THE ROLE OF BOREAL FORESTS AND FORESTRY IN THE GLOBAL CARBON BUDGET: A SYNTHESIS

I.H. Fyles, C.H. Shaw, M.J. Apps, T. Karjalainen, B.J. Stocks, S. W. Running, W.A. Kurz, G. Weyerhaeuser, Jr. and P.G. Jarvis

INTRODUCTION

The circumboreal forests cover approximately 33% of the Earth's terrestrial surface, contain 25% of the vegetation carbon and 60% of the soil carbon, making up approximately 50% of the carbon stored in biomass and soil globally (Apps et al. 1993; Dixon et al. 1994, Schlesinger 1997). Boreal forests have often been reported as carbon sinks, meaning that carbon uptake in the biomass and soil exceeds carbon removals from those pools. Although the entire boreal forest is thought to be sink of 0.3 to 0.5 Pg carbon per year (Dixon et al. 1994, Apps et al. 1993)Bousquet et al. 2000, Gurney et al. 2002), this sink term varies both geographically and over time (Goodale et al. 2002). Thus for example, Kurz and Apps (1999) reported that Canadian boreal forests became a source in the 1980s as a consequence of large scale disturbances.

It is now widely acknowledged that climate models project the largest global warming trends to be in high latitudes (Running 2000). There is widespread evidence that this warming is already underway. Snow cover reduction, glacial retreat, sea ice cover, growing season length, river break up times, permafrost depth and air temperature records are all showing clear warming trends over the last 50 or more years.

The timing of the thaw in the spring and the freeze-up in the fall is a significant constraint on carbon fluxes in boreal forests (Gower et al. 2000). Because there is usually abundant solar radiation prior to the spring thaw, an early thaw may lead to an increase in the annual net carbon gain in regrowing stands relative to those experiencing a late thaw. By contrast with continental boreal spruce forest, young spruce stands at similar latitudes in the oceanic climate of the Atlantic fringe have net ecosystem fluxes of over 6 t C ha^{-1}, in part because there is no winter freeze up – leading to some carbon gain on almost every day of the year.

The carbon sink in the boreal forests today must be considered very vulnerable (Gower et al. 2000). Over wide areas, the net sink is both small and fluctuating, so that the permanence of the sink as atmospheric CO_2 concentrations and temperature continue to rise has become a crucial question (Jarvis et al. 2001). Short-term experiments demonstrate that the increase in photosynthesis that results from a rise in atmospheric CO_2 concentration tends to diminish at higher CO_2 concentrations, while both autotrophic and heterotrophic respiration increase, perhaps exponentially, with increasing temperature. This has led to the suggestion that the overall capacity to take up additional carbon from the atmosphere may decline progressively as climate changes (Scholes 1999). Thus it has been suggested that by about 2050 respiration will have increased so as to exceed photosynthesis and today's net terrestrial carbon sink will have become a carbon source. There are, however, contrary predictions. For example, analysis of a boreal forest in northern Sweden using the ecosystem model G'day indicates that net primary production will consistently exceed heterotrophic respiration so that the carbon sink rises to an asymptotic maximum and remains there for 100 years without significant decline.

In the boreal forests of Canada and Russia, large-scale natural disturbances play a large role in determining the outcome of carbon source/sink relationships. For example, Kurz and Apps (1999) reported that Canadian boreal forests became a source in the 1980s as a consequence of large scale disturbances. Changes in disturbance regimes bring about long-term changes in the age-class structure of these boreal forests. Forest age-class structures that are heavily skewed towards older ages, as observed in many regions of the circumpolar boreal forest may represent high C stocks that may not be sustainable into the future.

In the latter part of the 20th century the critical links between boreal forest ecosystems, carbon dynamics and global climate change were increasingly recognized by the scientific community. There was a clear need to share information better and to develop international collaborative research initiatives. The conference "The Role of Boreal Forests and Forestry in the Global Carbon Budget" held in Edmonton, Alberta, Canada May 8-12, 2000 was designed to be an end-of-the-century review of the state of a) our understanding of carbon dynamics of boreal systems and b) our ability to influence these through purposeful actions. This paper provides a synthesis of the papers published in the three special journals issues and the Proceedings (this volume) associated with the conference. As such, it represents a state-of-science summary of the circumboreal boreal forests' contribution to the global C cycle at the end of the 20th century.

The published papers and contributions from the keynote speakers have been grouped into five topic areas that form the sections of this synthesis; C Stocks and Fluxes; Effects of Natural Disturbances or Management Practices on Carbon Dynamics; Afforestation and Carbon Sequestration and Effects of Climate Change and Elevated CO_2 Concentration on C Dynamics.

The first section, in keeping with the major theme of the conference, focuses on updated estimates of carbon stocks and fluxes in Russia, Canada, China and western Europe. Estimation of C stocks were made at the national scale, factors controlling variability of estimates were investigated at the regional scale while processes were studied at sites within regions.

Advances in research on the effects of natural disturbances and forest management practices on C stocks and fluxes is the focus of the next two sections. Disturbance type, history and extent are now accepted as major factors influencing large scale carbon dynamics in boreal forests. Under conditions of a changing climate predicted by the IPCC (Watson et al. 2001), natural disturbances such as fire, insect defoliation and windthrow are expected to increase in frequency and extent and will influence C dynamics at all spatial scales. Silvicultural and harvesting practices affect C dynamics directly through changes in mortality and growth trends and may be used as management strategies to mitigate impacts of natural disturbances and purposefully alter source/sink relationships. Afforestation is addressed separately as a mechanism within the Kyoto Protocol for countries to offset net greenhouse gas (GHG) emissions. Finally advances in research on the influence of the predicted climate change and increases in atmospheric CO_2 concentrations on boreal forest C budgets and vegetation response are summarized.

CARBON STOCKS AND FLUXES

Since the last glaciation, large amounts of C have been taken up from the atmosphere by boreal forest ecosystems, accumulating in vegetation and soil organic C pools (Gower et al. 2000). In mature boreal forest stands, there may be up to eight times as much C in the soils as in the trees and other vegetation. With two or three exceptions, the boreal forest stands so far investigated with flux towers in Russia, North America, Europe exhibit C sinks with annual net ecosystem fluxes of 0.5 to 2.5 Mg C ha^{-1}. However, this sink must be considered very vulnerable and over wide areas where landscape scale processes, such as disturbances can result in large short and long-term emissions, the net sink is small and fluctuating. Estimates of C pools are therefore constrained by large temporal and regional variation, but measurements and model estimates of C sequestration, above and below ground C pools, and factors affecting those estimates are rapidly increasing for Russia, Canada, China and Europe.

Russia

Reported assessments of C stocks for the Russian boreal forest suggest that the vegetation was a sink for C during the last 40 years of the 20th century. Much of the C sequestered was accounted for by increases in the total area of rapidly growing young and middle-aged stands, the establishment of deciduous species and increase in the amount of coarse woody debris (CWD).

Using long-term forest inventory data, Shvidenko and Nilsson (2002) show that between 1961–1998 the vegetation of Russian forest lands had an annual average C sequestration of 210$\pm$30 Tg C yr^{-1} of which 153 Tg C yr^{-1} was in live biomass and 57 Tg C yr^{-1} was in dead wood. However, the temporal variability of the sink estimate was very large: for the 5 year averages used in the analysis, the C sequestration varied from about 60 to more than 300 Tg C yr^{-1}. Within the forested area, the higher C sequestration was a result of a systematic expansion in the area of young and middle-aged stands and a corresponding decline in mature and overmature stands. Increases in CWD (about 57 Tg C yr^{-1}) that were reported for the last 10 years by Shividenko and Nilsson (2002) were associated primarily with fire and insect defoliation.

The total amount of C stored aboveground in forests managed in the Russian Forest Fund (RFF) is currently about 34 Pg in phytomass and between 5.4 and 3.6 Pg C in CWD (Shvidenko and Nilsson 2002; Utkin et al. 2002). These authors point out that while there was a significant increase in the area of young and middle-aged stands the mature and overmature stands still account for more than half (57%) of the phytomass C in the RFF.

Total stocks of organic C in soils (to 2 m depth) of the Russian Federation was estimated to be 367 Pg of which nearly half (164 Pg) was in the top 30 cm (Stolbovoi 2002). The total amount of soil C was estimated to be 172 Pg in the RFF and 183 Pg for soil C for all forests in Russia (Utkin et al. 2002). The C density in the soils of the Russian boreal forest is about 11.5 kg m^{-2} for the 0-1 m layer, similar to values found for Canada. The trend in the spatial distribution of C density in the soil C pool is nearly the reverse of that observed for C in the phytomass pool and results in a similar total C density (17-20 kg C m^{-2}) in all ecosystem types within subzones, through zones and through provincial profiles across Russia (Utkin et al. 2002).

The large area of peatlands in Russia contributes significantly to soil C storage and and total accumulation of organic C in deep peat (more than 50 cm thick) is estimated to be 156 Pg in the 0-2 m layer (Stolbovoi 2002). Studies such as that by Glebov et al. (2002) that examine peat forming processes, are required to increase baseline knowledge of C stocks in boreal peatlands in Russia.

Regional assessments of the size of forest C pools highlight the importance of geographical differences, forest age-class structure and species dynamics on the evaluation of C dynamics. Krankina et al. (2002) quantified regional stocks of CWD in seven major forest regions of Russia and concluded that variation among regions is so large that extrapolating information from one region to another would be difficult and misleading. They found that stocks of CWD in the western part of Russia were, on average, lower (4-5.8 Mg ha^{-1}) than in eastern regions (11–14.4 Mg ha^{-1}). These differences were associated with differences in the nature of prevailing disturbance (clearcut harvesting in the west and natural disturbance in the east). Lower decomposition rates in the east, due to its harsher climates, may also be a contributing factor.

