CLIMATE OF CHANGE

Taking Credit

CANADA AND THE ROLE OF SINKS IN INTERNATIONAL CLIMATE NEGOTIATIONS

David Suzuki Foundation
Finding solutions

WEST COAST
environmental law

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Introduction

The Kyoto climate treaty talks will reconvene in July, 2001 in Bonn, Germany after talks broke down last November in The Hague (CoP6).

According to analysts, one of the primary reasons for the impasse in negotiations was the bitter and divisive disagreements concerning the role that terrestrial carbon sinks should play in the Kyoto Climate Change Protocol. Terrestrial carbon sinks are one of the most complicated and controversial issues to emerge within the Protocol process.

Allowing countries to receive credit under the Kyoto Protocol for using forests and lands to absorb and store carbon will continue to be controversial until the key issues are settled. With strong rules and guidelines based on sound science, storing carbon could be part of a menu of options aimed at slowing the build-up of atmospheric carbon dioxide levels. Without sound crediting rules, countries such as Canada may utilize interpretations that could allow them to weaken the emission reduction commitments made under the Protocol.

With this in mind, The David Suzuki Foundation commissioned *Taking Credit: Canada and the Role of Sinks in International Climate Negotiations.*

Author Chris Rolfe focuses on the negotiations concerning sinks that have taken place so far, including why some countries support expansive crediting of sinks whereas others strenuously oppose their inclusion in the Protocol. Co-authors Dr. Darwin Anderson and Dr. Robert Grant provide a detailed technical explanation of the science of sinks and the carbon cycle upon which policy decisions must be based. They also explore whether forests and land management provide the same long-term benefits for the climate system as does reducing emissions from fossil-fuel combustion.

Many had hoped that the November CoP6 meeting would finalize the rules and guidelines of the Kyoto Protocol, thereby encouraging countries to begin the urgent task of meeting their emission reduction targets.

In the lead-up to the next round of Kyoto Protocol meetings, we hope that this report will serve as a useful guide in explaining the significant, but complicated role that terrestrial carbon sinks play in international climate negotiations and the continuing need for substantial reductions in greenhouse gas emissions.

> *"If we really care about the next century, we, as a planet, must take action… We need a solution that will help reduce global warming. A solution that Canadians can be proud of."*
>
> Prime Minister Jean Chretien

1

Sinks and International Climate Negotiations

With increased scientific understanding of both the threat of climate change and the role sinks could play, negotiating parties need to intensify their efforts if they are to find solutions that protect the environment.

The issue of "sinks" rose to increased public prominence in November 2000, at the sixth international climate summit at The Hague, known as CoP6.[1] The media reported that "sinks" were at the heart of an impasse in the negotiations. On the one hand, Canada, the United States, Japan, and Australia wanted to count the carbon dioxide (CO_2) removed from the atmosphere by their forests and agricultural soils towards their commitment to reduce greenhouse gas emissions. On the other hand, the European Union wanted to limit credits for carbon removed by forests and soils. Both camps claimed that science and environmental integrity were on their side. By the end of two weeks of talks, the parties remained far apart. The world had entered negotiations at The Hague with the objective of securing a deal that would turn the emission reduction commitments of the Kyoto Protocol into reality, but was able to agree to little more than another round of talks in 2001.

Those talks are now slated for the last two weeks of July 2001 in Bonn, Germany. With increased scientific understanding of both the threat of climate change and the role sinks could play, negotiating parties need to intensify their efforts if they are to find solutions that protect the environment.

This chapter reviews the negotiations over sinks that have taken place to date. Chapters 2 and 3 examine why some parties argue for crediting sinks whereas others strenuously oppose and/or limit their inclusion in the 1997 Kyoto Protocol. Chapters 4 and 5 provide a detailed technical examination of the science of sinks that policy decisions should be based upon.

Sinks, sources, reservoirs, and the UNFCCC

In 1988 Canada hosted the World Conference on the Changing Atmosphere, which was held in Toronto. This seminal gathering of experts from 46 countries called for an international convention on climate change. The negotiations concluded in 1992 with the signing of the United Nations Framework Convention on Climate Change (UNFCCC) at the Earth Summit in Rio de Janeiro. The nations signing the convention promised to "promote and cooperate in the conservation and enhancement … of sinks and reservoirs of all greenhouse gases … including biomass, forests and oceans."

In this context, *reservoirs* means stores of carbon that might otherwise be released to the atmosphere. Soil organic matter and forests are carbon reservoirs. *Sinks* are processes that remove greenhouse gases from the atmosphere. For example, growing forests remove CO_2 from the air during photosynthesis. Forests and soils can also be a *source* of greenhouse gases when they emit more greenhouse gases than they remove from the atmosphere. (Chapter 4 discusses the carbon cycle, including sinks and sources, in greater detail.)

The UNFCCC also committed the industrialized nations of the world to adopt policies and measures aimed at returning emissions to their 1990 levels by 2000. Such measures were to include all sources of emissions as well as reservoirs and sinks. Despite this commitment, emissions from industrialized countries – especially Australia (15% increase from 1990 to 1998), Canada (13% increase), the US (11% increase), and Japan (10% increase) – continued to grow through the 1990s.[2]

The Kyoto Protocol

In 1995 the Intergovernmental Panel on Climate Change (IPCC), charged by the World Meterological Organization and the United Nations Environmental Program with examining the state of scientific research on global climate change, released its Second Assessment Report. The report concluded that "the balance of evidence suggests that there is a discernible human influence on the global climate."

The international community quickly recognized that stronger commitments were necessary to protect the world's climate. In 1995 the 160 nations that had ratified the UNFCCC – known as "Parties" to the UNFCCC – agreed to negotiate stronger commitments by 1997. This process culminated in the Third Convention of Parties (CoP3) in 1997. The meeting was held in Kyoto, Japan, and negotiated the first international agreement with unambiguous commitments to reduce emissions – the Kyoto Protocol.

If the Protocol is ratified by a sufficient number of nations,[3] these commitments will be binding in international law, but only on the nations that ratify the Protocol. This need for consensus gives considerable negotiating power to nations opposed to strong action on climate change, as in the case of the recent US announcement that it would withdraw from the Kyoto Protocol. Under the terms of the UNFCCC, nations will be required to take action only if they agree to take action.

The Kyoto Protocol is one of the most complicated agreements ever negotiated by the international community.

The Kyoto Protocol is one of the most complicated agreements ever negotiated by the international community. The formula for determining different commitments by industrialized countries gives some sense of its complexity:

- Article 3 of the Protocol establishes a commitment period between 2008 and 2012 (the "First Commitment Period") during which the industrialized nations listed in Annex B (the "Annex B Parties"[4]) must limit their emissions of six greenhouse gases.
- Parties are given a quota of allowable emissions (the "assigned amount") based on a certain percentage of emissions in a base year.
- For most purposes, the base year is 1990. Canada's assigned amount is 94% of 1990 emissions times 5 (to reflect the five years in the First Commitment Period). The US assigned amount is 93% of 1990 emissions times 5; the European Union's is 92% times 5.

The Kyoto Protocol does not set targets beyond 2012, but is based on the assumptions that parties will negotiate subsequent commitment periods that will start in 2013 and that developing nations will also accept specific "assigned amounts" following concrete action by developed nations.

The Kyoto Protocol also includes several "flexibility mechanisms" – joint implementation (JI), the Clean Development Mechanism (CDM), and international emissions trading – intended to reduce the costs of achieving reduction targets defined by international law. While their design can potentially introduce loopholes that allow overall emissions to increase,[5] the cost savings and flexibility offered by the mechanisms were key to achieving broad partial agreement on the Kyoto Protocol in 1997. Except for CDM and sinks, these mechanisms are not discussed at any length in this report.

The Kyoto Protocol provides Annex B or Industrialized Parties with "flexibility" by allowing them to emit more greenhouse gases from fossil fuels if they take certain actions to protect reservoirs or enhance sinks.

Sinks and the Kyoto Protocol

The Kyoto Protocol provides Annex B or Industrialized Parties with "flexibility" by allowing them to emit more greenhouse gases from fossil fuels if they take certain actions to protect reservoirs or enhance sinks.[7] These countries can then get "credit" for certain increases in the carbon sequestered in forests and soils and use it to meet their targets for

BOX 1.1: THE NEGOTIATORS

The CoP6 negotiations are dominated by several key parties and groups of nations:

- **Jan Pronk**. Dutch Environment Minister Jan Pronk is chair of CoP6, which began at The Hague and is scheduled to continue in Bonn in July 2001. As chair, he has tried to facilitate a deal by developing several compromise proposals.
- **The Umbrella Group**. Canada, the US, Japan, Russia, Ukraine, Australia, Norway, New Zealand, and Iceland all belong to the Umbrella Group. This group has been the leading proponent of "flexibility mechanisms" in the negotiations and has been criticized as favouring flexibility over environmental integrity. The Umbrella Group is divided over sinks: Canada, the US, Australia, and Japan favour broad crediting for a variety of activities that enhance sinks; Norway has argued against credit for "business as usual sinks";[6] and New Zealand does not support increased credit for sinks.
- **The European Union**. The European Union (EU) is generally seen as a greater champion of environmental integrity than the Umbrella Group. It has opposed expanding the types of sink activities that can be credited during the First Commitment Period, and has opposed credit for sink enhancement or reservoir protection in developing countries.
- **G-77/China**. The G-77/China is the third main negotiating bloc. It represents the diverse countries of the developing world, from the Alliance of Small Island States (AOSIS) to the Organization of Petroleum Exporting Countries (OPEC). It opposes, or wants very tight limits on, the crediting of sink activities in the industrialized world. The G-77 is divided on whether developing countries should be able to generate valuable credits for enhancing sinks or protecting reservoirs through the CDM. Latin American countries generally support it; Asian countries generally oppose it.
- **AOSIS**. The Alliance of Small Island States has members whose survival is endangered by rising sea levels caused by climate change, and has taken strong environmental stands on many issues. Until scientific, policy, and methodological issues are resolved, AOSIS opposes expanding credit for sinks in both the industrialized world and developing countries.
- **Environmental Integrity Group**. Consisting of Switzerland, Mexico, and Korea, this group has generally promoted environmentally defensible positions while recognizing the need for flexibility. It has favoured inclusion of sinks but opposed credit for business as usual sinks. It supports discounts on any sink-related credits to reflect uncertainty.

the First Commitment Period.[8] Credit for sequestration comes in the form of an addition to the countries' assigned amount, which permits an increase in emissions from combustion of fossil fuels or other human processes. Conversely, certain losses in carbon sequestration levels lead to carbon debits that reduce a country's allowable emissions.

DEFINITIONS

At Kyoto, Parties (all nations that had ratified the UNFCCC) agreed to include only a limited number of sinks activities in the system of credits and debits. Article 3.3 of the Protocol states that Annex B Parties[9] will be credited (or debited) with verifiable changes in carbon stocks due to afforestation, reforestation, and deforestation.[10]

Negotiations continued at the next climate session, CoP4 in Buenos Aires in 1998. All Parties clarified the intent of Article 3.3, saying that Annex B Parties would be credited (or debited) with any increase (or decrease) in sequestered carbon in the period 2008-12 due to afforestation, reforestation, or deforestation if those activities took place since 1990.[11] By CoP6 at The Hague in 2000, all Parties had generally agreed that afforestation and reforestation in the context of Article 3.3 meant converting non-forest land to forest. This excluded regeneration of forests after logging,[12] closing a significant loophole.

ADDITIONAL ACTIVITIES

While there is general agreement regarding the treatment of reforestation, afforestation, and deforestation, the inclusion of additional activities such as agricultural soils remains unresolved. Article 3.4 states that Parties will decide on how, and which, activities related to forestry, agriculture, and land use change in Annex B countries will be included in the second and subsequent commitment periods. These activities are often referred to as "additional activities," meaning additional to Article 3.3

While there is general agreement regarding the treatment of reforestation, afforestation, and deforestation, the inclusion of additional activities such as agricultural soils remains unresolved.

SINKS IN THE CLEAN DEVELOPMENT MECHANISM

The Protocol is silent on whether activities that sequester carbon or protect reservoirs in developing countries can be credited. At present, certified emission reductions, or CERs, can be generated under the so-called Clean Development Mechanism (CDM).[13] The CDM is supposed to be both a process for giving industrialized countries access to low-cost reductions in the developing world and a process for supporting the South with sustainable development practices. CERs, reflecting emission reductions in the developing world, can be added to the allowable emissions quota of the industrialized Annex B Parties, enabling the latter to increase their domestic emissions.

Because the CDM does not specifically refer to credit being given for protection or enhancement of reservoirs or sinks, the EU and others have argued for the exclusion of sinks from the CDM. Canada, Japan, Australia, the US, and some developing countries have taken the opposite view in the hope of maintaining maximum flexibility.

The sinks standoff at CoP6

The unresolved issues described above lie at the heart of the current impasse over the implementation of the Kyoto Protocol. At the CoP4 meeting in Buenos Aires, it was clear that the details of the Kyoto mechanisms, the treatment of sinks, and other matters would be contentious. The participants did, however, agree to the "Buenos Aires Plan of Action" – a schedule that set CoP6 as the deadline for resolving key issues.

Credit for "business as usual" sequestration of carbon by forests and soils has been criticized as a windfall for countries with the potential for large carbon sinks; other countries justify credit for non-additional sinks as "part of the Kyoto deal."

BOX 1.2: WINDFALL OR PART OF THE KYOTO DEAL?

Credit for "business as usual" sequestration of carbon by forests and soils has been criticized as a windfall for countries with the potential for large carbon sinks; other countries justify credit for non-additional sinks as "part of the Kyoto deal." Several facts suggest that credit for all sequestration on managed forest lands was not part of the Kyoto deal:

- *Article 3.4 rules out credit from pre-1990 activities.* The Kyoto Protocol states that additional sequestration activities counted in the First Commitment Period under Article 3.4 must have taken place since 1990. This runs counter to comprehensive crediting for sequestration on managed forest lands. The current uptake of carbon by managed forests in most industrialized countries is the result of regrowth after harvesting, often initiated decades ago in the case of Canada and the US. In many cases there has been no effort to increase carbon sequestration since 1990. Canada, the US, and Japan have tried to claim that such sequestration qualifies because it is the result of current forest management activities.
- *Article 3.4 refers to additional "human-induced activities."* Much of the sequestration that would be credited under Canadian, US, and Japanese proposals is the result of purely natural factors. In some cases, the only human activity is allowing natural processes to occur.
- *Such credit would run counter to the overall reduction target and the purpose of the Kyoto Protocol.* Article 3.1 states that overall reductions of industrialized nations should be at least 5% *below* 1990 levels in the First Commitment Period. As discussed in Chapter 2,[14] proposals for crediting all sequestration occurring in managed forests and on agricultural lands would allow an *increase* in both direct industrial emissions (fossil fuel emissions and all other emissions not associated with the Land Use, Land Use Change, and Forestry sector) and net emissions (direct industrial emissions minus removals and emissions from the Land Use, Land Use Change, and Forestry sector). Under a proposal made by Canada in August 2000, the amount of credit generated could potentially be sufficient to eliminate any need for additional action by industrialized nations.
- *Negotiators were not in a position to rely on sequestration.* In Canada's case, negotiators of the 1997 Kyoto deal could not have been relying on credit from non-additional sinks because at that time it was uncertain whether Canada's managed forests and soils were a source or a sink for greenhouse gases.
- *The US defended the deal without credit for business as usual forest management.* After Kyoto, the State Department defended the American Kyoto target as achievable. Their defence was based on the assumption that forest management would not be credited.[15] Subsequently the US argued for rules that generated large amounts of credit from business as usual sequestration.

Credit for sequestration in agricultural soils was not agreed to at Kyoto, raising important issues. Yet sequestration on agricultural lands in the 2008-2012 period would often be due to changes in agricultural practices since 1990. The relatively small scale of credit for business as usual sequestration on agricultural soils is far less than business as usual sequestration in managed forests.

THE DEBATE

Before CoP6, little progress was made in resolving any of the issues, and negotiations at CoP6 started out slowly. By the end of the first week the negotiating texts – essentially draft legal decisions – contained thousands of brackets, each set of brackets indicating the unwillingness of one or more participants to accept the bracketed text. Because decisions under the UNFCCC are made by consensus, it is essential to remove all brackets for final agreement.

THE COUNTRIES' POSITIONS

Although the issue of sinks is complex, the negotiating dynamic is relatively simple. Canada and Japan entered the debate from one extreme. Canada advocated "a comprehensive land based approach" under Articles 3.3 and 3.4:

- Parties would receive credit (debit) for all verifiable increases (decreases) in the carbon stock on agricultural or managed forest lands during the first and subsequent commitment periods.
- All carbon pools (for example, wood products, above- or below-ground biomass, forest litter, soil carbon) must be counted unless there is evidence that they are not sources of greenhouse gases.
- Any future emissions from these carbon stocks would be accounted for in future commitment periods. Thus if a country took credit from growing forests, for example, it could not subsequently ignore emissions from forest fires or other processes within these forests or farmlands.

Leaving aside its implications for the overall effectiveness of the Kyoto Protocol (which are discussed in Chapter 2), the Canadian position has the advantage of being relatively simple and comprehensive. Japan took a position similar to Canada's.

The United States took a slightly different stance. It suggested that during the First Commitment Period credit from forests should be discounted,[16] or Parties should be only allowed to claim credit for carbon sequestration that exceeded an undefined threshold (for example, 50% of 1990 levels).

At The Hague, Canada, the US, and Japan reconciled the differences in their positions and presented a united position on sinks. An initial proposal by the three provided for comprehensive, undiscounted inclusion of forests and agricultural soils for most countries combined with a discount on forest sinks for countries with extremely large sinks (likely only the US and Russia).

Canadian, Japanese, and American officials have argued that comprehensive crediting is scientifically appropriate and provides incentives for sustainable forestry. The three nations' position, however, may be driven more by perceived political expediency. As noted earlier, the three nations are all large emitters and have each had substantial increases in greenhouse gases since 1990. Because forests and agricultural soils in the US and Japan are expected to be major net sinks in 2010, comprehensive crediting offers large amounts of credit without the need to take additional action to reduce greenhouse gas emissions. Canadian government officials have generally assumed that our forests and soils will also be large net sinks and thus contribute to meeting the Kyoto target. Together with flexible rules under the other flexibility mechanisms, the three countries clearly see credit for sinks as making the Kyoto Protocol easier to implement and easier to ratify.

Canada, the US, and Japan have also strongly supported including all forms of forest and agricultural soil sequestration projects in the Clean Development Mechanism.

Canada, the US, and Japan have also strongly supported including all forms of forest and agricultural soil sequestration projects in the Clean Development Mechanism. Other negotiating allies have not supported their position. Australia, for instance, has accepted the exclusion of deforestation prevention projects from the CDM in the First Commitment Period.

Most climate protection non-governmental organizations (NGOs), the EU, the Environmental Integrity Group, the Association of Small Island States, and a number of other developing countries have stated that adding activities under Article 3.4 during the First Commitment Period could reduce the overall integrity of the Kyoto Protocol. Concerns raised include fears that:

- The accounting rules would allow global emissions to increase
- Storing carbon in trees and soils can transfer risks and responsibilities to future generations because of the impermanence of sinks
- The difficulty of measuring carbon removed by trees, soils, and other sinks could make commitments harder to enforce
- Rules would create perverse incentives to cut native forests

AOSIS nations took the strongest stance, advocating the complete exclusion of additional activities during the First Commitment Period. The EU's position was that no additional activities should be used under Article 3.4 during the First Commitment Period unless key issues are dealt with. If additional activities were considered under Article 3.4, the EU proposed a number of strict accounting rules that would have significantly limited the amount of credit available. Both AOSIS and the EU also sought to exclude sequestration projects from the Clean Development Mechanism.

Several other countries suggested compromise positions. Norway – normally an ally of the US, Canada, and Japan – took the position that for the First Commitment Period, countries should be credited only for the direct effect of new activities since 1990 that went beyond business as usual. It stated that the intention of Article 3.4 was to focus on the second and subsequent commitment periods. Switzerland and environmental NGOs in favour of credit for sinks supported similar proposals.

During and after The Hague meeting, Canada pointed to European intransigence as the reason for the breakdown in talks, and criticized the two Pronk papers as being biased in favour of the EU.

THE RESULT

Faced with a standoff over sinks – and similar standoffs over other issues – CoP6 president Jan Pronk proposed a series of high-level decisions on key issues (the "November 23 Pronk Paper"[17]). Both the EU and the US, Canada, and Japan trio responded to the Pronk Paper with their own proposals. Their differences could not be reconciled in time and The Hague meeting adjourned without a decision.

WHO WAS RESPONSIBLE FOR THE IMPASSE AT COP6?

During and after The Hague meeting, Canada pointed to European intransigence as the reason for the breakdown in talks, and criticized the two Pronk papers as being biased in favour of the EU. Europe, on the other hand, blamed Canada and other members of the Umbrella Group. Who was to blame?

While a standoff can occur only when both sides refuse to compromise sufficiently, an examination of changes in the parties' positions indicates that the EU essentially made significant shifts in position. Before The Hague, the EU position was that no additional activities should be added under Article 3.4. At The Hague the EU agreed that all net sequestration by managed forests should be counted up to the level of any debits under Article 3.3. This eliminated the debits Canada incurred because of high deforestation rates (according to its own calculation, Canada annually deforests an area 30 times greater than it afforests).[18] The Europeans have also agreed to include forest management and agricultural soils (albeit subject to very large discounts for both).

During CoP6, Canada corrected aspects of its initial position that would have eliminated much of the environmental benefit of the Kyoto Protocol (see Chapter 2). It has, however, made few concessions that affect the amount of credit it expects to receive. The shifts in Canada's position mainly involved applying discounts to the amount of carbon sequestered by Russian and American forests. In other words, while Canada, Japan, and most other countries would be able to claim credit for every tonne of carbon sequestered by their forests, the US and the Russian Federation (the two countries with the largest forest carbon sinks) would be able to claim credit for only a fraction of their sequestration.

Table 1.1 shows what various Canadian and EU positions represent for Canada. It indicates significant changes in the EU position that benefit Canada. The table is based on the projections of carbon sequestration on managed forest lands and agricultural lands that Canada submitted to the climate negotiations in August 2000. (It thus assumes that Canada would receive credits from adding forest management, an assumption that has been called into question by other analyses.)

Based on the August 2000 submission, Canada's most recent position would still generate at least 97% of the credits Canada would have received under its original comprehensive carbon accounting position. Table 1.1 also shows that the April 2001 Pronk proposal represents a compromise between the EU and the Canadian positions.

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What to look for regarding sinks at CoP6.5

The June 2001 negotiating text prepared by CoP6 chair Pronk was simply the latest in a long series of proposals to find common ground on credits from non-additional sinks. Inevitably there will be more. The following are the different proposed accounting rules that are likely to be central to the negotiations. Suggestions regarding how Canada will behave are based on Canada's past positions.

- **First, second, and third tier**. Pronk's June 2001 negotiating text creates different rules for three tiers of sequestration under Article 3.4. The first tier is forest management up to the level of any deforestation debits under Article 3.3; most parties have supported crediting 100% of sequestration in this tier. The second tier is sequestration in managed forests beyond the level counted in the first tier; all parties have agreed to some discounting in this tier. The third tier is for agricultural soils. Pronk proposes accounting on a net-net basis for agricultural soils. Expect Canada to try to have forest management beyond a certain threshold moved into the third tier, where it will receive full credit.
- **Discount rates**. Pronk calls for a discount rate of 85% on the second tier. Expect the EU to call for a higher discount rate and Canada to call for a lower rate. A higher rate will decrease credit for non-additional activity, increasing actual emission reductions and the environmental effectiveness of the Protocol. On the other hand, a lower rate will decrease incentives to change forest practices.
- **Japanese exemption**. Special rules related to population density, energy intensity, and forest cover create a special exemption for Japan. Discounts do not apply to the second tier. Expect Canada to seek a similar exemption.

