Enhancement of Greenhouse Gas Sinks:

A Canadian Science Assessment

PERD POL 6.2.1 FINAL REPORT

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Many of these scientists have also contributed to the review and editing of the various chapters included here.

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FOREWORD

The environment has recently become an urgent concern of the Canadian public. It seems that everyone is calling for action right away. It is, therefore, also a major priority of Canadian governments.

However, the right action is not always easy to determine. It is here especially that decision makers within governments must look to the scientific community for advice based on the best research available.

One of the most important environmental concerns facing all governments today is that of climate change, and the biggest question related to this concern is, "How can governments best reduce emissions of greenhouse gases and enhance the processes that help remove them from the atmosphere, in order to eventually stabilize their atmospheric concentrations at a level that will avoid dangerous climate change?".

It was the science community that sounded the first alarm bells about climate change. It is also the science community that must help decision makers decide on what actions to take to address this question.

Clearly, measures to reduce greenhouse gas emissions from our human activities must be a primary consideration in responding to the above question. However, another option is to undertake measures that could return excess atmospheric greenhouse gases to natural reservoirs in the Earth and oceans. To understand what these measures might be, how successful they would be, and how the amount of gases sequestered can be quantified needs science.

The Program of Energy Research and Development (PERD) has funded related research in Canada for more than two decades. By PERD standards, there is a long road that has brought us to this point. That road began in 1981, more than 25 years ago, when Bryan Cook and John Legg, both with the Office of Energy Research and Development, began to realize that climate change was not just some academic issue for discussion by scientists, but would one day have major implications for energy policies in Canada. In collaboration with Environment Canada, they submitted a proposal to PERD for funding of an advisor on climate change science. PERD recognized the value of such an advisor, and accepted the proposal for funding. However, PERD also recognized that energy-related greenhouse gas emissions needed to be considered within the context of much larger natural global cycles of carbon. Hence, there was also a need to fund research related to measuring and understanding these natural fluxes of carbon between the atmosphere, land and oceans. PERD support of related projects within NRCan's Canadian Forestry Service (CFS), Agriculture and Agri-Food Canada (AAFC), Environment Canada (EC) and Fisheries and Oceans Canada (DFO) began a few years later – in the mid 1980s.

After the Kyoto Protocol was signed in 1997, it became apparent that any ability to undertake activities to enhance biological sinks of greenhouse gases, and to claim those as offsets to gas emissions from other sources in national reporting by the parties of the UN Framework Convention on Climate Change, could only be acceptable if the reporting involved was clear and transparent. In response to this added challenge, OERD consolidated its funding of carbon cycle research into an integrated, results based program aimed at improving our capacity to accurately report human induced sources and sinks of greenhouse gases involving Canadian ecosystems, and to advise policymakers on actions to enhance greenhouse gas sinks. An inter-departmental team of science advisors was assembled to lead this activity (known within PERD circles as Program at the Objective Level (POL) 6.2.1 for the 'Enhancement of Greenhouse Gas Sinks', or more simply the EGGS POL). The program has been recognized as a model for successful collaboration and integration of research across departmental and scientific disciplines.

I'm delighted to report that the program has been highly successful. The proceeds of this research have helped to make Canada a leader in developing protocols for verifiable reporting of greenhouse gas sources and sinks. The same expertise has also helped Canadian officials to participate in related deliberations under the United Nations Framework Convention on Climate Change from a position of sound knowledge.

I want to thank the leadership team for the EGGS POL and the many scientists from AAFC, EC, F&O and NRCan that have been involved in the actual research for their dedicated work. It is their efforts that have been instrumental in producing these results.

The Program of Energy Research and Development decided to conclude its funding of research into greenhouse-gas sinks at the end of the 2006-07 fiscal year. It did so not because it thought such research is no longer important. Rather, it wanted to focus scarce R&D resources on high priority energy technologies. In short, the limited resources available to the Program were very much needed in other areas of research and technology.

This is an ideal time, therefore, to take stock and examine what the future priorities are for research into the sources and sinks of greenhouse gases within and adjacent to Canada, who should fund such research, and how it should be organized. However, to do so, we first need to assess how far we have already come.

That is where this report comes in.

GRAHAM CAMPBELL
Director General
Office of Energy Research and Development
Natural Resources Canada

CHAPTER 1

An Overview of the Background Science and Goals of Canadian Research Activities Relevant to Enhancement of Greenhouse Gas Sinks in Canada

Co-ordinating and Lead Author | **H. Hengeveld**

1.1 Introduction

The constant flow of carbon and its various compounds between terrestrial ecosystems, the oceans and the atmosphere plays a fundamental role in global ecological processes. Plants take up carbon from the atmosphere through photosynthesis and release it back to the atmospheric through respiration and combustion. Atmospheric CO_2 is also directly absorbed by ocean surfaces, where it is cycled through ocean food chains. Oceans return almost as much carbon dioxide to the atmosphere through outgassing processes. Carbon is also transported as inorganic and inorganic compounds within ecosystems, between ecosystems, freshwater systems and oceans, and between surface and deep oceans.

These carbon fluxes between land, ocean and atmosphere also function as important feedbacks within the global climate system, on times scales from years to millennia and longer. Hence, understanding the natural carbon system and its response to external influences is an essential aspect of improved prediction of future climates.

It is now clear that human activities are impacting on these natural processes and feedbacks, both through land-use and land-use change, and through the direct emissions of carbon dioxide into the atmosphere due to combustion of carbon based fuels. Therefore, understanding how ecosystem management might help reduce the release of greenhouse gases from ecosystems or enhance ecological sinks is also an important consideration in developing and implementing policy options aimed at reducing the risks to ecosystems and human society related to rapid climate change.

Intricately linked to the carbon cycle is the nitrogen cycle. This cycle affects the supply of nutrients for biological growth and influences the production and removal of atmospheric nitrous oxide (N_2O), an important greenhouse gas.

This introductory chapter will provide an overview of the current state of knowledge with respect to these cycles, both in terms of their natural pre-industrial behaviour and the changes that have and are likely to take place due to human activities. It will also introduce the science behind the inclusion of carbon sinks in the United Nations Framework Convention on Climate Change

(UNFCCC) and its Kyoto Protocol and the challenges in reporting sources and sinks of greenhouse gases related to human land-use and land-use change activities in a transparent and verifiable manner.

1.2 The global carbon cycle

1.2.1 Pre-industrial global carbon reservoirs and their annual fluxes

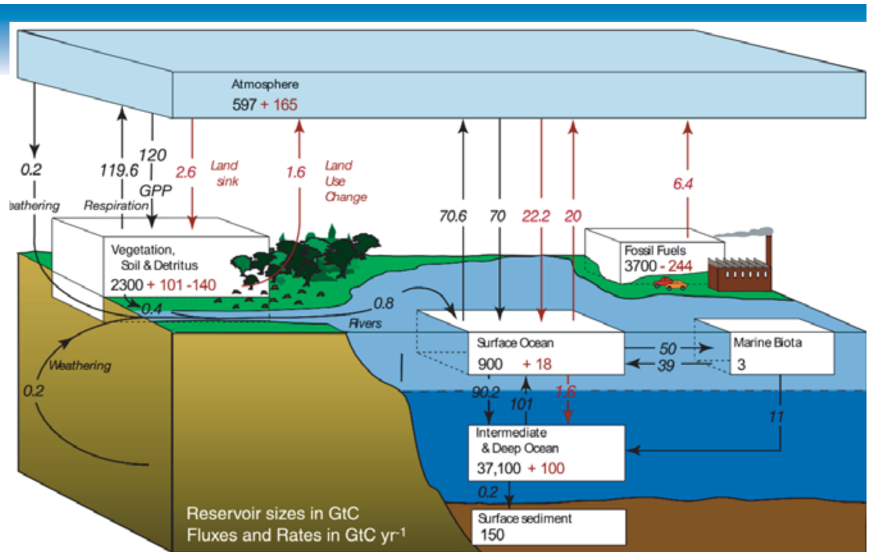
Very large reservoirs of carbon have been locked up into sedimentary rock and fossil deposits over time scales of millions of years. Since natural changes in these reservoirs are normally very slow, they do not factor significantly in changes of carbon fluxes on time scales of centuries or less. The exception may be the catastrophic release of methane from frozen hydrates under the ocean floor. There is evidence that these can be abruptly released in large quantities during times of climate change and thus may be an important factor in the evolution of atmospheric concentrations of methane in future centuries.

In contrast, the world's oceans, lake sediments, terrestrial soils and litter and above ground biomass are all components of an active carbon cycle that is in a constant state of flux at times varying from days to centuries (Denman, 2007). Their roles are as follows (*see Fig. 1.1*):

- ***Oceans:*** This is the largest carbon reservoir within the active carbon cycle. In their pre-industrial state, intermediate and deep oceans, including sediments on the ocean floor, held some 39 billion metric tonnes (Gt C) of carbon, mostly in inorganic form. The upper 100 meters of the ocean, where much of the biota is found, contained another 900 Gt C. Since deep ocean waters are circulated back to the surface on a very slow time scale (~1000 years), most of the deep ocean carbon remains sequestered there for centuries. On the other hand, ocean surface waters in pre-industrial environments absorbed and released an estimated average of 70 Gt C from and to the atmosphere each year;

- ***Terrestrial Ecosystems:*** The total carbon content of global land ecosystems, including wetlands and water bodies, is significantly lower than that within oceans. Estimates for the mid-18th century (considered the end of the pre-industrial period) suggest a total reservoir of some 2300 Gt C, 80% of which is within soils and surface litter, the remainder as above ground vegetation. However, net primary production absorbed some 60 Gt C/year into land ecosystems through photosynthesis, while respiration and biomass decay/combustion annually returned about the same amount back to the atmosphere;

FIGURE 1.1



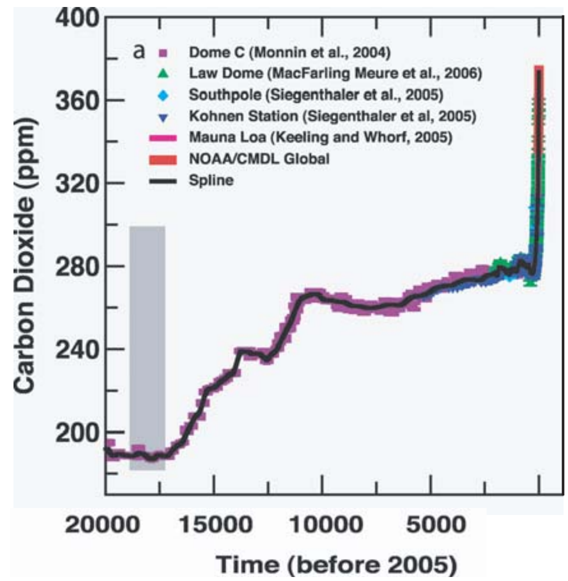
The global carbon cycle for the 1990s, showing the main annual fluxes in Gt C yr^{-1} : pre-industrial 'natural' fluxes in black and 'anthropogenic' fluxes in red.

- ***The atmosphere:*** Within the atmosphere, carbon is found primarily in the form of CO_2 (although there are also much smaller quantities of methane, carbon monoxide and solid carbon particles). Based on ice core data from Greenland and Antarctica, pre-industrial concentrations of CO_2 were about 280 parts per million (ppm), equivalent to a carbon reservoir of almost 600 Gt C. Given the net annual flux of 130 Gt C between the atmosphere and other carbon reservoirs, this suggest that the turnover of carbon within the atmosphere is relatively rapid – about once every four to five years;

Reconstruction of past atmospheric composition and climates from Antarctic ice core data indicate that atmospheric CO_2 concentrations have varied between low concentrations of about 200 ppm during glacial periods and 280 ppm during interglacials. There is a very close coupling between changes in these concentrations and Antarctic temperatures. Although experts argue that the large glacial-interglacial swings in climate were likely triggered by changes in the Earth's orbit around the change (which affect the magnitude and distribution of solar insolation), initial changes in climate appear to have caused large changes in CO_2 fluxes between the atmosphere and other carbon reservoirs (primarily oceans) that affected atmospheric concentrations of CO_2 and hence the intensity of greenhouse forcing. Studies suggest that this important feedback may have contributed about 50% to the amplitude of the glacial cycles;

Earth's climate has been in an interglacial mode (known as the Holocene) for the past 10,000 years. During this period of time, atmospheric concentrations of CO_2 have varied within a narrow range of 260 to 280 ppm. Since changes in atmospheric CO_2 concentrations are a measure of the net flux of carbon between the atmosphere and other carbon reservoirs (much like a bank account balance indicates the net difference between deposits and withdrawals), this suggests that, despite their large magnitudes, the net annual balance between fluxes into and out of the atmosphere (averaged over time) was near zero for most of the Holocene – until the past 200 years (*see Fig. 1.2*).

FIGURE 1.2



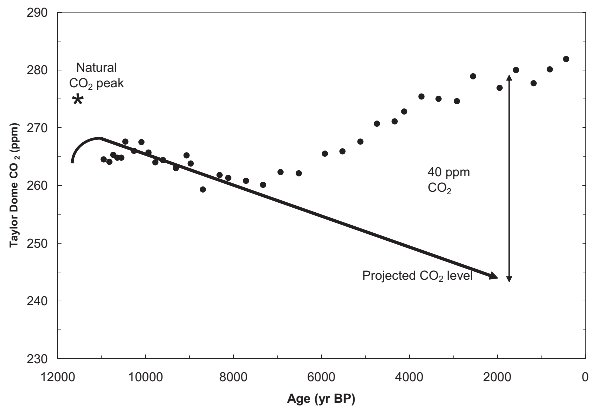
Trends in atmospheric CO_2 concentrations during the Holocene suggest that the pre-industrial natural carbon cycle was, on average, well balanced (IPCC 2007).

1.2.2 Human influences on the global carbon budget

Various studies suggest that human interference with the global carbon cycle already began with the onset of agriculturally-based human settlements in Asia in the early Holocene (see Chapter 2). Although very small on an annual basis, this slight imbalance of net carbon flux between land ecosystems and atmosphere slowly accumulated into a slight rise in atmospheric CO_2 concentrations (*see Fig. 1.3*). Land-use change continued to be the primary source of human-induced CO_2 emissions into the atmosphere until about 1900.

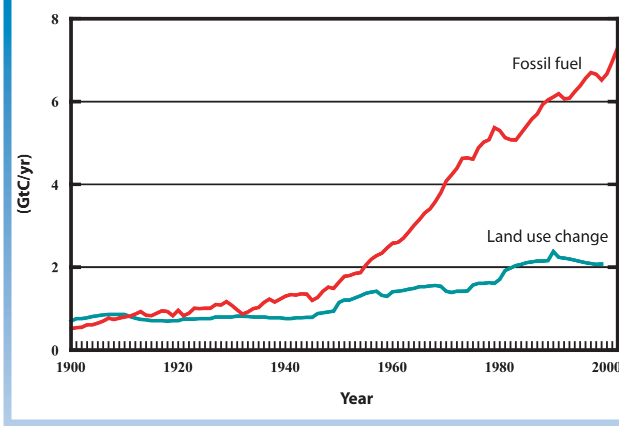
However, the rapid expansion of industrialization across the western world and the related development of the internal combustion engine introduced a significant new source of CO_2 emissions from the combustion of coal, oil and natural gas – all from fossil reservoirs long removed from the natural active global carbon cycle. By about 1910, emissions from fossil fuel combustion had exceeded those from land-use change. In 1957,

FIGURE 1.3



CO_2 concentrations reconstructed from Antarctic ice core data, compared with Holocene CO_2 trend projected toward values reached during previous inter-glaciations. The departure of the ice core CO_2 record from the projected trend about 8000 ybp may mark the onset of influences due to human land-use change (Ruddiman, 2003).

FIGURE 1.4



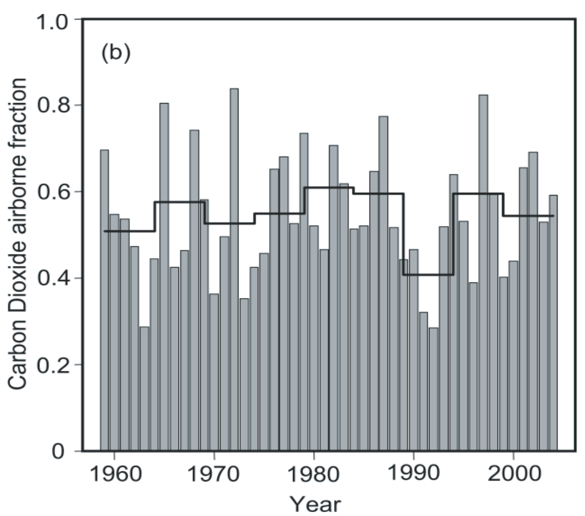
Human emissions of CO_2 into the atmosphere have progressively increased over time. Those from fossil fuel combustion have more than tripled over the past 50 years.

scientists first expressed alarm about the rate of CO_2 rise in the atmosphere and the possible effect this might have on global climate. By that time, fossil fuel emissions had increased to 2.3 billion metric tones of carbon per year, and atmosphere concentrations had risen to 315 ppm, already exceeding what we now know to be the highest levels detectable in ice cores spanning the last 650,000 years. Emissions have continued to rise since then. Meanwhile, emissions from tropical deforestation and other land-use changes have increased at a more moderate rate (*see Fig. 1.4*). Latest reports indicate that average emissions from these combined sources between 2000 and 2005 had reached about 8.6 Gt C/year, and that by the end of this period atmospheric concentrations had increased to 380 ppm.

A global network of atmospheric composition monitoring stations show that the amount of CO_2 in the atmosphere has continued to rise in response to these new additions to the carbon cycle, but at a slower rate than that annually released into the atmosphere through human emissions. In fact, during 2000-2005, slightly less than half of the emitted carbon remained in the atmosphere to contribute to rising CO_2 concentrations. The rest has been removed through photosynthesis and absorption processes, and stored in the terrestrial ecosystems and oceans reservoirs. The amount of excess carbon removed will vary considerably from one year to the next, so that some years experience less than 20% removal while others experience more than 70% removal (*see Fig. 1.5*). That is because the processes for removal are sensitive to changes and variations in global climate.

In terrestrial ecosystems, the combined effects of the direct positive effect of higher atmospheric CO_2, of warmer climates and of increased nitrogen nutrients to ecosystems have enhanced global vegetation productivity and thus enhanced the annual CO_2 uptake through photosynthesis relative to the release through respiration. During the past decade, this net flux has been on the order of 2-3 Gt C/year. Even after allowing for the anthropogenic emissions from land-use change (especially deforestation), there remains a net carbon flux from atmosphere to land of about 1 Gt C/year. Higher atmospheric CO_2 concentrations have also pushed more CO_2 into the ocean surface waters, resulting in a rise of flux into the oceans each year from pre-industrial levels of 70 to about 92 Gt C/year. Annual outgassing from the oceans into the atmosphere has also

FIGURE 1.5



Trends in the fraction of carbon dioxide emitted from fossil fuel combustion that remains in the atmosphere. While, on average, about 50% of these emissions are removed though enhanced net up-take by terrestrial ecosystems and oceans, this amount varies significantly from year to year (Denman, 2007).

increased, but at a slower rate. The net result is a net annual sink in the oceans since 1990 of about 2.2 Gt C.

1.2.3 Human influences on the global methane budget

The second most abundant form of carbon in the atmosphere is methane (CH_4). During pre-industrial times, its atmospheric concentration varied between about 400 parts per billion (ppb) during glacial periods and 700 ppb during interglacials. Although this is less than 1% of that for CO_2, methane is, on century time scales, about 23 times as potent as a greenhouse gas (per unit of mass). Hence, it is also an important secondary contributor to the enhanced greenhouse effect.

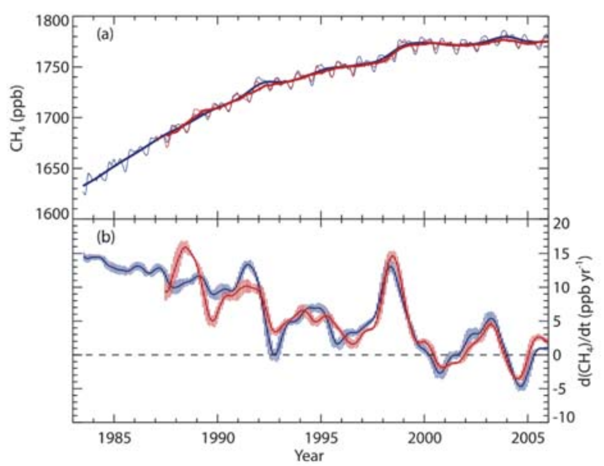
The primary natural source of atmospheric methane is its production and release through biomass decay in the absence of oxygen. This occurs primarily in wetlands that span land masses across the world, and from the venting of gases by ruminant animals such as cows, buffalo and sheep. Secondary methane sources include oceans, termites and geological reservoirs such as frozen hydrates. Although pre-industrial emissions from human activities such as cereal crop production that involve periodic land flooding (e.g. rice paddies) and large scale domestic livestock husbandry added to these, about 80-90% of total emissions in the mid-18th century (estimated at about 200-250 Mt CH_4/year) were likely from natural sources.

However, during the past century, the human role in methane fluxes has increased dramatically. In addition to large expansion of sources from rice paddies and domestic livestock, current biogenic anthropogenic sources include the storage of animal manure, the large scale flooding of ecosystems for hydro-electricity generation systems, and waste treatment facilities. Humans also release significant quantities of methane from non-biogenic sources, primarily from fossil fuel extraction, energy delivery systems involving coal and natural gas, and biomass burning. Today, total global methane emissions are estimated at about 600 Mt CH_4/year, with more than 60% attributable to human sources (Forster *et al.*, 2007).

The primary process for removing methane from the atmosphere is the chemical reaction with the hydroxyl radical OH, the atmospheric cleanser that also removes many other undesirable trace gases from the atmosphere. A secondary removal process (about 20%) is through chemical reactions within terrestrial soils. These processes are sufficiently rapid to result in a half life of methane within the atmosphere of about 8 years.

However, the global methane budget is complex, and many of the biological processes remain poorly understood. For example, during the 1980s, the atmospheric concentrations of methane were increasing by about 10 ppb/year, suggesting a net global budget imbalance of about 30 Mt CH_4 per year. However, during the 1990s, methane concentrations barely increased at all (*see Fig. 1.6*). Studies suggest that neither changes in human emissions nor an increase in atmospheric removal processes appear to be the primary reason for this decline in growth rates. Rather, experts suggest natural response of global ecosystems to variations in climate may be responsible, and that growth rates may well return to previous levels in the near future.

FIGURE 1.6



Trends in methane concentrations (top panel) show that current levels are more than double that for pre-industrial conditions (~700 ppm). However, annual increases have dropped dramatically during the past decade (bottom panel) (Forster *et al.*, 2007).

1.3 Global nitrogen cycle

The stable nitrogen molecule (N_2) is the most abundant gas within the atmosphere (79%). In this form, nitrogen is non-reactive and hence has little effect on climate or ecology.

However, nitrogen's most stable atmospheric compound, nitrous oxide (N_2O), is a very potent greenhouse gas. Although found in very low concentrations (about 0.3 ppb), per unit of mass emission it is about 300 times as potent as carbon dioxide. Hence, it also has been a significant secondary cause of climate change.

Within terrestrial and aquatic ecosystems, nitrogen (like phosphorus and iron) is a major limiting nutrient in biological productivity. Its abundance within ecosystems is also an important variable in the carbon cycle. Furthermore, other more reactive nitrogen oxides (NO_2, NO and ammonia) are implicated in atmospheric transport of nitrogen to ecosystems (which, in modest amounts, can enhance ecosystem productivity but in excessive amounts can cause ecological damage due to soil acidification) and in the atmospheric chemistry of ozone (thus affecting tropospheric ozone concentrations).

Therefore, understanding the biological fluxes and chemistry of nitrogen is important in understanding ecological sources and sinks of both carbon dioxide and nitrous oxide.

1.3.1 Global nitrous oxide budget

Natural sources release an estimated 10 million tonnes of nitrogen (Mt N) in the form of nitrous oxide into the atmosphere each year. These come primarily from vegetated soils (about 60%) and ocean surfaces. A small secondary source is its production through chemical process within the atmosphere. However, because it is a very stable compound that does not react readily within the troposphere, it has a long atmospheric lifetime on the order of 120 years. This allows the gas to penetrate upward into the stratosphere, where intense solar radiation breaks it down. This stratospheric chemical destruction is its primary sink.

Over time, emissions of nitrous oxide from human activities have added significantly to the natural sources. Experts estimate that human emissions are now on the same order of magnitude as emissions from natural sources. Primary human activities that contribute to its release include the use of fertilizer in agricultural production (almost 60% of human emissions) and contamination of rivers, estuaries and coastal zones (15-20%). Other secondary anthropogenic sources include biomass burning, fossil fuel use, industrial processes, landfill and human waste, and atmospheric nitrogen deposition on ecosystems. Although higher N_2O concentrations have also increased its flux into the stratosphere and its destruction rate, this rise has not kept pace with the rise in emissions. The net annual imbalance has led to a slow rise in atmospheric concentrations over time, with current concentrations now about 16% above those for pre-industrial times.

1.3.2 Global emissions of nitrogen oxides and ammonia

Annual emissions of the more reactive nitrogen compounds have increased even more dramatically, with anthropogenic emissions now estimated to be almost three times greater than that of natural sources. Primary human sources include fossil fuel combustion and biomass burning. The large increase in emissions has substantially increased their atmospheric concentrations and hence their deposition on terrestrial ecosystems. However, because these gases are short-lived, their distribution is highly variable in space and time.

Ammonia emissions from natural sources introduce a total of about 11 Mt N into the atmosphere each year. Human activities have added another 30 or so Mt N per year to these emissions, so that total emissions are now about four-times pre-industrial levels. Primary sources of anthropogenic emissions include use of fertilizers for agriculture (about 80%) and biomass burning.

Research into the carbon cycle and ecological sources and sinks of carbon dioxide need to consider the complex impacts that such deposition of NO_x and ammonia may have on ecological productivity.

1.4 The carbon cycle within Canada's ecosystems and adjacent oceans

While a global network of stations monitoring atmospheric composition has allowed a reasonably accurate assessment of the net annual global carbon flux into the atmosphere, the regional distribution of the sources and sinks of carbon dioxide and the processes that contribute to them are complex and much more difficult to estimate. Tropical regions where large scale deforestation is still in progress tend to be a large source of atmospheric carbon, while temperate forests in Europe and North America appear to be a large sinks. The magnitude of these regional sources and sinks can vary considerably from year to year, largely due to variations in regional climate. During any given year, for example, an area like the Amazon may undergo a severe drought that causes large emissions of carbon due to forest fires while Canada may be experiencing a warm, moist summer that stimulates above normal biological uptake of carbon from the atmosphere. The next year, these roles may be reversed. Inverse model studies, where atmospheric transport models are used in conjunction with a network of surface measurements of atmospheric CO_2 concentration, can be used to estimate trends and patterns of such regional carbon fluxes. These suggest that, while tropical regions are not currently a large net source or sink for carbon, during the 1990s, North America has consistently removed about 200 to 300 million tonnes of carbon from the atmosphere each year, and the European region up to twice that amount (Potter *et al.*, 2003).

The role of terrestrial and marine ecosystems within and adjacent to Canada must be considered within this context of a global carbon cycle that varies dramatically from region to region and year to year. Canada's total land area is about 9.1 million km^2 (about 6% of the Earth's land area). Of this, about 35% is covered with forest, 14% with wetlands and another 7.5% is used for agricultural purposes. It also has three oceans that surround it from the west, north and east. Particularly in mid-latitudes, these oceans have high biological productivity and contribute substantially to the global flux of CO_2 between atmosphere and ocean. Hence, understanding the role of these ecological regions in absorbing and releasing greenhouse gases from and to the atmosphere contributes to a better understanding of the global carbon cycle and its behaviour. Furthermore, it is these regional natural sources and sinks that provide the background against which to assess the potential for reducing emissions and enhancing greenhouse gas sinks.

1.4.1 Canada's Agricultural lands

As noted in the Sinks table report (National Sinks Table, 1998), Canada's agricultural land base is about 68 million hectares. About 45.5 million hectares (the "improved" or "managed" farmland) is annually cropped, summerfallowed or in improved pasture. Natural land for pasture (rangeland) includes about 15.5 million hectares, while other land (woodlands, wetlands etc.) comprise almost 7 million hectares. The total agricultural land area has remained stable since the 1960s but the cropland area has grown as a result of the conversion of rangeland and reduction in summerfallow.

Of the 45.5 million hectares of improved farmland, 86% (39.1 million hectares) are in the four western provinces. Another 12.9% (5.8 million hectares) are in Ontario and Québec. About 8 million hectares of cropland were summer-fallowed in 1990. Conventional cropping techniques include tillage prior to seeding, single rate fertilizing and spraying of fields, and tillage again after harvest. These practices have allowed farmers to produce abundant food supplies for Canadian and export markets for the past 80 to 200 years.

The pool of soil organic carbon in Canada's cropland is estimated to be about 6 billion tonnes to a depth of 1 meter. Historically, since cultivation of these croplands began, an estimated 1 billion tonnes of soil organic carbon has been lost. Much of this loss occurred in the first couple of decades of cultivation, and has been accentuated by intensive tillage, biomass burning and removal of residues. After the first decades, the rate of loss slowed when the readily decomposable soil organic carbon was depleted, and as farmers gradually adopted improved soil conservation practices.

Canada has an extensive base of perennial grasslands totaling about 15.5 million hectares in 1990. Most of the grassland is extensively managed with seasonal grazing. Overgrazed pastures store less carbon. Under grazing also reduces the ability of grasses to maximize carbon sequestration, as the length of vegetative growth during the growing season is shortened.

While 15 to 30 percent of the carbon originally present in the surface soil layer has been lost since cultivation, most of this loss occurred in the first two decades of cultivation. Simulations using the CENTURY Model suggest that average net annual emissions from cropland in Canada dropped from 10 million tonnes of CO_2 in 1970 to about 7 million tonnes of CO_2 in 1990. This implies that soil carbon is reaching a new equilibrium, largely due to smaller amounts of land being converted into cropland, decreases in summerfallow, increases in no-till farming and increased fertilizer use in the prairie provinces.

Measurement of carbon in agricultural soils has been routine for many years, given its importance as a key indicator of soil quality. The key issue with regard to CO_2 sequestration is around the certainty of the measurement of a relatively small annual increment of carbon that may be added through sequestration activities. With a well designed sampling and analysis program, the variability within fields and over time, which can mask small changes in soil carbon, can be overcome.

A second issue relates to the need for a cost-effective way of measuring, monitoring and verifying carbon change in soils which will be accepted by the international community. This latter need is likely a precondition to having the soil carbon sink accepted as a means of reducing or offsetting national greenhouse gas emissions.

The extensive research that has been undertaken to address these and other gaps in knowledge are discussed in detail in Chapter 2.

1.4.2 Canada's Forests

The Sinks Report (National Sinks Table, 1998) notes that Canada's national forest inventory includes 418 million hectares (ha) of forest, of which 244.6 million ha are considered timber productive forest. These represent about 7.1% of the global forest area.

An analysis of the carbon dynamics in Canadian forest ecosystems over the period since 1920 suggests that major changes occurred during the past 80 years. From 1920 to about 1970, Canadian forests experienced several decades during which natural disturbances were low relative to the period 1860 to 1920. As a result, the age-class structure of the forests shifted towards greater average age. Older forests contain larger biomass and dead organic matter C pools, but their ability to take up additional C decreases, and their susceptibility to fire and insect disturbance increases. Since 1970, however, natural disturbances, in particular fires and insects, greatly increased. Higher disturbance rates reduced total biomass C pools, transferring much of the residual C to dead organic matter pools, which will decompose and result in additional C releases. The net effect of the observed changes in natural disturbance patterns has been a shift in the role of Canadian forests from a large C sink to year-to-year fluctuations between a small source and a small sink.

Long-term fluctuations in the natural disturbance regimes in Canada have contributed to the changing role of forests as either a sink or source of C. Analyses of the future role of these forests demonstrate that they are likely to eventually revert to a C sink, and that the timing of this change is highly dependent on the assumption about future natural disturbance rates. Furthermore, warmer temperatures and rising global atmospheric CO_2 concentrations (the so-called fertilization effect), could also enhance net ecosystem productivity and C dynamics. Offsetting these forces for enhanced growth and C uptake will be enhanced decomposition processes under warmer climates, and the possible effects of drought on productivity and fire loss. The net effect of these forces is the subject of ongoing research discussed in Chapter 3.

1.4.3 Canada's Wetlands and Peatlands

Canada's 148 million hectares of wetlands represent 15.9% of its land area, and over 24% of the world's wetlands. In northern Canada, wetlands cover 81% of the Hudson Plains, 41% of the Boreal Plains and 38% of the Taiga Plains. In southern Canada, they cover 11.4% of the Prairies, 5.1% of the Atlantic Maritime, and 7.5% of the mixedwood plains of southern Ontario and Québec (National Sinks Table, 1998). For the most part, the vast wetland areas of the north are not affected by direct human influence or land management activities. Exceptions are site-specific hydro, mining and non-renewable energy developments. The areas of moderate land-use pressure correspond to areas of potential large-scale hydro developments.

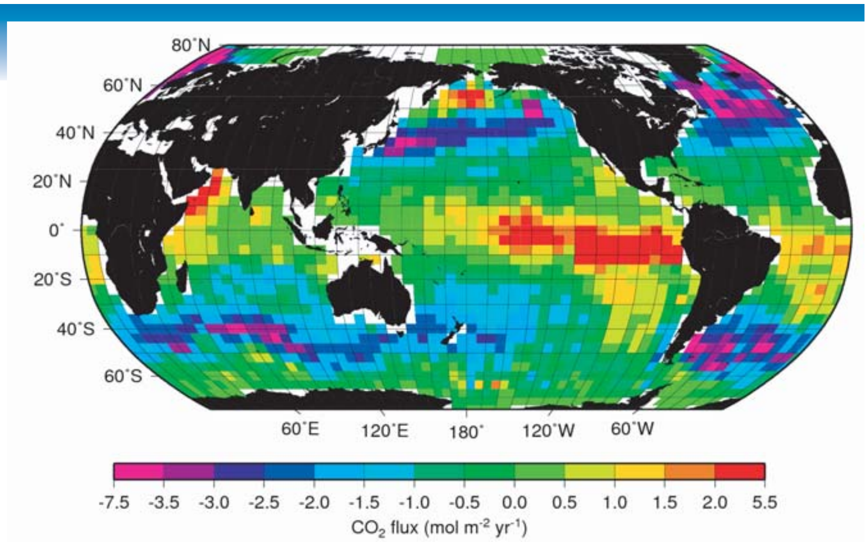
Land-use pressures are highest in the working landscapes of southern Canada, where population, agriculture and development activities are greatest. The status of wetlands in these areas is governed by land-use practices on lands that are primarily owned and managed for other purposes. Agricultural expansion has been the major wetland impact in Canada. Regional studies estimate that 65% of Atlantic coastal marshes, 68% of southern Ontario wetlands, up to 70% of prairie wetlands, and 80% of the Fraser River Delta have been converted to other land-uses. Examples are also extensive in the St. Lawrence lowlands, St. John River valley and Annapolis valley. Furthermore, 80% to 98% of the wetlands surrounding many major urban centres have disappeared.

