to biodiesel, referred to as *transesterification*, mixes the fat or oil with methanol and a catalyst to produce biodiesel (methyl ester) plus glycerine. Impurities are then removed. Glycerine is a by-product with many commercial applications, such as soap making. Biodiesel is an attractive fuel in that it is non-toxic, biodegradable and contains no sulphur or other aromatics (air pollutants).

In 2007, biodiesel production in Canada was limited to a few processing plants that used either animal fats or yellow grease (waste grease obtained from restaurants and other sources). These plants produced about 0.09 gigalitres per year (a relatively small amount). Several new plants have been proposed, which will lead to an expansion of the biodiesel industry; at present, biodiesel sales represent about 0.3% of total diesel fuel sales in Canada. The U.S. currently produces roughly one third of the world's biodiesel and is set to nearly triple its production by 2008, using primarily soybean oil as the feedstock. The tripled production is expected to represent about 4% of diesel consumption in the U.S. At present, worldwide production of biodiesel takes place mostly in Europe.

Biogas

Biogas can be produced through the anaerobic digestion of manure and other organic materials. This process uses bacteria to convert complex organics into simpler ones. The process releases CH_4, CO_2 and trace amounts of other gases. Once biogas has been produced, unwanted gases can be removed, leaving useful CH_4, which has the potential to replace non-renewable energy sources such as natural gas and propane for residential cooking and heating. Methane can also be used in internal combustion engines to generate electricity and heat, although the efficiency of the system is low if only used to generate electricity.

Anaerobic digester systems range from covered manure storage structures to heated and regulated enclosed digesters. Large-scale, advanced anaerobic digestion systems are currently in use, mostly in Europe. Canada has a few working digesters, most of which use biogas to generate electricity and heat. These systems are continually improved through new technologies, more efficient anaerobic bacteria and better slurry composition, making them increasingly profitable to install. The effluent from the system is high in fibre and has a higher nitrogen concentration than untreated manure, which makes it an effective soil amendment or mulch for farm fields.

Wood-combustion energy

Combustion of wood has been used for centuries as an energy source. The production of fast growing woody biomass provides the potential to use it by itself or with coal in the production of electricity. (Excess straw from crop production could be used in a similar way.) The forestry industry in Canada utilizes waste wood products to generate steam, electricity and heat. Woody biomass can be gasified to produce a synthetic gas, which can be used in place of propane or natural gas.

A convincing energy balance sheet?

For biofuel to be considered a viable alternative to fossil fuel, it must provide a net energy gain, show environmental benefits, be economically competitive and be producible in large quantities without reducing food supplies. To assess if a biofuel provides real benefits when displacing fossil fuels, detailed life cycle analysis is required.

We can assess whether biofuels provide a net energy gain by viewing a farm as an *island economy*, whereby one determines the total energy required to grow and convert crops to biofuels. In *growing* crops as biofuel feedstock, one must account for energy use in: seeds and seed treatment; all field operations including land preparation, seeding and harvest; heating and maintaining buildings; producing and applying fertilizer and pesticide; and manufacturing machinery and equipment. In *converting* crops to biofuels, one must consider transport from farm-gate to a biofuel facility or processing plant, and all energy sources required within the facility, including its construction.

From the 1970s until recently, the energy required to produce corn and convert it to ethanol was greater than the energy in the ethanol produced. Today, with higher corn yields, reduced energy inputs into corn production and increased efficiencies in the industrial production of ethanol, corn ethanol can now provide about 25% more energy than the energy required for its production. However, a

positive energy balance has not been found in all studies. The positive balance is based on a portion of the energy required to grow the grain and produce the ethanol being allocated to the co-product called distillers dried grains, and use of lower input rates for corn production. Ethanol from wheat was found to be 6% less energy efficient than from corn.

The energy balance for biodiesel also depends on the feedstock source. Waste oils and fats will obviously have a large positive energy balance. Biodiesel production from first-time oils from soybean and canola produces about twice as much energy as the energy that goes into producing and processing the oil. While canola production requires more energy inputs than soybean for crop production, the oil yield of canola is higher than soybean, which means that the two crops net about the same ratio of energy output per unit of energy input. Efficiency gains in the past decade include higher yielding crops, improvements to the industrial oil extraction process and better trans-esterification processes that produce more methyl ester and less glycerine.

A profound effect on farming

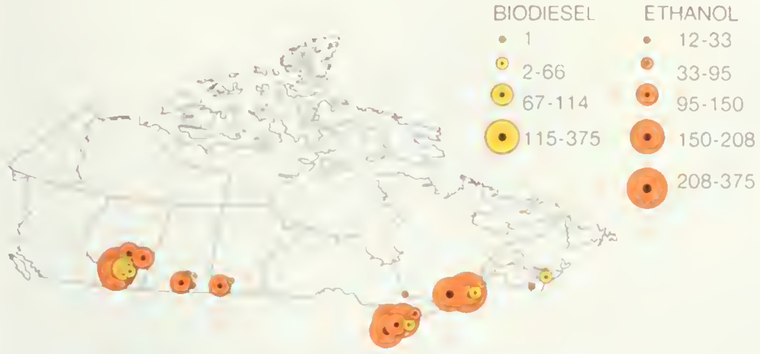
Canada has about 40 million hectares of cropland. Some of the main crops used in biofuel production are wheat, grain corn, canola and soybeans. Forages, barley and oats also require cropland to produce feed for cattle, sheep, hogs and other animals. Canada's large domestic populations of cattle, hogs and poultry will all be affected if more cropland is used for biofuel production.

Meanwhile, biofuel production in North America has increased the demand for cereals and oilseeds, resulting in increased crop prices. For crop producers, higher prices have increased the income from cropping, increased the value of farmland and affected cropping decisions. Land use will change as producers switch to the more profitable crops. In the case of corn, this will likely result in increased mono cropping and contribute to soil erosion. Other environmental risks will also increase as corn requires higher rates of fertilizers, herbicides and insecticides than most other crops. Additional soil conservation efforts by producers may reduce, but likely not avoid, the negative impacts of increased annual crop production on soil, water and air quality.

Beyond political, economical, energy or environmental considerations, the biofuel industry raises an ethical question: Should agricultural land be used to grow food for humans or fuel to power our vehicles? Given that North America has historically produced surplus grain, ethanol production will not result in local food shortages but will increase food prices. Globally, biofuel production could reduce food aid to Less Developed Countries and exacerbate famines. Clearly, a complete assessment of the impacts of grain ethanol production requires a global view. While ethanol production from grain is one of many options to manage the energy crisis, is it viable in the long term?

