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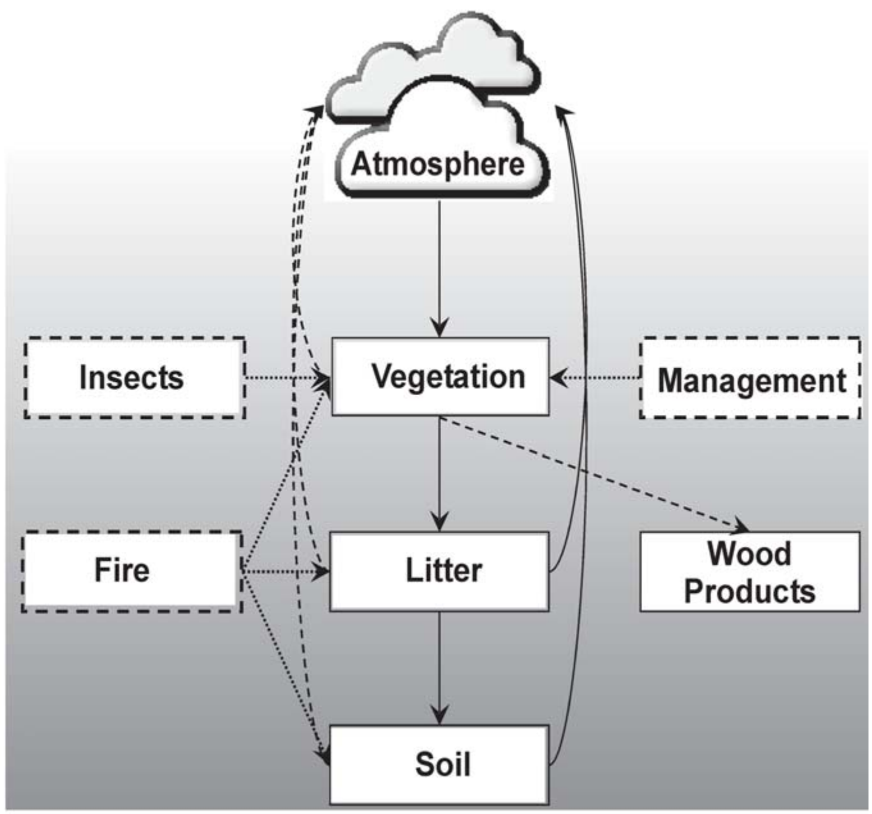
The Ontario Ministry of Natural Resources Large-Scale Forest Carbon Project:

A Summary



Ontario

The Ontario Ministry of Natural Resources Large-Scale Forest Carbon Project:

A Summary

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Abstract

Forest carbon and how it changes over time provides an indicator of the sustainability of forest management. It is also a sign of sequestration or emission of carbon dioxide between forests and the atmosphere that can affect the mitigation of atmospheric greenhouse gas accumulation and global climate change. To address the need for information on Ontario's forest carbon budget, a large-scale forest carbon modelling project was initiated. The background and objectives of this project are described in this report. Three complementary approaches are being used to estimate large-scale forest carbon storage in Ontario's forests: (1) the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), (2) a modified version of FORCARB, which is the model developed by the USDA Forest Service to estimate carbon in U.S. forests, and (3) direct estimation of forest biomass carbon using Ontario's growth and yield and forest resources inventory data (CAM, the Carbon Allometry Method). Application of the modelling approaches used in this project will meet the reporting requirements for forest carbon specified by the Kyoto Protocol and associated accords. Further, the results of this project will contribute to Ontario's reporting on Forest Sustainability Indicator 4.1 (Ontario's forest sector contributions to global carbon enrichment).