Natural peat-forming wetlands store carbon, release small amounts of nitrous oxide and larger amounts of methane. However, when they are drained and converted to other uses, large amounts of carbon dioxide and nitrous oxide are released, while methane emissions drop or are removed. For example, both the drainage of peatlands and their inundation from hydro developments may cause significant changes in their role as sources and/or sinks of greenhouse gases.

1.4.4 Canada's Oceans

As illustrated in *Figure 1.7*, some of the most important sinks of carbon in the oceans occur in waters adjacent to Canada. Estimates indicate that the mid and high latitude components of the North Atlantic and North Pacific Oceans alone absorb a net 1.2 billion tonnes of

FIGURE 1.7



Estimates of average annual sea-to-air flux of CO_2, computed using measurements of surface water CO_2 collected since 1956. Large sinks are apparent in the mid-latitude regions of the North Pacific and the north Atlantic.

excess carbon from the atmosphere each year (Denman, 2007). Of particular interest to Canada is the role of the Labrador Sea, which is one of the key areas where surface ocean waters sink into the deep ocean, thus transporting anthropogenic CO_2 into the deep ocean. Canada has an important responsibility and long history of excellent research in carbon cycle research in these regions.

There is growing appreciation of the importance and complexity of factors governing such oceanic uptake of CO_2 and subsequent export of organic carbon to the deep sea. For example, the discovery that iron is a limiting nutrient for major regions of the world's oceans has profound implications for understanding controls on ocean carbon uptake, as well as for evaluating carbon management options. Yet the responses of air-sea CO_2 fluxes and marine ecosystems to daily, seasonal, and interannual variations in nutrient supply and climate are as yet not well documented. Furthermore, carbon fluxes and dynamics on continental margins or in the coastal ocean, where sediment-water interactions are significant and terrestrial inputs and human-induced perturbations are large, require further analysis. The future behavior of the ocean carbon sink is most uncertain because of potentially large feedbacks among climate change, ocean circulation, marine ecosystems, acidification and ocean carbon cycle processes.

Internationally, agencies and countries are expressing interest in the prospect of large scale purposeful fertilization/enrichment of the oceans as a method for reducing greenhouse gases and as a potential solution for meeting their obligations under the Kyoto Protocol, although the existing agreement does not allow for carbon credits for ocean disposal. Accordingly, Canada must be "armed" with strong scientific information and expertise to effectively debate ocean CO_2 sequestration proposals with other nations.

Ultimately, advanced dynamical physical-biogeochemical models are required to simulate the complex processes involved. However, development of such models is only possible if the processes are understood and can be adequately parameterized – and understanding these processes necessitates observation of behavior.

1.5 Enhancement of GHG sinks – A Canadian Government Objective

The United Nation's Framework Convention on Climate Change (UNFCCC), to which Canada is a signatory, includes as its ultimate objective the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNEP, 1992). Under the Kyoto Protocol to the UNFCCC, Canada committed to a 6% reduction in its greenhouse gas emissions by 2008-12 relative to 1990 emission levels as an initial commitment towards this objective. About eighty percent of Canada's greenhouse gas emissions in 2005 were due to the production and use of energy, mostly in the form of carbon dioxide. The Kyoto Protocol, however, also permits countries to initiate projects to stimulate or enhance the uptake and retention of atmospheric carbon dioxide by forest ecosystems (referred to as carbon sinks) and allows for future negotiations for similar sinks in other reservoirs of carbon. Such additional sinks may include carbon uptake in agricultural soils, wetlands and biological sequestration of carbon in oceans. Carbon sequestered through actions under the Kyoto Protocol and subsequent agreements can then be considered as offsets to other greenhouse gas emissions and thus contribute to activities required to achieve Canada's Kyoto commitments. The Protocol stipulates that such sinks must be reported in a transparent and verifiable manner.

However, as already noted, the natural cycles of carbon and nitrogen that control the release and uptake of greenhouse gases are complex, and sensitive to changes in environment, and vary in space and time. Understanding these cycles and the processes that control them is key to quantifying the amount of greenhouse gases that can be removed from the atmosphere through overt human actions in a verifiable manner, and hence be counted as emission offsets under Kyoto. Although the international and Canadian research communities had progressed significantly in improving this scientific understanding of these cycles by the late 1990s, much more work was needed before verifiable reporting of greenhouse gas uptake through sinks projects would be achievable. Therefore, in 1999, the Office of Energy Research and Development, using a new results management framework that identified and implemented research and development activities targeted at achieving pre-set long term goals and objectives, established a POL 6.2.1 research activity on Enhancement for Greenhouse Gas Sinks (EGGS). The EGGS POL plan that emerged over the next year and was implemented in 2000 sought to build upon the foundation of past related research, but to focus efforts on coordinated research directed specifically at those aspects of the science relative to future reporting of sinks under the Kyoto Protocol. Partners in this POL include Agriculture and Agri-Food Canada, Environment Canada, Fisheries and Oceans Canada and Natural Resources Canada. The research would complement related greenhouse gas cycle research already being conducted by government laboratories within these departments and within the university community. It was also recognized that, since much of the research conducted within the existing research activities was focused on better understanding of the role of greenhouse gas fluxes as feedbacks within the climate system, some of the POL projects, although focused on sinks research, would be conducted collaboratively with the broader climate change research community.

The intent and objective of the EGGS POL activities, as specified by PERD, were as follows:

- Strategic Intent 6 - minimize the negative impacts of climate change on the energy sector;
- Strategic Direction 2 - provide S&T to enhance the uptake of GHGs from the atmosphere;
- Objective 1 - the development of: a better understanding of the relevant GHG cycles; and steps to increase the net GHG uptake and sequestration from the atmosphere by forest ecosystems, agricultural landscapes and oceans.

OERD staff have also indicated that, in addition to the primary focus as prescribed by the above objective, some EGGS POL resources should be invested into the impacts of biomass flooding by hydro reservoirs on greenhouse gas emissions.

The assigned POL objective had considerable support from the "*Option Paper on Land-Use, Land-Use Change and Forestry in Canada and the Kyoto Protocol*", submitted to the National Climate Change Secretariat in September, 1999 by the Sinks Table convened under the National Climate Change Process (National Sinks Table, 1999). That report provided a number of specific recommendations with respect to research required to help Canadian negotiators in international discussions on carbon sinks and provide the basis for credible reporting of such sinks. The Table concluded that "forestry and agricultural sinks should play a role in a national Implementation Strategy. Considerable investment into research and information is required now, so that Canada will be able to provide accurate and verifiable estimates of the change in carbon stocks when required and to provide guidance to negotiators". The Table also identified Canadian agricultural soils as having the larger potential for sequestering carbon within the time period of the first Kyoto reporting period of 2008-12, while forests have larger potential in the long term. Specific Table recommendations relevant to the assigned EGGS objective included the following:

- Recommendation 2.1 "Relevant government departments should encourage their scientists and technical experts to undertake the research priorities identified in close collaboration with peers within the international community, and to use expertise appropriately in future negotiations related to carbon sinks within the context of the Kyoto Protocol";
- Recommendation 3.12 "determine the potential effect of climate change on predictions of carbon sequestration through activities proposed in recommendations 3.1 to 3.5";
- Recommendation 4.2 "the linkage between the wetland restoration with the conservation practice on cropland, pasture management and conversion of marginal cropland to perennial grass strategies should be taken into account";
- Recommendation 4.6 "conduct research on nitrous oxide and methane emissions related to the four strategies noted above (i.e. 4.2 to 4.5). Determine whether there are additional emission reductions

or lower net carbon sequestration resulting from the five strategies of all greenhouse gases. Include fuel use, and nutrient management effects";

- Recommendation 6.1 "continue to consider wetlands as a potential Kyoto sink, in particular through the organization and coordination of science and policies relevant to such sinks";

- Recommendation 6.2 "develop a central focus for related research in Canada to properly assess, through focused workshops, the current state of knowledge and research priorities relevant to wetlands management as potential carbon sinks. One option for achieving this goal is to establish a wetlands research node under the BIOCAP program of Canadian universities".

Furthermore, in its Options Paper submitted to the National Climate Change Secretariat, the Science, Impacts and Adaptation Table also discussed the issue of research related to sinks extensively (National Science, Impacts and Adaptation Table, 1999). For example, in chapter 3, page 9, it argues that "There are two key scientific concerns:

- There are important scientific uncertainties with respect to how carbon is stored in our forest, soil and wetland ecosystems, how carbon accumulates and is retained within these sinks, and how measures adopted to sequester carbon may affect the emissions of other greenhouse gases. There are equally important uncertainties in the sources of greenhouse gases from agricultural and other managed ecosystems;

- Changes in temperature and water resources under warmer climates may have important implications for the long-term effectiveness of some of the mitigation measures being considered as options for meeting the Kyoto commitment."

In the subsequent discussion in the report, the Table further states that "As noted in the Greenhouse Gas Sinks Table, Forest Sector Table and Agriculture and Agri-Food Table Options Papers, the area of Canadian ecosystems affected by human activities, (and therefore to be assessed for contributions to sources and sinks of greenhouse gases under the Kyoto Protocol and subsequent agreements), can be estimated with reasonable accuracy provided that improved land-use inventories and more careful monitoring systems for land-use change are developed. However, the magnitude and sustainability of the carbon sink (that is, the net quantity of carbon dioxide removed from the atmosphere and stored as carbon) per hectare of land area involved is much more difficult to establish, particularly if climate conditions and other controlling environmental factors change significantly. Furthermore, changes in land-use also have poorly understood implications for emissions or removal of other greenhouse gases, such as nitrous oxide and methane. Thus, these uncertainties present important barriers to credible and verifiable reporting of sustainable carbon sinks and other greenhouse gas fluxes resulting from carbon sequestration measures. Key issues include:

- The sequestration of carbon in a particular ecosystem like a forest or an agricultural field may have related implications for adjacent systems such as wetlands, peat bogs or coastal ocean systems. For example, Canada's peatlands, which contain about 10 times as much carbon per unit surface area as forest biomass and agricultural soils combined, are primarily found within the boreal forests. Hence, any measures to sequester carbon in the latter through afforestation, should consider the consequence for the production of methane and nitrous oxide within peat bogs. Since the related processes involved are poorly understood, the related effects of sequestration measures will be difficult to assess;

- There is very little information on how these environmental changes (i.e. climate change and increased concentrations of carbon dioxide and nitrogen compounds in the atmosphere) will alter carbon flux processes within the ecosystems, and hence the estimation of carbon sequestration under the Kyoto Protocol is made more difficult;

- Complex ecosystem models are needed to accurately describe these processes and relationships in an integrated and dynamic manner. While a number of such models have been developed within Canada and have gained considerable international recognition as quality tools for studying carbon dynamics within the respective ecosystems, these have been designed for applications other than assessment of carbon sequestration potential due to human management. They also continue to inadequately simulate the behaviour of some of the carbon components within soils, particularly those related to respiration. These models need to be further developed, validated against observations, and tested within the international climate system science community;

- Sequestration of carbon into the oceans, either through direct dumping of carbon dioxide into the deep ocean or by removal through enhanced biological production induced by iron fertilization activities in nutrient deficient ocean surface waters, is being investigated by some countries as an alternative approach for reducing the growth in atmospheric carbon dioxide concentrations. There are still many technical and environmental questions related to the viability or acceptability of such measures. It is unlikely, therefore, that they will be considered within national mitigation strategies under the Kyoto protocol in the near future. However, Canada's negotiators do need to be cognizant of the potential, the state of the climate system science, and the benefits and/or hazards of such sinks, should they be tabled by other countries. The very large potential magnitude of such sinks and the potential for irreversible, long-term harm to the ecosystem of enhancement techniques such as iron fertilization may make such research of particular importance in the long-term;

- Some hydroelectric complexes also result in the flooding of large amounts of vegetation within the water storage reservoir. Studies have concluded that such flooding can result in the release into the atmosphere of large volumes of methane. Since methane is much more potent per unit volume as a greenhouse gas than carbon dioxide, some of the gains from reducing the greenhouse gas emissions by displacement of fossil fuel burning power stations may be negated. However, as with wetlands, the processes which govern the generation and release of methane from hydroelectric reservoirs remain as yet poorly understood and require further investigation."

The Table went on to recommend that Canada should "Implement a program to study green house gas sources and sinks processes, especially those for our forests, agricultural soils, wetlands, and oceans" (pg 44).

In January, 1999, at the request of the Technical Committee on Science and Adaptation Tasks of the Climate Change Action Fund, a group of Canadian scientific experts on terrestrial greenhouse gas flux processes (from both government agencies and academia) met in Toronto to consider research priorities related to terrestrial carbon sequestration to help meet the recommendations of the relevant NCC Tables. The meeting provided far more detailed recommendations on the research required to meet Canada's related needs re Kyoto. Various members of the EGGS POL committee, or their alternates, were in attendance. The meeting results have been published in a special report (Hengeveld and Beaulieu, 1999).

Independently, during the 1998 5th Technical Meeting on Sources and Sinks of Greenhouse Gases and Aerosols (Hengeveld and Meyer, 1998), members of a special expert working group on sinks agreed that the magnitude of potential carbon sequestering in forests (through Kyoto activities or improved silviculture), agricultural soils, and oceans (through nutrient fertilization) are similar, but that the feasibility is greatest for agricultural soils and least for oceans.

1.6 POL 6.2.1 EGGS research strategy

Given the POL objectives provided by OERD and the various recommendations from working groups on related research priorities, activities under the POL were to address three specific areas of research: i) identifying and understanding the human influences on key processes that govern the fluxes of GHGs within the Canadian forest, agricultural, and ocean ecosystems; ii) developing models to describe the interrelationships between human activities and these processes; and iii) using these models to assess the quantity of gases that can be removed from the atmosphere by measures under the Kyoto Protocol and subsequent agreements. The activities would address four sub-objectives, as well as an advisory function, as follows:

1.6.1 Forest Sinks

OBJECTIVE: *A better understanding of the impact of human activities on the processes that control the flux of GHGs within, to and from Canada, managed and unmanaged forest ecosystems, including wetlands and freshwater bodies within their watersheds; the development/assessment of methods for quantifying the net effect of measures taken to enhance the uptake of GHGs within these ecosystems; improved estimates of the effects of human activities on the storage and release of GHGs in Canada's forest ecosystems; and the communication of such information to policymakers as a scientific basis for the development of GHG sequestration programs.*

Studies suggest that Canada's forest ecosystems fluctuate between being a sink and source for atmospheric carbon dioxide over annual, decadal and century time scales. Current information at the time indicated that Canada's forests had been accumulating carbon over most of the past century at the average rate of 173 MtC per year. Over the last 30 years or so of that period, however, apparent changes in climate and forest disturbances related to fire, insects and harvesting appeared to have changed this significant sink into a net source of carbon dioxide. Although estimates of Canada's forest carbon budget had improved over the previous decade, considerable uncertainties about the forest sink-source magnitude and status remained. These included: i) the past and current role of disturbances related to fire, insects, and our management of the forest; ii) the fertilization effect of increased atmospheric carbon dioxide and deposition of NO_x from atmospheric pollution on the net uptake; iii) the amount of carbon being removed and stored in forest soils and wetlands; iv) the sensitivity of carbon fluxes and storage to variations in climate and climate change; and v) the role of wood products in carbon storage.

These uncertainties affected and hindered the ability to assess and verify the magnitude and sustainability of increased carbon sequestration achieved through measures adopted under the Kyoto Protocol. To reduce uncertainties and expand the range of potential sequestration options being considered under the Kyoto Protocol, further research was clearly required. Recent expert meetings, convened to examine the status of carbon cycle research and the uncertainties associated with current approaches for estimating the forest carbon cycle, had identified a number of key research priorities that would contribute and expand upon the Kyoto requirements for transparency and verifiability. These included determining the effects of:

- reforestation, deforestation and afforestation activities in increasing the storage/release of carbon in managed forest ecosystems;
- forest management activities on the storage and release of carbon in forest soils and soil detritus, peatlands and wetlands;
- elevated CO_2 and atmospheric pollution (NO_x, SO_x) on storage/release of atmospheric carbon in managed and unmanaged forest ecosystems; and
- climate variability and change on the net uptake of carbon in managed and unmanaged forest ecosystems.

A variety of national and international research projects had already been developed to address these uncertainties and develop the tools needed to understand the processes within the forest carbon cycle. Projects planned under the EGGS POL would seek to more carefully address the effects of human activities on forest ecosystem GHG processes and their effects on the response of Canadian forest ecosystems, including wetlands and water bodies within them, in the context of contributing to and expanding upon Canada's Kyoto Protocol commitments. Results would be used to implement appropriate improvements in forest carbon cycle models needed to better estimate the effects of human activities on enhancing and sustaining forest ecosystems as sinks and reservoirs for atmospheric carbon. These projects would benefit significantly from the related work conducted under government A-base programs and funded through NSERC and other special programs such as the CCAF.

1.6.2 Agricultural Soil Sinks

OBJECTIVE: *A better understanding of the processes that control the flux of GHGs within, to and from Canada's agricultural ecosystems, development/ assessment of methods for accurately quantifying the net effect of measures taken to enhance uptake of GHGs within these systems; improved estimates of the effect of human activities on their net uptake of GHGs; and the communication of such information to policymakers as a scientific basis for the development of GHG sequestration programs.*

Within Canada, cultivation of agricultural soils over the past century had resulted in total losses of about 1100 Mt of carbon. Most of this carbon had been released into the atmosphere as carbon dioxide. However, it was estimated that, because of the depletion of available soil carbon pools and better agricultural practices during the past decade, the rate of release of carbon dioxide into the atmosphere had diminished so that, by 1999, Canada's agricultural soils were neither a large sink nor a large source of CO_2. Studies suggested that a major program to recover some of the C lost from Canada's agricultural soils could provide significant fossil fuel emission offsets under the Kyoto Protocol if negotiators agreed to include such enhanced sinks within national emissions inventories. However, there remained significant questions about the relative importance of various farming practices and the ability to measure, verify and maintain carbon sinks within agricultural soils. These were:

- What are the factors controlling the uptake and emissions of CO_2, CH_4 and N_2O from and to agricultural soils?
- Can we synthesize our understanding of the factors controlling GHG fluxes with robust and reliable models?
- What is the capacity of various soil types for further C storage?
- What is the impact of alternative farming practices such as reduced tillage, reduced summerfallowing, increased use of fertilizers, increased use of forage/legume crops in rotation, etc. on the net GHG uptake?
- What is the impact of climate change on the success of measures to increase the carbon sequestration within agricultural soils?
- How would changes in cropping practices to enhance carbon sinks and the methods and type of nitrogen fertilizer applied affect nitrous oxide emissions?
- What is the role of wetlands within and adjacent to the agricultural landscape?
- What is the impact of soil erosion on C storage and on the net greenhouse gas fluxes?

The present level of understanding of biogeochemical processes within agricultural soils and their responses to changes in temperature and soil moisture were particularly important barriers to properly address these questions. Likewise, a better understanding was required on how carbon stored within the soils is partitioned between crop residues, organic carbon and inorganic carbon. Furthermore, in order to estimate net effects of programs to enhance carbon sinks in a verifiable manner, appropriate improvements in measuring and modelling tools for scaling up from the highly variable conditions at the plot scale at which greenhouse gas fluxes are frequently made, to larger regional scales, were essential. This would require improving flux measurement techniques and developing and testing CO_2 and N_2O models for conditions all across Canada.

While international research programs aimed at better understanding the role of agricultural systems in greenhouse gases would address some of these questions, many of the concerns about processes were specific to soil types, climatic conditions and other factors. In order to help policy-makers adopt agricultural soils as C sinks at the international level, there were important research needs unique to Canada. The proposed research would focus on a combination of direct measurements and process modelling of both the C and the N cycles, and would complement a broader departmental soil research program.

1.6.3 Ocean Sinks

OBJECTIVE: *Better understanding of the processes that control the flux of GHGs within, into and out of ocean systems adjacent to Canada, assessing the potential and verifiability of measures to enhance GHG uptake within them (including the environmental risks); and the communication of such information to policymakers as a scientific basis for the international discussions re ocean based GHG sequestration programs.*

Theoretical studies and preliminary experiments in the late 1990s suggested that fertilization of regions of the ocean deficient in iron and other nutrients could enhance the biological processes that contribute to the annual oceanic uptake of carbon dioxide from the atmosphere and the deposition of the related carbon into the deep ocean for long term storage. The amount of carbon that could be sequestered into ocean systems through fertilization programs was thought to potentially be quite large, but there remained major concerns about both the environmental acceptability and the long-term stability of such sinks. It was therefore in Canada's best interests to strengthen, and participate in, international experiments examining the fertilization potential of the ocean so as to lever the maximum scientific effort from the international scientific community while at the same time assessing potential impacts on Canada's coastal environment should experiments show promise and proceed to a demonstration phase.

There were a number of key gaps in the understanding of the ocean processes involved in such carbon sinks. For example:

- oceanographers did not as yet understand where and how the excess anthropogenic CO_2 is being taken up by ocean systems;
- year-to-year climate variability clearly has an impact on net ocean uptake of carbon dioxide, but the processes that govern how such variability alters the carbon cycles were not well understood. Hence, the impacts of climate variability on the amount of carbon removed through fertilization programs and possible related environmental implications could not be predicted;
- the role of coastal ocean waters in removing carbon dioxide from the atmosphere may be important, but was not understood;
- ocean fertilization programs might also affect the release of nitrous oxide from affected ocean waters. However, the ocean nitrogen cycles processes that control such emissions and their sensitivity to environmental change were not understood;
- the larger ecological consequences of ocean fertilization experiments had not been investigated.

The international research community was actively involved in research activities that would gradually reduce some of the uncertainties about the role of the oceans in global greenhouse gases cycles. This research is particularly important in understanding how the global carbon cycle will respond to future human emissions of greenhouse gases as the oceans warm and the concentrations of carbon dioxide in the surface ocean increase. Canadian scientists, funded through NSERC and departmental A-base resources, were active participants in these activities. Related research under PERD would be an important complement to these activities, and would benefit from the results of the broader research agenda. However, under the EGGS POL, research would be focused primarily at addressing the questions about the practical and environmental feasibility of potential carbon sequestration enhancement programs within the oceans adjacent to Canada's coastlines, whether such programs were to be implemented by Canada or other countries. Carbon cycle models would need to be improved as tools to assess the fate of sequestered carbon. Related information would also be of key importance to possible negotiations of the admissibility of such programs as measures under the Kyoto Protocol and subsequent policy instruments.

1.6.4 Hydro-electric Reservoirs

OBJECTIVE: *Better understanding processes that affect the fluxes of greenhouse gases into hydro-electric reservoirs; development of methods to accurately quantify changes in net fluxes following hydro-electric developments; and the communication of such information to policymakers as a scientific basis for the development of GHG mitigation program options.*

Hydro-electric power generation is one option for replacing fossil fuel based electrical power generation with renewable alternatives that generate much less carbon dioxide emissions. However, various studies have indicated that, if such developments involve the flooding of large areas of land covered with forest or peatland ecosystems, they could induce major changes in the fluxes of greenhouse gases (particularly methane) into and from such reservoirs. The processes that govern these fluxes are sensitive to a number of factors, including the quantity of above and below ground carbon in the flooded ecosystems, and the depth of the water reservoirs after flooding.

One component of the EGGS POL was therefore focused on addressing the above uncertainties, thus helping to better understand the net greenhouse flux implications of fuel switching initiatives involving hydro-electricity.

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CHAPTER 2

Moving Canadian agricultural landscapes from GHG source to sink

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2.1 Introduction

The increase of greenhouse gases (GHGs) in the Earth's atmosphere, as a result of human activities, is contributing to a change of global climates, and therefore has the potential to affect many sectors of the economy. This is particularly valid for the agricultural sector, since the success of agriculture is extremely dependent upon climate.

It is now believed that global agriculture has played a significant role in contributing to the rise in the concentration of GHGs in the atmosphere. Until recently, early agricultural systems were considered to have been a minimal source of GHGs and thus to have had a minimal impact on global atmospheric GHG concentrations. However, signals in atmospheric trace gas concentrations have been discovered that contradict this belief (Ruddiman, 2003). For the period from 8,000 to 2,000 years before present, an anomalous increase in atmospheric carbon dioxide (CO_2) concentration of 20 to 25 ppm has been detected. This increase cannot be satisfactorily explained by a natural loss of terrestrial biomass, but appears to be related to forest clearing for agriculture in Europe and China. Similarly, an increase of 250 ppb in atmospheric methane (CH_4) concentration was observed about 5,000 years ago, closely coinciding with the adoption of "wet rice" farming in Asia. Hence, although farming prior to the industrial revolution has typically been regarded as having a benign impact on the environment, this is not necessarily true. Small changes, even with small populations, over long periods of time can be as important as large changes caused by large populations over a short time period.

The exploding global human population, which has tripled to more than six billion since 1930, and is projected to grow for several decades more is having a huge impact on agricultural activities. To feed such a growing population, the area devoted to intensive agricultural activities has increased substantially. Globally, croplands have increased from 265 Mha in 1700 to approximately 1,473 Mha presently, while the area under pasture increased from 524 to 3,215 Mha. Currently, approximately 36% of the global unglaciated land area is under intensive croplands or pasturelands (Desjardins *et al.,* 2007a), and there is practically no unused land remaining for either growing crops or grazing except large areas of tropical forest whose soils are very vulnerable to erosion and nutrient loss following slash and burn clearing (Sommer *et al.*, 2004). The intensification of agricultural activities has occurred in the form of increased cropping frequencies, increased fertilizer input, as well as increased pesticide and herbicide use.

This growth in land area for agricultural activities and the intensification of agricultural activities has had a profound impact on GHG emissions from the agricultural sector. A considerable part of the 80 ppm increase in atmospheric CO_2 concentration since the pre-industrial period has come from agricultural activities. Until the 1970's, it is estimated that more CO_2 had been released into the atmosphere from agricultural activities than from fossil fuel burning (Lal *et al.*, 1998). Globally, it is estimated that agricultural soils have lost 40 to 50 Pg C during the last two centuries and an additional 80 to 117 Pg C have been released from biomass loss due to change in land-use for agriculture (Lal *et al.*, 1998). The current net release of C from agriculture was recently estimated at 0.8 Pg C per year; that is, about 14% of the current fossil fuel emissions (Schlesinger, 1995). Similar effects are apparent for other greenhouse gases. Prior to the industrial revolution in the 18th Century, annual anthropogenic CH_4 and nitrous oxide (N_2O) emissions were relatively small, approximately 80 Tg CH_4 (Stern and Kaufmann, 1996) and 1 Tg N (Kroeze *et al.*, 1999), respectively. Since the industrial revolution, dramatic increases in domestic herd size, fertilizer usage and cropped and grazed land area have resulted in a large increase in these emissions. Current estimates of global annual anthropogenic CH_4 emissions are approximately 350 Tg CH_4, two-thirds of which is attributable to agricultural sources such as enteric fermentation in ruminants, rice cultivation and manure management systems (IPCC, 2001). Current global annual anthropogenic nitrous oxide (N_2O) emissions are about 7 Tg N. Approximately 70% of global anthropogenic N_2O emissions are of agricultural origin and emissions from agricultural soils represent almost 90% of agricultural emissions (IPCC, 2001).

As will be shown in the following discussion, the emergence of a wide range of modern technologies and improved practices in recent decades has helped to reduce the role of the global sector as a source of GHGs. However, it remains a significant contributor to the atmospheric GHG build-up.

Canadian agriculture, which uses the 15th largest agricultural land area in the world, also has and continues to contribute to climate forcing through greenhouse gas emissions and land cover change. The breaking of natural lands for agriculture has contributed about 4,000 Mt CO_2 to the atmosphere (Smith *et al.*, 2000). However, the following discussion will show that while Canadian agriculture continues to emit significant amounts of methane (CH_4) and nitrous oxide (N_2O), its soils are presently almost C neutral and have the future potential to regain a significant amount of the C that they had lost (Boehm *et al.*, 2005) and that a wide range of options for reducing GHG emissions and enhancing C sinks in agricultural lands will be presented, and the potential to reduce GHG emissions per unit of production will be discussed.

Various projects that are underway in Canada to monitor soil C change and GHG emissions will be briefly described. Recent progress in understanding processes associated with GHG emissions and C uptake by Canadian agricultural soils will be examined. Some broad objectives for further related investigations, such as seeking a better understanding of fundamental processes and anticipating future changes facing the farming community, will also be proposed.

2.2 Past, current and future emissions within the Canadian domain

Greenhouse gas emissions in the form of CO_2, N_2O and CH_4 are an inevitable result of agricultural activities. For example, tilling the soil accelerates the decomposition of soil organic matter, leading to net CO_2 emissions. This results in soils that generally have less soil organic matter as compared to undisturbed soils. The breaking of land, especially the organic matter-rich Chernozemic soils of the Canadian Prairie provinces that constitute over 80% of Canada's farmland, resulted in a rapid loss of 15-30% of the original soil organic matter

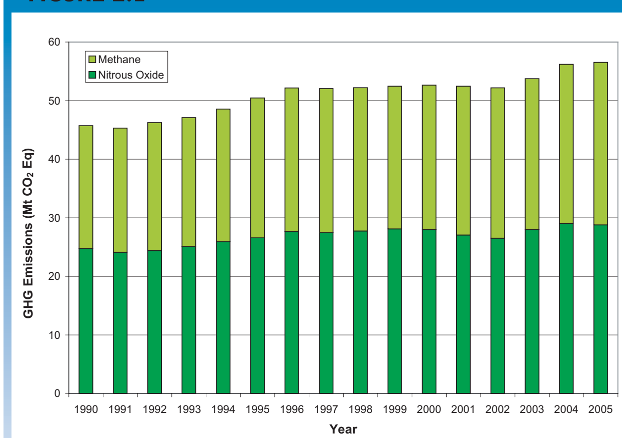
(Gregorich *et al*., 1995). The conversion of other types of land cover, such as either forest or grassland, to agriculture also results in net CO_2 emissions. Over time, the rate of soil organic matter loss has subsided in some regions. In fact, crop management and water conditions have changed the Canadian agricultural landscape from a net source of CO_2 to almost CO_2 neutral, as will be discussed later.

Undisturbed landscapes emit N_2O through natural processes. However, these processes are enhanced in agricultural landscapes because of the increased availability of nitrate-N. Specifically, this increase in N_2O emissions results from application of synthetic N fertilizers, the decomposition of crop residues and soil organic matter, and through the transport of N off-farm during leaching, runoff and volatilization. Livestock production also results in large quantities of CH_4 and N_2O emissions. In ruminant animals, a portion of ingested feed energy (4 -10%) is lost in the form of CH_4 through eructation or belching, while additional CH_4 and N_2O are emitted during manure storage and land application of manure.

Several programs exist to track GHG emissions from Canadian agroecosystems. As part of the National Agri-Environmental Health Analysis and Reporting Program (NAHARP) of Agriculture and Agri-Food Canada, the agricultural GHG budget has been estimated for every census year since 1981 (Desjardins and Riznek, 2001; Desjardins *et al*., 2005). Greenhouse gas emissions from Canadian agroecosystems are also estimated on an annual basis as a part of the United Nations Framework Convention on Climate Change (UNFCCC). Environment Canada (EC) is the federal government agency that has lead responsibility for reporting to the UNFCCC. However, in 2004, EC delegated the responsibility for developing the greenhouse gas inventory on agricultural lands to Agriculture and Agri-Food Canada (AAFC). To meet its obligation to EC, AAFC developed the Canadian Agricultural Greenhouse Gas Monitoring, Accounting and Reporting System (CanAG-MARS), a transparent and verifiable system for generating estimates of emissions and removals on managed agricultural lands. Canada's 2006 National Inventory Report to the UNFCCC was the first to include CanAG-MARS estimates. These estimates are reported by EC in their annual publication of the "*National Inventory Report: Greenhouse Gas Sources and Sinks in Canada*" (Environment Canada, 2007). The estimates begin in the baseline year of 1990 and are updated annually to incorporate the most current year's emission estimates, and to incorporate methodological improvements in calculations as a result of our most up-to-date knowledge.

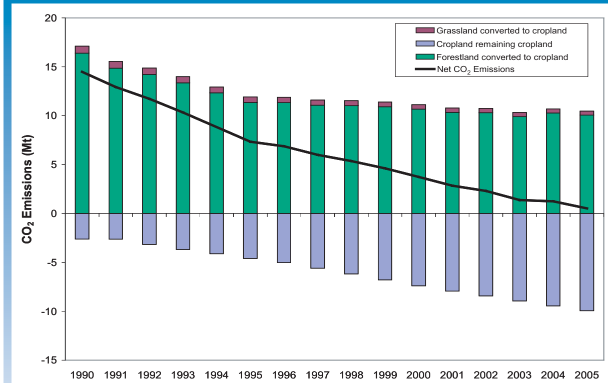
In 1990, Canada's total GHG emissions were 596 Mt CO_2 eq, of which 46 Mt CO_2 eq., or 7.7%, were attributable to CH_4 and N_2O emissions from the agricultural sector (Environment Canada, 2007). By 2005, Canada's total GHG emissions were 747 Mt CO_2 eq, an increase of 25% with respect to the baseline of 1990, whereas emissions of CH_4 and N_2O from the agricultural sector in 2005 were 57 Mt CO_2 eq. (7.6% of the national total), a 24% increase in emissions with respect to the baseline year of 1990 (*see Fig 2.1*). In 2005, the agriculture sector accounted for 66% of Canada's N_2O emissions and 25% of CH_4 emissions.