FIGURE 50

Distribution of Current (2007) and Planned (post-2007) Ethanol and Biodiesel Production Facilities Across Canada, million litres per year



Source Supplemented and adapted from data obtained from the Canadian Renewable Fuels Association, available online at http://www.greenfuels.org/ Klein, 2007 and corporate news briefings

A few producers have invested in biofuel processing plants, but most plants are large and owned and operated by established biofuel companies. For producers close to a biofuel facility, there is an incentive to plant the types of crops demanded by the facility. For example, ethanol production from wheat in western Canada requires wheat high in starch and low in protein. However, the ideal growing conditions for these types of wheat might not correspond to conditions near the facility. In time, crop-breeding programs will develop lines of wheat and corn hybrids that are better feedstock for biofuel facilities than the currently available lines.

As prices rise, livestock producers are experiencing higher feed costs. This is especially important in the case of corn and barley, which are major feed sources for the industry. Some low-cost by-products of biofuel production can be used by the livestock industry, but many questions remain about how much by-product can be fed to animals without adversely affecting animal performance and meat quality.

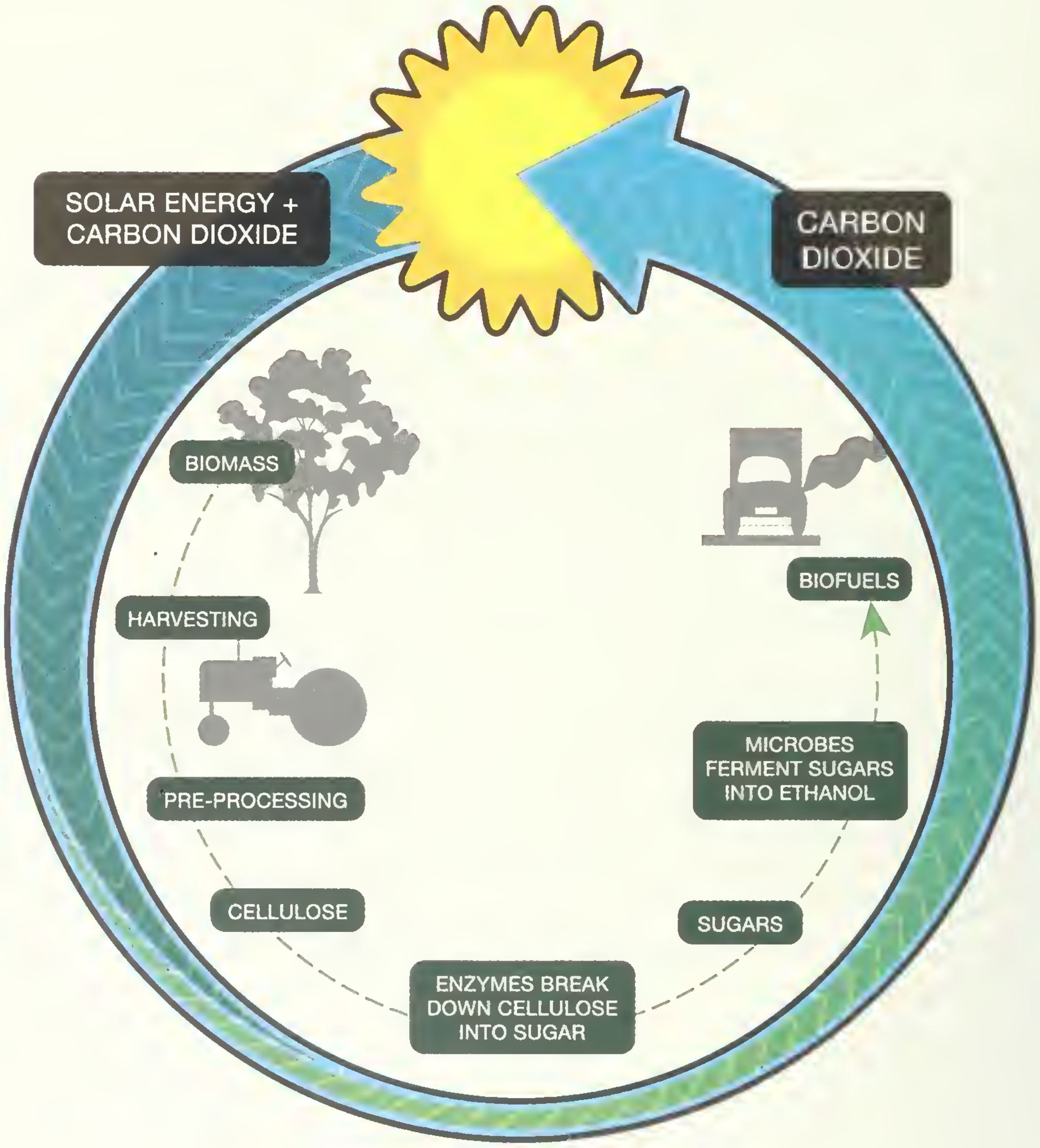
Reducing GHG emission

Biofuels are made from plant matter of recent biological origin, which means that the CO_2 emitted when they are burnt is from recycled carbon recently removed from the air, rather than from fossil fuels.

Recent analyses estimate that net GHG emissions for the production and combustion of corn ethanol are 18% lower than conventional gasoline, with uncertainty ranging from 36% below this mean estimate to 29% above it. Research shows that potential reductions may vary depending on such factors as the rate of tillage and the application of nitrogen to crops. Further study is needed on the flow of carbon and nitrogen through air, water and soil to improve our understanding of how we can produce biofuels with a positive GHG budget.

FIGURE 51

Overview of the Carbon Cycle



Strengthening rural communities

In 2006, Canada provided commercial subsidies to build new biofuel processing plants and to advance biofuel research and technological development. This included a new program to add five new ethanol processing plants that will increase Canadian production to 1.4 billion litres annually by 2008. These plants will produce sufficient ethanol that 35% of all gasoline in Canada could have a 10% ethanol blend.

The Biofuels Opportunities for Producers Initiative (BOPI), which helps to lower processing infrastructure costs, extended funding to agricultural producers to create and expand their ethanol production capacity. Sustainable Development Technology Canada (SDTC) recently extended financial support for four biofuel technology projects to process ethanol from cellulosic material and mustard seed in support of accelerating biofuel research and technology. Research will be conducted on the energy saving provided by the industrial and commercial applications of co-products, on the development of improved processing technology, and on how we can better evaluate the environmental and societal costs and benefits of biofuel production.

