Carbon credits and the conservation of natural areas

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Abstract: Increasing the amount of organic-carbon stored in the biomass of terrestrial ecosystems is an effective way to reduce the net anthropogenic emissions of greenhouse gases to the atmosphere. This can be done by conserving existing ecological reservoirs of fixed organic-carbon, maintaining or enhancing the rate of sequestration, and restoring stocks that have been depleted by past land-use practices. Most trading systems for greenhouse-gas offsets recognize the validity of projects that gain ecological offsets, and permit them to sell carbon credits in an emerging marketplace for these novel commodities. Although ecological carbon-offset projects have been criticized from a variety of perspectives, most of the supposed problems can be satisfactorily mitigated. In addition to offsetting emissions of greenhouse gases, ecological projects that accumulate carbon credits may have a strong cross-linkage to the conservation of natural values, which in itself is an important action for society to undertake. This is, however, less of a consideration for projects that are based on anthropogenic ecosystems, such as no-till agricultural systems and plantation forests, which provide relatively few benefits to native biodiversity and might even detract from that objective if developed on newly converted natural habitat. Moreover, the existing rules for carbon-offset systems exclude some kinds of ecological projects from the trading markets, even though they would result in avoided emissions or enhanced sequestration of organic-carbon. As the emerging marketplace for carbon offsets grows, it will be important to understand the co-benefits and side effects of offset projects on non-carbon values, including native biodiversity.

Résumé : L'augmentation des quantités de carbone organique accumulées dans la biomasse des écosystèmes terrestres constitue un moyen efficace pour réduire les émissions anthropogènes nettes de gaz à effets de serre dans l'atmosphère. On peut atteindre cet objectif en conservant les réservoirs écologiques de carbone organique existants, en maintenant ou en augmentant le taux de séquestration, et en restaurant les réserves qui ont été épuisées par les utilisations passées des territoires. La plupart des systèmes de compensation des gaz à effet de serre reconnaissent la validité des projets conduisant à des compensations écologiques et leur permettent de vendre des crédits de carbone dans un marché émergent visant ces nouveaux biens marchands. Bien que les projets écologiques de compensation du carbone aient été critiqués selon différentes perspectives, on peut mitiger de façon satisfaisante, la plupart des supposés problèmes. En plus de compenser les émissions de gaz à effets de serre, les projets écologiques qui accumulent des crédits de carbone peuvent présenter des liens étroits avec la conservation de valeurs naturelles, qui en soi constituent une action importante que doit entreprendre la société. Cependant, cette considération s'applique moins aux projets basés sur des activités anthropogéniques comme les systèmes de culture sans labour et les plantations forestières, qui rapportent relativement peu de bénéfices à la biodiversité indigène et peuvent même s'éloigner de l'objectif, si on les applique à des habitats naturels récemment convertis. De plus, les règles existantes pour les systèmes de compensation du carbone excluent certains types de projets écologiques du marché boursier, même s'ils permettraient d'éviter des émissions ou augmenter la séquestration de carbone organique. À mesure que les marchés émergents des compensations en carbone s'accroissent, il deviendra important de comprendre les cobénéfices et les effets secondaires des projets de compensation de valeurs autres que le carbone, incluant la biodiversité indigène.

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1. Introduction

Global climate change is now widely recognized as an issue that must be addressed if the most severe of its predicted environmental and socioeconomic impacts are to be avoided or mitigated. The Intergovernmental Panel on Climate Change (IPCC), in their fourth assessment report, state that "warming of the climate system is unequivocal" and that "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations" (IPCC 2007*a*). Because the climate-change problem is now broadly recognized and its causes are likely rooted in anthropogenic emissions of greenhouse gases (GHGs), chiefly carbon dioxide (CO_2), there are increased policy actions to reduce the rate of accumulation of GHGs in the atmosphere.

International agreements are an important driver of policy actions at all levels because they help to set the overall pace of reductions of GHG emissions. The Kyoto Protocol on Climate Change, adopted in 1997 by the Conference of the Par-

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ties to the United Nations Framework Convention on Climate Change (UNFCCC), established the first legally binding international commitments for participating "industrialized nations" to reduce their emissions of GHGs (UNFCCC 1997). The Kyoto Protocol is intended to provide the first step in the transition of the international community from its present fossil-fuel-intensive energy economy to a more carbon-neutral one, with the objective of achieving "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1997; Article 2). The Kyoto Protocol calls for reductions of emissions of GHGs during the period 2008–2012 relative to the 1990 emissions, and sets targets on a country-by-country basis. Canada, for example, has agreed to reduce its emissions to 6% below the 1990 levels, although it appears unlikely that this level of reduction will be achieved, largely because Canada is a major fossil-fuel producer and exporter to the United States (which did not ratify the Kyoto Protocol). Although the Kyoto Protocol provides an important initial action to dealing with anthropogenic climate change, future agreements will have to result in greater progress towards the UNFCCC objective of stabilizing atmospheric GHGs by engaging all major GHG-emitting economies, including the United States, China, and India, and by refining the GHG accounting rules. Only in doing so will sufficient momentum be established to steer the global economy away from its current over-dependence on fossil-fuelled energy.

One effective way to reduce the atmospheric concentration of CO_2 is to conserve or enhance existing biomass-carbon in the living biomass and (or) dead organic matter of ecosystems (ecological carbon sinks). Negotiations held subsequent to the Kyoto Protocol in Bonn (July 2001) and Marrakesh (November 2001) resulted in an accounting framework that recognizes the important role of ecological carbon sinks in climate change mitigation, and permits countries to reduce emissions through so-called LULUCF activities (land use, land-use change and forestry). Emerging regional and national systems, such as Canada's Offset System for Greenhouse Gases (Government of Canada 2008), also allow the use of certain types of ecological carbon sinks to offset anthropogenic emissions of GHGs. In these systems, projects that conserve ecological carbon sinks (e.g., avoided deforestation) or that enhance their rate of fixation (e.g., afforestation, reforestation, silviculture) can be used to generate carbon credits, which can then be traded to GHG emitters that have been unable to reduce their emissions in a cost-effective manner. The creation of a GHG emissions-trading system establishes a market price for carbon offsets and uses market forces to help achieve GHG emission reductions in a cost-effective manner (Sandor et al. 2002).

Ecological carbon sinks in the LULUCF sector have the potential to make an important contribution to climate change mitigation in Canada and elsewhere. Terrestrial ecosystems, such as forests, actively sequester CO_2-C from the atmosphere and store it in plant biomass, dead organic matter, and soil. As plants grow, their photosynthetic fixation of CO_2 exceeds its release by respiration, resulting in a net uptake from the atmosphere and an increase in the storage of carbon in biomass. As plants die and decompose, much of their sequestered carbon is released back to the atmosphere as CO_2. However, if the annual inputs of litter are smaller than the rate of decomposition, there will be a net accumulation of dead organic matter and soil-carbon in longer-term storage. It has been estimated that almost 2500 Gt (1 Gt = 1 billion tonnes = 1 Pg = 10^{15} g) of carbon are stored in global vegetation and soil (IPCC 2000). Forests contain almost half (1150 Gt) of this terrestrial pool, with two-thirds of forest carbon (790 Gt) occurring in soil. For comparison, the atmosphere contains about 806 Gt of carbon, almost all of which is CO_2.

Terrestrial ecosystems exert a powerful influence on the global climate system (Foley et al. 2003), and ecological carbon sinks are already making an important contribution to climate-change mitigation, largely via natural processes such as the accumulation of biomass in forests. The world's terrestrial ecosystems currently absorb a significant but declining proportion of total anthropogenic GHG emissions. During the period 2000 to 2006, more than half of anthropogenic GHG emissions were offset by natural ecological carbon sinks, including 30% by terrestrial ecosystems and 24% by oceanic ones (Canadell et al. 2007*a*). It has been projected, however, that the capacity of terrestrial ecosystems to act as sinks for GHG emissions may decline as global warming progresses (Fung et al. 2005; Scholze et al. 2006; Canadell et al. 2007*b*).

