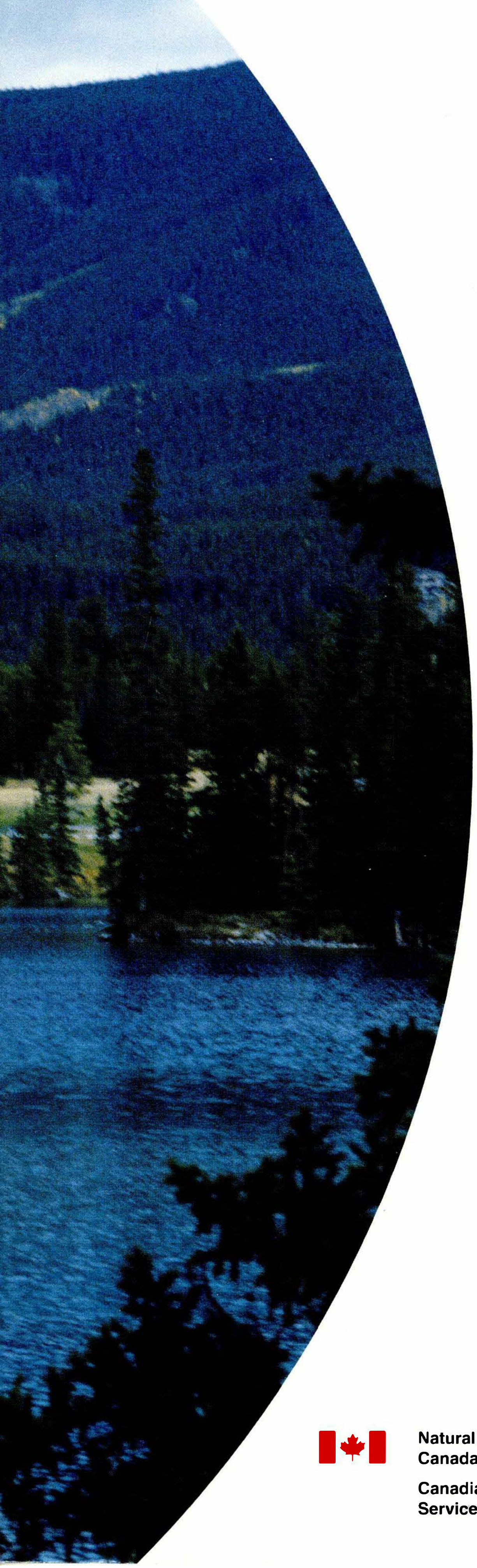

International Science Conference

ABSTRACTS

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

May 8 – 12, 2000
Edmonton, Alberta, Canada

Natural Resources Canada / Ressources naturelles Canada
Canadian Forest Service / Service canadien des forêts

IBFRA: International Boreal Forest Research Association

ABSTRACTS

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

May 8-12, 2000
Edmonton, Alberta, Canada

Michael J. Apps and Jenni Marsden, Editors

May 2000

Compiled by

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FOREWORD

Welcome to the IBFRA 2000 conference on *The Role of Boreal Forests and Forestry in the Global Carbon Budget* hosted by the Canadian Forest Service in Edmonton, Alberta. The purpose of this foreword is to give a little background to IBFRA, the conference, and how this book of abstracts was produced and how it is organized.

Who is IBFRA? The International Boreal Forest Research Association (IBFRA) was formed in 1991 as a relatively informal association of interested scientists and government agencies. By 1994, countries participating in IBFRA included Canada, Finland, Norway, Russia, Sweden and the USA. The stated mission of IBFRA has been to

> *"... promote and coordinate research to increase the understanding of the role of the circumpolar boreal forest in the global environment and the effects of global environmental change on that role."*

IBFRA Conferences. IBFRA works towards these goals through a set of Working Groups and by promoting international science conferences and symposia. The present conference, an outcome of the IBFRA Carbon Working Group, represents the latest in a series of successful conferences dedicated to IBFRA's mission. Previous IBFRA events have been held in Canada, Finland; Norway; Russia, Sweden and USA.

Why this conference? When the IBFRA 1994 Science conference on *Boreal Forests and Global Change* was held in Saskatoon, Canada, interest in the contribution of boreal forests and forestry to the global carbon cycle was already heating up. The proceedings of that conference, published both as a book and as a special issue in *Water, Air and Soil Pollution*, featured 13 papers (or about 25% of the total) dealing with carbon and nutrient cycling. The increased interest in the subject amongst scientists, resource managers, and policy advisors is evident by the present conference, which has nearly 200 presentations devoted solely to issues associated with the carbon budgets of boreal forest systems. In common with the 1994 conference, the dynamic role played by disturbances—both natural and human-caused—are featured heavily in many of the presentations.

Some of the questions posed at the IBFRA 1994 conference still remain significant scientific challenges today (see for example reviews by Pastor 1996[1] and Cannell 1997[2]). In addition to these on-going questions, the meeting that took place in Kyoto in 1997 has added an entirely new dimension and a new urgency to the science of forest carbon cycles. Although the IBFRA 2000 conference will deliberately stay outside policy negotiation issues, the science that is to be discussed will, we believe, provide some of the essential technical understanding that is needed for development of sound boreal-specific policy decisions. Many of the papers to be presented in the IBFRA 2000 conference, whose abstracts appear in this collection, address some of these challenges.

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[1] Pastor, J. 1996. Unresolved problems of boreal regions: editorial Review Essay. Climatic Change 33: 343-350.
[2] Cannell, M.G.R. 1997. Review of Boreal Forests and Global Change. Forestry 70:1

The Abstracts Volume. This volume contains the abstracts for nearly 200 papers that will be presented at this conference on *The Role of Boreal Forests and Forestry in the Global Carbon Budget.* The call for papers generated unexpected interest and resulted in far more submissions than originally anticipated. One or more members of the Program Committee reviewed all submitted abstracts. Authors of accepted abstracts were invited to prepare updated abstracts and these were then edited for both format and content. This abstracts book is the culmination of a team effort whose members include the Publication Committee, Jenni Marsden, Norah MacKendrick, Lisa Bowker, Judy Samoil, and of course the authors themselves. However, the production of this abstracts book and the conference itself would not have been possible without the generous support of our sponsors, whose contributions are most gratefully acknowledged.

Guide to Program and Posters. Although an attempt has been made to organize the presentations into broad themes, the distinctions are somewhat arbitrary. Abstracts in this volume are organized by theme, with the keynote presentation first, followed by the verbal presentations (in the same order as they will be presented), and then the poster abstracts in alphabetical order.