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Introduction

The influence of increasing atmospheric greenhouse gas concentrations on global climate is one of the most widely recognized environmental concerns of the 21st Century, with serious ecological and economic consequences (Crowley 2000, IPCC 2001, Marland *et al.* 2003). Climate change resulting from the anthropogenic increase of atmospheric greenhouse gases, including carbon dioxide (CO_2), may significantly affect Ontario's forests (Colombo *et al.* 1998, Schindler 1998). Sixty-six per cent of Ontario, or about 70 million hectares, is forested. Ontario contains 17% of Canada's forested land (OMNR 2002) and the area of Ontario's forests equals the combined land area of Germany, Italy, Switzerland and the Netherlands[1]. Changes to Ontario's large forested area brought about by forest management and natural disturbance have the potential to either sequester or release large amounts of CO_2 to the atmosphere. This carbon exchange can alter atmospheric greenhouse gas accumulation and in turn affect global climate change. This project uses computer models to assess the magnitude of forest carbon storage in Ontario and changes to it over time.

Previous estimates of Ontario's provincial forest carbon budget were based on national-scale databases (Liu *et al.* 2002, Peng *et al.* 2000, 2002). The spatial resolution of those estimates was low because the province was divided into only three large spatial units. This project will build upon previous work by producing higher resolution estimates of the amount of carbon in Ontario's forests using data from provincial forest management units. New estimates will also conform to projected future forest condition (i.e., age, species composition, and area) based on Ontario's forest management plans. Since the net balance of carbon exchanged between Ontario's forests and the atmosphere is an indicator of sustainability (OMNR 2002), forest carbon budget estimates should be based on provincial databases and reflect planned forest management activities in Ontario.

Canada ratified the Kyoto Protocol in December 2002 but has until 2006 to decide if changes in carbon in its forests due to forest management will be part of this accounting (Article 3.4 of the Kyoto Protocol). Intensive forest management can increase carbon storage (Heath 2000, Parker *et al.* 2000, Timmer and Teng 2003) and increasing carbon sinks can be used to offset emissions of atmospheric CO_2 from burning fossil fuels. Therefore, a system has been developed to monitor and predict carbon stocks in Ontario's forests to improve data and information available to those responsible for provincial forest management policy, forest management unit supervisors in government and the forest industry, and the public. Here we report on Ontario's approach to large-scale forest carbon modelling.

Approaches

This project will generate forest carbon budgets at the forest management unit level based on approved provincial Forest Management Plans (FMPs) using Forest Resources Inventory (FRI)[2] data (Fig. 1). Using stand-level inventory records and information from forest management plans ensures congruity between carbon budget estimates and planned forestry activities, especially harvesting.

Three approaches are being used to estimate Ontario's forest carbon budget: (1) application of the Canadian Forest Service's Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), (2) use of the model FORCARB, developed by the United States Forest Service, and (3) direct estimates of forest

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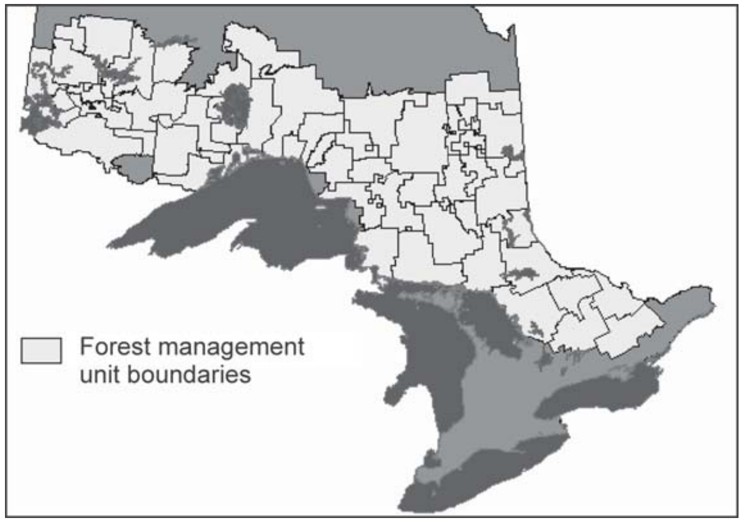
[1] Source: http://ontariosforests.mnr.gov.on.ca/spectrasites/internet/ontarioforests/forestoverview.cfm; accessed June 7, 2004

[2] Ontario's forest resources inventory is the compiled data from the province's managed forests. This inventory describes the area, species composition, and dominant tree species height, age, site class, and stocking of all managed crown forest (OMNR 1996).