Efforts to reduce net anthropogenic emissions of GHGs by maintaining or enhancing ecological carbon sinks will also bring additional non-carbon co-benefits, including those related to the conservation of natural ecosystems (Freedman and Keith 1996; Bonnie et al. 2002). The conservation of biodiversity is in itself an important societal goal, and it has been subject to its own international agreement — the Convention on Biological Diversity enacted in 1993 under the auspices of the United Nations Environment Program. The establishment of an economic value for carbon sequestration as an ecological service could leverage considerable financial resources for projects that are intended to conserve biodiversity by protecting or restoring ecosystems, while also providing higher rates of carbon fixation and storage than might otherwise have occurred.

In this paper, we examine and discuss two important tactics that would offset emissions of GHGs by enhancing and maintaining ecological carbon sinks in terrestrial ecosystems. The first tactic is to conserve natural ecosystems that already store large amounts of carbon in their biomass (existing reservoirs). The clearing of natural vegetation, especially mature forests, has been a major source of emissions of GHGs to the atmosphere, particularly during the past several centuries (Houghton 2003). When forest, grassland, or wetland ecosystems are converted into agricultural or urbanized lands, large emissions of CO_2 result because the accumulated stocks of organic carbon in living vegetation and organic matter in soil becomes decomposed or burnt, and there is a decline in net ecosystem productivity and the capacity to store additional organic carbon on an annual basis (Allen 1985; Mann 1986; Post and Mann 1990; Cambardella and Elliott 1992; Johnson 1992; Freedman and Keith 1996; Lal et al. 1999; Wang et al. 1999; Entry et al. 2002; Guo and Gifford 2002; Houghton 2003; Freedman 2007*a*). Houghton (2003) estimated that land-use change worldwide resulted in emission of 156 Gt C between 1850 and 2000.

Although most of the emissions were from tropical deforestation, land-use change in Canada has also resulted in the loss of ecologically sequestered carbon. The conservation of carbon-rich natural ecosystems would help to avoid additional such emissions. Internationally, special focus is being placed on addressing the problem of tropical deforestation through the emerging policy mechanism known as REDD (reducing emissions from deforestation and degradation) within the greater carbon-offset marketplace. Within that context, there are large opportunities to reduce the rate of conversion of natural ecosystems in Canada and to so avoid the associated emissions of GHGs.

A second tactic to achieving a net reduction of GHG emissions involves the restoration of productive natural ecosystems in places where the previous land-use is anthropogenic habitat of relatively low sequestration capacity. Such a conversion from anthropogenic land-use to natural vegetation usually results in a large increase in ecological carbon storage, particularly if a forest develops. Across broad regions of the United States, for example, forest cover became more extensive during the past century because of fire suppression, reduced harvesting of fuelwood, and the regeneration of secondary forest onto abandoned marginal agricultural lands (Caspersen et al. 2000). The increased storage of organic-carbon in those US forests during the 1980s was equivalent to an offset of 10%–30% of US fossil-fuel emissions of CO_2 (Houghton et al. 1999). Similar changes have occurred in parts of eastern Canada, particularly in the Maritime Provinces.

Other opportunities for the LULUCF sector to contribute to GHG-emissions reduction, such as the use of sustainably produced biofuels to displace fossil fuels, or the use of forest products to offset the use of more carbon-intensive building materials, could also play an important role in a climate change mitigation portfolio (Keith 2001; Lemus and Lal 2005). Renewable energy and materials-substitution strategies can be used to help reduce GHG emissions, but these are not offset strategies per se because the organic-carbon harvested from forests or other biomass sources will ultimately be emitted into the atmosphere (except in certain anaerobic landfill situations or where carbon capture and storage technologies are also applied). Here we focus on ecological carbon offsets associated with the conservation and restoration of ecosystems, because these provide an exceptional mix of environmental benefits. Although the cross-linkages between ecological carbon offsets and the conservation of biodiversity are already widely recognized, there remain important misconceptions about certain types of offset strategies and factors that provide the best mix of GHG and conservation benefits.

Most carbon offset trading systems recognize the role of ecological carbon sinks, but the rules by which they are made eligible for credit in certain GHG-trading systems (including the emerging offset system of Canada) will favour certain types of conservation projects while excluding others. As such, it remains unclear whether carbon-offset trading will have a positive effect on the conservation of biodiversity in Canada. In this paper, we begin to address this issue by reviewing the existing literature and by examining some of the most widely held misconceptions and assumptions about the cross-linkages of carbon-offset trading and the conservation of biodiversity. Although much of our case material is Canadian, the issues examined in this paper are international in context.

2. Ecological carbon sinks and carbon offset trading

The use of ecological carbon sinks to offset anthropogenic GHG emissions has been a topic of discussion in the scientific and policy literature related to climate change for several decades. Numerous studies have analyzed the potential contribution of ecological carbon-sink strategies to offsetting emissions of GHGs (e.g., Vitousek 1991; Freedman et al. 1992; Marland and Marland 1992; Trexler and Haugen 1994; Brown et al. 1996; Freedman and Keith 1996; Lashof and Hare 1999, Stinson and Freedman 2001; Kirschbaum 2003; Wilson and Hebda 2008), or have evaluated the costs of generating offsets through forest management and other land-use strategies (e.g., Sedjo et al. 1995; Richards and Stokes 2004; van Kooten et al. 2004; Boyland 2006). By and large, this research has shown that ecological carbon sinks have the potential to play an important role in helping society to stabilize atmospheric GHG concentrations, but it is also clear that these sinks are restricted in scope. At most, because of the limited land areas that are available, ecological sinks can offset only a fraction of fossil-fuel emissions of CO_2 and other GHGs. As such, the main focus of actions to reduce emissions of GHGs must be on reducing emissions associated with the use of fossil fuels, rather than on offsetting them. Nevertheless, ecological carbon sinks do have a helpful role to play.

The concept of using ecological carbon sinks to offset emissions from fossil fuels rests on the nature of CO_2 and its cycling and residence time in the atmosphere. Because the atmospheric residence time of CO_2 is long relative to its average mixing rate, emissions by sources and removals by sinks anywhere on the globe affect atmospheric concentrations everywhere. For this reason, it is conceptually feasible to offset CO_2 emissions using carbon sinks, in the region or country where the emissions are occurring, or in another.

The use of ecological carbon sinks is often presented as a transitional strategy- one that can help society to reduce its net emissions of GHGs while buying time for the development and penetration of non-fossil energy technologies into the mainstream global economy (Lecocq and Chomitz 2001). Although it is clear that a transition away from dependence on fossil-fuelled energy will take time, and that this shift must be made if the GHG-climate problem is to be resolved, the contribution of ecological carbon sinks should not be thought of simply as part of a transitional strategy (Kirschbaum 2003). Pacala and Socolow (2004) introduced the notion of “stabilization wedges” and explained how emission reductions could be realized using current technology by taking action along a number of fronts, including ecological carbon sinks. They estimated that activities such as afforestation, reforestation, reduced deforestation, and widespread adoption of conservation tillage could potentially contribute as much as 2.0–2.5 Gt C $year^{-1}$ in reduced emissions within about 50 years, which would be a substantial contribution to the global reduction of net emissions.

The Kyoto Protocol allows countries to include carbon sinks in their national GHG accounts (Article 3), and also to engage in emissions trading (Article 6). The Clean Development Mechanism (CDM) and Joint Implementation (JI) were introduced to encourage international investment in projects that reduce net global GHG emissions (Article 12). The CDM allows industrialized countries (i.e., those with capped emissions) to receive credits towards their emission-reduction obligations by investing in projects in developing countries that result in a net reduction in GHG emissions. Joint implementation projects are similar, but they involve agreements among industrialized countries. Both CDM and JI projects can involve investment by project proponents in ecological carbon sinks to gain credits against their own emissions. The CDM in particular was introduced to encourage investment in projects that contribute to emissions reduction while also contributing to other environmental and socioeconomic objectives, in recognition of the strong cross-linkages among these development priorities (Hardner et al. 2000).