Each poster abstract has been assigned a Poster Locator Number and these are shown on the top of each abstract page. These numbers will help you to locate the poster in the poster halls, using the map supplied in your registration kit. Each theme has also been assigned a color code and each poster has its Poster Locator Number on a color-coded sheet at the top right of the poster panel. We have deliberately mixed the poster themes in the poster halls to reduce congestion during the poster theme sessions.

Your Program and Organizing committees have consciously attempted to make the poster sessions a key component of the conference. We have deliberately limited the number of verbal presentations (but given each a relatively generous time slot) and avoided parallel sessions in order to encourage maximum interaction of all conference participants. Ample time is provided during refreshment and lunch breaks to wander around the exhibits and meet with your colleagues. In addition, we are very happy to have three dedicated poster receptions and on your behalf warmly thank the sponsors for hosting these receptions. We invite you to make use of the breaks and reception events to mix, mingle, and discuss the stimulating material prepared by the authors.

Once again, on behalf of the Canadian Forest Service and your conference committees, let me extend a warm welcome to the IBFRA 2000 conference on the *Role of Boreal Forests and Forestry in the Global Carbon Budge* and best wishes for a successful week.

Mike Apps
Conference and Program Committee Chair

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The conference organizers thank the following organizations for their much-appreciated support. Without them, the conference would not be such a success.

ALBERTA FOREST PRODUCTS ASSOCIATION

Established in 1942, the Alberta Forest Products Association is the common voice of responsible forest products manufacturers in Alberta. We are dedicated to stewardship and sustainable development of the forest resources for the benefit of all Albertans.

Our 66 members form the major component of Alberta's fourth largest manufacturing sector, which provides 40,000 jobs for Albertans. They produce lumber, pulp and paper, panelboard, and secondary manufactured products, representing annual sales of more than $3 billion. Our members are committed to responsible environmental standards and sustainable forest practices, which are focused through our FOREST*CARE* Program. To learn more about the Alberta Forest Products Association and our members, visit our web site: www.abforestprod.org

ALBERTA-PACIFIC FOREST INDUSTRIES INC.

Alberta-Pacific Forest Industries Inc. is North America's largest single line northern bleached kraft pulp mill. Known for its award-winning environmental practices and research, Alberta-Pacific is currently seeking opportunities to recognize sequestration as a carbon credit, in line with emission reductions. This is being accomplished through new research projects and partnerships with government, industry, and communities such as the Kikino Metis Settlement. Here, a pilot project is being implemented to develop and test innovative policies and practices aimed at reducing net greenhouse gases emissions and encourage sustainable development. For more information on this and other Alberta-Pacific programs, please contact Brydon Ward at 780-525-8148.

Canadian International Development Agency

The Canadian International Development Agency (CIDA) is the lead player in delivering Canada's official development assistance program. The cornerstone of its program is to support sustainable development in order to reduce poverty and to contribute to a more secure, equitable, and prosperous world. Canada provides development assistance in the form of goods, services, transfer of knowledge and skills, and financial contributions in more than 100 of the poorest countries in the world.

Canadian Pulp and Paper Association

The Canadian Pulp and Paper Association represents the interests of many of Canada's major forest products companies. These companies are the active managers of some 100 million ha of Canada's forests. Climate change may have a significant long-term effect on forests. Their operations and forest protection programs have an impact on carbon sequestration and emissions. If forests are more fully included in the Kyoto Protocol, management strategies directed at increasing rates of carbon sequestration may be implemented. Canada's forest industry has a keen interest in forests and climate change.

Climate Change Action Fund

The Government of Canada's Climate Change Action Fund (CCAF) was established to help Canada meet its commitments under the Kyoto Protocol. Activities under CCAF are divided into four components: Foundation Analysis, which works toward development of a national implementation strategy; Science, Impacts, and Adaptation, which targets research to better understand climate processes and to assess the impact of climate change on the regions of Canada and the options for adaptation; Technology Early Action Measures, which is working toward cost-shared support for the development of emission-reducing technologies; and Public Outreach, which focuses on public education and outreach activities directed at informing Canadians about climate change and encouraging them to take action.

ENERGY FROM THE FOREST

ENFOR (ENergy from the FORest) is a Canadian Forest Service program of research and development on the production of forest biomass for energy. Funding is provided by the federal interdepartmental Program of Energy Research and Development (PERD). ENFOR's objective is to generate knowledge and technology that will result in a marked increase in the contribution of forest biomass to Canada's energy supply.

The ENFOR program deals with biomass supply matters such as inventory, growth, harvesting, processing, transportation, environmental impacts, and socioeconomic impacts and constraints. In addition, the program undertakes climate change studies with respect to the impact of a biomass feedstock and its capacity to sequester carbon. Please visit the ENFOR web site at:
http://www.NRCan.gc.ca/cfs/proj/sci-tech/prog/enfor_e.html

EUROPEAN FOREST INSTITUTE

The European Forest Institute (EFI) is an independent and non-governmental research body conducting forest research at the European level. EFI is an international association guided by its members, which form an extensive researcher network across Europe and beyond. Currently EFI has 131 members from 36 countries. EFI's main fields of research are forest ecology and management, forest products markets and socio-economics, forest policy analysis, and forest resources and information.

For further information, please contact the EFI secretariat at:
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Fax +358 13 124 393
Email: efisec@efi.fi
WWW: http://www.efi.fi

FOOTHILLS MODEL FOREST

Canada has taken the lead in researching ways to sustain and enhance our forests. The government of Canada, through the Canadian Forest Service, initiated the Model Forest Network in 1992. It introduced this system of 11 Canadian and a number of international research sites dedicated to building partnerships locally, nationally, and internationally to generate new ideas and on-the-ground tools for sustainable forest management. This process has brought together hundreds of partners including academia, industry, governments, communities, Aboriginal peoples, the public, and other stakeholders.

Alberta is represented in the Canadian network by the Foothills Model Forest in Hinton. At 2.75 million hectares (27,500 square kilometres), the Foothills Model Forest is the largest model forest in the world. It includes Jasper National Park, Weldwood of Canada Limited's (Hinton Division) working forest management area, Willmore Wilderness Park, and other provincial Crown lands.

FORINTEK CANADA CORP.

Forintek Canada Corp. was established in 1979 as Canada's research institute for the solid wood products industry. It is a research partnership comprised of over 150 solid wood manufacturing companies across Canada, the federal government, and six provincial governments. Our research activities are directed toward the sectors of sawn lumber, composite panels, and engineered value-added products in the areas of manufacturing, market support, and forest resource assessment. Forintek has two state-of-the-art research centres in Vancouver (corporate office and western lab) and Sainte-Foy near Quebec City (eastern lab) plus offices in Edmonton (regional office) and at Carleton University in Ottawa (fire research group).

