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USE OF A FOREST ECOSYSTEM-LEVEL-MODEL TO INVESTIGATE RESPONSES OF BOREAL LANDSCAPE PRODUCTIVITY TO CLIMATE

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ABSTRACT

Anticipated changes in global climate due to increasing concentrations of atmospheric greenhouse gases may have significant socio-economic impacts on Canadian forest resources, and on their evident function as terrestrial carbon sinks of global significance. Assessments of these possible impacts will be best achieved through use of national-scale integrating models of the Canadian forest land base. Important climate-sensitive processes occur at both large scales (ecosystem disturbances) and fine scales (growth, respiration and decomposition); it is essential to consider both levels of organization if an integrating model is to assess consequences of climate change correctly. This paper outlines the ongoing development of an integrating carbon budget model of the Canadian forest sector, which will accept metadata generated by process models of higher resolution (spatial and temporal). An approach to sampling the landscape using a modified forest ecosystem model is presented as a means of scaling the output from small scale models up to the large scale.

INTRODUCTION

The recently developed Phase 1 Carbon Budget Model of the Canadian Forest Sector (CBM-CFS1) (Apps and Kurz 1991; Apps et al. 1991; Kurz et al. 1991, 1992), produced a Canada-wide assessment of the forest sector carbon (C) budget for a single reference year, 1986. After dividing the country into 42 spatial units based on ecological classification (Ecoregions Working Group 1989) and provincial administrative boundaries, the yearly C budget was derived from compilations of available data on the distribution and dynamics of biomass and soil carbon, disturbance statistics, and the fate of forest products. This analysis revealed that although the Canadian forest sector as a whole was a small net-sink for atmospheric carbon, it could be very sensitive to changes in climate-related events, such as an increase in forest fires (Kurz et al. 1992).

A newer version of the model, CBM-CFS2, is now being used to investigate the longer-term sensitivity of the national forest C budget to changes in growth rates, disturbance regimes and other ecosystem processes, such as those which may result from changes in management and/or climate (Kurz and Apps 1992). In CBM-CFS2, large-scale responses to environmental conditions are proscribed rather than simulated, to allow possible consequences for the C budget to be investigated; no attempt is made to simulate the detailed effects of changes in climate and management on ecosystem structure and function. It is now widely recognized however, that the key processes influencing vegetation productivity and distribution are generally nonlinear and of ten highly sensitive to changes in small-scale conditions. Furthermore, many researchers have suggested that vegetation zones of the northern hemisphere will migrate northward in response to climate warming (Zoltai 1988; Rizzo and Wiken 1989; Zoltai et al. 1991; Prentice et al. 1992a), affecting both the area and net productivity of each ecoclimatic region, and hence the large-scale C budget. CBM-CFS2 does not presently consider changes in the distribution of recognized biomes (Kurz and Apps 1992). In this paper, an approach is described for including forest ecosystem-level response models within the prognostic CBM-CFS framework.

OBJECTIVES

Resource managers and policy makers are increasingly expected to consider the potential impacts of climate, management and other factors influencing the productivity of Canada's forests. This almost certainly requires predictive models based on valid simulations of the processes affecting the carbon dynamics of forests and other ecosystems. The ongoing work briefly described here is aimed at parameterizing response surfaces generated by ecosystem process sub-models for use as input data (metadata) for the CBM-CFS. This approach should allow the development of a means of scaling mechanistic representations of key ecological and ecophysiological processes operating at the stand level, including primary production, disturbances, succession, soil carbon dynamics, and atmospheric exchanges, to the spatially and temporally aggregated information required for national forest sector C budget analysis. The objective is to facilitate scenario analyses (Apps and MacIsaac 1990) of the possible responses of Canada's forest C budget to anticipated environmental and managerial changes.

RATIONALE

The world's most extensive forest biome is the boreal forest.In Canada, boreal forest covers approximately 43% of forested land area, and is estimated to harbour 40% of the total inventory of biospheric carbon.Subarctic ecosystems cover about another 20% of Canada's forested area, and although data are scarce, these appear to contain about 35% of total carbon (Apps et al. 1992).In recent years, international attention has been increasingly focused on the northern circumpolar forested regions as possible terrestrial carbon sinks of global importance (e.g. Tans et al. 1990; Apps et al. 1993).