Figure 1.

Administrative boundaries of Ontario's 50 forest management units (as of 2003) that comprise the Area of the Undertaking, in which Crown Forests are managed under the *Crown Forest Sustainability Act*.



biomass carbon at the time of the last inventory update using data from the FRI and the provincial Growth and Yield Program's permanent sample plots. With FRI data, carbon pools representing various live-tree components are predicted using allometric equations. Thus, we refer to this approach as the Carbon Allometry Method, or CAM.

Using three complementary approaches helps to validate the results. Discrepancies among estimates may indicate problems, such as inadequate model structure, gaps in model assumptions, or biased estimates of model parameters that will need to be corrected. Conversely, consistency among estimates provides some assurance of their relative accuracy.

Methods

The Large-Scale Forest Carbon Budget Project uses large amounts of data. Specifics about source data and modelling approaches being used are provided below.

The basis for large-scale carbon budget modelling in Ontario and source data for carbon budget estimates

The FORCARB and CBM-CFS models predict carbon in forest biomass, litter, and soil (Fig. 2). The biomass pool consists of the above- and belowground parts of living vegetation. In CBM-CFS, the only vegetation counted is trees, whereas FORCARB estimates carbon contained in trees and understory vegetation. As vegetation grows, it accumulates carbon by sequestering it from the atmosphere, thus acting as a carbon sink. Mortality of trees, branches, foliage, and roots moves carbon from the biomass to the litter pool (also known as dead organic matter). As litter decomposes, carbon is released to the atmosphere as CO_2 or is transferred to the soil carbon pool. Carbon in the soil is also released to the atmosphere through decomposition, but much more slowly than from litter.

Disturbance affects the amount of carbon in biomass, litter, and soil. Typically, carbon budget models consider the effects on carbon cycling caused by disturbances such as harvesting, fire, and insects. Harvesting removes carbon in merchantable stems from the forest and adds carbon from logging debris to the litter pool. Carbon removed from forest biomass by harvesting is released directly to the

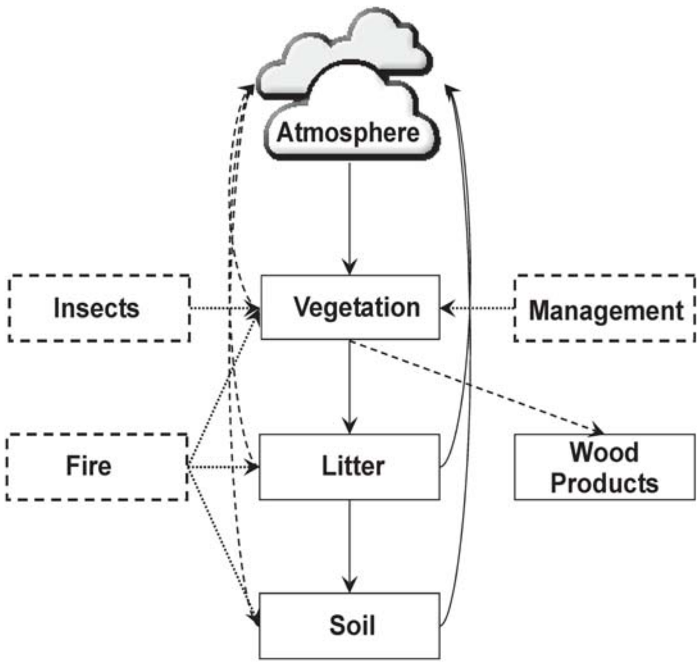


Figure 2.