- **Boundary conditions**. Pronk's June 2001 negotiating text paper proposed boundary conditions that would limit the extent to which countries could utilize sinks. It limits both the amount of credit that can be obtained from forest management in Annex B countries and the credits from CDM projects. Canada, the US, and Japan have opposed any boundary condition, and will likely try to limit application of the boundary condition to sequestration from forest management below a specified threshold. Expect Canada to try to increase the size of the boundary condition.

TABLE 1.1. **WHO IS SHOWING FLEXIBILITY?**[19]

PROPOSED APPROACH[20]	ESTIMATED CREDIT (DEBIT) CANADA RECEIVES, MILLION TONNES CARBON/YEAR	WHAT CHANGES IN POSITION MEAN TO CANADA,[21] MT CARBON/YEAR
Canada's position pre-Kyoto:[22] Credit for all net sequestration on agricultural soils and forest land during 2008-12.	8.8	
Canada's position pre-Hague: Credit for all net sequestration on agricultural soils and forest land during 2008-12.	8.8	0
Canada's 20 November 2000 position:[23] Credit for all net sequestration on agricultural soils. Comprehensive inclusion of forest management, but subject to 66% discount if over 20 megatonnes but under unspecified threshold.	8.8	0
Canada's 24 November 2000 position:[24] Credit for all net sequestration on agricultural soils. Comprehensive inclusion of forest management, except for 5% discount and cap (4% of 1990 emissions) applied to sequestration over Article 3.3 debit but under unspecified threshold.		
• Assumed threshold set at 80% of projected sequestration beyond first interval	8.65	0.19
• Assumed threshold set at 100% of projected sequestration beyond first interval (yields minimum credit)	8.6	0.24
Pronk proposal of April 2001 and June 2001:[25] Agricultural soils included on net-net basis. 100% forest management counted up to level of Article 3.3 debit, and discounted thereafter. Boundary condition limits total credit from sinks (including credit purchased on international market).	5.0	Not applicable
EU interpretation of Kyoto Protocol: Article 3.3 only; no correction for asymmetry.[26]	(4.3)	
EU proposal pre-Hague: No forest management. Correction to Article 3.3 "asymmetry."[27]	(4.16)	0.14
EU proposal of 25 November 2000: Comprehensive inclusion of forest management up to level of Article 3.3 debit; 97% discount of forest management that exceeds Article 3.3 debit; 30% discounting of agricultural soils.	0.12	4.4

- **Net-net accounting.** Net-net accounting means that countries get credit only for increasing the rate of sequestration from 1990 levels. If applied to forest management, it could eliminate much of the credit for non-additional activities, but because of declining rates of sequestration it would make Kyoto targets more difficult to achieve. For this reason, net-net accounting is unlikely to be applied to forest management in the First Commitment Period.
- Pronk's June 2001 negotiating text proposes net-net accounting for agricultural soil sequestration. This benefits Canada because its agricultural soils were a source in 1990. Expect Canada to agree to net-net accounting for agricultural soils.

The US withdrawal from the Kyoto Protocol

While the United States has been a vocal supporter of full inclusion of sequestration activities under the Kyoto Protocol, its March 2001 rejection of the Protocol was not the result of the failure to achieve a deal on sinks at The Hague. Announcing the US government's withdrawal from the Kyoto Protocol, President George W. Bush stated that the rejection was based on the fact that the Protocol does not set emission limits for developing countries, that the agreement would be too expensive to implement, and that the science on global warming was still not certain.

The US decision is likely to isolate Canada further at the climate talks. The sinks issue had already split Canada, the US, and Japan from other members of the Umbrella Group, which had supported more limited credit from sequestration. Within the US, there is growing demand from environmental and religious organizations, and from some elements within business communities and Congress, for the Bush administration to reverse its decision and support the Kyoto Protocol target and timeline. It remains to be seen what role the US will play at CoP6.5.

Within the US, there is growing demand from environmental and religious organizations, and from some elements within business communities and Congress, for the Bush administration to reverse its decision and support the Kyoto Protocol target and timeline.

Science, policy, and politics

While the recent proposals of Canada, the US, the EU, and Jan Pronk have significantly different impacts (see Chapter 2), they are united by one common feature: their design reflects politics, not science. The various crediting intervals and thresholds proposed have been attempts at political compromise.

Although crediting and debiting for changes in sequestration levels due to so-called "Land Use, Land Use Change, and Forestry" (LULUCF) activities under the Kyoto Protocol have been the subject of extensive policy analysis since Kyoto and the subject of a special report released in 2000 by the Intergovernmental Panel on Climate Change (IPCC), the negotiations have tended to focus on a "numbers game," with some countries trying to maximize potential credit and others trying to minimize it. Some of these proposals risk environmental integrity and atmospheric protection. Methodologies for crediting proposed by the IPCC may be a more fruitful source of compromise.

The following chapters discuss how the crediting and debiting systems for sequestration on agricultural and forest lands could create loopholes and reduce the effectiveness of the Kyoto Protocol. Chapter 2 discusses competing concerns regarding the inclusion of forest and agricultural soil management under Article 3.4, and points to potential solutions. Chapter 3 discusses the inclusion of sinks under the Clean Development Mechanism.

2

Counting Carbon in the Industrialized World

Ending the stalemate over sinks in a way that maintains the environmental integrity of the Kyoto Protocol will, however, require a basic understanding of the scientific and policy issues related to sinks.

As discussed in Chapter 1, the crediting of carbon sequestration from forest management and agricultural land management has been one of the most divisive issues in global climate negotiations. As negotiators put forth various proposals for discounts, thresholds, and boundary conditions, the underlying concerns often fade into the background. Ending the stalemate over sinks in a way that maintains the environmental integrity of the Kyoto Protocol will, however, require a basic understanding of the scientific and policy issues related to sinks.

Adding additional activities under Article 3.4

Those favouring the addition of new activities that qualify for credit under Article 3.4 argue that:

- "A tonne is a tonne." Avoiding a tonne of emissions from deforestation or sequestering a tonne through changes to agricultural practices has the same impact on the atmosphere as avoiding a tonne of emissions from fossil fuels.
- Credit for sequestration can reduce the cost of achieving a given environmental target, thereby buying time for the development of low-emission technologies and possibly permitting deeper reduction targets.
- Credit for sequestration provides incentives for sustainable agriculture and forestry.

Those opposing the addition of forest management and agricultural land management under Article 3.4 during the First Commitment Period generally acknowledge the importance of protecting carbon reservoirs and recognize that credit for enhancing sequestration could reduce the short-term costs of compliance with the Kyoto Protocol. They argue, however, that:

- Credit for business as usual activities will reduce or eliminate the environmental impact of the Kyoto Protocol.
- Uncertainty in the measurement of sequestration could reduce the verifiability of Kyoto commitments and hide excess emissions.
- The impermanent nature of carbon sequestration shifts the risks of climate change and responsibility for reducing emissions onto future generations.
- Credit from Land Use, Land Use Change, and Forestry (LULUCF) activities could significantly diminish the need for reductions in fossil fuel emissions, allowing increased investment in energy sources and technologies that are not consistent with long-term climate protection goals.
- Credit for sequestration can encourage unsustainable forest practices.

This chapter examines these arguments, discusses the effectiveness of various proposals for dealing with the concerns expressed, and identifies potential solutions. It also looks at several relatively technical issues related specifically to Article 3.4: ensuring against perverse incentives to log natural forests and ensuring that definitions of key terms do not create loopholes.

A tonne is a tonne?

Proponents of receiving credit for increases in carbon sequestration argue that avoiding a tonne of emissions from deforestation or sequestering a tonne through changes to agricultural practices has the same impact on the atmosphere as avoiding a tonne of emissions from fossil fuels. Thus, they argue, each activity should be treated the same. Doing so would create an incentive to decrease Canada's high rate of deforestation (30 times higher than its rate of afforestation) and to rehabilitate soils and forests that have been degraded by human activity.

On one level this argument is correct. In terms of the atmospheric concentrations of greenhouse gases, the immediate impact of sequestering a tonne of carbon is the same as that of avoiding a tonne of carbon emissions. Without doubt, avoiding deforestation or rehabilitating degraded lands can help mitigate climate change.

Without doubt, avoiding deforestation or rehabilitating degraded lands can help mitigate climate change.

The argument ignores several key points, however:

- Sequestering a tonne of carbon dioxide (CO_2) will have the same impact on the atmosphere as reducing a tonne of emissions only if the carbon remains sequestered permanently. Avoiding a tonne of emissions from fossil fuels has a permanent impact on atmospheric concentrations. However the impact of sequestration is initially large and slowly declines over the course of centuries. This is indicated by Area B in Figure 2.1. The impact of sequestering a tonne is the same if sequestration is permanent. If carbon is subsequently released, however, the impact is equivalent to a reduction at the time of the sequestration (Area B) combined with an emission at the time of release (Area A). In the long term, atmospheric concentrations are higher where a short-lived sequestration is used as a substitute for emission reduction.
- To solve this problem, it has been suggested that countries be held responsible for

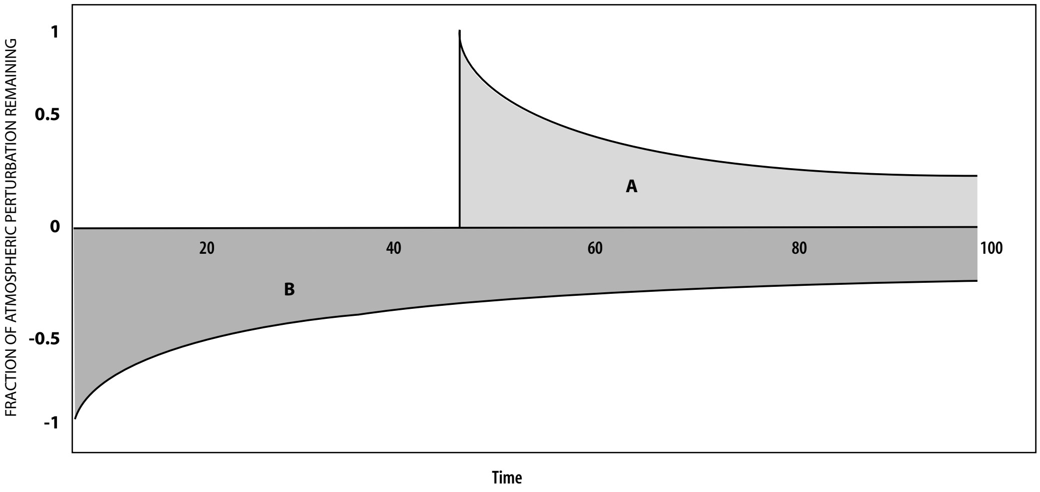

FIGURE 2.1

future emissions from their land base. As discussed later, however (see “Impermanence of carbon sequestration” on page 20), this approach shifts responsibilities to future generations and adds to the risk of climate change.

- The incorporation of sequestration into the Kyoto Protocol can radically reduce the Protocol’s effectiveness by permitting an immediate increase in net emissions (total emissions minus total sequestration) entering the atmosphere. This is discussed in greater detail later (beginning with the section “Credit for business as usual sequestration”).

Sequestering a tonne of carbon dioxide will have the same impact on the atmosphere as reducing a tonne of emissions only if the carbon remains sequestered permanently.

Cost savings and buying time for low-carbon technologies

A key argument from proponents of crediting and debiting changes in carbon sequestration is that efforts to protect carbon reservoirs or increase carbon sequestration are often less expensive than reducing emissions from fossil fuels. Utilizing sequestration can therefore reduce the cost of achieving Kyoto targets. Economic modelling projects suggest that providing credit for changes in forest management and agricultural land management in Annex B countries could reduce the overall costs of compliance with the Kyoto Protocol by about one-third.[28]

In the longer term, however, potential cost savings may be limited. Management practices to increase sequestration will not have an indefinite impact. Although there is some evidence that biologically diverse ecosystems continually remove carbon from the atmosphere, the prevailing wisdom is that carbon reservoirs in forests and soils eventually reach a point where no more CO_2 is removed from the atmosphere. This suggests that sequestration can be used to offset emissions only for a limited time. Proponents of giving credit for sinks argue that this potential should be used, buying time and deferring emission reductions until low-cost alternatives to fossil fuels are developed.

Although the use of sinks will likely reduce the short-term costs of compliance for emitters, arguments along these lines have several weaknesses:

- They assume that low-cost emission reduction opportunities are not currently available. While cost estimates for reducing emissions vary, studies for Canada’s National Climate Change Process project that overall Canadian compliance costs will be negligible.[29]
- Estimates of the costs of emission reduction often ignore its potential benefits, in terms of a more competitive economy or non-market benefits such as fewer premature deaths and lower health care costs due to air pollution.[30]
- Short-term cost savings through the use of sequestration may lead to long-term increases in compliance costs. The ability to invest in low-cost sequestration rather than in emission reductions may encourage companies to continue investing in carbon-intensive industries such as tar sands extraction rather than in low-emission industries, renewable energy, and energy efficiency.

While it might be possible to offset the emissions from some of these investments with sequestration and still achieve the Kyoto targets, the investments are not compatible with longer-term climate goals. Global emission reductions of 60% or more are needed to stabilize the world’s climate,[31] and Canada will need to make reductions that are far deeper than those required by the Kyoto Protocol. The costs will be greater if Canada has invested heavily in carbon-intensive industries instead of in new technologies and clean industries, and will include the cost of abandoning “stranded” investments in those carbon-intensive industries.

Incentives for sustainable forestry and agriculture?

Proponents of adding agricultural soils and managed forests to the Kyoto Protocol under Article 3.4 argue that doing so would encourage sustainable forest and agriculture practices. Opponents often argue the exact opposite.

To a limited extent, both arguments are correct. In the forest sector, practices such as protection of old growth and extension of rotation periods can maintain carbon reservoirs and enhance carbon sequestration, and are beneficial to the environment. On the other hand, credit for increased carbon sequestration can encourage:

- Monocultures of fast-growing species that can replace native grasslands or even native forests, and also deplete soil and ground water
- Forest fire suppression, possibly leading to loss of important grassland or fire-dependent ecosystems and to the build-up of fire-prone materials in forests
- Intensification of pest control, with a corresponding increase in pesticide use

The negative impacts of fire suppression and pest management are of particular concern in Canada and the United States, where, according to some estimates, these practices are expected to achieve the vast majority of increases in forest sequestration: over 80% in Canada and 70% in the US.[32]

In the agricultural sector, conservation tillage is generally seen as not only sequestering carbon but also reducing the costs of production and having positive impacts for water conservation and air, soil, and water quality. On the other hand, it also frequently leads to increased herbicide use, with attendant ecological impacts.

Ideally, the rules regarding credit for enhanced sequestration should ensure that such credit encourages only sustainable practices. A coalition of US-based environmental groups, such as the Natural Resources Defense Council (NRDC) and World Wildlife Fund (WWF), has been promoting a series of eligibility rules to help ensure that sequestration projects have positive environmental impacts. Such rules would, for example, prohibit the replacement of natural ecosystems with monocultures or prohibit interference with natural fire cycles. Both the European Union and environmental NGOs have also proposed a requirement that LULUCF activities under Articles 3.3 and 3.4 be consistent with treaties protecting biodiversity and wetlands.

Unfortunately, the prospects for international rules to ensure environmentally friendly activities under Articles 3.3 and 3.4 are uncertain. At Sixth Convention of Parties (CoP6) at The Hague, Canadian and American representatives supported the shifting of references to biodiversity and wetland treaties into the non-binding preamble of any decision. The June 2001 negotiating text of CoP6 chair Jan Pronk states that LULUCF activities under the Protocol "shall be implemented in such a way that they contribute to the conservation of biological diversity and the sustainable use of natural resources." Specific rules will not be developed until at least 2003, however, and Canadian negotiators have criticized this and similar proposals as rewriting of the Protocol.

The costs will be greater if Canada has invested heavily in carbon-intensive industries instead of in new technologies and clean industries, and will include the cost of abandoning "stranded" investments in those carbon-intensive industries.

CLIMATE EFFECTIVENESS VERSUS ENCOURAGING SUSTAINABLE FOREST PRACTICES

Although European and, to a lesser degree, Pronk's proposals for counting sinks attempt to maintain the principles of environmental effectiveness in the Kyoto Protocol, they reduce or eliminate incentives to carry out many of the additional activities that would benefit the climate and forest or agricultural ecosystems. The proposals call for simply multiplying most forest sequestration by discount factors to reduce credit from non-additional sequestration. They also call for caps or "boundary conditions" on the total amount of credit that can be generated through Article 3.4, to ensure that excessive credit is not generated from non-additional activities if sequestration rates are greater than currently estimated.

Unfortunately, caps and high discount rates remove the incentive to change forest or agricultural practices in ways that benefit the climate. For example, the June 2001 negotiating text calls for a boundary condition that would eliminate any incentive for Canada to decrease deforestation or to increase conservation tillage, rotation periods, or mature forest protection. A proposed EU discount of 97% eliminates almost all incentive for action.

Credit for business as usual sequestration

Non-additional sequestration is sequestration that would occur even without climate mitigation action, because of factors such as the changing age structure of forests or the impacts of nitrogen and greenhouse gas pollution that accelerate forest growth in the short term.

Opposition to adding new activities for the First Commitment Period under Article 3.4 has been fuelled in part by fear that countries would get large amounts of credit for sequestration that is "non-additional" or "business as usual." Non-additional sequestration is sequestration that would occur even without climate mitigation action, because of factors such as the changing age structure of forests or the impacts of nitrogen and greenhouse gas pollution that accelerate forest growth in the short term.[33]

Credit for non-additional sequestration would also mean an increase in atmospheric concentrations of greenhouse gases. Without such credit, the atmosphere benefits both from reductions in fossil fuel emissions and from carbon being sequestered by forests and agricultural soils. With such credit, emissions from fossil fuel would not go down, and net emissions to the atmosphere (emissions minus sequestration) would increase. Credit from non-additional sequestration is sometimes referred to as *ineffective credit* or *credit for ineffective sinks.*

Prior to The Hague, Canada and Japan proposed credit for all verifiable sequestration on forest and agricultural lands and debits for any reductions in the carbon stocks of forests and agricultural soils. There would be no attempt to distinguish between sequestration due to natural factors or past history and sequestration due to new and additional activities. On the other hand, the EU, the Environmental Integrity Group, and Norway have tried to limit or eliminate credit for non-additional sequestration.

SIGNIFICANT POTENTIAL LOOPHOLE

Estimates of non-additional sequestration that could be credited if forest management is added to the Protocol under Article 3.4 are huge. For example, the amount of credit generated throughout Annex B countries under Canada's initial comprehensive accounting approach to forests and agricultural soils could equal the "Kyoto Gap" – the gap between projected business as usual emissions and what would be required for Annex B Parties to comply with the Kyoto Protocol. Estimates of the amount of carbon absorbed by forest management activities in Annex B countries vary between 445 million tonnes and 727 million tonnes per year, equivalent to between 9.5% and 15% of Annex B emissions in 1990.[34] In comparison, the US Department of Energy estimates the Kyoto Gap for Annex B countries at about 14% of 1990 emissions.[35]

The potential credit may be even larger. The global uptake of carbon by forests and soils is estimated at roughly 2,300 megatonnes per year.[36] Most of this uptake – 2,100 megatonnes, according to recent estimates – occurs in the Annex B countries of the Northern Hemisphere.[37] Crediting this amount of carbon uptake would allow overall

Annex B emissions to increase by over one-third. While most of this amount is currently uncreditable, either because it cannot be verified through on-the-ground measurements or because it lies in unmanaged forests, the amount indicates the potential for huge increases in credit from non-additional sequestration in managed forests.

Uncertainty in current and projected sequestration levels makes limiting credit for business as usual sequestration extremely difficult. If there were an accurate way to predict business as usual sequestration in 2008-2012, one could simply say that countries would receive credit for all sequestration beyond business as usual. Current estimates of sequestration are, however, simply too uncertain to provide an accurate estimate of future sequestration.

One solution may be to give credit only for increases in sequestration from 1990 levels, using the same methodology to calculate both 1990 sequestration and sequestration in the commitment period. While estimates of sequestration in the commitment period may be too high, systematic measurement errors will be balanced out by overestimates of 1990 sequestration. This approach is known as “net-net accounting” because it compares net emissions in 1990 with net emissions in the commitment period. Unfortunately, net-net accounting is unlikely to be accepted for forest management in the First Commitment Period because it would increase the Kyoto targets of many countries. For example, Sweden would receive a debit equivalent to 18% of its 1990 emissions.[38] Net-net accounting may be a solution for future commitment periods.

For agricultural soils, either using net-net accounting or crediting of all sequestration in the commitment period is likely to generate credit from business as usual activities. However, the amount of credit would probably be much smaller than for forest management.[39]

The Canadian government has estimated that its managed forests are a small net sink of carbon, and has projected that its forests will continue to be a sink in 2008-12....

Other work indicates that Canada’s forests as a whole are currently a net source of greenhouse gas emissions.

BOX 2.1: BUSINESS AS USUAL CREDIT: WHAT DOES CANADA GET?

If sequestration in managed forests of Annex B countries were fully credited, it is generally accepted that Russia, the US, and the countries of the EU would receive significant amounts of credit. The same may not be true for Canada.

The Canadian government has estimated that its managed forests are a small net sink of carbon,[40] and has projected that its forests will continue to be a sink in 2008-2012. These conclusion are uncertain, however. According to Canada’s most recent greenhouse gas inventory:

> Methodologies for estimating emissions and removals from land use change and forestry are more complex than those used in other IPCC categories; involving more steps, and requiring more data, factors and assumptions. Results should be treated as first estimates that reflect the direction (i.e., source or sink) and magnitude of emissions or removals. They are characterized by a high degree of uncertainty (over 100% in every case).[41]

Other work indicates that Canada’s forests as a whole are currently a net source of greenhouse gas emissions.[42] More recent unpublished analysis suggests that managed forests could be a source of emissions depending on variables such as fire, weather, and definitions of managed forest.[43]

Thus, based on business as usual practices, adding forest management under Article 3.4 could give Canada either a small debit or a small credit. Compared with the 10 megatonnes of credit per year that Canada would receive under optimistic business as usual scenarios, the US would receive an estimated 288 megatonnes of credit per year if all forest management sequestration were credited (as initially proposed by Canada).[44]

According to the EU, the Alliance of Small Island States (AOSIS), the Environmental Integrity Group, and others, credit for sequestration should be discounted and/or caps should be placed on the total amount of credit that can be gained from forest management.

The intent of the various formulas, discounts, and boundary conditions proposed by the Parties and CoP6 chair Pronk (see Chapter 1) has been to reduce credit from non-additional sequestration. The formulas succeed to varying degrees. Table 2.1 shows how different proposals for adding forest and agricultural soil management under Article 3.4 would *increase* net emissions (that is, direct industrial emissions minus sequestration by sinks) from Annex B countries. Only increases in emissions due to credit for non-additional sequestration are shown. Not included are:

- Increases in fossil fuel emissions that may be offset by additional forest or soil sequestration due to elevated CO_2 concentrations
- Sequestration that is used to offset Article 3.3 debits for deforestation

The increases are shown in tonnes and as a percentage of the projected gap between Annex B business as usual emissions in the First Commitment Period and allowable emissions under the Kyoto Protocol. The "percentage of projected Annex B gap" is an indication of how much business as usual sequestration would reduce the effectiveness of the Kyoto Protocol.