Major research projects have since been initiated to increase understanding of the processes occurring within these ecosystems, including the BOReal Ecosystem Atmosphere Study, BOREAS (BOREAS Science Steering Committee 1990) and the Northern BIosphere Observation and Modelling Experiment (NBIOME, Apps 1993).

As a contribution to both projects, Forestry Canada has initiated a boreal forest transect case study (BFTCS), which will extend the two sites to be studied under BOREAS to include the northern and southern limits of the Canadian boreal forest.The transect covers a distance of approximately 1000 km along a northeast-southwest climatic gradient, (from Batoche in Saskatchewan to Gillam in Manitoba) and will form the basis of an extensive, integrated study of boreal forest processes.Using the BFTCS as a source of data for development and testing, the CBM-CFS framework will be used to incorporate and constrain a suite of smaller scale sub-models which can be tested against the field measurements from which past and present C budget assessments are derived. Once satisfactory agreement has been achieved, the integrated model structure will be used to explore future responses of regional and national forest resources to anticipated changes in climate.

MODELLING APPROACH

Such a challenging task will necessarily involve a strong dependence on the scientific validity of the scaling approach adopted.Two major levels of scaling will be built into the nested suite of models.Simulations of fine-scale processes such as net photosynthesis, evapotranspiration and soil decomposition, will be used to develop species-level response surfaces, which will then be used as metadata for the driving functions of various appropriate ecosystem-level competition models.In turn, the output from these larger scale models will be used as metadata to drive the large-scale C budget model. Changes in vegetation distribution in response to changes in the environment may also be predictable using this approach. The overall concept is illustrated as a flow-chart in Figure 1. Two metamodels are required, operating at two levels of aggregation. Metamodel I will collate small-scale processes at the stand/forest scale, while MII will operate at the regional/biome scale, generating input data for the CBM-CFS.

Assuming good information about the carbon storage and transfer processes within an identifiable "homogeneous" area can be obtained, reasonably accurate estimates of the C budget for each such area should be possible. It then becomes a relatively simple matter to sum the estimates for the entire region of interest, but only so long as there are no significant interactions among these homogeneous areas, (e.g. disturbances and seed dispersal). Vegetation biomass and growth rates, for which information can be obtained from forest sample plots, are important components in deriving an areal C budget. Ecophysiological relationships can also be determined between the climatic variables recorded at a range of different sites, and individual species'

