THE BOREAL FOREST TRANSECT CASE STUDY: GLOBAL CHANGE EFFECTS ON ECOSYSTEM PROCESSES AND CARBON DYNAMICS IN BOREAL CANADA

D. T. PRICE and M. J. APPS

Canadian Forest Service, Northern Forestry Centre, 5320 - 122 Street, Edmonton, Alberta T6H 3S5, Canada

Abstract. The Boreal Forest Transect Case Study (BFTCS) is a multi-disciplinary ecological study organised around a 1000 km transect located in central Canada. The transect is oriented along an ecoclimatic gradient in a region likely to undergo significant environmental change within the next few decades, and crosses the climate-sensitive boreal forest biome, including the transitions north and south into tundra and grassland respectively. Originally conceived as an extension to the BOReal Ecosystem Atmosphere Study (BOREAS), the 10-year BFTCS project projects the intensive canopy-scale measurements and modelling advances obtained from BOREAS to a wider range of sites with a longer-term perspective. In addition to considering ecophysiological processes with time-frames of the order of one year or shorter, BFTCS addresses the effects of larger scale, longer term processes including vegetation succession and ecosystem disturbances. The BFTCS currently provides practical linkages among ecosystem monitoring, field experiments and regional scale modelling. It will ultimately provide a knowledge-base of key processes and their environmental sensitivities, and assessments of possible climate feedbacks, which can be used to assess the possible consequences of global change both regionally and globally.

Keywords. BOREAL, FOREST, TRANSECT, ECOSYSTEM, MODEL, CARBON, BOREAS, CANADA.

1. Introduction

Boreal, tundra and subarctic (collectively termed "high-latitude") terrestrial biomes, cover approximately 25% of the Earth's land surface, and are estimated to contain 800–900 Pg carbon (C), or about one third of the global terrestrial ecosystem total (Gorham, 1991; Apps *et al.*, 1993; Woodwell and Houghton, 1993; Chapin and Matthews, 1993). These biomes consist of many ecosystem types, including "warm–dry" and "cool–wet" boreal forests, wetlands and grasslands, with many ecotonal intergrades, typically forming a very heterogeneous landscape. The forest component of this landscape is typically of fire-origin. Hence, the interaction of topography and fire history leads to an intimately mixed mosaic of stands of varying ages and species composition, often interspersed with patches of other vegetation communities. Many of the component ecosystems are expected to be very sensitive to changes in climate, with observable responses likely to occur at all scales of organisation i.e., in stand-level processes (energy and gas exchange) (e.g., Bonan *et al.*, 1990; Oechel *et al.*, 1993), in community-level dynamics (patch-level seeding, competition and succession) (e.g., Zoltai and Vitt, 1990; Price and Apps, 1995, unpubl. ms.) and in the frequency and intensity of disturbances (particularly fire and insect infestations) occurring at the landscape and even regional scales (e.g., Clark, 1990; Kurz *et al.*, 1992, 1995b). The expected sensitivities suggest the general hypothesis that should climate warming occur, as is commonly predicted by general circulation models (GCMs), then the combination of effects at these different scales would cause the structure (i.e., species composition and spatial distribution) of existing northern high-latitude vegetation to

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change. This would inevitably lead to significant effects on the functional characteristics of these ecosystems, which could be of considerable socio-economic impact both regionally and globally. For example, Bonan *et al.* (1992) simulated the complete removal of the boreal forest and concluded that effects on surface albedo and roughness might lead to significant cooling of the global climate.

While such a negative feedback may appear possible in the longer term, there is also much concern about the possible short-term (next 50–100 yr) impacts of global change on the apparent role of northern terrestrial biomes as an important contributor to the so-called "missing carbon sink", which may be retarding the accumulation of anthropogenic CO_2 in the global atmosphere (e.g., D'Arrigo *et al.*, 1987; Tans *et al.*, 1990, 1993; Apps *et al.*, 1993). Recent and ongoing work is drawing attention to the possibility that anticipated global changes (i.e., climate warming and land-use conversions, including deforestation) may result in accelerated releases of terrestrial stored C (Woodwell and Mackenzie, 1995; Oechel *et al.*, 1993), causing these biomes to become net sources of CO_2, and hence producing a feed forward to the greenhouse warming effect (Woodwell, 1989; Woodwell and Houghton, 1993; Gorham, 1991; Townsend *et al.*, 1992).