Carbon fluxes and pools simulated by typical forest carbon budget models. Solid rectangles represent carbon pools. Dashed rectangles represent disturbances and management actions, with dotted arrows from them pointing to the most directly affected carbon pools. Solid and dashed arrows between carbon pools correspond to natural or management-induced fluxes of carbon, respectively.

atmosphere (e.g., fuelwood) or stored in forest products (e.g., lumber). Post-harvest practices such as slash burning and prescribed fire for site preparation accelerate litter decomposition and soil carbon release. Forest fires affect carbon by (a) releasing carbon directly to the atmosphere from the combustion of vegetation, litter, and soil organic matter and (b) increasing the litter pool through tree mortality. Insect infestation affects carbon storage by (a) converting tree biomass to insect biomass, some of which is then released to the atmosphere by insect respiration and faeces decomposition, (b) reducing tree growth and, in severe cases, (c) causing mortality.

Projected harvest rates and fire regime data required for carbon budget estimates are being derived from Ontario's forest management plans. In Ontario, forest management is conducted in a region referred to as the Area of Undertaking, which exists as a province-wide band of forest with northern and southern extremities of approximately 51° and 45° N, respectively. The Area of Undertaking is divided into forest management units (Fig.1) covering from approximately 130,000 to 1.6 million hectares and varying from hardwood-dominated stands in the Great Lakes–St. Lawrence forest region to conifer-dominated boreal forest. Forest management plans for each forest management unit are prepared for five-year periods. These five-year plans are prepared using forest management scenarios (i.e., different levels of silvicultural activity and natural disturbance) developed with the Ontario Ministry of Natural Resources' (OMNR) Strategic Forest Management Model (SFMM).

Data provided by timber supply analyses (completed with SFMM) used in the forest management plans are the primary information sources for carbon estimates in the CBM-CFS and FORCARB models. Therefore, planned forest management activities will be reflected in the carbon budget estimates. The integration of SFMM information into these models requires the development of specialized data management and import programs. The functionality and data requirements for each of the three carbon budget model approaches are described in the following sections.

Carbon budget modelling using CBM-CFS

The most widely applied forest carbon model in Canada has been the family of models known as CBM-CFS, which have been used to predict carbon budgets at national (Kurz and Apps 1999), provincial (Kurz *et al.* 2002), and forest management unit (Price *et al.* 1997) scales. This model simulates carbon in six biomass pools (i.e., merchantable stemwood, branches and tops, submerchantable trees, coarse roots, foliage, and fine roots), and four dead organic matter pools (i.e., slow, medium, fast, and very fast cycling rates) (Kurz and Apps 1999). The slow cycling dead organic matter pool is humified carbon in mineral soil. Medium and fast cycling dead organic matter is woody material from four of the biomass pools: merchantable stemwood, branches and tops, submerchantable trees, and coarse roots. Very fast cycling dead organic matter is the fine roots and foliage shed annually by trees. Biomass carbon accumulation is simulated in CBM-CFS using merchantable volume growth curves; merchantable volume is converted into carbon contained in the six biomass pools. The transfer of carbon from living biomass to dead organic matter is simulated in three processes: litterfall, age-related mortality of individual trees associated with stand breakup, and disturbance. In the model, carbon moves among dead organic matter pools and into the atmosphere by decomposition at rates determined by mean annual air temperature.

The CBM-CFS model recognizes seven disturbances: forest fire, insect-induced stand mortality, clearcut logging, clearcut logging with slash burning, salvage logging following fire, salvage logging following insect-induced stand mortality, and partial cutting. The rate at which carbon moves between pools depends on the type of disturbance. For example, fire causes carbon to be lost from the forest by combustion whereas harvesting removes carbon in merchantable biomass.

