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Developing carbon-based ecological indicators to monitor sustainability of Ontario's forests

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Abstract

With 2% of the world's forests and 17% of Canada's forested land, Ontario plays a major role in maintaining Canada's forests and managing them sustainably. Ontario is developing a set of criteria and indicators of sustainable forest management (SFM) to aid in conservation and sustainable management of its temperate and boreal (BO) forests. The criteria and indicators are intended to provide a framework for describing and assessing processes of SFM at a regional scale; and to improve the information available to the public and decision-makers. This paper describes three ecological indicators, evaluated using a carbon (C) budget model, a forest inventory database, and disturbance records to assess long-term sustainability of Ontario's forest ecosystems based on the environmental conditions of the past 70 years. Results suggest that total net primary productivity (NPP) of Ontario's forest ecosystems increased from 1925 to 1975 and then decreased between 1975 and 1990; Ontario's forest ecosystems acted as a C sink between 1920 and 1980, and a C source from 1981 to 1990, mainly due to decreased average forest age and NPP caused by increased ecosystem disturbance (e.g. fire, insect and disease infestations, harvesting) since 1975. Current estimates from this analysis suggest that there is significant potential for Ontario's forests to function as C sinks by reducing ecosystem disturbances and increasing growth and storage of C in the young forests throughout the province.
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1. Introduction

Awareness of the need for environmentally sustainable economic development was raised by the widely cited Brundtland report Our Common Future (WCED, 1987). Published over a decade ago, the issues identified in the report—in which the concept of "sustainable development" was introduced—remain as unmet challenges. The Brundtland report defines sustainable development in terms of inter-generation equity as "ensuring that (humanity) meets the need of the present without compromising the ability of future generations to meet their own" (WCED, 1987). Sustainable development has more recently been the major focus of international attention in Agenda 21, set up at the Earth Summit held in Rio De Janeiro in 1992. As a result of the Rio meeting, some national governments have responded to the call to establish sustainable development strategies (CCFM, 1992;

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HMSO, 1994). Developing criteria and indicators for sustainable forest management (SFM) is an important step toward meeting the forestry commitment made at the United Nations Conference on Environment and Development (UNCED, 1992). The ongoing debate on sustainable development has moved from defining this broad concept to examining ways in which it can be measured (Cocklin, 1989; Bossel, 1996; Wardoyo and Jordan, 1996; CCFM, 1997; Morris et al., 1997).

SFM represents a new paradigm for forestry in Canada (CCFM, 1992). Canada is developing a set of criteria and indicators of SFM for domestic purposes (CCFM, 1995, 1997) and has been actively involved in initiatives to define criteria and indicators for forests in Europe (the Helsinki Process) and for temperate and BO forests in general (The Montreal Process, 1997), which will establish international criteria and indicators for the conservation and sustainable management of temperate and BO forests.

Ontario holds about 2% of the world's forests and 17% of Canada's forested land. Maintaining long-term ecological sustainability of Ontario's forests involves managing temporal and spatial patterns of ecosystem conditions at both stand and landscape levels (Perera et al., 2000). In its broadest sense, SFM embraces both the concepts of ecosystem management (in which multiple resource values are made explicit) and the concepts of sustainable development (in which the needs of future generations are explicitly considered) (Kimmins, 1997). Understanding the dynamics of forest ecosystems, and the factors that influence these dynamics, provides the basis for the sustainable use of forest resources and the conservation of their environmental values. Of particular importance is that at a periodic intervals they are subjected to large-scale natural and anthropogenic disturbances (such as wild fire, insect outbreaks, and harvesting), whose relationship and interaction with environmental variability and change is imperfectly understood (Candau et al., 1998; Perera et al., 1998; Fleming et al., 2000; Li, 2000). Moreover, forests are under increasing pressure both through the direct effects of harvesting and land-use change, for example, as well as the indirect effects of anthropogenic changes in the global climate system (Colombo et al., 1998; Parker et al., 2000; Flanningan and Weber, 2000).

In this paper, we (1) provide an overview of the development of Ontario's criteria and indicators for SFM; (2) quantify three specific ecological indicators (net primary productivity (NPP), net ecosystem production (NEP), net biome production (NBP)) that relate global carbon (C) budgets to the long-term sustainability of Ontario's forest ecosystems under a changing environment; and (3) discuss associated challenges and future research needs.