TABLE 2.1. **INCREASE IN NET GLOBAL EMISSIONS DUE TO ADDITION OF FOREST MANAGEMENT AND AGRICULTURAL SOIL SEQUESTRATION UNDER ARTICLE 3.4.**[45]

	ESTIMATED CREDIT FROM NON-ADDITIONAL SEQUESTRATION[46]					
	BASED ON FAO DATA[47]			BASED ON NATIONAL SUBMISSIONS[48]		
PROPOSAL[49]	MT CARBON/YR	% OF ALLOWABLE EMISSIONS	% PROJECTED ANNEX B GAP[50]	MT CARBON/YR	% OF ALLOWABLE EMISSIONS	% PROJECTED ANNEX B GAP
Canada's position pre-Hague	755	16	116	581	12	89
Canada's 20 November 2000 position	385	8.1	59	310	6.6	47
Canada's 24 November 2000 position – 80% threshold	339	7.2	52	295	6.2	45
Canada's 24 November 2000 position – 100% threshold	205	4.3	31	195	4.1	30
Pronk paper, 9 April 2001	68.9	1.5	11	105	2.2	16
June 2001 negotiating text	76.9	1.6	12	106	2.2	16
EU, 25 November 2000	16.8	0.4	2.6	16.4	0.3	2.5

For purposes of comparison, projections of credit are based on different estimates of current or future sequestration in forests.[51] The November 2000 proposals by Canada, the US, and Japan were silent on a key variable – the threshold over which they wanted 100% of forest management sequestration to be credited. Table 2.1 shows estimates for two possible thresholds, one of which provides the lowest possible estimate of non-additional sequestration.[52]

Table 2.1 shows that Canada's most recent proposal would reduce the global environmental effectiveness of the Kyoto Protocol by at least 30% and possibly 50%. European proposals would have only a marginal effect, while Pronk's June 2001 proposal could reduce effectiveness by an estimated 12-16%.

Uncertainty related to sinks

Critics argue that without special rules to deal with uncertainty related to sinks, a number of issues would arise. Uncertainty in this context refers to the accuracy of sequestration or emissions estimates that are used to determine compliance with the Kyoto Protocol. The uncertainty would:

- Reduce the transparency of countries' commitments
- Decrease the extent to which compliance with emission limits can be verified
- Increase the possibility that countries would exaggerate the amount of sequestration in order to increase emissions or sell excess emission quotas

According to the EU, the Alliance of Small Island States (AOSIS), the Environmental Integrity Group, and others, credit for sequestration should be discounted and/or caps should be placed on the total amount of credit that can be gained from forest management. Other nations agree that uncertainty can be an issue, but argue that it can be reduced to a point where it is no worse than uncertainty from other elements of nations' emissions inventories.

In weighing these arguments the following factors should be kept in mind:

- *Although uncertainty in some other classes is equal to that from the LULUCF sector as a percentage, the absolute uncertainty is greater for sinks.* Within Annex B the only class of emissions with uncertainty similar to that of the LULUCF sector is nitrous oxides. Nitrous oxides, however, amount to only 6% of Annex B emissions, whereas the LULUCF sector sequesters 9.5-15% of emissions.[53] Within Canada, the only class of emissions whose level of uncertainty equals the LULUCF sector's ±100% uncertainty is nitrous oxide from anesthetics, but this accounts for only 0.05% of Canada's emissions compared with the LULUCF sector, which is estimated to offset 5% of emissions.[54] The differences in absolute quantities are therefore significant.
- *For the above reasons, uncertainty could mask overall non-compliance.* If additional Article 3.4 activities were to offset 11% of Annex B emissions and uncertainty could be limited to ±50%, it might be impossible to know whether countries had actually reduced emissions below 1990 levels.[55]
- *A potential solution – discounting for uncertainty – is also unlikely for the First Commitment Period.* Special accounting rules for sinks could encourage improvements in measurement techniques while ensuring that sequestration is not overcredited. Both the EU and the Environmental Integrity Group have supported discounting sequestration credits by an amount that reflects uncertainty in measurement. For example, if the US estimate of forest management sequestration (289 megatonnes of carbon per year[56]) were accurate to within 50%, the US would be able to get credit for only 144 megatonnes. This approach has been rejected by Canada, the US, and Japan. Parties are currently discussing only across-the-board discounts that do not reflect differing levels of uncertainty.

Impermanence of carbon sequestration

As discussed earlier, sequestering a tonne of CO_2 is not equivalent to reducing greenhouse gas emissions by a tonne. Carbon in forests and in the upper layer of soils can be quickly re-released to the atmosphere as a result of forest fires, logging, the cessation of practices such as conservation tillage, and climate change itself. If carbon is sequestered in soils or forest for only a decade, the overall impact on the atmosphere is negligible. Atmospheric concentrations are lower during the decade but rebound subsequently. In contrast, a one-year reduction in fossil fuel emissions will lead to a centuries-long reduction in concentrations of CO_2 in the atmosphere.

Parties to international climate negotiations have recognized this fundamental difference by stating that once land credit is given for sequestration on an area of land under Article 3.3 or 3.4, subsequent human-induced emissions from that area must be accounted for. This helps ensure that countries cannot get credit for enhancing carbon reservoirs and then ignoring future releases from the same reservoirs, but it fails to solve the problem of the impermanence of carbon sequestration for several reasons:

- *Countries have not accepted responsibility for emissions resulting from forest fires, drought, insect infestations, or other causes that are not clearly human-induced.* Canadian officials have said that countries should accept responsibility for these emissions, but this negotiating position/proposal is linked to credit for natural sequestration – that is, credit for non-additional sinks.
- *There is a risk of increasing long-term atmospheric concentrations of CO_2.* If countries are permitted greater emissions because they have sequestered carbon in trees or soils, more carbon will be released into the active carbon pool, which consists of the atmosphere and the biosphere. The carbon stored in trees and soils is available to the atmosphere (unlike carbon stored in oil, coal, or gas deposits), and climate change simulations suggest that large amounts of carbon currently sequestered in soils and forests may be released over the next century, accelerating future climate change.[57] Carbon stored in the biosphere as a result of human sequestration activities may be a small fraction of all carbon in the biosphere but it is particularly susceptible to fire, disease, and other catastrophes. For example, fire suppression may enhance sequestration in the short term but can also create tinderbox conditions that increase the risk of fire and subsequent release of large amounts of CO_2 into the atmosphere.
- *It transfers responsibility to future generations.* If countries are debited for future releases of sequestered carbon, they may simply take stronger action and offset those releases by making deeper cuts in the amount of carbon released in the future. In essence, this transfers an additional risk and responsibility to future generations, who would have to make the tough decisions to cut emissions.
- *It transfers risk to government and to society at large.* If countries are given credit for carbon sequestration under the Kyoto Protocol, their governments are likely to give corporations credit for projects that sequester carbon. Corporations could use the credit to increase their own emissions, but if they restructure or go out of business, government would be left responsible for the carbon debit.
- *Future generations may be unable to offset biotic carbon releases.* They may be overwhelmed by the need to reduce their direct emissions – by 50% or more globally in the long term – while offsetting emissions due to sequestration reversals. Faced with these pressures, countries are more likely to fall short of their emission reduction commitments and to shun deeper cuts.

Carbon in forests and in the upper layer of soils can be quickly re-released to the atmosphere as a result of forest fires, logging, the cessation of practices such as conservation tillage, and climate change itself.

- *Future carbon releases are likely to accelerate the rate of climate change.* Storing carbon in trees or soil reservoirs for several decades may help delay climate change, but if releases from these reservoirs are not matched by deeper emission reductions, climate change could be faster and more damaging in the future.[58]
- *"Credit now, debit later" overvalues sequestration relative to reduction.* Both the United Nations Framework Convention on Climate Change and the Kyoto Protocol recognize that climate change is a long-term problem. Different greenhouse gases are rated based on their cumulative effect on the climate over a 100-year timeframe. The credit now, debit later approach is inconsistent with such a long-term view. If a tonne of carbon is sequestered for only 46 years, the cumulative impact on warming over 100 years is only 37% of the impact of an actual emission reduction.[59] An investor comparing sequestration and reduction, however, would discount the future debit and treat the two as similar.

It should be noted that permanence issues are not the same for all types of sequestration projects. Protecting existing old growth does not increase the risks to future generations in the same way as suppressing forest fires or planting monocultures of fast-growing species. Other sink enhancement projects, such as changes in tillage practices, are also less susceptible to natural disturbances, albeit more susceptible to changes in management practices.

> Storing carbon in trees or soil reservoirs for several decades may help delay climate change, but if releases from these reservoirs are not matched by deeper emission reductions, climate change could be faster and more damaging in the future.

Over-reliance on sinks

Like estimates of business as usual sequestration from forest management and agricultural soil management, estimates of the potential for additional sequestration are uncertain. The potential credit from forest management, wood products management, and agricultural soil management activities would allow most of the 20 Annex B countries studied to achieve their reduction commitments through sequestration. Relying on additional sequestration alone, the US could potentially increase emissions by 4-12% from 1990 levels, instead of having to meet its -7 % Kyoto target. EU countries would be able to increase emissions by 8-11% instead of meeting the -8% target agreed to in Kyoto.[60] This study estimates that 600 megatonnes of carbon per year will be sequestered through additional activities by Annex B countries in the First Commitment Period, compared with the US Energy Information Agency's estimated gap of 653 megatonnes between business as usual emissions and the Kyoto targets in 2010.[61]

Other estimates are lower. The Intergovernmental Panel on Climate Change estimates the realistic potential for revegetation and cropland, grazing land, and forest management in Annex B Parties to be 269 million tonnes of carbon per year,[62] which would achieve over one-third of the reductions needed to comply with the Kyoto Protocol. Others suggest that, given the likely value for sequestration credits, additional activities under Article 3.4 in Annex B will achieve only about 20% of the projected gap between Annex B business as usual emissions and the Kyoto targets.[63]

Despite this range of estimates, it is clear that if agricultural soils and forest management are added under Article 3.4, there will be significant sink credits that could potentially overwhelm direct industrial emission reduction efforts.

Perverse incentives

Critics have also suggested that Article 3.3 can reward countries for deforestation. Potentially, areas deforested since 1990 or since negotiation of the Kyoto Protocol could be subsequently reforested for credit during the commitment period. To eliminate any incentive to deforest and reforest, several countries and environmental groups have recommended not crediting reforestation on land deforested after either 1990 or 1997.

Under Article 3.3, there is a risk that northern countries will seek credit for planting or seeding forests in areas where new forests would have a limited and possibly negative impact on climate change due to increases in the amount of sunlight converted to heat rather than reflected back to space. No one has proposed ways to eliminate or restrict such credits.

3

Counting Carbon in the Developing World

The Clean Development Mechanism (CDM) contained in the Kyoto Protocol enables industrialized nations to receive credits for investing in emission reduction projects, and potentially sequestration projects, in developing countries. It is also supposed to help developing countries achieve sustainable development.

Whether CDM projects involve sinks or more straightforward emission reductions, calculating credits is a difficult task. Credits generated by CDM projects are determined by comparing actual "with project" emissions with a hypothetical "without project" emission baseline. The "without project" baselines are counterfactual – best guesses of what would have occurred without a project. To fully offset the effects of increased emissions in industrialized countries, baselines must represent the level of emissions that would have occurred without the project, and the projects must be projects that would not have occurred in the host nation without the CDM.[64] The need for "additionality" and the need for accurate baselines make calculating CDM credits a challenge, with or without the inclusion of sinks.

The Clean Development Mechanism (CDM) contained in the Kyoto Protocol enables industrialized nations to receive credits for investing in emission reduction projects, and potentially sequestration projects, in developing countries.

Sinks and the CDM

The Kyoto Protocol is silent on whether credit can be generated from the establishment of sinks or the protection of carbon reservoirs in developing countries. This silence has generated a good deal of attention in the post-Kyoto negotiations to finalize interpretation of the Protocol.

Negotiations have distinguished between various types of CDM projects:

- *Afforestation and reforestation* – projects that plant trees either on grasslands, formerly forested areas, or agricultural land. They can include agroforestry (planting trees in conjunction with agriculture), establishing plantations to produce wood products and/or to sequester carbon, or restoration of native forests.
- *Prevention of deforestation* – projects that protect existing, generally natural forests.
- *Soil sequestration* – projects that either reduce the rate of soil loss due to agriculture or sequester carbon in agricultural soils.

The November 2000 and April 2001 iterations of the paper[65] by CoP6 chair Jan Pronk, as well as the June 2001 negotiating text, proposed limiting Land Use, Land Use Change, and Forestry (LULUCF) projects in the CDM to afforestation and reforestation during the First Commitment Period (2008-2012). Canada, the United States, and Japan opposed restrictions on the types of projects that would be eligible for CDM credits, and opposed any limits on the amount of such credits that can be generated. Other members of the Umbrella Group[66] have been less hawkish. For example, Australia has accepted the exclusion of credit for avoided deforestation during the First Commitment Period.

Since the CDM is intended to help developing countries achieve sustainable development, it would seem reasonable to develop rules to ensure that CDM projects are, indeed, sustainable.

The European Union has opposed the inclusion of any LULUCF projects in the CDM. Developing countries are divided on the issue. The G-77/China supports excluding the prevention of deforestation and land degradation from the CDM for the First Commitment Period. This reflects a compromise on the part of traditional opponents of including sinks in the CDM (India, China, South Korea, the Philippines, and the AOSIS countries), but several Latin American countries continue advocating the inclusion of deforestation prevention projects in the first or second commitment periods.[67]

Outstanding issues and concerns

ENVIRONMENTAL AND SOCIO-ECONOMIC IMPACTS

LULUCF projects that might qualify for the CDM can have both positive and negative effects on local communities and the environment. For example, a number of projects have protected or could protect biodiversity and provide sustainable development:

- Swaths of rainforest that might otherwise be logged have been protected. Proponents of such projects have worked with local communities, trying to ensure that they have an economic interest in rainforest protection and trying to provide economic alternatives to forest-endangering, CO_2-emitting practices.
- Some projects have involved providing legal protection for existing, traditional forest use by indigenous communities.
- Managing agricultural lands to store more carbon is also likely to reduce soil erosion, increase soil fertility, and enhance food security.
- Reforestation of denuded or degraded land with mixed native species can reduce erosion and restore biodiversity.

Other projects, however, have been criticized for their negative environmental and socio-economic impacts:

- Monocultures of pine and eucalyptus have been planted because they maximize short-term sequestration of carbon. Replacement of natural grasslands and forests with these plantations has led to significant loss of biodiversity in and around plantations.[68]
- Afforestation with these species can decrease the flow of water from catchments and cause water shortages during droughts, and all types of afforestation can affect groundwater and local river flows.
- Plantation projects can displace local communities. For example, the completion of one sequestration project in Uganda could lead to 8,000 farmers and fishermen being evicted from the plantation area.[69]

Since the CDM is intended to help developing countries achieve sustainable development, it would seem reasonable to develop rules to ensure that CDM projects are, indeed, sustainable. Canada and other Umbrella Group countries have resisted such rules, however, arguing that developing countries should have the sovereign right to define sustainable development in their own way. This approach would also encourage competition among developing countries: those that impose strict sustainable development criteria could lose investment to those with laxer standards.

Efforts to develop rules to ensure a minimum of environmental integrity in LULUCF projects have so far met with little success. Several US and Latin American environmental groups have suggested adopting rules that would disallow projects involving the conversion of natural ecosystems, or on land that has been deforested since the Kyoto Protocol was negotiated. The EU has also suggested that LULUCF projects in general be consistent with other international obligations. Members of the Umbrella Group, however, have opposed requiring LULUCF projects to be consistent with treaties protecting indigenous peoples, biodiversity, and wetlands, and see little need for additional rules to deal with such projects.

Pronk's proposal to include afforestation and reforestation in the CDM, while excluding the prevention of deforestation, has heightened fears that the CDM could promote projects with negative environmental and socio-economic impacts. Most of the LULUCF projects in developing countries that are considered the best in terms of their impacts on biodiversity and local communities tend to be forest protection projects, while those that have been most heavily criticized are afforestation and reforestation projects. (The reasons for excluding prevention of deforestation relate to the problems of leakage and scale associated with such projects.)

Pronk has also proposed that rules to deal with adverse socio-economic and environmental effects be negotiated in 2002, after agreement is reached on principles considered more immediate. Given past experience, it is uncertain whether effective rules could then be negotiated.

A driving concern of those opposed to reforestation projects in the CDM is that credit for reforestation could actually encourage deforestation.

PERVERSE INCENTIVES

A driving concern of those opposed to reforestation projects in the CDM is that credit for reforestation could actually encourage deforestation: developing countries would have incentive to log or burn natural forests and claim credit for forests planted to replace them, even if the original forest sequestered far more carbon. This same perverse incentive exists under Article 3.3 of the Kyoto Protocol before the First Commitment Period, and there have been cases of carbon-rich natural forests being replaced by carbon plantations in both developing and industrialized countries.

In industrialized countries both emissions from deforestation and CO_2 removal from the atmosphere due to reforestation will be counted after 2008, but no such protection exists in relation to the CDM. Several US environmental non-governmental organizations (NGOs) have proposed rules eliminating credit for reforestation on land deforested before 2000, but these proposals have not been promoted by any country.

IMPERMANENCE OF CARBON SEQUESTRATION

Carbon in forests and soils can be quickly released into the atmosphere as a result of forest fires, logging, the cessation of practices such as conservation tillage or fire protection, and climate change itself (see Chapter 5 for a detailed discussion). To fully offset the atmospheric impacts of an additional tonne of CO_2 emissions, an equivalent amount of carbon must be sequestered permanently; to be consistent with the Kyoto Protocol's long-term approach, it must be sequestered for at least a century. As discussed in Chapter 2, the temporary sequestration of carbon can have some temporary value for the climate, but it can also shift risks onto future generations.

To date, most of the LULUCF projects in developing countries have been of limited duration, promising only to monitor carbon stocks and/or guaranteeing to keep carbon sequestered for 20, 40, or 60 years. Given projections of severe losses of biomass in tropical areas over the next century,[70] this raises concerns that sequestered carbon that is now credited under the CDM could be released in the future.

Although these risks can be reduced through the design of a project, they cannot be eliminated. For example:

- A discount can be applied to credit for carbon sequestered, but what if more carbon is released into the atmosphere than the amount of the discount?
- Projects can be designed so that the local community has a stake in protecting the forests, but what if forests burn as a result of factors beyond the community's control?
- Risks can be spread over several projects, and credits can be discounted to reflect risk (sometime referred to as "self-insurance"). But what if climate change or other factors result in forests and soils in entire regions becoming sources of emissions (as is projected for many tropical areas in the next century)?

To date, few concrete proposals have dealt with the impermanence risk. CoP6 chair Pronk has said that rules for dealing with this should be worked out by CoP8, in late 2002. Nations advocating broad inclusion of LULUCF projects in the CDM, such as Japan, Australia, Canada, and the US, have simply proposed that the issue be dealt with through a combination of project design and risk management. They have not been willing to accept developed-country responsibility for offsetting emissions should a sequestration project be reversed in the future. There has also been little support for requiring that sequestration projects be maintained and monitored for the minimum period – 100 years – consistent with the Kyoto Protocol's focus on long-term solutions.[71]

All CDM projects pose challenges because of the need to accurately determine additionality and set baselines that reflect what would have occurred without the project.

MEASUREMENT

All CDM projects pose challenges because of the need to accurately determine additionality and set baselines that reflect what would have occurred without the project. The challenge is especially great in the context of afforestation, reforestation, and soil sequestration projects.

For a CDM energy project to fully offset emissions, it is necessary only for the baseline to reflect what would have occurred without the project in the 10 or 15 years during which the project generates credits. Emission reductions from the baseline due to the project will have a permanent impact on the atmosphere that offsets increased emissions in industrialized countries.

On the other hand, afforestation, reforestation, or soil sequestration projects will fully offset increased emissions only if the baseline is accurate far after the time at which sequestration occurs, and only if the sequestration is permanent. For example, sequestration of carbon by plantations will fully offset increased emissions only if the sequestration would never have occurred without the project. A project that simply brings a plantation into being 5 or 10 years earlier provides little benefit in offsetting "permanent" emissions such as those from fossil fuel use.

To date, there have been no serious proposals for dealing with this problem.

LEAKAGE

Emission reductions or sequestration of carbon by a project can be cancelled out if the project indirectly causes emissions or decreases sequestration elsewhere. For example:

- A project may successfully protect an area of forest from slash-and-burn agriculture, but farmers may simply move somewhere outside the project boundaries and continue the same level of slash-and-burn, resulting in no gain for the atmosphere.

- If trees are planted for carbon sequestration and then later made available for timber production, the expectation of lower timber prices could reduce investment in plantations that do not get credit.

This phenomenon of leakage is not unique to forest projects, and projects can be designed to avoid it (for example, by providing farmers with alternatives to slash-and-burn agriculture). Nonetheless, leakage remains a particular problem for forest protection projects and can be as high as 100% if such projects are poorly designed. Where new forests have been established to generate carbon credits and timber for the global commodities market, the estimated rate of leakage is 40%, compared with 5-20% in the energy sector.[72]

SCALE

Finally, there is concern that the amount of credit that could be generated by CDM projects might siphon off resources from emission-reducing activities in the energy, industrial, and transportation sectors that are essential for long-term climate protection. This is especially true if credit can be generated from projects to prevent deforestation.

Estimates of the cost of reducing carbon emissions by protecting forests in developing countries range from 10 cents per tonne to $15 per tonne. Based on economists' best guess of $1 per tonne for prevention of deforestation, CDM LULUCF projects could dominate the emission reduction efforts of Annex B countries. Economic models show that if they were eligible for credit, they would account for over 40% of the emission reductions required by the Kyoto Protocol. Less than 15% of reductions would occur through domestic action.[73]

4

Terrestrial Carbon Sinks as Carbon Offset Mechanisms

A scientific consensus has emerged that rising concentrations of certain gases – the so-called greenhouse gases, which include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) – in our atmosphere are altering the exchange of radiation between the earth and space. This alteration is leading to a general rise in global temperatures and changes in global weather patterns. These changes, and their impacts on terrestrial and oceanic ecosystems, are difficult to predict in detail, but it is generally accepted that their onset must be slowed as much as possible.

Reducing fossil fuel combustion contributes directly to reducing the rate of accumulation of greenhouse gases. On the other hand, the potential contribution from changing land use practices is less direct and requires further scrutiny.

Slowing the onset of climate change requires substantially reducing the rates at which CO_2, CH_4, and N_2O are accumulating in the atmosphere. There are two ways to do this:

- Reducing the emission of these gases from combustion of fossil fuels and other industrial processes such as cement making, and from deforestation
- Changing from land use practices that cause organic matter to be converted into these gases to land use practices that retain organic matter as soil and plant carbon in terrestrial ecosystems

Reducing fossil fuel combustion contributes directly to reducing the rate of accumulation of greenhouse gases. On the other hand, the potential contribution from changing land use practices is less direct and requires further scrutiny. This chapter and the next will examine the basis for this contribution.

In principle, 1 tonne (t) of CO_2 not emitted because of reduced combustion of fossil fuel is equivalent in its effect on atmospheric concentration to 1 t of CO_2 that is removed from the atmosphere and stored as organic carbon in terrestrial ecosystems when a land use practice is changed. In fact, however, these effects are different. The tonne of CO_2 not emitted remains in a fossil fuel deep underground, and will never be released to the atmosphere except by deliberate human intervention. On the other hand, the tonne of CO_2 stored as organic carbon in terrestrial ecosystems may soon be converted back to CO_2 through natural respiration processes, natural phenomena such as fire or pests, or human intervention such as logging or tillage. Organic carbon in terrestrial ecosystems and in their wood- or straw-derived products are stored for periods ranging from several months to several centuries, unlike fossil fuels, which reside for millions of years underground. (Carbon can also reside in soil as inorganic carbonates, although the extent of exchange between atmospheric and carbonate carbon is not well known.)

This difference raises several questions:

- Is the storage of additional carbon in terrestrial ecosystems by changing land use practices a valid alternative to the reduction of human-caused emissions? If so, to what extent?
- What specific changes in land use practices provide a valid alternative, and under what conditions should they be allowed to do so?

To answer these questions, it is necessary to examine the processes by which ecosystem carbon is converted to and from CO_2. This chapter summarizes the processes, and Chapter 5 describes how changes in land use practices will affect them.

Basic processes of carbon exchange in terrestrial ecosystems

Globally there are about 760 gigatonnes (Gt = billion tonnes) of carbon as CO_2 in the atmosphere, 800 Gt as organic matter in vegetation, 1,650 Gt as organic matter in soils, and 40,000 Gt as plankton and sediment in the oceans. Terrestrial ecosystems convert atmospheric CO_2 into organic carbon and convert organic carbon back into CO_2. Differences between the rates of these conversions cause changes in the amount of organic carbon stored in these ecosystems.