The Canadian forest carbon budget for 1950-1990 has been estimated using CBM-CFS (Fig. 3a) (Kurz and Apps 1999). Carbon contained in trees (above- and belowground tree biomass carbon) increased during 1950-1970, likely because of relatively low disturbance rates during the period 1920-1969 (Kurz and Apps 1999). Increased disturbance after 1970 increased carbon fluxes from trees to the forest floor, dead wood, and soil organic matter pools (Fig. 3a). Despite a decrease in carbon storage after 1970, the net increase in total carbon stocks between 1950 and 1990 indicates that during this 40-year interval Canada's forests were a carbon sink.

The results in Figure 3a are based on coarse-scale forest inventory data and information. The use of SFMM data will significantly improve the sensitivity of the model in determining Ontario's forest carbon budget. The information from SFMM needed by CBM-CFS can be divided into three categories: forest inventory, forest dynamics, and land classification. Stand-level FRI is the main source of data for SFMM. Forest stands are aggregated into groups known as *forest units* [3] to organize the FRI data. Yield curves are assigned to forest units based on the average species composition, stocking, and site class. Finally, the area for the age-class structure (hectares per 10-year age class) of each forest unit is derived.

Information describing changes in forest species over time are part of the SFMM timber supply simulation. Changes in species composition are determined by *transition rules* that describe what a forest unit becomes following natural disturbance, harvesting, or undisturbed forest succession. These transition rules are adopted from SFMM and used in CBM-CFS, so that the appropriate forest unit and yield curve can be assigned after a transition caused by a stand-replacing disturbance or natural forest

[3] A "forest unit" consists of forest stands similar in species composition, stocking, and site class (OMNR 1996).

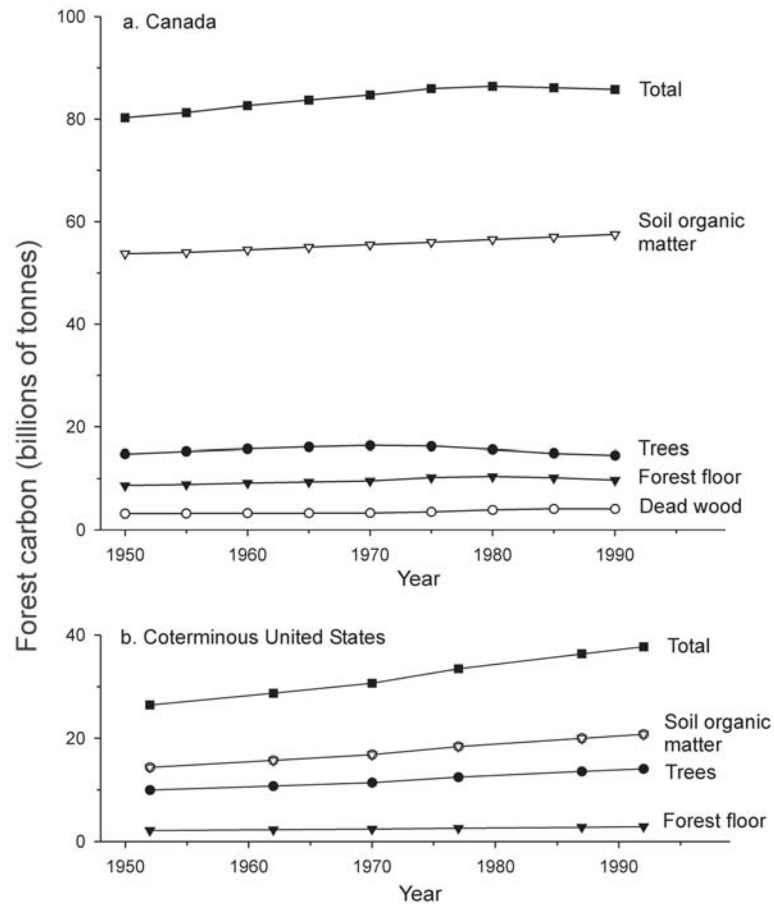


Figure 3.