The outlook for biofuels in Canada

The Government of Canada is committed to reaching an average renewable fuel content for gasoline of 5% by 2010 and 2% for diesel fuel and heating oil by 2012. To support this goal, the government has allocated resources to help develop a renewable fuels industry. Three noteworthy programs are Biofuels Opportunities for Producers Initiative (BOPI), which helps farmers hire technical, financial and business-planning advisors who can develop sound business proposals and undertake feasibility and other supporting studies; the Agricultural Bioproducts Innovation Program (ABIP), which aims to integrate resources to build greater research capacity in agricultural bioproducts and bioprocesses; and the ecoAgriculture Biofuels Capital (ecoABC), which has allowed some farm-based renewable fuel plants to proceed with development plans.

The long-term success of the renewable fuel industry will depend on many factors, including the price of petroleum fuel, the supply of agricultural products used to produce renewable fuels and the cost of producing the renewable fuels. In 2007, high petroleum prices were beneficial to the economics of renewable fuels, but short supplies of agricultural products (corn, wheat, soybean, canola) resulted in higher prices for the feedstock used to produce renewable fuels and higher costs to produce renewable fuels.

FURTHER READING

Farrell, A.E., et al. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311:506–508.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences* 103:11206–11210.

Klein, K. and D.G. LeRoy. 2007. *The biofuel frenzy: what's in it for Canadian agriculture?* Alberta Institute of Agrologists. Banff, Alberta, 44pp.Available online at: http://www.aia.ab.ca/index.cfm/ci_id/2077/la_id/1/document/1/re_id/0. Accessed October 30, 2007.

Newlands, N.K., J. Foyle, and L. L. Yang. 2006. *Potential net reductions in greenhouse gas emissions from farm bioenergy production in Canada.* ASABE Proceedings of the 4th World Congress of Computers in Agriculture and Natural Resources: 770–774. Available online at: http://asae.frymulti.com/request.asp?JID=1&AID=21971&CID=canr2006&T=2. Accessed October 30, 2007.

Smith, E.G., H.H. Janzen and N.K. Newlands. 2008. Energy balances of biodiesel production from soybean and canola in Canada. *Canadian Journal of Plant Science* 87:793-801.

Rejuvenating the Air

POLICIES TO QUANTIFY AND REDUCE GREENHOUSE GAS EMISSIONS

Climate change is a long-term, global problem, yet there is still considerable uncertainty concerning which changes are likely to take place, when, to what degree and how climate change will affect our lives. The major effects may not be felt for decades or even centuries; yet we are reasonably certain that greenhouse gas (GHG) emissions to the atmosphere will have long-lived, cumulative effects, which demands that we act now. The absence of immediate impacts creates a significant policy challenge: how can decision makers encourage people to change their behaviours now to prevent a future problem about which there is still such uncertainty?

More difficult still will be to find ways to achieve policy objectives internationally. The atmosphere knows no boundaries—GHGs emitted in one country or region flow freely across others. In fact, some of the greatest climate change impacts are predicted to occur in regions with the lowest GHG emission levels. The far northern latitudes, where the highest temperature increases are likely to occur, are one such example. Small tropical islands are another; they could be completely inundated if sea levels rise.

To stabilize GHG concentrations at levels that will prevent serious climate change will require widespread GHG mitigation efforts throughout the world. This chapter examines the evolution of international agreements and strategies aimed at mitigating climate change—and how Canada has responded to that evolution. It also highlights groundbreaking new agricultural GHG mitigation practices and the determined efforts of individual Canadian farmers who have adopted strategies for their own land.

Managing climate change on the world stage

The global effort to combat climate change began in 1979 at the First World Climate Conference, an intergovernmental meeting held in Geneva that examined how climate change might affect human activities, especially agriculture, fishing, forestry, hydrology and urban planning. The participants issued a declaration for world governments "to foresee and prevent potential man-made changes in climate that might harm the well-being of humanity" and identified that the leading cause of global warming is increased atmospheric concentrations of CO_2 resulting from the burning of fossil fuels, deforestation and changes in land use.

In 1988, the World Meteorological Organization and the United Nations Environment Programme established the Intergovernmental Panel on Climate Change (IPCC). IPCC's role is to assess available scientific, technical and socio-economic information and report on the risk of human-induced climate change, its potential impacts and options for adaptation and mitigation. The first climate change assessment report by the IPCC, released in 1990, was an important step on the road to the first international global climate change agreement, the United Nations Framework Convention on Climate Change.

The Climate Convention, which has been adopted by 192 counties, is based on the *precautionary principle*. The precautionary principle is a "better safe than sorry" approach. It states that if there is a risk of severe and irreversible damage to human health or the environment, lack of complete scientific certainty about all of the causes and effects should not be used as a reason to delay action. By ratifying the Climate Convention, governments around the world recognized that despite some uncertainty about how the greenhouse effect might change climate, the potential impacts are so serious that the only responsible course is to take action now.

The Convention aimed to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous climate change. It contained voluntary targets for GHG emission reductions and advocated reducing emissions to 1990 levels. Developed countries are required to submit national reports on GHG emissions and to support similar reporting by developing countries through financial and technical assistance.

Governments and scientists recognized that the voluntary targets adopted under the Convention would have to be strengthened to prevent serious climate change. Governments involved in the Climate Convention continued to negotiate deeper and more legally binding emission reduction commitments. In 1997, they reached agreement on the Kyoto Protocol, a set of emission targets aimed at reducing global GHG emissions to 5% below 1990 levels between 2008 and 2012. The Kyoto Protocol became international law on February 16, 2005. The countries, including Canada, that agreed to participate in the Protocol are part of the first international agreement based on legally binding emissions reduction targets and the first international environmental agreement that will try to achieve its objectives using markets, such as a carbon trading market.

EMISSIONS REDUCTION AS CURRENCY

Emission trading is a promising tool to help reduce the cost of achieving emission reductions. In a carbon market, sellers such as farmers generate carbon credits by reducing their emissions or enhancing removals; buyers purchase credits to offset their own emissions. A market system can provide buyers with relatively low-cost credits and farmers and other businesses with economic incentives for adopting and developing low-emission technologies and practices. The value of traded carbon is not expected to be high enough, at least in the short term, to cause farmers to shift the focus of their production systems to carbon credits instead of food and fibre, but emission trading might tip the balance in favour of GHG-mitigating practices in certain cases.

Most parties to the Climate Convention have ratified their Kyoto Protocol commitments. In July 2006, 61% of emissions from developed countries were covered by the Kyoto Protocol. Commitments vary among countries: compared to 1990 levels, Canada's target is -6%; Denmark and Germany have a target of -21%; and Greece has a target of +30%. The United States (which produces about 25% of the world's emissions) and Australia are the two most significant developed countries that did not ratify the Kyoto Protocol—although both countries have domestic programs aimed at reducing GHG emissions.