The conversion of CO_2 into organic carbon occurs through photosynthesis in plants and is called **gross primary production** (GPP). The biological conversion of organic carbon back to CO_2 occurs through two basic processes:

- Respiration by plants, called **autotrophic respiration** (R_a) because the organic carbon being converted is a direct product of GPP
- Respiration by microorganisms and larger fauna, mostly in the soil, called **heterotrophic respiration** (R_h) because the organic carbon being converted is derived from plant material

Organic carbon can also be converted back to CO_2 through non-biological disturbances such as combustion or harvesting. These conversions are shown in Figure 4.1.

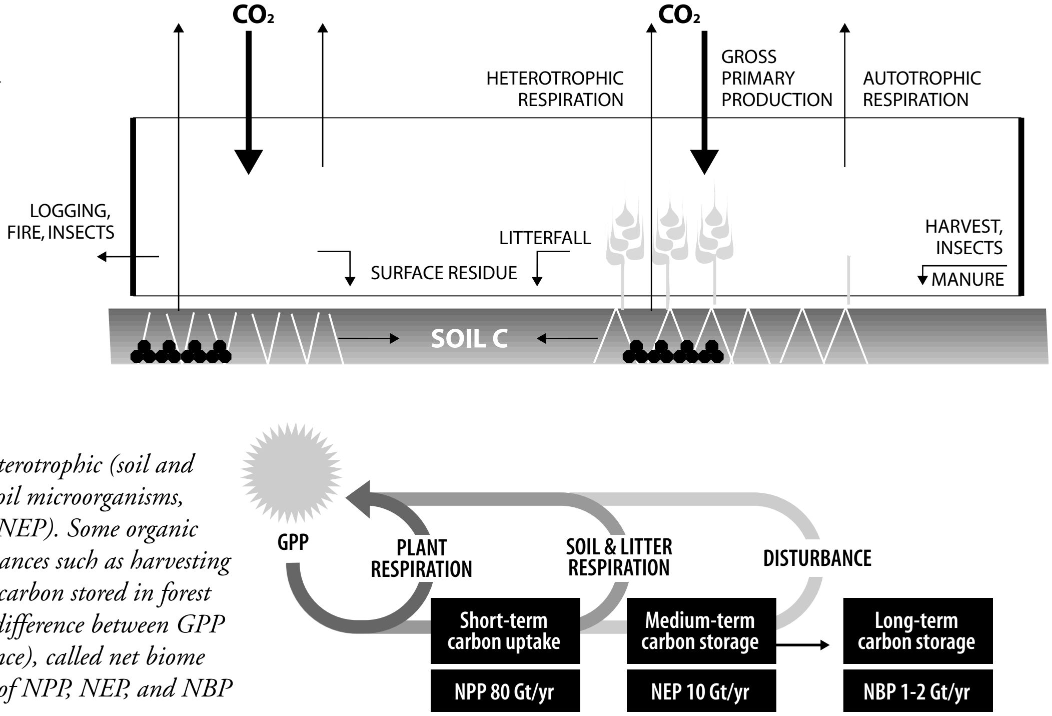

FIGURE 4.1. **PROCESS OF CARBON EXCHANGE IN TERRESTRIAL ECOSYSTEMS.**

CO_2 is converted into organic carbon in plants in the process called gross primary production (GPP). Some of the products of GPP are returned to the atmosphere as CO_2 through autotrophic (plant) respiration (R_a), leaving net primary production (NPP); some are added to soil organic carbon as litterfall. Soil organic carbon is converted back to CO_2 through heterotrophic (soil and litter) respiration (R_h), mostly by soil microorganisms, leaving net ecosystem production (NEP). Some organic carbon can be lost through disturbances such as harvesting or fire. The net change in organic carbon stored in forest and agricultural ecosystems is the difference between GPP and (R_a + R_h + loss from disturbance), called net biome production (NBP). Global values of NPP, NEP, and NBP are shown.

When GPP exceeds (R_a + R_h + loss from disturbance), the ecosystem is gaining carbon and is said to be a **net carbon sink**. When GPP is less than (R_a + R_h + loss from disturbance), the ecosystem is losing carbon and is said to be a **net carbon source**. Long-term changes in ecosystem carbon therefore arise from the relationship between GPP and (R_a + R_h + loss from disturbance) over time. This relationship consists of three components:

- The difference between GPP and R_a, called **net primary production** (NPP), is the rate at which organic carbon is introduced into an ecosystem.
- The difference between NPP and R_h, called **net ecosystem production** (NEP), is the rate at which ecosystem carbon changes over time in the absence of disturbance.
- The difference between NEP and loss from disturbance is called **net biome production** (NBP) and is the true measure of long-term changes in ecosystem carbon.

These three related processes are discussed in the following sections.

NPP is the process whereby all organic carbon on earth was originally formed, including carbon in all terrestrial and oceanic ecosystems and in all fossil fuel deposits.

Net primary production (NPP)

NPP is the process whereby all organic carbon on earth was originally formed, including carbon in all terrestrial and oceanic ecosystems and in all fossil fuel deposits. NPP is affected by a wide range of environmental conditions, and so varies greatly at different times of the year and in different parts of the world. Some of these environmental conditions are under human control and can potentially raise NPP in managed ecosystems above that in natural ones.

As described earlier, NPP is the difference between GPP and R_a. GPP is about 120 Gt carbon per year globally. R_a is between 45% and 50% of GPP in agricultural ecosystems, grasslands, and deciduous forests, and over 60% of GPP in coniferous forests. NPP is thus about 60 Gt carbon per year globally (see Figure 4.1). Any environmental condition that affects GPP or R_a will affect NPP. These conditions include the following.

SOLAR RADIATION

Solar radiation is the source of the energy used to convert CO_2 into organic carbon, and therefore imposes an upper limit on GPP. Actual GPP is usually kept below this limit by other environmental conditions, although radiation itself may be the limiting factor during tropical rainy seasons, when environmental conditions are otherwise optimal.[74]

TEMPERATURE

Temperature strongly affects NPP. This is because the GPP of most terrestrial plants rises with temperatures up to about 30°C but declines with temperatures above 35°C. On the other hand, R_a rises strongly with temperature with no maximum within natural temperature ranges, and so offsets a larger fraction of GPP in warmer climates. NPP is thus optimum between 20°C and 25°C, and is limited by low GPP at lower temperatures and by rapid R_a at higher temperatures.

Tropical ecosystems are near or slightly above optimum temperature year-round, and so have the largest NPP (see Table 4.1). Temperate ecosystems are near optimum temperature during the summer, the duration of which therefore determines their NPP. The boreal and tundra ecosystems most commonly found in Canada are strongly temperature-limited year-round, and so have low NPP.

TABLE 4.1. HOW TEMPERATURE AFFECTS THE NPP OF ECOSYSTEMS NOT LIMITED BY WATER.[75]

ECOSYSTEM TYPE	MEAN ANNUAL TEMPERATURE (°C)	NPP (TONNES OF CARBON/HA/YR)
Tropical evergreen rainforest	25	15
Warm temperate deciduous forest	15	9
Warm temperate coniferous forest	15	8
Cool temperate deciduous forest	10	6
Boreal deciduous forest	1.5	4
Boreal coniferous forest	-1.5	2.5
Tundra	-10	1.25

The different temperature sensitivities of GPP and R_a are important in determining the likely effects of climate warming on NPP. Tropical ecosystems with year-round temperatures already near or above optimum would benefit little from warming and may, in fact, suffer declines, whereas temperate and boreal ecosystems with seasonal or year-round temperatures below optimum would benefit from more rapid NPP over a longer growing season. (However, growth of forests in areas that are currently tundra or agricultural land could potentially exacerbate climate change as a result of an increase in the solar radiation absorbed by forests compared with barren, especially snow-covered, soil.)

If NPP were limited by radiation and temperature alone, it would be much larger than it currently is. Other factors that limit NPP are of interest because they are to some extent under human control and so could be managed to some degree to increase the rates at which new ecosystem carbon is formed. These factors are:

- Water
- Nutrients
- Soil quality
- Atmospheric CO_2 concentration

WATER

The NPP of many ecosystems is limited by water. In such ecosystems, NPP depends directly on how much water the ecosystem receives relative to how much it needs:

- The amount of water an ecosystem receives can be measured as **annual effective precipitation** (P, the amount of water that can sustainably be evaporated and transpired by plants, accounting for water lost through runoff or drainage).
- The amount of water an ecosystem needs can be estimated as **annual potential evapotranspiration** (ET_p, the amount of water that would be evaporated and transpired by plants in the absence of water limitation).

In regions where P is less than ET_p, NPP is closely related to the ratio of P to ET_p; in regions where P is greater than ET_p, NPP is not greatly limited by water unless precipitation is very seasonal (see Table 4.2). Deserts occur where P is less than 30% of ET_p, grasslands and savannahs occur where P is less than 90% of ET_p, and forests occur where P is greater than 90% of ET_p.[76]

In regions where P is much less than ET_p, agricultural NPP can be raised by irrigation (I) until (P + I) approaches ET_p, as currently occurs on 250 million hectares, about one-sixth of total agricultural land in the world. Because of atmospheric circulation patterns caused by the orbital geometry of the earth, these ecosystems are usually found between 15° and 30° north and south of the equator, where NPP is completely dependent upon irrigation. Based on climate models, it is anticipated that climate change will also affect hydrological cycles, which in turn may affect NPP.

Based on climate models, it is anticipated that climate change will also affect hydrological cycles, which in turn may affect NPP.

TABLE 4.2. HOW WATER AFFECTS THE NPP OF ECOSYSTEMS NOT LIMITED BY TEMPERATURE.[77]

ECOSYSTEM TYPE	P:ET_p[78]	NPP (TONNES OF CARBON/HA/YR)
Tropical evergreen rainforest	1.5	15
Seasonal tropical rainforest	1.0	12
Open woodland	0.75	9
Savannah	0.5	4
Desert	0.25	1

NUTRIENTS

New plant biomass is formed when organic carbon from GPP is combined with nutrients taken up from the soil or atmosphere. If there are not enough of these nutrients, GPP and hence NPP are reduced. Nitrogen (N) is the nutrient most widely limiting to NPP in temperate and boreal ecosystems, but phosphorus (P) is also widely limiting, especially in many tropical soils. In undisturbed ecosystems the most important source of N is the atmosphere. One cubic metre of air contains as much N as a tonne of wood. Almost all N in air is biologically inert, however, and must be converted to a biologically active form before it can be taken up by plants to support NPP.

In undisturbed ecosystems, this conversion can be accomplished through two processes:

- Fixation of atmospheric N by specialized bacteria and algae that live in water, soils, or plant roots and use plant-derived carbon for energy
- Oxidation by lightning and subsequent deposition through either precipitation or direct uptake from the atmosphere

Global estimates of biological N fixation are about 90 megatonnes (Mt) per year, mostly by bacteria in the roots of plants called legumes that are adapted to host N-fixing bacteria. Global estimates of N deposition are much smaller.

During the past 50 years, humans have increased N inputs into terrestrial ecosystems through additional processes:

- Chemical N fertilizers are manufactured by applying heat and pressure to atmospheric N, and so are an alternative to biological N fixation for adding biologically active N to ecosystems. Rates of N addition through fertilizers have been rising rapidly, and at 100 Mt per year now exceed those through biological fixation. Agricultural NPP depends heavily on such additions, without which the earth could feed perhaps only one-half to two-thirds of its current population.[79] Higher agricultural NPP from the use of fertilizers has permitted the conversion of some agricultural land to grassland or forests during the past 30 years, thereby raising carbon storage on these lands.
- The combustion of fossil fuels releases about 20 Mt per year of oxidized N into the atmosphere. Some of this may be deposited through precipitation, adding to natural deposition rates, mostly on land near sources of fossil fuel combustion (it should also be noted, however, that these airborne deposits may have significant negative impacts on ecological systems and on human health).

- Nitrogen inputs can also be increased in agricultural and managed forest ecosystems by adding manure or sewage sludge (again, with some other impacts).

Ecosystems that receive additions of N from fertilizer, atmospheric deposition, and organic wastes typically have higher NPP than those that do not.

Excess N can be leached into groundwater or be lost to the air after soil microbes convert it back to gaseous forms (denitrification), especially where N is added in excess of ecosystem requirements for NPP. Much of the added N is chemically joined to organic carbon during plant and microbial growth, so that 50-55 Mt per year of this N is retained in plant and soil organic matter. A conservative estimate is that this retained N raises ecosystem carbon storage by about 600 Mt per year.[80] The implications of N fertilization for ecosystem carbon storage – including emissions of the potent greenhouse gas nitrous oxide – are discussed further in Chapter 5.

Limitations to NPP from P availability are less well understood than are those from N availability. Plant uptake of P is determined more by conversion of existing soil P from unavailable to available forms than by atmospheric inputs, which are very small. These conversions are strongly controlled by soil pH (a measure of soil acidity), so that plants growing on soils with pH outside an optimum range often experience P deficiencies. Such deficiencies on acidic soils commonly found in warm, humid ecosystems can be addressed by raising soil pH through liming.

Soils from which substantial amounts of NPP have been removed by harvesting can become deficient in P even if pH is optimal. Such deficiencies require P fertilizer, which is mined and processed from mineral deposits. Carbon storage can be raised by P fertilization, but little is known about how much this can be done.

SOIL QUALITY

Several properties of soils other than nutrient availability may limit NPP. Slow water infiltration, low water holding capacity, and high salinity limit the availability of water to plants, thereby increasing water limitations to NPP. Soil acidity limits root growth and nutrient uptake in many terrestrial ecosystems.

In many cases, non-optimal values for these properties result from human disturbance during agricultural activity. Non-optimal values can lead to abandonment of agricultural land and therefore continuing deforestation. Limitations imposed by these properties tend to be site-specific (although salinity and acidity are fairly widespread in dry and humid ecosystems, respectively), and can be alleviated by well-designed soil conservation programs.

Soil conservation has successfully reduced the area of agricultural soils on the Canadian Prairies affected by salinity, currently about 1 million hectares (Mha).[81] Some ecologists believe that declines in soil quality caused by disturbance pose a greater threat to the sustainability of agricultural NPP than do changes in global climate, and so need to be considered in any assessment of environmental change.

ATMOSPHERIC CO_2 CONCENTRATION

The GPP of most terrestrial ecosystems is limited by atmospheric CO_2 concentration. In theory, a doubling of this concentration, as expected by the end of this century, could increase NPP by up to 30% if soil nutrients are not limiting. Increases in NPP measured in experiments where atmospheric CO_2 concentration is doubled are more commonly

20% or less, depending on the severity of nutrient limitations. The GPP of ecosystems dominated by certain tropical and subtropical grasses may increase to a lesser degree with atmospheric CO_2 concentration. Higher concentrations also cause a reduction in plant water use per unit GPP, improving water conservation. Thus, increases in NPP with atmospheric CO_2 concentration are comparatively greater in water-limited ecosystems than in ecosystems not limited by water (see Table 4.3).

TABLE 4.3. CHANGES IN WHEAT PRODUCTION UNDER AN APPROXIMATE 200 PPM ELEVATION OF ATMOSPHERIC CO_2 CONCENTRATION (C_A) EXPECTED TO BE ACHIEVED GLOBALLY BY 2050.[82]

IRRIGATION	C_A (PPM)	NPP (TONNES OF CARBON/HA)	NPP_{550}:NPP_{355}
Low	355	6.8	1.2
	550	8.0	
High	355	9.3	1.1
	550	10.2	

Net ecosystem production

The plant material formed from NPP is eventually added to the world's soils as litterfall unless it is burned or harvested (see Figure 4.1). Most of this material (for example, in leaves or roots) resides only briefly in plants before being added to the soil. The material that forms wood in trees, however, can reside in the plant for more than 100 years if not disturbed, long enough to be considered securely stored in the ecosystem.

Depending on soil and litter properties, about 75-85% of carbon in plant litterfall is returned as CO_2 to the atmosphere over time through R_h (heterotrophic respiration) by microbes and fauna.

Depending on soil and litter properties, about 75-85% of carbon in plant litterfall is returned as CO_2 to the atmosphere over time through R_h (heterotrophic respiration) by microbes and fauna (see Figure 4.1). This decomposition is strongly affected by temperature, and occurs within a year in tropical climates, in 1-3 years in temperate climates (perhaps longer in semi-arid ecosystems), and over several years in boreal climates. Over time, above-ground litterfall can cause substantial accumulations of organic carbon in surface litter, especially in forests, where values of 10 t carbon per hectare may be reached.[83] This carbon is vulnerable to loss by fire in forest ecosystems and by tillage in agricultural ecosystems.

The remaining 15-25% of carbon in plant litterfall is used during R_h to produce litterfall residues, microbial biomass and microbial residues that react in the soil over time to form humus. Humus also undergoes R_h, but much more slowly than litterfall. The residence time of carbon in humus ranges from several decades in tropical climates to several centuries in temperate and boreal climates. Residence times for humus in Chernozem soils estimated by radiocarbon dating range from a few hundred years to over a thousand years.[84] The residence time increases with depth, from 400 or 500 years near the soil surface to 2,500 years at depths of 15-30 cm.[85] Terrestrial carbon is thus most effectively sequestered as humus well below the soil surface in temperate and boreal climates. The large store of organic carbon in Canadian soils is due to the slower decomposition of litterfall and humus in colder climates, particularly in soils (including peatlands) of the Boreal, Subarctic, and Arctic ecozones, and in the cultivated Chernozem soils of the Prairie Ecozone.

Carbon in humus is less vulnerable to loss by disturbance than plant and litterfall carbon, so humus is the most secure form of carbon storage in terrestrial ecosystems.

Any CO_2 fixed by plants and stored as humus can be considered to have been effectively removed from the atmosphere for the period of interest in climate change negotiations. Unfortunately, only a small amount of litterfall in terrestrial ecosystems is stored as humus.

Total R_h is the sum of the respiration from litterfall and that from humus. NEP is the difference between NPP and total R_h, and is the true measure of changes in ecosystem carbon in the absence of disturbance. Examples of NEP in different ecosystems are shown in Table 4.4.

TABLE 4.4. NEP OF DIFFERENT ECOSYSTEMS DURING ACTIVE REGROWTH.[86]

ECOSYSTEM TYPE	ANNUAL MEAN TEMPERATURE (°C)	P:ET$_P$	NEP (TONNES OF CARBON/HA/YR)
Tropical evergreen rainforest	25	1.5	1.0-5.0
Seasonal tropical rainforest	25	1.0	4.5
Warm temperate deciduous forest	15	1.25	5.0
Warm temperate coniferous forest	15	1.25	4.5
Cool temperate deciduous forest	10	1.25	3.0
Boreal deciduous forest	1.5	1.0	1.5
Boreal coniferous forest	-1.5	1.25	0.75
Tundra	-10	1.5	0.15

Global estimates of NPP and R_h are about 60 and 50 Gt carbon per year, respectively, so that global NEP is about 10 Gt carbon per year[87] (see Figure 4.1). These carbon transfers are about 10 times the rate of carbon emission from fossil fuel use. The effect on atmospheric CO_2 concentration of a relatively small change in global NPP or R_h would therefore be comparable to that of a relatively much larger change in human-caused CO_2 emissions. For example, a rise in global R_h of 5% without one in NPP would eliminate any terrestrial offset to human-caused CO_2 emissions, and would have an effect on atmospheric CO_2 concentrations comparable to a rise in fossil fuel combustion of almost 50%. Any solution to rising atmospheric CO_2 concentration must therefore consider how NPP and R_h will be affected by land use practices and climate change.

Both NPP and R_h are strongly affected by environmental conditions, but in different ways that cause the NEP of different ecosystems to vary widely. The effects of environmental conditions on NPP have been discussed earlier. Environmental conditions that affect R_h include:

- Litterfall quality
- Soil properties
- Soil temperature
- Soil water content

LITTERFALL QUALITY

The composition of litterfall affects both its rate of decomposition and the fate of its decomposition residues. Woody litterfall decomposes much more slowly than foliar or root litterfall because of its high cellulose content, and so tends to reside longer in the soil. Litterfall from coniferous forests decomposes more slowly than that from deciduous forests because of its higher lignin content and the low pH (high acidity) of its residues. Higher lignin contents in litterfall also yield more residues that react to form humus in the soil, so less CO_2 is lost through R_h. Undisturbed coniferous forests therefore tend to accumulate large amounts of soil carbon over time, unless other environmental conditions favour litterfall decomposition.

SOIL PROPERTIES

Clay in soils reacts with residues from litterfall and microorganisms to form humus. For a given rate of litterfall, soils with higher clay content accumulate more humus than sandier soils, and are therefore better for increasing carbon storage from changes in land use practices.

SOIL TEMPERATURE

R_h increases strongly with soil temperature as does R_a with plant temperature, roughly doubling with an increase of 10°C. R_h continues to increase up to very high temperatures, unlike NPP, which reaches an optimum at about 25°C and declines at higher temperatures. For a given NPP, warmer soils will therefore accumulate less humus than colder soils.

The long-term consequence of temperature effects on NEP are apparent in the global distribution of soil carbon. Even though boreal forests contribute only 7% of global NPP, they contain about 23% of global soil carbon, and are thus important repositories of terrestrial carbon. On the other hand, carbon accumulation in warmer soils is limited, and most carbon tends to accumulate in plant biomass with shorter residence times.

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SOIL WATER CONTENT

Decomposition of litterfall and humus carbon is slower if soil is dry, because microbes lack habitat and therefore access to litterfall and humus. On the other hand, dry soils limit NPP and hence litterfall comparatively more than R_h, and so dry soils tend not to accumulate carbon.

Decomposition is also slower if soil is very wet because R_h is slowed when microbes do not have enough oxygen. Wet soils limit NPP comparatively less than R_h if plant species are adapted to wet conditions, and so wet soils tend to accumulate carbon. On the other hand, they can emit methane, another potent greenhouse gas, which can completely offset their removal of carbon from the atmosphere.

Net biome production

NBP is NEP minus losses from disturbances. It is the ultimate measure of ecosystem sink or source activity.

Excluding human-caused disturbances, global terrestrial NBP has been estimated to be about 2 Gt carbon (with 1 Gt carbon uncertainty) per year[88] (see Figure 4.1), which offsets about one-third of human-caused CO_2 emissions. Both plants and soils are vulnerable to episodic losses of accumulated carbon through natural (fire, insects) or human-caused (logging, tillage, harvesting) disturbances. These losses occur during the disturbance event through the direct removal of some of the phytomass and surface residue carbon and the sudden transfer of some of the remaining carbon from living phytomass to dead residue, which can then decompose.

Further losses (or, in some cases, gains) occur for many years after the disturbance event through its impacts on the subsequent recovery of the ecosystem (for example, impacts of logging, discussed in Chapter 5). On the other hand, stands that have been undisturbed for long periods of time may become "overly mature" and may suffer declining NEP because of disease and dieback.

Because disturbances occur in different places at different times, their impacts on NEP during and after the event are spatially variable. Areas of land with larger proportions of recently disturbed or overly mature stands have lower NBP than areas with larger proportions of maturing stands. Any large-scale estimate of NBP must therefore consider the time since disturbance for all the component ecosystems within the area of interest.