Manning Diversified Forest Products Research Trust Fund

Manning Diversified Forest Products (MDFP) established the MDFP Research Trust Fund in 1993 to promote the adoption of forest management research results by the forest industry. The mission of the Research Trust Fund is to support research that furthers understanding of the boreal forest and sustainability of the social, cultural, and economic values in the northwest boreal region of the province of Alberta. It supports a wide range of environmental studies that include fish and wildlife inventories, silvicultural studies, forest product development, forest education, and career training. The Research Trust Fund was established and is maintained by an MDFP contribution of $2 per cubic metre of wood harvested. This amounts to about $500,000 per year available to support research projects across Alberta.

Millar Western Forest Products Ltd.

Millar Western Forest Products Ltd. is a privately owned western Canadian forest products company. Its products, sold around the world, include softwood dimension lumber and value-added building materials and hardwood and softwood bleached chemi-thermomechanical pulps (BCTMP). Millar Western operates a sawmill and BCTMP mill in Whitecourt, Alberta, and a sawmill in Boyle, Alberta. It also has contracts to manage and market the output of two high-yield zero-liquid-effluent discharge BCTMP mills in Meadow Lake, Saskatchewan, and Chetwynd, B.C. Millar Western is the world's largest supplier of BCTMP and produces more than 10% of Alberta's dimension lumber.

SUNCOR ENERGY INC.

Suncor Energy Inc. is a Canadian integrated oil and gas company, engaged in exploration, production, refining and marketing of oil and gas and other energy products through three principal operating groups.

Oil Sands produces and markets custom-blended refinery feedstocks and transportation fuels from its oil sands mine and upgrading facility near Fort McMurray, Alberta. Exploration and Production explores for, acquires, develops, and produces oil and natural gas in western Canada and markets its production throughout North America. Sunoco refines and markets petroleum products and chemicals and operates a refinery in Sarnia, Ontario, and a network of retail gasoline outlets throughout Ontario.

SUSTAINABLE FOREST MANAGEMENT NETWORK

The Sustainable Forest Management Network (SFM) is a unique university-based organization that supports multidisciplinary research to find better ways of managing the boreal forest through collaboration with governments, industries, and First Nations. Working together, the SFM Network and its partners have identified areas of sustainable forest management where research can be applied to solve specific problems. Our research network includes world-class researchers from the relevant natural, social, and applied sciences - over 75 researchers at 25 universities across Canada participate in the Network.

Our research is aimed to preserve the ecological functions and biodiversity inherent in Canada's forests. In addition, it is aimed to improve the nation's forest-based economy by developing new technologies, new knowledge, and new strategies for the management and conservation of this valuable renewable resource.

WELDWOOD OF CANADA LTD.

Weldwood of Canada Limited is a major forest products company manufacturing pulp, lumber, plywood, and laminated veneer lumber at eight wholly owned and five joint-venture mills in British Columbia and Alberta.

Weldwood has a proud tradition of excellence linked to more than 50 years of forestry operation. We are recognized for our commitment to the highest standards of environmental stewardship. Our strong operating track record is supported by a focus on maintaining highly efficient mills through the application of innovative technologies that support the development of an increasingly diverse product mix to meet sophisticated customer needs worldwide.

WEYERHAEUSER COMPANY

Weyerhaeuser Company, one of the world's largest integrated forest products companies, was incorporated in 1900. In 1999, sales were $12.3 billion. It has offices or operations in 13 countries, with customers worldwide. Weyerhaeuser is principally engaged in the growing and harvesting of timber; the manufacture, distribution, and sale of forest products; and real estate construction, development, and related activities. Additional information about Weyerhaeuser's businesses, products, or practices is available at www.weyerhaeuser.com.

THEME 1: BOREAL FOREST CARBON BUDGETS

KEYNOTE PRESENTATION:

VERBAL PRESENTATIONS (in order of presentation):

THEME 1

THEME 2: MONITORING AND MEASURING BOREAL FOREST CARBON FLUXES AND STOCKS

THEME 2

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KEYNOTE PRESENTATION

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THEME 3

THEME 4: SOCIAL AND ECONOMIC ISSUES, INCLUDING IMPLICATIONS OF THE KYOTO PROTOCOL

THEME 4

THEME 1

Boreal Forest Carbon Budgets

Boreal Forest Carbon Budgets

Werner A. Kurz[1]

The circumpolar boreal forest covers *ca.* 1.4 billion (10^9) hectares. Current estimates of carbon stocks in biomass and dead organic matter (including soil carbon pools) and of their changes differ widely, exemplifying the uncertainties about the role of the boreal forest in the global carbon budget. The carbon budget for large areas of forest ecosystems should be based on a systems approach that accounts for the dynamics of all significant carbon pools.

The appropriate indicator for the net change in ecosystem carbon storage is net biome production (NBP), which is calculated as net ecosystem production (NEP) minus losses from natural and anthropogenic disturbances. Assessments of the ecosystem carbon stock dynamics in Canada over several decades identify large changes in the role of these boreal forests as either a sink or a source of carbon, determined largely by the changes in large-scale disturbances such as wildfire, insect outbreaks, and to a lesser extent harvesting. Superimposed on the long-term dynamics in NBP is a pattern of high between-year variability resulting from years with very high or very low natural disturbances.

Current age-class structures of the boreal forest in Canada and Russia show a disproportionate amount of area in the mature age-classes. In these regions: 1) the transient age-class structure is the result of substantial changes in disturbance regimes during the past century; 2) these changes have contributed to changes in the forests' role as sources or sinks of carbon; 3) the level of carbon stocks may be near a temporary high point; and 4) these levels may not be sustainable into the future.

Even if forest managers who have "inherited" the current situation harvest at rates that are consistent with the growth potential of the management area (which is one aspect of sustainable management), ecosystem carbon storage of that area can decrease for two reasons: either disturbances (including harvest) will shift the age-class structure towards younger ages, or continued aging in the absence of disturbance will result in overmature forests. In contrast, the managed boreal forests in Scandinavia appear to be accumulating carbon because natural disturbances play a lesser role and because the current age-class structure differs from that in other parts of the boreal forests. Processes that are expected to change the carbon density (i.e., tons per ha), such as carbon dioxide fertilization, nutrient deposition, elongation of growing season, and some intensive forest management activities may increase carbon stocks, while increases in decomposition rates, higher disturbance rates, and land-use change will decrease carbon stocks in all areas of the boreal forest.