2. Development of criteria and indicators in Ontario

Criteria and indicators are used to condense the world's complexity into a manageable amount of meaningful information to help us make informed decisions and direct our actions appropriately. With the increasing complexity of environment-development problems, the urge of science is to produce ever more data and indicators. A criterion is a category of conditions or processes by which sustainable ecosystem management may be assessed (CCFM, 1995; OMNR, 2001). An indicator is a measure of an aspect of the criterion. A criterion is characterized by a set of related indicators that are monitored periodically to assess change. An indicator should have four basic attributes. It (1) must be easy to understand; (2) must be something that can be measured; (3) should measure something believed to be important or significant in its own right; and (4) should be comparable among geographical areas, preferably internationally (Anderson, 1991; Morris et al., 1997; Peng et al., 1998a).

The seven criteria for Ontario's forests, which are defined by 68 related indicators (OMNR, 2001), and are viewed as essential components of the sustainable management of temperate and BO forests are:

1. conserving biological diversity in Ontario's forest;
2. maintaining and enhancing forest ecosystem condition and productivity in Ontario;
3. protecting and conserving Ontario's forest soil and water resources;
4. monitoring Ontario's forest contributions to global ecological cycles;
5. providing for a continuous and predictable flow of economic and social benefits;
6. accepting Ontario's social responsibilities for sustainable forest development; and
7. maintaining and enhancing Ontario's framework for SFM.

Criteria 1–6 relate specifically to Ontario's forest conditions, attributes or functions, and to the multiple values or benefits associated with the environmental and socio-economic goods and services that forests provide. Criterion 7 relates to how Ontario's overall policy framework facilitates SFM and supports efforts to conserve, maintain or enhance the condition, attributes and benefits captured in criteria 1–6. Taken together, these criteria and indicators provide a common understanding and implicit definition of what is meant by SFM. The criteria and indicators will help to provide a provincial reference for policy makers and forest managers when formulating policy, improve the quality of information available to decision-makers and the public, and provide better information in support of the forest policy debate at national and international levels.

Over the next 20 years it is anticipated that demand for timber production will increase beyond supply in Ontario. Without the development of appropriate management and decision support indicators, it will be difficult to manage our forest ecosystem productivity in a sustainable fashion. Of particular interest to us are the indicators associated with forest ecosystem productivity and net C balance of forest ecosystems in Ontario. Under the Kyoto Protocol, Canada has agreed to reduce its greenhouse gases (GHG) emissions by 6% from the 1990 level by 2010. With 38% of Canada's population and 17% of Canada's forested land, Ontario plays an important role in Canada's C budgets. Forests could help Ontario achieve a greenhouse gas emissions reduction target by increasing the removal of carbon dioxide from the atmosphere and storing it in both vegetation and soil. If forests are to be used to help meet greenhouse gas emission reduction targets, it is important to have an accurate estimate of the state of Ontario's forests. Ontario needs to investigate its C budget in detail and report on its net C balance (e.g. C sinks and sources) to help meet the national commitment (OMNR, 2001).

3. Methodology

3.1. Model description

We used the C budget model for the Canadian forest sector (CBM-CFS2, Kurz and Apps, 1999) and forest inventory database to assess values for these indicators for Ontario's forests for the last 70 years. The details on the model are published in Kurz et al. (1992), Kurz and Apps (1999), and Apps et al. (1999). Therefore, we only provide a short description of the model in this paper. The CBM-CFS2 is a general framework for accounting for C stocks and fluxes in forest ecosystems. The model considers biomass, soil organic matter and forest products C pools. It incorporates data and simulated processes required to estimate the C budget of the forest, including C storage in above- and belowground biomass and soils, and C exchange among these reservoirs and the atmosphere (Fig. 1). It also simulates forest growth, mortality, decomposition, and the effects of disturbances on the forest ecosystem. The effects of disturbance (principally wildfires, insect outbreaks, and harvesting) on forest age structure and on C releases to the atmosphere and forest floor are calculated on a 5-year cycle.

The inputs of the model include area, forest types, forest age, site condition, harvesting and natural disturbance statistics, and management activities such as planting. The model can be used to generate detailed output files and summary information for each spatial unit and ecoclimatic province in Canada. It can also provide estimates of the C stocks in these pools and C fluxes for Ontario's forested land. During the last decade, the CBM-CFS2 has been used at national (Kurz and Apps, 1995, 1999), provincial (Kurz et al., 1996a; Peng et al., 2000; Liu et al., 2002), and forest management unit scales (Price et al., 1996, 1997). For example, it has been used to:

1. demonstrate the importance of natural disturbances as a major factor governing large-scale temporal dynamics of C in Canadian forests over the last century (Kurz and Apps, 1995, 1996), possible outcomes in the future (Kurz and Apps, 1995), and the role of forest products in this balance (Apps et al., 1999);
2. assess the effects of intensive harvesting on C dynamics (the Foothills Forest in Alberta) and compare with those likely to have occurred in the same ecosystem subject only to natural disturbances (Price et al., 1997);
3. assess the effects of the transition from a natural to a managed disturbance regime in different forest biomes in Canada (Kurz et al., 1998); and