Early analyses of the sensitivity of Canadian high-latitude vegetation zones by Zoltai *et al.* (1991), Rizzo and Wiken (1992), and others, have indicated that significant shifts in vegetation boundaries and productivity would occur under GCM-derived equilibrium climate projections, possibly causing new communities to establish in the present-day boreal region, resembling those currently established under warmer climates further south. Such interpretations are generally based on the arbitrary assumptions that anthropogenic CO_2 emissions will cease at twice the pre-industrial atmospheric concentration, causing the greenhouse warming effect to stabilise, and that vegetation and soils will ultimately develop into new "steady-state" ecosystems determined by a few key climatic factors (e.g., Rizzo and Wiken, 1992; Prentice *et al.*, 1992; Smith *et al.*, 1992). As the paleo-ecological record implies, some existing vegetation communities may disappear altogether, to be replaced by new, previously unrecorded ecosystems (Solomon and Bartlein, 1992; Campbell and McAndrews, 1993).

In reality however, if global warming does occur, it is evident that plausible changes in vegetation structure may create both positive and negative feedbacks. Some feedbacks are likely to result in steady-state endpoints (e.g., changes in average albedo) while others will be more immediate and transient in nature (e.g., CO_2 release from drier organic soils and methane releases from melting permafrost). From the human socio-economic viewpoint, understanding the transient behaviour during the warming period, i.e., the next 50–100 years, will be of far greater significance than the ultimate steady-state condition (which may take several hundred years or longer to attain). Therefore it is clearly important, both scientifically and in the interests of resource management, to better understand the short-term dynamic responses of the boreal vegetation to anticipated global changes.

Shuttleworth (1991) outlined a conceptual model planet (Modellion) in which large-scale simulation experiments could be carried out on Earth's physical climate system. He argued that such model worlds are necessary because of the obvious lack of proper controls on large-scale physical experiments, and because the major impacts of global change need to be known long before they actually occur. Extension of this philosophy to a large regional transect (albeit of an area much smaller than that of the entire planet) can provide an effective means of aligning models with reality. Regional transects allow some physical experimentation (notably field manipulations, as well as long-term ecosystem monitoring over large areas) which can be combined with predictive modelling at high spatial resolutions, to validate predictions of future spatial and temporal dynamics.

2. Transect Description

The Boreal Forest Transect Case Study (BFTCS) is an extensive, long-term study based on a contiguous, mid-continental transect crossing an important climate-sensitive northern terrestrial biome. The major purpose is to support/co-ordinate integrated studies of boreal forest processes, as a means of obtaining information about the current structure and function of the Canadian boreal biomes and, in particular, their probable responses to global change

Covering approximately 1000 by 100 km, the transect is located in a region where the relief is generally flat with only 700 m elevational change and no major geophysical obstacles along its entire length (Figure 1). It is oriented approximately southwest–northeast along a pronounced ecoclimatic gradient, perpendicular to the current vegetation boundaries of the southern boreal forest with the aspen parkland of central Saskatchewan, and of the northern boreal forest with the low subarctic tundra (or "subarctic woodland") vegetation of northern Manitoba (Ecoregions Working Group, 1989).