[1] ESSA Technologies Ltd., Canada.

The Role of Fire Disturbance, Climate, and Atmospheric CO_2 in the Response of Historical Carbon Dynamics in Alaska from 1950 to 1995: A Process-based Analysis with the Terrestrial Ecosystem Model

A.D. McGuire[1], R.A. Meier[2], Q. Zhuang[3], M. Macander[4], T.S. Rupp[2], E. Kasischke[5], D. Verbyla[4], D.W. Kicklighter[6], and J.M. Melillo[6]

To evaluate how historical carbon (C) storage in Alaska may have been influenced by fire disturbance, climate variation, and rising atmospheric carbon dioxide (CO_2) between 1950 and 1995, we conducted three simulations using the Terrestrial Ecosystem Model (TEM) that included responses of carbon storage to: CO_2 only, CO_2 and climate, and CO_2, climate, and fire disturbance.

Between 1950 and 1995, the simulations of TEM indicate that carbon storage in Alaska increased between 2.0 and 2.9 10^{12} g (Tg) C yr^{-1} depending on assumptions of fire severity. The partitioning of effects indicate that rising CO_2 was responsible for an increase in carbon storage of 3.6 Tg C yr^{-1} and that climatic variation was responsible for a loss of 0.3 Tg C yr^{-1}. The simulations indicate that fire disturbance, which included changes in carbon storage associated with both fire emissions and subsequent succession, was responsible for the loss of 0.4 to 1.3 Tg C yr^{-1} depending on assumptions for fire severity. In contrast to the overall period, historical fire disturbance accounts for increases in carbon storage of between 3.1 and 10.0 Tg C yr^{-1} during the 1980s for the lowest and highest assumptions of severity, respectively. This result suggests that re-growth associated with past fire disturbance was greater than losses associated with fire emissions during the 1980s, and that the strength of the re-growth effect increases with fire severity.

Our analysis suggests that fire disturbance, rising CO_2, and climate variation all play substantial roles in carbon dynamics for Alaska, and that modeling contemporary carbon dynamics for boreal forests requires a temporally and spatially explicit approach that incorporates the historical effects of fire disturbance.

[1] Alaska Cooperative Fish and Wildlife Research Unit, University of Alaska, United States; [2] Institute of Arctic Biology, University of Alaska, United States; [3] Department of Biology and Wildlife, University of Alaska, United States; [4] Department of Forest Sciences, University of Alaska, United States; [5] Environmental Research Institute of Michigan, Center for Earth Sciences, United States; [6] Marine Biological Laboratory, The Ecosystems Center, United States.

Projecting Future Canadian Forest Fire Regimes and Impacts under a Changing Climate

B.J. Stocks[1], M.D. Flannigan[1], B.M. Wotton[1], J.B. Todd[1], W.R. Skinner[2], D.L. Martell[3], B.D. Amiro[1], K.G. Hirsch[1], J.A. Mason[1], K.A. Logan[1], and V. Kafka[1]

Forest fire is the dominant disturbance regime in Canadian forests, burning an average of 3 million hectares annually. Direct fire management costs are approximately $ 500 million annually, with larger indirect costs. Forest fires are also a major influence on the carbon sink/source strength of Canadian forests, with direct effects on atmospheric emissions and the global carbon budget. Climate change projections suggest a strong increase in the frequency and severity of weather conditions conducive to forest fires across Canada, translating directly into increased fire activity, shortened fire return intervals, a shift in forest age class distribution, and a decrease in biospheric carbon storage. Projecting the extent and impact of future Canadian fire regimes is essential to developing effective adaptation strategies and policies.

An investigation was initiated, currently supported by the Canadian Climate Change Action Fund, aimed at projecting future fire regimes in Canada using the best scientific information available. Provincial and territorial fire records and hourly/daily Environment Canada weather records post-1950 have been compiled and integrated to develop spatially and temporally explicit gridded databases. The spatial fire database is used to estimate the percent area burned annually within Canadian ecoregions, and in combination with Canadian Forest Fire Danger Rating outputs, to determine fuel consumption, carbon loss, and emissions by ecoregions. Analysis is underway to determine predictive relationships between the area burned and weather/fire danger conditions in order to quantify the parameters that have driven fire activity over the past half-century.

Preliminary results indicate that the frequency and strength of mid-tropospheric anomalies are a major driver of fire activity in Canada. A national time-series of fire danger is also being completed for the 1953 to 1998 period to determine regional-scale trends in fire danger, with an emphasis on the frequency of extreme fire danger conditions, to determine if fire weather in Canada has changed during this period. Concurrently, high-resolution regional-scale projections of future fire climate have been constructed through involvement in the development of a Canadian Regional Climate Model, including validation of current and projected fire danger conditions. This information is integrated with outputs from the fire weather/fire activity analysis to develop plausible future fire regime scenarios that are analyzed in terms of impacts on forest communities, wood supply, and national and global carbon budgets. In turn, these results will aid in the development and evaluation of adaptation strategies.

[1] Canadian Forest Service, Natural Resources Canada, Canada; [2] Climate Research Branch, Atmospheric Environment Service, Canada; [3] Faculty of Forestry, University of Toronto, Canada.

Modeling the Response of Regional Fire Regimes to a Warming Climate in Alaska: Towards an Understanding of the Effects of Vegetation Pattern and Land Use

T. Scott Rupp[1], Anthony M. Starfield[2], and F.S. Chapin, III[3]

The response of boreal ecosystems to climatic warming has an important potential feedback to climate. Understanding the transient response of these ecosystems to climatic warming is a challenge because of the complex interactions of climate, disturbance, and recruitment across the landscape.

We used a spatially explicit state-and-transition model (ALFRESCO) to simulate fire ignition and spread, climate-vegetation-fire interactions, and scenarios of vegetation change in the Alaskan boreal forest in response to climatic warming. The simulations suggest rapid changes in disturbance regime and vegetation within the boreal forest in response to changes in climate. Fire and vegetation are connected by a negative feedback; early successional post-fire vegetation is less flammable than late successional vegetation. Vegetation composition, in turn, is part of a negative feedback in which post-fire vegetation has greater evapotranspiration and lower sensible heat flux, resulting in a cooler, moister climate that reduces fire probability. Fire-induced changes in vegetation led to a more homogenous landscape dominated by early successional deciduous forest. These results suggest that the higher albedo deciduous forest dominance would have a negative feedback to climate warming due to changes in albedo and energy partitioning, and landscape pattern would influence disturbance dynamics, which feedback to regional carbon dynamics.