Long before the Kyoto Protocol was implemented, emissions trading had gained widespread acceptance as a market-economics approach to achieving reductions in the emissions of air pollutants. Moreover, trading systems can achieve their objective in a manner that avoids the more traditional “command and control” regulatory approach, which is viewed by many economists as being more economically disruptive and less able to exploit least-cost opportunities to reduce pollution (Sandor et al. 2002). Systems of cap-and-trade and emission-reduction credits both provide industry with flexibility in the chosen method, location, and timing of emission reductions, while sending a transparent signal about their value to society. As an emissions cap is lowered or obligations to reduce them are raised, there is increased economic incentive to market players to reduce their emissions, and where possible, to generate offsets for sale. This is comparable to the system of trading for SO_2-emission offsets in the US, which has resulted in greater reductions than were legally required and at costs an order of magnitude lower than the highest forecasts (Sandor et al. 2002). It should be noted, however, that the US trading system for SO_2 is focused on large point-sources of emissions, whereas a carbon-trading system is likely to be more broadly based, including many smaller sources, and its establishment will therefore be a considerably more complex undertaking.

The regulatory, policy, and infrastructural elements required to support national, regional, and global GHG emissions trading are becoming established worldwide. A number of tradable permit systems are in operation in addition to those established under the Kyoto Protocol (that is, under the CDM and JI). The European Union’s Emission Trading Scheme (EU-ETS) is currently the largest GHG cap-and-trade system, and others have been established elsewhere, including Japan’s Voluntary Emissions Trading System and the Chicago Climate Exchange (also voluntary) in the United States. According to the World Bank, the aggregate value of global carbon-trading markets exceeded US$10 billion in 2005 and was projected to be US$25–$30 billion in 2006 (Kapoor and Ambrosi 2006). The market has recently been driven by increasing prices in the EU-ETS marketplace, which traded US$8.2 billion in 2005, representing a 40-fold increase over the previous year (Natsource 2006).

All this activity may complicate GHG emissions trading in the short term, until clear linkages among the existing trading marketplace become established (Jaffe and Stavins 2007). The emerging Canadian emission-trading market will be complex because the national and provincial systems are not being established in coordination. A domestic offset system for GHGs is being established in Canada (Government of Canada 2008), but several provinces have joined the Western Climate Initiative (a North American regional cap-and-trade system) either as partners or observers, and Alberta is establishing its own system (Alberta Environment 2008).

Even though ecological carbon-sink projects are accepted in most emerging GHG-offset trading systems (including those in Canada), they are not free of controversy. Ecological-sink projects have attracted debate because of concerns about the veracity and security of the carbon credits that are claimed, as well as the specific contribution they will make to climate-change mitigation (Kapoor and Ambrosi 2006; Dembo and Davidson 2007). These criticisms emerged in large part as a result of the Kyoto Protocol negotiation process, where emission-reduction targets were established before carbon-accounting rules were negotiated. Carbon sinks may have been viewed by some parties as a means of circumventing negotiated emission-reduction targets because of concern over windfall sinks (i.e., the possibility of naturally occurring carbon sinks being treated as emission reductions in the accounting). Moreover, the dearth of information about ecological carbon sinks allowed misconceptions about them to persist. However, many of the frequently raised concerns about ecological carbon sinks can be addressed using straight-forward arguments:

- **Certifiability**. Ecological carbon offsets have been criticized because of difficulties associated with their quantification and verification. These concerns must, however, be extended to all monitoring of GHG emissions and offsets if an offset trading system is to be effective. Like any GHG emission-reduction projects, those using ecological carbon offsets must produce certifiable reductions before they can be registered and traded into a formal trading system. To be eligible to generate offset credits in Canada’s offset trading system, for example, projects will have to achieve quantified and verified reductions of GHGs. Projects will have to (1) identify or create a quantification protocol, (2) register, (3) report and verify emission reductions or offsets, and (4) certify those reductions before issuance of offset credits (Government of Canada 2008). This level of rigor is normal across formal offset-trading systems, and it is necessary for effective reductions of net emissions. In any event, the challenges of measurement and monitoring that may be unique to ecological carbon offsets can be overcome by the use of established methodologies. Many agencies already provide measurement guidelines and protocols that employ standard and accepted methods of ecological quantification (e.g., IPCC 2007*b*; Pearson et al. 2007; WBCSD and WRI 2007).
- **Permanence**. Fossil-fuel emissions of CO_2 involve the release of geologically sequestered carbon into the active part of its global cycle. In comparison, offsets associated with ecological fixation involve sequestration into reser-

voirs that are still part of the active carbon cycle. In this sense, ecological offsets are not “permanent” because organic-carbon sequestered in a forest or another kind of ecosystem may be re-emitted to the atmosphere as a consequence of an anthropogenic or a natural disturbance. However, the risk of this sort of “reversal” can be accounted for in carbon-offset trading systems by requiring that credits for any lost carbon be insured, or replaced with another source of credits. Moreover, the stewardship of areas that support carbon credits can include management actions intended to reduce the frequency or severity of disturbance events.

- **Additionality**. A frequently raised concern about ecological carbon offsets relates to the differentiation of natural sinks and those arising from direct mitigative action. During negotiations for the Kyoto Protocol, for example, some parties sought to ensure that natural ecological sinks could not be used to generate offsets. The rationale was that countries fortunate enough to have large amounts of ecological sequestration might have used these as offsets to meet their emission reduction targets. In the CDM therefore, ecological carbon-offset projects must produce emission reductions that are “additional to any that would occur in the absence of the certified project activity” (UNFCCC 1997; Article 12). In Canada’s offset-trading system for GHGs, projects must achieve reductions in emissions that are both “incremental” and “unique” (Government of Canada 2008). In fact, most projects to conserve natural ecosystems and wilderness will be undertaken primarily because of the benefits they provide in terms of biodiversity, environmental services, and recreational opportunities; on their own, these benefits may be sufficient to secure the necessary funding, even without taking into account the carbon-sequestration benefits. These circumstances might exclude such projects from offset-trading systems that have an additionality requirement (such as the CDM), even if they provide demonstrable carbon benefits. Nevertheless, in this sense additionality for projects in ecological conservation can be demonstrated by showing that they would not have been economically feasible in the absence of extra funding made available by selling carbon credits. Consider, for example, a case of a forest landowner facing two competing offers for a property: (1) one from a developer who would convert the land to a non-forested land use and (2) another from a conservation group seeking to maintain the forest in a natural condition. The latter offer may only be economically feasible if carbon offset credits (associated with the avoided deforestation) can be sold to raise some of the financial capital necessary to purchase the land for conservation purposes. In this case, the project would meet the requirement of additionality. Of course, additionality is only a criterion if the carbon credits are to be counted under the Kyoto rules — many potential buyers of ecological offsets would be satisfied by having supported an integrated project that yields a broad spectrum of demonstrable environmental benefits, one of which is carbon offsets.
- **Leakage**. Projects that generate carbon offsets simply by displacing equivalent CO_2 emissions to another location provide no real reduction in GHG emissions. For example, the protection of a tract of forest from deforestation will maintain carbon sequestration within the boundaries of that project. If, however, the project causes deforestation elsewhere to meet a regional demand for new arable land, then the carbon benefits of the forest-protection scheme can be considered to be reduced or even nullified by “leakage”. In this sense, leakage is an important issue, but it is not unique to ecological offsets.
- **Albedo**. Certain changes in vegetation cover can have a substantial impact on the albedo of the surface (Foley et al. 2003). Some modeling studies have suggested that if the extent of forested area in northern latitudes were increased, the positive forcing on the surface energy balance associated with reductions of albedo (i.e., increased surface warming) could be stronger than the negative forcing associated with increased CO_2 sequestration in the forest (Gibbard et al. 2005). However, this remains a relatively theoretical consideration, and further studies are needed to clarify the net climate forcing of changes that result in both carbon sequestration and reduced albedo.

3. Ecological carbon-offset opportunities

Ecological carbon-offset opportunities are varied, and they differ considerably among terrestrial ecosystem types and land-ownership and management tenures. In this section, we describe the natural and anthropogenic factors that affect carbon sequestration, with particular reference to Canadian terrestrial ecosystems. We then briefly review estimates of carbon storage and sequestration capacity of terrestrial ecosystems that are prominent in Canada. These data help to frame the potential scope and scale of ecological carbon offsets and their contribution to achieving a net reduction of GHG emissions.