Developing countries do not have emission reduction targets under the Kyoto Protocol. It was agreed that targets for developing countries would be set in later agreements once developed countries—which have been responsible for most GHG emission increases thus far—had taken the first steps to reduce their emissions.

Countries can meet their targets in two ways: by reducing emissions of GHGs and by generating biological carbon *sinks*[2] to offset their emissions. Sinks can be created by planting new forests, reducing deforestation and through other activities related to the management of forests, croplands and grazing lands.

---

[2] *A biological carbon sink is a transfer of CO_2 from the atmosphere into a reservoir, such as a forest or soil, through the process of photosynthesis.*

How the Kyoto Protocol affects agriculture

Under the Climate Convention and Kyoto Protocol, countries must report emissions from the agriculture sector, specifically the sources and gases shown in Table 9. Agriculture produces about 8% of Canada's GHG emissions, including most of its emissions of N_2O and CH_4.

TABLE 9

GHGs and Sources of Emissions for the Agriculture Sector that must be Reported Internationally

SOURCE	ACTIVITY	GHG
Enteric fermentation	Ruminant livestock	CH_4
Manure management	Handling or storage of livestock manure	CH_4, N_2O
Rice cultivation	Flooded paddy production	CH_4
Agricultural soils	Synthetic N fertilizer	N_2O
	Animal manure applied to soils	N_2O
	Manure from grazing animals on pasture	N_2O
	Crop residue decomposition	N_2O
	Cultivation of organic soils	N_2O
	Volatilization	N_2O
	Leaching, erosion and runoff	N_2O
Field burning of agricultural residues		CH_4, N_2O
Prescribed burning of savannahs		CH_4, N_2O

Agriculture is a biological production system. Emissions of CO_2, CH_4 and N_2O are a natural part of agricultural production and will never be completely eliminated. However, it is the goal of the international agreements to encourage the search for better ways of managing inputs of nutrients and energy so they are used more efficiently by the crops and ànimals rather than *leaked* away as gases or dissolved in water.

Cropping systems can also be managed to remove CO_2 from the atmosphere through carbon sequestration in soils. Under the Kyoto Protocol, countries have to account for all their GHG emissions and removals from the conversion of croplands to forest (afforestation and reforestation) and the conversion of forest to agricultural land (deforestation). Countries also have the option to count changes in carbon stocks resulting from improved management. This provision was, at first, controversial because carbon storage in agricultural soils is reversible. For example, the stored carbon could be lost if land managers change their management practices or climate change reduces crop production.

Canada's climate change and GHG mitigation activities

Canada ratified the Kyoto Protocol in December 2002. Canada's domestic climate change and GHG mitigation activities include the agriculture sector. In Canada GHG mitigation and climate change objectives are integrated within the country's overall environmental and sustainability agenda for the agriculture sector.

Farmers manage farmland to sustain crop production over the long term. They make their decisions by weighing all factors involved in their production system and deciding what combination of activities and practices will offer the best possible overall economic and environmental outcomes. Agriculture policy developed by governments often has the aim of supporting farmers to achieve broader social or public goals, including environmental goals such as adaptation to climate change and GHG mitigation.

Fortunately, GHG mitigation is largely a matter of good land management, conservation of resources and careful management of the carbon and nitrogen cycles. Many GHG mitigation practices provide other benefits, economic and environmental. Thus, although it would be difficult to motivate people to reduce emissions for environmental impacts that are not yet clearly defined, many farmers are adopting good practices quite willingly because of those other benefits.

When scientists began to look for ways to reduce GHGs associated with crop and livestock production, they found that many recent changes and innovations in cropping and livestock systems already reduce emissions. Therefore, GHG mitigation provides a fresh new impetus for understanding and promoting the use of these beneficial practices.

HOW CANADIAN FARMERS ARE RESPONDING

PORK PRODUCER RECEIVES PRESTIGIOUS EMERALD AWARD

Dennis McKerracher, a High River, Alberta pork producer couldn't believe his ears when he heard he had won the coveted emerald award in the Research and Innovation category of the Alberta Emerald Foundation for Environmental Excellence.

McKerracher won for a yearlong, on-farm research project to examine how waste water and GHGs can be reduced in hog operations. Supported by the Greenhouse Gas Mitigation Program for Canadian Agriculture, Climate Change Central, the Canadian Pork Council and Alberta Pork, McKerracher's project measured and compared the impacts of using ball bite versus standard water drinker systems in his 500-head, all-in, all-out grower operation.

His research found that over a one-year period the group of pigs selected to drink from the ball bite system used 35% less drinking water than the group using the standard drinkers. Ball bite drinker systems release water when the pig bites down on a ball, pushing a leaver that releases water.

The study results are significant. Water savings on McKerracher's operation means that he has to pump less of it. Not only is this more cost effective, but it also saves him time. And the less water used, the more efficient the farm's manure management—resulting in a lower production of GHGs.

"To leave as small an ecological footprint as possible is my responsibility as a farmer. To be able to make a difference on my own hog operation is great. But to see the potential far-reaching, positive effects that my project could have on the environment and my industry is the best reward to me."

Canadian Pork Council June 21, 2006

ZERO TILL DELIVERS A BIGGER BANG FOR FEWER BUCKS

Jim Halford is a strong advocate of zero-till farming and direct seeding. The southeast Saskatchewan farmer retired his tillage equipment more than 20 years ago and has been reaping the rewards ever since.

Halford says that on parts of his Indian Head-area farm hard red spring wheat yields have increased by nearly 15 percent over conventionally farmed land, while nitrogen fertilizer requirements have been cut by 40 percent. He attributes these somewhat surprising and continuing benefits to long-time zero-till farming and precise fertilizer placement.

"It's due to the higher levels of organic matter in the soil," says Halford. "As the organic matter increases, it increases the ability of the soil to mineralize nitrogen and make it more available to the crop."

On Halford's sandy-loam, clay-type soil, no-till has meant about a 40 percent reduction in current fertilizer rates, while harvesting a very respectable 45 to 50 bushel HRSW crop. It's the difference between applying 50 to 60 pounds of nitrogen versus a more traditional 90 pounds per acre, which saves Halford $12 to $16 per acre.

The production and economic benefits of zero till fit well with a national objective to reduce GHG emissions related to agriculture, says Doug McKell, executive director of Soil Conservation Council of Canada. The council administered the soils and nutrient management components of the national Greenhouse Gas Mitigation Program for Canadian Agriculture. The program's mandate was to promote awareness and adoption of practices that benefit production and at the same time reduce GHG emissions.