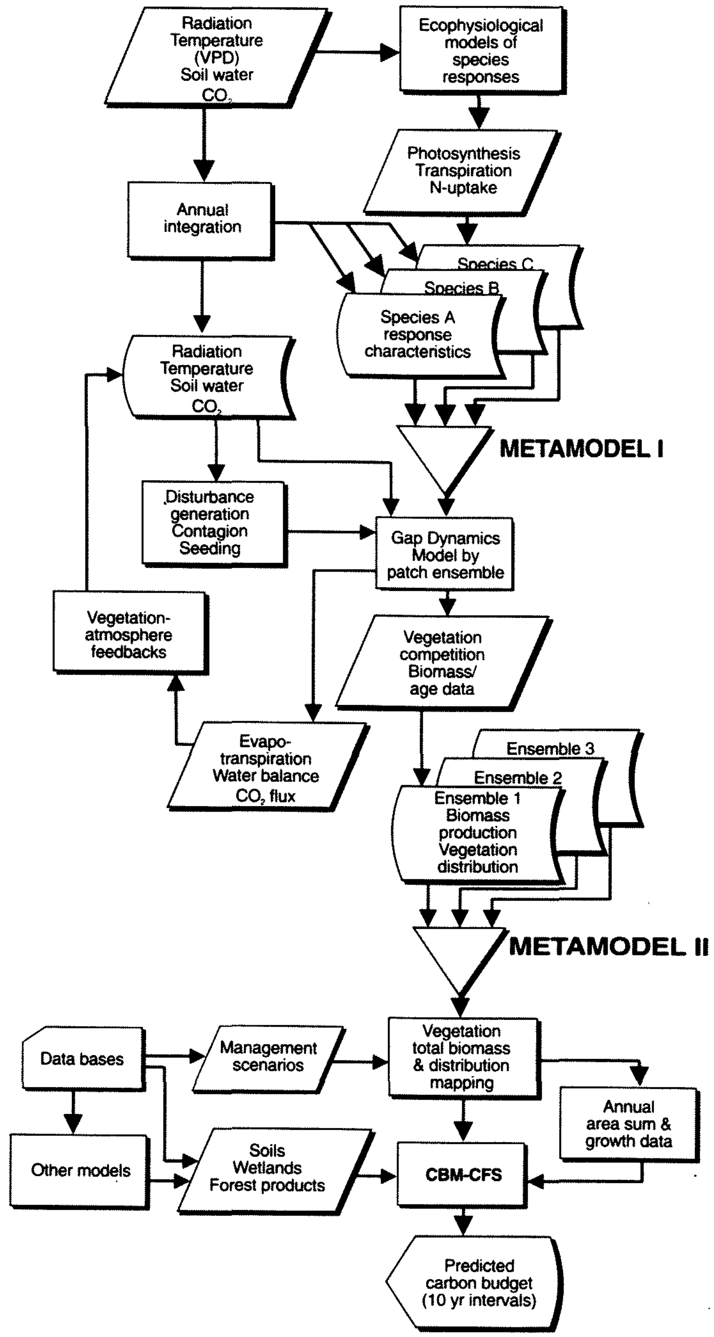

Figure 1. Conceptual flow-chart showing proposed modeling approach for a prognostic carbon budget model of the Canadian forest sector. The top section (above the triangle representing Metamodel I), deals with species-level ecophysiological functions. These converge into a data base of metadata for input into the middle section, (between the two triangles), which deals with stand level functions and effects on ecosystem structure (distribution and composition of stand types simulated by a gap model).

The term "ensemble" is explained in the text. Note that climatic forcing is considered an important factor affecting disturbances, while vegetation feedbacks, (exchanges of CO_2 and water vapor) are also represented. The bottom section, below the triangle representing Metamodel II, integrates ecosystem process simulations, and other sources of data used by the CBM-CFS, to estimate the large-scale carbon budget.

responses (i.e. rates of photosynthesis, respiration, transpiration and nutrient uptake) measured at those sites. BOREAS will provide this kind of information, for a few intensively studied sites, while BFTCS should extend the applicability of the derived relationships to a much larger range of conditions. The objective is to develop functional relationships based on data collected at high temporal and spatial resolution (the response surfaces), for appliction in a much larger scale model, operating over much longer time steps. For example, the relationship of net photosynthesis rate to environmental variation observed over periods of the order of minutes to days, will be used to estimate annual trajectories of net biomass accumulation, based on monthly or even annual climate records. This is an undeniably difficult task, and in the short term it will probably be necessary to make many simplifying (and possibly incorrect) assumptions. This collection of species-specific ecophysiological response functions, based on real data obtained from BFTCS studies, BOREAS or the literature where possible, will form the basis of Metamodel I, which will be used to parameterize the driving functions for the ecosystem-level simulations.

Currently, forest gap phase dynamics (or "gap") models are being explored as the means of simulating boreal ecosystem dynamics, mainly because they are commonly reported in the literature and as a class, evidently work well, though with recognised limitations. The original gap models were developed for temperate and tropical forests where a successional cycle normally occurs within the climax community (Botkin et al. 1972; Shugart 1984; Solomon 1986). Boreal forest succession is not generally considered to be the result of a gap phase replacement process; rather it is normally controlled by periodic disturbances such as fires. Furthermore, regeneration of shade-intolerant pioneer species is disturbance frequency-dependent, leading to some suggestions that boreal climax species such as jack pine and black spruce may even be adapted to encourage disturbance by fire (see Heinselman 1981).