3.1. Factors affecting carbon sequestration

Carbon sequestration and storage in terrestrial ecosystems is affected by a variety of environmental and ecological factors, all of which are key considerations in the design and management of ecological carbon offset projects (Prentice et al. 1992; Woodward et al. 1995; Law et al. 2002; Apps 2003; Luyssaert et al. 2007). Natural influences on ecosystem carbon sequestration include: climatic and site factors, the disturbance regime, and the kinds of ecological communities that may develop. Anthropogenic stressors and management regimes also affect the rates and capacity of carbon sequestration in terrestrial ecosystems.

- **Climate** is related to the intensity and seasonality of precipitation, surface temperature, length of the frost-free growing season, and other factors that exert large influences on the productivity of ecosystems. In general, moderate climatic conditions permit faster rates of carbon sequestration and larger amounts of biomass accumulation. A relatively moist and warm climatic regime will, for example, favour the development of old-growth forest, largely by inhibiting the ignition and severity of wildfires — this kind of ecosystem accumulates more biomass than any other and may maintain a positive rate of net production for several centuries. In contrast, severe climatic conditions support ecosystems that accumulate much less biomass, such as desert (if moisture is severely limited) or tundra (a short growing season with little heat accumulation). Limiting climatic conditions are prevalent throughout much of Canada, particularly in the northern and drier regions of the country. Furthermore, future climate changes are expected, and they may result in the extensive development of drier conditions, which could reduce ecosystem productivity and biomass storage (Scholze et al. 2006).

- **Site quality** is affected by such factors as tilth of the soil, nutrient availability, acidity or alkalinity, texture and mineralogy of the parent material, and drainage. Higher-quality sites support greater productivity and often have a larger accumulation of biomass. Poorly drained sites, including wetlands, may store large amounts of dead organic-carbon because their anaerobic conditions inhibit decomposition, but this material usually accumulates relatively slowly compared with well-drained forested habitats. Moreover, wetlands may emit substantial amounts of methane as a product of anaerobic decomposition, and this GHG has a warming potential 25 times greater than that of CO_2 (IPCC 2007*a*) (see section 3.2.3 below).
- **Disturbance** initially reduces net carbon fixation by damaging vegetation, while also reducing the amount of biomass present by increasing its oxidation by either decomposition or, in the case of fire, by combustion (Pregitzer and Euskirchen 2004). Disturbance dynamics may include periodic events of mass mortality of the dominant species of an ecosystem, followed by a period of successional recovery. A stand-replacing disturbance may be caused by a wildfire, windstorm, insect outbreak (e.g., of defoliating insects or bark beetles), or disease epidemic. Disturbance typically results in a loss of some accumulated biomass capital, which occurs rapidly during a fire because of combustion, or more slowly during the re-organization phase of succession when the rate of decomposition exceeds that of net primary production. The period of successional recovery is relatively short for grasslands, and much longer for forests, particularly to re-attain an old-growth condition. At the landscape scale, the frequency of stand-replacing disturbances influences carbon storage by affecting the age-class structure of the forest (Kurz et al. 1998). Frequently disturbed landscapes have a greater predominance of younger successional communities, while those disturbed less often have a greater abundance of mature and older-growth stands (which typically store more carbon).
- **The nature of the plant communities present** is also influential, because some species are inherently more productive than others, or they grow relatively large and so can store larger amounts of carbon, or they may promote an accumulation of dead biomass. These biological influences are affected by factors that affect the intensity of competition, such as the spacing of trees within a forest, and also by other environmental influences, including those noted above. The species composition and dominance of many existing natural communities will re-organize to better suit the environmental conditions that develop in response to global warming, as less-well suited species decline and better-adapted ones become more abundant (Cramer et al. 2001; Hamann and Wang 2006).

There are also important anthropogenic influences on the amount of carbon stored in the biomass of terrestrial ecosystems. Much of Canada's southern land area has already been cleared of its natural ecosystem cover and converted to agricultural or urbanized land-uses. Even on lands that have not been converted, the vegetation may have been affected by management practices either directly (e.g., timber harvesting or livestock grazing) or indirectly (e.g., fire suppression). Both current and historical land-use and management have a large influence on the carbon sequestration of terrestrial ecosystems. The key anthropogenic influences, which are not necessarily mutually exclusive, are briefly discussed below.

- **The conversion of natural ecosystems**, such as forest or grassland, into ones used for agricultural, residential, or industrial land-uses generally results in a large decrease in carbon stored in both living biomass and dead organic matter. The difference in carbon stocks is ultimately balanced by a large emission of CO_2 to the atmosphere. Unlike natural disturbances, an anthropogenic conversion is not followed by a period of biomass re-accumulation during succession, because the ecological recovery is prevented by management actions. Deforestation, or a long-term replacement of forest with a non-forested ecosystem, results in an especially large per-hectare emission of CO_2 to the atmosphere, and it has been responsible for about one-third of anthropogenic emissions of CO_2 since 1850. The conversion of old-growth forest into plantation forest also results in a substantial net reduction of carbon storage, although the effects are less than those associated with conversion to agricultural or urbanized land-uses. The conversion of prairie grassland into cultivated land has a much smaller per-hectare emission rate, but the aggregate emission has been large because of the extensive areas affected. The draining of organic-rich wetlands to develop agricultural land also results in a large per-hectare emission of CO_2 because of the decomposition of accumulated peat under newly oxidizing conditions.
- **Anthropogenic disturbances** include the harvesting of timber and other sorts of biomass, as well as fires ignited by people. In the sense meant here, disturbances are set apart from ecological conversions in that successional recovery is possible. Like natural disturbances, anthropogenic ones result in less biomass stored on the site, although the organic capital may re-accumulate during successional recovery. Often, however, economic considerations will prevent a full recovery of the original ecosystem. For example, timber might be harvested from a tract of natural old-growth forest, by either a clear-cut or a selective harvest, and the ecosystem may then be allowed to regenerate. The rate of recovery may even be enhanced by silvicultural management, which could entail some combination of site preparation, tree planting, and thinning of an extremely dense regeneration of tree saplings. Typically, however, the next harvest would occur when the regenerating trees become economically mature, which is at a much younger age than that required to re-develop an old-growth condition. For this reason, over an entire rotation, secondary forests managed for timber production store much less organic carbon than comparable tracts of old-growth forest (Fleming and

Freedman 1998; Kurz et al. 1998; Stinson and Freedman 2001). Nevertheless, both at maturity and over the successional sere, any managed forest stores much more carbon than do ecosystems that have been converted to agricultural or residential land-uses.

- **Other anthropogenic stressors** also affect the net production and carbon storage of ecosystems, including the intensity of pollution by gases, metals, pesticides, or hydrocarbons, as well as climate change forced by anthropogenic influences. In general, any large increase in the intensity of anthropogenic stressors will result in a decrease in the rate of net ecosystem production and less accumulation of organic matter (Freedman 1995, 2007*a*). In some cases, however, moderate increases in certain potential stressors may enhance the rate of carbon sequestration — for example, the productivity of many terrestrial ecosystems is increased at moderate levels of nitrogen deposition from the atmosphere in the form of gaseous NH_4 and NO_x or NO_x^- and NH_4^+ dissolved in precipitation, any of which may have anthropogenic sources (Galloway et al. 2004; Magnani et al. 2007).
- **Management practices** can be used to reduce the intensity of environmental stressors, and so to increase the rate and amount of biomass accumulation in managed stands. In forestry, for example, overly dense stands of trees may be spaced to lessen the intensity of competition, while grasslands may be irrigated or fertilized to increase productivity. In some cases, intensive management practices may be used to increase the productivity and carbon storage of existing ecosystems, for instance when abandoned pasture or heathlands are afforested to develop plantations or other kinds of forest. These sorts of enhancements are already occurring over such large areas that they are affecting the carbon balance of temperate and boreal forests (Garcia-Gonzalo et al. 2007; Magnani et al. 2007).