In Middle Zavolgie (western Russia), forest land use has played an important role. C stocks in stem wood, examined over a 40 year period showed that stem wood C had increased from 277 Tg in 1958 to about 307 Tg in 1995. This increase was ascribed to increased establishment of rapidly growing deciduous species (Kurbanov and Post 2002). The total area of young and middle-aged stands had increased by 27% over this period, resulting in a high rate of annual C sequestration through rapid regrowth. A study carried out over a growing season in central Siberia also showed significant C sequestration occurred in young deciduous forest stands (Meroni et al. 2002). Pine stands in the same region, dominated by young (0-40 yr) and middle-age stands (40-60 yr) also show rapid growth, with maximum C sequestration taking place between 40 and 70 years of age (Kurbanov 2002). Natural, fully stocked and unmanaged pine stands have a maxiumum net ecosystem exchange of 1.5 Mg C ha^{-1} yr^{-1} compared to 1.1 Mg C ha^{-1} yr^{-1} in disturbed and managed stands.

In Lakyda et al. (2002), C storage in the phytomass of Ukrainian forests was estimated at about 500 Tg of which about half (266 Tg) was contained in coniferous forests. A study of litterfall and soil organic matter (SOM) in the Krasnoyarsk region of middle Siberia showed that C accumulation in above and belowground SOM was greatest in larch stands and that coniferous stands contain 3 to 4 times more dead organic matter C in the above- and below-ground woody debris than deciduous stands in which decomposition is faster (Vedrova and Mukhortova 2002).

Two Russian studies used models to estimate future changes in biomass and soil C under current climatic conditions. Korovin et al. (2002) simulated long-term forest vegetation dynamics in Siberia and Far East Russia to show that a management strategy that gives sustainable maximum yield would also lead to stabilization of changes in biomass C. This, they suggest, was the result of an even balance amongst forests of different age structures.

For the Leningrad Administrative Area Chertov et al. (2002) used the model SOMM to assess the C balance in forest soils. After a 100- year simulation, a 30% decline in SOM in the organic layer and a 20% increase in SOM in the mineral soil resulted in a net increase of about 8%, or 20.7 Tg of C. Total C input to the soil and C emission from decomposition were roughly equal and reflect the relative stability of SOM pools in the forest soils of the region under the existing climate, stand structure and forest management.

Canada

The vulnerability of the C sink in boreal forests, referred to above, was illustrated in a simulation model study by Liu et al. (2002). Total forest biomass C in Ontario increased from 1.83 Pg to 2.56 Pg between 1920 and 1970 and then declined to 1.70 Pg by 1990. Carbon in soil and forest floor dead organic matter increased from 8.3 Pg to 11.0 Pg between 1920 and 1985 but then decreased to 10.95 Pg by 1990. Ontario's forest ecosystems sequestered between 41 and 74 Tg C yr^{-1} before 1975 but later became a C source releasing 7 to 32 Tg C yr^{-1}. This study is discussed in more detail in the section on disturbance.

Other Canadian studies examined factors affecting the variability of C estimates with a particular focus on belowground C pools. Global, national and regional scale estimates of C pools and fluxes are commonly based on a notion of average site conditions that are hard to define in highly heterogeneous landscapes. Better knowledge of the magnitude of this variability, factors that cause the variability in the landscape and how they are related to stand growth and C turnover is required to improve estimates of C dynamics at all spatial resolutions.

In central Canada, uncertainties in soil C estimates have been examined at polygon and regional scales (Bhatti et al. 2002). At the polygon scale, one empirical method estimated consistently higher soil C than another method—a difference that may be related to geomorphic and microclimate influences not accounted for in the lower estimate. Regional estimates, made using the two empirical methods and a model simulation, ranged from 6.2 to 27.4 kg C m^{-2}. Higher soil C simulated by the model arises in part because it accounts for components of the forest floor detritus that were not included in the other estimates.

In western Alberta, Banfield et al. (2002) used a model simulation to provide a regional estimate of biomass, forest floor and soil C stocks while forest inventory, plot and soil polygon data provided an estimate of their spatial variation. They found that inventory-based biomass-to-age relationships could be modified using a relationship between clay content and biomass C to assess variation across a region as well as to improve predictions at a higher spatial resolution.

Such a simple correction was not found, however, in a smaller scale study in northern Alberta (Little et al. 2002). Differences in leaf area index (LAI) and soil C between the top and toe of slopes in boreal mixed-wood forest conditions, illustrated small-scale variation that was not easily related to site factors.

Information about the C content, the chemistry of forest soil organic matter, and factors that control later stages of litter decomposition can also be used to assess factors causing variability in soil C dynamics. Tremblay et al. (2002) showed that in productive upland soils of southern Quebec, the C content of the forest floor and mineral soil could be predicted from forest floor thickness, soil horizon colour, texture class and pH — factors easily accessible in soil survey data. Models were developed and used to construct maps that indicated sites where C accumulation in forest soils may be susceptible to forest management practices.

Preston et al. (2002) found that C and N stocks and distribution of C and N amongst the size fractions of organic matter, varied between two Brunisolic soils and a Cryosol in three upland forest sites in central Canada. The clay-textured Cryosol had higher C and N stocks and a higher proportion stored in the very small ($< 63\ \mu$m) size fraction compared to the sandy-textured Brunisols. An increase in C stocks in the mineral soil horizons appeared to follow a trend of decreasing lessivage (mass transport within the soil profile), increase in pH and increase in exchangeable calcium.

Effects of litter quality and climate on decomposition rates of 10 different plant tissues and 1 wood block, were examined during a 6 year exposure at 18 upland sites across Canada (Trofymow et al. 2002). The mass remaining after six years could be effectively predicted from a limited range of climate (temperature and summer precipitation) and litter quality (acid-unhydrolyzable residue, AUR, and AUR/N) variables. The best set of variables for predicting decomposition, however, varied with the age of the litter, changing over the six year period. In the first year, litter quality properties and winter precipitation were important in predicting decomposition while in subsequent years, temperature, summer precipitation and a variety of litter-quality factors including AUR/N, were most useful.

Measurements of aboveground C have also been related to site characteristics. In Ontario, Chen et al. (2002), found that the relationship between net primary production (NPP) and stand age of black spruce (*Picea mariana* [Mill.] B.S.P.) was modified by site index (SI). Productive sites reached a maximum NPP after 40 years while less productive sites (peatlands) reached a maximum after 160 years. Differences in C allocation to woody components also varied with stand age and SI.

Longer term direct observations of C fluxes using eddy covariance techniques at various sites in the BOReal Ecosystem Atmosphere Study (BOREAS) region are providing useful insight on C dynamics. Measured C fluxes in black spruce, jack pine (*Pinus banksiana* Lamb.) and aspen (*Populus tremuloides* Michx) stands over one year in Saskatchewan have been made as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) initiative which seeks to extend the BOREAS observations to longer times (McCaughey et al. 2002). The study found that C fluxes were similar in the conifer sites but the C uptake for aspen was double that for black spruce in the summer while during winter and fall aspen lost significantly more C (Arain et al. 2002).

China

The long history of forest use by humans in China has led to large areas of degraded forests in the boreal regions of China (Jiang et al. 2002). However, China has some of the largest afforested/reforested areas in the world and high rates of afforestation and reforestation have resulted in the creation of larger forest areas than were expected under past forest development plans. This has had a large effect on the recent assessment of C budgets of forests in the temperate region of China (Xu and Zhang 2002).

Estimation of the current temperate forest C budget has been made using new data that includes tree C density in different age classes, soil C dynamics, wood utilization and the latest forest development plan (Xu and Zhang 2002). The F-CARBON model was developed to account for variation in the biomass densities and growth rates of the different age classes of forests and calculates the C emissions resulting from harvesting, burning and decomposition. For 1990, the C stock in China's temperate forest was estimated at 11.1 Pg C and the forest was a net sink for C with an uptake of 42.2 Tg yr^{-1}. Net uptake is predicted to increase gradually to 87.7 Tg C yr^{-1} in 2050 largely because of a predicted increase in biomass C.

Larch forests (Larix spp.) are important timber resources in China but are sensitive to global climate change. Forest biomass and net primary production (NPP) in the larch forests of northern China were estimated by Zhou et al. (2002) using models based on forest inventory data (FID). These models take into account the change in the ratio of forest biomass to volume with stand age and the effect of stand age on forest NPP. The relationships between NPP and biomass were not linear and these authors stress that natural and planted forests need to be treated separately when biomass and NPP of the forest are estimated. Wang and Zhou (2002) created a new NPP model based not only on FID but also on climatic data. This biology-climate model successfully simulated observed NPP data from larch forests and the authors suggest it may be applied to existing forest inventory data in other countries.

Europe

The C budget of soils and trees in the forests of western Europe was calculated for 1950 to 2040 (Liski et al. 2002). The C stock of both trees and soils increased over the period but the soil increasingly became the major C sink. In 1990, the estimated soil C sink was 26 Tg yr^{-1} or 32-48% of the contribution by trees but by 2040, the soil sink was projected to be 43 Tg yr^{-1} – about 65% that of the trees. The increase in soil C was attributed to an increase in litter inputs over time as the stands aged.