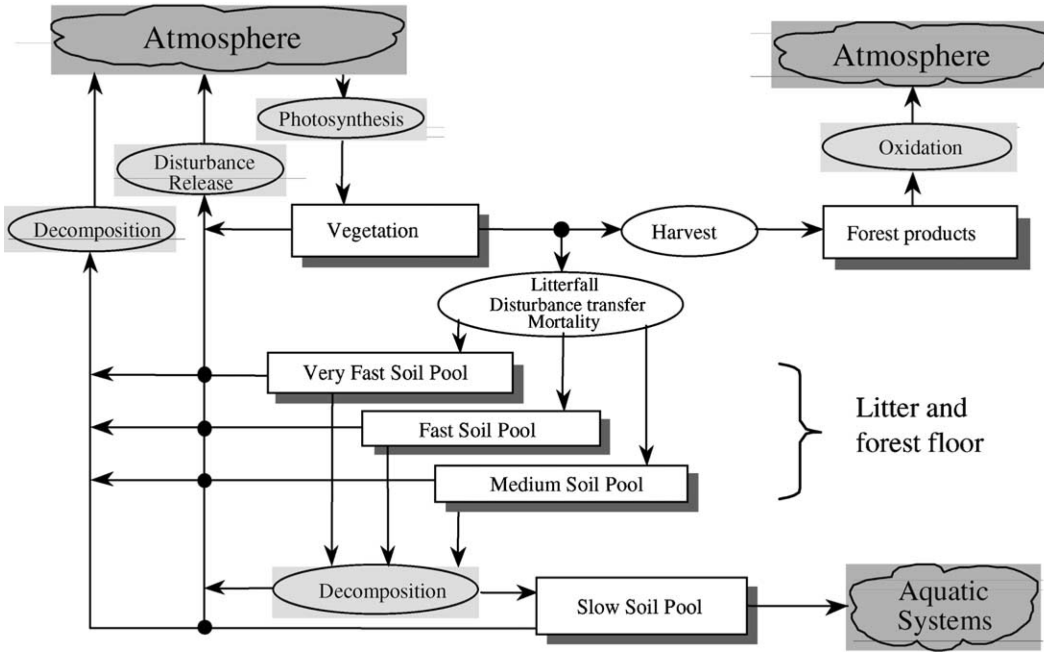

Fig. 1. A simple diagram of C stocks and fluxes included in the C budget model of the Canadian forest sector (CBM-CFS2).

4. examine various policy implications, including the role of Canada's forests in meeting the Kyoto Protocol, and the sensitivity of national GHG accounting under Intergovernmental Panel on Climate Change (IPCC) guidelines to different data and assumptions (Greenough et al., 1997).

3.2. Description of ecological indicators

Of the 68 indicators, three are of particular interest: (NPP, NEP, and NBP) because of their relationship to forest growth, ecosystem productivity and disturbances, and climate change. They are also closely related to ecosystem functions that are one of core components of sustainability of the ecosystem. There are two concepts embedded in the term "sustainability": sustainability of timber yield and sustainability of the ecosystem. The latter refers to sustaining the integrity of the natural forest in terms of its structure, function and composition (i.e. species composition and biological diversity).

3.2.1. Net primary productivity (indicator 2.2.4)

NPP represents the net C input from the atmosphere to terrestrial vegetation (Melillo et al., 1993). It is a measure, used to describe forest ecosystem condition and link forest growth with C dynamics (Peng and Apps, 1998, 1999; Peng et al., 1998a,b). For this reason, it is widely used as an indicator for the sequestration of atmospheric CO_2 by plants, as well as for forest ecosystem production in terms of biomass production of all species and types of flora and fauna. It is of fundamental importance to human because we rely on a significant portion of this biomass production for fiber, fuel, and food. Nearly 40% of the world's annual NPP is directly managed for human use (Vitousek et al., 1986).

In theory, NPP is defined as the difference between gross primary productivity (GPP) and autotrophic respiration (R_a) (Kimmins, 1997). It is the net amount of canopy C accumulated by a tree over a specified time interval—usually 1 year. In practice, NPP can be calculated by summing up the growth of all tissue produced during a year, including that consumed by herbivores or added to the detritus pool (Landsberg and Gower, 1997).