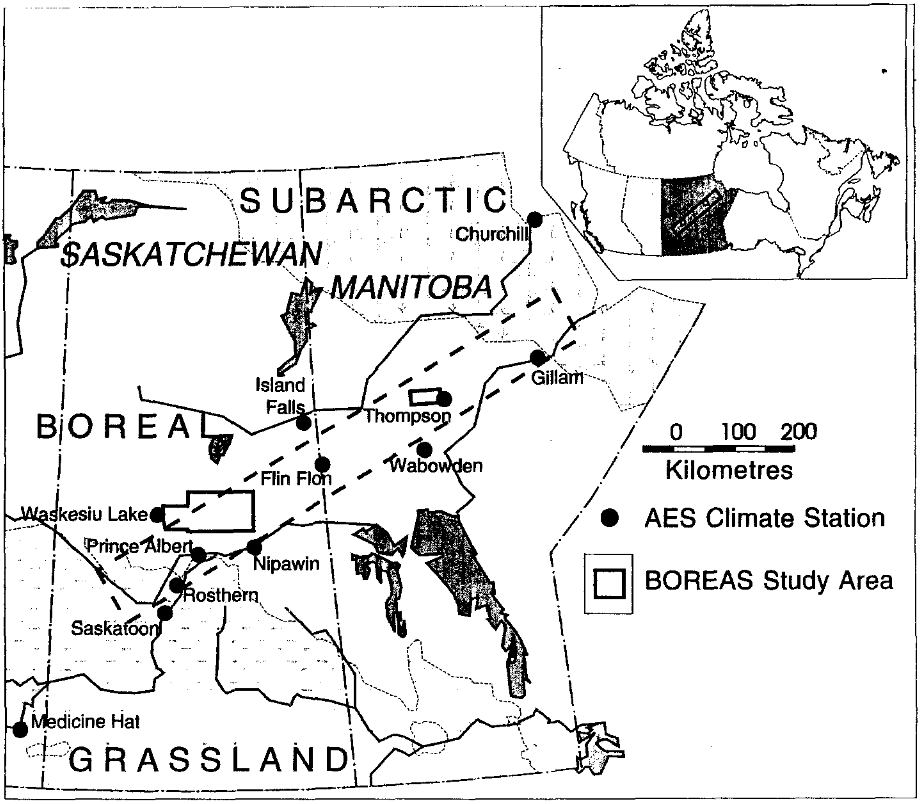

Fig. 1. Location of the Boreal Forest Transect Case Study (BFTCS) in Canada, showing major ecological zonations, positions of local long-term weather recording stations, and the BOREAS study areas.

TABLE I

Climate stations in BFTCS area, January and July mean temperature, annual precipitation and estimated annual potential evapotranspiration (PET): AES, 1951–1980 normals, and GISS 2×CO_2 climate scenario (Hansen *et al.*, 1988). PET was estimated using Jensen *et al.* (1990) following Hogg (1994).

	1951–1980				2×CO_2			
Climate station	January temp. (°C)	July temp. (°C)	Annual precip. (mm)	Annual PET (mm)	January temp. (°C)	July temp. (°C)	Annual precip. (mm)	Annual PET (mm)
Churchill	-27.5	11.8	403	130	-15.7	17.0	520	235
Gillam	-27.1	15.0	450	238	-16.5	18.9	540	342
Thompson	-26.6	15.7	544	295	-17.8	19.7	652	431
Wabowden	-24.5	16.9	464	308	-16.4	20.8	547	446
Flin Flon	-22.4	18.2	474	365	-14.9	21.8	563	492
Waskesiu Lake	-20.7	16.3	464	385	-13.3	19.8	549	522
Nipawin	-21.2	18.4	403	462	-14.6	21.6	471	614
Prince Albert	-21.5	17.4	398	444	-14.7	20.7	463	589
Rosthern	-20.1	18.3	373	500	-13.4	21.3	430	657
Saskatoon	-19.2	18.5	348	520	-12.9	21.6	396	688
Medicine Hat	-12.7	19.9	347	686	- 6.5	22.4	390	910
Means	-22.1	16.9	424	394	-14.2	20.5	502	539

At the north-eastern end, conditions are relatively cold and wet, while in the south-west, the climate is relatively warm and dry (Table I). Although the gradient in precipitation is not particularly steep, estimates of annual potential evapotranspiration (PET), show a steady increase from Churchill in north-eastern Manitoba, to Medicine Hat in southern Alberta. The gradient in PET is a major factor determining the current boreal forest zonal distribution in the southern ecotone; growing season soil moisture deficits probably play a critical role in determining forest structure and productivity (Price *et al.*, 1993; Hogg, 1994). In the north, low winter temperatures are a more important physiological limitation to growth and species survival.

Soil types vary from predominantly chernozemic in the prairie grassland areas, through mixtures of luvisols, humo-ferric podzols and fibrisols (peats), overlying glacial deposits, to cryic fibrisols (organic soils with discontinuous permafrost) overlying Canadian Shield bedrock in northern Manitoba (Clayton *et al.*, 1977). These differences in soil type result in a general gradient of decreasing site fertility moving from south to north. The interaction of climatic and nutritional gradients hence results in maximum site productivities generally occurring toward the middle of the transect area in the mid-boreal zone.

The transect area also exhibits a gradient in land-use pressure, ranging from dryland agriculture in the prairie grassland and commercial forest management in the southern boreal forest, to low-impact traditional uses such as trapping, hunting and firewood collection in the more sparsely populated north. Large uncontained forest fires of natural origin are a major disturbance factor across the entire western boreal forest (e.g., see Flannigan and Van Wagner, 1991; Sirois, 1992; Bergeron and Flannigan, 1995), but the level of investment in protection and suppression tends to be higher in the more productive and accessible areas of the south, with the result that greater losses from fires tend to occur in the more remote northerly areas.