Joosten and Schulte (2002) caution that changes in management practices and environmental variables in Germany over the past 60 years have led to change in stand and tree characteristics. The authors found that tree density, ratio of height to DBH and average crown ratio were all significantly different from commonly used, but apparently out-of-date yield tables. The study suggested that the most reliable approach for calculating above-ground tree C was a cubic regression function that calculates the growing stock volume, and converts this directly into tree C content.

EFFECTS OF NATURAL DISTURBANCES ON CARBON DYNAMICS

Natural disturbances, in particular fire and insects, play an important role in the C dynamics of the circumpolar boreal forest on both short and long time scales (Kurz 2000). In the short term, disturbances cause direct emissions of C to the atmosphere as well as the transfer of C from living biomass pools to dead organic matter pools resulting in delayed emission through decomposition. In the long-term, changes in disturbance regimes bring about changes in the age-class structure of boreal forests. Major disturbances create large areas of rapidly growing young trees but also large amounts of decomposing residual dead organic matter. During a disturbance, and for a time after it, the net loss of C through decomposition (or combustion in the case of fire) may exceed the uptake of C in regrowth, and the affected stands function as C sources. As these stands age, the trees accumulate C from the atmosphere and replenish the decomposing forest floor stocks of C. Thus, changes in disturbance regimes at the landscape scale can result in periods in which large areas of forests act as either sinks (average age is increasing) or sources (average age is decreasing).

Average disturbance rates in Canada's forests have nearly doubled since 1970, largely as a result of increased incidence of fires, having a profound influence on the C budget (Kurz and Apps 1999). The effect of this increased disturbance was demonstrated by Liu et al. (2002) in their study of the boreal forest in Ontario. They found that between 1970 and 1990, increased disturbance (fire, insects and harvesting) resulted in the C sink changing to a C source. The young average age of the forest in 1990 (36.2 yr) indicates a high potential for C sequestration and under a less severe disturbance regime Ontario's forests would convert back to a sink.

In a study at the national scale, a simulation experiment related the amount of C stored in the Canadian boreal forest landscapes to length of fire cycle (Li and Apps 2002). More ecosystem C was stored in landscapes with long fire cycles than in landscapes with short fire cycles. In addition, more frequent small fires and less frequent large fires appear to be associated with long fire cycles and result in less variation in ecosystem C. Less frequent small fires and more frequent large fires, associated with short fire cycles result in larger interannual variation in ecosystem C.

The effect of changing the fire cycle on tree density and C storage was simulated in aspen stands and white spruce (*Picea glauca* (Moench) Voss) - aspen stands in central Canada (de Groot et al. 2002). In Alberta reducing the fire cycle from 263 yr to 196 yr increased aspen stem density and total C stocks. Because the fire cycle of 263 years is greater than the lifespan of aspen, trees were overmature and declining. Reducing the fire cycle prevented this decline and allowed vigorous regeneration after fire. Reducing the fire cycle from 88 yr to 65 yr in aspen stands in Saskatchewan resulted in a smaller average stem diameter and less C stored. Overall however, the shorter fire cycle of the Saskatchewan aspen stands will promote rapid suckering of aspen and these stands will store twice as much C as the Alberta aspen stands with the longer fire cycle. This suggests that there is a fire cycle between 88 and 196 years that will allow aspen stands to reach a maximum C storage. Overall C storage was not affected by the fire cycle in aspen-spruce stands although aspen density increased relative to spruce in the 65 year cycle.

Fire also influences the energy flow at the soil surface which in turn affects soil respiration, post-fire vegetation regrowth and C sequestration. Growing season albedo, measured before and after fire in a black spruce ecosystem in Alaska, was reduced in 46% of the burned area, increased in 40% and stayed the same in 14% of the burn (French et al. 2002). Whether albedo increased or decreased depended on the pre-burn vegetation and the burn severity. However, after five years of vegetation regrowth, albedo was higher throughout the burned area than in the unburned area.

Changes in vegetation composition can have a significant effect on the fire regime. Rupp and Starfield (2002) simulated the role of black spruce ecosystems in the fire regime of the interior Alaska boreal forest and found that both the number of fires and the total area burned increased as black spruce stands became an increasingly dominant component of the forest landscape. Increasing the areal extent of white spruce stands resulted in fewer fires and smaller area burned. Ecosystem flammability accounted for the majority of the differences in the distribution of the average area burned. These results suggested that not only do differences in vegetation have a significant impact on the fire regime, but that the large scale fire events resulting from increased black spruce forest also have the potential to alter future distribution of the vegetation.

The short term impact of fire on the global C budget is also significant but high interannual variability and difficulties in acquiring accurate data make estimations of the size of the impact problematic. For example, Conard et al. (2002) suggested that the extent and global importance of forest fires in the boreal zone in Russia have often been underestimated. Using remote sensing data, it was estimated that in 1998, a major fire year, 13.3 million ha of forest burned in Russia releasing between 135 and 190 Tg C or 14 to 20% of the average annual global C emissions from forest fires.

These authors believe that this is a conservative estimate and suggest more research is required to improve measurements of the extent and severity of forest fires and their potential impacts on C emissions in the boreal zone.

Assessment of C emissions associated with forest fires has been examined by several Russian authors. In Central Siberia, regional C emissions from fires of differing intensity were estimated from C accumulation in different types of pine stands with various mean fire intervals (Ivanova et al. 2002). These authors reported that emissions can vary by an order of magnitude between fire seasons because of high interannual variability in the burned areas and fire intensity. Estimates of total C emissions resulting from forest fires also require knowledge of long-term, post-fire C dynamics that occur during succession (Sofronov et al. 2002).

Isaev et al. (2002) developed a map of forest fire damage that could be used to assess C emissions in Siberia. The degree of stand damage in a burned area, estimated from national security satellite images and large–scale aerial photography, correlated well with differences in the normalized difference vegetation index (NDVI) for pre- and post-fire images. Superimposition of stand damage and potential ground/ crown fire maps produced a map which shows the spatial distribution of fire types and intensity and which could also be used to produce estimates of C emissions.

Lightening strikes are a major source of boreal forest fire ignition and, in Siberia, start 30% of all forest fires (Ivanov 2002). A study of seasonal and daily storm dynamics (1986-1992), and storm data over a 20 year period, showed that lightening-induced fire ignition was associated with local storms and occurred most often in stands dominated by light needle tree species (Ivanov 2002). Areas with high geomagnetic anomaly also appeared to have a larger number of lightening strikes.

Volokitina et al. (2002) studied the dynamics of biomass consumed during fire, depending on seasonal and weather factors, and proposed a method to construct large-scale fuel maps in Russia, based on the existing classification of vegetation fuels. Vegetation fuel classes, which play a leading role in fire incidence and spread, and a critical class of drought are included on the map in order to estimate how much biomass will be consumed in a fire.

Fire is not the only important disturbance agent in the boreal forests. Over the period 1920 to 1995, Canada's forests experienced some 2.22 million km^2 of stand-replacing disturbances, of which 48% involved fire and 36% insects (Kurz and Apps 1999, W.A. Kurz and M.J. Apps, unpublished data*)*. The importance of insect defoliation on C storage in Canada's forests is currently being modeled to assess and develop forest management options and strategies for mediating the effects of insect disturbance (MacLean et al. 2002).

Insect defoliation is not only a direct disturbance of the forest ecosystem but may also increase the potential for fire outbreaks. In Ontario, 417 thousand km^2 was defoliated by spruce budworm (SBW) (*Choristoneura fumiferana* (Clem.) at least once between 1941 and 1996 (Fleming et al. 2002) and 7.5% of the areas containing trees killed by SBW were burnt in western Ontario compared to 4.8% in the eastern part of the province. These regional differences may result at least in part from slower decomposition of dead fuels in the drier, western climate. The higher decomposition rate in eastern Ontario not only shortens the length of time after SBW-caused tree mortality during which the fire potential remains high, but also reduces the likelihood that such a stand will be burned before it regenerates. In a climate change scenerio of warmer and drier conditions, it is likely that slower rates of decomposition and more frequent drought conditions will result in more fires in post-outbreak stands.

In addition to direct stand mortality and interaction with fire, insect defoliation contributes to the dieback and reduced growth of trembling aspen observed in some Canadian provinces since the early 1990s (Hogg et al. 2002). Trembling aspen is the most important deciduous tree species in the Canadian boreal forest and is a significant component of the C cycle at the national scale with about 1000 Tg of C contained in the aboveground biomass. Dieback in Grande Prairie, Alberta was related to insect defoliation as well as drought and thaw-freeze events, all of which may be increased by climate change and affect C sequestration by the forested ecosystems of the region.

Windthrow is also a major disturbance over much of the boreal region, creating large amounts of CWD and in the process transferring large amounts of C from storage in trees to storage in the soil compartment where it may have a much longer turnover time. Windthrow was the main disturbance in the unmanaged boreal forests of the Saint Petersburg region of Russia where it strongly influenced the dynamics of C in both living and dead wood (Shorohova and Soloviev 2002). C stored in living trees ranged from 30 to 172 Mg C ha^{-1} and was largest in even-aged stands when the growing stock was increasing (as in the immature phase) or relatively stable (as in the mature phase). The amount of C in CWD (4.5 – 61.5 Mg C ha^{-1}) was largest in ecosystems undergoing stand breakup (i.e., where the growing stock declines), such as those stands suffering windthrow. This phase lasted from one to several decades depending on the intensity of the windthrow event and other stand conditions.