The equation is : $\text{NPP} = \Delta B + D_B + C_B$

where ΔB is the change in biomass over a year (annual biomass increment), D_B is detritus produced during the year, and C_B represents biomass consumption by herbivores during the year.

3.2.2. Net carbon balance (indicator 4.1.1)

The global C cycle is the most important natural process linking forests with climate change. Forests play an important role in the global C cycle because they store a large amount of C in vegetation and soil, and exchange C with the atmosphere through photosynthesis and respiration (Dixon et al., 1994; IPCC, 2000). The net C balance represents the net exchange of C between forests and the atmosphere, and is an indicator of C sinks or sources. It is also an important factor in global warming and climate change (IPCC, 2000).

NEP and NBP are key indicators used to describe the annual net C balance of forest ecosystems (IGBP Working Group, 1998; IPCC, 2000). NEP denotes the net accumulation of C by an ecosystem. It is the difference between the rate of production of living organic matter (NPP) and the decomposition rate of dead organic matter (heterotropic respiration, R_H). R_H includes losses by herbivory and the decomposition of organic debris by soil biota. NBP denotes the net production of organic matter in a region containing a range of ecosystem (a biome) includes, in addition to R_H, other non-respiratory losses by ecosystem disturbances (e.g. fire, insects, harvesting etc.); NBP is a small fraction of initial uptake of CO_2 from the atmosphere and can be positive or negative. It is appropriate for calculating net C balance of large areas (100–1000 km^2) and longer periods of time (several years or more).

The relationship between these indices can be described by the following equations:

$$\mathrm{NEP} = \mathrm{NPP} - R_H$$

NBP = NEP—non-respiratory C losses through ecosystem disturbances where NPP is the net production of organic matter by plants in an ecosystem.

For Ontario, NPP was calculated as annual ecosystem biomass increment plus annual litterfall (before disturbances). NEP was calculated as NPP minus soil C emissions, representing the net C balance of forest ecosystems (before disturbance). NBP was calculated as NEP minus harvest removals and direct C emissions caused by disturbances.

3.3. Inventory data and spatial units

Forest inventory information used in the CBM-CFS2 was derived from the National Forest Biomass Inventory (NFBI) (Bonnor, 1985). The NFBI contains about 50,000 grid cells (9.5 km × 9.5 km) for all of Canada's forested land and includes considerably more area (440.8 M ha) than the forest inventory since it estimates biomass in low productivity areas and non-commercial forests. Information in the NFBI was summarized for 42 spatial units representing the boundaries of ecoclimatic provinces (Ecoregions Working Group, 1989). In CBM-CFS2, Ontario's forested land is divided into four ecoclimatic regions: subarctic (SA); boreal BO; cool temperate (CT); and moderate temperate (MT) (Fig. 2). The SA region has no forest cover or biomass. The other three regions contain 45 forest ecosystem types that have been classified using the criteria: land type class, productivity, stocking, forest type, and site quality. Within each ecoclimatic region, spatial boundaries are not defined for these forest ecosystem types but their area is known. Forest ecosystem types are further split by age classes for C budget accounting. Each record in the database represents a specific age class of a specific ecosystem type within an ecoclimatic region, but the exact location is not known.

3.4. Growth curves, disturbances, and soil carbon dynamics

In CBM-CFS2, forest growth is described by a growth curve (i.e. biomass over age) that identifies four phases of stand development: regeneration, immature, mature, and overmature (Kurz and Apps, 1999). Each phase is represented by a specific growth curve that indicates the annual net accumulation of aboveground biomass. A pair of tree growth curves (one each for hardwoods and softwoods) describes each ecosystem type. Currently, 45 forest types with 90 growth curves are used by CBM-CFS2 to present aboveground biomass dynamics of forest ecosystems in Ontario. For each growth curve, the parameters for each growth phase, and the rules for transitions between growth phases, are derived from the NFBI. Growth rate is a dependent variable of forest age. Light, leaf area, tree species, and soil water content variables are not included. Growth