An example of NPP, NEP, and NBP following a severe fire in a Siberian pine stand is shown in Figure 4.2.[89] In this example, an initial loss of carbon through combustion is

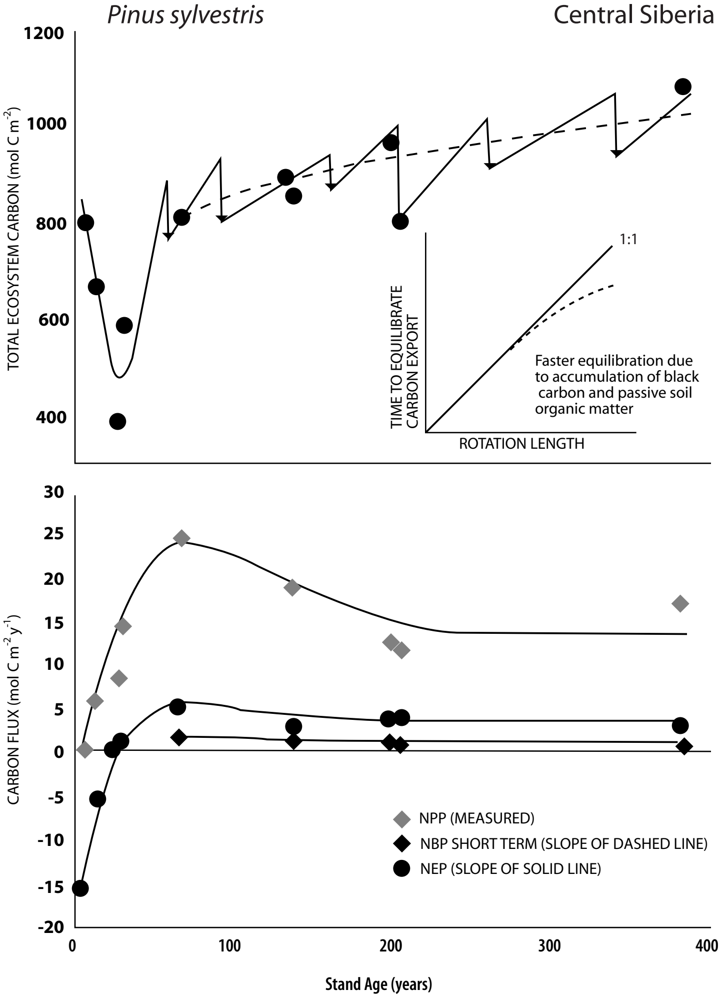


FIGURE 4.2. CHANGES IN NET PRIMARY PRODUCTION (NPP), NET ECOSYSTEM PRODUCTION (NEP), AND NET BIOME PRODUCTION (NBP) (BOTTOM) AND CHANGES IN ECOSYSTEM CARBON (TOP) AFTER A STAND-REPLACING FIRE IN A SIBERIAN PINE FOREST.

For the first 30 years after the fire, the recovery of NPP is slow while heterotrophic respiration (R_h) is high, so NEP is negative and ecosystem carbon declines. As NPP increases during forest recovery, it offsets and eventually exceeds R_h, so ecosystem carbon eventually increases. Periodic fires cause sudden losses of ecosystem carbon. NEP is represented by the slopes of the solid lines for ecosystem carbon between disturbances, and NBP is represented by the average slope of the dashed line for ecosystem carbon including disturbances. (Note: 1 mol carbon per m^2 per year = 0.12 t carbon per ha per year).[90]

followed by further loss during decomposition of residue left after the fire. Later recovery of forest NPP eventually leads to a recovery of ecosystem carbon stocks. A forested region in Siberia would consist of stands with a variety of ages since stand replacement, and hence a variety of NPP, NEP, and NBP within the range indicated in Figure 4.2. Canadian boreal forests may experience more frequent stand-replacing fires that may have more adverse impact on NBP, and may age sooner, than indicated in Figure 4.2. NBP accumulated globally over the last few millennia has given rise to the entire carbon stock of the terrestrial biosphere, about 800 Gt in vegetation and 1,650 Gt in soils.

The intensity and extent of losses from natural disturbances are difficult to predict, but affect 2-4 Mha of Canada's 418 Mha of forest area each year. The magnitude of these disturbances may increase with rising boreal temperatures believed to be caused by increasing atmospheric CO_2 concentration.

By burning all or most of above-ground biomass and much of the surface litter, a fire can destroy in a single day the carbon accumulated by a forest over the course of many decades.

Because humans have only limited control over natural disturbances, such disturbances are not currently included in the Kyoto Protocol (although negotiations for their inclusion are continuing). They pose a threat to terrestrial carbon stocks (see Figure 4.2), however, and so affect their permanence. By burning all or most of above-ground biomass and much of the surface litter, a fire can destroy in a single day the carbon accumulated by a forest over the course of many decades. An average fire burns 7.5 and 5.7 t carbon per hectare of plant and soil carbon, respectively.[91] At average rates of regeneration, it would take about 30 years to replace these losses. Insect damage is less visible but can reduce NPP by 25% during the year of an outbreak. Subsequent carbon losses from respiration of plant residue after fire or insect damage can be as great as those during the disturbance. Natural disturbances are less of an issue in Canada's 68 Mha of agricultural land.

Each year human-caused disturbances affect almost all of Canada's 45 Mha of managed farmland and about 1 Mha of its 225 Mha of managed forests. These disturbances can have large effects on the NBP of both forest and agricultural lands because they not only remove carbon stocks but may also delay the later recovery of these stocks by adversely affecting soil quality. The NBP of managed forests may be less than 30% of their NEP.[92] Because human-caused disturbances can be managed to raise or lower NBP, they are of interest in determining national carbon balances for the purposes of the Kyoto Protocol. Chapter 5 discusses the effects of these disturbances on NBP and Canadian carbon balances.

5

Effects of Land Use Practices and Climate Change on Carbon Exchange in Terrestrial Ecosystems

Atmospheric carbon dioxide concentrations are increasing because emissions from fossil fuel combustion, other industrial processes, and deforestation exceed global net biome production.
Terrestrial ecosystems can store more carbon and thereby help slow this increase only if their NBP is raised above current rates.

Atmospheric carbon dioxide concentrations are increasing because emissions from fossil fuel combustion, other industrial processes, and deforestation exceed global net biome production (NBP) (see Chapter 4). Terrestrial ecosystems can store more carbon and thereby help slow this increase only if their NBP is raised above current rates.

Several changes in land use practices believed to raise NBP have been proposed for inclusion as carbon emission offsets in Articles 3.3 and 3.4 of the Kyoto Protocol (see Chapter 1). Three major concerns that have been raised about these changes will help determine whether they are included:

- Are they undertaken explicitly to raise NBP beyond current rates (that is, are they additional to “business as usual” practices)?
- Are they of sufficient duration to have a meaningful effect on atmospheric CO_2 concentrations (that is, are they “permanent” within the timeframe of concern)?
- Can their effects on carbon storage be measured (can they be verified independently)?

Improved methods of measuring and calculating changes in plant, litter, and soil carbon are vital to the verification of terrestrial carbon sinks in both agriculture and forestry, and therefore to their inclusion in the Kyoto Protocol. Current techniques for measuring soil carbon have a precision of about 5% in agricultural soils (depending on the depth of soil sampling), and perhaps less precision in forest soils. If a soil contains 50 tonnes (t) of carbon per hectare, changes of less than 2.5 t per hectare are difficult to verify from direct measurement. Yet a change in land use may require more than 10 years to raise carbon storage by this amount. Changes in soil carbon attributed to changes in land use can therefore be measured with any confidence only in long-term research plots or agricultural fields under a continuously maintained set of land use practices. Such plots or fields are costly or difficult to maintain and so are limited in number.

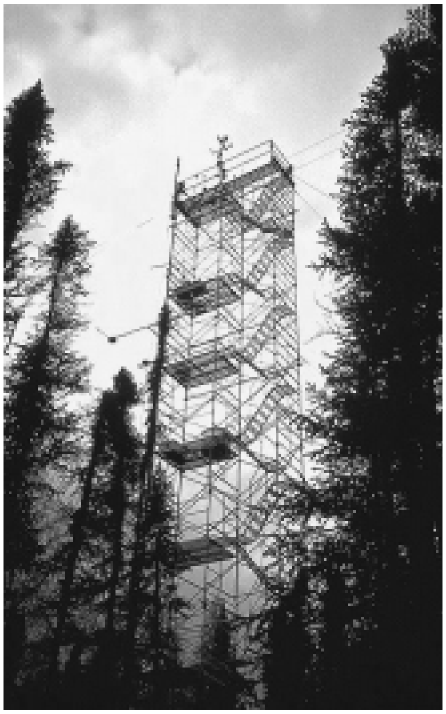
The measurement of changes in carbon storage is an active area of research. Improved techniques for measuring carbon in plants, litterfall, and soils are corroborated by techniques for measuring the rates at which CO_2 enters and leaves different components of terrestrial ecosystems (see Box 5.1). These measurements are increasingly being used to test mathematical models of ecosystem carbon transfers based on scientific theory. Eventually more sophisticated models could be used to make more accurate predictions about changes in carbon stocks.

Kyoto Protocol issues of additionality, permanence, and verification were discussed in Chapters 2 and 3. Some of the changes in land use practices included under Article 3.3 of the Protocol or proposed for inclusion under Article 3.4 are discussed further in this chapter.

BOX 5.1: DEVELOPMENTS IN MEASURING ECOSYSTEM CARBON STORAGE

Recent developments are increasing the confidence with which changes in carbon storage by terrestrial ecosystems can be verified. One of these developments is **eddy correlation**, where the exchange of CO_2 between ecosystems and the atmosphere can be measured directly using instruments mounted on a tower over a forest, wetland, or agricultural field.

These towers, one of which is shown in the photo below, provide much information on the site and weather conditions under which forest stands and agricultural fields gain or lose carbon. The towers are now being sited over different-aged stands following clearcuts and burns in order to measure disturbance effects on net ecosystem production (NEP) at different stages of forest recovery.



Results from the eddy correlation method can be aggregated over time and corroborated by improved methods for directly measuring short-term changes in soil carbon using sampling techniques guided by geographic information systems (GIS). They can also be corroborated by remotely sensed images of vegetation taken from satellites or aircraft that can be used to estimate ecosystem net primary production (NPP) over large areas at high spatial resolution.

These methods by themselves, however, cannot be applied to all site, climate, and land use conditions under which agriculture and forestry occur. Rates of CO_2 exchange and changes in carbon storage calculated using these methods are therefore being compared with the results of mathematical models of carbon transformations in terrestrial ecosystems. If such comparisons are successful under known site, climate, and land use conditions, the models could then be used to project changes under other such conditions where measurements cannot be conducted.

Changes in soil carbon attributed to changes in land use can therefore be measured with any confidence only in long-term research plots or agricultural fields under a continuously maintained set of land use practices.

Forests

The 440 Mha Canadian forest sector is estimated to include 12 gigatonnes (Gt) of carbon in trees, 76 Gt in soils, and 0.6 Gt as forest products,[93] although there is some uncertainty in these estimates. This carbon stock is sensitive to natural and human-caused disturbances. The increasing extent of natural disturbances (such as fires and pests) in recent years is believed to be changing Canadian forests (managed and unmanaged) from a carbon sink (NBP > 0) before 1980 to a carbon source (NBP < 0) thereafter,[94] even though net ecosystem production (NEP) is about 110 megatonnes (Mt) of carbon per year.

Within the forest sector, peatlands are an important carbon sink of about 26 Mt per year. About 1 Mha of forests are logged each year; about half are reseeded or replanted, and about half are allowed to regenerate naturally. In addition, about 15,000 hectares (ha) of previously non-forested land undergoes afforestation each year.

LOGGING

Logging can reduce NBP in two ways:

- The removal of a substantial fraction of above-ground carbon accumulated over several decades before logging
- The partial loss of water and nutrient cycling capabilities needed to restore forest NPP, if logging operations are conducted in ways that adversely affect soil quality

The net impact of tree removal on atmospheric CO_2 depends on how the wood is used. Most wood used as paper will return to the atmosphere as CO_2 through combustion or decomposition within a few years. Wood used as wood products is returned to the atmosphere through combustion or decomposition in landfills less rapidly than it is removed from forests, so there is an ongoing accumulation of wood products.[95] The accumulation of Canadian forest products has been estimated at 25 Mt of carbon per year.[96]

The residence time of carbon in some wood products is long enough to reduce the concerns about permanence for inclusion in the Kyoto Protocol. Current Intergovernmental Panel on Climate Change (IPCC) guidelines, however, specify that wood products are not included in carbon stocks and harvested wood carbon is therefore considered, for carbon sequestration purposes, to return immediately to the atmosphere.

The Kyoto Protocol accounts for neither loss of carbon from harvested wood nor residence of carbon in wood products. Accounting for carbon removal and storage from logging remains an area of debate, and IPCC guidelines are under review. The National Sinks Table[97] has placed a high priority on determining the implications for Canada of including wood products as a carbon storage mechanism. Alternatively, harvested wood may also be used as biofuel, in which case it is rapidly and fully returned to the atmosphere and completely lost to the ecosystem. Depending on the efficiency with which biofuel is produced, however, it can replace a similar amount of fossil fuel, thereby avoiding net CO_2 emission from non-renewable sources.[98] (See the section "Biofuels" pg 58)

The extent to which water and nutrient cycling capabilities are changed after logging depends on specific forestry practices, such as the portions of above-ground biomass removed from the site and the disturbance of the soil during removal. Whole-tree logging with off-site burning of slash (the non-bole parts of the tree) may cause significant loss of above-ground nutrients, whereas retention of slash on site causes only partial loss because much of the above-ground nutrients are in the foliage. There is already a move within the forestry industry towards retention of slash, either by returning slash from whole-tree harvesting or by removing it on site and harvesting only the tree bole. Retention of slash is believed to improve forest regrowth by increasing seed stock, suppressing competition from other plants, and improving long-term nutrient availability. The extent of this improvement, however, and its possible contribution to carbon storage, remains unverified.

The expanded adoption of logging practices such as slash retention that improve nutrient conservation beyond the current approximately 20% of logged area could be considered an additional contribution to NBP that would address the concern of additionality for inclusion in the Kyoto Protocol. More research is needed, however, to establish whether it addresses the concerns of permanence and verifiability.

Logging also substantially reduces transpiration, leading to wet soil conditions under which nitrogen and other nutrients can be lost to the atmosphere through microbial processes and to the geosphere through leaching and runoff. Selective industrial logging is a relatively new practice in which some trees are left standing to create two or more age cohorts in the regenerating forest. This reduces loss of nutrients and transpiration, but is economically more costly than the "clearcut" model, which is still the industrial standard. Further research is also needed to establish the contribution of selective logging to subsequent NBP and carbon storage.

REGENERATION AND AFFORESTATION

Although growth by pioneer species after logging may be rapid, above- and below-ground litterfall may remain small until nutrient cycles are restored and tree nutrient reserves are rebuilt. These small inputs from litterfall during regeneration often fail to offset large CO_2 emissions caused by heterotrophic respiration (R_h) of residual plant material from the logged forest (foliage and branches if slash is kept on site, and roots containing a substantial amount of carbon in a mature forest). This residual material usually varies from 10 to 20 t of carbon per hectare,[99] and except for the largest roots, decomposes rapidly as described in Chapter 4.

Under boreal conditions, NPP recovers more slowly and may take as long as 25-30 years before exceeding R_h. Another 30-40 years may then be required to offset earlier carbon losses.

CO_2 emissions from these residues may be accelerated by the higher temperatures found in soils exposed to solar radiation after removal of forest cover.[100] Net carbon loss from a coastal fir forest may be almost 6 t per hectare during the first year after clearcutting,[101] although losses during subsequent years are likely to be smaller. Several years may pass before the NPP of the regenerating forest starts to exceed R_h so that NEP is no longer negative and net losses of ecosystem carbon cease. Increases in NEP must then be sustained for several more years or decades to offset the accumulated losses of carbon since logging. The time required for recovery of NEP depends on site conditions, especially temperature but also nutrient status. The recovery of NEP can be hastened by site preparation practices such as scarification, seeding, and planting.

Examples of how NEP might change with time after logging of a coniferous forest stand under temperate conditions (mean annual temperature = 15°C, as in a pine plantation in the southern United States) and boreal conditions (mean annual temperature = -1.5°C, as in a spruce stand in northern Canada) are shown in Figure 5.1. These conditions represent the extremes of the temperature range within which coniferous stands are found. The time course of NEP following logging in northern Canada may be compared with that measured after fire in a Siberian coniferous forest stand (see Figure 4.2). Under temperate conditions, NPP recovers rapidly and may start to exceed R_h four years after logging. Another two years are required, however, for NPP to fully offset earlier losses from R_h of residual plant material and soil carbon.

Under boreal conditions, NPP recovers more slowly and may take as long as 25-30 years before exceeding R_h. Another 30-40 years may then be required to offset earlier carbon losses. It has been found that 10-30 years are required for the NEP of regenerating boreal forests to recover to values found in mature stands, depending on site conditions.[102] Further research is needed to establish these periods for different forest types. For example, aspen stands recover NPP more rapidly than coniferous stands because aspen can

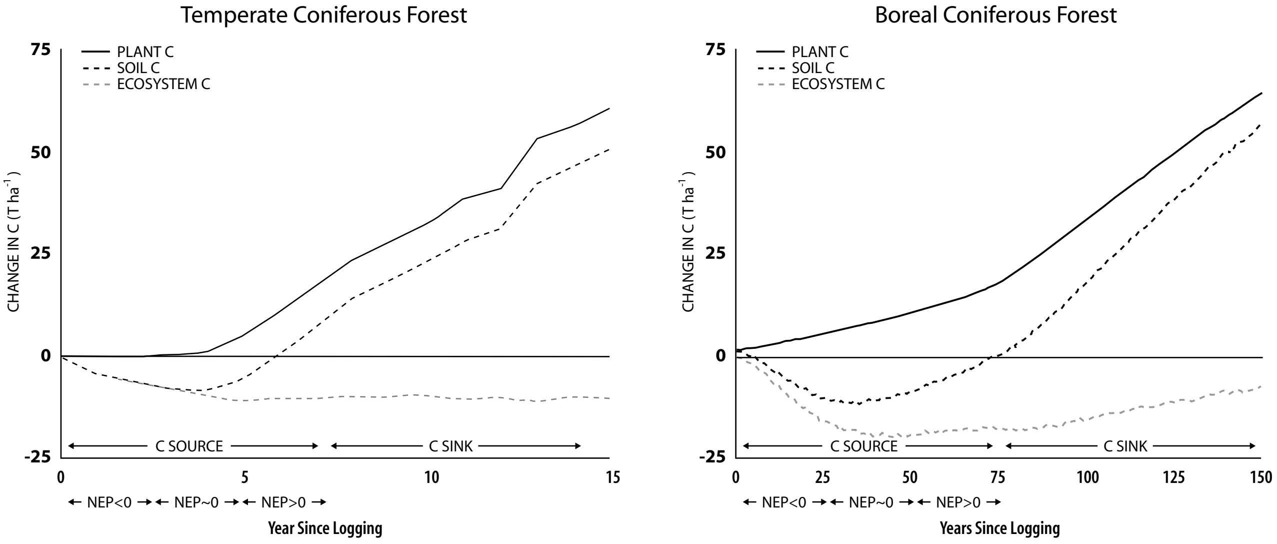


FIGURE 5.1. CHANGE IN NET ECOSYSTEM PRODUCTION (NEP) WITH TIME AFTER LOGGING OF A TEMPERATE AND A BOREAL CONIFEROUS FOREST.

Forests become sources of carbon (C) for some time after logging because soil C is lost through heterotrophic respiration (R_h) more rapidly than plant C is gained by net primary production (NPP). When this occurs, net ecosystem production (NEP = NPP - R_h) is negative and there is a net loss of C from the forest ecosystem. This diagram shows how long and how large a loss of C would occur after clearcut logging of temperate and boreal coniferous forests. In the case of fast-growing pine plantations in the United States, NPP recovers rapidly and offsets R_h after 2.5-5 years. When this occurs, NEP becomes zero and ecosystem C is stabilized, but at a lower value than when the forest was logged. Thereafter NPP exceeds R_h so that NEP becomes positive and the ecosystem starts to regain C. After 6 years the earlier loss of C is recovered, and the ecosystem again becomes a net sink for CO_2. In boreal forests, the loss and recovery of ecosystem C after logging takes much longer. NEP recovers to zero 25-30 years after logging and the forest becomes a net sink for CO_2 after 75 years. These periods of C loss and recovery represent the extremes of those likely to be found in coniferous forests.

regenerate from existing root systems rather than from seed, and so retains more of its carbon and nutrient stores after logging. Aspen forests, which cover much of the area between the prairie grassland and the boreal forests, would therefore experience smaller net losses of carbon after harvesting.

Once forest regrowth reaches maximum cover, its stand NPP and possibly NEP can exceed those of an older stand, causing more rapid accumulation of ecosystem carbon. These changes in NEP after logging indicate that the consideration of ecosystem carbon storage during harvesting and regrowth must be based upon the entire life cycle of harvested stands, not just upon the later phases of regeneration and maturity. Such consideration would recognize that the decline in ecosystem carbon after logging creates a carbon debit that must first be made good before changes in NEP from land use practices in logged stands would contribute to mitigating climate change. At a larger spatial scale, forest NBP needs to be calculated by aggregating the NEP of all stands as determined by the time elapsed since last disturbance.[103]

Consideration of NEP during the entire forest life cycle when calculating NBP would encourage the retention of older (although not overmature) forests, which have been

These changes in NEP after logging indicate that the consideration of ecosystem carbon storage during harvesting and regrowth must be based upon the entire life cycle of harvested stands, not just upon the later phases of regeneration and maturity.

shown to remain active in carbon sequestration to advanced ages[104] (see Box 5.2). The measurement of NEP at different stages of the forest life cycle is now an active area of research. The National Sinks Table[105] has estimated a potential annual sink of 1.7 Mt of carbon per year from planting and seeding, and an additional potential sink of 1.5 Mt per year from natural regeneration after harvesting. These sinks are likely to be overestimated, however, because they do not account for the period after harvest during which the regenerating forest is a carbon source (see Figures 4.2 and 5.1).

There are some forest management practices that, if expanded beyond current rates of use, could raise NEP and thereby contribute to carbon sequestration. For example:

- Site preparation practices such as scarification, seeding, and the use of faster-growing genetic stock may promote early and rapid regeneration of forest NEP after logging.
- Selective thinning and fertilization of forests, and increased protection from pests and fire, can extend the duration of higher NEP, permitting longer logging cycles to improve forest NBP. The National Sinks Table[106] has estimated that improved pest control could raise forest carbon stocks by 3 Mt per year, although there were concerns about the environmental consequences of large-scale pesticide use.

These practices may raise merchantable wood carbon stocks and thereby contribute to carbon sequestration in wood products. The use of these practices to offset emissions will depend upon how carbon sequestration in wood products is treated in the Kyoto Protocol. The effectiveness of these practices in raising total ecosystem carbon storage, as opposed to wood carbon that will later be harvested, has not been verified and requires further research.

The net carbon gain from afforestation must be calculated by subtracting the NEP of the ecosystem being replaced. Other ecological impacts (for example, biodiversity) must also be considered in the evaluation of potential afforestation areas.

The above- and below-ground residual plant material at a non-forested site is usually less than that left after a forested site is logged, so the initial carbon loss during early afforestation is less than that during early reforestation. The NEP of afforested sites, especially those planted with fast-growing hardwoods, would more quickly reach the values in Table 4.4 than that of reforested sites. These values greatly exceed those of the grassland or cropped land on which afforestation is taking place as long as P:ET$_p$ (precipitation to annual potential evapotranspiration; see Chapter 4) ratios are high enough to maintain a forest. The higher NEP of afforested sites is maintained over long periods of time if disturbances are avoided, and that part of NEP retained in wood can be easily measured.

Because afforestation is included in the Kyoto Protocol, it has received the highest priority as a forestry sink mechanism in the National Sinks Table.[107] The National Sinks Table estimates that current afforestation creates a sink of 0.5 Mt of carbon per year, and that maximum potential afforestation on 8 Mha of land would create an additional sink of 8.2-12.3 Mt per year. This estimate is based on an NEP of 0.10-0.15 t of carbon per hectare per year, which is consistent with values of NEP for boreal forests given in Table 4.4. The net carbon gain from afforestation must be calculated by subtracting the NEP of the ecosystem being replaced. Other ecological impacts (for example, biodiversity) must also be considered in the evaluation of potential afforestation areas.

FERTILIZATION

Fertilization with nitrogen can substantially raise the NPP, and hence the NEP, of boreal and temperate forests by hastening the acquisition of nutrient capital by trees. Several studies of coastal fir stands in British Columbia, lodgepole pine stands in Alberta, and black spruce stands in Ontario and Quebec indicate that fertilization may increase annual wood increment by 30-50%. Fertilization may also lessen the impact of insect infestation on NPP.