EFFECTS OF MANAGEMENT PRACTICES ON CARBON DYNAMICS

Uncertainty surrounding the regulatory policy response to increased global CO_2 emissions makes decisions about how to manage forest resources difficult (Weyerhaeuser 2000). However, most of the choices today are straightforward even in the absence of a definitive international forest C accounting protocol. Reducing fossil fuel CO_2 emissions through energy conservation and increasing C sequestration by growing more wood are both likely to be valuable to producers of forest products.

A market price for reduced C emissions will likely provide incentives for maximizing forest regrowth through practices such as early regeneration and careful stocking control, for minimizing forest waste while maintaining soil productivity and for managing fire and pest outbreaks. There may also be incentives to fertilize forests and to shorten rotation age if carbon storage in forest products is taken into account (although this is not the case under present IPCC guidelines for reporting).

Foreward looking forest product companies, however, will not wait for certainty before they act on the carbon issue but instead are beginning now to assess the C budgets of their forest operations and to introduce ways to mitigate their emmissions. To this end, current forest C models must be refined to better predict the effects of management practices at local levels and longterm field observations need to be put in place to confirm model predictions.

The use of three simulation models to examine the effects of silvicultural and harvesting practices on long-term C storage in North American and Chinese forests were reported. The ecosystem simulation model, FORECAST, was used to investigate the effects of harvest frequency and tree species on C storage in a boreal mixed-wood forest type in northeastern British Columbia, Canada (Seely et al. 2002). The initial conditions were created from a mixed-wood stand on a mesic site of medium nutritional quality with a fire interval of 150 years and a total simulation time of 300 years. The model predicted larger total ecosystem C storage with increased rotation length, regardless of tree species. The influences of species on ecosystem C storage and accumulation rates were, however, evident: for equivalent rotation lengths (•90 yr) total C storage was largest for aspen followed by pine and spruce. Species biomass accumulation rates were highest in the shortest rotations for aspen (< 75 yr), in mid-length rotations for pine (75 yr) and longer rotations for spruce (>100 yr). Soil C showed a slow decline in managed stands relative to those undergoing natural disturbances.

The STANDCARB model was used to examine the effect of various management techniques in a coastal forest dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirab.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg) in Oregon, U.S.A. (Harmon and Marks 2002). This forest is distinguished from the boreal forest by its wetter climate and longer growing season. Conversion of old-growth forest to any other management or disturbance regime resulted in a net loss of C whereas the conversion of an agricultural system to forest plantations doubled the total C stored in about 100 years. The model found that C storage increased as rotation length increased but decreased as the harvest intensity (fraction of trees harvested and detritus removed) increased.

The CENTURY 4.0 model was used to examine the dynamics of C stocks and the impacts of different harvesting regimes in the Chinese boreal forest (Jiang et al. 2002). Simulations were run for 2000 years to establish a steady state initial condition, and scenarios were run for 5000 years with analyses performed on the last 400 years. Results were similar to the above models with C storage lower in short rotation (30 yr) forest plantations than in long rotation (200 yr) plantations. The effect of different harvest regimes on total C stocks, averaged over 100 yr, resulted in 131 Mg C ha^{-1} under whole tree harvesting (100% removal of stems, 90% removal of branches), 158 Mg C ha^{-1} under conventional harvesting (100% removal of stems, branches left on site) and 462 Mg C ha^{-1} under a no-harvest reference regime. The model simulations suggest that reducing harvest intensity and extending rotation length may be a good strategy for maintaining the sustainability of production and maximizing C storage in Chinese boreal forests.

All three models showed that increasing rotation length increased C stocks in the forest ecosystems. The FORECAST model (Seely et al. 2002) suggested that by selecting appropriate species combinations and rotation lengths, it may be possible to balance the competing demands of fiber production and C storage. A landscape that includes stands with management practices optimized for timber production and stands with management to maximize long-term C storage could meet both these demands. Simulations with STANDCARB (Harmon and Marks 2002) and CENTURY 4.0 (Jiang et al. 2002) also suggested that an adequate supply of wood products may not be incompatible with practices that increase C stocks. For example, partial harvest and minimal use of fire may provide as many forest products as a traditional clearcut/broadcast burn system while at the same time increasing C stocks in the forest ecosystem.

Short term effects of harvesting techniques reported in two Canadian field studies, supported the results of the simulation models. In north central Ontario, Lee et al. (2002) showed that partial cutting (2/3 volume removed) in a second-growth boreal mixed-wood stand resulted in higher C assimilation rates in woody biomass of the saplings and trees than clearcutting over a five year period, although the results of both treatments were lower than in the unharvested control plots. The forest floor, sampled seven years after harvesting showed no differences in organic mass among the treatments likely because of an increase in litter fall from rapidly re-established ground cover and aspen and similar decomposition rates among the treatments. The authors suggested that if harvesting were to occur, ecosystem C assimilation in boreal mixed-wood would be maximized under a partial cutting regime although the lower timber productivity and higher costs associated with this harvesting technique may reduce its attractiveness.

Direct observations of above-ground and below-ground fluxes of CO_2 on a vegetated five-year old sub-Boreal clearcut in central British Columbia showed that the site was a sink for CO_2 during the growing season (Pypker and Fredeen 2002). However, if the entire year was considered, belowground efflux was sufficiently high to make the site a source on an annual basis. Natural deciduous plants were a much more important CO_2 sink than the planted conifers (375 and 48 g C m^{-3} respectively) and the authors suggest that removal of deciduous “non-crop” vegetation should be avoided to minimize the loss of C in the early stages of stand development.

Nitrogen (N) fertilization is a management technique that not only increases tree productivity but also forest C storage. In the FORECAST model described previously, Seely et al. (2002) simulated the application of 250 kg N ha^{-1} in years 10 and 25 of a 30 year harvest cycle of an aspen stand and found that there was a net increase of 13% in average C storage in all ecosystem pools. Most of the increase was attributed to greater C retention in wood products and biomass pools.

Field studies in Canada and Siberia suggest that the effects of N fertilization vary with site quality and change over time. A productive, overstocked, 45-year old jack pine forest in northeastern Ontario did not respond to normally recommended rates of N fertilization (Foster and Morrison 2002). Fertilization with urea at five levels up to 448 kg N ha^{-1} did not affect either the gross and net stand C increment (compared to a control) after about 10 years or the maximum amount of C in the stand over 30 years, although an increase in dbh in co-dominant trees was noted at 10 years. The unfertilized stand was able to capture sufficient inherent site N to expand its crown mass and N content until maturity and, from a management perspective, productive jack pine stands on high quality sites should be given low priority when considering the use of N fertilization to increase short-term C sequestration.

The effect of N fertilizer on even-aged pine stands (15 to 110 years old) in Siberia showed that 200 and 400 kg N ha^{-1} resulted in a transient increase in the overall phytomass of trees during the first 3 years followed by a second peak in growth 7 to 8 years later (Buzikin et al. 2002). This "echo effect" was small in large diameter trees when fertilizer doses were small and the smallest trees showed a decline in increment after fertilization. The "echo effect" may be attributed to increased production of needles resulting in larger amounts added to the litter layer and increased N recycled through the soil.

Annual additions of complete fertiliser containing ca 70 kg N ha^{-1} to young boreal stands of Norway spruce (*Picea abies* (L.) Karst.) over 15 years in northern Sweden have resulted in over four-fold increase in stem volume and C storage (Gower el al. 2000). Large annual net ecosystem C fluxes of 6 – 7 Mg C ha^{-1} have been measured over the past five years in Sitka spruce on a moderate quality site, intermittently fertilised with urea in oceanic Scotland at a latitude similar to that of the BOREAS sites in Saskatchewan (Gower et al. 2000). However, in the overall context of exchanges of GHGs between forests and the atmosphere, some reservations must be made at the present time with respect to increases in C sequestration as a result of fertilisation with N. There is a possibility, as yet not adequately evaluated, that addition of N-containing fertilisers may lead to significant emissions from forest soils of nitrous oxide, N_2O. Molecule for molecule, this gas has a global warming potential 300 times that of CO_2, so that even small emissions may off-set substantial amounts of net CO_2 uptake.

AFFORESTATION AND CARBON SEQUESTRATION

Afforestation and reforestation are recognized under the Kyoto Protocol as potential mechanisms that may be used by countries to offset their greenhouse gas emissions by increasing the strength of their biological C sinks. Afforestation and reforestation can be defined as the conversion of non-forested lands to forests with the only difference being the length of time during which the land was without forest. Reforestation occurs when planting trees on non-forested land that was forested at any time within the 50 year prior to 1990, whereas afforestation occurs on land that has never been forested or at least was not forested in the similarly defined 50 year period. The achievement of real afforestation gains is tied to the anticipated economic returns from both the additionally sequestered carbon and the additional timber produced.

In Saskatchewan, Canada, the land base potentially available for afforestation (estimated as private lands currently under unimproved pasture and within 100 km of existing mills) is about 260,000 ha and could potentially sequester 5.9×10^6 Mg of C over the next 80 to 100 years (Johnston et al. 2002). Economic predictions showed that the desirability of afforestation with aspen, white spruce or hybrid poplar plantations declined as the discount rate increased beyond 3%. Distribution of revenues from timber sales to land owners early in the life of the plantation and putting an economic value on sequestered C would increase the viability of afforestation in Saskatchewan.

Another Canadian study of the afforestation potential in Ontario and the Prairie provinces identified the C price needed for the net present value of afforestation to be equivalent to the opportunity cost of agricultural land use (Stephens et al. 2002). For parts of Ontario, afforestation with red pine may be economically viable at C prices between \$15 and \$35 Mg^{-1} C. For the Prairies, afforestation using hybrid poplar was viable at prices above \$25 Mg^{-1}C.