The general projections for future climates derived from GCM simulations indicate changes in mean annual temperature and precipitation within the next 50–100 years. Table I shows that the greatest warming is anticipated during winter, at the northern end of the transect. Since the greatest seasonal temperature variation is in the north, this warming effect will therefore greatly reduce the north–south summer temperature differential. For example, the GISS model (Hansen *et al.*, 1988) predicts a change in this differential from 8 °C currently to only 3.5 °C under $2\times CO_2$. The GCMs are less consistent in their projections of future precipitation. It appears however, that the greatest increases in annual rainfall will also occur at the northern end of the transect, whereas the greatest increases in annual PET will be at the south, leading to significantly warmer and drier conditions there (Table I; see also Hogg and Hurdle, 1995, this volume).

3. Experimental Design

3.1. Rationale

The apparent climate sensitivity of high-latitude ecosystems combined with the GCM predictions of maximum climate changes in mid-continental locations strongly suggests that regions such as the BFTCS area are likely to be among the first to exhibit systematic responses to global change. Hence they may be considered "information-rich" systems with potentially large returns of knowledge for the research effort invested. BFTCS attempts to maximise this return by looking not only at the relatively stable central regions of the boreal biome, but also at the transitions with adjacent biomes to the north and south.

A working hypothesis is that these ecotones are likely to be particularly sensitive to change, since the vegetation is on the edge of transition from one quasi-stable state to another (Holling, 1992; Apps, 1993). A corollary to this hypothesis is that the first signs of change will manifest as "fragmentation" of the landscape at the biome boundaries. Due to the greater sensitivity of these ecosystems to changing conditions at the extremes of their geographic range and a likely increase in disturbance rates (Flannigan and van Wagner, 1991; Kurz *et al.*, 1995b), smaller and increasingly disjoint patches may be expected (C. S. Holling, University of Florida, pers. comm., 1993).

The *direction* of change will also be a very important indicator, e.g., are there signs that grasslands are replacing the aspen parkland (as suggested by Rizzo and Wiken, 1992)? Are krummholz woodlands in the boreal/tundra transition developing into upright seed-producing forms, resulting in increased northward seed dispersal and establishment of previously unrecorded woodland islands north of the current tree line? (e.g., MacDonald *et al.*, 1993). Have the proportions of the landscape covered by each ecosystem type within the transition zone changed in recent years? If so, is the mechanism hydrological (e.g., as reported for permafrost peatland area by Vitt *et al.*, (1994) and Zoltai and Vitt (1990)), or biogeochemical? (Oechel *et al.*, 1993; Gignac *et al.*, 1991; Rastetter *et al.*, 1991; Schindler and Bayley, 1994), or a change in disturbance frequency, or a combination of these?

The possible impacts of global change on boreal ecosystems outlined above warrant detailed investigation,. but economic and practical constraints make it impossible to subject the entire boreal region to intensive study. Some ecosystem processes may be investigated in the laboratory, or in field experiments, while others may be explored using simulation models. The problem is to be able to aggregate the effects of small-scale processes over an area extensive enough to assess their importance at the regional scale, when considering interactions with larger-scale processes such as ecosystem disturbances.

Under a changing environment, ecosystem disturbances can have significant effects on regional ecosystem dynamics, such as succession and productivity (Overpeck *et al.*, 1990). These effects are caused mainly by changes in disturbance frequency, which will lead to shifts in forest age-class distribution, and species composition. Disturbances should not alter regional dynamics when they occur at a constant frequency. Factors influencing the disturbance frequency, however, such as a warming climate leading to increased losses from fires and insect attacks (the latter due to longer summers and warmer winters), or protection programs leading to reduced losses, will almost certainly affect forest structure (Apps, 1993). In turn, these changes are likely to change the spatial integrals of biological processes such as net C assimilation (Kurz *et al.*, 1995b), and of physical climate processes including radiative and convective transfer, with consequences for the regional energy balance and hydrology (Shuttleworth, 1991; BOREAS Science Steering Committee, 1991; Hall *et al.*, 1993).