BOX 5.2: OLD-GROWTH FORESTS OR YOUNG KYOTO FORESTS?

There are contrasting viewpoints within the scientific community about how NBP is affected by the age at which forests are harvested. E.-D. Schulze, C. Wirth, and M. Heimann of the Max Planck Institute for Biogeochemistry in Germany argue that replacing old-growth forests with young, so-called Kyoto stands that will be used in national carbon balances may in fact accelerate loss of carbon from forest ecosystems.[108] They believe that this loss will be caused by decomposition of residual biomass from the old-growth forest. G. Marland, B. Schlamadinger, and R. Matthews of the Oak Ridge National Laboratory in the US, the Institute of Energy Research in Austria, and the Alice Holt Research Station in the United Kingdom, respectively, observe that a solution frequently proposed to eliminate the incentive for harvesting old-growth forests is to allow carbon credits only for forests on land that was not forested in 1990.[109] Schulze and colleagues reply that no time limit has been set for the inclusion of Kyoto forests, and that industrial countries are unwilling to accept carbon debits from harvesting activities. These debits may be so large that harvesting could increase atmospheric CO_2 concentrations more than reforestation and afforestation could reduce it.

Marland and colleagues also observe that accumulation of carbon in wood products as well as the use of forest biomass as biofuel should offset losses from forest harvesting. Schulze and colleagues reply that the residence time of carbon in wood products is much shorter than in wood and soil, and that residence times of carbon in soil increase with forest age. Furthermore, the energy cost of wood transport exceeds the energy yield from wood-derived biofuel. They believe, therefore, that old-growth forests have a distinct and separate function in maintaining the global carbon balance.

J. Borden of Simon Fraser University in Canada observes that we must account for carbon storage in the wood products of harvested forests.[110] He also points out that accelerated recovery of NPP after logging due to genetically improved trees, intensive silviculture, and improved pest and fire control may offset losses from harvesting. He concludes that the benefits of forest management must be compared with those of forest conservation.

The age at which forests can be harvested while maintaining maximum long-term NBP will depend on site conditions such as forest health, pest infestations, fire, and the rapidity with which forest NEP can be recovered during regeneration. It will also depend on the longevity of the wood products derived from the harvest. These conditions need to be recognized when estimating the impact of harvest management on forest carbon storage.

For example, logging slow-growing boreal forests is unlikely to contribute to reducing atmospheric CO_2 concentrations, whereas replacing low carbon content scrub in the southeastern US with fast-growing pine that is used for timber houses may contribute to reductions in concentrations. In coastal BC, fast growth rates from regenerating coastal fir have to be weighed against the large initial releases of carbon when old-growth is logged.

The age at which forests can be harvested while maintaining maximum long-term NBP will depend on site conditions such as forest health, pest infestations, fire, and the rapidity with which forest NEP can be recovered during regeneration.

The efficiency with which nitrogen in fertilizer is incorporated into tree or soil biomass improves if it is added to a rapidly growing forest at rates that do not exceed the nitrogen uptake capability of plants and soil microorganisms. This uptake capability appears to be about 100-140 kg of nitrogen per hectare per year in boreal forests,[111] but may eventually be constrained by limitations in other nutrients. If applied gradually over time,[112] almost all added nitrogen can be retained within the forest ecosystem with very little loss to the atmosphere or groundwater. However, additions beyond ecosystem nitrogen uptake capability lead to the loss of nitrogen through denitrification and leaching, both of which have undesirable environmental consequences. Denitrification can lead to increased emissions of nitrous oxide (N_2O), a potent greenhouse gas, and leaching can lead to eutrophication of downstream water. Some current fertilization practices involve applications of 300 kg of nitrogen per hectare or more once in several years. Such rates may lower the efficiency of nitrogen utilization and hence of carbon sequestration, and can cause denitrification and leaching.

Certainly nitrogen availability limits carbon accumulation in most forests. Plants require nitrogen to fix CO_2 from the atmosphere, and soil microorganisms require nitrogen if they are to stabilize carbon litterfall as humus. This is because humus is formed at a C:N ratio of approximately 15:1.[113] This ratio suggests that the long-term accumulation of carbon would be 15 t for each tonne of nitrogen retained in soil, and a larger value for each tonne of nitrogen retained in wood. This larger value could be of shorter duration, however, depending on disturbances, harvesting, and wood use. An estimate based on soil retention alone would better address concerns of permanence for inclusion of fertilization as a carbon sink mechanism. This ratio of 15 t carbon to 1 t nitrogen is consistent with that used by Melillo[114] and others to estimate carbon storage caused by increasing nitrogen additions to terrestrial ecosystems. Accumulation of carbon should be credited only to N fertilizer that is retained within the ecosystem, namely, N applied at rates within the uptake capability of the forest. This would discourage overuse and the negative impacts noted earlier.

There are, however, two carbon costs to the use of N fertilizer that should be deducted from any gains in ecosystem carbon:

- About 1.2 t of carbon is oxidized and released as CO_2 per tonne of nitrogen used to manufacture, distribute, and apply N fertilizer.[115]
- Nitrogen fertilizer may cause episodic emissions of N_2O, a greenhouse gas with 130 times the global warming potential of CO_2 on a mass basis (IPCC estimates).

Such emissions tend to occur on wetter soils after precipitation.

Current IPCC methodology assumes that 1.25% of nitrogen fertilizer used in agriculture is lost to N_2O emissions, although this value is probably too high for forests. Research indicates that 0.2-1.0% of nitrogen added to forests can be lost as N_2O, depending on soil wetness.[116] Using average values of 1.2 t of carbon per tonne of nitrogen and 0.6% of nitrogen fertilizer emitted as N_2O-N (nitrogen in the form of N_2O) (although the latter value will be very site-specific, depending on nitrogen limitation to forest NPP and on rates and timing of fertilizer application), the carbon cost of nitrogen fertilizer is approximately 2 t of carbon per tonne of nitrogen, which should be deducted from any carbon gain attributed to fertilizer use.

An alternative to nitrogen fertilizer that would not incur these ecological costs would be biological nitrogen fixation by trees such as alder. Such trees are frequently used to accelerate regeneration by hastening the recovery of nitrogen cycling after logging, although their later removal may be a problem. Biological nitrogen fixation requires that approximately 6 t of carbon be converted to CO_2 in order to fix 1 t of nitrogen, but this carbon is a product of gross primary production (GPP) and so would be considered a renewable alternative to the carbon used in fossil fuel to manufacture fertilizer. Furthermore, nitrogen produced by biological fixation does not usually raise N_2O emissions measurably in undisturbed ecosystems. Subject to verification from further research, the expanded use of nitrogen-fixing plants in forest regeneration could become an effective way to raise NEP.

CLIMATE CHANGE

The projected effects of management on forest NBP need to be calculated under the climatic conditions expected to arise as a result of increasing concentrations of CO_2 and other radiatively active gases. Several contrasting effects of climate change on NBP need to be considered:

- **Higher atmospheric CO_2 concentration and higher temperatures will increase NPP.**

In a wide range of short-term experiments (90-300 days) with growth chambers or open-top chambers, doubling atmospheric CO_2 concentration increased the growth of tree seedlings by 20-120%,[117] with mean increases for broadleafs and conifers of 63% and 38%, respectively.[118]

Under natural conditions, such an increase in forest NPP may be limited by nutrient availability. Additions of nitrogen and phosphorus have been reported to cause larger increases in growth of tree seedlings when atmospheric CO_2 concentration is elevated.[119] Without fertilization, nitrogen limitations on NPP may be partially alleviated by greater root growth[120] or biological nitrogen fixation[121] driven by more rapid GPP. Because elevated atmospheric CO_2 concentration reduces transpiration and increases water use efficiency, the increase in forest NPP may be larger in water-limited environments.[122]

The effects of elevated atmospheric CO_2 concentration on forest NPP have been evaluated mostly in short-term experiments on seedlings under confined conditions. Long-term effects under natural conditions cannot be directly inferred from those experiments because of their limited phytomass and rooting volume,[123] although long-term effects are likely to be smaller.[124] A 25% increase in NPP of a 15-year-old pine plantation after two years under 560 versus 360 ppm CO_2 was reported in a Free Air CO_2 Enrichment (FACE) experiment,[125] but exposure of trees to elevated atmospheric CO_2 over several years caused an eventual decline in the response of NPP.[126] Recent findings from the FACE experiment appear to corroborate this decline.[127]

Due to experimental constraints, these studies considered only the effect of a sudden stepwise increase in atmospheric CO_2 concentration on forest NPP. The effect of a gradual increase over 50-100 years may be different from that reported in the studies. Over longer periods, more litterfall from higher GPP could increase biological nitrogen fixation so that a balance with CO_2 fixation would be maintained.[128]

- **Higher soil temperatures will increase R_h.**

R_h rises strongly with temperature, so substantial losses of soil carbon have been hypothesized to occur in warming soils, a process that may accelerate increases in atmospheric CO_2 concentration. The hypothesis is based on the assumption that the response of R_h to soil temperature and water content is largely independent of its response to carbon inputs from GPP.

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Recent analyses of longer-term forest carbon balances indicate that R_h is more closely coupled with GPP than with soil temperature. This suggests that rising temperatures and atmospheric CO_2 concentration will cause more proportional increases in NPP and R_h, so NEP may be less affected by higher soil temperatures than earlier believed.

The coupling of R_h with GPP occurs partly through their joint dependence on nitrogen. The same microbial processes that cause R_h also cause nitrogen to be transformed from its organic state in litterfall to the mineral state in which it is taken up by plants. Therefore more rapid mineralization and uptake of nitrogen is found in warming soils;[129] this may alleviate nitrogen limitations on the rise in NPP enabled by rising atmospheric CO_2 concentration and air temperatures.[130] Thus the adverse effects of soil warming on NEP may not occur unless other limitations to NPP (disturbances, micronutrient deficiencies) intervene.

The combined effects of climate change on the NEP of boreal and temperate forests are currently believed to be positive, due primarily to an extended growing season caused by higher temperatures.[131] Accumulated gains of 80 and 30 t of carbon per hectare above those under current climatic conditions have been estimated for boreal deciduous and coniferous forests, respectively, over the course of 100 years following stand replacement under currently hypothesized climate change (increases in atmospheric CO_2 concentration, temperature, and precipitation projected under an IS92a emission scenario).[132] These gains are projected to be almost entirely in wood rather than soil, and so would be vulnerable to disturbance (see bullet point below).

These increases in forest carbon storage are an indirect impact of humans on forests, and thus raise concerns about additionality with regard to their inclusion in the Kyoto Protocol as mechanisms for emission offsets. Forest management practices would have to raise NEP above that expected under climate change in order to address these concerns.

- **Higher temperatures will increase the magnitude and frequency of disturbance**.

As discussed in Chapter 4, higher temperatures may increase the magnitude and frequency of fire and pest infestations, particularly those of fire if increases in evapotranspiration exceed the increases in precipitation anticipated under higher temperatures[133] and cause drying of surface litter. Greater carbon loss from disturbance could offset greater NEP from rising atmospheric CO_2 concentration and temperature, causing gains in NBP, if any, to be substantially less than those in NEP. Projection of changes in disturbance under climate change is an active area of research and will likely affect analyses regarding the permanence and additionality of forest sinks.

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Agriculture

The approximately 1,650 Gt of carbon present as organic matter in the soils of the earth are a significant portion of the global carbon cycle. Globally, crop-based agriculture occupies an estimated 1.7 billion hectares of land with an estimated carbon stock of 170 Gt. Cultivation of this land has caused the loss of about 50 Gt of this carbon to the atmosphere,[134] accounting for about one-third of the total increase in atmospheric CO_2 over the last 200 years.

The 45.5 Mha of cropland in Canada currently contain about 6 Gt of carbon, most of which is within the 39.1 Mha of cropland in Western Canada. On average, the soils contain about 120 t per hectare, varying from 80 t per hectare for the Brown soils of semi-arid regions to 200 t per hectare in the more humid grasslands with deep Chernozem soils.[135]

About 1 Gt of carbon, roughly equivalent to five years of Canadian fossil fuel emissions, has been released by cultivation of cropland[136] during the past century. Most of this release occurred within the first decade or two after breaking of the land,[137] mainly in the first four decades of the 20th century, when conversion of prairie and forest to cropland was most rapid. During this period emissions from land clearing and cultivation were about 50 Mt per year, considerably more than emissions from fossil fuel at the time. Much of the carbon was lost from the tilled topsoil, although some studies indicate reductions in carbon at depth, as shallow-rooted annual crops replaced deeper-rooted perennial grasslands.

Canada's cropland has a significant potential for offsetting CO_2 emissions, subject to the key factors noted above: additionality, permanence, and verifiability. Sequestering even a portion of the estimated 1 Gt of carbon lost from cultivation on that basis would go significantly towards meeting Canadian obligations to reduce net emissions of greenhouse gases. The land use practices that will sequester carbon most effectively need to be examined in the context of those key factors, especially in relation to the primary goal of agriculture, which is to produce food as economically as possible with minimal or positive environmental consequences. The impact of climate change on agricultural production and soil carbon storage also needs to be considered, as has been discussed for forestry. Most strategies that enhance carbon sequestration also yield benefits in soil conservation and are effective in conserving soil moisture and nutrients, so they contribute to more sustainable agricultural practices.

Canada's cropland has a significant potential for offsetting CO_2 emissions, subject to the key factors noted: additionality, permanence, and verifiability.

Land use practices that add organic matter to the soil all have a common theme: "Soil carbon levels are governed by balance between inputs of carbon through plant residues, and losses of carbon, primarily through decomposition. Thus, management to increase carbon can be directed towards increasing residue inputs and/or reducing decomposition rates."[138] Within Canada, these land use practices include:

- Reducing the area of land in summer fallow, especially tilled summer fallow
- Reducing tillage through conservation tillage systems
- Producing higher yields and therefore more residues by fertilizing soils
- Making better use of manure on cropland
- Using improved crop rotations, particularly those that include a legume and therefore require less inputs of nitrogen fertilizer with its attendant costs in CO_2 and N_2O emissions

The effectiveness of carbon sinks from each of these land use practices will be discussed below.

TILLAGE

Tilling a soil increases the rate at which organic matter decomposes. It does this by:

- Breaking apart soil aggregates and making the organic matter accessible to microorganisms
- Removing the plant cover, resulting in warmer and moister conditions that speed up microbial processes
- Increasing the supply of oxygen to the microorganisms

Tilling a soil has been compared to opening the damper in a fireplace – by improving oxygen circulation and increasing contact between soil carbon and microorganisms, it fans the flames of soil carbon decomposition and release to the atmosphere.[139] Conversely, reducing tillage is like closing the damper – it slows decomposition and favours soil carbon storage.

The accelerated loss of soil carbon caused by tillage has led to increasing adoption of reduced or zero tillage cropping systems with direct seeding of crops in Canada and elsewhere.

The accelerated loss of soil carbon caused by tillage has led to increasing adoption of reduced or zero tillage cropping systems with direct seeding of crops in Canada and elsewhere. Crop residues (litterfall) accumulate on the soil surface, protecting it from erosion. This litterfall decomposes more slowly than that mixed into the soil by tillage because it has less contact with soil microorganisms[140] and soil water. Surface litterfall also reduces soil evaporation,[141] lowers soil temperature slightly,[142] and decreases oxygen uptake for microbial decomposition of soil carbon,[143] thereby reducing the decomposition of root residues.

Researchers observed slower decomposition of straw in zero versus conventional tillage systems on Gray Wooded soils in northern Alberta;[144] they concluded that greater addition and slower decomposition of crop residues would mean more carbon sequestered in the zero tillage system. The conservation of soil moisture by the surface residue layer under conservation tillage may allow continuous cropping of semi-arid soils, thereby replacing summer fallow in the drier parts of the Prairie region (Brown and Dark Brown soil zones), where about 40% of the land has been in summer fallow each year. Conservation tillage systems, however, require higher inputs of fertilizers and pesticides, mainly herbicides, all of which have an energy cost that can be related to CO_2 emissions during their production and which also have other ecological impacts.

Other studies corroborate the increase in carbon storage with reduced or zero tillage:

- Carbon storage increases in soils under reduced or zero tillage, with increases of 0.10 to 0.15 t per hectare per year above those in more heavily tilled soils.[145]
- Gains of 0.3 and 0.5 t of carbon per hectare per year in semi-arid and subhumid soils, respectively, have been reported during the first three years of direct seeding versus conventional tillage in Saskatchewan[146] (see Box 5.3: “Carbon Sequestration in Prairie Soils”).
- Zero-tilled farmland gained 6.4 t of carbon per hectare in 11 years compared with adjacent farmland under cereal-fallow rotation and conventional tillage in the semi-arid part of Saskatchewan.[147]
- Gray soils under zero tillage in the moist Peace River region of British Columbia had higher amounts and more biologically active forms of organic carbon and nitrogen than those under conventional tillage.[148]
- Zero tillage combined with continuous cropping resulted in gains of 5 t of carbon per hectare over conventionally tilled summer fallow during 11 years on clayey soils in the Brown Soil zone of southwestern Saskatchewan. Similar practices caused smaller gains of carbon in soils with lower clay content, and no gains in sandy loam soils with little clay (see “Soil properties” in Chapter 4). Most of the gains in soil carbon occurred during the last 4 years of the 11-year experiment because higher than average rainfall increased NPP. The researchers emphasized “the necessity of accounting for the influence of both texture (clay content) and probable residue production when attempting to forecast C storage in soils as a function of agricultural practice.”[149]

Not all studies have reported increases in soil carbon under zero tillage, however. Comparisons of long-term tillage experiments with corn on two soils in southern Ontario found that minimum tillage and zero tillage had no significant impact on soil carbon.[150]

In summary, most comparisons on both experimental plots and in farm fields have indicated increased carbon storage under conservation tillage. The increases are likely a consequence of reduced disturbance of the soil and a related decrease in decomposition.[151] In addition, there is a savings of about 0.1 t of carbon per hectare per year in fossil fuel emissions from reduced vis-à-vis conventional tillage because of reduced machinery and tractor use. Many of the comparisons have been between conventionally tilled land with summer fallow every second or third year and zero tillage with cropping every year. Some of these gains should probably be attributed to continuous cropping rather than tillage, in that crop residues are produced every year.

It is clear that these gains in soil carbon arise from a specific change in a land use practice (tillage) undertaken to increase soil carbon storage, and that these increases are measurable. Reduced or zero tillage may therefore be an effective land use practice for soil carbon sequestration. Since reduced or zero tillage is already being widely adopted within the agricultural community and is currently practised on about 16% of agricultural land, its credited effectiveness as a carbon sink should respect the principle of "additionality" and therefore should be based on its accelerated adoption beyond that projected from existing "business as usual" trends.

It is clear that these gains in soil carbon arise from a specific change in a land use practice (tillage) undertaken to increase soil carbon storage, and that these increases are measurable.

There remains uncertainty about the permanence of these increases in carbon storage:

- The rapid gains measured over three years in one study[152] may not be sustained over longer time periods, so that the slower gains measured in a long-term study[153] may be more representative of long-term tillage effects.
- Reversion to conventional tillage can occur at any time, based on short-term management decisions. Farmers manage their soils for more efficient crop production, and regard increased organic matter not as an end in itself but as a means of developing more fertile and less erodible soils. Reversion within a decade or two would cause a rapid loss of much of the gains in carbon storage. This is because gains during the first decade are mostly in litterfall residues in the upper 5-10 cm of the soil that are still decomposing rapidly and so are vulnerable to accelerated decomposition if disturbed. Most research suggests that little of this carbon is being transformed into humus for long-term storage, or moved deeper into the soil. More permanent gains in carbon storage would require continued adherence to reduced or zero tillage over several decades, during which humus could slowly be formed from the surface litterfall. The maximum amount of surface litterfall or humus that can be accumulated under reduced tillage is unknown.
- There is also some uncertainty about the definition of reduced or zero tillage. Some definitions allow considerable disturbance during fall tillage as long as direct seeding is practised in the spring. Practices that lead to improved carbon storage have at most one low-disturbance tillage event besides direct seeding, so some care needs to be taken in estimating areas of land on which sequestration due to tillage is occurring.

BOX 5.3: CARBON SEQUESTRATION IN PRAIRIE SOILS

The Greenhouse Emissions Management Consortium (GEMCo) is a group of power and utility companies in Canada that, as major emitters of CO_2, were looking for changes in agricultural land use practices that would increase soil carbon storage and thereby offset some of their emissions. GEMCo initiated the Prairie Soil Carbon Balance (PSCB) Project, which after three years found that zero tillage and direct seeding did raise soil carbon storage.

One hundred fifty-one farm fields in Saskatchewan were converted to direct seeding in 1996-97 and their soil carbon was compared with that in benchmark microsites or tillage strips maintained in each field. A special sampling protocol was developed to reduce the effects of spatial variability in soil carbon that can confound efforts to detect changes.

The results from this protocol revealed that across Saskatchewan, soils gained 1.25 t of carbon per hectare to a depth of 30 cm during the first three years of direct seeding. This gain was an average of 0.8 t of carbon per hectare in the semi-arid ecozone, and 1.5 t of carbon per hectare in the subhumid ecozone. The findings were stated to quantify and verify the effectiveness of direct seeding in reduced or zero tillage systems as a carbon sink mechanism.

It should be noted, however, that most longer-term studies indicate a lower gain of soil carbon from direct seeding – perhaps 0.15 t of carbon per hectare per year. The higher PSCB value may have arisen from concurrent changes in fertilization and rotation practices, while the lower long-term value arose from tillage alone. Verification of gains in soil carbon from changes in land use practices requires long-term research plots, such as those at Breton, Alberta, shown in the photograph below. Some findings from these plots are shown in Figure 5.2.

Results from the PSCB Project were used to develop a carbon sequestration trading scheme in which up to 2.8 million t of CO_2-equivalent emission reduction credits were purchased from farmers in Iowa through the IGF Insurance Company. IGF Insurance will work with CQuest Ltd., a network of service providers that define, measure, verify, audit, transfer, deposit, register, and assure the creation and transfer of CO_2 emission reductions (ERs). The CERCs for GEMCo are expected to originate from agricultural practices such as minimum-till and no-till farming, cropland retirement, buffer strip development, afforestation, reforestation, improved timber management, on-farm power generation from biomass, and methane abatement from livestock waste.

GEMCo members purchase the CERs in order to promote credit for these activities based on the speculation that they may be credited under future emission trading programs.

FERTILIZATION

Chemical fertilizers

Most agricultural ecosystems are nitrogen-limited, so NPP and therefore carbon inputs to soil will be increased by the addition of N fertilizer and the resulting increase in crop residues or litterfall. The extent to which this increase in NPP will contribute to long-term carbon storage will be affected by the fraction of NPP that is harvested:

- When only the grain is harvested and the remainder of NPP is returned to the soil as litterfall, much of the added N will contribute to carbon storage.

- If almost all of above-ground NPP is harvested as forage or straw plus grain, the contribution of N fertilizer to carbon storage will be less.

As previously discussed for forests, only N fertilizer that does not exceed the uptake capacity of the ecosystem to which it is added will contribute to carbon storage. This uptake capacity or potential amount of carbon added to the soil by growing crops is defined by potential NPP, which may be constrained by water or temperature.

Research findings vary on the contribution of N fertilizer to soil carbon storage in Canada. For example:

- One study found that most of the 20 kg N per hectare per year of N fertilizer applied during 24 years of continuous wheat on a Brown soil in Southern Saskatchewan was present in the increased stores of organic matter in the soil.[155] Each kilogram of recovered organic N had stabilized about 8 kg of organic carbon compared with unfertilized wheat over the same period. Even after 24 years, about one-third of the additional carbon storage in fertilized versus unfertilized wheat was in the form of partially decomposed crop residues that would be vulnerable to loss if fertilization were discontinued.