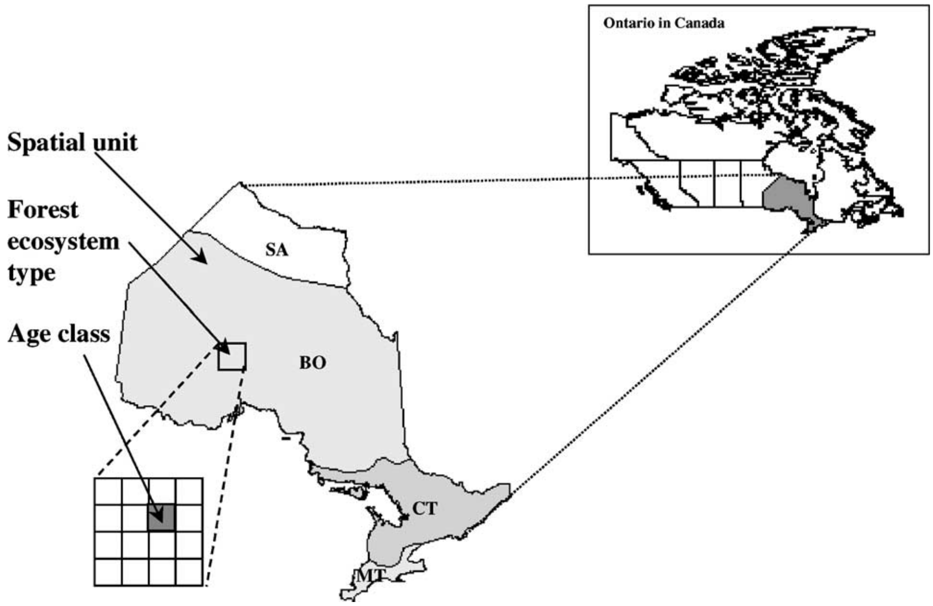

Fig. 2. Three spatial data levels for CBM-CFS2. SA: subarctic; BO: boreal; CT: cool temperate; MT: moderate temperate.

rates are derived from forest growth curves based on age.

For each softwood and hardwood component, forest biomass is divided into six parts: foliage (A), branch and top (B), sub-merchantable (C), merchantable (D), fine roots (E), and coarse roots (F). Belowground biomass, i.e. coarse and fine roots, is estimated for softwood and hardwood species using regression equations developed by Kurz et al. (1996b).

Disturbances play an important role in the development of Ontario's forest stands because they are often stand-replacing and thus, change overall forest age structure. The CBM-CFS2 model identifies seven types of disturbances: forest fire, insect-induced stand mortality, clear-cut logging, clear-cut logging with slash burning, salvage logging following fire, salvage logging following insect-induced stand mortality, and partial cutting. For each spatial unit and disturbance type, a specific disturbance matrix has been assigned to calculate the proportion of each ecosystem C pool transferred to the atmosphere, forest product sector, and to other pools (Kurz et al., 1992). The area affected by each disturbance and the year of disturbance is input to the model. There is no feedback scheme that links forest biomass or age class with the extent and type of disturbance each year. The model uses a set of predefined criteria to allocate disturbance area to ecosystem types and ages. After disturbance, the unaffected area keeps the same properties as before. The disturbed area switches to a new age class (usually the beginning of regeneration). New records are formed in a new time step. If records are combined, the area-weighted C content of each pool is calculated.

The CBM-CFS2 model distinguishes four types of soil C pools: very fast, fast, medium, and slow. These soil C pools receive input from processes such as litterfall, turnover, tree mortality, and disturbances. The very fast pool receives all foliage (A) and fine root biomass (E). The fast pool receives tree branch and top biomass (B), sub-merchantable biomass (C) and coarse roots (F). The medium pool receives all stemwood biomass of merchantable trees (D). The slow pool represents humified organic matter and receives its input by decomposition from the other three pools (Fig. 1). Each pool has a different decomposition rate calculated from a base decomposition rate defined at 10 °C and adjusted for the mean annual temperature of each spatial unit, assuming a Q_{10} of two (i.e. for every 10 °C increase in temperature, decomposition rates double) (Kurz and Apps, 1999). Since CBM-CFS2 does not simulate the dynamics of forest peat C, associated estimates are excluded in this report.

3.5. CBM-CFS2 simulation runs

The CBM-CFS2 simulation was retrospective back to the 1920s, so not only can we evaluate current C condition, but we can also get the trends over the past 70 years. Input data were mainly based on the forest biomass inventory database of 1985 (see Kurz et al., 1992; Kurz and Apps, 1995, 1999). For the entire Ontario region, there are 45 forest types available. Two growth curves (hardwood and softwood) for each forest type were parameterized based on inventory data. Decomposition rates and disturbance matrixes were derived from various data sources and published literature (Kurz et al., 1992; Kurz and Apps, 1999). In this study, model simulations began in 1989 with simulated initial ecosystem conditions that are the endpoint of the 70-year retrospective model run for the period 1920–1989 (Kurz and Apps, 1995, 1999). The modelled distribution of forest age classes and the biomass C and soil C pools are all affected by the forest dynamics of the 70-year period prior to 1990. Further details on the assumptions underlying the retrospective analysis can be found in Kurz and Apps (1995, 1999).