The latter point is not widely appreciated by earth system scientists attempting to assess the role of surface vegetation in the global climate (Sellers *et al.*, 1989; Dickinson *et al.*, 1993). The "soil–vegetation–atmosphere–transfer" (SVAT) surface parameterization schemes currently favoured by GCM modellers typically do not consider spatial and temporal vegetation dynamics. Usually, the landscape is broadly classified into static vegetation types such as "tundra", "old conifers" or "young hardwoods". Intensive studies of species ecophysiology should yield parameterizations appropriate for such classifications, but problems will be encountered when the proportions of these vegetation types, and their vertical structures (i.e., species composition, height, leaf area index etc.), alter in response to environmental changes.

The concept for BFTCS emerged as a means of integrating within a single study framework, both modelling and experiments (including remote sensing) carried out over a relatively large area and a time period of at least ten years. The objective was to gain maximum value from several large collaborative projects, both planned and underway, while facilitating independent studies by local researchers targeted at specific problems not adequately addressed by the larger scale projects.

3.2. SCALING METHODOLOGIES

In recent years, there has been an increasing trend toward large multidisciplinary field studies which encourage collaborative field work and data analysis. Access to wide-coverage multi-spectral remote sensing products has increased enormously, while low-cost, high-performance computing has resulted in increasingly sophisticated simulation models covering a range of paradigms. It is now feasible to link such models both "laterally" by coupling ecosystem models to physiologically-based canopy process models and to models of local area hydrology and microclimate; as well as "vertically" in the manner of nested hierarchies (leaf → canopy → patch → landscape → region). Indeed, large scale field experiments such as the Boreal Ecosystem–Atmosphere Study (BOREAS) are largely devoted to testing the hypotheses expressed in such linkages.

BOREAS is a joint Canada–U.S. study based on satellite, aircraft and ground observations, aimed at detailed understanding of canopy level processes governing boreal forest function under two distinct environmental regimes (Figure 1). There are two main components to the study: intensive measurements of physical and ecophysiological processes (with typical time-frames of seconds to weeks); and development of models to extend this understanding to the landscape scale (10–50 km) where aircraft and satellite remote sensing measurements may be used for validation (Hall *et al.*, 1993). Hence, an important goal of BOREAS is to develop and test spatial scaling methodologies. The nested experimental design (cuvette → canopy flux-measurement tower → aircraft-mounted sensors → satellite) allows simultaneous measurement of radiative transfers, and energy, mass and momentum fluxes, between forest and atmosphere at several scales. This will also be essential to validate and/or revise aggregation hypotheses (e.g., Gardner *et al.*, 1982; Shuttleworth, 1991), which can then be used in larger scale models of vegetation processes and vegetation–atmosphere exchanges. Remote sensing techniques are expected to be a key observational tool for longer term monitoring of ecosystem processes at the landscape and regional (transect) scales.

The BFTCS area encloses all the major BOREAS study sites (Figure 1), providing a logical step for testing aggregation techniques at the regional scale. The experimental component of BFTCS extends the spatial and temporal ranges of BOREAS from a few discrete sites studied intensively for one growing season, to a greater number of sites studied in much less detail over a much longer period. The modelling component supports this extension, by integrating models of the small-scale processes into models of ecosystem dynamics operating at larger scale and over longer durations (time-frames of years to decades), including disturbances, vegetation succession, and human influences (Price and Apps, 1993).

4. Studies in Progress

Experimental work in BFTCS covers many of the disciplines needed to assess vegetation/climate interactions, ranging from studies of ecophysiological processes affecting primary productivity and respiration, and accumulation and decomposition of organic matter in soils, to studies of disturbance history and its correlation with past climates. Collaborative studies with several Canadian universities include studies of C dynamics in forest soils and the application of a regional climate model (RCM) nested within the Canadian Climate Centre's GCM (Caya *et al.*, 1995, this volume).

4.1. Biomass Inventory and Productivity Assessments

As a component study of BOREAS, almost 100 forest sites have been surveyed within the BFTCS area (Halliwell *et al.*, 1995, this volume). At each site, standard measurements of stand density, basal area and standing volume, and soil variables have been made, together with estimates of detrital mass and understory vegetation composition. These data are being combined with studies of species allometry (S. T. Gower, University of Wisconsin, pers. comm., 1995) to provide estimates of vegetation biomass, C storage density, and annual production, as functions of site conditions.