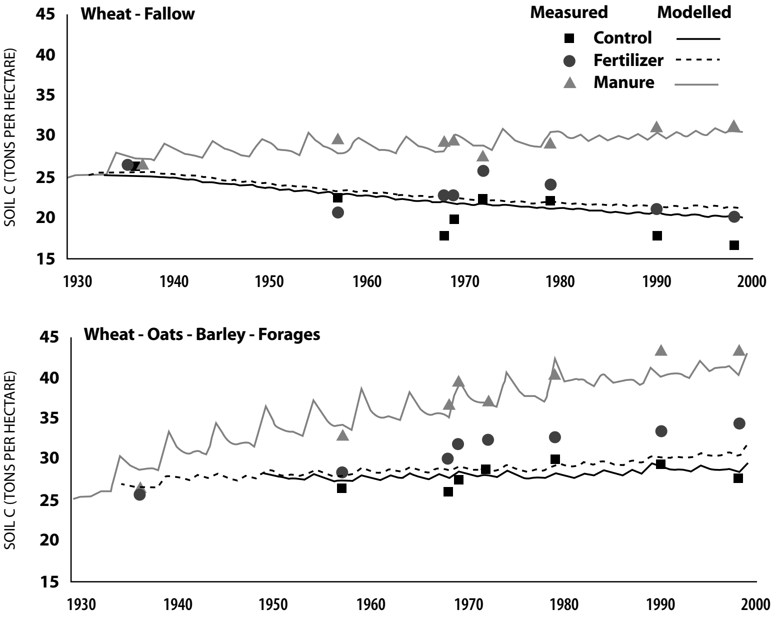

FIGURE 5.2. **RESULTS FROM LONG-TERM STUDIES OF SOIL CARBON GAIN DUE TO CHANGES IN LAND USE PRACTICES.**

There are only a few sites where research has been conducted long enough to accurately measure the effects of agricultural land use practices on soil carbon. One such site is on a forest soil at Breton, Alberta, where the effects of different crop rotations and additives on soil carbon have been measured over the past 70 years. These data (represented by symbols) show the benefits of manure and forage in raising soil carbon (C) by about 10 t per hectare each during this time. Much of our understanding of how we can raise or lower soil carbon with different land use practices comes from data such as these. The data are limited, however, so they are used to test mathematical models (results from one such model, ecosys, are presented as lines) that may then be used to predict land use effects on soil carbon under other, untested conditions.[154]

Given that, depending on harvesting practices, only a fraction of the N added as fertilizer will be retained in the soil, and that this N will stabilize only about 10 t of carbon per tonne of N, net gains in carbon storage from N fertilizer appear to be marginal.

- Similarly, another study found that about 30% of the 45 kg N per hectare per year of N fertilizer applied during 32 years of continuous wheat on a Black Prairie soil in Central Saskatchewan could be recovered later as organic N.[156] Each kilogram of this recovered organic N had stabilized about 12 kg of organic carbon compared with unfertilized wheat over the same period. Only one-tenth of this carbon remained as litterfall residue after 32 years, so most of the additional soil carbon storage from fertilizer could be considered fairly permanent as humus. Later, it was reported that soil carbon was about 6 t per hectare higher in fertilized continuous wheat than in unfertilized continuous wheat after 37 years of cropping, the last seven under minimum tillage.[157]
- The addition of both N and P fertilizer to continuous corn in Ontario was found to raise crop carbon inputs by 62 t per hectare and soil carbon by 6 t per hectare over 35 years.[158] These findings indicate the need for continuity of a land use practice if carbon storage as humus is to occur.

In some cases, fertilizers have failed to contribute to soil carbon storage:

- In Central Saskatchewan, no additional carbon storage from fertilizer was found after 32 years in wheat-fallow rotations, indicating a limited capacity for additional N uptake caused by fallowing.[159]
- In Southern Alberta, there was no contribution of 80 kg N fertilizer per hectare per year to soil carbon after seven years under continuous wheat, due possibly to water limitations on NPP.[160]
- It was concluded that fertilization would result in only small increases (0.05-0.10 t per hectare per year) in soil carbon where summer fallow is part of the crop rotation, especially in semi-arid climates.[161] Larger but still modest increases in soil carbon can be attributed to fertilizer in the more humid regions, where production potentials are higher, and are linked to other land use practices that raise soil carbon storage, such as continuous cropping, crop rotation, and the use of minimum or zero tillage.

As previously discussed for forests, the CO_2 costs of fertilizer manufacture (about 1.2 t of carbon per tonne of nitrogen) and equivalent CO_2 emissions from N_2O release (1.25% of N fertilizer used in agriculture emitted as N_2O-N multiplied by 130 times the global warming potential of CO_2 on a mass basis, according to current IPCC methodology) suggests a total CO_2 cost of about 5 t of carbon per tonne of N fertilizer. It is possible that less than 1.25% of N fertilizer is emitted as N_2O in drier Prairie soils, so this value is the subject of current research. This cost should be deducted from any additional carbon storage attributed to N fertilizer. Given that, depending on harvesting practices, only a fraction of the N added as fertilizer will be retained in the soil, and that this N will stabilize only about 10 t of carbon per tonne of N, net gains in carbon storage from N fertilizer appear to be marginal.

The inclusion of fertilization as a carbon sink mechanism in agriculture would depend on whether it sequesters carbon beyond that in harvested NPP, as stated in the first criterion – additionality – described at the beginning of this chapter. These are competing ends for N, in that the N used to sequester carbon is not available to increase harvests. In practice, well-managed fertilization contributes to both, so establishing additionality is difficult except perhaps in the case of pasture grasses, where fertilizer use is limited.

On the other hand, much current fertilization contributes to neither sequestration nor harvest, but is lost to the geosphere or atmosphere (see "Nutrients" in Chapter 4). Carbon sequestration could be increased without additional fertilization by reducing these losses through improved fertilizer management: using amounts, formulations, placements, and application schedules of fertilizers best suited to plant and soil needs. The greater carbon sequestration will in turn further reduce N losses by improving N retention in soil.

Given the economic and ecological costs of fertilizers, there appears to be little incentive to use them solely to sequester carbon. For effectiveness as a carbon sink mechanism, fertilizer use would also have to be continuous for at least two decades to allow the formation of humus from added carbon, thereby achieving some degree of permanence.

Manure

In this section, *manure* refers to materials accumulated by livestock in enclosures, including feces, urine, and materials such as crop residues that are used as bedding. An exception is the manure from barns that are flushed with water, and the manure stored as a slurry in lagoons for later application to land.

The application of animal manure has been consistently shown to increase soil carbon (see Figure 5.2) in two ways:

- Manure is a direct carbon source, about 20% of which will be stabilized as humus. About 40% of the crop carbon removed from the land and consumed by animals is returned (the remaining 60% is used for animal respiration and growth). Gains in soil carbon from application of manure at rates exceeding 40% of harvested carbon would therefore have to be offset by losses of soil carbon in land from which the excess carbon was harvested.
- Manure increases crop NPP by providing N and P and by improving the hydrologic properties of soil. This is similar to the effect of chemical fertilizer, without the carbon cost of manufacture but with a higher carbon cost for transport.

These gains depend largely on the quality of manure management. Poor management causes nutrient loss during storage and application, and so loss of potential carbon sequestration. Improvements in manure management undertaken to raise soil carbon storage could therefore be considered an effective carbon sink mechanism, with the same concerns for permanence as those mentioned for chemical fertilizers.

The storage and application of manure, especially liquid manures stored in lagoons, can also cause the emission of methane (CH_4), a potent greenhouse gas. Methods to reduce such emissions could be an important contribution to reducing greenhouse gas emissions in agriculture.

CROP ROTATIONS

Fallowing

Gains in carbon storage by agricultural soils require continuous inputs of plant litterfall. These inputs are interrupted by several land use practices that cause soil carbon to be lost. One such practice is summer fallowing, which has caused considerable loss of organic carbon from Canada's soils, especially in the Prairies (Figure 5.3). The purpose of summer fallowing is to store soil moisture during a fallow year for use by a crop the following year. The land is kept bare of vegetation, which has been done in the past by tilling the soil and killing weeds. Soil organic carbon decreases because there are no plant inputs and because the exposed soil becomes warm and moist, favouring decomposition. As previously discussed, tillage during fallow accelerates decomposition and hastens carbon loss.

> Gains in carbon storage by agricultural soils require continuous inputs of plant litterfall. These inputs are interrupted by several land use practices that cause soil carbon to be lost.

FIGURE 5.3. THE EXPOSURE OF SOIL DURING SUMMER FALLOWING CAUSES CONSIDERABLE LOSS OF ORGANIC CARBON THROUGH EROSION AND FAILURE TO REPLENISH RESPIRING SOIL CARBON STOCKS.

This loss is most apparent in the lighter colour of the soil in the upper portions of the landscape, where erosion is greatest and replenishment smallest. Such landscapes can be most effective at sequestering carbon if they are placed in soil conservation programs.

Soils may be fallowed as frequently as every second year where water is most limiting and soil water storage therefore most important, or less frequently where water is less limiting. Soils fallowed less frequently contain more organic carbon, although differences are often not large. For example:

- One study found that sandy loam to silt loam Dark Brown soils in Saskatchewan had the lowest organic carbon contents when fallowed every second year, higher organic carbon when fallowed every third to fifth year, and highest organic carbon when continuously cropped (not fallowed at all),[162] but the differences were not large.
- Another study found that soil under fertilized wheat in Southern Saskatchewan gained 0.16 t of carbon per hectare per year when fallowed every third year instead of every second, and an additional 0.10 t per hectare per year when not fallowed at all.[163] Similar gains under wheat were found in Southern Alberta.[164]
- A study that compared soil organic carbon in several crop rotations on Brown soils under conventional tillage in semi-arid Southern Saskatchewan found that average annual gains of organic carbon (in tonnes per hectare) in relation to land in an unfertilized wheat-fallow rotation between 1967 and 1996 were:[165]
  - 0.11 for a fallow-wheat rotation fertilized with N and P
  - 0.09 for fallow-wheat-wheat rotations
  - 0.23 for a fallow-rye-wheat rotation
  - 0.32 for continuously cropped land fertilized with N and P
  - 0.12 for continuous wheat fertilized with P only
  - 0.28 for a wheat-lentil rotation with fertilizer

Periodic sampling showed that organic carbon contents stayed relatively constant regardless of treatment through the 1970s and 1980s, then increased sharply in response to a seven-year period with above-average yields (and residue inputs) in the moist decade of the 1990s. These changes indicate the climate sensitivity of land use effects on soil carbon storage.

The comparatively rapid gains in the wheat-lentil rotation in the last study listed above show the value of including leguminous crops such as lentil in rotations. These crops support N-fixing bacteria in their roots, as discussed in Chapter 4. The products of N fixation raise the N content of the leguminous crop, and thus that of its litterfall, at the expense of some fixed carbon.

The amount of N-enriched litterfall returned to the soil by leguminous crops can be increased by the practice of green manuring – working the green crop into the soil in early summer to increase soil carbon and nitrogen. Green manuring reduces N fertilizer requirements and improves carbon sequestration. A recent study in Southern Saskatchewan, however, found that carbon gains from lentil green manure were minimal, probably because carbon inputs were not large and the N-rich plant material decomposed rapidly when worked into the soil in midsummer.[166]

There may be greater carbon gains from a productive, water-efficient legume such as chickling vetch with a good N-fixing potential, but these gains must be balanced against possible higher emissions of N_2O during the decomposition of N-rich litterfall.

Forages

Another practice that interrupts inputs from plant litterfall in agricultural ecosystems is annual cropping. In undisturbed ecosystems vegetation is perennial, with continuous NPP and litterfall except during extreme cold. A large fraction of this litterfall is deposited through large perennial root systems deep into the soil, where it is less vulnerable to loss from disturbance (see Chapter 4). Annual crops on the other hand provide little or no litterfall to Canadian soils except during June, July, and August, and have smaller, shallower root systems that leave most litterfall nearer the soil surface, where it is vulnerable to disturbance. Thus, while some gains in soil carbon can be achieved by increasing the frequency of annual cropping at the expense of fallowing, further gains can be achieved by increasing the frequency of perennial forage at the expense of annual cropping. These gains can be increased further if N-fixing legumes such as alfalfa or clover are included in the forage. These legumes can fix as much as 0.25 t of nitrogen per hectare per year, the non-harvested fraction of which can stabilize about 10 t of carbon per tonne of nitrogen.

Studies show a consistent contribution of forages to soil carbon storage. For example, studies found gains in soil carbon of:

- 0.14 t per hectare per year in a six-year fallow-wheat-wheat-forage-forage-forage rotation compared with a two-year wheat-fallow rotation over 41 years on a dark Brown soil in Southern Alberta[167]
- 0.11 t per hectare per year in the same two rotations over 30 years on a thin Black Chernozemic soil in Central Saskatchewan[168]
- 0.15 t per hectare per year in a five-year wheat-oats-barley-forage-forage rotation compared with a two-year wheat-fallow rotation over 70 years on a Gray Wooded soil in central Alberta[169]

Gregorich and co-workers found that topsoil carbon in an alfalfa-alfalfa-corn rotation was increased by 20 t of carbon per hectare above that under continuous corn after 35 years.[170] Furthermore, soil under the alfalfa-alfalfa-corn rotation had 27% more carbon stored deeper in the soil than that under continuous corn, because of the deeper and larger root systems of alfalfa. The soil carbon below the plow layer under this rotation was found to be more biologically resistant to microbial decomposition and therefore likely to be a more permanent carbon sink. The authors concluded: "Residue quality is an important factor in increasing the retention of carbon in agroecosystems and … soils under legume-based rotation tend to be more 'preservative' of residue carbon inputs, than soils under monoculture."

Collectively, these studies indicate that soil carbon storage can be raised above that under cereal cropping systems by about 0.15 t per hectare per year if perennial forages are maintained for a significant part (say, two of five years) of a rotation cycle, and more if they are maintained longer.

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It should also be noted that wheat-fallow or continuous corn cropping systems provide a low baseline from which to calculate gains in soil carbon. The magnitude of this increase depends upon the fraction of above-ground forage NPP that is harvested. Large removals of forage NPP through frequent and intense grazing or cutting will reduce these gains, whereas proper management of forage grazing or harvesting will increase them. Increasing the forage component of a crop rotation is usually achieved at the expense of economic NPP, and so could be distinguished from commercially driven land use practices. It would therefore meet the first criterion of effectiveness as a carbon sink by being undertaken for the express purpose of increasing carbon storage. These gains in carbon storage could be maintained as long as the forage component of the crop rotation was maintained, so they are durable gains that can be measured and verified. Returning cropped land to continuous forage with only light grazing would create the most effective carbon sink, akin to that from afforestation but adapted to drier climates.

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GRASSLANDS

Soil carbon storage can be further increased by returning cropped land to continuous forage through set-aside programs. The conversion of cropland to grassland has increased carbon storage by 0.7-0.8 t per hectare per year in several Midwestern states during the first five years of the Conservation Reserve Program (CRP).[171] This increase is larger in soils with higher clay contents, and smaller in soils with more sand (see "Soil properties" in Chapter 4). Perversely, it is also larger in soils that have already lost much of their carbon through past abusive land use practices than in those that have not.

The rise in soil carbon after six years in the CRP was found to be confined to litterfall residue, indicating that conversion to grassland must be sustained over long periods if more permanent storage of carbon as humus is to occur.[172] The cumulative effects of converting cropped land to continuous forage can be large. It has been estimated that soil carbon in cropped fields abandoned to rangeland would recover to precropped levels (an increase of about 25 t of carbon per hectare) after 55 years or so.[173]

Conversion of cropped land to continuous forage is the land use change that would be most effective as a carbon sink mechanism in the agricultural sector. It has several advantages:

- It is clearly undertaken for the purpose of sequestering carbon in soil.
- It is of a more permanent nature than tillage or fertilization.
- It does not require annual management decisions to be maintained.
- Its contribution to soil carbon storage can be measured clearly after 5-10 years.

BIOFUELS

Biomass produced in both the forestry and agricultural sectors can be converted into biofuels that can replace fossil fuel as an energy source. This biomass can come from annual crops such as sugar or cereal, or from short-rotation woody crops grown on land released from food production. Under certain conditions, these crops may meet the criteria for eventual inclusion as sinks under the Kyoto Protocol. Energy generated from these crops can also displace fossil fuels.

Potential biomass production in Canada is constrained by low NPP in cold climates (see Table 4.1), so Canada is not as well placed as temperate and tropical countries to reduce fossil fuel use in this way. Waste material from processing forest and agricultural products can also be used to produce biofuel, however. At present twice as much carbon is produced in this waste material as is used in fossil fuel, so fossil fuel use could be reduced considerably if only a small fraction of this waste material could be made into biofuels. The reduction in fossil fuel use should be partly offset (perhaps 15%) by the loss of soil carbon from waste material that is not returned to the land.

The potential displacement of fossil fuel by biofuels has been estimated globally as 0.3-1.2 Gt of carbon per year, mostly in temperate and tropical ecosystems.[174] Unfortunately the production of crops for biofuels is not economically favourable under current accounting practices and so its use as a carbon storage mechanism is still limited. The production of biofuel from some agricultural crops can require as much as 50% energy equivalent in fossil fuel, which would have to be deducted from the quantity of fossil fuel replaced by the biofuel. The energy cost of transporting wood can exceed the energy yield of the biofuel produced from it.[175] Under different economic conditions – more expensive fossil fuel, or financial recognition of the biofuel contribution to permanent carbon storage – biofuels could make a larger contribution to slowing the increase in atmospheric CO_2 concentrations.

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CARBON SINK POTENTIAL OF CROPLANDS

The carbon sequestration potential of Western Canada's croplands was estimated as part of the Prairie Soil Carbon Balance (PSCB) Project[176] (see the Box 5.3: "Carbon Sequestration in Prairie Soils"). The estimate was based on calculations by a mathematical ecosystem model (Century Model) using data for climate, land use (from Statistics Canada's 1996 agricultural census), and soil types, including organic carbon and clay contents, landscape positions, and other relevant attributes.

The calculations indicated that the croplands of all three Prairie provinces are sequestering carbon at a rate of 5.9 Mt per year. Alberta was estimated to be the largest net sink, gaining 2.5 Mt per year, followed by 1.7 Mt per year in Manitoba and 1.6 Mt per year in Saskatchewan. The greater sequestration in Alberta and Manitoba reflected the greater proportion of land in continuous cropping vis-à-vis Saskatchewan, where estimated losses from the large area of land in summer fallow offset much of the estimated gain of 1.4 Mt per year due to the higher proportion of land in conservation tillage. Average losses in summer fallow were estimated at 0.21 t of carbon per hectare per year, while average gains in continuously cropped land under conventional and conservation tillage were estimated at 0.35 and 0.50 t of carbon per hectare per year, respectively.

There were regional differences in carbon sequestration determined by climate. The moist Black soil zone was estimated to sequester 3.1 Mt per year (0.23 t per hectare per year) in 40% of the area under study. Sequestration rates in the semi-arid Brown and Dark Brown soil zones were lower. The wooded Gray soil zone was estimated to have a higher per-hectare potential to sequester carbon, but has less cropland.

There are opportunities to increase carbon sequestration in Western Canadian cropland by changing land use practices. For example:

- Converting land from rotations with summer fallow to continuous cropping was estimated to result in an average gain of 0.56 t per hectare per year in all soil zones, even with conventional tillage. Converting continuously cropped land to zero

tillage was estimated to result in an additional average gain of 0.15 t per hectare per year. These gains were smallest in the semi-arid Brown soil zone and largest in the moist Gray soil zone.
- Converting 10% of the land in Western Canada from crop-fallow rotations to continuous cropping was estimated to result in an additional gain of 1.9 Mt per year.
- Converting 10% of the land in Western Canada from continuous cropping to zero tillage was estimated to result in an additional gain of 0.8 Mt per year.

Estimates from the PSCB Project of the carbon sequestration potential of Western Canada's cropland are consistent with other estimates,[177] which indicate that:
- This cropland could be a carbon sink of about 6 Mt per year under current land use practices, and
- This sink could be increased by 1-3 Mt per year with decreases in summer fallow and tillage that could be realized by the 2008-12 reporting period for the Kyoto Protocol.

As indicated in the earlier sections on agriculture, however, this increase is finite in duration. Many farmers in the Black soil zone, the area with the greatest sequestration potential, have been practising continuous cropping, fertilizing, and some form of conservation tillage for at least the past two decades. Early adoption of land use practices that have been favourable for soil carbon storage and that have met the key principles for valid sinks may well deserve recognition under any eventual Kyoto regime. It is likely that the carbon storage potential of the soils has already been partly used, and could be used up within the next two or three decades.

The inclusion of agricultural sinks in the Kyoto Protocol should complement and reinforce existing soil conservation programs.

Summary

At the beginning of Chapter 4 we asked:
- Is the storage of additional carbon in terrestrial ecosystems by changing land use practices a valid alternative to the reduction of human-caused emissions? If so, to what extent?
- What changes in land use practices provide a valid alternative, and under what conditions should they be allowed to do so?

This chapter has identified and discussed several changes in land use practices that address to varying degrees concerns about the additionality, permanence, and verifiability of increases in carbon storage in forests and cropland soils. From this discussion emerge three key issues emerge in assessing changes in ecosystem carbon storage:
- Permanence of carbon storage
- Time-dependence of carbon storage
- Whole-system accounting of carbon storage

The permanence of terrestrial carbon storage remains a concern. A general requirement for permanence is the continuity of the land use practice that raises carbon storage.

PERMANENCE OF CARBON STORAGE

The permanence of terrestrial carbon storage remains a concern. A general requirement for permanence is the continuity of the land use practice that raises carbon storage. The adoption of such a land use practice for a few years followed by reversion to the former practice contributes little or nothing to carbon storage. There is a possibility that future developments, such as deeper-rooted annual crops with more biologically resistant plant residues, or mechanical methods to move carbon deeper into the soil, would make terrestrial storage more permanent.

There are obstacles to the continuity of land use practices, however, especially in agricultural ecosystems:

- Increasing carbon storage requires that farmers change from known practices, such as risk-averse summer-fallow systems with conventional tillage, to possibly riskier continuous cropping systems with reduced tillage and the potentially higher financial and ecological costs of increased herbicide and pesticide use.
- Problems with nutrient sequestration (caused by carbon sequestration) and weed control (caused by reduced tillage) or changes in market conditions following this change can create incentives to till the soil, such as occurred when the Prairie soils were brought into production a century ago. Such tillage would cause a rapid loss of any carbon storage from the earlier land use change.

There are obstacles to the continuity of land use practices, however, especially in agricultural ecosystems

Farmers must be shown that it is to their long-term advantage to continue conservation practices that promote carbon storage because these practices also contribute to better structured and less erodible soils, and to a more sustainable supply of nutrients.

Addressing the issue of permanence therefore requires a long-term commitment to changes in land use. Ways to encourage this need to be developed as part of any agricultural carbon storage program. These commitments need to be in place if a change in land use practice is proposed for inclusion and credits under the Kyoto Protocol.

Further assessment of the permanence of terrestrial carbon storage for Kyoto Protocol purposes would be helped by a clearer definition of the timeframe for which storage is required and credits recognized. Perhaps this requirement should be defined in terms of the period of time during which the rise in atmospheric CO_2 concentration needs to be slowed before the conversion from fossil fuels to renewable energy can be implemented. Because additional carbon storage in agricultural soils is in a finite and dynamic pool, changes in agricultural land use practices provide a more valid alternative to emission reduction if this period of time for Protocol accounting purposes were 30-50 years than if it were 100-200 years. Since the Kyoto Protocol uses a 100-year timeframe for evaluating the global warming potential of greenhouse gases, any credit attributed to such changes would have to be appropriately discounted to be consistent with this long-term perspective.

TIME-DEPENDENCE OF CARBON STORAGE

The rates at which agricultural and forest ecosystems gain or lose carbon under a given set of land use practices depends on the length of time that the practices have been in place. Examples of this time-dependence in forests are given in Figures 4.2 and 4.3, where maximum NEP is achieved only several years or even decades after harvest. On the other hand, very old forests may undergo a gradual decline in NEP. In agricultural ecosystems, changes in carbon storage are thought to be most rapid during the first 20-40 years after a land use change, and to become slower thereafter.

These changes in NEP with time need to be accounted for if changes in land use practices are proposed for inclusion in the Kyoto Protocol.