Zero-till farming produces a wide range of production and economic benefits, says Halford, who is well known across North America as the developer of the Conserva Pak Seeding System. He notes that proper placement of seed and fertilizer is important to a successful crop. And as soil quality improves, inputs are able to reach their fullest potential.

The benefits of zero-till cropping build with time, so the longer land is farmed without tillage, the more soil quality improves. For example, soil organic matter increased about one percent every five years of zero tillage. Over 13 years of zero tillage, organic matter increased from 2.7 to 5.1%.

The increase in soil organic matter translates directly into higher rates of nutrients being mineralized and made available to the crop, says Dr. Jeff Schoenau, a University of Saskatchewan soil scientist. It's not a sudden process that happens the first year of zero-till farming. In the first three to five years of zero till, fertilizer requirements may actually increase, he points out. But, as the organic matter increases, the conversion begins.

Soil Conservation Council of Canada

GROUNDBREAKING IDEAS FROM THE SCIENTIFIC COMMUNITY

NET FEED EFFICIENCY HOLDS GREAT PROMISE FOR CANADA'S BEEF INDUSTRY

Canada's beef industry stands to gain well over $200 million annually in feed savings by adopting technology to select animals for *net feed efficiency*, says a leading beef scientist with more than 25 years experience in beef cattle production and management.

"In all my years in the beef industry, I have never seen a trait come along with higher potential than net feed efficiency," says Dr. John Basarab of Alberta Agriculture, Food and Rural Development (AAFRD). Net feed efficiency, also known as residual feed intake, is a relatively new discovery, but it's rapidly gaining recognition internationally among scientists, private industry and innovative producers.

Australia was the first to develop commercial technology for measuring individual animal feed intake in the mid 1990s, a key measure for calculating net feed efficiency. But the technology was prohibitively costly to produce and operate.

Following an investigative trip to Australia, Basarab and colleagues Dr. Bob Kemp and Dr. Warren Snelling approached Alberta-based GrowSafe Systems Ltd. about developing a less costly and more efficient model.

The result was a new standard in feed intake measurement equipment produced at one-tenth of the cost of the Australian model and operated with less than one-fifth the labour. The scientists also established a proof of concept for net feed efficiency as a valuable measurement tool in a series of studies funded in part by the Canada Alberta Beef Industry Development Fund (CABIDF). In 2006, the technology and approach have made great strides in commercial adoption. "More people are testing commercial bulls, and those bulls are going into industry and in many cases being sold at a higher price," says Basarab.

"If we are to take advantage of net feed efficiency, one of the priorities for the beef industry over the next three to five years will be to identify the best bulls that have the trait," he notes. "Right now in Alberta, the approximately five percent of industry that represents the leading innovators is taking the lead, and we'd like see use of the technology gradually broaden throughout the industry."

Canadian Cattlemen's Association

CATTLE FEED AND REDUCED EMISSIONS

A study was conducted by the University of Guelph at Elora Dairy Research Farm and Mayhaven Farms in Rockwood, Ontario to look at how feeding cows dry-rolled corn and an extract of palm oil (myristic acid) could reduce CH_4 emissions.

The formation of CH_4 by the cow is a loss of energy from the feed, accounting for up to 12% of the feed energy. Given that CH_4 gas is not used by the cow for milk production, it represents a loss of feed energy that could increase feed costs. Dry-rolled corn and myristic acid were incorporated separately into the total mixed rations of the cows' daily diet. The CH_4 emissions were collected and measured in the breath of the cows with the aid of custom built head hoods. Experiments compared steam-flaked and dryrolled corn to see which produced a higher gaseous output of CH_4. Dry-rolled corn produced 7% less CH_4 per day per kilogram of milk produced than steam-flaked corn. Myristic acid did even better, lowering CH_4 emissions by 28% per day per kilogram of milk produced.

Although myristic acid is the clear winner in terms of CH_4 reduction, dry-rolled corn is only a slight change from standard diets. Incorporating dry-rolled corn into the diet is therefore probably the easier and more practical change for producers to make. And dry-rolled corn would benefit not only the health of the cow, but also the environment.

Dairy Farmers of Canada

IMPROVING THE BOTTOM LINE THROUGH CROPLAND MANAGEMENT

There is a long history of soil carbon research in Canada and farmers have generally been aware that loss of soil organic matter is linked to soil degradation. Canadian farmers have been among the pioneers developing crop production systems based on direct seeding, minimum tillage and continuous cropping that maintain soil quality. Farmers' primary motive for using innovative practices is financial—the practices provide better economic returns under present market and farming conditions. However, the practices are now recognized for the significant environmental benefits they offer, especially maintaining and enhancing soil organic matter with its rich store of soil organic carbon and nitrogen. (See earlier chapters on carbon and nitrogen for full descriptions of these processes.) Under the Kyoto Protocol, increases in soil organic carbon that result from changes in cropland and grazing management can be used as carbon credits to offset GHG emissions during the first commitment period.

Agriculture and Agri-Food Canada

FURTHER READING

Environment Canada. 2007. *National Inventory Report: 1990–2005, Greenhouse gas sources and sinks in Canada.* Environment Canada, Greenhouse gas division.

Janzen, H.H. 2001. Soil science on the Canadian prairies—Peering into the future from a century ago. *Canadian Journal of Soil Science* 81:489–503.

Paustian, K., J. Antle, J. Sheehan, and E.A. Paul. 2006. Agriculture's role in greenhouse gas mitigation. Prepared for the Pew Centre on Global Climate Change, Arlington, VA. September (www.pewclimate.org)

Wall, E. and B. Smit. 2005. Climate change adaptation in light of sustainable agriculture. *Journal of Sustainable Agriculture* 27:113–123.

WMO. 1979. Proceedings of the World Climate Conference: a conference of experts on climate and mankind. Geneva, 12–32 February 1979. WMO - No. 537. ISBN 92-63-10537-5.