4.2. Cidet

The ongoing Canadian Intersite Decomposition ExperimenT (CIDET) is a nation-wide comparison study of forest floor litter decomposition rate (Trofymow *et al.*, 1995, this volume). Sets of mesh bags containing litter collected from 21 forest ecoclimatic regions across the country, (including three paired lowland/wetland boreal forest sites in the

BFTCS area) have been staked out in groups at each site. Decomposition rates are being assessed and cross-compared annually over a 10-year period, to assess the interacting effects of substrate quality and climate. This study is designed to complement a similar LTER (Long Term Ecological Research) program in the USA (Harmon *et al.*, 1990).

4.3. Peatland Studies

Peatlands are a major feature of the landscape for much of the BFTCS area, and represent significant accumulations of atmospheric carbon due to low decomposition rates, resulting from low average temperatures and anaerobic conditions. Permafrost is present across more than half the length of the BFTCS, with most of the forested regions lying in the discontinuous permafrost zone. These areas are likely to be sensitive to slight increases in temperature, hence climate warming could have major effects on the productivity and patch-scale dynamics of wetland–forest ecosystems. Dated peat deposits may be used to determine past changes in peat accumulation rates, and serve as proxies for past climatic conditions in the BFTCS area. In the southern parts of the boreal forest, patterns in the vegetated landscape are associated with melting of permafrost islands, and may be an indicator of warming within the last 150 years (Vitt *et al.*, 1994). To explore possible future changes, models of peat ;and forest interactions are required and both conceptual models (e.g., Zoltai, 1994) and simulation models (e.g., Apps *et al.*, unpublished ms.).

4.4. Disturbance Histories

Most stands in the western Canadian boreal forest are of fire-origin, indicating that large-scale natural disturbances are a key factor influencing forest structure and successional development in this region. In order to assess the possible trends in disturbances due to wildfire and insect attacks under a warming climate (e.g., Flannigan and Van Wagner, 1991; see also Bergeron and Flannigan, 1995; Fleming and Volney, 1995, this volume), it is imperative that disturbance histories be established for stands under investigation within the BFTCS area. Such work is being undertaken by Stocks and colleagues (B. J. Stocks, Canadian Forest Service, pers. comm.,1993).

Some 3.28 Mha burned in Manitoba in 1989, one of the warmest years on record (Hirsch, 1991), illustrating the potential sensitivity of boreal ecosystems to a warming climate. The strong influence that such changes may have on future C budgets has been stressed by Kurz *et al.* (1995b). Reconstruction of past climates and their relationship to changes in disturbance frequency is possible from paleo-ecological data (e.g., Campbell and McAndrews, 1993; MacDonald *et al.*, 1993); from fossil charcoal deposition studies (e.g., MacDonald *et al.*, 1991; Clark, 1988, 1989); from dendro-chronological studies (e.g., Van Wagner, 1978; Clark, 1989; Filion *et al.*, 1993); and from historical records (Kurz *et al.*, 1995a). Models are also being developed to explore the impacts of spatially connected disturbance processes on spatial and temporal vegetation dynamics in the landscape (Li and Apps, 1995, this volume) and to assess possible consequences of climate change on insect and tree host phenological interactions (Fleming and Volney, 1995, this volume).

4.5. Remote Sensing

By providing large-scale time-series data, remote sensing is potentially very useful for monitoring regional changes in vegetation structure. U.S. and Canadian agencies are collaborating in data acquisition and analysis of remote sensing data as an integral component of BOREAS and BFTCS. Vegetation boundaries are being mapped and changes monitored. Over a period of several years to decades, vegetation dynamics monitored in this way may be compared to predictions derived from regional- and transect- scale model simulations.

For areas where change is manifest, ground-based studies can be deployed to test and refine the understanding of the causal mechanisms. As part of BOREAS, intensive field measurements took place during 1993 and 1994 in the two large study areas near the northern and southern ecotones of the boreal forest (Figure 1). A further intensive field season is planned for the summer of 1996. Abundant process data have already been obtained from these sites selected for stand uniformity and general suitability for energy balance and trace gas flux measurements, but there will be relatively little information about larger scale and longer term processes.