(a) Forest carbon in Canada during 1950-1990 estimated by CBM-CFS. Total carbon stocks are divided into live trees and dead organic matter carbon contained in dead wood, forest floor, and soil organic matter (data adapted from Kurz and Apps 1999). (b) Forest carbon in the coterminous United States during 1952-1992 estimated by FORCARB. Total carbon stocks are divided into live trees and dead organic matter carbon contained in forest floor, and soil organic matter (data adapted from Birdsey and Heath 1995).

succession. Analysis of the assumptions, transition rules, and parameter values used in CBM-CFS will ensure consistency with the future forest as predicted in Ontario's forest management plans.

Carbon budget modelling using FORCARB

FORCARB is a forest carbon accounting model developed by the U.S. Forest Service to estimate carbon budgets on U.S. timberlands (Birdsey *et al.* 1993, Heath 2000). It has been used to generate regional and national-scale estimates of carbon storage in U.S. forests (Birdsey and Heath 1995). FORCARB was also used to produce the 2001 U.S. submission to the United Nations Framework Convention on Climate Change on Land Use, Land Use Change, and Forestry (U.S. State Department 2000).

FORCARB estimates forest carbon in four pools: trees (including all above- and belowground portions of all live and dead trees), understory vegetation (all live vegetation not defined as trees), forest floor (dead organic matter above the mineral soil horizons, including litter, humus, and other woody debris), and soil (all organic carbon in mineral horizons to a depth of one metre, excluding coarse tree roots) (Plantinga and Birdsey 1993). Carbon content in each pool is estimated based on tree volume and forest area data contained in a timber supply model (Smith and Heath 2001). FORCARB previously simulated only the effect of harvesting on forest carbon (Heath and Smith 2000, Heath *et al.* 2002). A new module that accounts for changes in carbon pools caused by wildfires has been developed at OMNR's Ontario Forest Research Institute (OFRI) and integrated into FORCARB.

The U.S. forest carbon budget (1952-1992) generated by Birdsey and Heath (1995) using FORCARB is shown in Fig. 3b. Increased carbon storage between 1952 and 1992 indicated that U.S. forested land was a carbon sink during that period (Fig 3b). The increase can be attributed to land-use changes in the eastern U.S., where large areas of agricultural land reverted to forests over the last century (Birdsey and Heath 1995). Forest carbon accumulation in eastern U.S. in forests established on former agricultural lands offsets a forest carbon stock decline in western U.S. forests (Birdsey and Heath 1995).

FORCARB uses merchantable timber volume to predict carbon in trees, understory vegetation, forest floor, and soil. Inputs required by FORCARB include merchantable timber volume projections provided by the SFMM timber supply model. Proximity to northern U.S. forests enables model parameters for carbon content of trees and other pools (i.e., other vegetation, forest floor, and soil) in the U.S. to be applied to Ontario forests. However, we will evaluate the suitability of these parameters for forests in Ontario that are not adjacent to the U.S.

Carbon budget modelling using CAM

The Carbon Allometry Method (CAM) estimates carbon in the biomass component of forests using data from the FRI and Ontario's Growth and Yield Program's permanent sample plots (PSPs). Specifically, estimates of biomass carbon are derived from stand structural features (e.g., dominant tree age, height, and stocking) contained in the FRI database for stands in which the PSPs are located. Biomass carbon densities (tonnes per hectare) for each stand type (types based on species composition and age) are applied to the FRI data for each forest management unit. The model outputs estimate biomass carbon content for each forest management unit at the time of last FRI update.

Conversion of PSP data to carbon uses allometric equations that relate oven-dried biomass of an entire tree and its components (i.e., stemwood, stem bark, branches, and foliage) to the tree's diameter. Numerous allometric equations are available for all major tree species in Ontario (Ter-Mikaelian and Korzukhin 1997). Total aboveground biomass of each tree summed over the entire PSP provides an estimate of total aboveground oven-dried biomass for the PSP. A carbon content of 50% is assumed when converting dry biomass to mass of carbon (Smith *et al.* 2002).