What Could Happen

GREENHOUSE GAS EMISSIONS UNDER FUTURE CONDITIONS

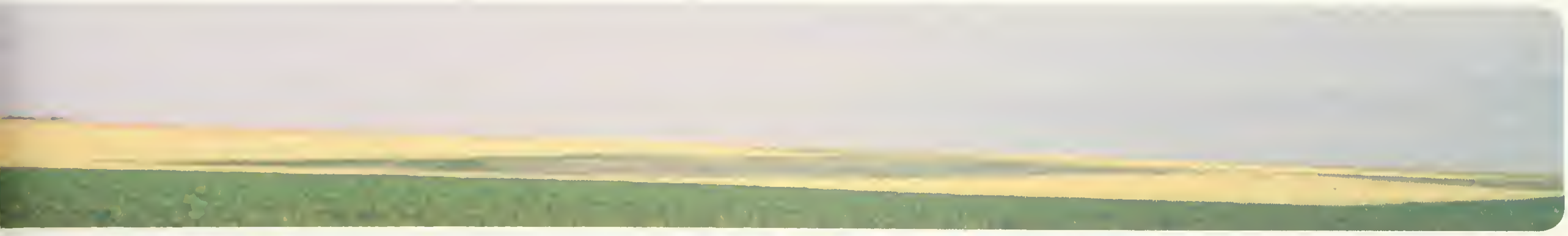
While there are plenty of opportunities to make agriculture more efficient in terms of its GHG emissions, a rapidly growing world population and increasing demand for food and improved diets means that GHG emissions from agriculture will continue to grow. The United Nations has predicted that the world's population will grow from 6.5 billion in 2005 to 9.1 billion in 2050.

Population growth is expected to be higher in developing than developed countries. If food production in developing countries increases to meet the rising demand, it is likely that GHG emissions from agriculture will also rise in those countries. Incomes are also expected to grow, which means that food preferences and demand for improved diets (i.e., more livestock products) could further increase GHG emissions from food production.

To feed the increasing population, global livestock production is projected to more than double from 229 million tonnes in 2001 to 465 million tonnes in 2050. Milk production is also expected rise from current levels of 580 million tonnes to 1,043 million tonnes by 2050. The U.S. Environmental Protection Agency projects that under business-as-usual conditions and rates of population growth, global emissions from agriculture will increase by 25% between 2000 and 2020, with an increasing share of emissions coming from developing countries.

[illegible]

On a global scale, agriculture accounts for about 40% of total land use and about 70% of water use. It has changed major nutrient cycles. It has more than doubled the size of the nitrogen cycle—and contributes about 10-12% of global GHGs, including most of the world's CH_4 and N_2O.



Our changing use of land

Globally in 2000 there were about 5,000 million hectares of agricultural land compared to about 4,500 million hectares in 1960. An increase in agricultural land area and new crop production technologies has allowed food production to keep pace with increasing food demand and global population growth. However, this has not occurred without cost to the environment.

Every year for the past 40 years, on average, 6 million hectares of forest and 7 million hectares of other land types have been converted to agriculture, mainly in the developing world. Expansion of livestock production is a key driver of deforestation, especially in Latin and South America where it is estimated that 70% of the forested land in the Amazon has been converted to pastures and croplands. Scientists have said that tropical deforestation might be the key determinant in whether or not GHG emissions are stabilized at a level that will prevent climate change. They report that up to one quarter of global, human-induced emissions result from tropical deforestation; the emissions from deforestation in Brazil and Indonesia almost equal the total emission reduction targets of the Kyoto Protocol.

Outside the tropics, emissions from land use and land-use change activities have shifted from a *source* of GHGs in the 1980s to a small *sink* in the 1990s, as some agricultural lands are returned to forest, forest fire-fighting efforts increased and cropland soils gain carbon due to changes in land management. However, whether terrestrial sinks in the temperate region can survive in the face of long-term climate change is uncertain.

Non-CO_2 GHG emissions from agriculture are also expected to increase over the next decades. Agriculture is the largest human-induced source of CH_4 and N_2O and the Environmental Protection Agency in the United States indicates that this is not likely to change. The main source of N_2O emissions is agricultural soils; the main source of CH_4 is livestock.

Agricultural production is expected to increase to meet demand in Asia, Latin America and Africa. In 1990, developed countries contributed about one third of emissions of N_2O from soils, but by 2020, projections indicate that will drop to 23% with emissions from China and Asia up by 50% and Africa, Latin America and the Middle East up by more than 100%. The growth in global CH_4 emissions will come mainly from China, Latin America, Africa and Asia, where urbanization and per capita income are expected to generate increased demand for livestock products. In contrast, emissions in developed countries are expected to decline over time due to increased production efficiency and lower export demand.

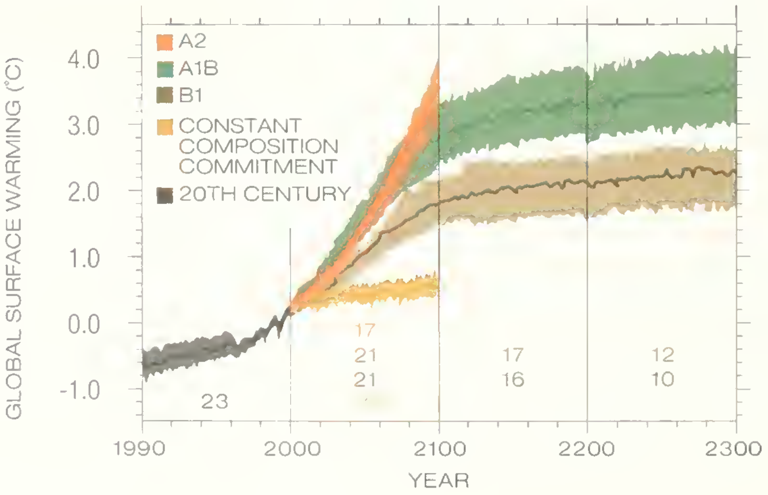
Our changing climate

Scientists make projections about the future of our climate by running global climate models—generally referred to as global circulation models—based on scenarios that represent a range of possible future conditions, including atmospheric GHG concentration, population size, socio-economic development and technology change. These projections are heavily dependent on assumptions about future conditions and the path that will likely lead us there. However, there is growing agreement that our future climate will be warmer with more extreme climate and weather events.

The climate scenarios of the Intergovernmental Panel on Climate Change project that mean global temperatures are likely to increase by 0.2ºC per decade for the next two decades, as illustrated in Figure 52. Projections at the high end of the range reflect scenarios with high rates of population growth and emissions of GHG continuing at current rates into the future (A1B). Low-range projections are based on assumptions of slowing population growth and significant effort to mitigate GHG emissions over the next decades (B1). The global estimates do not provide good information about temperature changes at regional and local levels. There is increasing effort to learn how to use the information from global circulation models to predict future climate in local regions.

FIGURE 52

GLOBAL WARMING PROJECTIONS FOR A RANGE OF POSSIBLE PATHS TO THE FUTURE



Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Values beyond 2100 are for stabilisation scenarios. The number of models that were run for a given scenario are indicated by the coloured numbers given for each period and scenario at the bottom of the panel.