[1] Forest Soils Laboratory, University of Alaska, United States; [2] Department of Ecology, Evolution, and Behavior, University of Minnesota, United States; [3] Institute of Arctic Biology, University of Alaska, United States.

Modeling the Impact of Disturbances on the Carbon Budget of Boreal Zone Forests

Anatoly Shvidenko[1] and Michael Apps[2]

Disturbances are processes that facilitate forest succession dynamics. The intensity, severity, temporal, and spatial distribution and consequent impact of disturbances on the forest carbon budget are inherently stochastic and non-stationary in character. However, the lack of regional long-term observations and a changing environment have hindered the development of reliable stochastic models. We propose a deterministic approach in which the impact of disturbances on the carbon budget of boreal forests is represented as a dynamic superposition of three groups of processes. These processes generate: 1) direct emissions during a year of disturbance; 2) post disturbance fluxes (both atmospheric and lateral); and 3) fluxes associated with the recovery processes in the disturbed forest ecosystems. Each of the processes involved are interconnected and interdependent, and their major features are defined by landscape properties as well as landscape- and ecosystem-specific disturbance regimes.

Appropriate synthesis of the data (modeling) requires a historical reconstruction of the processes over long times (characterized by biological time constants that can be greater than 150 years for the boreal zone). We developed a classification of disturbances, a proposed model structure, and explicit analytical descriptions of the three groups of processes. Specific disturbance types that were examined include fire, insect outbreaks, disease, harvest, pollution, and industrial land-use change. Major system considerations were examined—such as processes to be included, relevant spatial and temporal scales, availability and reliability of information, compartmentalization of pools, problems of spatial up-scaling and completeness. Confidence in model output, and the effects of lack of precise data, intricacies of the system modeled, or oversimplification of model representation, cannot be comprehensively estimated in a formal way. Instead, we estimated precision and error using classical error propagation theory and *a priori* subjective probabilities. Analysis of sensitivity of the output to variation of initial data, model assumptions, and parameters was used for independent estimation of uncertainties. The deterministic approach used does not distort the sign or magnitude of the net carbon fluxes caused by disturbances, provided appropriate accounting for past disturbances is included. Applications of the model are illustrated by the evaluation of the impact of disturbance on the carbon budget of the Northern Eurasia boreal zone for different years, 1990 (moderate disturbance levels) and 1998 (severe disturbances).

[1] International Institute for Applied Systems Analysis, Austria; [2] Canadian Forest Service, Natural Resources Canada, Canada.

The Balance of Production, Fire, and Decomposition in Controlling Carbon and Nitrogen Storage in Boreal Systems

Jennifer W. Harden[1], Terry Fries[1], and Michelle Mack[2]

A long-term mass balance model for carbon and nitrogen storage offers a perspective on how and why storage varies across the landscape. In our model, dynamics of soil carbon storage were parameterized for cycles of burning and regrowth of shallow moss and trees, coupled with the input and decomposition of dead wood and charred remains of organic matter that become buried by regrowing moss and litter. The burn – regrowth cycles were allowed to recur at average fire-return intervals for soil drainage classes, and cumulative inputs by net primary production (NPP), losses to decomposition, and losses to fire were tabulated throughout the de-glacial and post-lacustrine history of North America. Measurements of NPP, decomposition rates, carbon contents of soils and vegetation, and fire frequency were used to parameterize soil carbon storage of the northern Manitoba region of the BOReal Ecosystem-Atmosphere Study (BOREAS) Northern Study Area.

The relative amounts of carbon lost to decomposition *versus* fire vary greatly as a function of soil drainage class, with wetter sites losing less carbon to burning than better drained sites, resulting in greater deep carbon storage. Carbon losses to decomposition were more similar among sites emphasizing that differences in soil carbon indicate differences in fire history more than differences in decomposition rates.

The results of this model have important implications for climate change and nitrogen cycling. First, climatic changes sustained over long enough periods to affect soil drainage and water-table patterns would exert the largest change in soil carbon, and therefore atmospheric carbon levels. Second, increases in fire occurrence result in transient shifts in carbon flux because of changes in shallow carbon storage and its decomposition, changes in vegetation cover, and changes in soil temperature and decomposition rates. Third, since nitrogen remaining after fire varies greatly among stand types, burn severity exerts an important feedback to vegetation regrowth through nitrogen allocation. Last, policies of fire control and harvesting may have important impacts on species regeneration and on labile nitrogen because of the shift in the balance between decomposition and fire.

[1] U.S. Geological Survey, United States; [2] Institute of Arctic Biology, University of Alaska, United States.

Fire Regimes and the Carbon Dynamics of Boreal Forest Ecosystems

Chao Li[1] and Michael J. Apps[1]

Whether a forest ecosystem functions as a sink or source for atmospheric carbon is determined by the relative amounts of carbon taken up from and released to the atmosphere through changes in the biological state. For the biomass carbon pool in boreal Canada, the uptake of carbon is determined by the net biomass increase resulting from the complex set of processes in forest vegetation growth. The amount of carbon released to the atmosphere is largely determined by stand-replacement disturbances such as fire.

We tested the hypothesis that forest landscape source/sink functions are correlated to the frequency of fire disturbance. This test was performed with a simulation experiment by using a spatially explicit model for landscape dynamics (SEM-LAND). The simulation results support the hypothesis. Forest ecosystem sinks become sources when a threshold (return interval) is passed. This threshold depends on a number of factors. Assuming that all carbon within the killed biomass of the burned area will be released into the atmosphere, a turning point (switching from a carbon sink to a carbon source) was reached at a disturbance return interval of about 220 years (stochastic simulation results range from 181 to 500 years) for this particular landscape.

Variation in the threshold can arise, however, due to the uneven fire severity across the landscape that could result in different carbon release rates into the atmosphere. For example, with an assumption of 80% release to the atmosphere, the turning point was reduced to about 50 years. This result suggested that this forest landscape would function as a carbon sink if the return interval for fires of this severity was greater than approximately 50 years. Finally we note that the numerical results depend on the initial conditions and past disturbance history of the landscape, but the underlying hypothesis appears to be robust. Moreover, we note that when the changes in the ecosystem carbon (vegetation plus dead organic matter and soils) are considered, the net sink or net source cannot be sustained indefinitely; it is only maintained until new steady-state balances are reached, or conditions change.

[1] Canadian Forest Service, Natural Resources Canada, Canada.