Overall, ecosystems that are affected by frequent disturbances, whether natural or anthropogenic, will store much less living biomass and dead organic matter than do those that are less impacted. If the interval between disturbances is long enough, then older-growth ecosystems may develop. At the same time, the more intense the cumulative regime of natural plus anthropogenic environmental stressors, the smaller is the rate of productivity and the accumulated carbon storage in an affected ecosystem.

3.2. Carbon storage in terrestrial ecosystems

In this section, we present an overview of data relevant to the storage of organic carbon in typical temperate, boreal–montane, and arctic–alpine ecosystems, including terrestrial and freshwater systems. The data are relevant to Canada — we do not present data for tropical or subtropical biomes, but information on them is available in other sources (including: Whittaker and Likens 1973; Leith 1975; Allen 1985; Sombroek et al. 1993; Batjes and Sombroek 1997; Silver et al. 2000). Carbon offset trading in Canada may contribute to the conservation of biodiversity in tropical and subtropical biomes, but the focus on this paper is on the conservation of biodiversity within Canada and how this could be affected by carbon-offset trading.

Several review studies have provided data on the "typical" carbon storage in major kinds of ecosystems. Table 1 provides a summary of published estimates for broad ecosystem types in Canada.

Table 1. Typical carbon storage in organisms and productivity for biomes relevant to Canada (Whittaker and Likens 1973; Leith 1975).

Biome	Biomass ($t\ C\ ha^{-1}$)	Net primary productivity ($t\ C\ ha^{-1}\ year^{-1}$)
Temperate deciduous forest	70–135	5.0–5.4
Temperate conifer forest	80–>500[a]	5.9
Boreal forest	45–100	2.5–3.6
Temperate grassland	3.5–7.0	2.3–2.5
Tundra and alpine meadow	0.5–3.0	0.65–0.7
Desert and scrubland	0.5–3.0	0.32–0.35
Rock and polar desert	0.0–0.1	0.0–0.07
Swamp and marsh	12–68	10–11
Lake and stream	0.05–0.1	2.3–2.5

[a] the higher number is for old-growth conifer rainforest on the humid west coast (Trofymow et al. 2008).

3.2.1. Forests

Mature forest ecosystems have a higher biomass carbon density than any other kind of terrestrial ecosystem. Mature boreal forest typically has 45–100 t C ha^{-1} in biomass and a productivity of 3–4 t C ha^{-1} year^{-1}, while mature temperate forest has 70–135 t C ha^{-1} in biomass and a productivity of 5–6 t C ha^{-1} year^{-1} (Table 1). Much larger biomass accumulation can occur in coastal temperate conifer forests than elsewhere in Canada; with 150–250 t C ha^{-1} being typical, and accumulations exceeding 500 t C ha^{-1} in old-growth forest on Vancouver Island and in the US Pacific Northwest (Trofymow and Blackwell 1998; Smithwick et al. 2002; Trofymow et al. 2008).

About 8% of global forests are located in Canada, occupying 310 × 10^6 ha (43% of Canada's total vegetated land area), of which 66% are softwood, 22% are mixedwood, and 12% are hardwood (Power and Gillis 2006; FAO 2007).

The major effect of forest management on carbon storage is on the living biomass of vegetation, particularly of trees. Carbon stocks in large woody debris and the forest floor are also affected, depending on the harvesting and management practices employed. Immediately after a timber harvest there is a large increase in the amount of woody debris, but if the site is converted to shorter-rotation stands there is a long-term decline in the amount of large debris. Moreover, the quantity and quality of woody debris present in natural stands tend to be rather different from managed stands (Harmon et al. 1986). In general, however, timber harvesting has relatively little effect on carbon stored in the soil, except where followed by conversion of the site to an agricultural land-use, which may cause a loss of 24%–30% of the soil carbon stocks (Johnson 1992; Johnson and Curtis 2001; Murty et al. 2002).

The dynamics and potential carbon sequestration capacity of a forest must be evaluated at a number of spatial and temporal scales. The rate of carbon fixation and storage ca-

Table 2. Carbon storage in a selection of typical natural and plantation stands of forest in Canada. Data are for trees only, in above-ground plus below-ground biomass. The productivity data are averaged over the 100 year period. The data are from a compilation of information obtained from provincial departments of natural resources (Freedman and Keith 1996).

Dominant species	Age	Location	Site quality	Biomass (t C ha^{-1})	Productivity (t C ha^{-1} year^{-1})
Natural forest					
Sitka Spruce	100	BC coast	Good	474	4.7
Douglas-fir	100	BC coast	Good	485	4.9
Douglas-fir	100	BC interior	Good	182	1.8
Spruces	100	BC interior	Good	212	2.1
Spruces	100	ON	Good	161	1.6
Spruce-Fir	100	NB	Medium	49	0.5
Spruce-Aspen	100	BC ne	Good	220	2.2
White Spruce	100	AB	Good	154	1.5
Black Spruce	100	AB	Good	128	1.3
Black Spruce	100	ON	Good	98	1.0
Black Spruce	100	NL (insular)	Good	57	0.6
Balsam Fir	100	NL (insular)	Good	68	0.7
Lodgepole Pine	100	BC interior	Good	223	2.2
Pine	100	AB	Good	170	1.7
Red Pine	80	MB interlake	Good	117	0.8
Red Pine	100	ON	Good	172	1.7
White Pine	100	ON	Good	196	2.0
Jack Pine	100	ON	Good	103	1.0
Trembling Aspen	100	BC interior	Good	282	2.8
Trembling Aspen	100	AB	Good	201	2.0
Trembling Aspen	100	ON	Good	223	2.2
Tolerant hardwoods	100	ON	Good	127	1.3
Tolerant hardwoods	100	PE	Good	99	1.0
Plantation forest					
Douglas-fir	100	BC	Medium	273	2.7
Spruce	100	BC	Medium	178	1.8
White Spruce	100	ON	Medium	110	1.1
White Spruce	100	PQ	Medium	110	1.1
Black Spruce	100	ON	Medium	97	1.0
Black Spruce	100	PQ	Medium	95	1.0
Black Spruce	100	NL	Good	93	0.9
Balsam Fir	100	NL	Good	111	1.1
Lodgepole Pine	100	BC	Medium	185	1.9
Red Pine	100	BC	Medium	154	1.5
White Pine	100	ON	Medium	138	1.4
White Pine	100	PQ	Medium	143	1.4
White Cedar	100	PQ	Medium	95	1.0
Larch	100	ON	Medium	142	1.4
Red Alder	100	BC	Medium	280	2.8
Trembling Aspen	100	BC	Medium	165	1.7
Trembling Aspen	100	ON	Medium	223	2.2
White Birch	100	PQ	Medium	109	1.1

pacity of a particular stand is affected by its site conditions, species composition, stocking density, successional stage, and other environmental and biological factors (Schulze et al. 2000; Law et al. 2002; Pregitzer and Euskirchen 2004; Luyssaert et al. 2007). To a substantial degree, these influences are captured by standard forestry yield and growth models, which are the basis of economically and ecologically important decisions within the forest industry and its regulatory environment. A forested landscape is also affected by these factors, but it has an additional layer of complexity associated with its dynamic mosaic of stands occurring on various kinds of sites and of differing post-disturbance ages. These factors can also be modelled, as can be the influences of the natural or anthropogenic disturbance regime (including timber harvesting) and the effects of silvicultural management. The influences of these factors are inherent in the estimate of Myneni et al. (2001) that, as a broad average, a Canadian forest contains 44.0 t C ha^{-1} in its woody biomass (cf. 57.9 t C ha^{-1} in the US, 50.6 overall in North America).

A selection of values for tree biomass stocks in natural and plantation stands, at a reference age of 100, are presented in Table 2. Some of these forest types are dominated by long-lived species and can maintain positive rates of net production at ages greater than 100 years, so the values reported are not the maximum attainable stand-level carbon stocks in trees. Other stands are dominated by shorter-lived trees, and may senesce and start to lose part of their stock of biomass-carbon after a century or so of age.