The CAM approach provides a means of validating CBM-CFS and FORCARB biomass carbon estimates. In the short-term, we will provide carbon estimates based on CAM for each forest management unit that can be used as a single point-in-time validation of trajectories simulated by the CBM-CFS and FORCARB, and/or as input values to initialize the models. In the longer-term, we intend to develop equations predicting carbon content of various pools per unit area from FRI data that can be used to develop a model that combines the capabilities of a timber supply model with an instantaneous conversion of its predictions into carbon pool estimates (similar to the approach used in FORCARB).

The two sources of data used to produce CAM estimates are derived from the provincial Growth and Yield Program's network of approximately 1100 PSPs (Hayden *et al.* 1995) and the provincial FRI. Each PSP contains nested circular plots that provide data such as mortality (species and diameter at breast height of all standing dead trees), live trees (species and diameter of all live trees with diameter ≥2.5 cm), and downed woody debris (diameter of all downed trees at the point of intersection with one of the three transects run through the PSP) (Fig. 4). These data are used to generate carbon estimates per unit area for various biomass pools within each PSP.

Another source of data for CAM is the FRI. Species composition, stocking, height, age, and site class of dominant species from FRI are related to carbon estimates derived from Growth and Yield PSPs. For a given species and site class[4], we can relate biomass to age. Using allometric equations, biomass is converted to total tree (above- and belowground) carbon. These conversion equations are then applied to FRI data to estimate total biomass carbon in the forest management unit.

Progress to Date

CBM-CFS progress

A computer program to extract data from SFMM is under development at the Canadian Forest Service in consultation with OFRI. Considerable testing of the data extraction program's assumptions is underway at OFRI and the Canadian Forest Service. Once testing is complete, Ontario forest management data will be used in CBM-CFS to produce current and future carbon budget estimates for each forest management unit, OMNR administrative region (Northwest, Northeast, and Southern), and for the entire Area of Undertaking.

Preliminary model runs have generated 140-year projections of total forest ecosystem carbon for 22 of 50 provincial forest management units. Project staff are using the preliminary runs to identify and correct errors in the structure of CBM-CFS input files generated by the SFMM data extraction software. Updates to the CBM-CFS model continue to be released. The Canadian Forest Service intends to release a fully functional version of CBM-CFS in the near future. Following its release, our intent is to prepare carbon budget estimates for all provincial forest management units using this model.

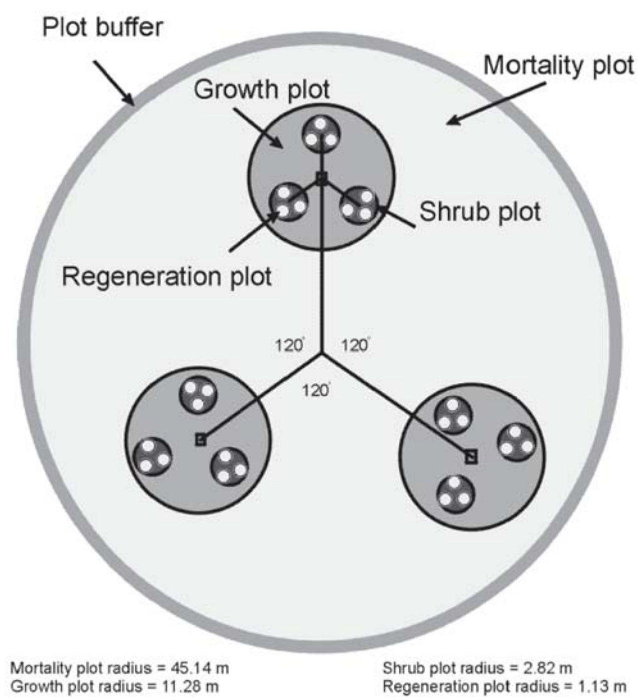


Figure 4.
Diagram of Ontario Forest Growth and Yield Program permanent sample plot design (from Hayden *et al.* 1995).