In the Ukraine, potential afforestation and reforestation of about 2 million ha of low productivity land and wastelands and creation of forest stands along rivers and canals would increase the forest area by almost 20% (Nijnik 2002). However, most of this afforestation would not be feasible using a discount rate of 4% unless the C sequestered had economic value. A Swedish study of forest strategies for reducing GHG, that did not include socio-economic considerations, suggested that within a 10-30 year time frame, afforestation with willow and intensive N fertilization of spruce stands would be the most successful strategies (Olsson 2002), but there are potential, but hidden dangers of N_2O emissions with intensive N fertilisation, as mentioned earlier.

Afforestation can also increase C stocks in the soil and such C is generally considered more resistant to changes in forest management than that stored in biomass. A chronosequence study of oak (*Quercus robar* L.) and Norway spruce planted on a former highly productive arable cropland in Denmark showed that, although C storage in the upper 5 cm of the mineral soil increased, at lower depths it declined as stand age increased to 29 years. This led to similar total (but differently distributed) soil C stocks of around 65 Mg C ha^{-1} along the chronosequence (Vesterdal et al. 2002). The decrease in soil C below 5 cm was thought to likely be a result of C inputs from the young stands being insufficient to match the ongoing decomposition of C inherited from agriculture. The authors suggest that afforestation of nutrient rich arable soils does not lead to significant sequestration of C in soils within 30 years although faster sequestration in afforested soils may occur on poorer soils where organic matter decomposition is slower.

Similarly, in a simulation of conversion of an agricultural system to a forest system in the Pacific Northwest, U.S.A., Harmon and Marks (2002) found that total C storage increased significantly in about 100 years but pointed out the importance of initial soil conditions to the end result.

In addition to its role in C sequestration, there are advantages of afforestation that have not been given an economic value, but are important to sustainability of the resource. Factors influencing this sustainability include soil stabilization, restoration of soil organic matter, maintainance of ground water quality, increasing wildlife habitat diversity and expanding the resource base (Johnston et al. 2002; Nijnik 2002; Vesterdal et al. 2002).

To supplement the benefits of afforestation, biofuels that are produced from wood and used to replace a portion of fossil fuel combustion, may be used to reduce net GHG emissions. O'Connor et al. (2002) used Delucchi's full fuel cycle GHG model to calculate GHG emissions from production and combustion of biofuels under different landscape scenarios. They found that over the long term (100–500 yr), use of forest residues (branches, tops, needles) as a biofuel was effective at reducing GHG emissions. These authors suggest that ethanol produced by short-rotation forestry on afforested land was significantly better at reducing GHG emissions than ethanol produced from short-rotation forestry on previously forested lands (O'Connor et al. 2002).

In order to document actual changes in afforestation and deforestation at a national scale, a suitable monitoring system must be put in place. In Canada, the recently developed National Forest Inventory (NFI) with its 20,000 primary sample units, each 2 x 2 km (400 ha) in size, will provide useful land-use data on forest C but may not be sufficiently precise to accurately estimate afforestation or deforestation that often occurs in small and scattered areas (Leckie et al. 2002). Integration of the NFI system with satellite imagery and existing land use records will improve measurements particularly where deforestation activity is high.

Persistent deforestation documented in southern portions of the boreal forest in Saskatchewan between 1960 and 1990 (Fitzsimmons 2002) also highlight the need for a more detailed accounting system of afforestation and deforestation. A comparison of sequential maps from Canada's National Topographic system allowed an estimate of changes in total wooded area but did not provide specific information on vegetation that would allow a calculation of forest C lost. Rates of deforestation were highest in agricultural regions (-1.21 to -1.27%) and negligible in public forests and parks. The authors suggest that in this region, continued clearing of existing forests could outweigh the potential C gains from afforestation and reforestation.

EFFECTS OF CLIMATE CHANGE AND ELEVATED CO_2 CONCENTRATION ON CARBON DYNAMICS

Accurately quantifying the rate and extent of high latitude warming, and the impacts of this warming on ecological systems should be a high priority for boreal scientists (Running 2000).

The studies included in this section modelled or measured effects of increased annual temperature, precipitation and/or CO_2 concentration on vegetation distribution and C stocks, and ranged in spatial scale from national to individual trees and in time from many years to several growing seasons. Results suggested that while climate change may cause shifts in vegetation distribution that could reduce forest area, forest productivity was generally increased by higher temperature and CO_2 concentrations.

In a study of boreal forests in northeast and northwest China, Ni (2002) found that increased mean temperature (3.5-4° C) and precipitation (51-88 mm), modeled by BIOME 3, resulted in a significant northward shift of the boreal forest. Under the present climate, higher and lower CO_2 concentrations (500 ppmv and 200 ppmv respectively), caused a reduction in the area of boreal forest which indicated a nonlinear effect on boreal forest distribution. Both climate change alone and climate change with CO_2 enrichment significantly reduced the C stored in vegetation and soils.

In Russia, Siberian climate change impacts are expected to be important and complex. Models simulating a 2° C increase in summer temperature and a 20% increase in annual precipitation predicted lowland vegetation to shift 250 m upslope and highland vegetation to shift 450 m upslope resulting in considerable reduction of tundra and light needled taiga, and expansion of the forest-steppe (Tchebakova and Parfenova 2002). The mountain forests surrounding Lake Baikal in Russia filter about 90% of the water flowing into the lake and the health and condition of these forests strongly determines the quality and quantity of its water. Thus, under expected warmer summer temperatures, the filtering capacity of the forest-steppe would be weaker than that of the mountain forests with a resulting potential deterioration of the quality of water in Lake Baikal. This could have significant consequences as Lake Baikal represents as much as ¼ of the world's reservoir of fresh water.

In his study of soil C in Russia, Stolbovoi (2002) hypothesized that soil warming caused by climate change may result in deeper peat accumulation in the tundra zone and expansion of the steppe into the temperate forest zone. Such changes he suggests, would result in increased levels of soil C in Russia in the future.

To examine the possible impacts of climate change on economic welfare and land-use shifts between forestry and agriculture in the United States, Alig et al. (2002) used two global circulation meteorological models to feed into two ecological process models, thereby creating four climate change scenarios for 2070-2100. They found that forest productivity, C storage and total economic welfare are all higher under all scenarios.

The effects of an annual temperature increase of 4°C, an 8.7% increase in annual precipitation and a CO_2 concentration of 700 ppm on the dynamics of the forest at the ecotone of the boreal and temperate forest in Northern China, were simulated using a modified adapted gap model BKPF (Chen 2002). After a 50-year simulation, the density and LAI of the forest regenerating from clearcutting were not significantly different, but the productivity and aboveground biomass were higher, under climate change than under current conditions. The effect of climate change on the current undisturbed forest was to reduce stand density by 20% and aboveground biomass by 90%. Althouth the stand productivity did not vary significantly, a significant change in species composition occurred.

Also in China, Jiang and Zhou (2002) used the CENTURY 4.0 model to simulate the effects after 50 years of a 2° C increase in temperature, a 20% increase or decrease in precipitation and a CO_2 concentration of 700 ppm, on cold temperate conifer forests dominated by *Larix gmelini* (Rupr.) Kuzeneva. Regardless of changes in precipitation, increasing the temperature caused soil C to decline, gross plant biomass and NPP to increase and the annual capacity of the forest to sequester C to increase by about 10%. Doubling the CO_2 concentration above current concentrations resulted in a 10% increase in forest NPP and slightly increased the size of the net C sink.

Yarie and Billings (2002) also used the CENTURY model to evaluate the effect of a 5° C increase in mean annual temperature on future C dynamics in the Alaskan boreal forest. All ecosystems (aspen, paper birch (*Betula papyrifera* Marsh.), balsam poplar (*Populous balsamifera* L.), white spruce and black spruce) showed a higher net ecosystem productivity (NEP) and all required less time after a disturbance to shift from being a C source to a C sink at the higher temperature. The model estimated that current vegetation of the boreal forest in Alaska absorbs approximately 9.65 Tg C yr^{-1} but with the temperature increase could absorb 16.95 Tg C yr^{-1}.

Many studies use models to predict the effects of climate change on forest C dynamics but different assumptions made by these models about ecosystem processes, make comparing their results difficult. The CENTURY 4.0 and the FOREST-BGC models, calibrated for a productive black spruce stand in Ontario were used to predict forest productivity under climate change and their outputs were compared (Luckai and Larocque 2002). Both models predicted similar relative increases in C storage with an average temperature increase of 6°C or an increase in CO_2 concentration to 700 ppmv, but they disagreed on the impacts of increased temperature in combination with elevated CO_2 concentration. Comparison of both models indicated that the representation of critical processes in these two forest ecosystem models is incomplete.

Several field studies on the effects of increased temperature and/or CO_2 concentrations on individual tree species were reported. Stands of Scots pine (*Pinus sylvestris),* at their northernmost limits on the border between Norway, Russia and Finland, were well-suited to revealing climatically induced growth trends (Alekseev and Soroka 2002). Recent increases in radial increment growth (over the last few decades) relative to the period of last registered warming (1930-40) was attributed to both climate warming and higher levels of CO_2.

In a long-term field study of the effect of CO_2 enrichment on four tree species, Sigurdsson et al. (2002) found that a CO_2 concentration of 700 ppmv increased the light-saturated rate of photosynthesis (C uptake) by 49-114%. The relative increase of photosynthesis by elevated CO_2 concentration was found to be strongly dependent on temperature and lead to the suggestion that enhancement of C uptake by elevated CO_2 concentration may be less at high latitudes.