Compared with information about trees, there are fewer data available about the amounts of carbon present in other components of forests, such as woody debris, the forest floor, and soil. Even so, it is well known that these components store large amounts of organic-carbon. In typical boreal and temperate forests, there is more carbon stored in dead organic matter and soil pools than in living biomass. However, much of the soil carbon is highly humified and resistant to decomposition. Some information on forest soil carbon stocks is available from research projects and national compilations of plot data (Siltanen et al. 1997; Shaw et al. 2005). Moreover, enough knowledge has been compiled about inputs and turnover of dead organic matter to develop models, such as the CBM-CFS3, which can simulate these aspects of carbon dynamics in forest ecosystems (Kurz et al. 2009). This model is used by the Canadian Forest Service and others to generate estimates of carbon stocks and their changes in major forest components (including living vegetation, woody debris, litter, and dead organic matter in soil; see Table 3) in a manner that is consistent with IPCC Good Practice Guidance (IPCC 2003).

Changes in the disturbance or management regime of a landscape are reflected in the age-class structure of stands (van Wagner 1978; Kurz et al. 1998). If the natural disturbance regime is characterized stochastic agents affecting vulnerable ecosystems, such as wildfire, the age-class structures may be in a non-equilibrium condition. This may also be the case if the disturbance regime is changing, for example in response to climate warming. Natural disturbances by wildfire and insect irruptions play a dominant role in most Canadian forest landscapes, and the area affected varies considerably, both inter-annually (Stocks et al. 2003) and over longer-term cycles (Royama 1984). During a year or period of extensive disturbances, the forested landscape may be a net source of CO_2 if emissions from damaged stands exceeds sequestration by undisturbed areas (Kurz and Apps 1999; Bond-Lamberty et al. 2007; Kurz et al. 2008). However, the opposite is more generally true — there is a net fixation of CO_2 at large spatial scales — and forests in general are an important global sink for anthropogenic emissions of GHG (Canadell et al. 2007*a*).

In view of these shifts between stands and landscapes acting as net carbon sinks and sources, it must be recognized that opportunities to generate carbon-offset credits will in large part be a function of past disturbances and management. Even in cases of older stands or landscapes where the forest is at or near its carbon-sequestration saturation level, there will be important opportunities to prevent losses of fixed carbon by taking measures to mitigate potential disturbances. Protection from anthropogenic disturbance is particularly feasible, for example, by creating protected areas where timber harvesting does not occur. In general, the carbon-offset benefits of such protection will be greatest where the risk of natural disturbance is low. Although it may not be possible to prevent all natural disturbances, even partly effective measures (such as the quenching of naturally ignited wildfires, where possible) will result in larger stocks of organic-carbon being stored at the landscape level.

3.2.2. Grasslands

Natural grasslands store considerable amounts of organic carbon in their vegetation and soil, albeit substantially less than in forests (Table 1; Whittaker and Likens 1973; Janzen 1995). According to Leith (1975), temperate grassland has a typical productivity of 0.5–7.5 t C ha^{-1} $year^{-1}$. However, the amount of carbon storage varies greatly among natural grassland types; tallgrass prairie stores much more biomass than do more arid grasslands (Table 4). About 0.52% of global grasslands occur in Canada, occupying 54.9×10^6 ha (5.5% of the land surface; WRI 2008; where data for “grasslands” are for lands with herbaceous cover, and tree and shrub cover < 10%).

When natural grassland is converted into annually cropped farmland, there is a large decrease in the organic matter stored within the ecosystem, typically by 20% to 40%, and occurring during the first 10 to 20 years following conversion (Mann 1986; Post and Mann 1990; Davidson and Ackerman 1993; Jensen et al. 1997; Guo and Gifford 2002). This change is mostly due to a loss of organic matter within the surface soil, which becomes depleted through an increased rate of decomposition caused by frequent disturbances associated with tillage, and in some cases by decreased inputs of plant litter. Losses of soil organic matter following the conversion of native grassland to cultivation are extensive and well documented (Haas et al. 1957; Schlesinger 1986; Davidson and Ackerman 1993; Kern and Johnson l993; Conant et al. 2001; Guo and Gifford 2002). The use of natural grasslands for cattle grazing may also reduce carbon storage, particularly if the system is overgrazed (Fearnside and Barbosa 1998; Abril and Bucher 1999; Derner et al. 2006).

In contrast, the conversion of annually cropped agricultural land into perennial grassland will increase the amount of carbon storage (Davidson and Ackerman 1993; Paustian et al. 1997*b*, 2000; Post and Kwon 2000; Conant et al. 2001; Guo and Gifford 2002). Such a naturalization to prairie will increase the organic carbon of soil by 25–59 t C ha^{-1} over a period of about 20 years, until a new steady-state is reached (Stinson and Freedman 2001).

Studies in Canada and the United States have shown that increased amounts of atmospheric CO_2 can be sequestered in soil by the use of agricultural conservation practices, including low- and no-till cultivation, improved fertilizer management, elimination of bare fallowing, the use of perennials in rotations, the use of cover crops, and improved erosion control (Paustian et al. 1997*a*; Dumanski et al. 1998; Smith et al. 2000*a*, 2000*b*; West and Marland 2002, 2003; West and Post 2002; Marland et al. 2003). In a literature review, Conant et al. (2001) found that the carbon content of agriculture soil typically increased by 30% under a variety of regimes of improved management.

3.2.3. Wetlands

Wetlands are habitats in which the water table occurs

Table 3. Quantities of organic-carbon (t C ha^{-1}) in major forest components in mature natural stands in southern New Brunswick (Fleming and Freedman 1998).

		Live biomass (above-ground)				
Stand type	Age	Trees	Shrubs	Snags	Woody debris	Forest floor
Hardwood (*n* = 3)	55–60	83.3	1.0	7.3	2.9	16.6
Mixedwood (1)	105	71.2	1.5	8.4	5.8	18.1
Conifer (3)	75–95	64.7	1.3	21.1	8.5	19.8

Table 4. Carbon storage (t C ha^{-1}) in plant biomass and in soil organic matter of grasslands. Data are from Derner et al. (2006).

	Plant biomass			
Prairie	Above-ground	Below-ground	Soil carbon (to 30 cm)	Total ecosystem
Tall-grass	1.9	26.7	61.4	90.0
Mid-grass	0.9	27.5	58.5	86.9
Short-grass	0.5	13.1	18.8	32.4

above, at, or near the surface for a long enough time to promote the development of hydric soil, hydrophytic vegetation, and biological activities adapted to a wet environment (Tarnocai 1980). In Canada, the major classes of wetlands are: bog, fen, swamp, marsh, and shallow open-water (National Wetlands Working Group 1988, 1997). The role of wetlands in carbon storage is complicated by the fact that they can be important sources of emission of biogenic CH_4 and CO_2 associated with microbial activity in sediment and peat (Prather et al. 1995; Magenheimer et al. 1996; Roger and LeMer 2001; Whiting and Chanton 2001; Christensen et al. 2003; Ding et al. 2003; Bridgham et al. 2006; Riutta et al. 2007). Wetlands contribute 91–237 × 10^6 tonnes of CH_4 $year^{-1}$, out of the global CH_4 flux of 600 × 10^6 t $year^{-1}$ (Ehhalt et al. 2001). Emissions of CH_4 are important because this gas has a relatively large greenhouse-warming potential, 25 times that of CO_2 on a per-molecule basis (IPCC 2007*a*). Nevertheless, a wetland system can act as a net sink for greenhouse gases if the removal of CO_2 by biological fixation exceeds the release of CO_2 equivalents of CH_4 plus CO_2 (Whiting and Chanton 2001).

Two broad wetland landforms are distinguished in Canada: (1) organic wetlands (or peatlands), which are mostly bogs but include some fens and swamps, and (2) mineral wetlands, which includes marshes (fresh and estuarine), shallow open water, and some fens and swamps (National Wetlands Working Group 1988, 1997; Bridgham et al. 2006). Peatlands are ombrotrophic, meaning they only receive water and nutrients from precipitation and dustfall, while mineral wetlands also get them from watershed sources and so are less acidic and more fertile. Mineral wetlands accumulate little or no peat because their climatic and edaphic conditions favour decomposition over the accumulation of dead biomass (Zoltai and Vitt 1995; Price and Waddington 2000).