FIGURE 2.1



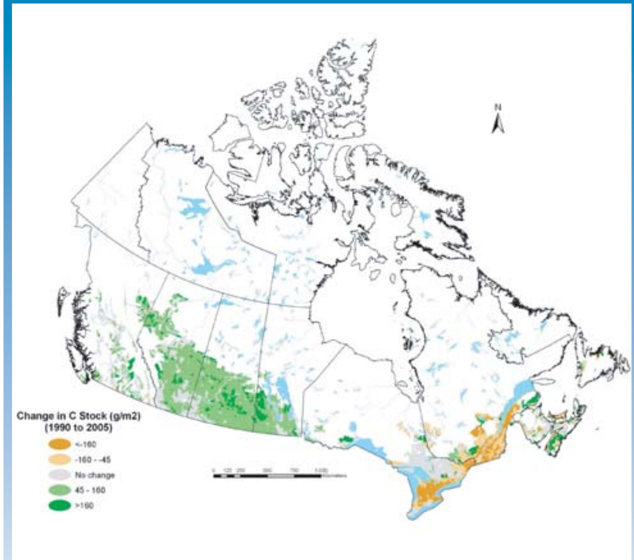
Methane and nitrous oxide emissions from Canadian agroecosystems, 1990-2005.

FIGURE 2.2



Carbon dioxide sources and sinks associated with various agricultural land-use and land-use change categories, 1990-2005.

FIGURE 2.3



Change in soil carbon stocks in agricultural soils of Canada, 1990-2005.

Carbon dioxide emissions from land-use and land-use change (LULUC) associated with agricultural lands is shown in ***Figure 2.2***. The three LULUC categories pertaining to agriculture include grassland converted to cropland (GL-CL), cropland remaining cropland (CL-CL) and forestland converted to cropland (FL-CL). Since 1990, GL-CL has been a relatively minor and constant source of CO_2, CL-CL has been a relatively major and increasing sink of CO_2 and FL-CL has been a relatively major but decreasing source of CO_2. On a net basis, the LULUC categories discussed here have gone from being a 14 Mt source of CO_2 to being approximately neutral with respect to CO_2 emissions. The change in soil C stocks between 1990 and 2005 in the upper 30 cm of agricultural soils in Canada for CL-CL is shown in ***Figure 2.3***. During approximately the same period, CO_2 emissions from the major energy consuming activities in Canadian agriculture increased from 19.3 to 20.0 Mt CO_2 (Dyer, 2008).

Methane and nitrous oxide emissions from the agricultural sector can be broadly divided into four categories: enteric fermentation (CH_4), manure management (CH_4 and N_2O), agricultural soils (N_2O) and indirect emissions (N_2O). Enteric fermentation is the major source of CH_4 emissions, while agricultural soils account for the majority of N_2O emissions. The increase in emissions in both of these categories between 1990 and 2005 has been driven primarily by increasing livestock populations. For instance, the beef cattle population has increased from approximately 12 million head in 1990 to 16 million head in 2005. Part of the increase in beef cattle population has been driven by an increased demand for beef products, while some of the recent increases can be attributed to the 'mad cow' crisis, which forced the closure of the United States export markets. Similarly, the swine population, which emits a significant amount of CH_4 from manure management systems, has increased from about 10 million heads in 1990 to 15 million heads in 2005, and the total poultry population increased from approximately 100 million heads in 1990 to 133 million heads in 2005. The increase in swine and poultry population has been driven exclusively by growing demand for meat products.
The dairy cow population is the only major animal production sector in Canada to decline during the period of 1990-2005, decreasing from 1.4 million heads in 1990 to 1.1 million heads in 2005. Significant gains in milk production per head over that same time have allowed milk production to keep pace with demand, even though the dairy cow population has decreased. Because of the gain in efficiency, Canada's GHG emissions per litre of milk produced has declined by about 10% from 1990 to 2001 (Vergé *et al*., 2007b; Dyer *et al*., 2008).

Future trends of greenhouse gas emissions from agroecosystems in Canada will depend upon many factors, including national policies with respect to production systems, consumer demands for food and fibre (Vergé *et al*., 2007a), emerging bioenergy markets (Smith *et al*., 2008), and potential national and international carbon offset trading systems. Therefore, no simple conclusions can be made regarding Canada's future GHG emissions from the agricultural sector. Given that human population is projected to increase nationally and internationally, it seems inevitable that efforts will continue to increase crop yields and domestic animal population will continue to grow to meet this demand. As a result, unless better management techniques are developed to optimize N use by crops, and unless management techniques can be developed to reduce emissions from enteric fermentation and manure management, it seems likely that Canadian GHG emissions from the agriculture sector will continue to increase.

Emissions from manure management systems could be mitigated through passive aeration composting (Pattey *et al*., 2005) and new technologies to anaerobically digest manure and capture the biogas produced for energy production. It has been estimated that 30% of manure from Canada's domestic animal population could be anaerobically digested. Implementing this practice on this scale would reduce GHG emissions by 30 Mt CO_2 eq. through the combination of the reduction in fossil energy consumed due to the production of biogas, the reduced need to manufacture fertilizer (as the digestate makes a high quality natural fertilizer) and the reduction in direct emissions from manure management systems (Monreal, 2008).

In terms of CO_2 emissions, there has been a recent trend that has seen Canadian agricultural soils shift from being a 14 Mt net source of CO_2 in 1990 to being approximately CO_2 neutral (0 Mt CO_2). This is primarily the result of an increase in carbon sequestered in agricultural soils (CL-CL in Figure 2.2) due to the adoption of no-tillage practices, the decrease in summerfallowing and an increase in perennial cropping systems at the expense of annual cropping systems in the prairie provinces (Desjardins *et al*., 2005). This soil C sink in agricultural land is likely to persist in the near future as farmers continue to adopt better management practices (BMPs) that enhance farm production and environmental quality. However, agricultural soils will not be able to sequester carbon indefinitely, for several reasons. All soil/crop/climate systems eventually reach equilibrium in terms of their ability to store carbon. Further, in order to maintain accumulated carbon, farmers must continue to practice the BMP that led to the accumulation of the carbon, as cessation of this practice will lead to CO_2 emissions and net soil organic carbon (SOC) loss. The management practices that have led to the accumulation of SOC are also dependent upon favourable climate conditions. If climate was to warm substantially, the C pools would very likely decrease substantially (Smith *et al*., 2007).

2.3 Options for reducing greenhouse gas emissions and/or enhancing carbon sinks in Canadian agricultural lands

As noted, agricultural emissions of greenhouse gases are associated with various aspects of crop and livestock production, and options for mitigating the emission of these gases mainly reside in selecting the most appropriate farming practice under a given situation (Desjardins *et al*., 2001). However, nutrient cycles within agroecosystems are closely linked, and management practices that are designed to reduce the emissions of one GHG may in fact increase emissions of another GHG. For this reason, it is important to consider the net reduction in emissions of all GHGs (CO_2, CH_4 and N_2O) when evaluating the effectiveness of management practices.

2.3.1 *Carbon dioxide* (CO_2)

Carbon in agricultural ecosystems either exists in the form of atmospheric CO_2, inorganic carbon, plant biomass or soil organic matter. Large quantities of carbon are transferred between these three pools on an annual basis. Atmospheric CO_2 is fixed by crops during photosynthesis and part of this carbon ends up in the soil from return of crop residues, root sloughing, and root exudation. Finally, organisms, such as fungi and bacteria, oxidize the organic compounds using the carbon as an energy source. The CO_2 produced by this respiration process is emitted into the atmosphere. Despite the large magnitude of these transfers of carbon, they are remarkably well balanced, with the uptake by photosynthesis largely offset by the respiration process. This summary of the carbon cycle in an agricultural ecosystem demonstrates that the natural long lasting pool of carbon in this system is soil organic matter, and that any gains or losses of soil organic matter correspond to equivalent losses or gains in atmospheric CO_2. Therefore, mitigation of net CO_2 emissions from agricultural soils will essentially result in increases in soil organic matter stocks. Storage of crop biomass in products such as construction material and biofuel pellets for heating, which displaces fossil fuel consumption, have the potential to reduce net GHG emissions.

Soil organic matter is essentially the sum of plant materials in various states of decomposition in soil. There are two options to increase carbon stocks in agricultural soils: i) by increasing the annual input of crop residues, and ii) by slowing down soil decomposition processes. Annual inputs of crop residues are influenced by all factors that affect crop production, such as weather, nutrients, type of crop, cropping frequency, type of tillage, etc. Decisions as to whether some crop residues are harvested or not (i.e. cereals' straw) also will have an obvious impact on the annual soil C inputs.

The decomposition rate of soil organic matter can be reduced by the adoption of several farming practices. Conventional seedbed preparation requires tillage operations to control weeds and incorporate crop residues into the soil. This also decreases soil density near the surface. Seeding a crop directly into the previous-year's crop residues (i.e. no-tillage) is an alternative to conventional practices that will influence soil organic C turnover. In such no-till systems, the low soil disturbance and reduced rate of decomposition (as compared to greater aeration and decomposition in conventional tillage) favours the formation of large soil aggregates in which organic matter is physically protected from decomposers. Moreover, crop residues at the surface of no-till soils reduce soil moisture evaporation, resulting in more efficient crop water use in no-till than in conventionally-tilled systems. Accordingly, crop yields and the return of crop residues to the soil are often increased under no-till, especially in semi-arid climates. A decrease in crop production would usually only occur under no-till systems in humid regions, particularly for fine textured soils where wet soil conditions and reduced soil aeration can contribute to reduced emergence and lower yields.

Summerfallowing (the practice of leaving land idle for a year in a crop rotation), gained popularity in the semi-arid prairies of Canada during the mid-20th Century. This practice was adopted as a means of conserving water and hence reducing the risk of crop failure in dry years. Because no crop is grown during the fallow year, no crop residues are returned to the soil, resulting in lower SOC stocks as compared to continually cropped systems. Furthermore, soils under summerfallow are usually warmer and wetter than in cropped soils, thereby increasing the rate of soil organic matter decomposition. As a result, in the prairie region of Canada, carbon can be sequestered in agricultural soils by decreasing the fallow frequency. Indeed, this is what has been occurring since the mid-1970's. The occurrence of summerfallow peaked at 11.4 Mha in 1976, but has been declining ever since, to 5.4 Mha in 2001 (Gameda *et al*., 2007).

Another option for mitigating net CO_2 emissions from the agricultural landscape includes the planting of trees, shrubs and grasses on marginal lands. Where soil moisture conditions are adequate, soil C stocks in agricultural land can be enhanced by increasing the amount of perennial plant biomass. However, since productivity on marginal lands is low, carbon sequestration will not be as large on these lands as compared to more productive croplands.

Recent estimates of the expected rates of C sequestration in soils achievable for various types of changes in agricultural management practices are summarized in ***Table 2.1*** (Janzen *et al*., 2005). The rates of potential carbon gain indicated in the Table are average rates over a projected duration of 20 years. The confidence level denotes the degree of scientific consensus on the suggested rates of C gain. H represents very good confidence in the projected numbers, M represents some disagreement but reasonable consensus that an effect exists, and L represents some disagreement over whether the effect even exists.

TABLE 2.1: An estimate of practices that could be applied in Canada to increase soil carbon sequestration in cropland and grazing land (Janzen *et al*., 2005).

Practice	Area (10^6 ha)	Rates (Mg C ha^{-1} yr^{-1})	Confidence
CROPLAND			
1. Reduced tillage	4-6	0.0 to 0.4	M
2. Eliminate summerfallow	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 to 0.5	M
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. nutrient amendment, irrigation, new species)	1	0.0 to 0.3	M

2.3.2 *Nitrous oxide* (N_2O)

N_2O production in soils is a function of two principal factors: i) the quantity of soil mineral nitrogen available for the reactions of nitrification and denitrification, and ii) the level of soil aeration (usually a function of soil moisture) which will determine if denitrification, the most important source of N_2O, will be favoured. Nitrification is the microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) under aerobic conditions, and denitrification is the microbial reduction of nitrate to dinitrogen gas (N_2) under anaerobic conditions. In both cases, nitric oxide (NO), and N_2O are intermediary, or byproducts formed during the reaction, but which do not undergo full oxidation or reduction.

Crop harvest and in some cases, leaching, exports large quantities of nitrogen which must be replaced if we are to maintain the fertility of agricultural soils. Fertilization of agricultural soils is thus an essential component of cropping systems. However, this nitrogen input often results in abrupt changes in the amounts of the various nitrogen forms in soil, causing temporary increases in the nitrogen content in the soil. This, in turn, often enhances the production and emission of N_2O (Burton *et al*., 2008). Soil freezing and thawing cycles, as well as snowmelt in the spring, also enhance N_2O emissions from fertilized fields (Grant and Pattey, 1999; Pattey *et al*. 2007, 2008). In eastern Canada, these emissions may represent about 30 to 50% of annual N_2O emissions.

Nitrogen fertilizer management practices that will reduce the N_2O emissions from agricultural soils must aim at avoiding the accumulation of soil mineral nitrogen by synchronizing the mineral and nitrogen supply with the needs of the plants (Zebarth *et al*., 2008). That is ideally, the quantity of nitrogen added should not exceed the plants need. It should be placed close to the roots, and should be in a form that is easily absorbed by plants. The amount of fertilizer applied is critical for N_2O emissions as they increase non-linearly with the rate of N applied (Grant and Pattey, 2003; Grant *et al*., 2006).

The determination of the amounts of synthetic fertilizer nitrogen required to achieve these goals is also a function of the quantities of nitrogen which will already be released during the growing season by the mineralization of soil organic matter. Tests are available to producers in Canada that allow an estimation of the contribution of a given soil to the crop nitrogen supply. The farming antecedents also influence the soil nitrogen contribution to a crop. The decomposition of crop residues from legumes, such as soybean during the year following their culture will generally provide 25 to 40 kg N per hectare (Drury *et al*., 2008). Fertilizers should thus provide the difference between the total plant nitrogen requirements and the nitrogen produced by the mineralization of the soil organic matter. A rational management scheme for nitrogen fertilizer will thus reduce the requirements of synthetic fertilizers (Burton *et al*., 2008).

A perfect synchronization of fertilizer application with consumption by the crop is seldom possible because of technical, agronomic or economic difficulties. However, this concept should be always considered when a program of fertilization is conceived. The form and the mode of application of the fertilizer can also influence the nitrogen use efficiency by the crop and thus affect the amounts of N_2O produced (Burton *et al*., 2008). For example, ammonium is quickly nitrified in the soil under ideal temperature and moisture conditions. Hence, for an application of nitrogen in a well-aerated soil, the nitrate form will thus generate less N_2O than the ammonium form of N because it will not involve nitrification, a source of N_2O. On the other hand, if the nitrogen is applied under conditions of imperfect aeration (very wet or compacted soils), the ammonium form is preferable because it reduces, for the short term, the risks of denitrification, the major source of N_2O formation (Gillam *et al*., 2008). Applying the N fertilizer in a shallow band (2 cm depth) can also reduce N_2O emissions by 26%, compared to deep placement (10 cm depth) (Drury *et al*., 2006).

Certain chemical substances, when added to the soil, can inhibit nitrification. The production of N_2O can then be largely decreased, since the retardation of nitrification will also depress denitrification by depriving it of nitrate (its nitrogen substrate). Slow-release nitrogen fertilizers can also allow for the distribution of the nitrogen contribution over a longer period, and thus limit accumulations of mineral nitrogen in the soil; however they are expensive and the overall reduction in N_2O emissions is not proven yet. The mode of fertilizer application can also have a direct influence on the nitrogen accessibility for plant roots. Generally, soil incorporation of nitrogen is more effective than surface application and banding close to the row (and the roots) is preferable to broadcast application (Harapiak *et al*., 1993).

Manure from livestock operations contains considerable nitrogen that is used to fertilize crops. Better management of manure nitrogen is required to limit losses during storage (Pattey *et al*., 2005) and to use it as fertilizer in the situations which are most appropriate for their nature (Mkhabela *et al*., 2008; Rochette *et al*., 2006). The efficient use of manure will allow for appreciable savings in synthetic fertilizers by the farmer and also result in important reductions in N_2O emissions (Rochette *et al*., 2008a).

The nitrogen added to agricultural soils does not solely come from synthetic fertilizers or manures. Legume crops such as soybean, lentil and alfalfa can fix nitrogen present in the atmosphere (80% of the air we breathe is molecular nitrogen or N_2) by symbiotic association through the bacteria Rhizobium. They have the ability to convert atmospheric N_2 into ammonium that can be metabolized by crops. Until very recently, it was believed that this nitrogen fixation was accompanied by a significant release of N_2O. However, recent studies have shown that this reaction produces little N_2O (Rochette and Janzen, 2005; Pattey *et al*., 2008). Legume crop residues returned to the soil are relatively rich in nitrogen and their decomposition stimulates N_2O production more than the residues of non-nitrogen-fixing plants. However, the emission of N_2O from legume crop residues is weak compared to emissions generated by the use of nitrogen fertilizers, provided the N returned to the soil in residues is small compared to the rate of fertilizer application. Consequently, the substitution of a fertilized non legume crop by a legume in a crop rotation reduces the net N_2O emissions. For example, the conversion of a corn monoculture system to a corn/soybean rotation will result in a reduction of N_2O emissions. For leguminous crops that return a higher amount of N to the soil in residues (e.g. alfalfa, and red clover) a reduction in N_2O emissions might not occur.

Soil tillage practices influence N_2O production by affecting soil density (and thus soil water and aeration) and crop residue incorporation. Reduced or no-tillage consists of a limited use of soil disturbing implements and the crops are often sown through the crop residues left on the soil surface after harvest of the previous year. No-tillage results in several important differences from conventional tillage 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 soil surface rather than incorporated into the profile. Residue decomposition and the transformations of mineral nitrogen are thus done under temperature and moisture conditions that are different than under conventional tillage. Poor aeration in clay soils, and under wetter conditions, reduces soil aeration thereby increasing denitrification rates and the potential for N_2O production. Indeed, in Eastern Canada, Rochette *et al.* (2008c) reviewed the published literature and found that generally, no tillage management increases N_2O emissions in the East where conditions are humid, whereas it reduces them in the semiarid Prairies (Grant *et al.,* 2004). Consequently, the beneficial effects of the adoption of no-tillage on soil quality and on the environment in the Prairies are not mitigated by an increase in N_2O emissions. On the other hand, the practice of no-tillage in fine-textured soils under humid conditions (e.g., in Eastern Canada) is likely to significantly increase the production and emission of N_2O, although this is not always the case (Drury *et al.*, 2008).

In terms of N_2O emissions, when crops are irrigated it is better to use frequent smaller irrigation events. This will avoid significant increases in soil water content and wetting/drying cycles that can result in N_2O emissions (Ellert and Janzen, 2008). Similarly, artificial drainage of excess water that ensures adequate conditions for crop growth also minimizes large N_2O emissions.

Under summerfallow, the soil is wetter and warmer than when a crop is growing. Summerfallow conditions favour the biological decomposition of soil organic matter. The mineralized nitrogen in the soil, in the absence of crop uptake, feeds the microbial transformations, thus enhancing N_2O production via nitrification and possible denitrification. Indeed, it was shown that the N_2O emissions from soils under summerfallow are of similar magnitude to those observed on cropped soils receiving nitrogen fertilizers. The adoption of reduced or no-tillage has made it possible to increase crop water-use efficiency and to reduce the need for using summerfallow. Thus, increased continuous cropping in the Prairies under no-tillage has made it possible to increase regional agricultural production without increasing N_2O production (Gregorich *et al*., 2008; Rochette *et al*., 2008b and 2008c).

2.3.3 *Methane* (CH_4)

Methane is produced when organic matter is decomposed in absence of oxygen. On farms, this situation mainly occurs in the digestive tract of ruminants (enteric fermentation), in manure storage structures and in wetland areas.

Strategies to mitigate CH_4 production from enteric fermentation can be grouped into those aiming at improving animal productivity and those based on reducing the CH_4 yield during digestion of the ingested feed. Improving animal productivity results in lower CH_4 emissions when less of the feed-intake energy is lost as CH_4 and when fewer animals are needed for a given amount of farm products (meat or milk). These gains in productivity can be achieved through improved animal nutrition, management, reproduction, or genetics. Examples of improved nutritional strategies include selection of carbohydrates that influence the proportion of the various volatile fatty acids produced during enteric fermentation. Accordingly, a decrease in cell-wall carbohydrates or an increase in starch in the animal diet favours propionate production and decrease CH_4 formation in the rumen. Also, grain-based diets usually result in lower rumen pH, which inhibits growth of methanogens (methane producing organisms). Lower CH_4 production can also be achieved by increasing the proportion of concentrates or legumes in the ration, by feeding highly-digestible forages, and by increasing feeding frequency.

Reduction in CH_4 production can also be achieved by manipulation of rumen fermentation. Addition of certain fats tends to depress CH_4 production because they serve as electron acceptors during biodegradation in the rumen. Other substances such as ionophores improve feed absorption by the animal, thereby decreasing availability of substrates for methanogens (McGinn *et al.*, 2004). These have been shown to be effective for a short period of time.

Approximately 11% of CH_4 emitted from Canadian farms is from manure storage (Environment Canada, 2007). Some CH_4 is produced when manure is managed as a solid form but the major source of CH_4 is from manure stored as a liquid (Pattey *et al.*, 2005). There are several options for reducing fermentation during liquid manure storage. Decreasing the amounts of organic substrates in the manure by increasing feed-efficiency or by using less bedding materials will result in lower amounts of substrates for methanogens. The rate of fermentation, like most other biological processes, also increases with increasing temperature. Accordingly, strategies such as maintaining lower mean annual temperature by using below-ground storage structures and emptying the manure tank prior to the warmest summer month results in lower CH_4 emissions. Fermentation stops when manure is applied to aerated soils. Therefore, shortening the storage duration results in incomplete manure fermentation and reduced CH_4 emissions.

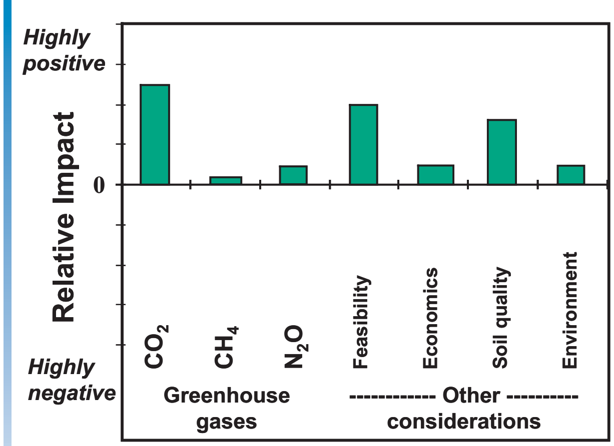
Net CH_4 emission reduction from manure storage can also be achieved through either the simple burning of CH_4 or its capture and use as an energy source. Biogas - a mixture of CO_2, CH_4 and other trace gases, with a CH_4 content of approximately 65%, is produced when manure is treated in anaerobic digesters. Simple burning of the biogas reduces the warming potential of the emitted gases, since CO_2 is 21 times less potent as a greenhouse gas when compared to CH_4. The environmental benefit is increased when the biogas is used on a farm as an alternative to fossil fuels to heat buildings or produce electricity. Additionally, anaerobic digestion of livestock manure under controlled conditions to produce biogas can provide livestock producers with the opportunity to increase net farm income.

Another manure handling technique that has the potential to reduce net GHG emissions is composting with passive aeration. This technique involves the composting of solid manure without turning the manure pile (Mathur, 1991). This technique was recently shown to be the most efficient method for minimizing CH_4 and N_2O emissions during storage (Pattey *et al.*, 2005).

2.4 Broader Impact of GHG Mitigation Strategies

Although it is desirable to minimize GHG emissions, we must remember that the producer is in the business of producing crops and livestock to earn a living. Therefore, mitigation practices that are likely to be adopted on farms must be economically feasible. Furthermore, other factors such as the ease of implementation, impact on soil quality and the environment must be taken into account before a GHG mitigation practice can be recommended. If a management practice is highly positive in terms of GHG mitigation, but highly negative in terms of some other societal value, then the net value of the mitigation practice needs to be determined before it can be recommended. *Figure 2.4* shows the net impact of a

FIGURE 2.4



Assessing the net impact of a GHG reduction strategy, such as the reduction in tillage intensity, must consider more than just the impact on GHG emissions.

TRANSPARENT AND VERIFIABLE UNFCC REPORTING OF HUMAN INDUCED GHG SINKS/SOURCES WITHIN THE AGRICULTURAL LANDSCAPE

As a signatory to the UNFCCC, Canada submits an annual inventory of anthropogenic GHG emissions and removals, including those from agricultural land management. This section describes the C accounting system developed by AAFC for use in developing the estimates for CO_2 as part of the Canadian Agriculture Greenhouse Gas Monitoring, Accounting and Reporting System (CanAG-MARS). Details for the estimation of the emissions of CH_4 can be found in Vergé *et al.* (2006) and in Rochette *et al.* (2008c) for N_2O.

CARBON ACCOUNTING PROCEDURE

Changes in land-use or land management that alter the balance between organic carbon additions and losses cause soil carbon content to increase or decline; if there is no change in land-use or land management, soil carbon stocks will tend (over many years) to a steady state with environmental conditions.

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

$$\Delta C = F * A \quad \text{Equation (1)}$$

where:

ΔC = Change in soil C stock, Mg C

F = Average annual change in SOC subject to LMC, Mg C $ha^{-1}yr^{-1}$.

A = Area of land management change, ha

The main source of national activity data (A in equation 1) is the Census of Agriculture. These data, are available for all farms every 5 years (1991, 1996, 2001, etc.).

There is a large literature of Canadian and international studies of management practices known to increase SOC in cultivated cropland (Bruce *et al.,* 1999; Janzen *et al.,* 1998). To be included in the emission inventory, good knowledge of magnitude and direction of such SOCs change were needed. The Census data provided such knowledge for reduction in tillage intensity (McConkey *et al.,* 2003; Janzen *et al.,* 1998), reduction in summerfallow (Campbell *et al.,* 2000; Campbell *et al.,* 2005), and conversion from annual to perennial crops (Bremer *et al.,* 2002; Campbell *et al.,* 2007).

In order to estimate F in equation 1, the Century plant-soil nutrient cycling model (Version 4) was used to simulate carbon and nutrient dynamics for Canadian grassland, cropland and forest ecosystems (Parton *et al.,* 1987; 1988). This model has been used widely to simulate SOC and tested and validated with moderate success for Canadian conditions (Bolinder *et al.,* 2004; Campbell *et al.,* 2000; Carter *et al.,* 2003; Grant *et al.,* 2004; Liang *et al.,* 1996; Monreal *et al.,* 1997; Voroney and Angers, 1995; Pennock and Frick, 2001). The model was calibrated and validated using processes developed by Smith, W.N. *et al.* (1997, 2000, 2001). Carbon factors used in the model are estimated as the difference in soil C 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 land management change of interest.

The calculations for national C change involve about one million quantities, each with its uncertainty. To analyze the net effect on the calculation of uncertainties, a Monte Carlo method was used, which draws randomly from the probability distributions of several hundred aggregate C change quantities. The probability distributions of C change from equation (1) was derived from an analytical analysis based on the uncertainty in F and A. The uncertainty in F was assumed to be composed of two parts – situational uncertainty and inherent uncertainty. Situational uncertainty was due to uncertainty in initial C state when LMC occurred and uncertainty in the agricultural systems upon which the LMC was imposed. Inherent uncertainty was the uncertainty due to uncertainty in model predictions and/or empirical data with known initial C state and farming systems.

reduction in tillage intensity in western Canada. In most cases, this practice is beneficial in increasing soil C sequestration, and thus removing CO_2 from the atmosphere. It is relatively neutral as far as CH_4 emissions are concerned and generally, lower N_2O emissions are observed under no-tillage systems. Furthermore, this practice is very feasible and economically viable and has additional benefits in terms of improving soil quality and being beneficial for the environment. As a result, the adoption of no-tillage practices in western Canada is highly recommendable as a GHG mitigation strategy.

2.5 How far have we come in meeting POL 6.2.1 goals?

As noted in Chapter 1, the goal of GHG sinks related research in the agricultural sector funded by PERD was to advance and implement our collective understanding of soil sinks in agricultural lands. Specifically, the objectives were to: 1. "investigate variables and processes that control GHG fluxes in agricultural ecosystems", and 2. "further develop models to quantify the effect of agricultural management on GHG uptake". This research was conducted as part of a larger stream of research into greenhouse gas fluxes within agroecosystems involving scientists from many disciplines at numerous sites. Funding from PERD fostered significant acceleration of that work, and helped address gaps in understanding aspects not yet adequately probed. This research has followed a collaborative, integrated approach illustrated in *Figure 2.5*. The intended results are a robust, reliable GHG inventory, and a definitive, credible set of practices, applicable nation-wide, for mitigating (minimizing) GHG emissions from farms. Because of the complexity of agroecosystems and their fluxes of GHG's, these objectives can be achieved only by the use of models, ranging from simple equations to highly-sophisticated simulation models. These models, in turn, depend on a solid understanding of the processes of GHG emission and removal, attained through focused fundamental research. The models also require the development of reliable methods to measure GHG fluxes, both to construct the models and to verify their outputs. The approach outlined in Figure 2.5 proceeds continuously and interactively, with incremental improvements in each category gradually improving sensitivity and rigour in related activities.

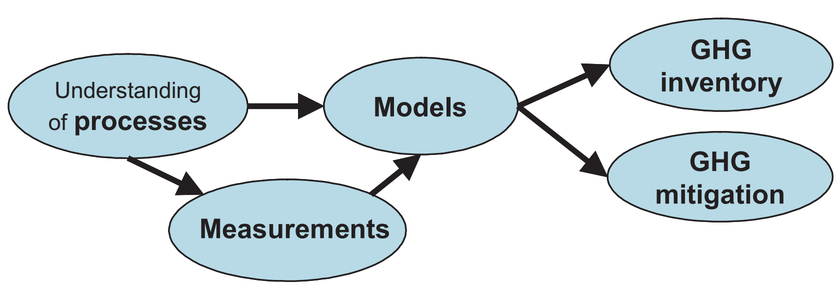
So how far have we come in this research effort since 2000? Details of specific findings can be gleaned from the appended list of research papers. Perhaps more instructive is a partial list of research facets where significant progress has accrued. These include:

a) **Improved understanding of the dynamics of carbon and nitrogen that underlie GHG emissions and removals:** For example, detailed studies of organic matter fractions have helped identify those forms related to long-term storage of C. This understanding, in turn, helps identify practices that build soil C by encouraging the formation of these long-term soil C stores.

b) **Better quantification of ancillary GHG fluxes, notably those related to energy use:** For example, research funded by PERD has provided improved estimates of CO_2 emissions from fossil fuel

FIGURE 2.5

Schematic layout of information flow in research on greenhouse gas emissions from agricultural lands in Canada.



consumption on Canadian farms (Dyer and Desjardins, 2003a, 2003b, 2006, 2007). These emissions, which vary among practices, need to be taken into account when calculating the net benefit of proposed practices for GHG mitigation. Other researchers (also with PERD funding) have estimated the net energy balance of biodiesel produced from canola and soybean (Smith *et al*., 2007). This work demonstrated that a large fraction of the energy benefits from such biofuels is offset by energy used in its production, but that there is still a net energy gain (i.e. the fossil fuel offset by the biodiesel produced is greater than the fossil fuel used to produce it).

c) **New methods for measuring fluxes:** A wide range of new or modified techniques have been developed for measuring fluxes of GHG's, especially CH_4 and N_2O. These can be applied at various scales, from local point sources to large regions, to provide improved estimates of agricultural emissions and to test the reliability of models. Examples include:
1) Using CH_4 concentration measurements from an open path laser together with a dispersion model of atmospheric transport to establish the characteristic of a source such as a lagoon or a barn (Desjardins *et al*., 2007b); 2) Collecting air samples associated with upward and downward moving air using an aircraft-based platform moving at a speed of 55 m s^{-1} at an altitude of 100 m and later analyzing the difference in N_2O concentration in a laboratory with a tunable diode laser to estimate the flux of N_2O on a scale of hundreds of square kilometers (Pattey *et al*., 2006b and 2007). The robustness and precision of techniques for measuring year-round N_2O fluxes from agricultural lands was improved (Pattey *et al*., 2006a).

d) **Enhanced understanding of how the effectiveness of mitigation practices varies among regions:** For example, a comprehensive review of long-term field trials showed that adopting no-till systems can induce significant gains in soil C - but not always. Typically, adopting no-till sequesters C into the drier soils of western Canada, but not in the more humid soils of central and eastern Canada.

e) **Broader, integrative analysis of GHG fluxes and removals:** Initially, much of the research on GHG's in Canadian farmlands focused on soil C sequestration. Since then, however, we have recognized that the other GHG's – N_2O and CH_4 – also need to be taken into account in evaluating the benefits of any practice. Thus, studies have increasingly examined the interactions among gases; for example, studies of soil C gains under no-till have also looked at how this practice affects N_2O emissions. Process-based models (such as ECOSYS and DNDC) were improved to better predict N_2O emissions from cropland. In addition, models – still rudimentary (e.g. a GHG calculator) – have been developed to examine whole-farm emissions, allowing practitioners to examine how a proposed practice might affect the *net* emissions arising from a farm (Janzen *et al*., 2006; see http://ncgavs.usask.ca/ghg_calculator/ for GHG calculator program download).

f) **Expanded databases of GHG fluxes:** A prominent legacy of the research funded by PERD and related funding agencies are the accumulated databases, from studies throughout Canada, of GHG measurements. These databases are valuable, enduring resources for future development of improved models (Boles, 2007) and for the development of national GHG inventory methodologies (Rochette *et al.* 2008c).

g) **Enhanced expertise:** A related legacy – one often overlooked – is the gradual accumulation, arising from this research, of a robust, multi-disciplinary expertise in the science of GHG emissions and removals. This expertise is valuable not only for future scientific advancement, but is widely consulted and a critical asset for forging improved public policy in the face of the growing urgency of climate change-related questions.

h) **New outlook on complexity:** In early stages of GHG research in Canadian agriculture, scientists were somewhat overwhelmed by the enormous variability and uncertainty in estimates of GHG emission and removal. Since then, we have made significant progress in accepting and accounting for this uncertainty in our research. Although many of our estimates still have large uncertainty, we have made progress in providing estimates that do not hide the uncertainty but still provide information useful to producers, policymakers, and other clients.

i) **Enhanced sense of place in global GHG science:** A prominent benefit of PERD-funded research has been the interaction of scientists in agriculture with those in other biomes. Consequently, where agricultural GHG research was once somewhat introspective, focusing only on farms, it now has a much broader scope; it looks not only at flows of C, N, and energy *within* agroecosystems, but also at exchanges between agroecosystems and other biomes.