4.6. Carbon Budget Model

The results of field studies (e.g., see Halliwell *et al.,* 1995) will also be used for validation of a large-scale process-based Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) developed from a national scale model (Kurz *et al.*, 1992, Apps and Kurz, 1993) as a component study of the BFTCS (Price and Apps, 1993). The major purpose of this model is to provide an integrating framework for estimating the contributions of vegetation productivity and other ecosystem processes (including soil and wetland dynamics, and large-scale disturbances) to regional and national C budgets (Kurz *et al.*, 1992). The CBM-CFS is a C-conserving mass balance model that tracks photosynthetic C uptake by living forest phytomass, and tracks the subsequent releases of C during transfers to detrital material, soils, peat deposition and forest products (Kurz *et al.*, 1992). The effects of disturbances on large-scale C dynamics are an important factor explicitly represented in this model, based on historical records. Linkage to studies of the relationships between climate and disturbance frequency mentioned earlier, will allow CBM-CFS to be used for assessing impacts of changes in disturbance regime resulting from anticipated future climate change on the regional C budget. Developed and applied originally at the national scale, it is now being applied and tested at the regional scale of BFTCS (Price and Apps, 1993) and the landscape/management scale of individual forest management units (Price *et al.*, 1994). These finer scale implementations of CBM-CFS are also being used to examine the sensitivity of the regional C budget to transient changes in climate and resource management.

4.7. Transect Ecosystem Models

Boreal ecosystems are typically organised in patches, with areas of homogeneous vegetation rarely exceeding 2 km^2 (although some lakes may be larger than this in total area, there are no large lakes in the BFTCS area). This means that most of the surface vegetation is organised at length scales of significantly less than 10 km, which in turn indicates that it may be appropriate to use simple area-weighted aggregations of the vegetation cover when estimating surface fluxes of water vapour and CO_2 as was found by Pinty *et al.* (1989) in the FIFE experiment (an earlier study comparable to BOREAS, but in the short-grass prairie of Kansas (e.g., see Shuttleworth *et al.*, 1989)).

The basic spatial unit for transect-scale simulations is the 10 km square, of which 1000 are needed to represent the entire BFTCS area. Data from BOREAS will allow scaling up from flux tower sites to 10 km (e.g., based on validations from BOREAS flux tower and flux aircraft measurements). Hence, BFTCS provides an opportunity to simulate interactions between vegetation and atmosphere at resolutions within a 10 km grid square combined with larger scale processes e.g., shifts in biome distribution and composition that can be simulated on a 10 km grid. Eventually these simulations will be combined with a nested regional climate model co-located over the transect area (Caya *et al.,* 1995). Interactions between 10 km squares will also be considered, particularly for those mechanisms affecting species migration and ecosystem succession: seed dispersal, management, and the spread of natural disturbances.

Using BFTCS as a source of data for development and testing, CBM-CFS can use metadata derived for the transect area from runs of several smaller scale sub-models, which can be tested and refined against field data (Price and Apps, 1993). These include: detailed models of ecophysiological responses; single-tree and stand-level growth models; ecosystem-level models of species competition and succession and of insect population dynamics; and regional hydrological and climate models. Future C budget assessments are not the only outcome: it will also be possible to develop maps of predicted changes in vegetation composition. The integrated transect model structure will be used to explore future responses of regional and national forest resources to anticipated changes in climate (Price and Apps, 1993), and to enable forest scientists to better determine the probable relative effects of possible climate change and various forest management options on rates of C sequestration and release by boreal forest ecosystems. It may also reveal further strategic research needs (i.e., gaps in knowledge) yet to be identified. With suitable parameterizations and further validation work, the model should be extensible to other forest ecosystems, and even to other major vegetation types.

5. Summary

In the boreal zone of central Canada, both natural and managed forest ecosystems appear particularly sensitive to global change, with potentially serious consequences both regionally (in vegetation composition and distribution) and globally (as feedbacks to the global climate). The Boreal Forest Transect Case Study (BFTCS) is an adaptive investigative approach that encapsulates within a single study area of some 100 000 km^2, the major ecosystems and ecological processes of the circumpolar boreal and tundra biomes likely to be affected by, and to feed back to, anticipated global change. Field studies of past dynamics and present-day processes will be used to develop and test a suite of predictive models, to better assess short-term (50–100 yr) transient ecosystem dynamics and their implications for management and policy.

A second benefit of this approach will be the development of appropriate environmentally-sustainable management practices, based on improved understanding of fundamental ecosystem processes and of their potential responses to environmental change. The co-ordinated investigation of ecosystem processes and human impacts within BFTCS is assisting researchers to provide answers to many policy-relevant questions concerning current and possible future interactions between boreal ecosystems and the global environment.

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