Peatlands do not usually have much standing water (although pools may occur) and they have a well-developed stratigraphy. This includes a waterlogged surface layer that varies among vegetational sub-units and influences the peat accumulation rate, and deeper more-compressed material that determines the overall shape, composition, and storage capacity of the landform (Moore and Bellamy 1974; Clymo 1983; van Dierendonck 1992). Peat depths of up to 12 m have been recorded in Canada (Tarnocai et al. 2000; Warner et al. 2004). In comparison, mineral wetlands usually have abundant standing water, generally to a depth less than 2 m, and their bottom substrate is either inorganic or has only a veneer of accumulated organic material (up to 40 cm; Warner and Rubec 1998). Although large amounts of peat may accumulate in peatlands, the rate of accretion is slow, typically 20–100 cm per century (Moore and Bellamy 1974; Gorham et al. 2003).

Typical peat is about 50% carbon on a dry-weight basis (Gorham et al. 2003). Peatlands occupy about 3% of the global terrestrial surface, but contain 16%–33% of the soil carbon (Gorham 1991, Maltby and Immirzi 1993). Wetlands in North America contain about 220 × 10^9 tonnes of organic C, almost entirely in peat, and equivalent to about half that stored in terrestrial ecosystems of the continent, and representing 43% of the global wetland pool (Bridgham et al. 2006).

About 18% of global wetlands occur in Canada, occupying 125 × 10^6 ha (14% of the land surface), of which 110 × 10^6 ha are peatlands (more than any other country; Tarnocai 1998; Tarnocai et al. 2000, 2001, 2005). These data do not include littoral wetlands along lakes and rivers or coastal estuaries. The wetland carbon pool in Canada is about 147 × 10^9 t C (see also Riley 1987; Riley and Michaud 1987; Tarnocai 1998). About 98% of the organic-carbon in wetlands occurs in peaty soil and 2% in living vegetation. Peatlands contain 87% of the wetland carbon in Canada. Moderately rich fens are the most frequent kind of peatland in boreal Canada, and they generally accumulate smaller depths of peat than do ombrotrophic bogs (Malmer 1986; National Wetlands Working Group 1988; Vitt 1990; Tolonen and Turunen 1996, Thormann et al. 1999). Peat accumulation requires that the rate of primary production be larger than that of decomposition, and it is affected by such factors as water saturation, acidity, and oxygen status and temperature of the surface substrate (Clymo 1984; Warner et al. 1993; Belyea and Warner 1996; Damman 1996; Clymo et al. 1998; Whiting and Chanton 2001).

Table 5. Carbon storage and annual accumulation in major wetland types in Canada (adapted from Bridgham et al. 2006).

			Mineral wetlands		
	Peatlands on permafrost	Peatlands not on permafrost	Freshwater	Saltmarsh	Mudflat
Area (10^6 ha)					
Current	42.2	71.4	15.9	0.044	0.6
Historial	42.4	72.6	35.9	0.13	0.7
Soil carbon (10^9 t)	44.2	102.9	4.6	0.01	0.10
Annual fixation					
Total (10^6 t year^{-1})	5.5	13.6	2.7	0.09	1.21
Rate (t ha^{-1} year^{-1})	0.13	0.19	0.17	2.05	2.02

Thormann et al. (1999) studied the rate of peat accumulation along a wetland gradient in boreal Alberta. The accumulation rate of peat was 1.7 t ha^{-1} year^{-1} in *Sphagnum*-dominated sites (bog and poor fen), 1.3 t ha^{-1} year^{-1} in brown-moss sites (moderate-rich fen and lacustrine sedge fen), and 1.0 t ha^{-1} year^{-1} in marshes with little bryophyte cover. The slower accumulation in marshes occurred in spite of their higher primary production, and was due to offsetting higher rates of decomposition.

Estimates of carbon storage and annual accumulation in major wetland types in Canada are summarized in Table 5. These data suggest that Canada has lost about 14% of its wetlands, mainly due to agricultural conversion of freshwater mineral-soil wetlands, but that peatlands have been affected much less (see also Rubec 1996). By far the largest amount of wetland carbon sequestration occurs in peatlands (83% of the annual fixation), because of their great area. However, the rate of fixation is much larger in estuarine wetlands because of their high unit-area productivity and the burial of organic matter in accumulating sediment.

In parallel with the case of forests and prairie, if natural wetlands are drained to develop agricultural or residential land, their accumulated store of organic carbon eventually oxidizes and contributes to increasing concentrations of CO_2 in the atmosphere. The same is true if peat is harvested and used as a source of energy, although the oxidation is more rapid. In contrast, the conservation of natural wetlands helps to keep their organic-carbon in place, and avoids these sorts of emissions.

It will be important to understand the likely implications of climate change for efforts to conserve wetlands. For example, if decreased precipitation results in a lower water table in peatlands, then the rate of oxidation of surface peat will increase. In northern peatlands, the loss of the permafrost could expose previously frozen substrates to both oxidation and methane release.

4.0. Linkages between efforts to conserve organic-carbon and those to conserve biodiversity

There are obvious cross-linkages between efforts to manage terrestrial ecosystems to achieve carbon offsets and those to conserve biodiversity. Many kinds of land-management actions that are undertaken to enhance ecological carbon sequestration or to protect existing reservoirs will also help to conserve biodiversity, and vice versa. By avoiding deforestation, for example, substantial emissions of ecologically sequestered carbon can be avoided, as will be a loss of habitat for native plants and animals. However, not all ecological carbon offset projects will contribute greatly to the conservation of native biodiversity (for example, projects to increase carbon stored in the soil of annual croplands). Conversely, some projects to conserve biodiversity will not provide certifiable carbon offsets for trading into the emerging carbon markets (for example, projects that would protect existing forest biomass). In this section, we examine the classes of ecological-sink projects that are within the scope of Canada's existing offset system for GHGs (Government of Canada 2008), including agricultural-sink projects and three types of forest projects. We also discuss the cross-linkages between the carbon-related and conservation impacts of these projects.

4.1. Afforestation

Projects that involve planting a forest on a site where one did not exist prior to at least 1990 can be undertaken to enhance carbon sequestration into woody biomass and other ecosystem components. These afforestation projects will result in verifiable offsets that can be registered and traded within Canada's GHG system, or in a regional offset system where one has been established (e.g., in Alberta).

Afforestation projects generate carbon offsets by increasing the sequestration and storage of organic-carbon, primarily into tree biomass but also in other ecosystem components, such as deadwood, litter, and soil organic matter. Afforestation projects can also benefit biodiversity, particularly if an attempt is made to restore native forest on previously deforested land (Freedman 2007*b*). Additional ecological co-benefits may include improved water quality downstream and in aquifers and improved slope stability on sites prone to erosion (Freedman 1995, 2007*a*). On the other hand, there are circumstances under which afforestation could diminish local water resources by increasing evapotranspiration (Jackson et al. 2005).

Conservation projects aimed at the restoration of native forest may not provide the greatest possible carbon sequestration per unit of land area if the restored vegetation is less productive than alternative non-native or silvicultural forest, such as high-yield poplars or other commercially valuable trees grown in plantations (Freedman and Keith 1996; Stinson and Freedman 2001). On the other hand, silvicultural plantations provide fewer biodiversity co-benefits (for case material from New Brunswick, see Freedman et al. 1994; Waldick et al. 1999; Johnson and Freedman 2002; Veinotte et al. 2003; Woodley et al. 2006).

Afforestation projects are unlikely to be undertaken on productive agricultural land unless the economics strongly favour carbon sequestration over food production. Nevertheless, carbon-offset markets could encourage afforestation on lands that might be used for other economic purposes. Moreover, high carbon prices could encourage the establishment of non-native, fast-growing plantations rather than natural forest. In other cases, however, the primary driver of an afforestation project might be ecological restoration, in which case the associated carbon offsets would be viewed as a secondary, value-added component.