Together, these and other findings have provided substantive advances toward the intended results of GHG research, including a reliable and comprehensive GHG inventory system, improved models, and a growing awareness of practices that will efficiently reduce GHG emissions from farms.

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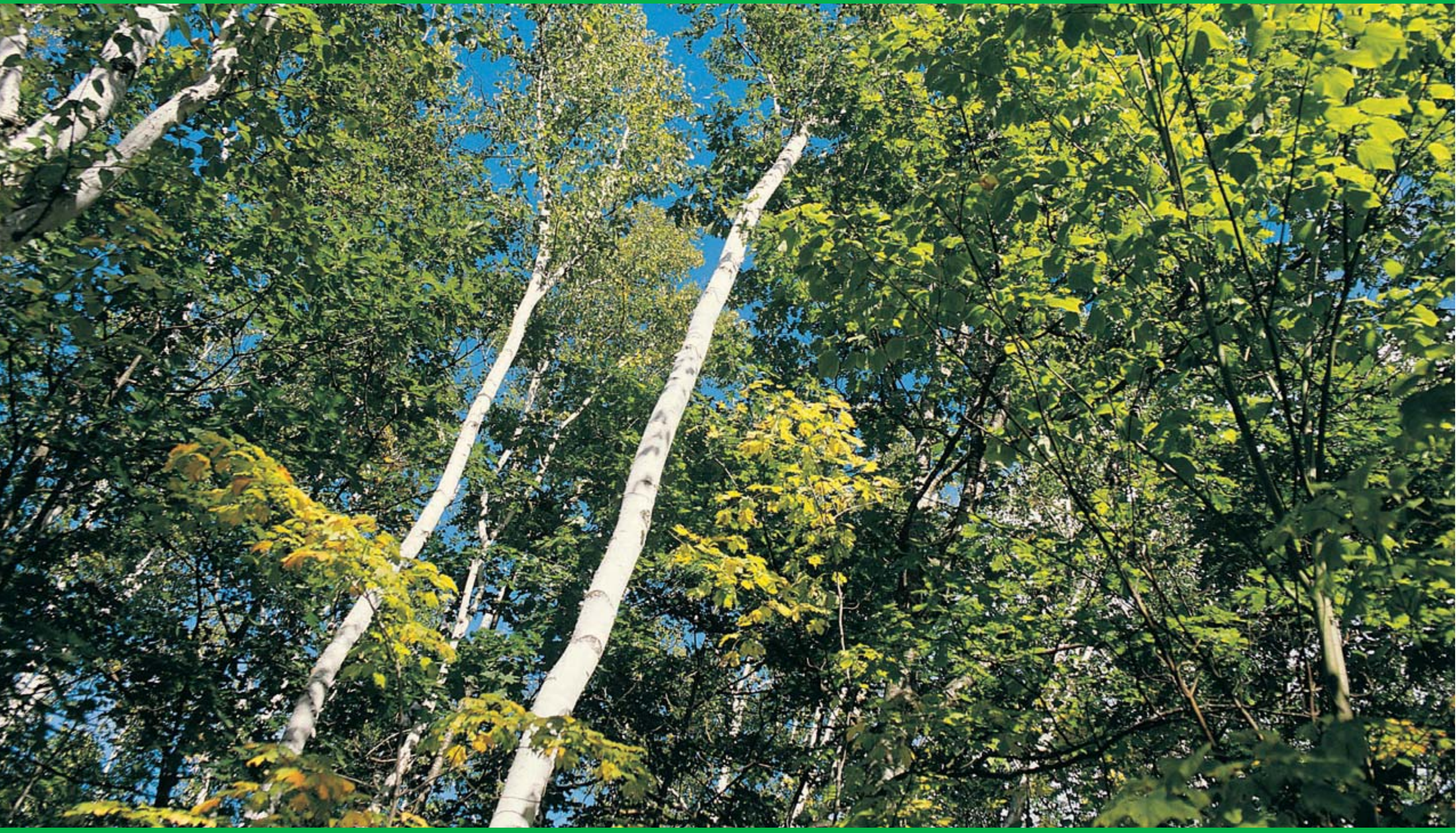


CHAPTER 3

Canada's forests – carbon source or sink?

Co-ordinating and Lead Author | **P. Hall**

3.1 Introduction

According to the United Nations - Framework Convention on Climate Change (UN-FCCC), member countries are to report annual anthropogenic emissions and removals, using guidelines from the Inter-governmental Panel on Climate Change (IPCC). With respect to land-use change and forestry, the IPCC guidelines call for the reporting of carbon stocks in all forests that experience "periodic or on-going human interventions that affect carbon stocks."

Accordingly, Canada submits regular reports to the UN-FCCC on our national GHG emissions, including the net carbon stock changes and non-CO_2 greenhouse gas emissions associated with land-use change forests. However, the definition of forests to be considered under the IPCC reporting guidelines creates a challenge for countries that have extensive forest ecosystems, much of which is untouched by human activities. Although Canada contains about 10% of the world's forest area, and about 30-35% of global terrestrial carbon is located in boreal forests, the area under human influence, or the 'managed' forest, is much smaller than the total forested area. Hence, estimates of carbon stocks in forests as reported to the UN-FCCC are based on 238 million hectares of managed forest - the forest considered to be under direct human influence and management.

Changes in forest use considered under the UN-FCCC are limited to afforestation (the conversion of non-forest land to forest) reforestation, and deforestation (the direct human-induced conversion of forest to other land-uses). Canadian negotiators need scientific guidance and quantitative analyses of the anticipated future contributions of forests and forest management activities to our net greenhouse gas balance. Important issues include:

- the baseline of carbon stock changes in managed forests over the next 3 decades;
- the range of impacts of forest management scenarios, outcomes, and costs;

- the likely impacts of global change on the forest carbon stock changes; and
- the partitioning of stock changes between direct human-caused and natural and indirect human effects;
- whether or not to make the inclusion of forest management activities mandatory for reporting;
- how to account for effects in absolute terms or relative to a baseline;
- whether to argue for caps on both sources and sinks; and
- how to attribute greenhouse gas sources and sinks to natural and anthropogenic effects.

Models and accounting tools are required to address these issues. Monitoring tools are used to calculate carbon stock changes for the period since 1990. These tools require detailed information on forest inventories, natural disturbances, land-use changes and forest management activities. Scenario analysis tools project future carbon stock changes based on assumptions of future rates of disturbance, land-use change and forest management activities. These tools help managers and policymakers choose among strategies for management of forests and policy options to increase carbon sinks. The ability to claim sinks credits will depend on the quality and uncertainty of the sinks estimates and on our ability to predict future sinks. Related research needed to meet the relevant UN-FCCC requirements need to focus on the following areas:

Modeling forest carbon stocks and stock changes. Models are the integrating tools to estimate national-scale GHG sinks and sources from experimental and observational data. Major uncertainties persist about the dynamics of carbon and GHG of deep organic soils, forested peatlands, and the interaction between wetlands and upland forests. It must be remembered that most of the boreal forest, as of all forests, consist of a complex mix of ecosystems. An improved understanding of natural disturbances on forest carbon dynamics is also essential, for stand-replacing disturbances such as fire or insect outbreaks and for non-stand replacing disturbances such as defoliating insects that cause widespread growth loss but little mortality.

Impacts of land-use change and forest management. Forest management actions affect most aspects of the dynamics of forest carbon stocks. For reporting and/or negotiating purposes detailed regional assessments of the impacts of a range of forest management actions on carbon dynamics are required. These actions include the effects of protection measures (fire/insects), salvage logging, site preparation, reforestation, afforestation, fertilization, and different systems of harvesting. Improving the quantification of the potential of forest management activities will be an ongoing necessity as adaptive forest management is implemented. Understanding and quantifying the impacts of forest management actions will better contribute to the distinction between direct and indirect human and natural effects.

Impacts of global change on forests. Global change will have significant impacts on stocks of forest carbon (as demonstrated by model analyses of the rates of natural disturbances), particularly wildfire and insect damage. Major scientific questions remain unsolved in the estimates of the impacts of global change on the continuous processes of forest growth, decomposition, and the resulting stand-level net carbon balance. Modelling forest responses is an area of active research that requires sustained funding: results of this work will not only help improve estimates of carbon budgets but will also contribute to the development of mitigation and adaptation strategies.

Verification of Forest Sinks Data. Sampling-based information on the characteristics and dynamics of forests are used to develop verifiable and transparent estimates of forest carbon sources and sinks. Scaling, estimation of errors and uncertainties, and approaches to verification of sample-based information all present significant scientific challenges. The potential of remote sensing and direct measurements of atmospheric CO_2 concentrations to verify regional carbon budgets needs to be further explored. Reducing uncertainties in the estimates of carbon stock changes directly affects our ability to claim carbon credits at the level of individual projects and at the forest ecosystem level.

Canada is internationally recognized for its advanced research on forest carbon cycling, for the development of remote sensing monitoring programs, and for the integration of data from many sources into forest carbon accounting tools. Recent increases in funding of this research through PERD and other programs has helped to enhance that research activity and to move significantly forward in our ability to meet UN-FCCC reporting requirements for sink credits and to advise our international negotiators. Our reporting system is based on modelled results and uses a structured reporting system compliant with the IPCC Good Practice Guidance report. *(See BOX 1.0)*

This chapter will summarize the GHG sinks research done under the PERD program over the past several years to address a number of generic policy related issues. It will first examine the role of past, current and future forest use and management as source and/or sink of atmospheric carbon, and consider how this has affected greenhouse gas emissions from forests. This will be followed by a discussion of the role of natural disturbances and climate feedbacks in current and future emissions, and the options for reducing such emissions and/or enhancing sinks. The next section will consider our current ability to provide transparent and verifiable UNFCCC reporting of human induced versus natural sinks and sources within the forest sector. Finally, the final sections of the chapter will assess how far we have come in meeting POL 6.2.1 goals, and where we need to go next.

3.2 Canadian forests as sources and sinks of greenhouse gases

3.2.1 Past forest use and management as source and/or sink of atmospheric carbon

An analysis of the history of carbon dynamics in Canadian forest ecosystems shows that major changes have occurred over the past century. Prior to the 1920's, Canadian forests had been C neutral. That is, they were neither a major sink nor source for atmospheric carbon dioxide. From 1920 to about 1970, natural disturbances were few relative to the period 1860-1920. There was also a major expansion of industrial forestry, particularly the pulp and paper industry and production of construction materials such as plywood and fibreboard. Forestry practices involved extensive clear-cut harvesting which altered the natural succession of forests, particularly in the carbon-rich boreal forest activities which generated significant emissions of carbon. However, at the same time, a program of fire prevention and suppression was implemented, even in many areas of the boreal forest where wildfire is the driving force behind natural succession. Carbon stocks gradually recovered from the effects of increased harvesting, but forests did not become a net sink until the 1950's. Forests then remained a significant sink for the next three decades.

A prominent result of these dynamics were changes in the age-class structure of forests with the proportion increasing of older forests containing more biomass and dead organic matter. Furthermore, the ability of the older forests to take up additional C was decreasing and their susceptibility to fire and insect disturbance increasing. During 1970-1989, the incidence of natural disturbances, wildfires and insect outbreaks, greatly increased as a result of the accumulated effects of past harvesting and fire-control practices and climate change. These higher rates of disturbance reduced total biomass C pools, transferring much of the residual C to dead organic matter pools which decomposed and released additional C; the net effect being a shift in the condition of forests from a C sink to a source. Projection of forest dynamics demonstrate that they will, over time, revert to a C sink, but this assumption is highly dependent on future rates of natural disturbance.

The nature of large-scale disturbances greatly influences the predictability of future emissions from forests. The incidence and extent of wildfire cannot be predicted and so confident prediction of emissions is not possible. Insect outbreaks arise periodically and follow a predictable pattern, so emissions from these disturbances can be projected, particularly if damage patterns have been previously documented. Recent results are demonstrating that prolonged droughts also result in a net emission from moisture-stressed forests, and that these emissions continue a year or two after normal precipitation returns. These emissions, although difficult to quantify, can be expected to be significant when droughts occur over large areas. Similarly, forest declines or stochastic events such as extensive areas of windthrow result in C emissions which are not yet quantified.

The CBM-CFS makes estimates of past C stock changes from 1990 to the present, and projects future C stock changes until 2012, the end of the Kyoto commitment period. Inventory data on forest C are obtained from provincial/industrial growth and yield information, empirical/process-based growth models, and growth and yield data from afforestation projects. Information from inventories of dead organic matter, soil organic carbon, biomass, and large-scale stochastic events are incorporated in the model. This information, together with carbon cycling in forest soils, data on land-use change since 1990 (obtained by remote sensing and coordinated across land-use sectors) is increasing the predictive capability of the model. However, significant improvements are still needed to reduce the uncertainties in these predictions. In particular, the model needs to include the effect of climatic variability on ecosystem processes, to better simulate the amount of litterfall (turnover of roots and decomposition of organic matter) and to address the role of peatlands, wetlands, and natural disturbances. The sensitivity of the national forest carbon budget to the impacts of human-induced activities also needs to be better understood and modelled. This enables policy-makers to calculate the probability of managed forests being a carbon sink; information required by the National Forest Sinks Committee.

Recent changes in temperature and precipitation regimes and changes in the global concentration of atmospheric CO_2 are predicted to affect net ecosystem productivity (NEP) and C dynamics by the so-called fertilization effect. Changes in growing conditions that enhance forest growth and thus C uptake are also enhancing decomposition processes and C release. The net effect of these opposing trends will impact the dynamics of carbon budget estimations.

Preliminary conclusions regarding carbon dynamics based on results of modelling are:

- under a warmer climate, increasing drought in the Prairie Provinces is likely to reduce forest cover and productivity; whereas forests in eastern Canada, which typically receive much greater annual precipitation, are likely to maintain and enhance forest cover, and increase growth and productivity,
- productivity and soil carbon stocks are best maintained by retaining residues from harvesting on-site under current climate and productivity conditions,
- large-scale disturbances of harvesting, wildfire, and insect damage have strong and direct effects on carbon budgets.

Model outputs have been improved by reductions in uncertainties of the relationships between stand age and net primary productivity; improvements in the estimates of litterfall and turnover of fine roots have also refined the model outputs. This information has enabled better estimates of the effects of disturbances on carbon budgets and an elaboration of the distinction between human-caused and natural impacts. There is an increasing confidence in the modelling results which improve incrementally as research becomes integrated into the models. This leads to an enhanced confidence in estimates and a greater realization of the extent of the variability in natural systems, the impacts from human activities and the risk associated with increasing climate variability. This process is ongoing as associated improvements are made in supporting data on soil carbon, large stochastic events and the physiological changes in vegetation.

A large-scale modelling experiment, the *Free-Air Carbon Dioxide Enrichment* (FACE) project (http://aspenface.mtu.edu/) employs factorial treatments of carbon dioxide and ground-level ozone on rapidly-growing clones of trembling aspen, white birch and sugar maple. The experiment is designed to produce dose-response functions for ozone (O_3) risk analysis for forests. The increased level of CO_2 enhances height and diameter growth, but when O_3 is present, the growth enhancement disappears. The influence of elevated CO_2 delays autumnal senescence from 5-7 days and increases winter dieback by about 12%. The presence of O_3 at current levels can be expected to counteract any fertilization from increased concentrations of CO_2. The presence of O_3 also causes increased levels of damage to foliage by diseases and insect defoliators. The mechanism consists of an alteration of the host/predator interaction which leads to more damage. The experiment has accumulated considerable data which explains the trends of early stimulation of growth from enhanced CO_2 being offset by the increased concentrations of ozone and damage from insects and disease. Other fertilization studies have shown unexpected impacts on the growth rates and net carbon assimilation by forest trees, indicating that under current and predicted climates, optimistic predictions of extensive carbon assimilation are unlikely. This information will be used in the CBM-CFS to predict forest response to atmospheric change.

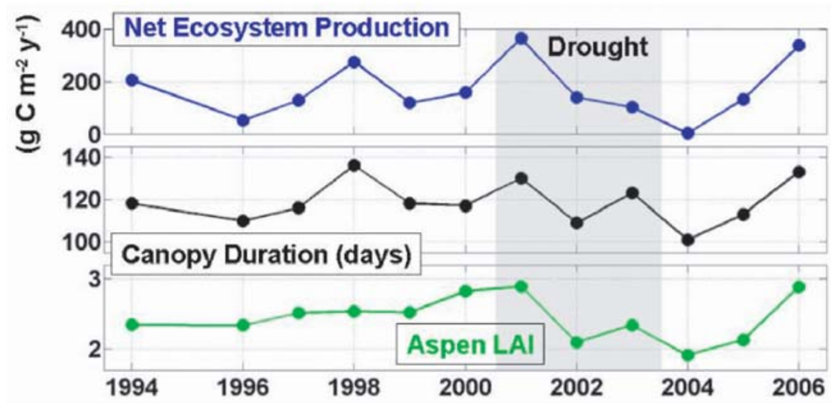
A long-term soil productivity experiment established in 1994 in Ontario was designed to determine the effects on black spruce (*Picea mariana*), jack pine (*Pinus banksiana*) and aspen (*Populus tremuloides*) of removal of different amounts of Nitrogen and C from the forest floor by harvesting and site preparation. Carbon stocks were materially enhanced by the addition of nitrogen, particularly when coupled with the other silvicultural techniques of harvest residue retention, vegetation control, and density management. Further studies are underway on the long-term effects of atmospheric nitrogen deposition. Results of the productivity experiments could be incorporated into management practices.

The effects of inter-annual climate variability on the C and water balances in boreal forests are being studied using measurements from flux-towers above the forest canopy to measure the exchanges of carbon, water and energy between forest and atmosphere. These data will help improve the spatial heterogeneity of the carbon cycle across the landscape and provide a better understanding of the climatic and biophysical factors controlling the carbon source/sink strength. The resulting integrated, stand-level database will be used to validate ecosystem process models, improve national carbon cycle models and develop climate-driven models for growth and yield. The data so far show boreal forests are very sensitive to spring warming, that NEP recovers rapidly following harvesting, and that the carbon and hydrologic cycles are closely coupled. The severe drought and recovery over the period 2001-05 led to a 30-40% decrease in forest growth coupled with severe mortality. Despite the return to moist conditions in June 2004, mortality continued to increase during 2004-2005 indicating that drought can cause significant regional impacts on aspen carbon uptake and persist after a return to normal precipitation.

Measurements of the net carbon exchange between the atmosphere and the forest show that old-growth forests are weak to moderate carbon sinks ***(see Fig.3.1)***. The primary climatic control is spring temperature, which has a more dynamic effect on deciduous forests than coniferous forests. In boreal deciduous forests, warm springs promote increased carbon sequestration by hastening leaf emergence. Annual photosynthesis is increased but respiration is unaffected. Annual NEP is

FIGURE 3.1

Decrease in annual net ecosystem production, canopy duration and leaf area index for an old aspen grove during a drought in western Canada.



more variable in deciduous forests, differences in carbon sequestration between a warm-spring and a cool-spring year is more than three-fold. In boreal coniferous forests, warm spring temperatures lengthen the growing period by hastening spring snowmelt. NEP responds quickly to changes in climate. The results of these studies show the highly sensitive nature of these forests to current temperature and moisture conditions, and the degree to which they are sinks or sources is closely controlled by these factors.

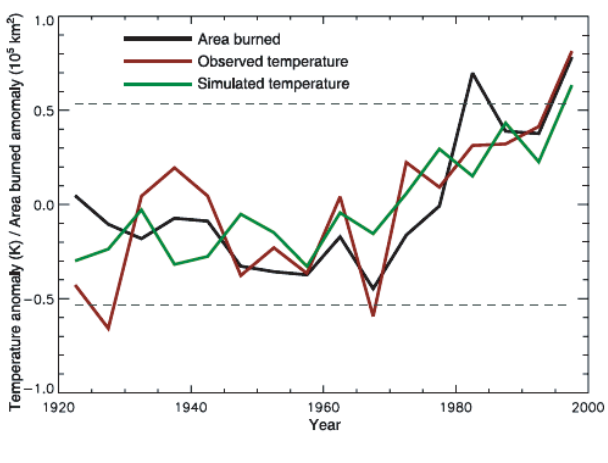
As this research develops, a number of science issues are being addressed:

- inter-annual climate variability to assess the potential impacts of climate change on the exchanges of carbon, water and energy between boreal forest and the atmosphere,
- climate change impacts on the productivity and health of the southern boreal forest,
- regional-scale verification of modelled NEP based on the time series of CO_2 concentration and other trace gases,
- evaluation of models to characterize effects of inter-annual climatic variability,
- improved estimates of atmospheric CO_2 fluxes, and
- a national overview of the variability in annual NPP and the relationship of annual NPP and inter-annual climate variability.

3.2.2 Canadian forest emissions

Canada has a requirement from the Kyoto Protocol to report anthropogenic carbon emissions from deforestation and has the opportunity to report sinks from post-1990 human activities in forests. Emissions from forests are governed largely by stochastic events occurring over extensive areas and are more or less well described and estimated. These events consist of wildfire and insect outbreaks, but other (less well-defined) events such as forest declines and windthrow also cause increased emissions. Fires are large stochastic events and not subject to prediction; whereas insect outbreaks follow a generally known course, and so allow predictable emission estimates. Both growth loss and mortality are measurable with current monitoring technologies. Wildfires burn (on average) two million hectares of forest land annually but the year-to-year variation ranges from 0.4-7.5 million ha. Emissions from fires are calculated based on the area burned and biomass consumed. Projections of area burned based on weather/fire

FIGURE 3.2



Relationship between temperature and area burned, 1920-2000. Gillett *et al.,* 2004 Geophys Res Lett 31:L18211.

danger under an altered climate indicate a 75-120% increase in area burned by the end of this century.

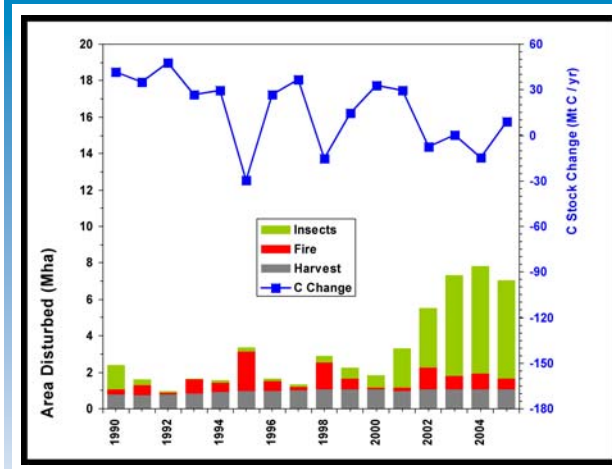
The area burned by wildfire is driven primarily by weather (*see Fig. 3.2*), but human impacts are important through causing forest fragmentation, increased population density and forest management activities. Past management policies which suppressed fires has also resulted in extensive areas of over-mature forest which became susceptible to large fires which are very difficult to control. An added complication will be the large fuel supply resulting from extensive forest mortality caused by bark beetles in British Columbia, a phenomenon partly caused by a warming climate.

Insect outbreaks cause growth loss and mortality which result in emissions over large areas, often in the tens of millions of hectares. The outbreak of Mountain Pine Beetle (*Dendroctonus ponderosae)* in British Columbia causes extensive mortality; the impacts of which on national emissions from 1990 to 2005, are considerable.

The effects of these disturbances are clear; forests were a sink until 2001 when an increase in insect-caused mortality resulted in huge emissions and a negative C balance. This was instrumental in developing the risk assessment on whether to include forest management under Article 3.4 of the Kyoto Protocol; should Canada elect forest management activities for inclusion in Kyoto reporting? Because of the increased mortality after 2001, the estimated likelihood of an emission source, including non-CO_2 GHG emissions, during 2008-2012 is ~90%. The managed forest was a carbon sink in 12 of the previous 16 years. However, after 2001 the trend was reversed (*see Fig. 3.3*). This formed the basis of the decision not to include forest management activities in the reporting of GHG emissions. Emissions are also affected by changes in land-use which includes agricultural expansion, urbanization, cutting of seismic lines and other deforestation activities. These all result in increased emissions, some of which are partly offset by the reversion of dis-used agricultural land to forest.

The large amounts of carbon stored in forest soils, particularly in the boreal and boreal-mixedwood forests,

FIGURE 3.3



Carbon stock changes in Canadian forests, 1990-2005.

means that an improved understanding of soil carbon dynamics is necessary to predict emissions. The PERD program supporting soil carbon research has enabled researchers to gain a better perspective on this part of the cycle. Investigations of soil carbon have shown that the amount of soil carbon generally increases with time, and that litter decomposition is a slow process which varies regionally and among species. There is substantial inter-annual variation in emissions which is closely related to temperature, indicating that emissions will increase as temperatures rise. Temperature changes over the past decade indicate that this is already happening. Climate warming, wildfire and harvesting strongly affect the amount of soil carbon because of the changes in decomposition processes that are affected as these factors vary. Disturbances are key as to whether forests are a source or sink of carbon because of the frequency and extent of disturbance from fire and/or insects. There are also large C reserves in peatlands, but little information is available on fire impacts on these sites.

Two examples of these uncertainties are the effects of large-scale drought and the year-to-year variation in growth rates:

- Boreal deciduous forests are highly sensitive to the date of spring warming as demonstrated by the rapid recovery of net ecosystem production in the spring and also following harvesting. Unless these ecosystems can be adequately monitored, prediction of ecosystem uptake and emissions will be uncertain. Drought can cause significant reductions in carbon uptake and this effect persists after a return to normal precipitation levels.

- There is considerable inter-annual variability in carbon sequestration from changes in growth and decomposition rates caused by climate variability. This variability is being measured using tree ring analysis which shows that growth rates vary among and within species and regions. There appear to be no national trends based on analysis to date. Changing temperatures affect forest growth and at the same time the atmospheric composition influences forest growth and development. As the atmosphere continues to change, uncertainties will persist as to future forest growth and development.

Wetlands store abundant carbon as a result of reduced rates of decomposition and are sensitive to climate change (particularly increased temperatures and drought) than the surrounding uplands. Although large areas can be assessed for fluxes using remote sensing, these methods do not adequately represent the complex topography characteristic of much of the boreal and mixedwood forest. Consequently, the C reservoirs of wetland areas are not well understood because topography strongly influences CO_2 storage and emissions. There is a wide variation in CO_2 emissions with topography with maximum levels in the transition between uplands and wetlands. This effect occurs in tolerant hardwood forests but not in coniferous or mixedwood forests.

For future commitment periods (post-2012) policymakers will need rules better suited to Canadian circumstances of forest age-class structure and natural disturbances. Current rules do not provide incentives for management actions to reduce emissions, particularly where there is a high risk of large emissions from uncontrollable large-scale disturbances.

3.2.3 The role of natural disturbances and climate feedbacks in current and future fluxes

The large quantities of C stored in forest ecosystems are affected by natural disturbances which are projected to increase as the climate changes. About one-third of global terrestrial carbon is located in the boreal forest and a tenth of the boreal forest is in Canada. There are close links between C budgets and large-scale disturbances of harvesting, wildfire and insect damage, but humans have limited control on the net C balance because of the inability to limit natural disturbances. Much of the annual wildfire burns within a few days of favourable weather patterns leading inevitably to large losses. Disturbances then are the key as to whether forests are a source or sink of carbon because of the frequency and extent of disturbance from fire and/or insects (*see Fig. 3.4*). Carbon sources come from the burned vegetation and from increased emissions from soils and decomposing carbon in young forests. Burned forest-land up to five years from the fire are net carbon sources, but between ages 5 and 13, these same forests become a carbon sink, indicating a rapid recovery from the point of view of carbon. Eventually forests become sinks and remain so until maturity in the absence of other disturbances. The impact of these wildfires on the landscape is striking and indicates where fire will be the agent of change in the boreal forest in the future.

Although fires are large stochastic and unpredictable events, insect outbreaks follow largely predictable courses, at least where population changes can be monitored. This ability to monitor and predict, results in better estimates of carbon fluxes. Under a changing climate, however, pests with which we are familiar will likely become more damaging, and the emergence of formerly innocuous pests, coupled with the increased risk of invasion of exotic pests, will have unpredictable effects on forests already affected by a changed climate. Where pests and fire interact there is an increased risk of wildfire in insect-damaged forests. A warmer and drier climate is expected to increase the risk of damage from defoliating insects, particularly spruce budworm (*Choristoneura fumiferana*) which, in turn, increases the risk from fire because of the added fuel from dead and dying trees. Other defoliators and bark beetles will also increase in activity with a warming climate. The issue of the impacts of diseases on forests and carbon emissions is of concern but there is little information on the subject. Substantial losses from destructive pathogens have occurred in the past and might be expected to increase in the future if forests are under stress from other causes. The incidence of large-scale forest declines or windthrow induced by anomalous weather may also increase - the incidence and impact of these is unknown.

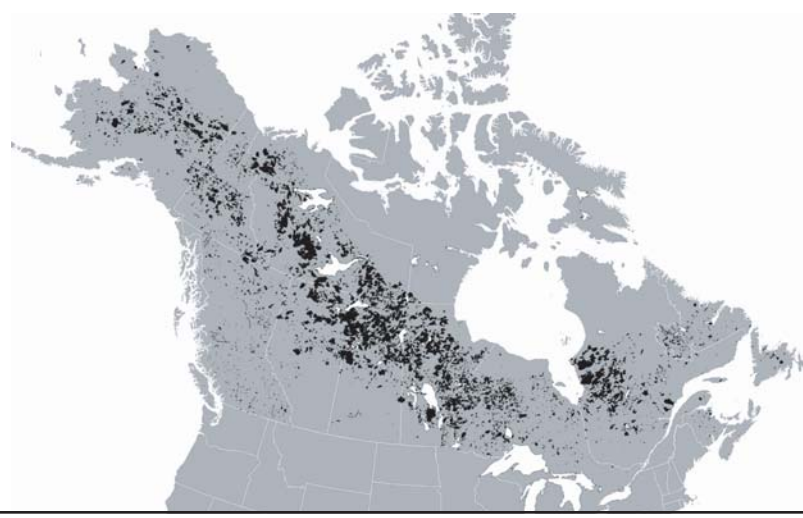
3.3 What are the options for reducing such emissions and/or enhancing sinks?

3.3.1 Context

Aside from concentrating on the risks and concerns of increasing sources of GHG from forests, whether from anthropogenic activities or natural disturbances, the question of enhancement of sinks engages policymakers because of potential opportunities for enhancing carbon

FIGURE 3.4

Distribution of large wildfires greater than 200 ha, 1980-1999. The fire polygons were kindly provided by Canadian fire agencies (provinces, territories, national parks) and the State of Alaska.



sinks and reducing losses in forests. There are many stand-level actions with potential for mitigating GHG emissions that have limited incremental carbon impacts in the short-term but may have greater and more permanent effects for carbon storage in the long-term. Long-term carbon effects are mostly dependant on continuing actions that result from permanent changes in forest management practices. There are certainly risks in projecting the effects of current activities into the future, but activities based on forest science at least have a good base from which to begin, and are subject to future risks which are not predictable.

The socio-economic impacts of forest management actions generally include an increase in the potential supply of wood from increased levels of harvesting. This would, at the same time, increase the amount of carbon storage from these actions. The socio-economic impacts will vary regionally, reducing prescribed burning that will impact reforestation efforts in British Columbia, whereas controlling spruce budworm will have greatest impact in eastern Canada. Chemical control of spruce budworm infestations and fertilization of forests may cause increases in emissions in the short-term, but would result in more stored carbon in the long-term. The successful implementation of actions is not limited by technology or experience, although infrastructure limitations may limit the rate of application. The potential carbon storage gains from actions such as managing residues, fertilization, and increased planting are highly dependent on local site conditions. Furthermore, on-going improvement in sustainable forest management practices (driven by provincial regulations, market forces and public preferences) in order to effectively utilize the potential for enhanced sinks will require substantial government initiatives. Potential actions that have a long-term impact require cost-benefit analysis and a Life Cycle Analysis to estimate total emissions.

Given that significant climate change is already unavoidable, there is a major need for policymakers to develop and implement adaptation strategies. A consensus exists that both mitigation and adaptation needs to be pursued as an integrated strategy; adaptation is necessary because no response to impacts is not an option. A reduced ability to deal with risk leads to fewer options and greater losses. Projected changes in climate over the next few decades will pose major challenges to forest ecosystem management. Afforestation, for instance, increases forest area, carbon stocks in biomass, litter and soils and the potential for future harvest. Several million hectares are potentially available for afforestation limited only by competition with agriculture. Management plans should maximize the adaptive capacity of forests and the communities that rely on them, as practices cope with, and adjust to, forest disturbances while maintaining diversity. Once forest ecosystems exceed certain critical ecological thresholds, change in their composition can become rapid and result in very different ecosystems within a short period. Adaptive strategies, intelligently implemented, can influence the evolution of our forests.

Adaptation, by definition, is the adjustment by individuals, communities and countries to environmental conditions to increase fitness for existence under new and changing conditions. The process of adaptation is ongoing whether or not the climate changes; as conditions change so must policies and actions to ensure sustainability. Although forest ecosystems will adapt autonomously to climate change, their importance to society means that society wishes to influence the direction and timing of this adaptation to change. Adaptation moderates vulnerability to change. Adaptive actions are not just something to be applied in the future - actions are needed now in anticipation of future conditions. Many changes have already taken place in forest management in response to current climate change so the basis for further adaptive action has been established.

In the case of wildfire as a disturbance, several considerations are accepted by forest managers and policymakers. Traditionally, forest management has taken place in forests with moderate fire regimes with a return fire cycle of 100-150 years. Forestry operations are now concentrating on northern/boreal forests exposing fire management to new productivity and disturbance regimes, shorter rotations and more frequent wildfires. Forest management plans based on inclusion of natural disturbances assumes that this strategy also maintains biodiversity; stand structure, forest health, integrity of soil and water resources, and the economic values supporting sustainability. Managed forests have an improved adaptive capacity because they are younger and more accessible and designed with continued management in mind. Managed forests also differ from natural forests in their structure being more fragmented and varied in species composition and so more resilient to adaptation measures and to a changing climate. It is important to remember that suppressing *all* fires is not possible, but managers have to decide where, when and how to prevent unacceptable damage to lives and property. This requires a more refined zoning system representing commercial, economic and social values to decide whether wildfires are to be suppressed, limited or to let burn.