4. Results and discussions

4.1. Quantifying temporal changes in NPP

Based on the CBM-CFS2 model, total NPP in Ontario steadily increased from 278 to 352 Tg C per year between 1925 and 1975, then continuously decreased to 268 Tg C per year between 1975 and 1990 (Fig. 3), mainly due to decreased average forest age caused by increased ecosystem disturbances (e.g. fire, insect outbreaks, harvest) after 1975 in boreal forests in northern Ontario. In fact, BO forests dominate Ontario's total forest NPP because of their large area. The boreal forest region currently has an age-class structure with a large proportion of young forests (average age approximately 40 years), because of frequent forest fires that occurred between 1985 and 1989 (Perera et al., 1998). In contrast, average forest age in Great Lakes-St. Lawrence and Carolinian forests (GLSL) is higher, and these forests are mostly hardwood species managed using a shelterwood or selection silvicultural system, not often subject to major disturbance.

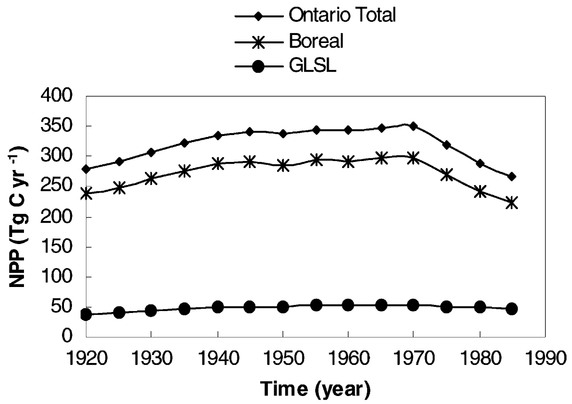

Fig. 3. Historic NPP dynamics in Ontario's forest ecosystems. Boreal: boreal forests; GLSL: Great Lakes-St. Lawrence and Carolinian forests.

Generally speaking, forests in southern Ontario have relatively higher productivity than forests in northern Ontario. A recent study by Liu et al. (2002) reported that mean NPP ranged from 355 to 477 kg C ha^{-1} per year for the boreal forest region in Ontario, and from 482 to 1200 kg C ha^{-1} per year for the GLSL region. These results are consistent with the regional average NPP estimates made by Band et al. (1999), Band (2000), and Schnekenburger et al. (2001), based on an approach that integrated remote sensing data and use of the RHESSys NPP model across the entire Ontario landscape.

4.2. Quantifying temporal changes in NEP and NBP

Total simulated NEP and NBP (Fig. 4a) were relatively stable between 1925 and 1950, then fluctuated between 1955 and 1975. Fluctuations are mainly caused by changes in C balance via C uptake from atmosphere (NPP), plant and soil respiration, and C emission following ecosystem disturbances (e.g. fire, insect outbreaks, harvesting) (Peng et al., 2000). Obvious declines in simulated NEP and NBP occurred after 1975, mainly due to decreased NPP caused by reduced average forest age that resulted from frequent forest fires between 1985 and 1990 (Perera et al., 1998). Similar temporal patterns of NEP and NBP are found in the boreal region that occupied about 89% of total ecosystem area in Ontario. The difference in trends of NEP and NBP between boreal (Fig. 4b) and Great Lakes-St.

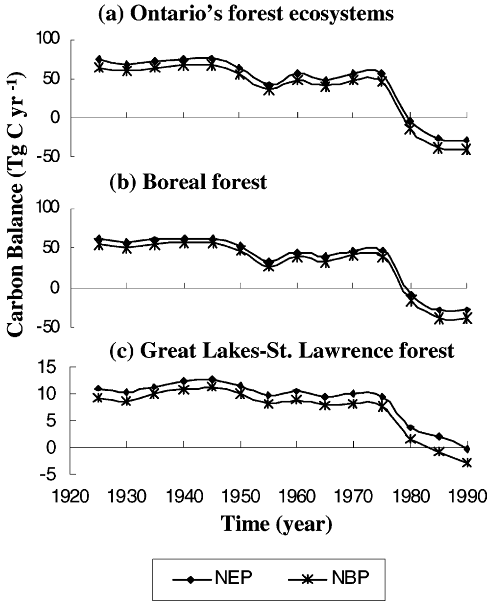

Fig. 4. Carbon balances of Ontario's forest ecosystems between 1925 and 1990. (a) Provincial total; (b) boreal forest; (c) Great Lakes-St. Lawrence forest. NEP: net ecosystem forest; NBP: net biome production.