Modeling the Effect of Climate Change on the Carbon Balance of Boreal Forests under Different Water and Nutrient Limitations

Miko U.F. Kirschbaum[1]

Climate change can affect the carbon balance of boreal ecosystems through many processes, and the ultimate response of different systems may be affected by the response of any one of those processes, or their interactions. Increasing carbon dioxide concentration affects photosynthesis and stomatal conductance, and increasing temperature affects photosynthesis, frost damage, organic matter decomposition rates, and water loss.

In addition to these direct effects, there are many indirect effects. Temperature is a key variable affecting the rate of organic matter decomposition, but the effect of temperature can be further modified by moisture availability. Normally, decomposition would be stimulated by warming. However, under conditions where warming has a greater indirect effect by drying the soil than a direct effect by stimulating organic matter decomposition, the net effect of warming could be an inhibition of organic matter decomposition. The balance of these interacting factors can shift with changes in the degree of nutrient and water limitations in different systems.

Direct and indirect effects and their interaction in response to climate change were investigated using the forest-growth model CenW that simulates forest growth and trends in soil organic matter. The interactions between these various factors on the ultimate carbon balance of boreal forests were described. Responses of sites limited by water and nutrient availability were compared.

The presence of snow can significantly affect soils processes. Snow insulates the soil and prevents extremely low soil temperatures in winter, but it also delays re-warming in spring. Decomposition of organic matter and nitrogen mineralization are thus restricted to a short period in summer. Climate warming is likely to significantly shorten the period of the year when the soil is insulated by snow, and thereby lengthen the period over which decomposer organisms can be active. This has the potential to make nutrients much more available for plant uptake.

While boreal ecosystems are not usually water limited, they can be vulnerable to water shortages because most of the decomposer activity is restricted to a very short warm period in summer. If that warm period coincides with a dry spell, it can lead to a drying out of the surface soil and can greatly diminish mineralization.

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Simulated Carbon Balance in Forest Soils of Leningrad Administrative Area, Northwestern Russia

O.G. Chertov[1], A.S. Komarov[2], S.S. Bykhovets[2], and K.I. Kobak[3]

A simulation of the carbon balance in forest soils was carried out for boreal forests comprised of Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and deciduous stands in the Leningrad Administrative Area, Russia. A model of soil organic matter dynamics was applied in the simulation.

The data on carbon pools (organic layer plus 50 cm soil) in forest soils over an area of 4.35 Mha (excluding mires) was used as the initial data for a 100-year model simulation. Annual litter inputs with 15% standard deviation were assessed as a proportion of stand biomass, on the basis of known biological productivity data. The stand biomass was calculated by conversion of the forest inventory data. Soil temperature and moisture were simulated on the basis of meteorological data for previous decades without any trends. Changes of age structure, effects of fire, insect attacks, pollution, and recreation were not taken into consideration.

The results of the simulation demonstrate that the soil carbon pool was quite stable in well-drained soils. The soil carbon pool increased 1.8 times in a small group of poor dry sandy soils, and decreased 1.3 times in poorly drained soils ($p > 0.999$). There was an increase in the soil carbon pool of the forest floor under coniferous stands, and an accumulation of humus in the mineral topsoil under deciduous stands. Soil organic carbon decreased in young stands and increased middle-aged and old stands. There was a 10% increase in the total carbon pool of forest soils for the whole area over the 100-year simulation (from 266 to 286 Mt C). Total carbon of the litter was 8.3 Mt C yr^{-1} and the carbon dioxide release from the soils was 8.1 Mt C yr^{-1} at the end of simulation. Therefore, over the simulation period the forest soils of the area were a modest net atmospheric carbon sink.

The regional assessment of the soil carbon pool and its dynamics will be the next step in providing more detailed comparison with the recent evaluation of soil carbon in all Russian forests.

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Veneer Bog: A Potential Significant Source of Atmospheric Carbon?

H. Veldhuis[1], R.G. Eilers[1], and G.F. Mills[2]

Veneer bogs occupy extensive areas of the Boreal Shield and Taiga Plains Ecozones of Canada. They differ from most other peatlands by having a variable, generally shallow depth of peat (0.2 to 1.2 m thick) within the same peatland, and by not having a permanent water table near the surface. These properties make veneer bogs more susceptible to wildfire and more dynamic with regard to loss and sequestration of organic carbon compared to other peatlands.

During wildfire most of the moss and peat are lost. Post-burn vegetative recovery will eventually reclaim much of the original peatland area. However, it is postulated that climate warming may increase the frequency of wildfires. This will reduce permafrost distribution, accelerate decomposition of unburned peat, reduce the rate of peat accumulation, and diminish or preclude the recovery of veneer bogs.

Data obtained from point investigations and along transects in a number of veneer bogs show a wide range in depth of peat and great variation in peat characteristics with respect to bulk density and carbon content. It was also found that extensive areas of veneer bog are underlain by soils that have developed under moderately well to imperfectly drained conditions, indicating that at least some of the time these peatlands refer back to mineral landscape status. The rooting of the larger trees in mineral soil, with peat built-up around their location and the occurrence of very small trees rooting in peat emphasizes this condition. It is estimated that, 120 years after the last wildfire, a typical veneer bog contains between 370 and 520 tonnes of organic carbon per hectare above the mineral contact. A survey of the BOReal Ecosystem-Atmosphere Study (BOREAS) Northern Study Area revealed that, of this 730 km^2 area, 35% or 257 km^2 consist of peatland of which 28% or 72 km^2 consist of veneer bog. This represents a potentially significant sink for atmospheric carbon. But, if predicted warming scenarios come true, most, if not all of these peatlands will eventually disappear thereby reducing the amount of carbon sequestered in the Boreal Shield and Taiga Plains Ecozones.

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[2] Soil Resource Unit, Soils and Crops Branch, Manitoba Agriculture (Retired), Canada.

Growth and Dieback of Aspen Forests in Northwestern Alberta in Relation to Climate and Insects

E.H. (Ted) Hogg[1], James P. Brandt[1], and Bob Kochtubajda[2]

Trembling aspen (*Populus tremuloides*) is the most important deciduous tree species, both ecologically and commercially, in the Canadian boreal forest. Since the early 1990s, aspen dieback has been noted over parts of the southern boreal forest and aspen parkland in western Canada. In this study, tree-ring analysis and forest health assessments were conducted in 18 mature aspen stands near Grande Prairie, Alberta, to examine causes of reduced growth and dieback. Defoliation histories were reconstructed based on light-colored tree rings and records of past insect outbreaks.