Source: IPCC AR4 WG1 Chapter 10, Global Climate Projections. Available online at. http://www.ipcc.ch/graphics/graphics/ar4-wg1/ppt/figure10.ppt, accessed January 22, 2008.

CLIMATE CHANGE IN CANADA

Scientists have applied climate information produced by the Canadian Centre for Climate Modelling and Analysis global circulation model (Canadian Coupled GCM with aerosol) to the three Prairie provinces under two conditions: current climate and future climate associated with a doubling of atmospheric CO_2. The model predicted that under a future climate, on average, high temperatures would increase by 2°C to 3°C and low temperatures increase by about 3°C. Compared to current climate, precipitation was predicted to increase by 3% to 7%. The results suggest that Alberta will benefit the most from increased summer and winter precipitation, whereas eastern Saskatchewan and Manitoba will experience little change or smaller increases. It is important to note that projected changes in precipitation are more uncertain than estimates about temperature change. Since there is a growing-season moisture deficit in much of the Prairie region, even slight declines in the availability of moisture could significantly harm crop production.

There is considerable evidence that climate is already changing:

- The global mean surface temperature has increased by 0.6 ± 0.2°C over the past century.
- The 1990s was the warmest decade of the past 1,000 years.
- The daily surface temperature range has decreased between 1950 and 2000 over land, with nighttime minimum temperatures increasing at twice the rate of daytime maximum temperatures.
- There have been more hot days and fewer cold or frost days over the past several decades.
- Continental precipitation has increased by 5 to 10% over the 20th century in the northern hemisphere and declined in parts of Africa and the Mediterranean.
- The number of heavy precipitation events have increased at mid and high northern latitudes and the frequency and severity of drought has increased.
- Sea-ice cover has decreased.
- Shifts in species distributions have been observed.
- The global average sea level has increased.

For Canada, a high-latitude country, warming is expected to be more pronounced than the global average, with the north and southern and central Prairies warming more than other regions. Most regions will likely be warmer with longer frost-free seasons and increased evapotranspiration.

Climate change could alter our agricultural landscape

Agriculture is both extremely important to the Canadian economy and inherently sensitive to climate change. Climate controls the geographical distribution of agricultural systems in Canada and exerts strong control over year-to-year variation in cropping success through drought, flooding, pest problems and storms. Climate affects agriculture, positively and negatively, at scales ranging from individual plants and animals to global networks.

Our crops

Climate change will influence Canadian crop production, but projections show great variation and a new set of risks *and* opportunities. For example, some modeling exercises suggest that farmers may be able to plant their crops earlier so crop growth will be complete before the hot, dry conditions in the late summer. If farmers are able to adapt to climate change in that way, yields of canola, corn and wheat might not suffer and the range of crops that can be produced in Canada might expand.

On the other hand, increased moisture stress and drought are concerns for irrigated and non-irrigated crops across the country. While climate change is expected to cause shifts in moisture patterns and rates of potential evapotranspiration, there is still considerable uncertainty about the magnitude and direction of the changes. Longer growing seasons and higher temperatures could increase water demand. Drought could be become more frequent.

Climate models suggest that climate warming will be greatest in winter months, which could reduce the risk of winter damage to sensitive crops, such as fruit trees and grapes. However, the absence of extreme cold in the winter could allow crop pests to survive. An increased frequency of extreme events, such as high temperatures, floods, droughts and storms, could also negatively impact future crop production in Canada.

Our livestock

Climate warming could benefit *and* harm livestock production. Benefits would be especially evident in the winter in the form of lower feed requirements, increased survival of the young and lower energy costs. Warmer summers, however, could cause problems related to heat-wave deaths—especially in poultry operations—reduced milk production and reduced reproduction in the dairy industry, as well as reduced weight gain in beef cattle.

Droughts and floods could reduce pasture availability and forage production, forcing producers to find alternative feed or reduce herd size.

Our soils

Climate change could negatively affect agricultural soil quality by influencing the quantity of soil organic matter, nutrient cycling and leaching, wind and water erosion and runoff, all of which could lead to an increase in emissions of CO_2 and N_2O from soils. On the other hand, climate change could improve soil quality, enhance carbon sequestration and reduce emissions of greenhouse gases if it were severe enough to force a land-use change from annual crop production to perennial crops and grazing lands.

Pests and disease

Scientists have reported a list of possible effects of climate change on crop pests and disease. These include increased weed growth due to elevated atmospheric CO_2; increased prevalence of livestock and crop pests and pathogens; and increased range, frequency and severity of insect and disease infestations. These changes will not have large effects on GHG emissions from crop production systems, although they could cause an increase in energy use associated with the manufacture, transportation and application of pesticides.

GHG mitigation offers opportunities for agriculture

GHG emissions are a natural part of the carbon and nitrogen cycles. Therefore, a certain level of emissions from any biological system is inevitable: CH_4 emissions from ruminant animals cannot be reduced to zero; N_2O emissions from decomposing crop residues cannot be avoided; emissions of N_2O and CH_4 from livestock manure cannot be eliminated.

However, some GHG emissions from crop and livestock production are avoidable; these represent leakage or inefficiency in the system of which both have environmental and economic consequences. For example, emissions of N_2O imply inefficient use of nitrogen fertilizer and CH_4 emissions from ruminant livestock indicate that feed is not being efficiently converted to milk or meat products.

There is a considerable body of literature about plant and animal production systems that can reduce GHG emissions and offer positive economic benefits. Examples include:

1. Use inputs—such as fertilizers and machinery—associated with large emissions of fossil fuels as efficiently as possible.
2. Use some of the biomass produced on agricultural land to produce bioenergy so as to partly replace fossil fuels. (The chapter on biofuels provides a detailed examination of biofuel production in Canada and in other countries.)
3. Use agricultural wastes to generate energy.
4. Adopt management practices that increase the amount of carbon stored in soils.

Adapting to climate change

Climate change has the potential to benefit and harm agriculture. Warmer temperatures, longer growing seasons and elevated CO_2 concentration may improve agricultural production; on the other hand, reduced soil moisture, more frequent extreme weather and storms and new crop pests could hurt production potential. Appropriate adaptations can reduce the effects, especially if they are part of an overall decision-making process at the farm and policy levels.

Developing countries are likely to face more difficulty adapting to climate change than developed countries such as Canada because of limited resources. Damage to land and water resources will strain financial and technological capacities and produce local consequences for food production. The capacity of a farming system to adapt to climate change is determined by the quality of its natural resources and associated economic, social, cultural and political conditions. Global projections indicate crop yield declines will be most severe in tropical, semi-arid developing countries, and least severe in high latitude developed countries—although scientists caution that the exact projections are still uncertain.