Increased winter temperature (+4°C) resulted in earlier bud break in downy birch (*Betula pubescens* Ehrh.) seedlings after one winter while an increase in CO_2 concentration to 650 ppm stimulated shoot elongation and biomass accumulation in subarctic and southern populations of birch from Norway and increased biomass in Norway spruce (Skre and Næss 2002). Strong interaction effects with nutrient levels were also noted.

The most significant changes in forest C sequestration are likely to occur in the spring when temperature strongly regulates events such as the timing of bud burst and the onset of photosynthesis (Leinonen and Kramer 2002). However, the ability to monitor spring freeze/thaw events at high latitudes is at present severely limited because of lack of people and human infrastructure for monitoring stations (Running 2000).

Remote sensing might provide an alternative technology for high latitude monitoring that is consistent, repeatable and complete in coverage (Running 2000). Past research found that persistent cloud cover and winter lack of solar illumination restricts the use of normal optical remote sensing. Radar research in the early 1990s, however, discovered that the backscatter signal from a radar sensor clearly identifies the distinction between frozen and thawed land surfaces, even under clouds and in complete darkness. A prototype radar satellite information system that would cover the entire 50 million km^2 of seasonally frozen land surface daily, and continuously monitor changes in the area of frozen ground has been developed. Daily freeze/thaw information from such a system provides an interesting new hydroecological measure of seasonal phenology by clearly quantifying the onset of spring snowmelt and somewhat later the budburst phenology of vegetation.

State-of-the-art terrestrial process-based models that currently tend to simulate the onset of spring drawdown of CO_2 too early and underestimate the interannual variablility (Dargaville 2002), would benefit from the increased accuracy provided by such information

Both the effect of increased temperature on spring recovery of photosynthetic capacity and interannual variability were studied in modelling and field experiments. Leinonen and Kramer (2002) compared three models, developed and parameterized for predicting the timing of bud burst in birch, and found that all models predicted earlier bud burst as a result of a 2°C increase in temperature. Comparison of the seasonal changes in the photosynthetic capacity of deciduous and coniferous trees resulting from the temperature increase was made using a fourth model, developed for Scots pine. Although the results of all four models are not directly comparable, since different mechanisms determine the photosynthetically active period in conifers and deciduous trees, they do demonstrate the difference in the temperature effects in models developed for different tree species. The pine model predicted a stronger increase in radiation under changing climatic conditions compared to the birch model.

A comparison of two model studies on the effects of air temperature on the recovery of the photosynthetic capacity of boreal conifers during spring, showed differences in the ecophysiological assumptions related to photosynthetic dormancy during winter, reversibility of the recovery and the effects of frost (Hänninen and Hari 2002). Both models predicted an increase in the photosynthetic capacity as a result of rising temperatures although the model developed and parameterized for Scots pine predicted earlier recovery than the model developed and parameterized for Norway spruce. Additional simulations, carried out to compare predictions for the photosynthetic production of Scots pine, showed that the Norway spruce model predicted 23% higher values than the Scots pine model on average. Both these studies (Leinonen and Kramer 2002, and Hänninen and Hari 2002) suggest that predicting future C sequestration in different tree species requires further model refinement.

Significant effects of comparatively high temperatures in the spring were measured in several field studies. In Canada the responses of a temperate mixed-wood stand in Ontario, and a boreal aspen stand in Saskatchewan, to interannual climatic variability from 1996-1998 were examined using eddy-covariance CO_2 flux measurements (Barr et al. 2002). Both sites showed large interannual variability in NEP but the causes of this variability were different. In aspen, a warm spring in 1998 caused early leaf out and increased photosynthesis but had little effect on respiration. In the mixed-wood forest, the same warm spring also caused early leaf out but increased respiration and drought stress. The contrasting impact of the warm spring on annual NEP at the two sites reflects competing influences of climate change on NEP: spring warming, which promotes photosynthesis and increases NEP, and increased soil temperature and drought, which promote ecosystem respiration and reduce photosynthesis, thus reducing NEP.

The responses of NEP to seasonal and interannual climatic variability were also studied by Arain et al. (2002), in an aspen forest and black spruce forest at the BOREAS sites in Saskatchewan. Warm springs enhanced NEP in both forests but high mid-summer temperatures significantly reduced the NEP at the black spruce forest as a result of higher ecosystem respiration. A newly developed C exchange model predicted that the aspen forest was a weak to moderate C sink while the black spruce forest was a weak C sink in cool years and a weak C source in warm years.

SUMMARY

Considerable progress has been made with improving estimation of C stocks in circumboreal forests. These efforts have effectively lead to the identification of key information and knowledge gaps enabling scientists to focus their research efforts. Advances have been made with improving techniques to increase accuracy of tree biomass estimation from inventory data. Challenges remain to unify and standardize estimation procedures and national data sets that must be brought together from a wide variety of sources including private land owners, private industry and highly diverse political jurisdictions.

Peatlands and other organic soils, which are known to contain a large percentage of the

C reserves in boreal forests remain a major challenge. There is a need to improve approaches to estimating C stocks in organic soils and to understanding of contemporary peatland processes in the context of a changing climate.

Progress has been made with integrating the effects of disturbance (natural and anthropogenic) on age-class structure and interpreting the resulting impact on large-scale temporal C dynamics. Future research in this area will have to integrate more complex relationships between predicted changes in weather patterns, their effect on multiple large-scale natural disturbances, changes in vegetation distribution patterns and their interaction with harvesting and silvicultural practices. The emerging and possibly greater challenge may lie in assembling this knowledge in a spatially explicit framework to facilitate the development and application of forest management tools to mitigate GHG emissions.

Researchers are beginning to tackle the problem of identifying regional or site specific factors that determine variablility observed at larger scales. Many of the papers presented at the conference examined factors controlling variability in soil carbon and detritus and the relationship or feedbacks between them and above-ground productivity. Model simulations in western Europe, where forests are intensively managed and impacts from natural disturbances such as fire are markedly less than in North America and Siberia, have shown that sequestration of C in soil increased in importance over time from 1950 to 2040. Understanding the processes that control C sequestration in soil is important, especially if a management strategy is invoked to reduce CO_2 emissions by controlling disturbance regimes in boreal forests where disturbance frequency is predicted to increase.

This trend towards understanding links between tree species, detrital inputs and soil will be pivotal in the development of management strategies for C mitigation and the increased understanding that is required for large scale assessments. The greatest gains will likely be realized by nesting regional studies within a larger-scale spatial framework that adequately reflects large-scale disturbance patterns (anthropogenic or natural) which are now understood to impact C dynamics strongly through their influence on age-class structure.

Although afforestation and reforestation (as defined in the Kyoto Protocol) are recognized as a creditable mechanisms for C sequestration under the Kyoto Protocol, many questions will have to be resolved for such programs to succeed. At a national scale, monitoring and reporting procedures to accurately estimate changes to areas of afforestation and deforestation need to be developed. At a scale where afforestation management practices could be applied, site specific ecological and regional economic considerations must be addressed to simultaneously satisfy the goals of increasing C sequestration and meeting the economic needs of private land owners. Land identified with potential for afforestation frequently occurs in the forest/grassland transition zone — areas that are expected to be highly sensitive to climatic change. Considerable research will be required to determine suitable tree species, rotations, and site types that are most likely to succeed in an afforestation program.

Tax incentives may be required to motivate land-use change from agriculture with short-term economic returns to forestry with long-term economic returns. Some economic value may have to be placed on the additional benefits of afforestation that contribute to sustainability of a broader suite of forest resources including soil and water quality and wildlife and their habitat.

Large-scale model simulations have tended to conclude that the increase in temperature predicted as a result of climate change will increase NEP. Several model simulations indicate that NPP will increase to a greater degree than the increase in heterotrophic respiration, although this is not uniformly agreed. Whilst addition of a carbon cycle to large-scale models and GCMs in real time is a major step forward, confidence in the the predictions is limited by incomplete understanding the C cycle processes, particularly their acclimation to temperature and CO_2, and linkages to nutrient cycles. Furthermore, many of these large-scale models do not yet adequately include the impacts of changing disturbance regimes on both production and respiration fluxes. Such changes are of particular concern with respect to forests in the boreal zone under a changing climate.

Models that predict vegetation distribution patterns in response to climate change indicate that vegetation zones may shift northwards and to higher elevations in response to an increase in mean annual temperature (MAT) and atmospheric CO_2 concentrations. Cross model comparisons for ecosystem response to both climate change and elevated CO_2 concentrations indicate caution should be exercised when broadly applying a model developed in one region or for one species.

Numerous studies show significant, if poorly understood, changes with altered temperature regimes and that temperature may be a more controlling factor than elevated CO_2 concentration in many forest ecosystems. On shorter time scales (decades) variations in the disturbance patterns that accompany changes in MAT and precipitation patterns may play a dominant role.

An increase in MAT is expected to exert a significant influence on NPP in the boreal region through earlier bud burst and earlier onset of photosynthesis. However, several papers showed that this response is species specific and that there are significant differences in response between coniferous and deciduous treesTemperature-induced causes of interannual variability were shown by eddy covariance studies in Canada to be different for a temperate mixed-wood stand and a boreal aspen stand. Another Canadian study indicated that higher temperatures affect NEP throughout the growing season (not just in spring) and that the nature of the effect is a function of stand type (Arain et al. 2002).