3.3.2 Forest management options for reducing emissions and enhancing sinks

3.3.2.1 Wildfire management

If, as projected, the wildfire regime is exacerbated by past harvesting and management activities, forest managers could implement (one or more of):

- a zoning system to determine the level of response,
- place more resources into fire suppression for protection of property, fibre, and wildlife habitat,
- development of 'fire-proof' forests, particularly in the wildland-urban interface, and
- engage in more intensive management to reduce risks from wildfire.

3.3.2.2 Insect damage reduction

Current projections of insect activity suggests more frequent and intensive outbreaks. Managers can enhance spray programs while developing environmentally-benign pesticides. This is a short-term option; in the longer term forest management in the form of harvesting methods and reforestation methods can alter forest composition and 'bug proof' the forest by altering species composition to reduce risk. Maintaining young forests with shorter rotations is also a way to reduce risk, as the exposure time is reduced, so is the risk. In the immediate term, managers can zone the forest as is often done for fire management, to determine which areas are to be protected.

A changed climate raises the possibilities of well-known insects behaving differently and of new invasive insects causing damage. Forest managers can use selective harvesting and other silvicultural methods to reduce risk/susceptibility while at the same time concentrating research activities on pest management. In the case of invasive pests, managers will have to improve detection and eradication techniques based on the life-cycle of these pests and how their reproductive biology may be affected by a changed climate. A warming climate is projected to provide a more benign environment for damaging pathogens, resulting in increased damage from stem and root diseases to forests already under stress from other factors. The topic of climate-induced damage from pathogens has received little attention compared to that on wildfire and insects. Given that situation, the most appropriate adaptation response strategy to deal with pathogens, is to alter species composition and/or reduce rotation age to minimize risk.

3.3.2.3 Drought impact management

One of the most widespread changes from a warmer changing climate is more frequent and prolonged droughts with far-reaching impacts on forest health. Harvesting may further reduce precipitation and water retention, and the increased soil moisture deficits cause subsequent regeneration failures. In the short-term, managers can alter harvesting to retain overstorey trees and reduce evapo-transpiration. Reduction of the annual harvest is also an option. In the medium term, reforestation with different species/varieties to accommodate lower moisture levels, and coordination of reforestation with predicted weather events or seasons is possible. Longer-term options include managing susceptible forests as conservation areas rather than as fibre supply areas or developing drought-tolerant species for reforestation.

3.3.2.4 Adapting to climate change

A feature of the warming climate is an extended growing season and more northern latitudes becoming more favourable for forest growth. Thus, parts of the forest will show increased growth rates and other areas will become increasingly out of phase with their environment, resulting in large areas of stressed forest. One response option is to select species for reforestation better adapted to these new conditions. Additional data on the variation in the lesser-known forest species (such as white birch, balsam fir and aspen) will be needed to augment the current information base. In the short-term, implementing changes in harvest schedules, increases in harvesting rates, and examining management strategies on smaller and different forest land bases is an option. Shorter rotations leading to younger forests will also reduce risk.

A warming climate will alter land-use patterns with implications for carbon sinks as more northern lands become suitable for agriculture and less valuable as forested lands. This poses a threat to carbon storage since agricultural lands are less able to store large amounts of carbon than forested lands. Responses for forest managers imply an increased level of land and forest management previously. Adaptation will occur naturally whether active management occurs or not. To maintain many of the economic and social benefits, more intensive and active management will be necessary.

3.3.2.5 Carbon storage in wood products

One mitigation option readily available is that of longer retention of carbon in harvested wood products and the increased use of wood products instead of fossil-intensive materials. The increased use of woody biofuels instead of fossil fuels to produce energy will also help in limiting or reducing emissions. Many of these technologies are mature and now require policy changes for implementation. Adaptation options can be designed and implemented to take advantage of substantial co-benefits in terms of employment, income generation, poverty alleviation, biodiversity, watershed conservation and the supply of secure and renewable energy.

3.4 The Canadian forest carbon budget research and the Kyoto/PERD reporting challenge

The long-term carbon dynamics of forest ecosystems and their sensitivity to climate variability and change are core needs of carbon source-sink activities. When modelling efforts began about two decades ago, there was little confidence in the ability to predict how carbon dynamics would respond to climate change. PERD-supported research was expected to reduce uncertainties about the impacts on the carbon sink in forests by improving the understanding of the biophysical processes that affect C dynamics. The provision of an integrated database to carbon budget modelling groups for model validation and improvement was a major part of this initiative.

Reducing uncertainties in the estimates of carbon stock changes would allow us to claim carbon credits at the scale of individual projects and the entire managed forest. Monitoring tools are used to calculate carbon stock changes for the period 1990 to the present and require detailed forest inventory information, data on natural disturbances, and changes in land-use and forest management activities. Scenario analysis tools then project future carbon stock changes based on assumptions of future rates of disturbance, land-use change and forest management activities. These tools help managers and policymakers choose appropriate strategies to enhance carbon sinks.

The understanding of carbon stocks and emissions over time and space is essential to characterize the spatial heterogeneity of the carbon cycle across the boreal landscape and to understand the climatic and biophysical processes controlling carbon dynamics in boreal forests. Measurements of net carbon exchange between the forest and the atmosphere are carried out using aerial and tower-based biophysical collection methods. The data show the sensitivity of boreal deciduous forests to spring warming, the rapid recovery of net ecosystem production following harvesting, and the tight coupling of the carbon cycle to the hydrologic cycle. The effects of inter-annual climate variability on the C and water balances are creating an integrated, stand-level database to validate ecosystem process models. With these data, scientists are able to evaluate and improve national carbon cycle models and eventually to develop climate-driven models for growth and yield. Demonstration and quantification of these effects has been one of the major accomplishments of the PERD program.

Research on emissions from variable topography shows peaks of soil surface CO_2 emissions compared to adjacent areas suggesting a differential production of CO_2 among upland and wetland landforms. These are common landforms on the Canadian Shield; failure to consider these 'hot spots' may lead to significant under- or over-estimates of CO_2. Research is ongoing on the process for scaling-up local effects to regional and national levels.

The impacts on the carbon sink of forest harvesting is also under study by the PERD program. Approximately one million hectares are harvested annually, about 0.5% of the managed forest area. Harvested areas are a carbon source, usually for less than ten years after which they become sinks. Recovery can be enhanced by retaining residues from harvesting on site. Productivity is also enhanced by a mid-rotation thinning and other silvicultural practices. Studies on carbon dynamics after harvesting show that C stocks are materially enhanced by the addition of nitrogen fertilizers. Other silvicultural techniques, including vegetation control and thinning, can also enhance carbon sinks and can be implemented through intensive forest management.

Issues of scale, aggregation of spatial data and land-use changes are being addressed using remote sensing methods. The Canada Centre for Remote Sensing (CCRS) of NRCan is studying the development of systematic relationships between stand age and net primary productivity for major forest species, including the necessary spatial data for applying these relationships to models. The use of 'Landsat' land cover maps to estimate carbon emissions from forests, quantify the burned areas over time and space and measure the active layer of permafrost. These activities have been extended to include a semi-automatic wetland mapping method using radar, optical remote sensing data and digital elevation data. These data will then combine species composition and disturbances to predict emissions. Outputs include maps of C budgets at scales from management units to regional/national levels.

PERD has supported process studies to understand what causes carbon dynamics and sinks to change over time. It is known that the growth of young trees is stimulated by increased concentrations of CO_2 when studied in controlled environments. However, when trees were grown in field studies under increased concentrations of CO_2 and ambient levels of ground-level O_3, no growth increases were observed. In addition, damage on the exposed trees was greater from insects and diseases than on trees grown in the absence of O_3. This indicates an increased level of uncertainty in predictions of growth enhancement caused by increasing concentrations of CO_2 in the atmosphere. It is interesting to note that not all of the research undertaken automatically results in a reduction of uncertainties. In this instance, an added uncertainty has demonstrated a possible fertilization effect offset by increased O_3 pollution.

Policymakers make use of predictive, descriptive and process models to estimate emissions and sinks and to project this information into the future. PERD and other federal programs have funded the ongoing development of several process-based models that address impacts of global change on forest carbon dynamics. Supporting research, such as the activities of the Fluxnet Canada Research Network (FCRN) also helps improve the understanding of the factors affecting forest carbon dynamics. This information, coupled with land-use changes since 1990 detected by remote sensing and coordinated across land-use sectors, is increasing the predictive capability of models. The sensitivity of the national forest carbon budget is being studied to better estimate risk and the impacts of human-induced activities. This enables policymakers to calculate the probability of managed forests being a carbon sink; information required by the National Forest Sinks Committee.

Policymakers are now limited by the constraints of the results of scenario analysis beyond the next decade or two, even as global change impacts are expected to increase in intensity. Current climate models are insensitive to growth variations resulting from inter-annual temperature and moisture and do not capture climate change impacts on growth rates. If these variations can be captured in tree-ring variation, carbon models could be better calibrated and validated. PERD-supported research into short-term growth variation measured through tree-ring analysis has shown significant regional-scale variations in the growth of widely-distributed boreal species. Results to date indicate that the forest growth has increased uniformly among species and regions between 1850 and 1950, but since then growth patterns have been variable both regionally and within wide-ranging species. It is not known whether this reflects changes in weather or direct human influence such as harvesting, fragmentation or land-use change.

The CBM-CFS model predicts C neutral forests becoming a source during the next decade and a half, in contrast to being a net sink from the 1950's to the 1980's. Forests have also become carbon sources in years in which wildfires exceeded the long-term average area burned. The increasing impacts of the Mountain Pine Beetle infestation in B.C. has begun to affect carbon balances on a national scale and projections are that in the next decade forests will be carbon sources. Carbon balances therefore reflect a combination of long term variation in forest C uptake in addition to the short-term variations induced by temperature, rainfall and disturbances; all of which are outside human control.

Uncertainties in modelling carbon stocks have been reduced to some extent in that there is more data on ecosystem processes. Predictive abilities are enhanced and consequently, in the ability to negotiate international agreements and recommend changes in forest management, is improved. Examples of such improvements include those in regional climate effects on tree growth, the impact of atmospheric changes on tree growth, and recovery of carbon stocks after harvesting.

There is an increasing confidence in the modelling results which improve incrementally year to year as new information is added to databases. This leads to an increased confidence in estimates and a greater realization of the extent of the variability in natural systems, the impacts from human activities, and risks associated with increasing climate variability. Improvements are being made in supporting data sources on soil carbon, analysis of large stochastic events and the physiological changes as vegetation responds to the climate. Research to date has produced improved models describing forest ecosystems as they respond to a changing climate, atmosphere and stochastic events. A constant factor is the potential for increased uncertainty in discovering new systems and processes once considered understood. As model outputs become more accurate, the inferences policymakers can draw from them will also improve. The process is, of necessity, continuous because the policy arena also changes as international agreements are concluded and changed for reasons other than scientific.

3.5 How far have we come in meeting POL 6.2.1 goals?

The goals set by the PERD program were to reduce uncertainties, enhance the efficacy of risk assessments and develop potential strategies for the enhancement of forest carbon sinks. The likely impacts of global change and risk assessments on changes in forest carbon and the partitioning of stock changes between 'natural' and anthropogenic causes is the basis of international negotiations. The critical nature of this information stems from the extensive forests in Canada and the role that fire and insects play in carbon balances. In all cases, we have an improved understanding of these dynamics, demonstrating that we have certainly come a long way in meeting PERD goals. After seven years of PERD-funded research we have been able to draw preliminary conclusions regarding carbon dynamics in forests. For instance:

- under a warmer climate, increased drought in the Prairie provinces is likely to reduce forest cover and productivity,
- in eastern Canada, equal or greater precipitation is predicted and coupled with warmer temperatures and forests are expected to increase growth and productivity,
- stocks of soil carbon can be enhanced by Nitrogen fertilization and by retaining harvesting residues on site,
- science has demonstrated cause and effect linkages between C budgets, harvesting and wildfire,
- the relationships between stand age and net primary productivity is now much better understood,
- measurement protocols are now available for many forest ecosystems contributing to more reliable models of forest carbon sinks, thus providing increased certainty to policymakers.

Global change itself is expected to have significant impacts on forest carbon budgets despite any management interventions in forests. Research aimed at quantifying the likely fire and insect disturbance regimes under different global change scenarios will further improve these projections. The question of verification of reported forest sinks is important for both reporting commitments and negotiations. The information now being used is based on a variety of sources, particularly on the characteristics and dynamics of forests - information which was not available before establishment of the PERD program. Inter-annual variability of tree growth is known to directly affect carbon dynamics through available moisture and temperature. This can be measured directly through the use of data on the variation in growth of tree rings, and these data are then used to calibrate and validate growth models directly. The data have demonstrated considerable short-term growth variation from region to region, from species to species and among species within regions. This enhances the reliability of estimates of carbon in forests and estimates of annual emissions.

Science-based information is being used to support the development of policy on negotiations and reporting commitments, specifically on the Kyoto Protocol, Articles 3.3 and 3.4, Afforestation, Reforestation, and Deforestation in Managed Forests. Issues such as the reduction of uncertainties and quantification of the impacts of disturbances in forests are critical for policymakers, and it is here that programs such as PERD have proven so useful. PERD has enabled significant progress to be made in the following areas:

- separation of natural, indirect, pre-1990 effects in the managed forest from post-1990 direct human induced effects,
- projection of fire and insect conditions over the next 30 years,
- accumulation/decay of carbon in soils under different forest management practices,
- understanding carbon storage potential in peatlands,
- understanding of forest ecosystem processes, and
- efficiency/accuracy of sampling and monitoring programs to verify models.

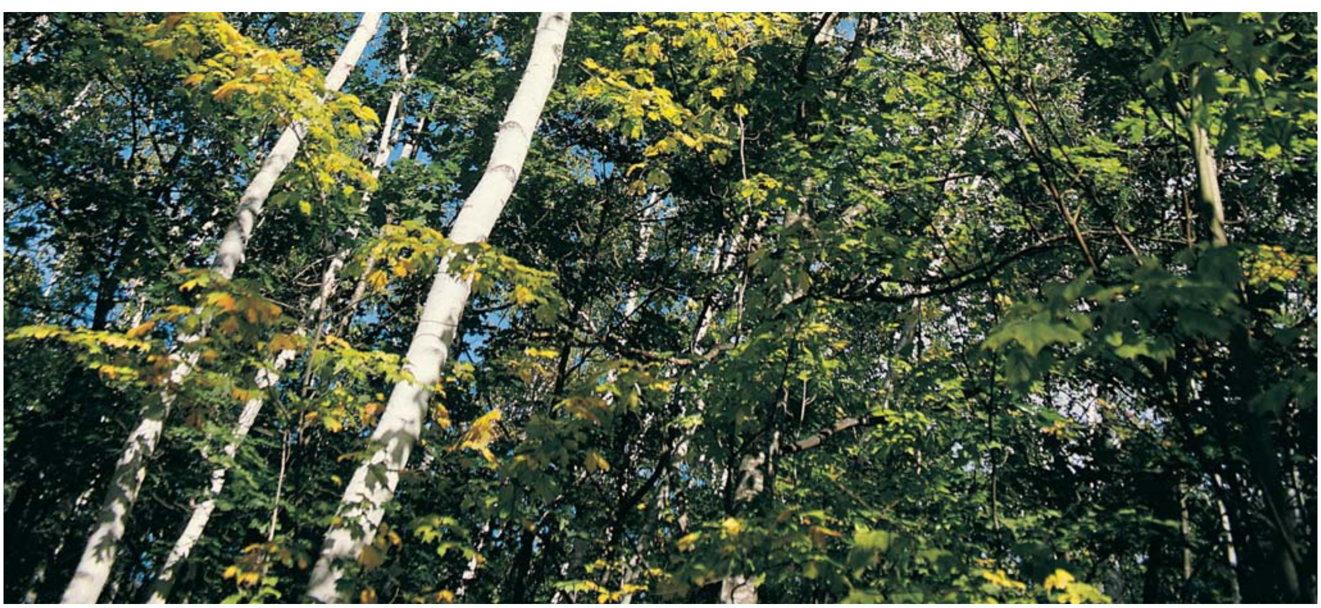
BOX 1.0

CANADA'S FOREST EMISSIONS REPORTING SYSTEM

In 2001, the Canadian Forest Service of Natural Resources Canada established a national Carbon Accounting Team (CAT) which is now leading Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS). This system, compliant with the requirements of the IPCC Good Practice Guidance report and the specific accounting and reporting requirements of the UNFCCC and Kyoto Protocol, is built on the PERD-funded Carbon Budget Model of the Canadian Forest Sector (CBM-CFS). Several versions of this model have been and are being used to report on Canada's sources and sinks.

The CAT has developed carbon accounting tools applicable at national, regional, operational and stand scales in collaboration with scientists at NRCan, Agriculture and Agri-Food Canada, Environment Canada, provincial resource management agencies, and universities.

The CAT has developed a national operational system to estimate annual wildfire C emissions under the NFCMARS supported by PERD. In additional to the resources for the operational implementation of the NFCMARS, renewed and sustained research funding is important to continue to improve the scientific basis of estimates of forest sinks. Canada is internationally recognized for its advanced research on forest carbon cycling, for the development of remote sensing monitoring programs, and for the integration of data from many sources into forest carbon accounting tools.



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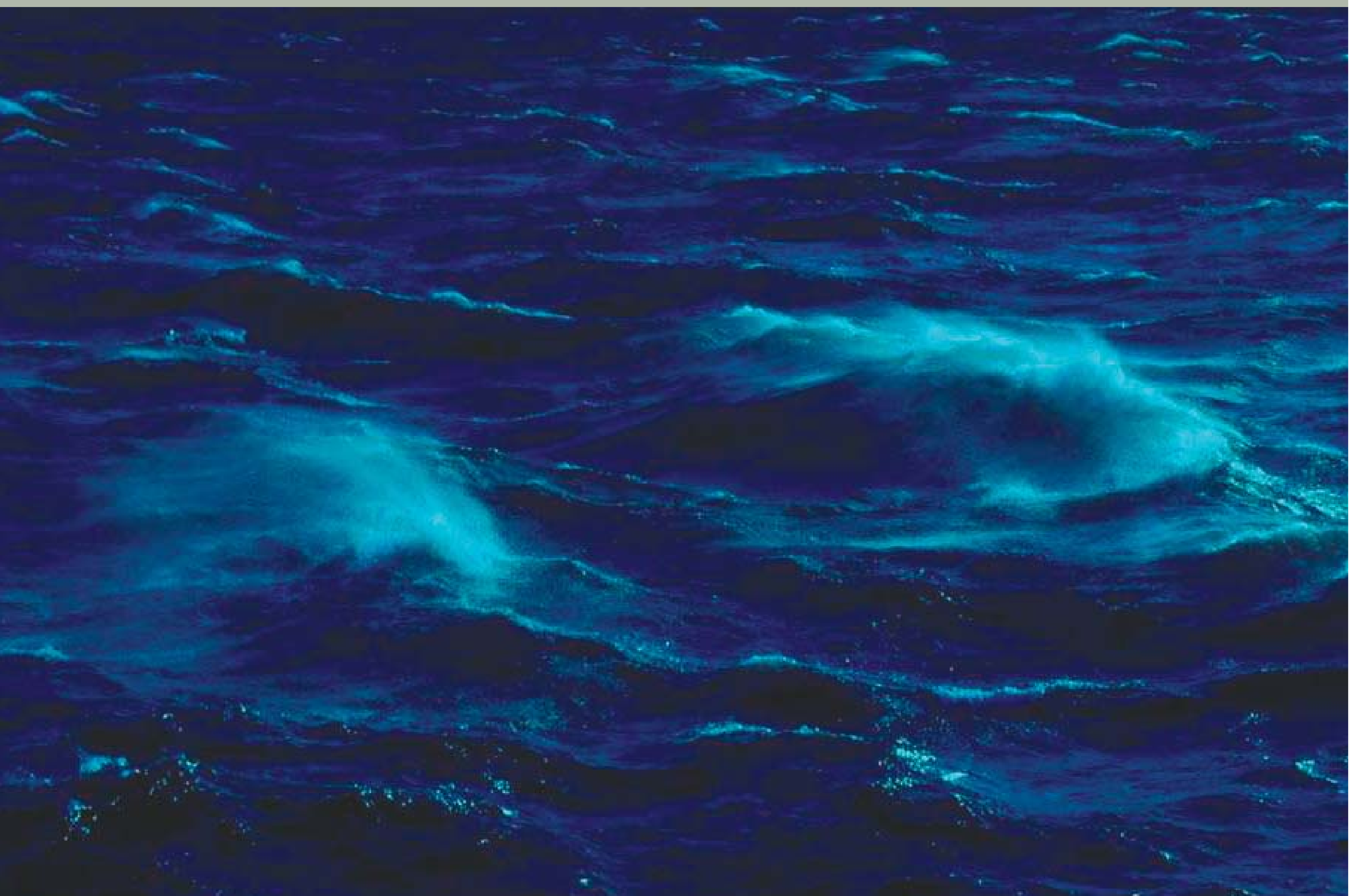

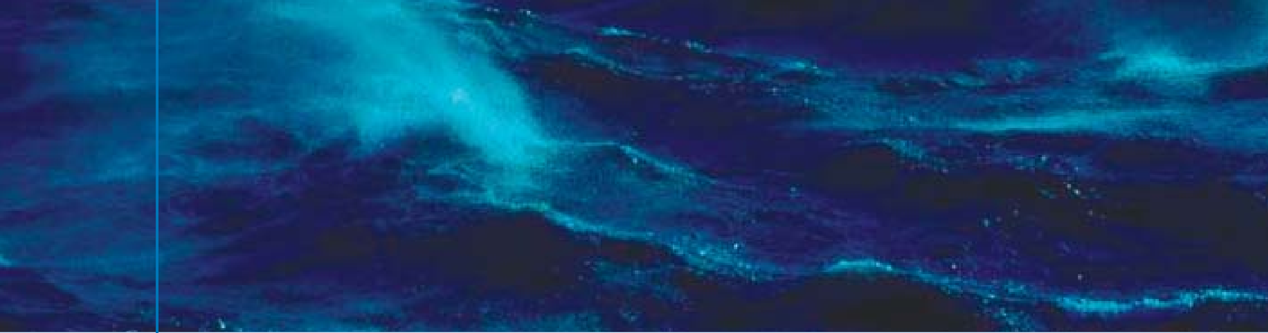

CHAPTER 4

Enhancing biological sinks in oceans: Is it practical?

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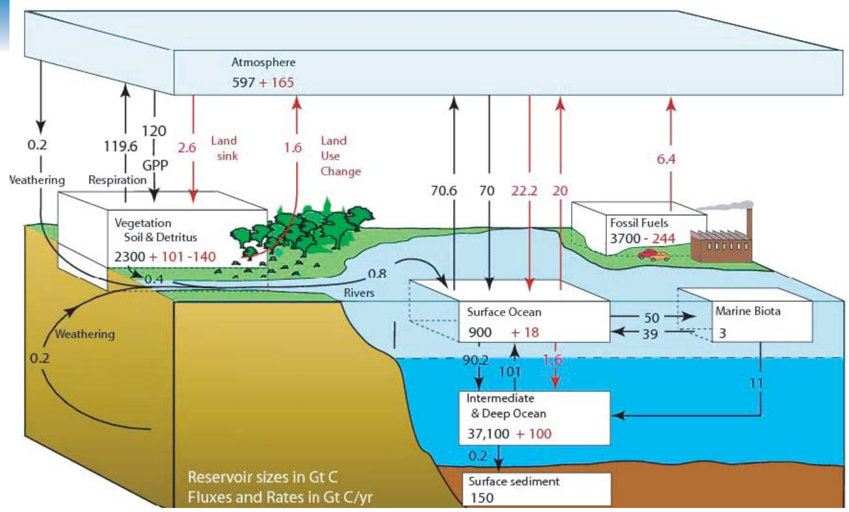
4.1 Introduction

Covering 70% of the Earth's surface and extending several kilometres deep, our oceans provide a huge sink for carbon dioxide (CO_2), the dominant *greenhouse gas* (GHG). As greenhouse gas levels rise in our atmosphere due to human activities, the ability of oceans to adsorb it is a dominant factor in predicting future warming trends in Canada, our three adjacent oceans, and across our planet. Warming is evident in most of our instrumental records over the past century. This warming has been particularly rapid in Alaska and northern Canada, where temperatures have increased by more than 2ºC since 1970 (IPCC, 2007a).

Ocean warming is not only a symptom of rising GHG levels in the atmosphere. It is also a perturbation that is affecting ocean circulation. For example, an enhanced stratification of the upper ocean is resulting in weakening gas exchanges between ocean and atmosphere which is creating a threat to ecosystems that rely on oxygen transported from the atmosphere to the interior ocean. The consequences of altering the movement of heat, fresh water, nutrients and gases within our oceans include impacts on regional climate, changes in ocean productivity, alterations of ecosystems, and loss of habitat for marine organisms.

As noted in Chapter 1, about one-third of the CO_2 resulting from the burning fossil fuels is adsorbed by our oceans (*see Fig. 4.1*). In the North Atlantic, surface waters are occasionally dense enough to sink to deep-ocean where they become part of the abyssal circulation of the world's oceans. In the subarctic Pacific, a region of gas exchange near the Asian coast also transports gases away from the atmosphere, but only to intermediate depths where they are isolated from the atmosphere for perhaps several decades. As spring arrives, carbon dioxide is fixed into organic matter by photosynthesis and into inorganic shell material for a variety of organisms. A large portion of this material is consumed and remineralized in the shallow ocean. However, some waste material sinks into the deep ocean and into ocean sediments where it is stored away from the atmosphere for decades to millennia. Carbon has been stored like this throughout geologic time. Vast carbon deposits in ocean sediments (and in continental land masses) are generally secure. However, some of these deposits may be mobilized as oceans warm and become more

FIGURE 4.1



The global carbon (dioxide) cycle for the 1990s, showing reservoir sizes in Gt C (boxes) and main annual fluxes (arrows) in Gt C yr $^{-1}$: preindustrial 'natural' in black and 'anthropogenic' in red (IPCC, 2007a).

acidic due to increased levels of CO_2. The releases of stored carbon from carbonates and frozen methane deposits are emerging areas of concern.

Predicting how oceans will change in future decades is a major challenge for modellers. Their information, however uncertain it may be, provides the information that societies, governments, industries, scientists and individuals need to prepare for the effects of global warming.

DFO modelling efforts that seek to address this challenge have been greatly enhanced through participation of scientists involved in programs such as Surface Ocean, Lower Atmosphere Study (SOLAS). Funding by the Panel of Energy Research and Development (PERD) allowed DFO scientists to contribute to the large experiments undertaken by Canadian SOLAS. The benefit to DFO and other government departments from such collaborations is immense, and includes essential improvements to models predicting the impacts of global warming. One SOLAS project tested the hypothesis that iron enrichment would increase the productivity of the subarctic Pacific, thereby increasing the rate of carbon storage in this region. This large experiment (three vessels and several million dollars in total) provided evidence that the ocean cannot be easily manipulated to increase its uptake of CO_2. The strong drawdown of nutrients and dramatic shifts in plankton populations suggest such perturbations would be very disruptive to entire subarctic ecosystems.

This chapter provides a review of activities and results of related research that DFO has conducted with the assistance of PERD POL 6.2.1 (Enhancement of Greenhouse Gas Sinks, EGGS). The review begins with an overview of the current state of understanding that has emerged from this research. Subsequent sections look at various monitoring, process and modelling activities in greater detail. Many of these results were used as the scientific basis for recent findings of the Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report on climate change science, in particular Chapter 7 of the working group I report on the Physical Science Basis of Climate change. Ken Denman of DFO was the lead author of that chapter, and Allyn Clarke a reviewer.

The review of DFO's activities supported by PERD will highlight findings dealing with major carbon transport processes.

In the past 15 years, oceanographic studies have moved towards large collaborative efforts involving communities of researchers and their access to resources. In the early 1990s, World Ocean Circulation Experiment (WOCE) undertook to survey the entire global ocean to provide a cohesive data set with which to advance our understanding of ocean circulation and its transport of heat, nutrients, gases and fresh water. Integral in WOCE was the collection of oxygen, carbon dioxide, chlorofluorocarbon (CFC) and other tracer data, to better understand the ocean's capacity to store atmospheric gases. During the WOCE period (1990-1997), Joint Global Ocean Flux Studies (JGOFS) undertook to measure the interannual variability of carbon (and other biogenic materials) transport at a variety of sites worldwide. Following JGOFS was Global Ocean Ecosystem Dynamics (GLOBEC), a program intended to better understand productivities of regional ecosystems. Recently, SOLAS provided a means for many of Canada's ocean and atmosphere scientists to study heat, water and gas exchanges between sea and sky. All of these global initiatives were focused on better understanding the role of oceans in moderating climate. Throughout these large programs, PERD funding supported small but essential components of the research.

So, how to separate out the importance of PERD contributions to these various programs? Of course this cannot be easily done. None of these programs could succeed without DFO ship access and research resources, or without enthusiastic involvement from university students and professors. This assessment of the successes of the Enhanced Greenhouse Gas Sequestration (EGGS) program of PERD will therefore be a review of major findings of DFO science over the past decade or more. All the information presented will have been supported in part by PERD. The substance of the report will come from presentations made at the PERD workshop held in Ottawa, February 2007, and from various PERD reports. Discussions will attempt to answer how we dealt with the objectives listed under the 2000-2005 EGGS Plan, which listed 6 goals of ocean research:

- To acquire observations of carbon cycling in the NW Atlantic and NE Pacific Oceans necessary for the development and evaluation of ocean carbon cycle models to be used for assessing CO_2 sequestration;
- To develop models of natural sequestration of atmospheric CO_2 in waters adjacent to Canada that integrate key chemical, biological and physical processes;
- To develop associated models of enhanced CO_2 sequestration through purposeful fertilization of oceanic regions and evaluate against existing observations from previous experiments in the Equatorial Pacific and the Southern Ocean;
- To participate in an international purposeful iron fertilization experiment in the NE Pacific Ocean (Ocean Station P) using models to design the experiment, conduct the experiment, and to synthesize the observations;
- To refine our capability to model and monitor key ocean carbon sinks in the waters adjacent to Canada in order to make major contributions to the assessment of GHG sequestration;
- To provide an internationally creditable scientific assessment of the possible achieved levels, feasibility and costs, and consequent environmental risks of enhancement of oceanic carbon sequestration by purposeful fertilization in oceanic regions adjacent to Canada.

4.2 The role of northern oceans as sources and sinks of greenhouse gases

The IPCC report on *Climate Change 2007: The Physical Science Basis* (IPCC, 2007a) states that *"the increases in atmospheric carbon dioxide (CO_2) and other greenhouse gases during the industrial era are caused by human activities. In fact, the observed increase in atmospheric CO_2 concentrations does not reveal the full extent of human emissions in that it accounts for only 55% of the CO_2 released by human activity since 1959. The rest has been taken up by plants on land and by the oceans."*

DFO research on GHG tends to focus on the ocean sequestration of CO_2, the gas responsible for ~70% of the observed global warming, rather on its role in either producing or assimilating other gases such as methane or nitrous oxide. In large part this is because carbon dioxide is a relatively long lived GHG in both the atmosphere and ocean, has been measured on comprehensive surveys such as WOCE, and has well known transport routes in oceans. Much less is known about CH_4 and NO, except that there are hot spots in oceans where they are produced and that they are turned over fairly quickly. Hence, carbon flux has also been the focus of most of the DFO research funded by PERD POL 6.2.1.

Figure 4.1 above shows the relative size of carbon sinks on Earth. The deep ocean, which is by far the largest repository, continues to accumulate the anthropogenic carbon that humans have been mobilizing through our uses of fossil fuels, land and forests. Improved estimates of ocean uptake (2.2 Gt C y^{-1}) suggest little change in this rate between the 1990s and early 2000s. However, models indicate the fraction of anthropogenic CO_2 stored in oceans will decline as atmospheric CO_2 levels increase. Warming oceans will result in their surface layers becoming more buoyant, thereby reducing the production of dense surface waters in winter that sink into the deep ocean. This will affect especially the North Atlantic, where most of the ocean sequestration of anthropogenic CO_2 occurs (*see Fig. 4.2*). In addition, reduced mixing will decrease the amount of nutrients returned to the ocean surface from intermediate depths, as has been observed in the subarctic Pacific. This will reduce the growth of phytoplankton and hence reduce the biological export of carbon from the surface to deeper waters.

Canadian research into ocean sinks has focused on the three northern oceans adjacent to Canada. Activities and results are discussed in the following sections.

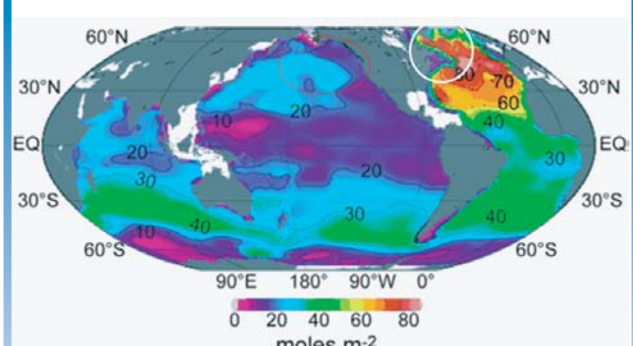
4.2.1 Carbon fluxes in the North Atlantic and Arctic regions

4.2.1.1 DIC fluxes in the Labrador Sea

North East Atlantic Deep Water (NEADW) and Denmark Strait Overflow Water (DSOW), together with Labrador Sea Water (LSW), compose the lower limb of the global ocean conveyor belt (*see Fig. 4.3*). In these regions, the formation of dense (cold and saline) waters in winter causes a sinking motion that transports large volumes of ocean surface waters to the deep regions of the ocean. Since atmospheric gases are adsorbed into the cold North Atlantic surface waters, this deep water formation process becomes a major conduit for the transport of atmospheric gases into the ocean deep waters, where they remain until the slow moving conveyor belt returns these deep waters to the surface some 1000 years later, in other ocean regions where upwelling occurs.