Nevertheless, some researchers have exploited the gap model's representation of spatially aggregated dynamics and introduced other assumptions which allowreasonable success in simulating observed boreal forest structural and functional development (e.g. Bonan 1989, 1991, 1992; Prentice and Leemans 1990; Prentice et al. 1992b).

In most gap models, the forest is assumed to exist under spatially uniform conditions of site productivity and climate, and is represented by a large number of small sample areas, termed "plots", or "patches", which are traditionally considered independent of all other like patches in the forest. Each patch supports randomized stand development and succession, through simulated regeneration, growth, competition and mortality of individual trees, though the ecophysiological processes for each tree are generally based on statistically-derived growth equations, which cannot be reliably extended outside the domain for which they were tested (Bossel 1991; King et al. 1990). Entire stands may also be destroyed at suitably randomized intervals through disturbance, so that the entire successional development can be reinitialized. In spite of the assumptions of spatial homogeneity, and simplistic growth representations, gap models are often able to simulate successfully the observed spatial distribution of forest structure (age, tree size and species composition). Part of the reason for this success must be that the randomized variability in growth and regeneration processes applied to individual trees and plots compensates for the lack of simulated variability in sites and climate. An obvious further explanation is that many gap model simulations have been calibrated in the area from which field data were obtained (i.e. they have a strong empirical basis).

In the present work, a novel enhancement is being investigated to overcome some of these apparent limitations. It is proposed that the variation among site types observed in reality can be represented as a distribution of distinct site types. In the model, this distribution would be represented as an "ensemble" of 10 to 20 or more patches, with differing site characteristics (soils and topography) stochastically distributed in proportion to those observed in reality (Figure 2). Further, the patches within each ensemble are considered to be in intimate spatial contact - hence resembling a sample of the heterogeneous forest mosaic. Forest growth on each patch is still simulated separately, but stand development is no longer considered completely independent of other patches, because some factors are allowed to affect the entire ensemble. These factors include climate, disturbance events and seed dispersal. In particular, a disturbance event occurring in any one of the patches within the ensemble has the possibility of spreading to all the others, through some form of contagion