Lawrence (Fig. 4c) regions are highly related to forest types, age class, and frequency of fire disturbances. In latter region, old hardwood forests (over 80 years) and less frequent forest fires, all of which affect C balances, account for these regional differences.

In addition, the relative young age (about 36 years old) of Ontario's boreal forests as reported by Liu et al. (2002) indicates a great potential for C sequestration and storage. Because decreases in the frequency of stand-replacing disturbances and the subsequent increase in the average age of immature forest stands will increase NEP, NBP, and C sequestration of the forest. The previous results (Liu et al., 2002) indicated that 1 Pg (10^{15} g) more C could be sequestered with a 10-year increase in forest age under a reduced disturbance regime, suggesting that active forest protection and management can enhance C sequestration and storage in Ontario's forest ecosystems.

4.3. Future challenges and research needs

4.3.1. Challenges

Future climate change is likely to have large impacts on Ontario's forest ecosystem productivity and net C balance during the 21st century. The Canadian general circulation model (GCM) predicts that a doubling of atmospheric CO_2 concentration will increase the mean air temperature of the growing season in Ontario by 3–5 °C and change regional precipitation regimes (Boer et al., 1992). The largest temperature increases are expected in northwestern Ontario. Growing season precipitation is projected to decrease by about 10–15% over northwestern and southern Ontario, but to increase by 10–20% in northeastern Ontario. Changes in atmospheric CO_2 concentration, temperature and precipitation regimes will likely affect the structure and function of Ontario's forests through their influences on forest regeneration, growth, mortality, physiological processes (e.g. photosynthesis, respiration) and ecological processes (e.g. the decomposition of soil organic materials) (Fig. 5). Such changes could result in northward shifts in the natural range of forest types and species (Colombo et al., 1998; Parker et al., 2000). Furthermore, changes in temperature and precipitation, coupled with a higher probability of hot, dry periods, are expected to increase the frequency of natural disturbances (e.g. forest fires). Consequently, climate change would affect the dynamics of NPP, NEP, and NBP, changing C sinks–sources dynamics of Ontario's forests.

Forest management practices affect the storage and cycling of C between forests and the atmosphere. For example, harvesting forest stands using practices that minimize forest floor disturbance keeps soil temperatures lower and reduces the respiratory release of soil C. Also, protecting forests from fire, lengthening rotations, and using wood in longer-lived forest products are related actions that increase the amount of stored C. A system of accounting for the amount of C stored in forests and wood products will enable Ontario to report on and relate forest management and land use practices to the net C balance of forested land (Peng et al., 2000; Parker et al., 2000). Factors, including climate change, ecosystem disturbances, and forest management will affect the sustainability of natural ecosystems, leading to an alteration of services that these ecosystems provide to humans (Fig. 5).

There are a number of ways to quantify forest ecosystem productivity (NPP) and net C balance (NEP and NBP). Generally speaking, field measurement and model estimation are two widely used approaches. Field measurements (such as permanent sample plot

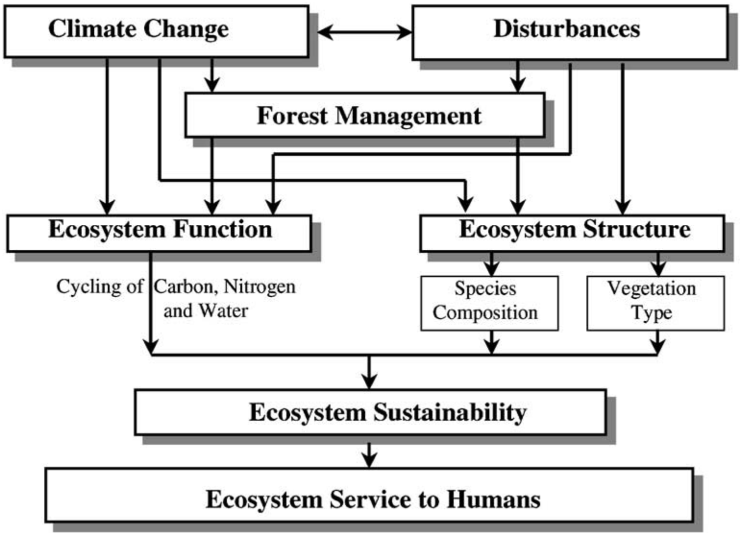

Fig. 5. Potential effects of climate change, ecosystem disturbances, and forest management on forest sustainability in Ontario.