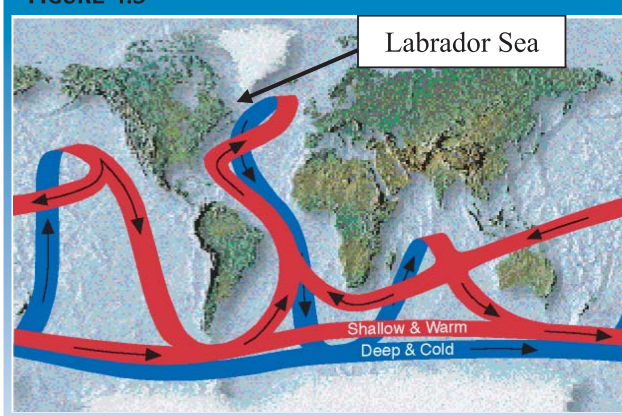
The role of the Labrador Sea in this process is a major focus of DFO research into carbon sinks. One part of this effort deals with improved understanding of the transport of dissolved inorganic carbon (DIC), which

FIGURE 4.2



Anthropogenic carbon storage in our oceans from Sabine *et al.*, 2004. ~48% of all fossil fuel emissions have ended up in the ocean, 1/3 of its potential to store CO_2. Circled are two areas being actively studied by DFO.

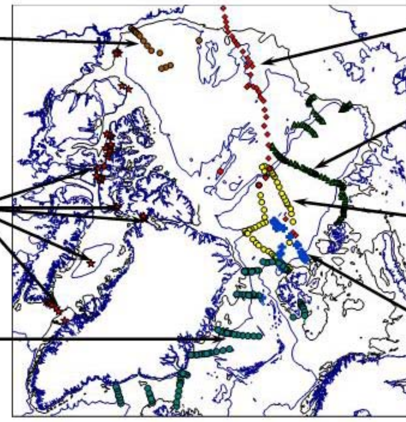
FIGURE 4.3



The general thermohaline circulation of world oceans, driven by the formation of cold, saline waters in the North Atlantic.

FIGURE 4.4

Arctic Ocean Expeditions, 1987-2002.



encompasses CO_2 in all its chemical forms in seawater together with alkalinity. Since the anthropogenic contribution to the very large natural reservoirs of DIC are relatively small and therefore difficult to detect, researchers also look at the oceanic distributions of chlorofluorocarbons (CFCs) to trace the uptake and transport of anthropogenic CO_2. CFCs have been manufactured since the middle of the last century and exhibited growing atmospheric concentrations until their use and release began to be curtailed by the Montréal Convention. Because the concentration of the several forms of CFCs proportionally changed over time in the atmosphere, their ratios are useful in deciphering when oceanic waters were last in contact with the atmosphere.

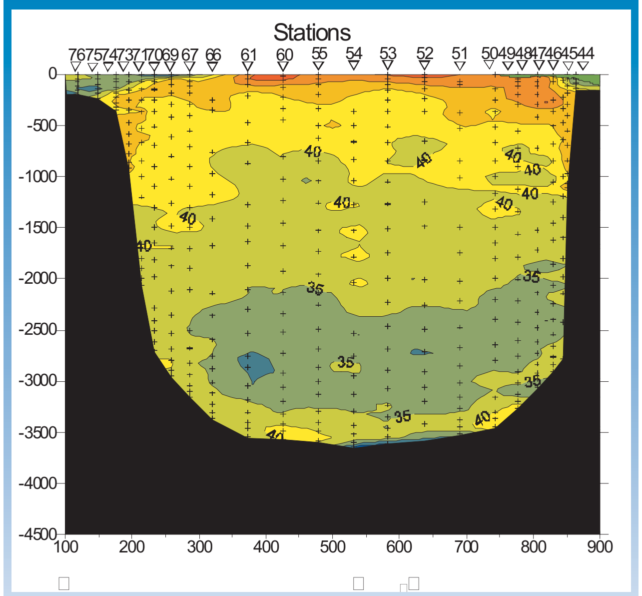
These tracer studies in the Labrador Sea provide researchers with a window to the processes that govern the variability of major long-term storage in the ocean. These studies are complemented by those in the North Pacific, where long-term upwelling returns deep ocean water, and its stored CO_2, back into contact with the atmosphere. Over the past two decades, these studies have helped quantify the natural and anthropogenic CO_2 inventories and fluxes between atmosphere and ocean, and have led to a better understanding of the controlling mechanisms for CO_2 flux variability in response to climate changes.

Much of the DFO research, supported by funding from PERD and other programs such as Climate Change Action Fund (CCAF), DFO Strategic Science Fund (SSF) and National Oceanographic and Atmospheric Administration (NOAA), has been undertaken as partners in a wide variety of international programs, such as Arctic Climate Systems Study/Climate and Cryosphere (ACSYS/CliC), Carbon Dioxide in the North Atlantic (CARINA), Climate Variability and Predictability Programme (CLIVAR), Joint Global Ocean Flux Study (JGOFS), Surface Ocean Lower Atmosphere Study (SOLAS), World Ocean Circulation Experiment (WOCE) and Carbon Data Synthesis in the Atlantic Ocean. Other partners in these activities have included Goteborg University, Scripps Oceanographic Institution, Finnish Institute of Marine Research, Lamont-Doherty Earth Observatory, and others.

Labrador Sea surveys conducted by DFO over the past ~15 years provide the longest time series of DIC and transient tracer measurements in the North Atlantic Ocean (*see Fig. 4.4*) and is providing some of the best evidence of ocean changes in response to climate (see also section 4.5 for ecosystem changes). Related chemical measurements are also providing a means of distinguishing carbon sequestration by physical and biological means. Results show that 1.9 +/- 0.4 Gt anthropogenic C is currently stored in the Labrador Sea. This represents 6.4% of the Atlantic inventory, even though this sea accounts for only 3.6% of the Atlantic's volume. On an annual basis, the Labrador Sea takes up 0.06 Gt C of anthropogenic CO_2. However, this rate depends on the depth of winter ventilation and is highly variable.

Figure 4.5 shows an example of such a survey conducted in 1997. It shows that anthropogenic carbon levels in deep waters of the Labrador Sea were between 30 – 50 μmol kg^{-1}. Lower anthropogenic C concentrations are found between ~2000 and 3000 m, where waters were last ventilated at the surface about 12 years earlier. However, higher concentrations are found near bottom, where waters appear to have experienced more recent ventilation (5-7 years). Such measurements of DIC and CFC fluxes are being used to improve models of North Atlantic and global circulation. These models are assisting in predictions of the relative importance of the solubility and biological pumps on CO_2 sequestration as surface waters continue to be impacted by global warming. Models and continued observations will both be required to answer questions about the variability of the Labrador Sea sink and the impact of climate warming on the ocean's ability to sequester CO_2. Models are the tools that allow us to project our observations into the future. However, many models are evolving rapidly as we improve our understanding of ocean processes. An apt quote for our times may be *"Models come and go, but a good data set lasts forever"* (Quay, 2000).

FIGURE 4.5



1997 anthropogenic CO_2 concentrations in the Labrador Sea, on a survey section from Labrador (left) to Greenland (right).

The data sets obtained through the collaborative international research programs have also enabled the scientists involved to estimate the anthropogenic C inventory in the Arctic Ocean (1.3 Gt C, 1% of the global ocean content), and its sequestration rate (0.026 Gt C y^{-1}, ~1% of the global ocean rate; Anderson *et al*., 1998). Still, questions remain about how changing ice conditions will affect the ocean uptake rate of CO_2.

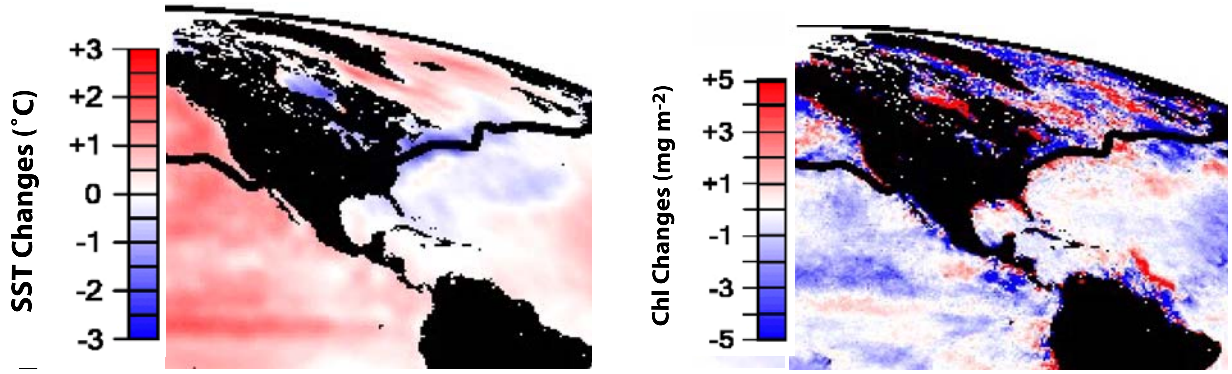
4.2.1.2 Biogenic carbon in the lower trophic levels of the Labrador Sea

Oceanic ecosystems are complex and not especially well understood at the planktonic level. Many ecosystem models reduce this complexity by defining only two phytoplankton groups based on size, along with their respective grazers, together with bacteria and a few environmental controls on growth and loss. This biology is then imbedded in an actively mixing ocean.

However, as ecosystems are stressed, some functional groups can be affected in ways that are not easily anticipated in such models. Recently, Barber (2007) presented a complex model showing the importance of picoplankton (0.2 to 5 μm size) in contributing to carbon export, stating new information suggests that "the role of picoplankton in carbon export and fish production needs further investigation in both observations and models".

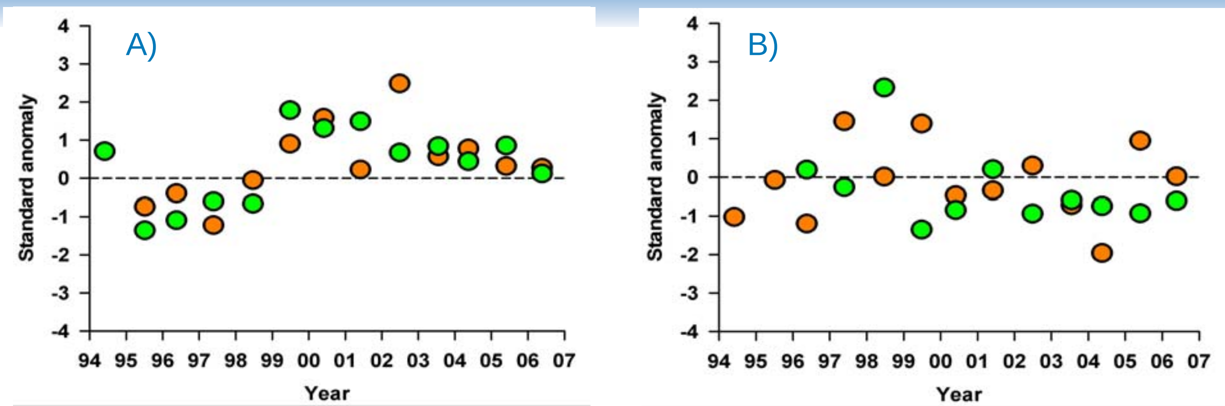
Other research is showing ocean response to climate changes. In warm ocean regions, the trend over the past decade has been for net primary production (as measured from satellite) to decrease as temperatures increase (Behrenfeld *et al*., 2006). In cooler waters such as those found in the North Atlantic (and Pacific), the opposite may occur as the increased stratification of the upper ocean results in higher average light levels for phytoplankton.

FIGURE 4.6



Changes in sea surface T (left) and chlorophyll (right) from satellites over the past decade (from Behrenfeld *et al.,* 2006).

FIGURE 4.7



Anomaly trends in (a) picophytoplankton (green) vs NO_3:Si ratio (red), and (b) bacteria (red) vs DOC (green) on the Labrador Shelf.

Satellite data suggest this may be occurring in the Labrador Sea (*see Fig. 4.6*). Such evidence leads to conjecture that:

- enhanced ocean stratification → increased phytoplankton biomass → increased dissolved organic matter → increased bacterial biomass → perhaps increased C export to deep ocean.

However, observations from repeat survey sections across the Labrador Sea since 1994 show something quite different:

- waters are warming → mixed layer is shoaling → nutrient balance is changing (more nitrate relative to silicate) → small phytoplankton are increasing → total phytoplankton biomass is **decreasing** → DOM is **decreasing** → bacterial biomass is **decreasing** → perhaps C export via the biological pump is decreasing.

Obtaining the evidence for these changes has required extensive sampling of plankton biomass, associated rate process, nutrients and physical properties of the upper ocean over more than a decade. In addition, satellite data (especially SeaWIFS for chlorophyll *a*) has provided details of annual cycles and interannual changes. By standardizing data sets against the mean of their time series, trends can be assessed. For example, the small phytoplankton on the Labrador Shelf (most of which have no obligate requirement for silicate) are more abundant when the nitrate: silicate ratio is high (*see Fig. 4.7*). In such a relative low silicate regime, the large phytoplankton (especially the silicate-requiring diatoms) would be at a competitive disadvantage. In the same region, bacteria biomass tends to covary with dissolved organic carbon and mesozooplankton biomass has been inversely proportional to phytoplankton biomass (more zoo = less chlorophyll). Weak trends in these correlations are strengthened when persistence is observed for many years.

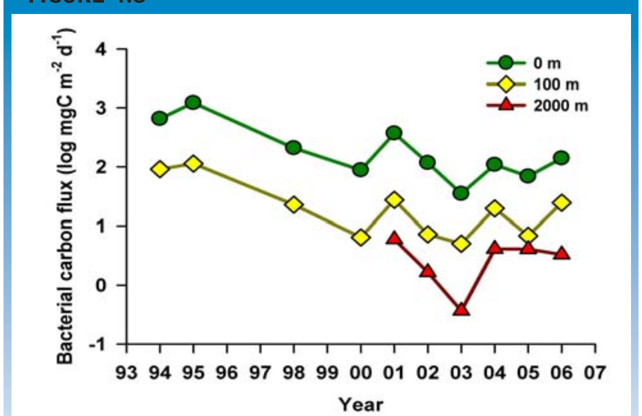
Carbon export from the surface ocean via the biological pump is typically assessed by trapping sinking detrital particles. In the Labrador Sea, this particulate flux exports ~1.3% of the annual primary production to depth (*see Fig. 4.8*). Vertical carbon transport is largely organic through spring and summer, but has a large inorganic constituent (calcium carbonate) in fall. Bacterial growth and respiration throughout the water column consume most of the organic carbon in sinking particles, converting the carbon into biomass for transfer to higher trophic levels, and to CO_2 for release to the dissolved carbonate pool. DOC fluxes are poorly assessed but potentially provide a substantial fraction of export carbon (see modelling results in section 4.6). Since 1993, the apparent amount of organic carbon consumed by bacteria has been declining.

From the studies carried out in sections 4.4 and 4.5, the current trend appears to be for the Labrador Sea to be a weakening sink for anthropogenic carbon, both due to a reduction in ocean ventilation (solubility pump) and changing ecosystem structure (biological pump). This trend is consistent with findings of recent IPCC reports (IPCC, 2007a).

4.2.1.3 Modelling natural carbon sinks in the Labrador Sea

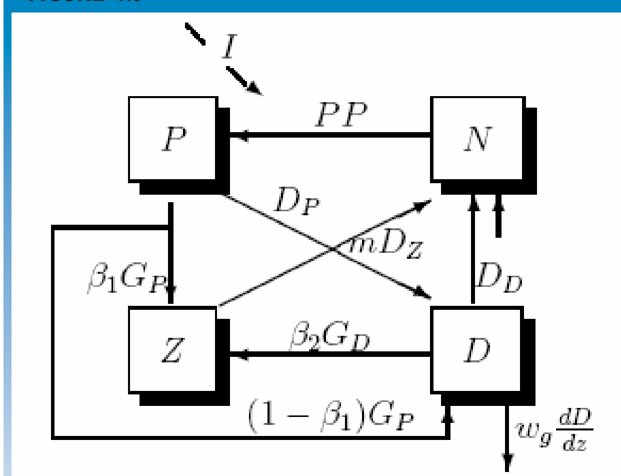
Models help resolve important transport processes both where rich data sets are too complex to interpret by simple correlations, and where data is insufficient to describe annual processes and changes over decades. Both Pacific and Atlantic models rely on a simple ecosystem (*see Fig. 4.9*) imbedded in an active upper ocean layer which is largely controlled by wind mixing and solar heating. As more is learned about the circulation of the upper ocean and the parameters

FIGURE 4.8



Downward flux of carbon susceptible to bacterial degradation.

FIGURE 4.9



A model of a simple ecosystem with boxes for nutrients (N), phytoplankton (P), zooplankton (Z) and detritus (D), with various rates of energy transfer connecting carbon pools (boxes).

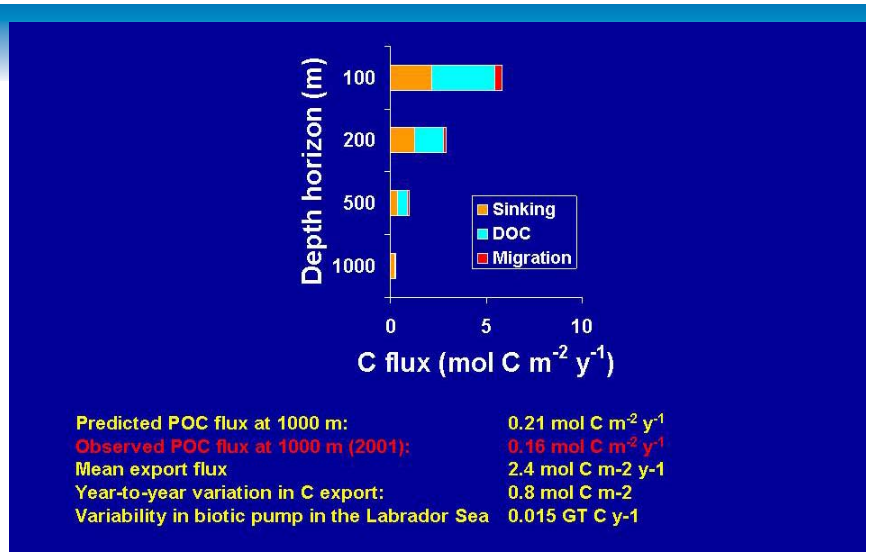
controlling biological communities through programs such as JGOFS and SOLAS, models evolve to better capture the dominant processes responsible for e.g. carbon transport in subarctic waters.

Tian *et al*., 2004, built a physical model of Labrador Sea circulation from observations in the 1990s to better understand the role of the seasonal productivity cycle in exporting carbon to deep ocean. Since this model was constructed with data from a deep ventilation event, it assumed annual mixing in winter to a depth of 2400 m. Vertical profiles of chlorophyll concentration, mesozooplankton, nitrate, ammonium, bacteria, and DOC and Continuous Plankton Recorder data of phytoplankton and mesozooplankton were used to constrain the biological model. In this model, boxes are homogeneous with respect to their function in the ecosystem and parameters describing flow between boxes are fixed over the domain of the simulation. One of the surprising results of the simulation based on this model was that DOC accounted for 56% of the biogenic carbon exported in the upper 500 m (*see Fig. 4.10*). Most of this export occurred at the onset of deep winter convection. However at 1000 m, sinking particles accounted for 96% of the downward flux and DOC for 4%.

The evolution of Labrador Sea ecosystem models has been towards allowing adaptation to environmental factors within boxes and amongst interactions between boxes. Model parameters can change depending on circumstances such as ambient temperature, food preferences, community size structure or, in the case of bacteria, the ease with which the DOC pool can be utilized. This approach is proving successful in reproducing major ecosystem features of several water types within the North Atlantic using a single model. Without temperature adaptation for processes, such as phytoplankton mortality and zooplankton grazing, phytoplankton abundances are misrepresented in subtropical and subarctic regions.

The Labrador Sea model has been used to test changes in the biological pump over a period of 50 years. The physical component of the model reproduces the observed trend towards increasing stratification of the ocean, a result perhaps of increased fresh water fluxes rather than ocean warming (this is consistent with trends in the subarctic Pacific, likely the result of increased evaporation in the subtropics). Increased stratification leads to variable trends in phytoplankton and bacterial biomass, but shows these populations tracking each other. However, more striking is the slow

FIGURE 4.10

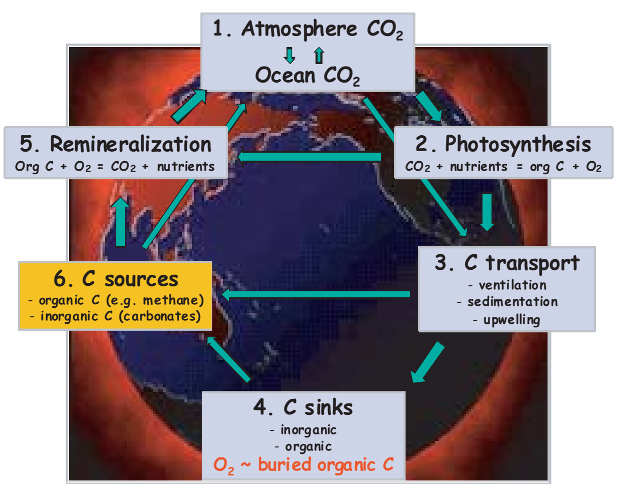


Biogenic carbon export to the mesopelagic zone (100-1000m).

decline in POC export over 50 y and the sharp decline in DOC export in the last decade, these exports declining by 0.7 gC m^{-2} y^{-1} between 1990 and 2005 according to model results.

In summary, the 50 year simulation of Labrador Sea shows that increased surface stratification is resulting in slightly lower primary production (the population is shifting towards smaller cells, see section 4.5) but reduced biogenic export over the past 15 years. Modelling captures some of the changes observed by satellites and observational programs. Sustained changes in forcing result in modelled regime shifts due to improvements in the representation of feedback loops. Improvements are needed in better representation of freshwater fluxes and trophic controls of bacteria. However, changes in the ocean are beginning to be persistent as a consequence of global warming and models are showing success in describing these consequences. The need for continued observation and modelling efforts in key high latitude regimes is greater than ever.

FIGURE 4.11



Major fluxes of carbon between atmosphere and ocean, and within the ocean.

4.2.2 Carbon in the North Pacific

The Climate Chemistry group at IOS, under the direction of C.S. Wong, has carried out measurements of carbon fluxes in the North Pacific since the mid 1970s. In 1982, they began deploying sediment traps at Ocean Station Papa (OSP) to measure fluxes of carbon and other biogenic particulate material to deep ocean. Over the past 3 decades, companion measurements have included primary productivity, nutrients, CO_2 in atmosphere and ocean, particulate organic carbon, dissolved inorganic carbon (DIC), alkalinity and, in recent years, iron. Early studies provided the basis for expanded research under PERD which included an increased deployment of sediment traps throughout the subarctic Pacific, routine measurements of DIC and alkalinity on survey sections, use of ships of opportunity to obtain seasonal changes in the surface waters of the subarctic Pacific, measurements of ocean tracers (e.g. CFCs) to assist in understanding gas absorption by oceans, and iron fertilization of the upper ocean to determine whether such enrichment could increase the ocean absorption of carbon dioxide. The findings of these programs will be reviewed in the context of the transport process described in *Figure 4.11*. The iron enrichment experiment is discussed in section 4.2.3 below.

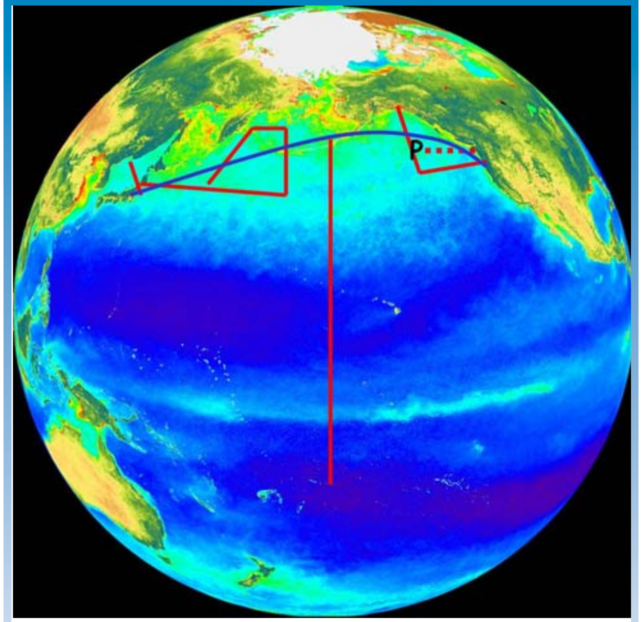
4.2.2.1 Atmosphere – ocean fluxes

Wong and Chan (1991) found that waters of the NE Pacific were a weak sink for CO_2, with uptake rates being estimated at 8 g C m^{-2} y^{-1} in the 1970s. Using ships of opportunity (SOO), blue line in *Fig. 4.12*) through the late 1990s, in collaboration with Japanese researchers (Zeng *et al*., 2002) estimated the subarctic Pacific (34 to 53ºN) CO_2 uptake at 0.26 Gt C y^{-1}, in excess of 10% of the annual oceanic sequestration of anthropogenic carbon. Indeed, most of the ocean storage of fossil fuel carbon occurs in the thermocline region of the upper ocean. Only in the North Atlantic is anthropogenic C found below 1500 m depth (see section 4.4), such deep storage accounting for ~7% of the ocean inventory (Sabine *et al*., 2004).

4.2.2.2 Primary Productivity

Except along continental margins, the subarctic Pacific is replete with nitrate, silicic acid and phosphate

FIGURE 4.12



Location of carbon flux studies in the North Pacific. P denotes *Ocean Station P* (OSP). Survey lines are shown against an image of ocean chlorophyll.

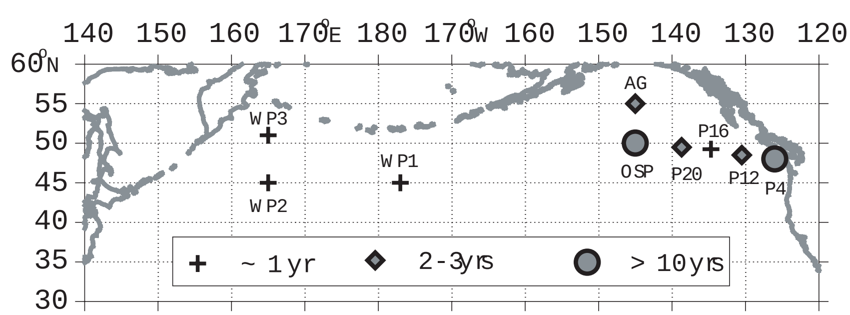
throughout the year because phytoplankton growth is limited by iron supply and light in winter. Wong *et al.*, (1995, Can. J. Fish. Aquat. Sci.) provided a good estimate of primary productivity for OSP of 140 gC m^{-2} y^{-1} based on *in situ* measurements taken over more than a decade. Surface ocean surveys along Line P from the coast of Canada to OSP, and across the Pacific on SOO, provided seasonal estimates of new production based on nutrient drawdown (Line P – 16 to 20 gC m^{-2} y^{-1}; SOO – 32 to 56 g C m^{-2} y^{-1}). During the JGOFS program of the mid 1990s, it became clear that iron was the limiting nutrient in the subarctic Pacific. This finding spurred the Climate Chemistry group to develop sensitive and contamination free measurements for iron in seawater. This capability then permitted the SOLAS iron enrichment experiment to be carried out in 2002, and, in addition, allowed this group to estimate iron transport away from the British Columbia and Alaskan coasts by mesoscale eddies (Johnson *et al.*, 2005). Earlier, Wong and Matear (1991) had noted that silicic acid can become a limiting nutrient at OSP upon occasion. They suggested increased iron transport may be responsible for this odd occurrence. During the iron enrichment experiment, silicic acid depletion was again observed, leading modellers to consider both iron and silicic acid as potentially limiting factors on phytoplankton growth.

4.2.2.3 Horizontal particle fluxes

By using sediment traps to collect sinking particles, fluxes of C and other biogenic elements (N, Si, iron, etc.) can be estimated to great ocean depth. Starting in 1982, as a result of collaboration with Woods Hole Oceanographic Institute, the Climate Chemistry group began deploying traps at OSP. Through the 1990s, this program expanded to include deployments throughout the subarctic Pacific (*see Fig. 4.13*).

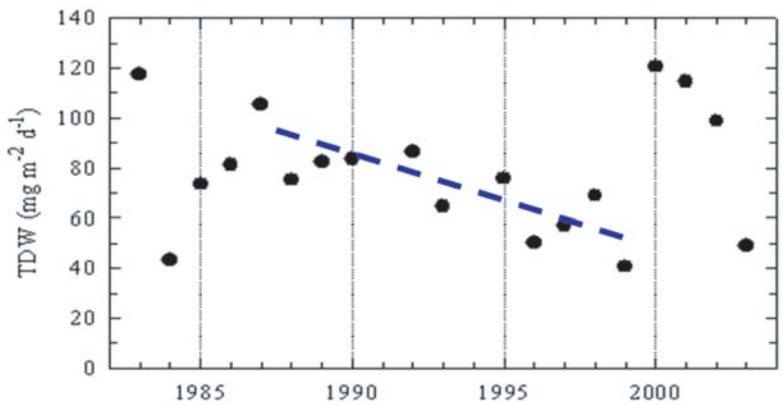
The general trend found at these sites were that carbon fluxes are higher near continental margins due to increased iron supply and enhanced mixing/ transport, which increases primary productivity. At OSP, fluxes were measured at 6.6 gC m^{-2} y^{-1} to 200 m

FIGURE 4.13



Sediment trap deployments in the subarctic Pacific Ocean between 1982 and 2006.

FIGURE 4.14



Annual total dry weight (TDW) of particle flux to 3800 m recorded at OSP. Note the period of declining vertical flux during the warm 1990s. Fluxes increased following the 1999 La Niña as surface nutrient levels rebounded from the lows of the mid to late 1990s.

and 1.1 gC m^{-2} y^{-1} to 3800 m (Wong *et al.*, 1999). Periods of high flux were occasionally observed, suggesting processes such as mesoscale eddies, Aeolian dust (iron) deposition events, or plankton swarms may greatly enhance carbon transport. Evidence of eddies passing through OSP was found in its 50 year data record (Whitney *et al.*, 2007). In the eastern subarctic Pacific, elevated offshore chlorophyll levels have only been associated with such eddies (Crawford *et al.*, 2007).

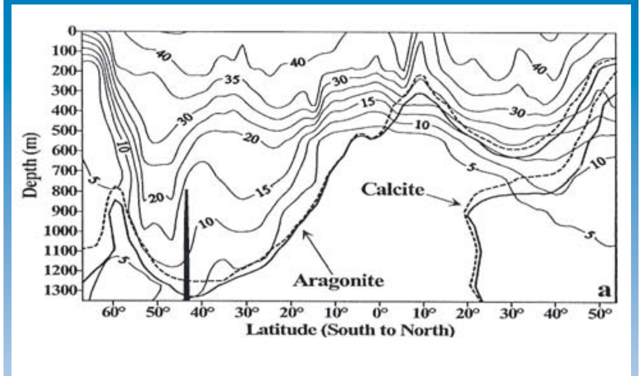
Sediment traps are an excellent way in which to observe interannual variability in primary productivity and vertical transports of C that may be induced by changes in stratification of the open ocean brought on by e.g. El Niño. The N Pacific was impacted by frequent El Niño events in the 1990s, with the result that the stratification of the upper ocean increased, winter nutrient supply to the mixed layer diminished (more for silicic acid than nitrate since deeper mixing is needed to access remineralized Si) and primary productivity deceased. Phytoplankton studies are not a routine part of the OSP monitoring program, however a weakened silicic acid supply is known to affect the growth of larger phytoplankton (diatoms), resulting in a community shift towards smaller cells (see section 4.5). Such a shift tends to result in less carbon export by biota (*see Fig. 4.14*). The sediment trap program is no longer operating since PERD funding ended in 2006.

4.2.2.4 Carbon remineralization and sinks

Trap studies show that ~3% of the carbon fixed by primary production sinks past 200 m and ~1% reaches 3800 m at OSP. Sea floor sediments in this region contain little C, also sedimentation rates are very low. Therefore C storage is dependent on seawater's ability to store remineralized CO_2 and the frequency with which deep ocean waters exchange gases with the atmosphere. Over the past 50 years, oxygen has decreased by 22% at OSP over the depth range of 100 to 500 m (Whitney *et al.*, 2007). Many other observations prove this trend to be common throughout the subarctic Pacific, the cause being reduced ventilation of the interior ocean along the coast of Japan and Russia. Increased upper ocean stratification appears to be caused by a freshening as well as a warming of the surface layer. Surface ocean freshening has been observed both in the North Atlantic and North Pacific, and is likely due to increased evaporation in subtropical and tropical waters, although glacial melt also contributes.

A reduction in ocean ventilation in the subarctic Pacific will result in biotic process becoming relatively more important in C sequestration. From CFC and DIC measurements made during WOCE, Matear *et al.*, 2003, estimated the North Pacific (20 to 65N) stored 1.1 Gt anthropogenic C through the 1980s. Yet nutrient supply to the surface layer is lessening as the North Pacific stratifies (Whitney *et al.*, 1998). Thus, observations support model contentions (see sections 4.6 and 4.8) that the biological pump is weakening.

FIGURE 4.15



The depth at which calcite and aragonite dissolve in the Pacific Ocean is shoaling over time, due to the increased acidity of the ocean brought about by increasing CO_2 levels. (from Feeley *et al.*, 2002).

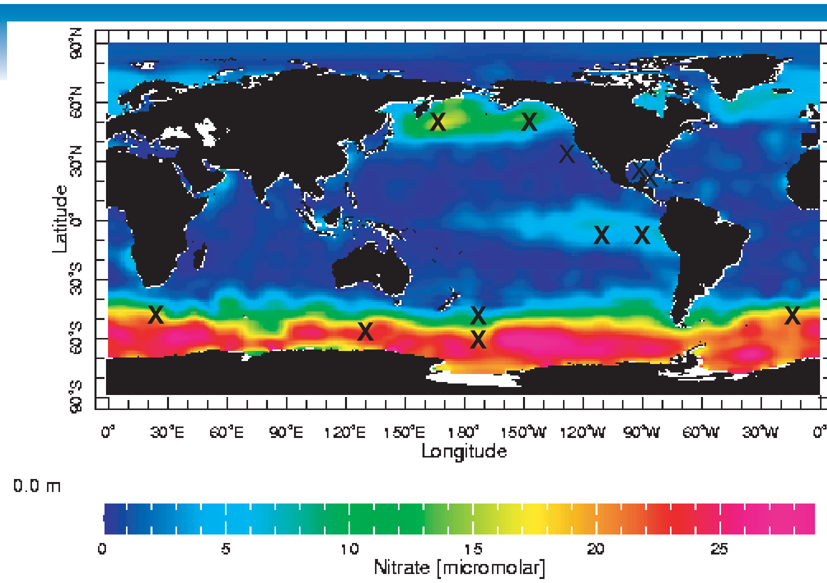
A concern over increased ocean C storage is that the dissolution depth for both forms of calcium carbonate is shoaling (*see Fig. 4.15*). At present, only a 200 m surface layer in the subarctic Pacific will allow carbonates to be stored in sediments. As oceans acidify due to the increased storage of CO_2, sedimentary carbonates will dissolve and marine organisms using carbonates in exoskeletons may find it difficult to survive. Changes in the intermediate waters of the subarctic Pacific (decreasing oxygen, increasing acidity, warming) are already impacting coastal ecosystems. In the upwelling region along the Washington and Oregon coasts, fish and crab kills are being seen each summer over the past several years, whereas they were not seen previously. Low oxygen (hypoxia) and high nutrients in upwelled waters combine to suffocate animals unable to move to refuge. On the BC coast, evidence from commercial fish catches suggests several groundfish species are being forced into shallower habitat as oxygen levels decline (Sinclair and Whitney, unpublished).