4.2. Avoided deforestation

Some offset-trading systems will allow avoided CO_2 emissions resulting from efforts to avoid deforestation to be registered and sold as offsets. Although the CDM and JI do not recognize these avoided deforestation offsets, there is a strong lobby to include them in post-Kyoto international agreements because of the large GHG emissions that are associated with deforestation, particularly in the tropics. Canada's domestic offset system will consider projects associated with avoided deforestation to be eligible for offset trading (Government of Canada 2008).

Avoided deforestation projects will co-conserve both existing organic-carbon and biodiversity by protecting natural habitat. However, offset projects that involve avoided deforestation can be problematic from a regulatory and philosophical standpoint, because proponents must demonstrate that there was a prior management plan that involved deforestation — it must be conclusively demonstrated that deforestation was avoided and that real GHG offsets were gained.

4.3. Forest management

There are opportunities to reduce emissions and enhance sinks of GHGs through forest management. Green house gas offset quantification protocols are being developed for forest-management activities in Canada's accounting system and for other regional systems, such as that being established for Alberta and for jurisdictions participating in the Western Climate Initiative. Canada elected not to include forest management in its GHG accounting for the first commitment period of the Kyoto Protocol (Government of Canada 2007), but it may be included in the future. Moreover, as the market price of offsets becomes better established in Canada and quantification protocols are developed and approved, there may be routine incorporation of carbon stewardship objectives into forest management planning (Neilson et al. 2007). There have, however, been relatively few studies that provide estimates of how forest-carbon sinks are affected by management activities (Stinson and Freedman 2001; Liski et al. 2001; Harmon and Marks 2002; Schmid et al. 2006; Seidl et al. 2007; Hennigar et al. 2008). The conclusions reached by such analyses will be highly sensitive to the accounting systems applied to the management scenarios and to the scalability of different strategies.

Some forest-management carbon-offset strategies will make positive contributions to the conservation of biodiversity while others may provide limited direct impact on biodiversity. In general, the positive ones will use "softer" practices that emulate the natural disturbance regime that is typical for the ecoregion (McRae et al. 2001). As previously noted, more-intensive practices that develop short-rotation plantations will result in fewer benefits to biodiversity.

A strong market for carbon offsets could create greater cross-linkages between the resource-stewardship objectives of the industrial forestry sector and those of conservation organizations than currently exist, but this will partly depend on how carbon is accounted for in offset trading systems. Current IPCC accounting rules (IPCC 1997) treat organic-carbon removals from the ecosystem, such as those that occur during timber harvesting, as if they were direct emissions to the atmosphere. However, some of the harvested carbon ends up in enduring manufactured products that may continue to sequester it for decades or even centuries (e.g., Apps et al. 1999; Stinson and Freedman 2001; White et al. 2005). Carbon-accounting systems that consider the full life cycle of forest products will provide different incentives to management than does the current Kyoto Protocol framework, which focuses on maximizing carbon storage on the landscape.

4.4. Agricultural sinks

The historic depletion of organic carbon stocks in Canada's agricultural lands presents an opportunity to reduce atmospheric CO_2 concentrations by recovering lost carbon in their soil, either through changes in agricultural practices or by restoring native grasslands. This opportunity is mostly associated with increasing the content of organic-carbon in soil, rather than the biomass of living vegetation. However, in cases where annually cropped lands or tame pasture are being managed in this way, there will be few benefits to native biodiversity. Only projects in which intensively managed lands are restored to facsimiles of native grassland used to graze livestock will result in substantial benefits to native biodiversity.

5.0. Conclusions

Offset trading has become a widely accepted approach to help meet goals to stabilize emissions of GHGs, as set out by international agreements such as the Kyoto Protocol, and by national and regional policy directives. As a consequence, carbon-offset markets are rapidly becoming established worldwide. Although these developments have to date progressed at a slower pace in Canada, they are starting to develop momentum. Several carbon-trading pilot projects have been undertaken and a domestic GHG-offset system is now being set up by the Government of Canada. Ecological-carbon offsets will play an important role in the emerging carbon markets of Canada because there are many opportunities to enhance carbon sequestration in ecosystems and to protect existing reservoirs.

While it is true that ecological carbon sinks are non-permanent, they do remove CO_2 from the atmosphere and the risks associated with reversals (i.e., loss of sequestered carbon back to the atmosphere) can be managed to a substantial degree. Even so, ecological carbon offsets will necessarily play a limited role in overall emission stabilization. This is because the ability of ecosystems to sequester organic carbon will eventually saturate, and much productivity must be put towards other economic uses, such as food production.

Temporal dynamics are also an important consideration.

Fig. 1. Conceptual model of the benefits of selected land-use and land management alternatives that could be pursued to generate GHG offsets and (or) contribute to the conservation of natural areas. Grenn house gas offsets and biodiversity benefits are coded green for high benefit, yellow for moderate benefit, and orange for little or no benefit.

	Benefit to GHG Offsets		Benefit to Biodiversity	
Conservation of an existing natural ecosystem (forest, grassland, or wetland)	🟩	High – existing C storage and sequestration potential are conserved. GHG offsets are realized up front.	🟩	High – existing habitat for native biodiversity is conserved.
Afforestation	🟩	High – forests store more organic-C than other terrestrial ecosystems. GHG offsets are gradually realized over time.	🟩 🟧	High to low – higher if the afforestation establishes a natural forest; lower if native vegetation is displaced by the establishment of fast-growing, non-native plantations.
Reforestation	🟨	Moderate – forest productivity at the landscape scale can be increased by accelerating regeneration following disturbance by reforestation activities.	🟨	Moderate – if all successional stages are present on a managed landscape, then most native biodiversity can be sustained (protected areas can accommodate the rest)
Intensive silvicultural management	🟨	Moderate – forest productivity can be increased by intensive silvicultural management	🟧	Low – intensive silvicultural systems are less favourable to biodiversity than systems that emulate the natural disturbance regime and natural forest stand structures.
Lengthened forest harvest rotation period	🟨	Moderate – higher levels of forest biomass C are maintained on the landscape. GHG offsets are gradually realized over time.	🟨	Moderate – wider range of successional stages are present on the landscape, including more mature forest.
Avoided conversion of old-growth to second-growth forest	🟩	High – old-growth forests store more organic-C than other forest ecosystems. GHG offsets are realized up front.	🟩	High – habitat for old-growth dependent native biodiversity is conserved.
Management to increase organic-C in cropland and tame pasture	🟨	Moderate – soil capital of organic-C is increased. GHG offsets are gradually realized over time.	🟧	Low – few benefits to native biodiversity.
Conversion of cropland or tame pasture to native grassland	🟨	Moderate – increases in soil organic-C and plant biomass. GHG offsets are gradually realized over time.	🟩	High – improved habitat for native biodiversity.

Many ecological sink strategies do not provide immediate GHG-sequestration benefits. For example, GHG-offset benefits from some types of forest projects accrue over a long time period, and such schemes may not be attractive from an investment standpoint unless non-carbon environmental and socioeconomic co-benefits are taken into consideration. Prospective investors in ecological GHG-offset projects may place different emphasis on evaluation criteria depending on their objectives, with some principally emphasizing GHG-offsets, and others the biodiversity benefits of conservation (Fig. 1). In the latter case, projects may be economically marginal unless their secondary, value-added GHG-offset attributes are also considered.

In this sense, ecological GHG-offset projects can contribute to the conservation of natural areas and to other objectives related to environmental stewardship. Green house gas offset trading has the potential to leverage considerable financial resources towards conservation projects that provide GHG co-benefits. The commodification of property rights and liabilities associated with emissions of GHGs and their removal from the atmosphere will provide increasingly strong financial incentives (as carbon prices rise) for the conservation and improved management of both natural and restored ecosystems the services they provide (Bonnie et al. 2002). Excessive focus on any one forest (or grassland or wetland) value, however, tends to lead to negative impacts on other values. It would be better if offset systems were to require proponents to take a broad, systems perspective to evaluating projects prior to their implementation. Canada's offset system does this, indicating that other environmental considerations will be taken into account when projects are evaluated. The valuation of offsets from this perspective should favour projects that contribute both to the mitigation of climate change and the conservation of natural values.

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