The results indicate that several factors contributed to the observed dieback. Forest tent caterpillar defoliation and drought in the 1960s and 1980s led to reduced growth and predisposed some stands to secondary damage by wood-boring insects and fungal pathogens. Winter desiccation and spring frost during several unusually mild winters in the early 1990s may have also contributed to the observed dieback. Under global change, the severity of these stresses is likely to increase, which poses a serious concern for the future health, productivity, and carbon sequestration of aspen forests in the region. This concern has led us to expand this work to the detection of regional-scale changes that may be occurring in response to global change.

[1] Canadian Forest Service, Natural Resources Canada, Canada; [2] Meteorological Service of Canada, Environment Canada, Canada.

Preliminary Assessment of the Potential of Adaptive Forest Management Strategies to Mitigate Impacts of Climate Change on Forests in Western Canada

Marcus Lindner[1] and David Price[2]

Following the 1997 Kyoto Conference there has been increased interest in management strategies to increase carbon sequestration in forests in order to offset fossil fuel emissions. Simulation studies with the forest gap model FORSKA-M in temperate forests of central Europe have indicated that forest management has considerable potential to mitigate the short to mid-term impacts of climate change on forest productivity and carbon storage.

In this study, FORSKA-M was parameterized for western central Canada to investigate the effect of alternative management strategies on forest development and productivity under climatic change in the Foothills Model Forest near Hinton, Alberta. The model was initialized with inventory data for 10 representative forest stands identified within the Model Forest. Since climate change may significantly increase the number and size of forest fires in Canadian boreal forests, baseline simulations without forest management were run to investigate the impact of increasing disturbance frequencies on average carbon storage. Possible management response strategies include: adjusting harvest rotation periods, improved fire control, and planting of lodgepole pine (*Pinus contorta*). These management options were tested with the simulation model to analyze their potential both to increase carbon storage and to mitigate the impacts of climate change in the Model Forest.

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A Common Framework for the Forest Carbon Budget of Eurasia and North America

Christine L. Goodale[1] and the National Center for Ecological Analysis and Synthesis (NCEAS) Carbon Working Group[2]

We are compiling a revised estimate of the net annual uptake and loss of carbon from temperate and boreal forests of Europe, North America, and Asia. Forest inventories in these regions provide extensive, detailed measurements of key components of terrestrial carbon budgets: forest stocks, growth, mortality, and harvests. Yet forest inventory data do not quantify all forest carbon pools (e.g., woody debris or soils), and different assumptions regarding conversion factors or the behavior of unmeasured pools can lead to large discrepancies in estimated net forest carbon uptake. Previous estimates of forest carbon uptake have made varying assumptions regarding these terms, or have excluded them altogether. We adopt a common framework for interpreting inventory growth data, quantifying the fate of harvested materials, and estimating carbon fluxes to and from dead wood and soil pools. The estimate integrates databases specific to Europe, Russia, Canada, the United States, and China, with adjustments to make the data from each region as comparable as possible. This effort is the first step in a project to reconcile model-based and inventory-based approaches to understanding carbon sinks in the terrestrial biosphere.

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[2] Members: Michael J. Apps, Richard A. Birdsey, Ruth S. DeFries, Jim Ehleringer, Christopher B. Field, Jonathan A. Foley, Christine L. Goodale, Michael Goulden, Mark E. Harmon, Elisabeth A. Holland, Richard A. Houghton, Jennifer C. Jenkins, Joerg Kaduk, Deepak Khatry, Gundolf Kohlmaier, Rik Leemans, Marcus Linder, Gert Jan Nabuurs, Sten Nilsson, Stephen W. Pacala, Louis F. Pitelka, Stephen Sitch, and David W. Schimel.

Dynamics of the Carbon Budget of the Russian Forest Sector in 1961–1998 and Scenarios for 2010

Sten Nilsson[1] and Anatoly Shvidenko[1]

In the analysis we used: 1) a methodology for full carbon (C) accounting of regional terrestrial ecosystems developed by the International Institute for Applied Systems Analysis (IIASA) Forest Resources Project; 2) the dynamics of forests and forest fund areas based on long-term inventory data and land-use dynamics; 3) a set of different auxiliary models to estimate the most important intermediate variables, e.g., phytomass by fractions, gross and net growth, net primary production, decomposition of dead organic material, transport of soil organic substances by water, etc.; 4) documented and reconstructed history of disturbances; and 5) analysis of production and consumption of forest products. Past dynamics of the carbon budget for Russian forestland (including unforested areas) is presented for the period 1961 to 1998. Two major features define the specifics of the budget: 1) long-term trends caused by dynamics of both land-use change of forest land and the forest management regimes used; and 2) inter-seasonal variation of fluxes which depend mainly upon regional weather conditions and connected fluctuations of regimes of disturbances, where wildfire and large-scale insect outbreaks play a crucial role.

It was concluded that the anomalies of the carbon budget increased during the period considered. The annual carbon efflux to the atmosphere irregularly varied from 1961 to 1998, from +140 Tg C yr^{-1} (source) to -360 Tg C yr^{-1} (sink), and the average for the whole period was about -240 Tg C yr^{-1} (sink).

The scenarios (called *consistent*, *pessimistic,* and *optimistic*) for the period 2000 to 2010 are based on a prolongation of development trends for the period 1961 to 1998, and are driven by the predicted development of the Russian economy, and by specifics of expected disturbance regimes. There seems to be a large potential for the Russian forest sector in the post-Kyoto world if sustainable forest and carbon management is implemented.

[1] International Institute for Applied Systems Analysis (IIASA), Austria.

Carbon Balance of Boreal Deciduous and Conifer Forest Ecosystems using the Canadian Land Surface Scheme (CLASS)

M.A. Arain[1], T.A. Black[1], D.L. Verseghy[2], and A.G. Barr[2]

Changes in temperature and precipitation patterns and associated feedback processes, especially the evaporation/soil moisture feedback, could significantly affect the carbon balance of boreal forests and the dynamics of soil carbon. A realistic single-layer model of surface-atmosphere exchanges of carbon dioxide, energy, and water vapor was created by incorporating a process-based two-leaf (sunlit and shaded) canopy conductance and photosynthesis model (based on the Farquhar, and the Wang and Leuning models) in the Canadian Land Surface Scheme (CLASS).