Assessments of C fluxes in boreal forest ecosystems suggest that while most stands may currently be sinks for C, natural disturbances such as fire and insects, and tree harvesting, make a forest region suseptible to becoming a C source. In Ontario, Canada, such a situation appeared to have occurred in the last 30 years, while in Russia, the large proportion of mature and over mature stands suggest that this region may also become a source as harvesting and natural disturbances increase.

In contrast to this, other work suggests that climate change will cause shifting vegetation patterns, increased soil C and higher forest productivity that could result in higher C sequestration in the boreal forest. Ongoing research into the effects of a warmer, earlier spring season, changes in C storage in peatlands and mineral soils, and better monitoring of C losses due to natural disturbances will all contribute to a more accurate assessment of future C dynamics. Evaluation of contemporary forest management practices suggest that longer rotations and partial harvesting can sequester additional C, and these gains can be consistent with timber production goals. Management simulations, however, need to be refined to better estimate the role of soil C and understorey vegetation in order to give a more complete picture of C dynamics in managed forest systems.

REFERENCES

Alekseev, S. A., and A.R. Soroka. 2002. Scots Pine growth trends in northwestern Kola Peninsula as an indicator of positive changes in the carbon cycle. Climatic Change 55(1-2): 183-196.

Alig, R.J., D.M. Adams and B.A. McCarl. 2002. Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. For. Ecol. Manage. 169:3-14.

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., Simpson, L. G. and Vinson, T. S. 1993. Boreal forests and Tundra. Water, Air and Soil Pollution 70:39-53.

Arain, M.A., T.A. Black, A.G. Barr, P.G. Jarvis, J.M. Massheder, D.L. Verseghy and Z. Nesic. 2002. Effects of seasonal and interannual climate variability on net ecosystem productivity of boreal deciduous and conifer forests. Can. J. For. Res. 32(5):878-891.

Banfield, G.E., J.S. Bhatti, H. Jiang and M.J. Apps. 2002. Variability in regional scale estimates of carbon stocks in boreal forest ecosystems: results from West-Central Alberta. For. Ecol. Manage. 169:15-27.

Barr, A.G., T.J. Griffis, T.A. Black, X. Lee, R.M. Staebler, J.D. Fuentes, Z. Chen and K. Morgenstern. 2002. Comparing the carbon budgets of boreal and temperate deciduous forest stands. Can. J. For. Res. 32(5):813-822.

Bhatti, J.S., M.J. Apps and C. Tarnocai. 2002. Estimates of soil organic carbon stocks in central Canada using three different approaches. Can. J. For. Res. 32(5):805-812.

Bousquet, P., P. Peylin, P. Ciais, C. LeQuere, P. Friedlingstein and P.P. Tans. 2000. Regional changes of CO_2 fluxes over land and oceans since 1980. Science 290:1342-1346.

Buzikin, A.I., I.S. Dashkovskaya, L.S. Pshenischnikova and V.Gr. Soukhovolsky. 2002. Increasing forest productivity: the impact of nitrogen fertilization with regard to the "Echo Effect". In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 23-28.

Cox,P.M., R.A. Betts, C.D. Jones, S.A. Spall and I.J. Totterdell. Acceleration of global warming due to carbon-cycle feeedbacks. Nature 408: 184-187.

Chen, W., J.M. Chen, D.T. Price and J. Cihlar. 2002. Effects of stand age on net primary productivity of boreal black spruce forest in Ontario, Canada. Can. J. For. Res. 32(5):833-842.

Chen, X.. 2002. Modelling the effects of global climate change at the ecotone of boreal larch forest and temperate forest in northeastern China. Climatic Change 55(1-2): 77-97.

Chertov, O.G., A.S. Komarov, S.S. Bykhovets and K.I. Kobak. 2002. Simulated soil organic matter dynamics in forests of the Leningrad administrative area, northwestern Russia. For. Ecol. Manage. 169:29-44.

Conard, S.G., A.I. Sukhinin, B.J. Stocks, D.R. Cahoon, E.P. Davidenko, and G.A. Ivanova. 2002. Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia. Climatic Change 55(1-2): 197-211.

Dargaville, R.A., A.D. McGuire, and P. Rayner. 2002. Estimates of large-scale fluxes in high latitudes from terrestrial biosphere models and an inversion of atmospheric CO_2 measurements. Climatic Change 55(1-2): 273-285.

de Groot, W.J., P.M. Bothwell and K. Logan. 2002. Simulation of altered fire regimes and impacts on boreal carbon dynamics. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 29-40.

Fitzsimmons, M. 2002. Estimated rates of deforestation in two boreal landscapes in central Saskatchewan, Canada. Can. J. For. Res. 32(5):843-851.

Fleming, R.A., J.N. Candeau, and R.S. McAlpine. 2002. Landscape-scale analysis of interactions between insect defoliation and forest fire in Central Canada. Climatic Change 55(1-2): 251-272.

Foster, N.W. and I.K. Morrison. 2002. Carbon sequestration by a jack pine stand following urea application. For. Ecol. Manage. 169:45-52.

French, N.H.F., E.S. Kasischke, J.E. Colwell, J.P. Mudd and S. Chambers. 2002. Preliminary assessment of the impact of fire on surface albedo. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 41-52.

Glebov, F.Z., L.V. Karpenko, V.L. and I.S. Dashkovskaya. 2002. Climatic changes, successions of peatlands and zonal vegetation and peat accumulation dynamics in the Holocene (the West-Siberia Peat Profile "Vodorasdel"). Climatic Change 55(1-2): 175-181.

Goodale, C. L., M. J. Apps, R. A. Birdsey, C. B. Field, L. S. Heath, R. A. Houghton, J. C. Jenkins, G. H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson, and A. Z. Shvidenko. 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications 12(3): 891-899.

Gower, S.T., P.G. Jarvis and S. Linder. 2000. Towards a Better Understanding of the Carbon Budgets of Boreal Forests. Keynote Address In Apps M.J. and J. Marsden, Eds: Abstracts, *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Abstracts. IBFRA conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service p.82.

Gurney, K.R., et al (26 authors) 2002. Towards robust estimates of CO_2 sources and sinks using atmospheric transport models. Nature 415: 626-630.

Hänninen H. and P. Hari. 2002. Recovery of photosynthesis of boreal conifers during spring: a comparison of two models. For. Ecol. Manage. 169:53-64.

Harmon, M.E. and B. Marks. 2002. Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, U.S.A.: results from a simulation model. Can. J. For. Res. 32(5):863-877.

Hogg, E.H., J.P. Brandt and B. Kochtubajda. 2002. Growth and dieback of aspen forest in northwestern Alberta, Canada, in relation to climate and insects. Can. J. For. Res. 32(5):823-842.

Isaev, A.S., G.N. Korovin, S.A. Bartalev, D.V. Ershov, A. Janetos, E.S. Kasischke, H.H. Shugart, N.H. French, B.E. Orlick, and T.L. Murphy. 2002. Using remote sensing to assess Russian forest fire carbon emissions. Climatic Change 55(1-2): 235-249.

Ivanov, V.A. 2002. Lightning fire in forests of central Siberia In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 53-62.

Ivanova G.A., V.D. Perevoznikova and S.G. Conard. 2002. Impact of fire on the carbon budget in pine forests of central Siberia. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 279-288.

Jarvis, P.G., B.S. Saugier, and E.-Detlef Schulze. 2001. Productivity of boreal forests. In Roy J., Saugier B. and Mooney H.A., Eds: *Terrestrial Global Productivity.* Academic Press. San Diego. pp. 211-244.

Jiang, H., M.J. Apps, C. Peng, Y. Zhang and J. Liu. 2002. Modelling the influence of harvesting on Chinese boreal forest carbon dynamics. For. Ecol. Manage. 169:65-82.

Jiang, Yanling and G. Zhou. 2002. The carbon cycle of *Larix gmelinii* forest ecosystems and impacts of management practices. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 63-72.

Johnston, M., S. Kulshreshtha and T. Baumgartner. 2002. Carbon sequestration on privately owned marginal agricultural lands: an ecological-economic analysis of afforestation in Saskatchewan. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 73-82.

Joosten, R. and A. Schulte. 2002. Possible effects of altered growth behaviour of Norway spruce (Picea abies) on carbon accounting. Climatic Change 55(1-2): 115-129.

Korovin, G.N., A.S. Isaev and E.A. Karpov. 2002 Forecast of carbon pools and fluxes in Siberian and far eastern Russian forests. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 312-322.

Krankina, O.N., M.E. Harmon, Y.A. Kukuev, R.F. Treyfeld, N.N. Kashpor, V.G. Kresnov, V.M. Skudin, N.A. Protasov, M. Yatskov, G. Spycher and E.D. Povarov. 2002. Coarse woody debris in forest regions of Russia. Can. J. For. Res. 32(5):768-778.

Kurbanov, E. A. 2002. Carbon sequestration in pine stands of middle Zavolgie of Russia. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 83-94.

Kurbanov, E. A. and W.M. Post. 2002. Changes in area and carbon in forests of Middle Zavolgie: a regional case study of Russian forests. Climatic Change 55(1-2): 157-171.

Kurz, Werner A. 2000. Boreal Forest Carbon Budgets. Keynote Address In Apps M.J. and J. Marsden, Eds: Abstracts, *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Abstracts. IBFRA conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service p.2.

Kurz, W. A. and Apps, M. J. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecological Applications 9(2):526-547.

Lakyda, P., O. Kolosok and M. Pentrenko. 2002. The role of the coniferous forests in the carbon budget of Ukraine. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 95-98.

Leckie, D.G., M..D. Gilllis and M.A. Wulder. 2002. Possible systems for measuring and reporting on deforestation in Canada under the Kyoto protocol. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 99-106.