In Canada, it is unlikely that climate change will drive the adaptation process by itself. Farmers will continue to adapt to the wide range of conditions they face each year: climate, markets, and policies, etc. Climate change, therefore, is likely to be considered one more element of an overall risk-management strategy. Meanwhile, options for climate-change adaptation are expected to fall under the following four categories:

1. Technological development

- new crop varieties such as new species and hybrids that are more heat tolerant and drought resistant or more adapted to climate extremes and pests
- water management innovations such as snow management in semiarid climates to increase water storage or zero tillage to reduce water loss from the soil
- seeding earlier to take advantage of longer, warmer growing seasons and to avoid a dry late-summer period

2. Government programs and insurance

- subsidies and private insurance
- water transfers and changes to crop insurance programs
- research on development of new species and hybrids
- carbon trading

3. Farm production practices

- crop diversification
- water conserving irrigation systems
- reduced tillage and chemicals
- adjusting shading and air conditioning for livestock
- use of sprinklers to cool livestock during heat waves
- increasing early-season grazing to avoid summer dry periods

4. Farm financial management

- income stabilization programs

In Canada and globally, agriculture is highly adaptive; but how well it can adapt outside the normal range of climate conditions is uncertain. Indeed, there are climate thresholds beyond which farms and crops could never adapt. Understanding where those thresholds lie—and how agriculture can be sustained within them—is an important challenge for the research community in Canada and around the world. Only through such understanding will our food sources remain secure.

FURTHER READING

Gitay, H., S. Brown, W. Easterling, and B. Jallow. 2001. Ecosystems and their goods and services. Pp. 235-342 In: J.J. McCarthy, O.F. Canziani, M.A. Leary, D.J. Dokken and K.S. White (eds.) *Climate Change 2001: impacts, adaptation and vulnerability; contribution of Working Group II to the Third Assessment Report on the Intergovernmental Panel on Climate Change.* Cambridge University Press. Available online at: http://www.grida.no/climate/ipcc_tar/. Accessed December 2006.

Lemmen, D. S. and R. Warren (Eds.). 2004. Climate change impacts and adaptation: a Canadian perspective. Climate Change Impacts and Adaptation Directorate. Natural Resources Canada: Ottawa. 175 pp.

McGinn, S., A. Toure, O. Akinremi, D. Major, and A. Barr. 1999. Agroclimate and crop response to climate change in Alberta. *Canada; Outlook on Agriculture,* 28:19–28. Cited in Lemmen and Warren, 2004.

Powlson, D.S., A. Riche, and I. Shield. 2005. Biofuels and other approaches for decreasing fossil fuel emissions from agriculture. *Annals of Applied Biology* 146:193–201.

Wall, E. and B. Smit. 2005. Climate change adaptation in light of sustainable agriculture. *Journal of Sustainable Agriculture* 27:113–123.

A Vision Restored

DREAMS OF FUTURE SOLUTIONS

Few of us see the future clearly. But we know with certainty that change is coming—and coming quickly—as there are more and more of us scrabbling about on a planet whose resources are dwindling. How do we satisfy our spiralling demands for energy and food without spewing more of the gases that imperil our climate? Our farmlands are in the midst of these stresses; and they must be a part of any solution.

In earlier chapters, we outlined emerging practices that might help avert unpleasant climate change; growing biofuels on farmland, for example, may help reduce our dependency on fossil fuels. Other practices surely will emerge. The ones we can foresee can be grouped under three categories.

Alternate energy sources

To wean ourselves from the fossil fuels that foul our air, we will need to find replacement energy sources to drive our societies. Many such sources have been proposed: nuclear power, wind power, water power, energy from hydrogen and solar energy. While these may seem unrelated to farming, many of them could affect how we farm. Wind generators may be situated on farmland and the solar panels of the future may also be sited there. What's more, the transmission of energy often occurs *across* farmlands. So while many energy systems may not derive from farms, the sources we choose may well affect how we farm the land. And if biofuels become important energy sources, demand for them will further re-shape our farmlands.

More efficient use of energy

Farms, especially intensive ones, use a lot of energy. Just as we are doing for other industries, we will need to look for ways to use energy more frugally on farms. We will need more fuel-efficient vehicles, better-insulated buildings and more efficient ways of transporting produce.

There are many opportunities for agriculture to increase its efficiency. Plant breeders may develop new crop varieties with higher yields or varieties that flourish with fewer inputs of irrigation water or energy-dependent chemicals. Livestock scientists may develop practices or animals that produce more meat or milk per unit of energy. Vaccines may emerge that suppress the release of CH_4 from cattle, cutting down on potent GHGs and at the same time enabling cattle to use feed energy more effectively.

Another promising way to reduce energy use on farms is through better management of crop nutrients. Making fertilizer, especially nitrogen fertilizer, uses a lot of energy (producing CO_2 emissions). Maybe we can exploit better the biological fixation of atmospheric N, so plentiful, to replace some nitrogen fertilizer. Perhaps we can genetically re-tool cereal crops to fix their own nitrogen; or at least, we can better use the nitrogen fixed by legumes for other crops. Further, we can devise new fertilizer forms and ways of delivering them to crops that avoid the leaks to the environment, thereby saving energy and losses of N_2O. For example, new sensors on satellites or on the ground may allow farmers to measure exactly how much nitrogen a crop needs as it grows, helping them to better match fertilizer rates to plant needs.

Another way to use nutrients more efficiently is to recycle them more cleanly. Nutrients in manure could be more efficiently returned to the land, either by new conveyance methods or, better, by placing livestock closer to where their feed is grown. Perhaps, even, we can find safe ways to recycle nutrients in human wastes that now we flush away.

Reconnecting consumers to farmlands

Once, most consumers lived on the land that grew their food; now they may live a continent away, with little thought about the ecosystems that sustain them. That may change. We may once again learn that what we eat affects what happens to our lands. Through changing diets, consciously designed and chosen, it may be possible for society to steer toward food-production systems that reduce emissions from farmlands. Further, future consumers may opt to save energy and emissions by using foods and other farm products grown close to home. In our increasingly urban societies, the biggest advances in food production may come, not in remote rural fields, but in the plots of urban farms.

These are just a few examples of how societies may increasingly acknowledge again the link between consumers and the land, thereby reducing GHG emissions. Tomorrow's innovators surely will envision more.

Closing thoughts

Many of the solutions to our current dilemmas are no doubt still beyond our purview. But the answers likely will emerge from a vision restored; from seeing our farmlands—the soil, the trees, the crops, the sky—not as resources to be spent, but as the home in which we live. For one way or another, wherever we may reside, we do all live on the land, we and our descendants too.