(PSP)) is to measure the net accumulation of stand volume or biomass at intervals of 1–5 years, or over the total period since stand establishment. However, the information derived from PSP data or stand forest inventory record is typically limited to merchantable timber and contains only measurements taken for stems larger that a minimum diameter at breast height. To date, no work has been done to synthesize plots and stand measurements into province-wide spatial patterns of NPP or NEP or NBP in a comprehensive manner (Band, 2000). Only few investigations have been conducted to measure forest biomass for individual tree species and estimated associated C budgets for forest stands (Morrison et al., 1993).

The most common bias of NPP, NEP, and NBP measurements and estimates comes from the assumption of a steady state and the omission of age-related changes in forest NPP and net C balance. Most of the models currently being used to simulate forest NPP and C balance represent the forest ecosystem as “stable” and “mature”, and do not account for the effects of disturbance on species composition, structure and function. Assuming “steady state” may be erroneous, especially for managed and younger forests. There are also a few potential sources of error associated with NPP measurements including: (1) the simple estimates of foliage production from leaf litterfall biomass; (2) exclusion of fine root and mycorrhizae productivity; and (3) quantifying the loss of NPP from herbivory in forests.

The values of our results are limited by:

- Inadequate validation of model output. Since CBM-CFS2 is not a stand-level model, it cannot be tested using site-specific or PSP data. Provincial or national scale data would be ideal for model validation, but the cost of obtaining these data is prohibitive.
- The spatial resolution of CBM-CFS2 was coarse in Ontario, that is only three spatial units are broadly considered.
- Although CBM-CFS2 has a general framework and uses averaged parameters, making it suitable for calculating C balance in Ontario, it includes only limited process-level simulation of the response of forest ecosystems to changes in global environment (Kurz and Apps, 1999). The current formulation of CBM-CFS2 does not explicitly predict the effects of changes in temperature, precipitation, atmospheric CO_2 concentration or N deposition, on the processes of growth and decomposition (Peng et al., 2000). One of the challenges for future work with CBM-CFS2 will be the representation of ecosystem processes by incorporating dynamic forest growth and C dynamic modules in a version modified for Ontario.

4.3.2. Research needs and recommendations

The NPP and net C balance of Ontario's forests are determined by a number of component processes of C acquisition and C loss, and a small shift in the magnitude of theses processes would have a large effect on C budgets. To increase our understanding of the mechanism and processes controlling C fluxes and balances and improve our ability to predict the potential effects of future changes in climate, land use (reforestation, afforestation, deforestation), and ecosystem disturbances (e.g. fire, insect outbreaks, harvesting), some further research is required. Priorities include:

- Developing and testing process-based forest growth and C dynamic models to predict the spatial patterns and dynamics of NPP and net C balance across Ontario's landscape to track historical and future changes in C stocks in relation to climate, reforestation, afforestation, deforestation, forest ecosystem disturbances, and forest products.
- Developing new field measurement techniques (such as eddy covariance—Ontario Flux Station) (Margolis, 2001), improving spatial resolution, and incorporating new local and provincial databases.
- Enhancing Ontario's existing forest growth and yield program by including measurements of NPP, NEP, and NBP for different age classes and forest types.
- Assessing the sensitivity of NPP and C balance to changes in species composition and forest structure following disturbance (e.g. fire, harvesting, insect and disease infestations).

5. Conclusions

Developing criteria and indicators for SFM is an important step towards meeting the forestry commitment made at the United Nations Conference on Environment and Development (UNCED, 1992). The IPCC (IPCC, 2000) and Kyoto Protocol offer a major boost for developing forest C related indicators. Ontario is developing a set of provincial-level criteria and indicators of SFM for meeting both domestic and provincial needs (CCFM, 1997; OMNR, 2001). The criteria and indicators are intended to: (1) clarify what constitutes SFM and provide a framework for describing and assessing process at a provincial level; (2) provide a reference point for developing policies for the conservation, management, and sustainable development of Ontario forests; and (3) improve the forest related information available to the public and decision-makers. As an example of a case study in Ontario, this paper made estimates of three interrelated ecological indicators using the CBM-CFS2 model, forest inventory data, and disturbance records. Results suggest that total NPP of Ontario's forest ecosystems increased from 1925 to 1975 and then decreased between 1975 and 1990; Ontario's forest ecosystems acted as a C sink between 1920 and 1980, and a C source from 1981 to 1990, mainly due to decreased average forest age and NPP caused by increased ecosystem disturbance (e.g. fire, insect and disease infestations, harvesting) since 1975. Current estimates from this analysis suggest that there is significant potential for Ontario's forests to function as C sinks by reducing ecosystem disturbances and increasing growth and storage of C in the young forests throughout the province. This type of critical information will help forest resource managers to make informed decisions about the sustainability of Ontario's forest ecosystems in an increasingly complex and rapidly changing environment in the 21st century.

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