[4] A site class is any interval into which the site index range is divided for purposes of classification and use. Site index is an expression of the biomass productivity of a forest site based on the height reached at a specified age, of dominant and codominant trees (Kloss 2002).

FORCARB progress

An interface has been developed to reformat the thousands of records contained in each SFMM timber supply analysis into a FORCARB input file. Preliminary trials were successfully completed using the Dog River-Matawin Forest Management Unit and the data input program has been tested with data from the entire set of Northwestern Region forest management units.

The Large-Scale Forest Carbon Modelling Group in OMNR has added a module to FORCARB to simulate the effect of wildfire on forest carbon. Accurate fire cycle estimates for timber supply analyses are important to ensure sustainable forest management (Bridge 2001). Each year, fire removes harvestable forest area, which is simulated in SFMM. The areas of natural disturbance and post-disturbance regeneration data are extracted from SFMM and used in FORCARB. Parameters defining the fluxes of carbon among pools following fire have been developed and are being verified based on studies of post-fire forest carbon dynamics (e.g., Little *et al.* 2002).

CAM progress

Compilation of growth and yield and FRI data resulted in a data set of 795 PSPs for which data are complete. The remaining 300 PSPs were missing either some of the growth and yield or FRI data because PSPs were established outside the Area of Undertaking (no FRI available), PSPs were established in stands classified by FRI as non-productive (and therefore no FRI was conducted), or both increment core data and stand establishment year for PSPs were unavailable (making it impossible to estimate stand age). Of the 795 qualifying PSPs, numbers of plots by dominant tree species are: jack pine (194), black spruce (151), trembling aspen (131), sugar maple (103), eastern white pine (71), red pine (42), white birch (29), and red oak (27). Other dominant species include American beech, balsam fir, balsam poplar, black ash, eastern hemlock, largetooth aspen, and yellow birch, but these were each represented by less than 10 PSPs.

Mean total aboveground tree biomass per unit area was calculated for each PSP using equations from Ter-Mikaelian and Korzukhin (1997). Preliminary analyses of PSP data by dominant species demonstrated that age and height were the best predictors of total aboveground tree biomass. It also revealed a frequent and often substantial discrepancy between PSP-based and FRI-based estimates of dominant species' age and height that may be attributed to (a) the PSP not being representative of average stand condition, and/or (b) a difference in methods and accuracy level between growth and yield and FRI estimates. Therefore, broad-scale application of equations developed using the combined PSP-FRI datasets to FRI data poses a risk of producing estimates that are either systematically biased or are associated with much wider confidence bands than those based on growth and yield data alone. Procedures to reconcile the differences between PSP-based and FRI-based estimates are being developed.

Conclusions

Efforts to offset greenhouse gas emissions will potentially include forest management practices aimed at increasing forest carbon sinks (Parker *et al.* 2000, Peng *et al.* 2002, Marland *et al.* 2003). A forest carbon budget offers a quantitative assessment of the exchange of carbon between forests and the atmosphere and can provide a measure of the effectiveness of human activities to increase the forest sink.

The three complementary approaches described in this report form the basis for forest carbon budget monitoring in Ontario. Previous studies observed trends in forest carbon storage based on data from national databases (Peng *et al.* 2000, 2002, Liu *et al.* 2002). A significant advance will be provided in Ontario's large-scale forest carbon project by using forest management unit data available from provincial sources, including stand-level FRI, growth and yield plots, and information such as forest succession and rates of fire disturbance obtained from approved forest management plans. Future large-scale carbon modelling will incorporate scenarios with varying management practices to predict their impact on carbon storage. The application of these results can be used to develop long-term planning and management strategies.

Forest management will undoubtedly require adaptations to account for alterations in species and behaviour of forest ecosystems accompanying climate change (Parker *et al.* 2000). These alterations will also be simulated in models that predict how climate change affects natural disturbance, forest growth, and litter decomposition to conduct large-scale forest carbon modelling based on predicted future forest condition.

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