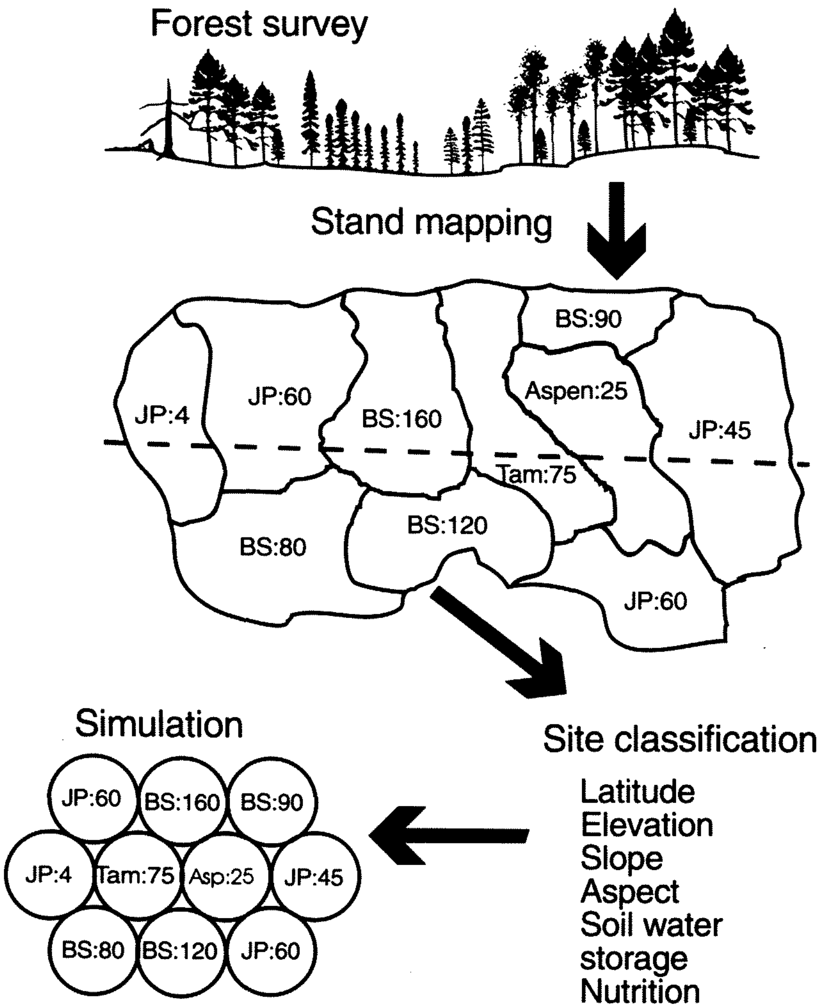

Figure 2. Diagram showing proposed representation of forest heterogeneity by a plot ensemble. Given a surveyed and mapped area of a typical piece of boreal forest mosaic, the range of structures illustrated in the section at top, is attributable to the effects of growth, competition and disturbances, and to the site characteristics of each patch (soil type and topography). In the model, the 10 patches are simulated as spatially connected sample plots (of equal area), with each plot awarded site attributes derived from the observed distribution of site variables.

(such as wildfire, or insect flight). This contagion process must be considered separately from the disturbance hazard (stand susceptibility to disturbance effects) which must be assessed on the basis of successional age, species composition, litter accumulation and environmental factors.

Each ensemble can be considered as a sample of a much larger area, which will be referred to as "a landscape" to signify that it may contain a considerable amount of visible variation (hills, lowlands, wetlands, lakes etc.). Somewhat arbitrarily, each landscape will represented by a 10 km square, which can be located on a map, and hence subjected to topographic and climatic conditions typical of that area. Initially, it will be assumed that all the topographic and soil variation contributing to the range of site types found within each square can be adequately represented by a single patch ensemble.

The forest ecosystem model is required to simulate biomass over age relationships for different site types, generating data in a manner analogous to a real forest biomass inventory. In the same way that real forest inventories are carried out at discrete intervals in time, the model is used to generate a "snap-shot" of the structural composition of the simulated forest stands, for example at 10-year intervals. These simulated stand data can be used to derive the growth functions used by the CBM-CFS (i.e. Metamodel II), in exact analogy to the use of the Canadian forest biomass inventory data base (Bonnor 1985), as reported in Kurz et al. (1992).

Under past climate conditions, the output from the model can be compared to records of forest inventory (where these are available), to provide validation of the approach, with the proviso that human influences may need to be considered. Once it has been established that the model does work satisfactorily for the observational record, it will be used to explore future responses, probably using climatic projections derived from GCM predictions of future climate. Hence, it should be possible to estimate future carbon budgets for the region of the BFTCS, and by extending this work, to the boreal forest as a whole, and eventually to other Canadian forest biomes. If the model can successfully simulate the currently observed forest structure on the one hand, while producing credible estimates of stand-level processes (such as spatially-averaged evapotranspiration and net CO_2 flux) on the other, then there is increased confidence that it is working correctly.

CONCLUSIONS

The total C budget of the Canadian forest sector is believed to be very sensitive toecological processes operating at the scale of individual forest stands. In order to reliably predict the effects of possible future changes in climate and management on the national C budget over the next 50-100 years, a mechanistic simulation of ecosystem responses will be essential, though successful development of such a model is a challenging task.

A likely approach to achieving this objective is to use a nested hierarchy of three levels of simulation, linked by two metamodels where output data from one level are used to generate response functions as drivers for the next level up. The three levels of simulation are (1) stand-level ecophysiology; (2) forest ecosystem dynamics, including the effects of spatial heterogeneity and disturbance contagion and (3)regional- or national-scale C budget assessments, ultimately linked to large scale climate models. If anticipated changes in climate do occur during the next 50-100 years, then the consequences for the Canadian forest industry could be of great socio-economic significance. Advance warning of the effects of these changes, as provided by the integrated large-scale carbon budget model described here, will give policy makers more opportunity to explore management options to prepare for and mitigate the possible adverse consequences.

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