4.2.3 Ocean CO_2 sequestration by Iron Fertilization – what have we learned?

Carbon enters the ocean from the atmosphere either through the solubility or biological pumps. The solubility pump describes the physical process by which CO_2 dissolves in cold ocean waters and is then transported to the deep ocean where it is sequestered for centuries to millennia. The most effective solubility pump is found in the North Atlantic where winter mixing occasionally produces dense waters that sink to the ocean bottom.

The biological pump refers to biotic processes in which CO_2 is taken up by plants and made into organic carbon. Some portion of this fixed carbon sinks out of the surface layer of the ocean as detritus. The North Pacific

FIGURE 4.16



A map of surface nitrate levels in the world's oceans. X marks the locations where iron enrichment experiments have been conducted.

is a region in which biota do not drawdown all of the nutrients (nitrate and silicic acid) and so the biological pump does not appear to operate at maximum efficiency. Light and iron restrict primary productivity through most of the subarctic Pacific, a finding that was well proven through the Canadian JGOFS program in the mid 1990s. From these results, and those in two other ocean regions with excess nutrient (the Southern Ocean and the equatorial Pacific, ***Fig. 4.16***), enhancing ocean sequestration of carbon by adding iron to the ocean in these regions was theorized.

Following on from large experiments carried on in the equatorial Pacific and Southern Oceans, the Canadian SOLAS community organized and obtained funding for an iron fertilization experiment near Ocean Station P (OSP) called Subarctic Ecosystem Response to Iron Enrichment Study (SERIES). Iron enrichment of a 10 x 10 km patch of ocean was carried out by the Climate Chemistry group at IOS, which scientists onboard 3 vessels from Canada, Mexico and Japan monitored chemical and biological changes over a 28 d period.

Measurements of iron, CO_2, tracers, dimethyl sulfide and organic carbon provided through support from PERD to Climate Chemistry were instrumental in the success of this experiment. In addition, DFO provided ship time and many routine physical and chemical measurements to help explain the drift, expansion and deformation of the iron enriched patch.

After 3 weeks, and two iron additions, a strong phytoplankton bloom exhausted silicic acid and iron in seawater, leading to a crash in the bloom and a large flux of silica from the surface layer. However, even though this experiment observed vertical export from the patch (other experiments did not observe this export), little carbon left the upper 100 m of the ocean. Evidently, open ocean ecosystems are effective in retaining most of the carbon and nitrogen fixed by primary productivity even under strong perturbation. A high silica export was observed, leading to the speculation that iron enrichment could deplete subarctic waters of silicic acid, thereby causing huge ecological shifts which could dramatically reduce energy transfer to higher trophic levels.

A biophysical model was developed to describe annual cycles at OSP that tracked nitrogen, carbon, silicic acid and iron. This model was adept at identifying processes controlling primary and secondary production under usual conditions. This model was able t oreproduce the observations in the iron manipulation experiment. When iron was added , both Fe and Si became critical limiting nutrients to phytoplankton frowth at OSP (Denman *et al.* 2006; Ianson *et al.* in prep).

Some of the important findings of this iron enrichment experiment that arose from observations and modelling are that:

- SERIES was unique because the patch was observed long enough to determine carbon export;
- carbon export was not enhanced;
- a second iron addition was necessary to create a diatom bloom
- total carbon export will decrease as fertilized patch size increases
- silicic acid (Si) is likely to become limiting in the Northeast Pacific under iron replete conditions;
- Si limitation by iron fertilization may cause pCO_2 in the long term to **increase**;
- Si limitation will be enhanced as the patch size increases;
- Iron fertilization drives nutrients deeper into the ocean and in time reduces the power of the biological pump to sequester carbon;
- **modelling results demonstrate that large-scale iron fertilization schemes would not aid in ocean sequestration of anthropogenic carbon.**

4.2.4 Impact of PERD on Canadian Centre for Climate Modelling and Analysis (CCCMA) model development

As a joint effort between EC and DFO, a modelling group was established at University of Victoria to advance Canada's understanding of global warming and its impacts on our regions of concern. Under the leadership of Ken Denman, an active ocean compartment has been developed to improve predictions of atmospheric changes projected in coming decades. An active ocean requires seasonal variation, active mixing and realistic biology. PERD funding has especially assisted this large effort by supporting the advancements of ecosystem modelling.

4.3 How far have we come in meeting POL 6.2.1 goals?

Without funding from PERD and other nationally directed sources such as DFO's Ocean Climate Program and Strategic Science Fund, Canadian oceanographers would have had little to contribute to the greatest environmental debate of this and coming decades - global warming. Strong research programs, some with well-designed observational elements, have provided data over the past decades from ocean areas infrequently visited by other nations, and are showing some striking changes in their physical, chemical and biological nature. Our studies in the subarctic Pacific, North Atlantic and Arctic Oceans permit Canadian scientists to discuss climate change with conviction. As a result, DFO researchers have made substantial contributions to the 2007 IPCC reports on Climate Change.

PERD related research has resulted in:

- Better understanding of the ocean-atmosphere carbon cycle (increased CO_2 levels are resulting in ocean acidification, which is increasing the solubility of carbonates; increasing ocean stratification is leading to reduced nutrient supplies to surface oceans and ecosystem changes due to weakening silicic acid supply; better assessment of primary productivity and vertical particle transport provides estimates of C transport to deep ocean at ~1% of primary productivity; importance of ocean ventilation in transporting CO_2 and oxygen into the ocean is better understood, implications of declining ventilation is realized, including loss of habitat of commercial fish species and other ecosystem components);
- Improved measurements of carbon cycling which have been used to initialize models being developed to predict impacts of global warming on ocean and land masses. These models suggest oceans are becoming a weaker sink for CO_2 than they have been over past decades. This is predicted to lead to an accelerating rate of CO_2 accumulation in atmosphere;
- Strong evidence that the ocean cannot be easily fertilized to sequester carbon (iron enrichment experiments have not been effective in sequestering C and show that any such manipulations would cause radical changes in ecosystems that support fisheries and other marine life);
- Improved biophysical models both for the Atlantic and Pacific based on participation in programs such as SOLAS and JGOFS. Increased ecological complexity and adaptability are leading to more realistic ecosystem simulations over wider geographic ranges.

Ken Denman of DFO was one of the lead authors of the report on "The Physical Science Basis" of climate change, this chapter's reviewers including R.A. Clarke of DFO. Their expertise evolved from ocean observations and modelling supported by PERD.

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CHAPTER 5

Greenhouse Gas Emissions from Canadian Hydroelectric Power Generation

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5.1 Introduction

As noted in Chapter 1, global wetlands constitute a major carbon reservoir. On average, they provide a net sink for carbon. However, because the decay of biomass in wetlands largely occur under anaerobic conditions, they also constitute a major natural source of methane. The relative roles of individual wetlands as sources and sinks of greenhouse gases depends on a range of physical and biological factors, particularly temperature and water table levels.

Human land-use change activities can affect the role of these wetlands as sources and sinks of greenhouse gases. For example, drainage of swamps can expose the carbon reservoir within these wetlands to oxidation, and hence cause them to become a significant source of CO_2. However, lowering water tables through drainage also reduces the anaerobic decay that produces methane emissions. Conversely, flooding of wetlands can enhance methane production.

In is within this context that experts first cautioned, in the early 1990s, that flooding of ecosystems for the purpose of generating hydroelectric power could be a significant added source of greenhouse emissions, particularly in tropical regions and for very shallow reservoirs (Rudd, 1993; Gagnon and Chamberland, 1993; Svennsson and Ericson, 1993; Galy-Lacaux, 1999). This increase in methane release results from the anaerobic decay of biomass inundated during the filling of the hydro reservoirs, and the escape of much of the methane generated into the atmosphere. In fact, some argued that the greenhouse gases produced from hydro reservoirs in some locations could be comparable, per unit of energy generated, with that produced by power generation plants using fossil fuels.

Recent studies suggest that this concern remains an issue. Some experts have suggested that related emissions for the 52,000 largest reservoirs around the world could be as high as 100 million metric tones – similar to that released by all of the Earth's natural wetlands. In some cases, emissions from these reservoirs could be very large. For example, while estimates for average greenhouse gas emissions from Brazilian hydro-reservoirs, using a full life cycle analysis, suggest that these are still less per kWh generated energy than the equivalent greenhouse gases emitted from combined-cycle natural gas turbine (CCGT) plants of 50% efficiency (dos Santos *et al*., 2004), those hydropower complexes with low power density (i.e. energy generated per unit area of water reservoir) produced similar GHG emissions to the CCGT plants. In particular, emissions are high for reservoirs that are shallow and plateau-like. Furthermore, while these studies have focused on the effect of flooding on methane emissions, most have inadequately addressed how these reservoirs affect net CO_2 flux or emissions of nitrous oxide (Fearnside, 2002, 2004; UNESCO, 2006; Delmas, 2005; IPCC, 2007; Lima, 2007).

Other researchers have countered that hydro reservoirs in northern latitudes have much lower greenhouse gas emissions than those in low latitudes. They also note that most emissions occur during the first decade after flooding. Beyond the first decade, reservoir emissions of greenhouse gases should decrease and eventually become similar to that of natural lakes at similar latitude. Furthermore, they argue that much of the flooded lands were wetlands that were already sources of methane. In fact, flooding these wetlands may actually suppress methane emissions by allowing much of the methane released at the reservoir bottom to be oxidized into carbon dioxide within the reservoir waters before they are released. Hence, when 'net' emissions are calculated, flooding from hydro generation could actually reduce net methane emissions. Emissions are also significantly lower for run-of-river power generation than for large reservoirs behind hydro dams. Deep water reservoirs at similar low latitudes tend to exhibit lower emissions (Tremblay, 2005; Huttunen, 2005; dos Santos, 2005).

Finally, hydro reservoirs also affect CO_2 fluxes. Some reservoirs have been shown to absorb CO_2 at their surface, but most emit small amounts as water conveys carbon in the natural carbon cycle (Tremblay, 2005).

The overall conclusions of these studies have shown that, for most hydro projects, net GHG emissions are likely to be low relative to the fossil fuel based generating plants that they replace. However, these can vary significantly between reservoirs. Furthermore, accurately measuring and reporting the incremental anthropogenic-related emissions from freshwater reservoirs remains a challenge (IPCC, 2007; UNESCO, 2006).

This issue is also important to Canadians. Large hydro reservoirs have been created in recent decades, and more are planned for the future. Most of these plans assume that these developments are 'greenhouse gas neutral'. That is, they should neither decrease or increase net emissions of greenhouse gases. Yet available research suggests that Canadian reservoirs in boreal regions (where the surface area-to-volume ratios are large and hence substantial quantities of organic biomass are flooded), could generate emissions equivalent to about 20 to 60 kilotonnes (Kt) of CO_2 per TWh of power generated. While only about 5% of that for fossil fuel based power plants (~500 to 1200 Kt CO_2 per TWh), it is a factor that needs to be considered in related energy policy choices (Duchemin, 2002).

It is within this context that the OERD requested the EGGS POL steering committee to include in its research activities a program aimed at enhancing existing Canadian research efforts into hydro reservoir emissions. The formal objectives identified for the PERD initiative were to:

- *better understand the processes that affect the fluxes of greenhouse gases related to hydroelectric reservoirs;*
- *develop methods to accurately quantify changes in net fluxes following hydroelectric developments; and*
- *communicate such information to policymakers as a scientific basis for the development of GHG mitigation program options.*

5.2 PERD research program into greenhouse gas emissions from hydroelectric reservoirs

In response to the above request from the PERD Panel, the PERD POL 6.2.1 steering committee proposed the following research strategy:

- **Measure fluxes from small reservoirs (flooded areas) and unflooded natural landscapes** at the Experimental Lakes Area. This project would examine whole ecosystem effects and GHG emissions associated with flooding of wetlands and upland forested areas of the Canadian Shield.

- **Develop a methodology and model for accurate inventory of GHG fluxes in existing hydroelectric systems.** The focus of this project would be to operate a comprehensive inventory and monitoring program for GHGs, in collaboration with hydroelectric companies.

- **Test predictive modelling of GHG fluxes based on types and size of areas flooded and duration of flooding.** Detailed models to simulate the changes in greenhouse gas fluxes due to flooding would be developed from the intensive studies on flooding experiments at the ELA and scaled up to apply to the large reservoir systems studied with the hydroelectric companies.

The Freshwater Institute (FWI) of DFO was provided with related PERD resources allocated to this program between 2000 and 2007, and tasked with implementing the research program and provide the lead on achieving the related objectives established for the program.

Researchers from the FWI first held extensive consultations with international peers and project partners to form the basis for a pertinent research plan. These consultations included:

- Discussions with Hydro Québec re the state of measurements of greenhouse gas emissions from Hydro Québec reservoirs;

- Meetings with BC Hydro contractors to assess the present state of knowledge of GHG in BC reservoirs and to recommend a GHG assessment program for the BC reservoir system;

- A workshop on flooding experiments at the ELA site, attended by the major partners, including participants from DFO, Manitoba Hydro, Hydro Québec, BC Hydro, University of Alberta, and University of Waterloo;

- Negotiations with Manitoba Hydro and their consultants re field work needed to help estimate greenhouse gas fluxes in three locations being considered for future hydroelectric installations;

- Collaboration with EC in developing related methodologies for the national GHG inventory.

These consultations helped provide the basis for developing a pertinent work plan for 2000-2005 PERD funding period. Subsequent annual workshops related to the ELA part of the program, which included the input of major partners such as Manitoba Hydro, Hydro Québec, BC Hydro, University of Alberta and University of Waterloo, provided a collaborative forum for further development of these plans. After the completion of the first PERD funding cycle in 2005, the plans were extended to March 2007.

Activities performed under this program and related results are reported in the following sections.

5.2.1 ELA Studies

5.2.1.1 Monitoring and process studies

The Experimental Lakes Area (ELA), where much of the PERD funded research into reservoir emissions was undertaken, is located on the Precambrian Shield of northwestern Ontario, approximately 250 km east of Winnipeg and 50 km east-southeast of Kenora. The ELA includes 58 small lakes (1 to 84 ha in area) and their drainage basins, plus three additional stream segments, which have been set aside for the purpose of whole-lake manipulation studies. The facility has been in existence since 1968, and is managed through a joint agreement between the Canadian and Ontario governments. With permanent buildings housing modern labs, living facilities and support services, it offers scientists and biologists a unique opportunity to do experimental research in nature instead of inside the laboratory. Entire small lakes are available to test hypotheses about freshwater ecosystems. The availability of laboratories on site allows a range of analytical work to be carried out on samples such as water, zooplankton, and fish with minimum delay.

This facility is therefore also an ideal location for the creation of small reservoirs to experiment with the aftermath of flooding events. The advantage of the ELA experimental approach is the ability to do controlled measurement before, during and after flooding. While such reservoirs are much smaller than those used for hydroelectric production, they do mimic the shallow areas of the larger commercial reservoirs that exchange waters with deeper parts of the reservoirs. This provides useful information for designing hydroelectric projects by predicting after-effects of reservoir flooding and drawdown. Among the flooding effects that can be studied is the release of greenhouse gases.

Researchers at the ELA already began building large containment structures in different types of forested areas (from scrub pine to dry forest types) in the early 1990s. These structures allowed them to simulate reservoir creation, typical of hydroelectric dams, through flooding and seasonal withdrawal of flooded waters. This ELA program is known as the Experimental Lakes Area Reservoir Project (ELARP). The main study area within this project is a large flooded reservoir known as “L979”, a 16.8 ha boreal wetland complex that includes a central pond and is vegetated with sphagnum moss and black spruce trees.

However, large hydro reservoirs also flood upland forests as well as peatlands. The upland regions have significantly different soils and vegetation and hence different amounts of stored organic carbon. In 1999, the ELA community also established a complementary Flooded UplanD Experiment (FLUDEX) at three upland sites. The sites included a moist forest area with high carbon storage, a dry forest area (medium carbon) and a very dry forest area (low carbon).

The addition of PERD funding for related research allowed a significant expansion of this research to start in 2000. That year, researchers began taking samples twice a week from the central pond area of the reservoir and analyzed these for CO_2 and CH_4 concentrations. In collaboration with University of Alberta researchers, detailed measurements of CO_2 concentrations were also taken at the three FLUDEX reservoirs. Finally, for comparison purposes, undisturbed reference lakes of similar size were also sampled for CO_2 and CH_4 concentrations. These samples were taken in conjunction with chemical and biological monitoring of the lakes. Measurements of primary production in these lakes and reservoirs were also taken to help interpret the observed natural GHG fluxes.

The network of ELA sites for GHG data collection was expanded in subsequent years, until all 17 of the actively sampled ELA lakes were included by 2004.

To make use of data collected for earlier programs at ELA (some extending back to 1973), all of the historic data for CO_2 and methane concentrations and for CO_2 fixation by algae at ELA were also compiled.

In addition to taking samples from the ELA reservoirs and lakes, researchers used PERD resources to begin the development of instruments to monitor GHG fluxes on a continuous basis. An important technical advance in this initiative was achieved in 2005-06 with the addition of methane sensors for continuous remote measurement of dissolved gases. This advance allowed a much better determination of the methane cycle in fresh water and a clearer understanding of the factors controlling methane production. The development of the methane sensor has allowed the design of a floating chamber for the continuous monitoring of bubble fluxes, believed to be an important flux of methane but not CO_2.

Partly due to the conclusion of PERD funding of the program, the last intensive greenhouse gas flux observation for the ELARP reservoir took place in 2006-07. The data collected represents the culmination of 12 years of seasonal flooding and may represent the beginning of a study on ecosystem recovery after disruption. As required by the ELA operating agreement, the existing dam will be removed and the natural flow regime restored at the end of this study.

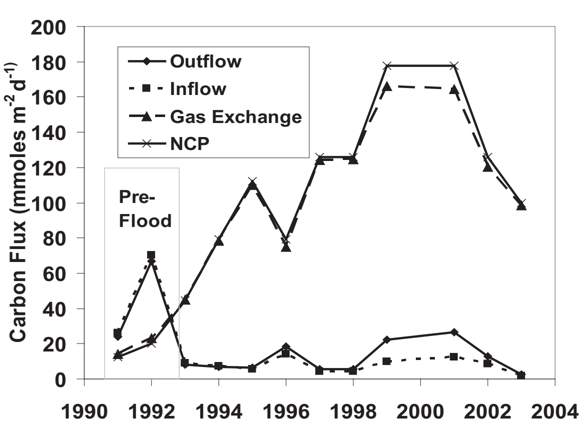
5.2.1.2 Analyses of ELA data

CO_2 emissions. Since the key area of interest in greenhouse gas production in flooded reservoir systems is the net contribution they make in adding to or withdrawing greenhouse gases from the atmosphere, net annual greenhouse gas fluxes must be calculated. Such calculations must consider the fluxes of greenhouse gases between reservoir and atmosphere throughout all seasons, and must include the entire system (including downstream lakes and source waters). For example, for

CO_2 fluxes from any given body of water, calculations of this net CO_2 production (NCP) must consider: the export of CO_2 downstream (the water outflow from that body times the CO_2 in that water); the import of CO_2 from upstream (water inflow times the CO_2 its contains); and the net transfer of gases between the body of water and the atmosphere above. The latter must be calculated using a gas flux model that applies a mass transfer coefficient dependent on wind velocity. CO_2 fluxes are also significantly influenced by temperature and the presence or absence of ice and snow cover. Because these variables constantly change, this becomes a complex calculation.

Figure 5.1 shows the results of analysis of the CO_2 fluxes for the ELARP L979 wetland system over multiple years. Note that the emissions rise dramatically during the first decade after flooding, than begin to decline. When integrated for the entire year, the analyses suggest a pre-flooding NCP of about 0.2 to 0.5 kg CO_2 $m^{-2}y^{-1}$ that increased to 1.6 kg CO_2 $m^{-2}y^{-1}$ immediately after flooding.

FIGURE 5.1

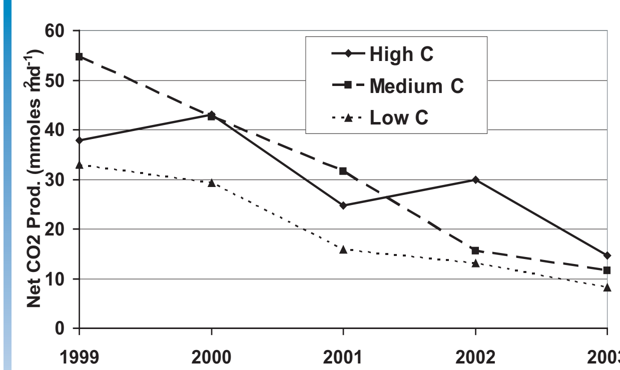


Trends in CO_2 fluxes at the ELARP L979 site between 1990 (pre-flood period) and 2003. Note that the values for carbon flux into the reservoir from upstream sources and out to downstream reservoirs are small and offsetting. Hence, the flux of carbon as CO_2 from the reservoir to the atmosphere (gas exchange) is very similar to net CO_2 production values. One mole of carbon has the weight of 12 grams. Source: Hesslein 2007.

In the three upland FLUDEX systems, estimates for NCP during the first year after flooding ranged between 0.3 and 0.5 kg CO_2 $m^{-2}yr^{-1}$. This decreased much more rapidly in subsequent years than at the L979 site, dropping to between 0.07 and 0.15 kg CO_2 $m^{-2}yr^{-1}$ after five years of flooding. By comparison, one of the NCP undisturbed reference lakes (Rawson Lake) was about 0.04 kg CO_2 $m^{-2}yr^{-1}$.

Results from the upland sites differ significantly from that of the wetland system. Prior to flooding, the FLUDEX sites had a relatively well balanced long term carbon budget, with net flux between land and atmosphere near zero. After flooding, NCP at all three sites rose significantly to levels similar to that observed at the ELARP site. Surprisingly, NCP was similar for all three sites, regardless of the carbon content within the landscape. The NCP at the FLUDEX sites increased significantly during the first year after flooding but, in contrast to the ELARP site, decreased noticeably during the next few years (*see Fig. 5.2*). Isotopic analyses suggest flooded biomass within these reservoirs was the primary source of the NCP, rather then inflow of dissolved organic carbon (Bodaly, 2004; Matthews, 2005).

FIGURE 5.2



Trends in NCP after flooding at the three FLUDEX sites. One mole of CO_2 has a mass of 44 gms. Source: Hesslein 2007.

The NCP results for both the ELARP and FLUDEX sites appear to be reasonable. In order for a body of water to have a positive net carbon dioxide production capability, it must receive more organic carbon (which decomposes into CO_2) than it loses. In old lakes, sediments are accumulating. Hence, unless there is a net inflow of organic carbon from elsewhere, they are natural sinks for carbon and should experience negative NCP. There is a large net inflow of carbon from the drainage basin as DOC. Much of that DOC flocculates and provides the carbon for sediment accumulation. Some of that flocculated carbon that settles to the sediment is metabolized to CO_2 by sediment bacteria and provides the net flux to the atmosphere. However, in artificial reservoirs, organic matter in newly flooded lands provides a new source of organic carbon that can contribute significantly to NCP. Over time, as this new source of carbon begins to deplete, this source of NCP diminishes. However, as the ELA experiments demonstrate, these reservoirs can remain a net contributor to CO_2 production relative to pre-flooding conditions for more than a decade after initial flooding.

Methane emissions. The ELA studies show that floating peat islands, which rise to the reservoir surface due to the buoyancy effect of gases trapped within the peat, are significant sources of methane emissions. These floating peat islands are also observed in large hydro reservoirs, and hence are significant.

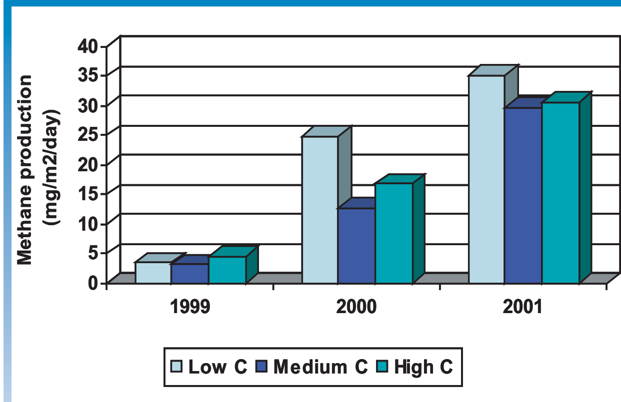
In the main ELA peatland study at L979, the undisturbed peatland surface was a small source of CH_4 to the atmosphere (about 1 mg CH_4 $m^{-2}day^{-1}$) before flooding. These low CH_4 flux rates are likely due, in part, to the oxidation within the thick unsaturated zone present throughout the peatland.

In 1995, two years after the initial flooding, average flux from a large floating peat island in the centre of the wetland complex was 280 mg of methane per m^2 per day. Seven years later it was still 269 ± 88 mg CH_4 $m^{-2}day^{-1}$, almost the same as in 1995. This is over 200 times greater than from the surface of undisturbed peat. This increase relative to pre-flooding peatlands is likely due to reduced oxidation of methane generated because of higher water levels within the floating peat mass. The flux from the open water surface of the flooded pond was 87 ± 19 mg CH_4 $m^{-2}day^{-1}$, a factor of about 3 lower than that from the peat island. Other floating peat island sites show even higher emissions (Scott *et al.*, 1999). Emissions are highly sensitive to temperature as well, dropping off rapidly in the fall as temperatures decrease and becoming minimal in winter when the wetland is ice covered (Saquet, 2003; Hesslein, 2007).

When the high values for peatland emissions at L979 are integrated with those from open water areas in the reservoir and accumulated over the entire 2002 open water season, average emissions for the 16.8 ha size reservoir were ~ 45 kg CH_4 m^{-2}. More than 60% of this appears to have come from the floating peat masses (Saquet, 2003). Studies into the decay rates of peat islands suggest a decay rate of less than 6% per year. Hence, such emissions could continue to be high for at least two decades after flooding (St. Louis, 2003).

Net methane fluxes were lower at the FLUDEX sites than the ELARP. In contrast to NCP, methane emissions progressively increased over the first three years after flooding, with methane bubbles becoming the dominant source of emissions by the third flooding season (*see Fig. 5.3*). Again, emissions were similar for all three sites, regardless of carbon stored within the reservoir (Bodaly, 2004; Matthews, 2005).

FIGURE 5.3



Net methane production at three FLUDEX sites from 1999-2001. Data source: Matthews, 2005.

Nitrous oxide emissions. Researchers also analyzed the nitrous oxide concentrations for the samples collected at the FLUDEX sites. Nitrous oxide is produced through denitrification in boreal soils and wetlands and hence is part of the nitrogen cycle, rather than the carbon cycle. While it had been anticipated that flooding could increase N_2O production, results of the FLUDEX experiments suggest the opposite. The data showed that N_2O concentrations in the reservoir surface waters were actually less than that in the atmosphere and that this undersaturation increased in the waters below the surface. Hence, the flooding appears to have caused the reservoirs to become a small sink for nitrous oxide. Researchers suggest this is due to the conservation of nitrogen within the flooded biomass (which in this area is nitrogen poor) as it decomposes. The rates of N_2O consumption did not appear to differ significantly between the three reservoirs. These results are in contrast to other studies in boreal regions, which suggest a small positive flux of nitrous oxide (Bodaly, 2004; Duchemin, 2002; Huttunen, 2002).

5.2.2 Develop a methodology and model for accurate inventory of GHG fluxes in existing hydroelectric systems

While there have also been relevant discussions with Hydro Québec and BC Hydro, most of the PERD funded research into greenhouse gas emissions from existing hydroelectric reservoirs has been undertaken in collaboration with Manitoba Hydro. Related activities and results are as follows:

5.2.2.1 Monitoring of greenhouse gas concentrations

Starting in 1999, DFO collaborated with Manitoba Hydro in designing and implementing a greenhouse gas concentration sampling network for existing hydro reservoirs in Manitoba. The first full year of weekly sampling by Manitoba Hydro personnel began at three generating stations on the Nelson River (Kettle Rapids, Limestone and Long Spruce) in 2000. The following year, this network expanded to the forebays of twelve major dams on the Winnipeg, Nelson and Saskatchewan

TABLE 5.1

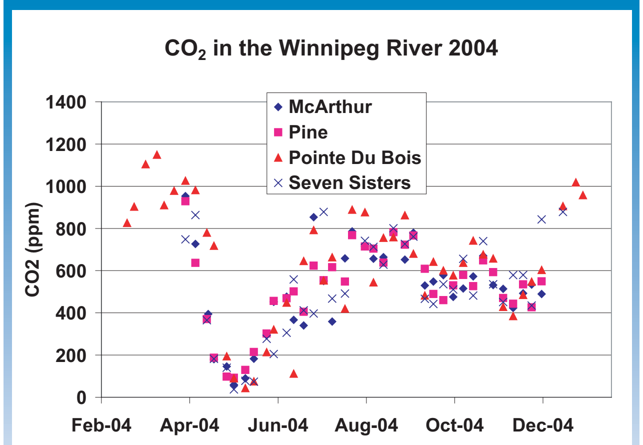
Hydro-reservoir dams in Manitoba, and their characteristics. Source. Hesslein 2003.

	In-Service-Date	Capacity (MW)	Energy (GWh)	Flooded Area (km^2)	Energy/ Flooded Area (GWh/km^2)
WINNIPEG RIVER SYSTEM					
Seven Sisters	1931/1952	150	1,010	8.4	120.2
McArthur Falls	1955	56	385	8.3	46.4
Great Falls	1928	132	910	3.5	260.0
Pine Falls	1952	82	640	1.1	581.8
Winnipeg Total		**420**	**2,945**	**21**	**138.3**
SASKATCHEWAN RIVER SYSTEM					
Grand Rapids	1968	472	1,540	1373	1.1
NELSON RIVER SYSTEM					
Jenpeg	1979	126	910	73	12.5
Kelsey	1961/1972	224	1,800	124	14.5
Kettle	1974	1,272	7,070	236	30.0
Long Spruce	1979	980	6,030	13.7	440.1
Limestone	1992	1,330	7,565	3.1	2440.3
Nelson Total		**3,932**	**23,375**	**450**	**52.0**
CHURCHILL RIVER SYSTEM					
Southern Indian Lake	1976			269	
Notigi Forebay	1976			492	
Churchill Total				**761**	
TOTAL CURRENT SYSTEM		**4,834**	**28,800**	**2,635**	**10.9**

Rivers. Their characteristics and age are presented in *Table 5.1*. The purpose of the weekly sampling was to establish a simple but robust method for routine monitoring of greenhouse gas concentrations within reservoir waters. The process for sampling was improved during the third year to address some drawbacks encountered in the initial approach. All samples were forwarded to laboratory in Winnipeg for analysis. Some initial problems with logistics and analyses were resolved by developing an improved sampling and transportation protocol. By 2003 the network was collecting good quality data.

In 2000, a prototype device for the continuous *in situ* analysis of CO_2 by infrared absorption was also successfully tested on Stevens Lake on the Nelson River, as well as at several reservoir locations on the Winnipeg River, and Lake of the Woods (the natural source of the Winnipeg River). The device allows areally integrated estimates of CO_2 to be calculated for large heterogeneous reservoirs (or lakes). Typically, when monitoring, the device was used to collect data hourly. A smaller, more robust and easier to manage version of the device was tested the following year. It is now being used by a number of agencies pursuing related monitoring programs, include Manitoba Hydro (with units installed at four dam sites), Hydro Québec (which has built about 10 of them for use in their reservoir studies), Ducks Unlimited, Univ. of Alberta, Univ. of Manitoba, Water Research Institute in Milwaukee, Univ. of Waterloo, and the Arctic Research division of DFO.

FIGURE 5.4



Seasonal trends in CO_2 concentrations for 2004 at four locations in the Winnipeg River. Source: Hesslein 2007.

Figure 5.4 shows a sample set of the weekly data collected in 2004 at the four stations along the Winnipeg River. All stations show a similar seasonal pattern: super-saturated concentrations of CO_2 of about 1100 ppm in the early spring when the river was still ice covered (compared to air concentrations of ~375 ppm); a rapid drop in late spring to levels below 100 ppm ; and a return to super-saturated conditions about 2x atmospheric concentrations in late summer. Data from the continuous monitoring system agree well with the weekly sample data.

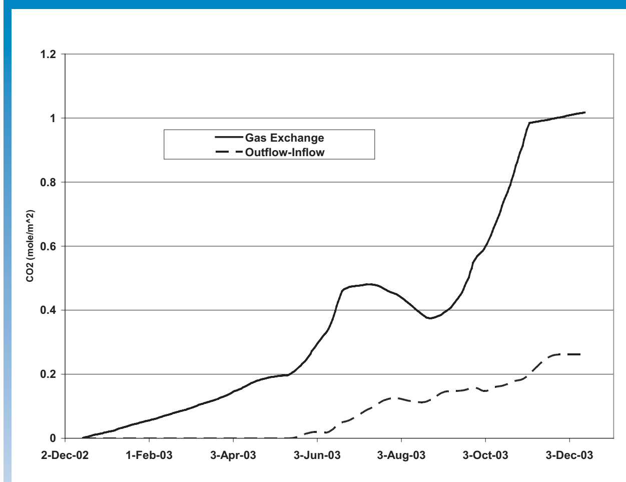
Results for the Nelson River network show a similar seasonal pattern, although with a smaller range. Concentrations reached a high of slightly below 1000 ppm in early spring and a low of about 250 ppm in late spring. Methane was not detected.