WHOLE-SYSTEM ACCOUNTING OF CARBON STORAGE

Land use practices are but one component of complex production systems in forestry and agriculture. Changes in these practices often involve changes in other components. The section “Chemical fertilizers” provided examples of how increases in the use of

Changes in carbon storage attributed to a change in land use must therefore be calculated from changes in all components of the production systems affected.

chemical fertilizers for carbon storage also cause increases in carbon emissions from fertilizer manufacture and increases in N_2O emissions from the soils on which fertilizers are used. These emissions must be applied against any increases in carbon storage from fertilizer use.

Similarly, conversion of cropland to pasture for low-quality grazing by ruminants could increase methane production, which would offset some of the gains in soil carbon storage. On the other hand, silvicultural practices such as thinning may raise merchantable wood carbon that, if invested in long-term wood products, could raise total carbon storage beyond that inferred from changes in forest NEP alone. Changes in carbon storage attributed to a change in land use must therefore be calculated from changes in all components of the production systems affected.

The total change in carbon storage offered by agricultural and forest ecosystems in Canada depends on the land use practices considered and on assumptions required for spatial and temporal aggregation. National estimates of the change in carbon storage in forest ecosystems during the first Kyoto Protocol commitment period depend critically on assumptions about time required for recovery of NEP after logging, and on areas of land that can be afforested:[178] the change could be positive or negative.

National estimates of the change of carbon storage in agricultural ecosystems during the first Kyoto Protocol commitment period depend critically on assumptions about rates at which improved land use practices are adopted and incentives for adopting them. The estimates vary from 0.5 to 7.0 Mt per year.[179] Clearly these estimates need to be refined before their contribution to national carbon exchange can be assessed.

Glossary

Abbreviations and Acronyms

AAU – Assigned amount unit
AIM – Asian Pacific Integrated Model
AOSIS – Alliance of Small Island States
ARD – Afforestation, reforestation, and deforestation
ASF – Atmospheric Stabilization Framework
BOREAS – Boreal Ecosystem-Atmosphere Study
C – Carbon
C*a* – Atmospheric CO_2 concentration
CDM – Clean Development Mechanism
CERs – Certified Emission Reductions
CH_4 – Methane
CO_2 – Carbon dioxide
CoP – Conference of the Parties to the UNFCCC
CRP – Conservation Reserve Program
ET_p – Annual potential evapotranspiration
FACE – Free Air CO_2 Enrichment
GEMCo – Greenhouse Emissions Management Consortium
GIS – Geographic information systems
GPP – Gross primary production
Gt C – Billion tonnes (10^{15} grams) of carbon
IMAGE – Integrated Model to Assess the Greenhouse Effect
IPCC – Intergovernmental Panel on Climate Change
IS92 – IPCC emissions scenarios developed in 1992
JI – Joint Implementation
LULUCF – Land Use, Land Use Change, and Forestry
MARIA – Multiregional Approach for Resource and Industry Allocation Model
MiniCAM – Mini Climate Assessment Model
Mt – Million metric tonnes (10^{12} grams)
N_2O – Nitrous oxide

NBP – Net biome production
NEP – Net ecosystem production
NPP – Net primary production
NRDC – Natural Resources Defense Council
OPEC – Organization of Petroleum Exporting Countries
PSCB Study – Prairie Soil Carbon Balance Study
R_a – Autotrophic respiration
R_h – Heterotrophic respiration
SBSTA – Subsidiary Body for Scientific and Technological Advice
SRES – IPCC Special Report on Emission Scenarios
TAR – IPCC Third Assessment Report
UNFCCC – United Nations Framework Convention on Climate Change
WWF – World Wildlife Fund

Terms

Additionality – The requirement that greenhouse emission reductions or greenhouse gas emission reduction projects be "additional" to those that would have occurred without the CDM.

Afforestation – Planting of new forests on lands that historically have not contained forests.

Annex B Parties – Industrialized countries that have legally binding emission reduction commitments under the Kyoto Protocol. Annex B Parties include almost all the wealthy countries of the Organization for Economic Cooperation and Development and economies in transition to a market economy in Eastern Europe and the former Soviet Union.

Annex I Parties – Industrialized countries that are Parties to the UN Framework Convention on Climate Change. Generally the same as Annex B Parties.

Annual potential evapotranspiration (**ET_p**) – The amount of water that would be evaporated and transpired by plants in the absence of water limitation.

Assigned amount – The quota of allowable emissions held by industrialized (Annex B) countries. Also see *Base year.*

Autotrophic respiration (**R_a**) – The conversion of organic carbon back to CO_2 through respiration by plants.

Baseline emission – A hypothetical reference case, or "business as usual" projection, of emissions or sequestration in the absence of an emission reduction or sequestration project.

Baseline scenarios – Scenarios that include the combined effects of net sources and sinks from natural processes and indirect and direct human activities in a world without climate change mitigation policies.

Base year – The year used to determine assigned amount. The assigned amount of countries is equal to direct industrial emissions in the base year times a percentage listed in Annex B to the Kyoto Protocol, times 5 for each of the five years of the First Commitment Period. For most purposes the base year is 1990.

BOREAS Project – A cooperative project that is being coordinated through a Canadian-American Scientific Steering Committee, whose objectives are: (1) to study exchanges of water, heat, carbon, and trace gases between the Boreal Forest and the atmosphere; and (2) to determine how these relationships affect the global environment.

“**Business as usual**” – The emissions levels, activities, or carbon sequestration levels that would occur without climate change mitigation action.

Carbon cycle – Conversion of atmospheric CO_2 into organic carbon, and organic carbon back to CO_2. (The exchange of carbon, mainly as CO_2, between the atmosphere and reservoirs on earth, namely, living organisms, soils, and the oceans).

Carbon pool – A reservoir or system that has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils, and the atmosphere.

Carbon stock – The absolute quantity of carbon held within a carbon pool at a specified time.

Certified emission reductions (CERs) – Emission reductions in developing countries that have been certified under the Clean Development Mechanism and are added to the allowable emissions quota (the “assigned amount”) of industrialized (Annex B) countries.

Chernozemic soil – Soil that developed under grassland or grassland-forest transition in cooler climates.

Clean Development Mechanism (CDM) – Mechanism established under Article 12 of the Kyoto Protocol, under which investments in emission reduction projects (such as clean energy technology) in developing countries generate certified emission reductions.

Climate change mitigation action/initiatives – Activities undertaken to reduce the risks of climate change.

Conference of the Parties (CoP) – The “supreme body” governing the UN Framework Convention on Climate Change, composed of all Parties to the agreement.

Conservation tillage – Methods of cultivating the soil that minimize the frequency of or avoid tillage, with the objective of retaining an erosion-controlling cover of crop residues on the soil surface. Sometimes referred to as *minimal tillage,* or as *zero-* or *no-tillage,* where the soil is disturbed only at planting, when seed and fertilizer are applied into narrow slits opened in the soil.

Deforestation – Long-term or permanent removal of forest cover and conversion to a non-forested land use.

Direct biological effect – Naturally occurring emissions from carbon reservoirs and removals by carbon reservoirs, including natural removals and emissions from managed forests and agricultural soils.

Direct human biological emissions, sources, and sinks – Direct, human-induced emissions from carbon reservoirs and removals by carbon reservoirs, including direct, human-induced removals and emissions from managed forests and agricultural soils. Does not include indirect and direct biological effects.

Direct industrial emissions – Emissions from fossil fuel production, transportation, and combustion; industrial processes; waste management; and agricultural activities such as fertilization. Does not include carbon sequestration or emissions from agricultural carbon reservoirs.

Discounting – A reduction in credit from estimated levels of greenhouse gas sequestration or emission reduction.

G-77/China – Negotiating bloc composed of over 130 developing (or "non-Annex I") countries.

Global carbon budget – A budget of carbon transfers among major carbon reservoirs of the earth, primarily the oceans, the land biosphere, and the atmosphere (where carbon exists as the compound CO_2 molecule).

Global Carbon Budget Model – A computer simulation tool, based on many physical and chemical relationships found within the global carbon cycle, that can be used to study the behaviour of the global carbon budget under changing conditions.

Greenhouse gas (GHG) emissions – Emissions of gases such as nitrous oxide (N_2O), methane (CH_4), and especially carbon dioxide (CO_2) that accumulate and act to retain atmospheric heat, thus causing the warming of the earth.

Gross emissions – Direct industrial emissions.

Gross primary production (GPP) – The conversion of CO_2 into organic carbon through photosynthetic fixation by plants.

Heterotrophic respiration (R_h) – The conversion of organic carbon back to CO_2 through respiration by microorganisms and larger fauna, mostly in the soil.

Holding capacity – The ability of the earth's soil to retain water. Reduced holding capacity may lead to soil erosion.

Humus – Organic matter in advanced stages of decomposition in the soil; gives soil a black or brown colour.

Incremental sources and sinks – Reductions in emissions or increases in sequestration due to climate change mitigation action (and hence not included in baseline scenarios).

Indirect biological effects – Emissions from carbon reservoirs and removals by carbon reservoirs through biological processes that are indirect effects of humans, such as changes in sequestered carbon due to CO_2 and nitrogen fertilization or climate change.

Infiltration – The permeation of water into the pores and interstices of the earth's soil and other surfaces.

International emissions trading – Mechanism established under Article 17 of the Kyoto Protocol, which provides for the transfer of assigned amounts between two Annex B Parties.

Intergovernmental Panel on Climate Change (IPCC) – Body established in 1988 by the World Meteorological Organization and the United Nations Environment Program. It conducts rigorous surveys of the worldwide technical and scientific literature and publishes assessment reports that are widely recognized as the most credible existing sources of information on climate change. The IPCC also works on methodologies and responds to specific requests from the UNFCCC's subsidiary bodies.

Joint Implementation (JI) – Mechanism established under Article 6 of Kyoto Protocol, which provides for the transfer of emission reductions between two Annex I Parties through particular projects.

Kyoto Gap – The gap between projected business as usual emissions and what will be required for Annex B Parties to comply with the Kyoto Protocol.

Land cover – The observed physical and biological cover of the earth's land as vegetation or man-made features.

Land use – The social and economic purposes for which land is managed (for example, grazing, timber extraction, conservation).

Lignin – The substance responsible for the hard, woody nature of plant stems and roots.

Micronutrient – An essential element that is required in trace amounts for normal plant growth.

Mitigate/mitigation – Reduction in negative impacts, in particular reductions in negative impacts of climate change through actions to reduce greenhouse gas emissions.

Managed forest – Forest that is managed by humans for one or more purposes. A precise definition of the managed forest has not been agreed to. Some countries argue that it includes land in parks that is set aside for recreational or wilderness purposes. Others suggest that it includes all land within a defined distance from a road.

Moisture-holding capacity – The ability of the earth's soils to retain water within their porous structure. The capacity increases as the content of clay and organic matter increases.

Natural sources and sinks of carbon dioxide – Biogeochemical processes, and sources and sinks of CO_2 that they cause, that occur naturally, without human contributions.

Net biome production (**NBP**) – Equivalent to NEP minus losses from disturbances; it is the ultimate measure of ecosystem carbon storage.

Net ecosystem production (**NEP**) – The rate at which new plant biomass is added to terrestrial or oceanic ecosystems; the difference between the GPP and R_a.

Net-net – An approach to counting carbon sequestration in which countries are given credit only for increases in the rate of sequestration from base year levels. Thus a country that sequestered 10 Mt per year in 1990 would need to increase the rate of sequestration to receive a credit in a future commitment period. A reduction in the rate of sequestration would create a debit.

Nitrogen (**N**) – The nutrient most widely limiting to NPP in temperate and boreal ecosystems.

Party – Any country that ratified the UN Framework Convention on Climate Change.

Phosphorus (**P**) – A nutrient widely limiting to NPP in many tropical soils.

Pool – Any system component that has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, organic soils, fossil fuel deposits, and the atmosphere.

Reforestation – A conversion of deforested land back into forested land. The IPCC definition of reforestation used in this report does not include regeneration after harvesting.

Reservoir – A pool. Component or components of biosphere or physical climate system where carbon or, more generally, a greenhouse gas or precursor of a greenhouse gas is stored.

Sequestration (**"sinks"**) – The process of increasing the carbon content of a carbon pool other than the atmosphere. Under the Kyoto Protocol, developed countries can meet part of their emission reduction commitments by enhancing the storage of carbon in the biosphere through certain land use change and forestry activities.

Sink – A reservoir that is removing greenhouse gases from the atmosphere. A given reservoir is a sink for atmospheric carbon if, during a given time interval, (1) more carbon is flowing into it than is flowing out, and (2) the changes in the remainder of the connected system are such that there is a net withdrawal of carbon from the atmosphere.

Source – A source of greenhouse gas emissions. A carbon reservoir can be a source of carbon to the atmosphere if, during a given time interval, (1) less carbon is flowing into it than is flowing out, and (2) the changes in the remainder of the connected system are such that there is a net release of carbon to the atmosphere.

Summer fallow – The practice of not growing a crop on land for a year (actually 21 months) in order to store that year's moisture in the soil for use by a crop the next year. It may also be used to control weeds and to build up available forms of nutrients in soil.

Technology transfer – The UNFCCC requirement that developed countries provide developing countries with access to advanced climate-friendly technologies.

Umbrella Group – Negotiating bloc composed of Canada, the United States, Japan, Norway, Australia, New Zealand, Iceland, Russia, and the Ukraine.

Verifiability – The ability to ensure that an emission reduction or carbon sequestration occurred in the amount claimed.

NOTES

1 Sixth Convention of Parties to the United Nations Framework Convention on Climate Change.

2 A handful of European countries (Monaco, Ireland, Spain, Greece, and Portugal) showed steeper increases, but the increases were less significant because of low emissions in 1990: see UNFCCC/SBI/2000/INF.13.

3 The Protocol shall enter into force when not less than 55 Parties to the Convention, representing 55% of total greenhouse gas emissions in 1990 for Annex I countries, have ratified nationally.

4 The industrialized countries that have legally binding emission reduction commitments under the Kyoto Protocol.

5 Potential loopholes are discussed in Cathy Wilkinson, *Negotiating the Climate* (Vancouver: The David Suzuki Foundation, 2000), available at <www.davidsuzuki.org>, and Chris Rolfe, *Earth in Balance Briefing Note Series* (Vancouver: West Coast Environmental Law Research Foundation, 2000), available at <www.wcel.org>.

6 "Business as usual" refers to activities that would have occurred in the absence of efforts to mitigate climate change.

7 In this context, flexibility results from an ability to increase sequestered carbon rather than reduce emissions.

8 Sequestration is the process of increasing the carbon content of a non-atmospheric carbon reservoir, such as through certain land use changes and forestry activities.

9 Industrialized countries that have legally binding emission reduction commitments under the Kyoto Protocol.

10 For definitions of afforestation, deforestation, and reforestation, see the glossary.

11 CoP4 clarified the obtuse language of Article 3.3, agreeing that the article meant: "The adjustment to a Party's assigned amount shall be equal to verifiable changes in carbon stocks during the period 2008 to 2012 resulting from direct human induced activities of afforestation, reforestation and deforestation since 1 January 1990. Where the result of this calculation is a net sink, this value shall be added to the Party's assigned amount. Where the result of this calculation is a net emission, this value shall be subtracted from the Party's assigned amount" (Climate Secretariat document UNFCCC/CP/1998/L.5.C).

12 Until recently Canada asserted that reforestation includes post-harvest regeneration. However, "reforestation" is defined by the IPCC 1996 Guidelines as conversion of unforested land that once contained forests back to forested status. The Guidelines are adopted into the Kyoto Protocol by Article 5.2. At The Hague negotiations, brackets around the definition of reforestation were dropped, indicating a general consensus that reforestation did not include post-harvest regeneration.

13 The CDM is a mechanism established under Article 12 of the Kyoto Protocol under which investments in emission reduction projects in developing countries generate certified emission reduction credits.

14 See the section "Credit for 'business as usual' sequestration."

15 Going into the Kyoto negotiations, the US had proposed a "net-net" approach to accounting (comparing net emissions in 1990 with net emissions in the First Commitment Period). This would have made any reduction target more difficult because of a projected decline in the US forest sink. A 15 January 1998 State Department fact sheet justified American agreement to a 7% emission reduction (after initially proposing only a stabilization target) because a change in accounting rules for sinks would make it 3% easier to achieve their target. The 3% figure is consistent with going from the net-net approach for all forests to counting only afforestation, reforestation, and deforestation. It is inconsistent with credit for non-additional sequestration due to forest management.

16 Discounting is the reduction in the level of credit claimed below the actual estimated level of reductions or sequestration.

17 Jan Pronk, "Note by the President of CoP6," 23 November 2000, 7:04 PM.

18 This figure is based on Canada's August 2000 submissions to the climate negotiations, compiled in UNFCCC document UNFCCC/SBSTA/2000/MISC.6.

19 The numbers in this table are based on calculations detailed in the West Coast Environmental Law Research Foundation publication *Sink Solutions,* available at <www.wcel.org/climate/>. Concessions by Canada to the EU are in the form of reductions in credit from projected sequestration; concessions by the EU to Canada are in the form of increases in credit for non-additional sequestration (based on the sequestration projection in Canada's August 2000 submission to the climate negotiations).

20 Descriptions of approaches are summaries. For full details, see *Sink Solutions.*

21 Compared with original position of party.

22 "Canada's Response to UNFCCC Questions on Sinks," 10 November 1997.

23 Unpublished proposal by Canada, the US, and Japan.

24 In UNFCCC document UNFCCC/CP/2001/MISC.1.

25 See WCEL report for explanation of Pronk proposal.

26 Article 3.3 is somewhat ambiguous, but the parties were able to agree, in most respects, on its meaning at the next session of negotiations after Kyoto. (See note 11 above).

27 The reference to "since 1990" in Article 3.3 creates a discrepancy between the actual and creditable stock changes caused by conversion of land to or from forest use. A nation might have a balance between carbon stock changes due to conversion of land from forest to agriculture and conversion of land from agriculture to forest. However, a country with long rotation periods, like Canada, would still receive a net debit because the sudden emission from deforestation is not cancelled out by growth on the fraction of land converted to forest since 1990. To remedy the discrepancy caused by Article 3.3, the EU proposed debiting countries only to the extent that their annual rate of deforestation exceeded their annual rate of afforestation and reforestation. For example, if a country deforested 100 hectares a year and re-established forests on 80 hectares, emissions from only 20 hectares would be counted. The EU proposal would have decreased Canada's deforestation debit slightly, but, because Canada deforests roughly 30 times as much land per year as it afforests, Canada would have had a net reduction in assigned amount of about 2.8%. (Canada's emissions from deforestation are estimated at 80,667 kilotonnes CO2 during the First Commitment Period: UNFCCC Secretariat document, UNFCCC/SBSTA/2000/INF.7/Add.1. This is reduced by 3.2%, the percentage of lands projected to be converted into forests between 1990 and 2012 compared with the projection of area deforested in the same period: see UNFCCC/SBSTA/2000/MISC.6).

28 Figure 2 in Erik Haites and Fanny Missfeldt, "The Potential Contribution of Sinks to Meeting the Kyoto Protocol Commitments" (June 2001). Paper presented to the European Association of Environmental and Resource Economists.

29 Haloa Inc., "Integrated Analysis of Options for GHG Emission Reduction with MARKAL" (12 May 2000). Paper prepared for the Analysis and Modelling Group of the Canadian National Climate Change Implementation Process.

30 John Last, "Taking Our Breath Away: The Health Effects of Air Pollution and Climate Change" (Vancouver: The David Suzuki Foundation, October 1998), and Doug Russell, "Keeping Canada Competitive" (Vancouver: The David Suzuki Foundation, October 1997).

31 Intergovernmental Panel on Climate Change, First Assessment Report, 1990.

32 P. Kauppi et al., "Technical and Economic Potential of Options to Enhance, Maintain and Manage Biological Carbon Reservoirs and Geo-Engineering," Chapter 4 of Working Group III contribution to the IPCC Third Assessment Report, 2001.

33 Increased carbon dioxide concentrations in the air can speed up growth, but this effect may be short-lived and may be increasingly counteracted by increased respiration and pest and fire losses due to climate change (see Chapter 4). Deposition of nitrogen compounds due to pollution can also stimulate growth.

34 The high figure is based on UN Food and Agriculture Organization data on areas of managed forests and current uptake rates compiled in the April 2001 Pronk paper. The lower figure is based on Annex B Parties' August 2000 projections for the First Commitment Period, with Russia's amount based on the work of the International Institute for Applied Systems Analysis, compiled in "New Proposals by the President of CoP6," 9 April 2001. Other estimates supplement the August 2000 projections by national greenhouse gases inventory data where no projections are made. See Chris Rolfe, *Sinking the Climate,* West

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39 Estimates are difficult because only 4 out of 37 Annex B countries projected sequestration by agricultural lands in the First Commitment Period, and only 7 countries have reported emissions or removals by agricultural soils in their inventories: UNFCCC/SBSTA/2000/3, 11 May 2000. Where estimates exist, they are typically far lower than estimates of forest sequestration.

40 The net removals from sequestration by forest and woody biomass stocks in timber-producing forests in Canada have been estimated at 37 megatonnes of carbon dioxide for 1996 (10 megatonnes of carbon): Art Jacques et al., *Canada's Greenhouse Gas Inventory, 1997* (Ottawa: Environment Canada, 1999). Projected sequestration for the period 2008-12 is 176 megatonnes of carbon dioxide (10 megatonnes of carbon for each of the five years): from Table 1, UNFCCC document UNFCCC/SBSTA/2000/INF.7/Add.1.

41 Jacques et al., *Canada's Greenhouse Gas Inventory, 1997.*

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45 The spreadsheets on which this table is based will be published by the West Coast Environmental Law Research Foundation in *Sink Solutions,* which will be available at <www.wcel.org/climate/>.

46 UN Food and Agriculture Organization (FAO) estimates are based on current business as usual. National projections of sequestration contained in the Annex B Parties' August 2000 projections of sequestration in 2008-12 are assumed to reflect business as usual. This is consistent with methodologies identified by different nations. For example, US estimates are "based on recent trends," "long-term baseline projections," or "business as usual scenarios" (see US submission of August 2000). Canadian projections for forest management are equal to current estimates of carbon removals by managed forests. Increases do not include credit used to offset debits under Article 3.3.

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50 Based on US Energy Information Agency, "International Energy Outlook 2000," which estimates that Annex B business as usual emissions will be 13.9% higher than the Kyoto Protocol's initial assigned amount. That estimate considered carbon only. It has been extrapolated to all greenhouse gas emissions, giving a projected gap of 653 megatonnes in 2010.

51 Two sources are used: (1) UN Food and Agriculture Organization data on current rates, and (2) the projections that countries submitted as part of the climate negotiations or, where projections were not given, the countries' own inventories.

52 Two threshold scenarios are used. One assumes a threshold equal to 100% of projected emissions. No additional sequestration is counted beyond this threshold. The other assumes that 80% of all projected sequestration from forest management beyond that in the first tier (offsets of debits under Article 3.3) is included in the second tier (discounted and capped).

53 A quantitative estimate of uncertainty within Annex B is impossible. Reporting of uncertainties related to the LULUCF sector is sporadic. See *Synthesis Report on National Greenhouse Gas Information Reported by Annex I Parties for the Land-Use Change and Forestry Sector and Agricultural Soils Sector,* 11 May 2000 (UNFCCC/SBSTA/2000/3) and *Methodological Issues Identified while Processing Second National Communications: Greenhouse Gas Inventories,* 4 September 1998 (UNFCCC/SBSTA/1998/7).

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Climate change is projected to accelerate over the next century, however, and future releases of sequestered carbon would speed it up even more. This may outweigh any benefit of delaying an emission, as the rate of climate change determines the ability of ecosystems to adapt to it. Limiting the rate of climate change is a key factor for a "safe landing" that avoids the worst impacts of climate change: Joseph Alcamo and Eric Kreileman, *The Global Climate System: Near Term Action of Long Term Protection* (Netherlands: National Institute of Public Health and the Environment, February 1996).

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