Lee, J., I.K. Morrison, J.-D. Leblanc, M.T. Dumas and D. Allan Cameron. 2002. Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial cut harvesting in a second-growth boreal mixedwood. For. Ecol. Manage. 169:83-101.

Leinonen, I. and K. Kramer. 2002. Applications of phenological models to predict the future carbon sequestration potential of boreal forests. Climatic Change 55(1-2): 99-113.

Li, C. and M.J. Apps. 2002. Fire regimes and the carbon dynamics of boreal forest ecosystems. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 107-118.

Liski, J., Perruchoud, D. and T. Karjalainen. 2002. Increasing carbon stocks in the forest soils of western Europe. For. Ecol. Manage. 169:159-175.

Little, T.I., D. Pluth, I.G.W. Corns and D. W. Gilmore. 2002. Post-fire forest floor development along toposequences of white spruce-trembling aspen mixedwood communities in west-central Alberta. Can. J. For. Res. 32(5):892-902.

Liu, J., C. Peng, Q. Dang, E. Banfield and W. Kurz. 2002. Historic carbon budgets of Ontario's forest ecosystems. For. Ecol. Manage. 169:103-114.

Luckai, N., and G.R. Larocque. 2002. Challenges in the application of existing process-based models to predict the effect of climate change on carbon pools in forest ecosystems. Climatic Change 55(1-2):39-60.

MacLean, D.A., D. Gray, K.B. Porter, W. MacKinnon, M. Budd, K. Beaton, R. Fleming and J. Volney. 2002. Climate change effects on insect outbreaks and management opportunities for carbon sequestration. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 119-128.

McCaughey, J.H., A. Barr, T.A. Black, B. Goodison, E.H. Hogg, R.B. Stewart, B. Amiro, D. Price, N. Stolle, J. Chen, S.T. Gower. 2002. The boreal ecosystem research and monitoring sites (BERMS) initiative: scientific accomplishments. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 129-136.

Meroni, M., D. Mollicone, L. Belelli, G. Manca, S. Rosellini, S. Stivanello, G. Tirone, R. Zompanti, N. Tchebakova, E.D. Schulze and R. Valentini. 2002. Carbon and water exchanges of regenerating forests in central Siberia. For. Ecol. Manage. 169:115-122.

Ni, J. 2002. Carbon storage and climate change in boreal forests of China: a local perspective. Climatic Change 55(1-2):61-75.

Nijnik, Maria. 2002. Contribution to climate stability via expansion of azonal boreal forests in the Ukranian Carpathians. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 137-146.

O'Connor, D.V., A.R. Esteghalian, D.J. Gregg and J.N. Saddler. 2002. Carbon balance of ethanol from wood: the effect of feedstock source in Canada. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 289-296.

Olsson, Mats. 2002. Strategies in Swedish forestry for reducing net CO_2 emissions. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 147-154.

Preston, C., C.H. Shaw, J. Bhatti and R.M. Siltanen. 2002. Soil C and N pools in forested upland and non-forested lowland sites along the boreal forest transect case study in central Canada. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 155-178.

Pypker, T.G. and A.L. Fredeen. 2002. The growing season carbon balance of a sub-boreal clearcut 5 years after harvesting using two independent approaches to measure ecosystem CO_2 flux. Can. J. For. Res. 32(5):852-862.

Running, S W. 2000. Monitoring and Measuring Boreal Carbon Fluxes: Regional to Global Extrapolations. Keynote Address In Apps M.J. and J. Marsden, Eds: Abstracts, *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Abstracts. IBFRA conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service p.83.

Rupp, T.S., A.M. Starfield, F.S. Chapin III, and P. Duffy. 2002. Modelling the impact of black spruce on the fire regime of Alaskan boreal forest. Climatic Change 55(1-2): 213-233.

Schlesinger, W.H. 1997 *Biogeochemistry. An Analysis of Global Change.* Academic Press, San Diego. Pp 588.

Scholes, R.J. 1999 Will the terrestrial carbon sink saturate soon? Global Change Newsletter 37: 2-3.

Seely, B., C. Welham and H. Kimmins. 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. For. Ecol. Manage. 169:123-135.

Shorohova, E.V. and V.A. Soloviev. 2002. Living and dead wood carbon dynamics in pristine boreal Norway Spruce forests subjected to windthrow disturbances. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 179-194.

Shvidenko, A. and S. Nilsson. 2002. Dynamics of Russian forests and the carbon budget in 1961-1998: An assessment based on long-term forest inventory data. Climatic Change 55(1-2):5-37.

Sigurdsson, B.D., P. Roberntz, M. Freeman, M. Næss, H. Saxe, H. Thorgeirsson and S. Linder. 2002. Impact studies on Nordic forests: effects of elevated CO_2 and fertilization on gas exchange. Can. J. For. Res. 32(5):779-788.

Skre, O. and Marius Næss. 2002. CO_2 and winter temperature effects on Norway Spruce and Downy Birch: a comparative study. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 297-311.

Sofronov, M.A., A.V. Volokitina and D.I. Nazimova. 2002. An approach to the assessment of the carbon balance and forest dynamics over large territories as influenced by forest fires and other disturbances. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 195-200.

Stephens, M.L., Daniel W. McKenney and Kathy Campbell. 2002. Afforestation potential in Canada: a spatial analysis of economic land suitability with carbon sequestration benefits. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. Pp. 201-216.

Stolbovoi, V. 2002. Carbon in soils of Russia. Climatic Change 55(1-2):131-156.

Tchebakova N.M. and E.I. Parfenova. 2002. Relationships between vegetation and climate change in Transbaikalia, Siberia. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 241-250.

Tremblay, S., R. Ouimet and D. Houle. 2002. Prediction of organic carbon content in upland forest soils of Quebec, Canada. Can. J. For. Res. 32(5):903-914.

Trofymow, J.A., T.R. Moore, B. Titus, C. Prescott, I. Morrison, M. Siltanen, S. Smith, J. Fyles, R. Wein, C. Camire, L. Duschene, L. Kozak, M. Kranabetter and S. Visser. 2002. Rates of litter decomposition over 6 years in Canadian forests: influence of litter quality and climate. Can. J. For. Res. 32(5):789-804.

Utkin, A.I., D. G. Zamolodchikov, G. N. Korovin and O.V. Chestnykh. 2002. Reserves and density of organic carbon in forests of Russia. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 227-249.

Vedrova, Estella F. and L.V. Mukhortova. 2002. Role of soil organic matter in the carbon cycle in forest ecosystems in the Krasnoyarsk Region. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 241-248.

Vesterdal, L., E. Ritter and P. Gundersen. 2002. Change in soil organic carbon following afforestation of former arable land. For. Ecol. Manage. 169:137-147.

Volokitina A.V., T.A. Stone and M.A. Sofronov. 2002. An assessment of the amount of biomass consumed from wildand fires based on vegetation fuel maps. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 273-284.

Wang, Y. and G. Zhou. 2002. Synthesis of field NPP data for China's *Larix* forests. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 261-268.

Watson, R.T. and the Core Writing Team (Eds.), 2001. Climate Change 2001: Synthesis Report. A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

Weyerhaeuser, G. Jr. 2000. Managing Forests for Carbon: An Industry Perspective. Keynote Address In Apps M.J. and J. Marsden, Eds: Abstracts, *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Abstracts. IBFRA conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service p.142.

Xu, D. and X-Q. Zhang. 2002. The role of China's temperate forests in the atmospheric carbon budget. In Shaw C.H. and Apps M.J., Eds: *The Role of Boreal Forests and Forestry in the Global Carbon Budget*, Proceedings of the IBFRA 2000 Conference, May 8-12, 2000, Edmonton, Alberta, Canada, Canadian Forest Service. pp. 269-278.

Yarie, J. and S. Billing. 2002. Carbon balance of the taiga forest within Alaska: present and future. Can. J. For. Res. 32(5):757-767.

Zhou, G., Y. Wang, Y. Jiang and Z. Yang. 2002. Estimating biomass and net primary production from forest inventory data: a case study of China's *Larix* forests. For. Ecol. Manage. 169:149-157.

PROCEEDINGS

The Role of Boreal Forests and Forestry in the Global Carbon Budget

Proceedings of IBFRA 2000 Conference
May 8-12, 2000
Edmonton, Alberta, Canada

C.H. Shaw and M.J. Apps, Editors

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

October 2002

Catalogue No.
ISBN

This publication is available at no charge from:
Natural Resources Canada
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton, Alberta, Canada
T6H 3S5

A microfiche edition of this publication may be purchased from:
Micromedia Ltd.
240 Catherine Street, Suite 305
Ottawa, Ontario K2P 2G8

NATIONAL LIBRARY OF CANADA CATALOGUING IN PUBLICATION DATA

International Boreal Forest Research Association. Meeting (2000 ; Edmonton,
Alberta)

The role of boreal forests and forestry in the global carbon budget : proceedings

"Proceedings of IBFRA 2000 Conference May 8-12, 2000, Edmonton, Alberta,
Canada"
Includes an abstract in French.
Includes bibliographical references.
ISBN 0-662-33068-4
Cat. no. Fo42-334/2002E

1. Carbon cycle (Biogeochemistry) - Congresses.
2. Taiga ecology -- Congresses.
3. Forest microclimatology- Congresses.
4. Forests and forestry - Congresses.
I. Shaw, Cindy, 1956- .
II. Apps, Michael J.
III. Northern Forestry Centre (Canada)
IV. Title.

SD390.5R64 2002 577.3'7 C2002-980285-7