The large variations in concentrations appear to be related to the role of ice, temperature and biological activity. In the winter season, the river waters are covered by snow and ice that largely eliminates the flux of gases between air and water. Water temperatures are cold and dark, suppressing both respiration and photosynthetic activity. The concentration of CO_2 in water builds. When the snow cover disappears, light already begins to penetrate through the ice to stimulate algal productivity in the water below. Open spots in the rivers also allow CO_2 to escape into the atmosphere. This growth removes CO_2 from the water, and CO_2 concentrations begin to drop by mid April. They reach minimum levels by mid May. There is supporting evidence of a large increase in diatoms during this period. However, once the ice cover disappears, the CO_2 concentration stops decreasing, than begins to rise again, until it reaches maximum summer levels of 600-800 ppm by mid July. One factor is the reduced solubility of CO_2 in water as temperatures rise. Week to week concentrations also become more variable. During the fall season, as temperatures begin to decline, CO_2 concentrations within the water slowly decline as well, reaching levels similar to atmospheric concentrations by the time ice begins to reform in November.

5.2.2.2 Calculating greenhouse gas emissions.

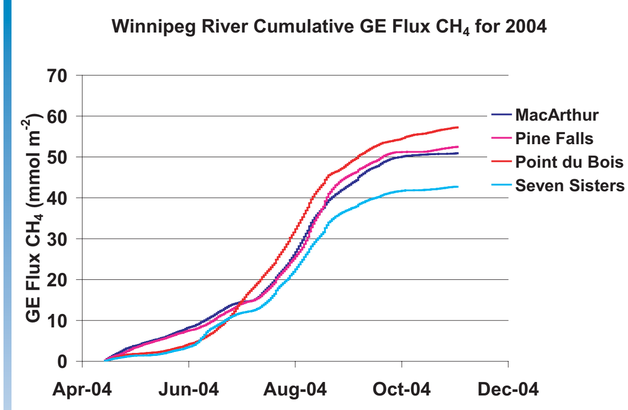
As noted re ELA data, calculation of NCP for a given water body requires information on water flows into and out of that body, the CO_2 concentrations of inflow and outflow water, and the water-air gas exchange. Available knowledge of related variables within the Manitoba Hydro electrical production systems allow a reasonable approximation of annual patterns of net CO_2 production (assuming equal CO_2 inflow- outflow during the winter ice covered season). Total estimated NCP for the Lac du Bonnet section of the Winnipeg River (*see Fig. 5.5*), allowing for the net transport of CO_2 out of the section, is about 1.28 mole $m^{-2}y^{-1}$. This is very similar to that determined for undisturbed lakes in the ELA area, suggesting that management of this section of the Winnipeg River for hydroelectric energy production has little long term effect on net CO_2 production and emissions. The organic matter that provides the source of NCP comes primarily as dissolved organic carbon (DOC). An independent estimate for Winnipeg River NCP production can therefore be calculated using DOC data for the Winnipeg River. Such estimates imply NCP for Lac du Bonnet of 1.05 mole $m^{-2}y^{-1}$, very similar to the above numbers based on direct CO_2 measurements.

FIGURE 5.5



Estimated cumulative fluxes of CO_2 due to gas exchange and transport by flows as calculated for Lac du Bonnet. Source: Hesslein, 2007.

FIGURE 5.6



Cumulative emissions of methane in the Winnipeg River during the 2004 season. Results indicate total production for the year of about 0.8 g/m^2, similar to that for undisturbed natural lakes. One mole of methane has a mass of 16 grams. Source: Hesslien, 2007.

As noted in the results of the ELA studies (see above) this appears reasonable, since the river dams that caused increased flooding of landscapes along the river occurred more than 50 years ago (*see Table 5.1*).

The methane data collected for the Winnipeg River hydro reservoirs show that emissions are highly correlated with temperature. They reach a peak in mid to late summer. A related model for sediment oxygen demand and methane production has been initiated. However, net accumulated emissions of methane from the entire Winnipeg River system (*see Fig. 5.6*) is much lower that that found at ELA flood sites.

Alternate measurement techniques developed by researchers at the Université de Québec à Montréal (UQAM) and employed at a number of existing hydro reservoirs in Québec have provided additional estimates of emissions from that region that are similar to those obtained for the ELA studies. The UQAM results suggest that in that region methane emissions from existing hydro reservoirs were also low, and nitrous oxide emissions from hydro reservoirs were very low. However, CO_2 emissions from some of the newly flooded reservoirs were large relative to pre-flooding background emissions, and could remain large for decades after flooding (Duchemin, 2002).

5.2.3 Modelling of GHG fluxes

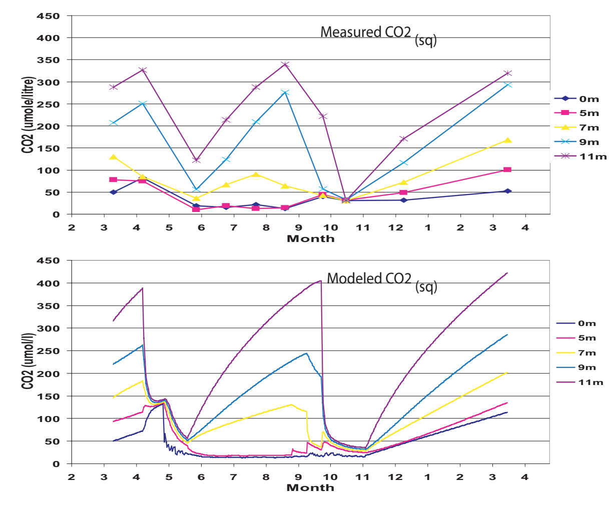
A number of models for simulating flooded reservoir CO_2 and methane generation and and flux have been developed. These include:

- Initial development of a simple empirically-based model for reservoirs at ELA. However, since this model was not process driven, it needed to be recalibrated with new data from each reservoir to which it are applied;
- Subsequently, a more advanced model was developed for use with data generated by the continuous CO_2 monitoring system installed at one of the ELA lakes. The model included both carbon-13 and carbon-12 budgets. Using both budgets provided a much higher level of confidence in the accuracy of the parameters in the model. This model was also used to calculate and interpret the fluxes of GHGs for the FLUDEX project;
- Investigators also developed a similar version of a CO_2 production model to simulate net CO_2 production from the reservoirs on the Winnipeg River. When calibrated against the weekly data, the simulations showed that a significant amount of the CO_2 produced in the Winnipeg River system is carried into Lake Winnipeg. The model developed for this also includes a sub-model for ^{13}C. This part of the model will be calibrated when all of the ^{13}C data is available (Some results of the model simulations are shown in *Figure 5.7*).

The modelling results show a strong positive relationship between CO_2 fluxes and dissolved organic carbon (DOC) concentrations. Primary production was found to be an important secondary factor in the control of midsummer fluxes but perhaps less important on an annual basis;

Studies on gas-exchange using the tracer gas SF6 were also carried out with University of Alberta researchers to understand the relationship of the mass transfer coefficient for gas exchange and low wind velocities. This relationship is important in calculating fluxes using the thin boundary layer method. The results showed higher gas exchange at low wind speed than predicted by the relationships commonly used in larger systems.

FIGURE 5.7



Comparison of measured CO_2 concentrations in a natural lake in the ELA region with that simulated with a simple empirical model. Hesslein, 2003.

5.2.4 Communication of Results to Stakeholder and Policymakers

The FWI investigators involved in the research pertaining to fluxes of greenhouse gases from hydroelectric reservoirs have used a variety of fora to communicate results to stakeholders, particularly policymakers. These include:

- Regular meetings with power authorities in several provinces to present results and discuss future research and monitoring collaboration with utility staff;
- Frequent discussions with Environment Canada staff involved in developing national greenhouse gas inventories to help develop methodologies for including hydro reservoir emissions;

- Presentations at PERD and FLUDEX workshops and other scientific fora;
- Annual submission of progress reports to the POL 6.2.1 steering committee for inclusion in annual reports to PERD;
- Research papers published in conference proceedings and peer reviewed literature. Many of these are listed in the attached bibliography.

5.3 Have PERD objectives been met?

In general, the results of the work accomplished under this component of the PERD POL 6.2.1 work plan have met or exceeded the objectives set out for the research. Results can be summarized as follows:

1. *Better understanding the processes that affect the fluxes of greenhouse gases related to hydroelectric reservoirs*

- CO_2 emissions rise significantly following flooding, and are in general related to the concentration of DOC in the reservoir water;
- These emissions continue for a decade or so beyond initial flooding, but return to that similar to natural lakes after several decades;
- Methane emissions from older reservoirs are small. However, from newly flooded northern ecosystems, they can be large. These emissions increase with rising temperatures, and are largest from floating peat islands that rise to the surface of the reservoir after flooding. Most of these emissions occur through bubbling processes;
- Methane emissions increase during the first few years of flooding, and may continue to be significant for several decades after flooding;
- In general, methane emissions from northern boreal ecosystems are likely to remain, on a per TWH basis, an order of magnitude smaller than that from fossil fuel based electricity power plant;
- In the years immediately after flooding, neither CO_2 nor methane emissions appear to be dependent on the quantity of organic matter being flooded;
- Nitrous oxide emissions may actually decrease, or become a net sink, after flooding.

These results already present a good sense of which types of flooded lands are likely to create high emissions, and which are not.

2. *Develop methods to accurately quantify changes in net fluxes following hydroelectric developments*

- Instrumentation and protocols for regular sampling of greenhouse gas concentrations within hydro reservoirs have been developed and improved, and now provide good quality data for routine calculations of related greenhouse gas emissions. A network of monitoring stations is already in place in Manitoba;
- Instrumentation for continuous monitoring of greenhouse gas emissions from reservoirs has been tested and improved, and is now installed at a number of Manitoba Hydro sites;
- Instrumentation for improved measurement of methane gas bubbling through floating peat islands is being tested.

3. *Communicate such information to policymakers as a scientific basis for the development of GHG mitigation program options*

The researchers involved in the program have communicated the results with the key stakeholders involved, and have helped create awareness of the need to include greenhouse gas emissions from hydroelectric reservoirs in the development of greenhouse gas inventories and in developing national energy policies.

In particular, the ELA group has worked closely with Manitoba Hydro, which is already considering related implications in its development and management policies.

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CHAPTER 6

Priorities for Future Sinks Research in Canada in a Post-PERD Context

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6.1 Introduction

The information presented in the preceding chapters demonstrates that much progress has been achieved in providing policymakers and program managers with sound scientific advice needed to accurately inventory anthropogenic greenhouse gas emissions and to effectively minimize these emissions and maximize sinks. This progress includes: improved techniques for measuring and quantifying sources and sinks and reservoirs of greenhouse gases related to terrestrial and marine ecosystems within and adjacent to Canada; improved understanding of how these processes work; and the development of biogeochemical models that can more accurately simulate the past, current and future behaviour of greenhouse gas fluxes from and into ecosystems.

These results also demonstrate how a relatively small investment in resources, such as that provided by PERD through its POL 6.2.1 activity - if well focused, coordinated and repeated at a sustained level over a number of years - can allow participation of key scientists in much bigger collaborative programs at the national and international levels. Such collaboration effectively leverages large resources from other partners – federal government departments, academia, private industry and/or agencies from other countries – to help address the deliverables identified by PERD under its POL 6.2.1 objectives.

However, as recognized in the deliverables identified under PERD for POL activities to 2007, the enhanced understanding of the global carbon and nitrogen cycles achieved to date only goes part of the way in addressing the many policy issues associated with human interference with these cycles. Much more needs to be done! That is because the carbon and nitrogen cycles are complex. They are also sensitive to large but poorly understood chemical, physical and biological feedbacks that exist within a dynamic global Earth system that includes a changing climate. Thus, the feedbacks and processes that govern these cycles may be different tomorrow than they are today.

Now that the time period for PERD investment into GHG sinks-related research within Canada has concluded, another important administrative question arises. How will future Canadian research into sources and sinks of greenhouse gas be coordinated and prioritized in the future? Who will lead the effort to coordinate and prioritize related research, and where will the leveraging resources required to help focus the research to effectively address identified priorities come from?

These are not new questions. They have been asked and discussed at a number of related workshops in recent years. The most recent of these occurred in Ottawa in February, 2007 (PERD, 2007). The following discussion reflects many of the thoughts expressed by leading experts and program managers during these discussions and through other related fora.

6.2 Research Priorities by Sector

The research agenda established to address policy questions related to sources and sinks of greenhouse gases, and to climate change issues in general, needs to be responsive and flexible. That is because, while understanding improves, the context for policy decision making also changes. Thus, new questions emerge.

Given the desire to keep an agenda that is responsive to changing needs, predicting specific future research questions is risky. Nevertheless, some broad objectives demanding further attention seem already evident. These are outlined sector by sector in the sections below.

6.2.1 Agriculture

The findings of the research to date, with respect to sources and sinks of greenhouse gases within the Canadian agricultural landscapes, have provided substantive advances toward the intended results sought under the PERD POL 6.2.1 program. This includes a reliable and comprehensive GHG inventory system, improved models, and a growing awareness of practices that will efficiently reduce GHG emissions from farms.

However, some broad objectives for further improvements in understanding include the following:

i) **Looking deeper – seeking better understanding of fundamental processes:** Predictive models and GHG inventories rest on a foundation of solid, comprehensive understanding of the underlying processes. The fundamental research that furnishes this understanding does not always yield immediate dividends, but it can provide solutions, still unseen, to vexing problems arising decades from now (Whitesides and Crabtree, 2007). Examples of fundamental research questions that may merit particular attention include:

- Quantification and understanding of rhizosphere processes. Plant carbon is the raw material for all new soil organic C, and much of that C enters the soil in roots and root-related materials. But we do not yet understand these processes very well, nor do we even have accurate estimates of how much C is added through these processes;
- Mechanisms of N_2O production, consumption and release to the atmosphere: Emissions of N_2O are highly variable, both in time and space. The precise origins within the soil profile, as well as the processes of formation and release, still remain obscure. Recent evidence even suggests consumption of N_2O by soils may also be a complicating factor (Chapuis-Lardy *et al.*, 2007) that has not been adequately considered. The integration of N_2O emission measurements over time and space require more scrutiny.

ii) **Looking farther – envisioning changes coming:** Agricultural lands, perhaps more than any other land-use, are subject to intensive and rapid change. In coming decades, there may be not only changes to climate and atmospheric CO_2 (both with potentially substantive influence), but also profound shifts in the amounts and types of products demanded from farmlands, and the way they are generated. Some examples of changes that deserve attention already now include:

- *Influence of changing climate, atmospheric CO_2, and management practices on stored soil C*: In recent years, much research has been devoted to enhancing soil C (C sequestration), but in the future, we may need to shift our focus to preserving C as soil C accrual reaches a plateau and new factors (e.g. higher temperatures, reversals of land-use) threaten to accelerate soil C decomposition;

- *Influence of expanded bio-fuel production:* Farmlands are increasingly seen as a source of feedstocks for producing ethanol, biodiesel, and other biofuels. This shift raises numerous new questions such as: What is the net benefit of such practices for reducing greenhouse gas emissions? What is the ecological cost to agroecosystems of increased C export? How do the changes in crop production required to furnish the biomass alter carbon and nutrient cycling in these landscapes?;
- *Changes in supplemental nitrogen:* Agricultural production has become increasingly dependent on industrially-fixed N. These fertilizer sources, however, are likely to become even more expensive because of the high energy demands of their manufacture. Further, inefficiencies in their use has, in the past, caused some environmental interferences. These and other factors may engender changes in N fertility management on farms, with potentially far-reaching implications for GHG emissions and other environmental indicators.

In the face of these and other coming changes, it might be helpful to envision how agroecosystems might look and behave in 30 or 50 years, and initiate research aimed at resolving the questions those new conditions might create. As well, it might be prudent to establish experiments now, for long-term evaluation of the impact of changes on agroecosystems.

iii) **Looking broader – an ecosystem approach:** Programs such as PERD have reminded us of the connections among biomes; the greenhouse gases, because they are emitted into the global atmosphere, require us to look beyond the artificial boundaries of scientific discipline, geography, or land-use. Though some progress has been made, more is urgently needed. In particular, we may want to study specifically the interfaces between biomes - perhaps emphasizing the science of the edges between farms and forests, between farms and wetlands, and, perhaps especially, between farms and urban areas. As urbanization continues, and as the boundaries between urban areas and other land-uses blur, this interaction between living spaces and working spaces may become especially worthy of study.

iv) **Looking beyond carbon sinks and greenhouse gases – the other ecosystem services:** Farmlands serve many functions, of which climate change mitigation is merely one (and, admittedly, not always the one deemed to be of highest priority). Consequently, managing lands to reduce emissions can be achieved only in light of these other ecosystem services – producing food, providing habitat, filtering water, providing aesthetic and recreational respite, and many others. Examining these ecosystem services, alongside climate change mitigation (and adaptation) will require closer synergy with other disciplines of science, learning, and arts.

6.2.2 Forests

Canada's ability to report on carbon stocks, claim sinks credits, and estimate emissions will depend on the reliability of the estimates generated from models. Models at various spatial scales are the integrating tools to obtain estimates of national-scale GHG sinks and sources from many different types of experimental and observational data. Better data and continuous improvement is necessary to ensure that negotiators have the best possible tools. The impact of human activities is important because we have control over our economy. Depending on which of the IPCC Scenarios we follow (IPCC A2 vs. B2 for instance) forecasts of disturbances vary widely. This is critical since disturbances from fire and insects are the key as to whether forests are a carbon source or sink. Climate change alters the forest ecosystem, particularly for fire and insect effects, and where pests and fire interact there are increased risks from wildfire. Many of the parameters describing these situations have yet to be developed and major uncertainties remain as to the impacts.

Forest management actions affect carbon dynamics and we need to understand the potential of afforestation and reforestation to maintain the carbon capacity of forest sinks. Policymakers need to know the impacts of a range of forest management actions, including the effects of protection from wildfire, insects, salvage logging, site preparation, forest fertilization, and harvesting methods. Forest managers will want to be able to measure accurately the role of afforestation and reforestation in the dynamics of carbon sinks. Understanding and quantifying the impacts of forest management actions will also contribute to the separation of direct human effects and indirect human and natural effects. Uncertainties persist about the carbon and GHG dynamics of deep organic soils, forested peatlands, and the interactions between wetlands and forests which are complex mixes of ecosystems. More work is also required to improve the understanding of natural disturbances on forest carbon dynamics, especially for non-stand replacing disturbances of defoliating insects that cause growth reductions but little mortality.

Consequently, despite the considerable progress made in the goals of the program, the ongoing and future needs are many and varied if the uncertainties are to be addressed in light of changing policy needs. Major uncertainties also remain in the estimates of the impacts of global change on the continuous processes of forest growth, decomposition, and the resulting stand-level carbon balance. Numerous unresolved scientific questions contribute to these uncertainties. Modelling forest responses to climate change is an area of active research that requires sustained funding to improve estimates of carbon budgets and contribute to the development of strategies for mitigation and adaptation.

The progress to date in developing effective tools for simulating the response of Canadian forests to environmental change and forest management activities is encouraging. As noted in Chapter 3, these models already provide effective advice to policymakers.

However, as with the simulation of carbon fluxes in Canadian agricultural soils, significant deficiencies in the ability to accurately predict future forest behaviour, particularly in response to changing climates and atmospheric composition, remain. These deficiencies continue to limit the confidence that can be placed on the advice to policymakers on greenhouse gas sinks. The model used to report forest carbon fluxes for Canada's reporting to the UNFCCC, for example, does not as yet include the effects of drought. Furthermore, the limitations of these models also affect the performance of Earth system models in simulating the complex feedbacks between climate and ecosystems, and hence their ability to accurately project future changes in atmospheric composition and climate. There is a need to look deeper.

Following are a number of priorities for related research:

i) **Expanding the range and detail of measurements:** Some components of the forest landscape are inadequately addressed or absent from the current modelling activities. These include:

- Forest peatlands, and past research into forest peatlands. Yet, these peatlands are an important component of the boreal ecosystems and the greenhouse gas fluxes they generate. Although the carbon reservoir within these peatlands is large, there is uncertainty about how large, or about the role of fire and other disturbances on peatland carbon fluxes. Furthermore, there is a need to improve the understanding of how changes in water levels within these peatlands affect fluxes;
- Decomposition of litter and underground carbon, particularly roots – in order to scale up from site specific studies, more needs to be known about belowground decomposition rates, and about how decomposition rates vary from site to site and depend on litter type, and why.

ii) **Including more components and feedbacks in forest ecosystem models:** Various models are now available to study carbon flux processes, simulate forest ecosystem behaviour and accurately estimate net greenhouse gas fluxes for inventory purposes. However, most inadequately capture the influence of environmental change and have missing components. For example:

- Fire models need to add a peatland component and add more black carbon fuel types;
- The large Canadian forest models such as CBM-CFS3 and the Fluxnet-Canada model need to include future climate change

projections, corrected growth curves derived from process models and improve *growth curve* (GC) "correction factors" (derived from process models) and climate-sensitive insect defoliation sub-models in order to better simulate past, current and future carbon reservoirs and fluxes.

iii) **Better understanding the complex feedbacks and variables within ecosystems:**

- Climate variability, particularly the fluctuations from drought to wet seasons, is an important contributor to interannual variability in greenhouse gas fluxes between forest landscapes and the atmosphere. Understanding the processes involved, both above and underground, are thus important in annual reporting of net fluxes and in projecting future response of such fluxes to climate change. There is a need to long-term (20+ years) measurements at various sites to improve such understanding. Both the response of autotrophic and heterotrophic respiration will need to be monitored and characterized. Furthermore, site specific results will need to be integrated with flux-tower and remote sensing data to evaluate the spatial coherency of responses and scale up stand results to landscape scale estimates;

- More study is needed into the coupling of the carbon and water cycles in forest ecosystems;

- Most models do not effectively address forest succession processes within there simulations. Understanding these processes and including them in simulation models is important both for projecting future response of forest carbon fluxes to a changing environment and for assessing the impact of forest management practices on the role of Canadian forests as net source or sink of greenhouse gases.

6.2.3 Oceans

In many respects, research results show that large scale iron fertilization as a means of enhancing ocean carbon sinks does not appear to be realistic. However, as indicated in Chapter 4, there are a number of related emerging issues important to policymakers that have become priority concerns. These include:

i) **Ocean acidification:** The rising concentrations of carbon dioxide in the atmosphere is contributing to a slow but steady rise in ocean acidity. How will this affect carbonates stored in the ocean? How will this affect the oceans' continued ability to act as a sink for CO_2 ? Which plankton species are at risk? What are the consequences for marine ecosystems, particularly shell-forming organisms?

ii) **Effects of global warming on carbon fluxes:** As in land ecosystems, changing climates can significantly affect the biogeochemical processes that govern the fluxes of ocean carbon. However, because the ocean is a dynamic fluid, climate change will also affect ocean circulation, and hence the physical transport of carbon. There is a related need for better understanding of the fate of carbon stored in the twilight zone (100 to 1000m), the dynamics of dissolved organic carbon and dissolved organic matter in the oceans, and the complex non-linearities in carbon cycle processes. Possible reduction of deep water formation in the Labrador Sea region caused by the freshwater input from the Arctic and surface water warming can reduce surface water density and hence cause the reduction of CO_2 uptake in the region. There are also discrepancies between related model simulations and observations that need to be understand and addressed. Bacterial dynamics within these models appear to be unstable and need to be improved. Thus, the requirement for continued observations and concurrent model development in key high latitude ocean regimes is greater than ever.

iii) **Sub-ocean gas hydrates:** In some regions of northern oceans adjacent to Canada, there are large deposits of frozen gas hydrates buried below the ocean floor. There are concerns that warmer ocean surface waters, when transported to the ocean bottom, may trigger significant release of the methane embedded in these hydrates.

6.2.4 Hydro Reservoir emissions

Results to date from research into hydro reservoir emissions of greenhouse gases have provided good insight into the relationship between the type of terrain being flooded and greenhouse gas emissions. However, there remain many unanswered questions, and some major challenges, before greenhouse emissions from existing large hydro reservoirs can be calculated with high confidence, and future emissions from possible new developments can be predicted with confidence. For example:

i) **Instrumentation and monitoring protocols need to be improved:** In particular, methods for capturing methane emissions released from reservoir bottoms as large bubbles need to be further developed and tested. Without a better understanding of the magnitude of emissions caused by such bubbles, it remains uncertain whether or not current measurements and calculations have significantly underestimated methane emissions from northern hydroelectric reservoirs. There is also a need for improved networking between various research groups involved in such studies for inter-comparison and validation of different measurement technologies.

ii) **Estimates of emissions need to be scaled up:** Although there is considerable spatial heterogeneity of reservoir emissions, most measurements are currently made in small reservoirs or at sub-reservoir scales. Methods need to be developed to scale such measurements up to develop aggregate estimates of emissions for complete hydro reservoir systems. Furthermore, techniques need to be transportable so that they can be applied to reservoirs across Canada, each of which has its own characteristics. This will require research into many factors other than local greenhouse gas fluxes that are important in understanding and attributing the source of net greenhouse gas emissions from hydro reservoirs to natural causes or human induced activities. For example, for many reservoirs, there is inadequate understanding of background emissions prior to flooding or water level regulation, and whether such background emissions already had a human element due to previous land-use.

iii) **Process-based models need to be developed:** Ultimately, the objective is to develop process-based models that can be applied to different hydrological basins to simulate past, current and future emissions, to assess implications of new developments and to advise facility managers in methods of minimizing emissions. The simple, empirically based models currently available are basin specific and do not have a predictive capacity. Hence, there is much more work needed to understand greenhouse gas genesis and emission processes and to develop dynamic models based on these processes. These models also need to be able to project the relative role of CO_2 and methane emissions. Although good measurements and process research are pre-requisites for developing such models, model development should be a priority.

iv) **Upstream sources and downstream emissions need to be included in estimates:** More attention needs to be paid to the origin of DOC entering reservoirs, and hence contributions to reservoir emissions that may not attributable to flooding processes. Likewise, some of the greenhouse gas emissions generated within a flooded reservoir may be released as a result of turbine degassing at hydro-electricity generators or leave the reservoir through reservoir outflows, to be released downstream. They may also be influenced by the timing and volume of water release from reservoirs due to hydro-electric system management. Methods to include these emissions will require involvement of aquatic and ocean experts.

6.3 Coordination and Funding

Carbon and nitrogen cycle studies have been an inherent component of research within the Government of Canada's resource based departments for many decades. That is because these cycles are an important aspect of productive farming, forest management and ocean food chains.

More focused research into the role of carbon and nitrogen fluxes in natural ecosystems within and adjacent to Canada as sources and sinks of atmospheric greenhouse gases began with the onset of PERD funding for related studies by DFO, AFFC and CFS in the mid 1980s. While the level of PERD funding slowly increased over the next 15 years, the projects involved were largely based on proposals submitted by scientists aimed at general improvement of monitoring and understanding of the carbon cycle within Canadian ecosystems and adjacent oceans.

This approach to funding research into sources and sinks of greenhouse gases changed significantly in 2000, when PERD introduced its results based program management structure. As part of this restructuring, it established POL 6.2.1, with the focused objective for improved understanding of the magnitude and processes that affect sources and sinks of greenhouse gases in Canadian ecosystems and adjacent oceans, and the development of related advice to policymakers on sinks might be enhanced through direct human activities. (The program that emerged is discussed in detail in Chapter 1.)

This focused funding, in addition to directly enhancing the research activities needed to address the identified goals, provided two other major benefits. First, it helped to coordinate research across diverse disciplines, between government departments and between government laboratories and academia, into a focused activity aimed directly at providing advice to policymakers. Secondly, it caused large amounts of financial and human resources already at work on more general aspects of the global carbon cycle to become focused on the specific questions being posed to meet the PERD identified goals. These, in effect, leveraged resources from other programs that far exceeded the direct PERD financial investment.

Government of Canada research managers have cited the success of PERD POL 6.2.1 in coordinating and focusing research activities as an example of how government science can be strengthened without large commitments for additional resources (Grace and Butts, 2007). They note that, by going beyond the individual mandate and traditional networks of the various partners involved in the research activity, the program was highly successful in forging new partnerships and shared goals that addressed a common national priority. It also helped to focus science on anticipated changes, rather than past changes, thus better equipping policymakers to make visionary decisions. This approach can help move government research activities from disconnected programs that primarily serve individual departmental mandates to an interwoven, cohesive effort that is better geared to provide the best advice to decision makers and hence improved service to Canadians.

The completion of the era of PERD funding for research into sources and sinks of greenhouse gases in March 2007 thus poses a dilemma. How should research managers now provide the infrastructure and seminal resourcing needed to provide such an integrated, cohesive effort aimed at addressing important policy issues through the research priorities?

That question was posed to a panel of senior managers of Earth system research programs within government and academia during a related PERD sponsored workshop in February 2007 (PERD, 2007). Contributors to the discussion included: Gordon McBean (Canadian Foundation for Climate and Atmospheric Sciences, and panel moderator), Brian Amiro (University of Manitoba/North American Carbon Program), Andre Isabelle (Natural Sciences and Engineering Research Council of Canada), Brian Gray (Environment Canada/ climate change science plan for the four federal natural resource departments) and Wendy Watson-Wright (Fisheries and Oceans Canada).

The comments provided by the panelists demonstrated two overarching points of agreement.

The first was that **governments and academia both have important but complementary roles** to play in developing scientific understanding on environmental issues. Government science is often issue driven, and plays a key in addressing current public policy questions and anticipating future ones. For example, the excellent science conducted through government programs like PERD has been critical for informing policy decisions about GHG emissions inventories, decisions about forest and grassland management, or that iron fertilization does not work. In contrast, while some funding of academic research is also strategically focused on partnership programs that address issue-oriented science and hence complement that within government laboratories, most is focused on discovery type research and on academic training.

Secondly, **long-term monitoring of environmental conditions is essential** for sound scientific research. This activity, together with the challenge of large scale complex modelling activities, require large capital and long-term staff investments and are primarily the responsibility of government science programs. Monitoring helps understand "what" is happening, while complex modelling provides the tools for projecting what may happen in the future. University studies complement this work with shorter time scale-targeted research projects that can help address "why" certain trends are occurring, and develop/test the process equations that simpler models used within the more complex models as predictive tools.

Further, in order to revitalize and resource an integrated, cohesive national research initiative on sources and sinks of greenhouse gases in a post-PERD era, they recommended that:

- a healthy long-term program (multiple decadal timescales) be considered as essential. Hence, the question is not if, but how;
- senior government research managers make a strong case for protecting the A-base still in place and for re-investment beyond this base, using a broad national Earth systems framework that looks at multiple benefits for various stakeholder priorities (including climate change, carbon cycle and biodiversity);
- this case be developed collaboratively between the federal/national resource departments and academia, with due consideration of the interests and responsibilities of provincial governments;
- such a research strategy seeks good integration across discipline boundaries, including the land-ocean-atmosphere interface;
- the Canadian Foundation for Innovation (CFI) and the Network of Centres of Excellence (NCE) can also be explored as sources of funding for coordinated and focused carbon cycle research within academia, and finally;
- the upcoming International Polar Year and the recent release of IPCC WG II report on climate change impacts be used as opportunities to make the case for revitalizing a national climate change/carbon cycle program with policymakers and the public.

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ACRONYMS, ABBREVIATIONS AND CHEMICAL SYMBOLS

AAFC	Agriculture and Agri-Food Canada
ACSYS/CliC	Arctic Climate Systems Study/Climate and Cryosphere
BMP	Better management practice
C	Carbon
CanAG-MARS	Canadian Agricultural Greenhouse Gas Monitoring, Accounting and Reporting System
CARINA	Carbon Dioxide in the North Atlantic
CAT	Carbon Accounting Team
CBM-CFS	Carbon Budget Model of the Canadian Forest Sector
CCAF	Climate Change Action Fund
CCCMA	Canadian Centre for Climate Modelling and Analysis
CCRS	Canada Centre for Remote Sensing
CFC	Chlorofluorocarbons
CFS	Canadian Forestry Service
CH_4	Methane
CLIVAR	Climate Variability and Predictability Programme
CO_2	Carbon Dioxide
DFO	Fisheries and Oceans Canada
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DSOW	Denmark Strait Overflow Water
EC	Environment Canada
EGGS	Enhancement of Greenhouse Gas Sinks
ELA	Experimental Lakes Area
ELARP	Experimental Lakes Area Reservoir Project
FACE	Free Air Carbon Dioxide Enrichment
FCRN	Fluxnet Canada Research Network
FLUDEX	Flooded UplanD Experiment
FWI	Freshwater Institute
GHG	Greenhouse gases
GLOBEC	Global Ocean Ecosystem Dynamics
Gt	Giga tones, or billion metric tonnes

IOS	Institute for Ocean Studies
IPCC	Intergovernmental Panel on Climate Change
JGOFS	Joint Global Ocean Flux Studies
LMC	Land management change
LULUC	Land use and land use change
Mt	Megatonnes, or millions of metric tonnes
N	Nitrogen
N_2	Nitrogen gas
N_2O	Nitrous oxide
NAHARP	National Agri-Environmental Health Analysis and Reporting Program
NCP	Net CO_2 production
NEADW	North East Atlantic Deep Water
NEP	Net ecosystem productivity
NFCMARS	National Forest Carbon Monitoring, Accounting and Reporting System
NH_4^+	Ammonium ion
NO	Nitric oxide
NO_3^-	Nitrate ion
NO_3	Nitrate radical
NOAA	National Oceanographic and Atmospheric Administration
NO_x	Nitrogen oxides
NPP	Net primary productivity
NRCan	Natural Resources Canada
NSERC	Natural Sciences and Engineering Research Council of Canada
O_3	Ozone
OERD	Office of Energy Research and Development
OH	hydroxyl radical
OSP	Ocean Station Papa
PERD	Program of Energy Research and Development
POL	Program at the Objective Level
Ppb	Parts per billion
Ppm	Parts per million
SERIES	Subarctic Ecosystem Response to Iron Enrichment Study
SF_6	Sulhpurhexafluoride
SOC	Soil organic carbon
SOLAS	Surface Ocean, Lower Atmosphere Study
SOO	ships of opportunity
SO_x	Sulphur oxides
SSF	Strategic Science Fund
Tg	Teragram, or trillion grams. 1 Tg = 1 Mt
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework on Climate Change
UQAM	Université de Québec à Montréal
WOCE	World Ocean Circulation Experiment