A simple model of autotrophic and heterotrophic respiration was combined with the canopy model to simulate net ecosystem productivity (NEP). The model was tested using eddy covariance flux and climate data from two boreal forest ecosystems, the Southern Old Aspen (SOA) and Southern Old Black Spruce (SOBS) sites in Saskatchewan, Canada. Both are being monitored under the Boreal Ecosystem Research and Monitoring Sites (BERMS) program, which is a follow-on to the Canada-USA collaborative BOReal Ecosystem-Atmosphere Study (BOREAS). In this model, although the sunlit and shaded leaves were exposed to different levels of photosynthetically active radiation (PAR), leaf temperatures were assumed to be the same. The effect of soil moisture on canopy conductance was modeled using the relative available soil water in the root zone. Photosynthetic model parameters were obtained separately for sunlit and shaded leaves by taking into account the PAR and nitrogen distribution in the canopy. The response of NEP to changes in temperature, precipitation, and growing season length at SOA was simulated for five years (1994, 1996 to 1999).

Simulated canopy conductance using this model showed better agreement with measured canopy conductance as compared with the Jarvis-Stewart multiplicative approach originally used in CLASS. Diurnal variation of simulated NEP showed good agreement with the measurements. Monthly values of simulated NEP and water vapor fluxes were similar to measured values over the five-year period for the SOA site. These tests indicated the importance of accurate estimates of forest leaf area index particularly at the beginning of growing season, and the need for parameter adjustment to account for changing phenology during the growing season.

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Carbon Budgets of Balsam Fir Stands across a Climatic Transect

P.Y. Bernier[1], M.B. Lavigne[1], F. Raulier[1], C.H. Ung[1], and G. Robitaille[1]

Annual carbon budgets were determined for three balsam fir (*Abies balsamea*) stands in a latitudinal transect in Eastern Canada for the years 1997 to 1999. The latitudinal transect was intended to be a surrogate for changes in temperature brought on by global climate change. The transect covers what is currently the southern portion of the balsam fir's range, but elevation differences between the different sites amplify the climatic differences along the transect.

Aboveground biomass and net primary production were estimated from diameter censuses, increment cores, and allometric equations. Belowground biomass, net primary production, and turnover were estimated with soil cores, in-growth bags, and minirhizotron. Net photosynthesis was modeled from first principles using local climatic data and canopy-level measurements. Above- and belowground respiration was interpolated from point measurements of stem and soil respiration.

Preliminary results show clear latitudinal differences among the three sites. Leaf area index of the stands decreased from the south to the north, along with the ratio of foliage mass to branch mass and the growth rates of stems. The proportion of sapwood for a given tree diameter also decreased from south to north, but the accumulation of biomass in the branches appeared constant over the three sites. Overall accumulation of aboveground dry mass decreased from about 12.5 Mg ha^{-1} yr^{-1} in southern New Brunswick to about 9.2 Mg ha^{-1} yr^{-1} at the Forêt Montmorency site. However, because leaf area decreased even more rapidly from south to north, the unit leaf rate actually increased from south to north, going from about 130 g m^{-2} yr^{-1} (biomass produced per square meter of foliage per year) to 180 g m^{-2} yr^{-1}. Data for allocation to roots are still being processed as this abstract is being written, but preliminary analysis of soil respiration and minirhizotron data suggests a much smaller allocation to fine root biomass in the Forêt Montmorency site compared to the southern sites. The results demonstrate that there is no simple relationship between annual temperature, allocation to different plant components, and the capacity of forests to sequester carbon.

[1] Canadian Forest Service, Natural Resources Canada, Canada.

The Ecosystem Approach to Estimating Carbon in Russian Forests

Vladislav Alexeyev[1], Michael Tarasov[1], Boris Ryabinin[1], and Richard Birdsey[2]

More than half of the carbon in tropical forest ecosystems is in phytomass, whereas boreal and temperate forests contain the largest proportion of carbon in other ecosystem components such as litter, soil, and coarse woody debris (CWD). Carbon of these components (primarily CWD and litter) is closely associated with characteristics of forest vegetation in specific conditions of soil humidity.

We have developed a new ecosystem approach to estimate carbon for the Russian forests. The methodology involves: 1) applying data on the litter carbon storage of forest-forming tree species, ages of stands, and forest types (in Russian and Scandinavian sense); 2) using the original data on carbon storage and the rates of CWD decomposition; and 3) unifying information from 1 and 2 with the carbon data for growing stock and soil. Carbon storage for the even-aged and the climax (subclimax) forests were estimated separately.

This approach allowed us to estimate the current carbon storage of vegetation, CWD, litter, and soil in ecosystems of primary tree species and age groups (including climax and subclimax forests). This was done for boreal ecoregions and administrative territories in European Russia. Similar estimates for Asian Russia are still under development.

It is important to emphasize that the ecosystem approach has an advantage over separate estimations of carbon in vegetation and soils because of the opportunity to combine the vegetation data with the soil data to form joint natural units, and to understand their interrelations and the temporal transformation of carbon. This approach permits us to understand and verify the carbon values in each compartment of the ecosystem under normal and extreme situations. Using this approach facilitates true estimation of carbon stocks and dynamics in boreal and temperate forests.

[1] St. Petersburg Forest Ecological Center, Russia; [2] USDA Forest Service, United States.

Synthesis of Field NPP Data and Evaluation of Ecosystem Services for Chinese Boreal Forests

Yuhui Wang[1] and Guangsheng Zhou[1]

The boreal forest covers a wide latitudinal range in a nearly contiguous circumpolar band about 50°N latitude. The boreal forest biome is characterized by short growing seasons, but wide seasonal swings in temperature and precipitation. Vegetation growth and productivity are strongly influenced by these seasonal climate dynamics. Strong year-to-year variations in climatic conditions result in pronounced between-year variation in these functions, especially in net primary production (NPP) and net ecosystem productivity (NEP). Thus, global climate change induced by doubled carbon dioxide (CO_2) will strongly affect the boreal forest ecosystems, which will in turn feedback on the climate system through changes in albedo, roughness length, etc. It is important to understand the characteristics of NPP of the boreal forest and the ecosystem services it provides in order to develop adaptation and/or mitigation strategies for the effects of global climate change.

The boreal forests of China mainly consist of *Larix gmelinii*, located at 49°20' to 53°30'N and 119°40' to 127°22'E. The characteristics of NPP of the Chinese boreal forest and its ecosystem services were analyzed based on field observation data. The results indicated that the total NPP of the Chinese boreal forest is 7.59 t ha^{-1} yr^{-1}. The tree layer accounts for 6.52 t ha^{-1} yr^{-1}, the shrub layer accounts for 0.640 t ha^{-1} yr^{-1}, and the herb layer accounts for 0.430 t ha^{-1} yr^{-1}. The NPP of the boreal forest is controlled by both environmental factors and biological factors. The results showed that NPP has a close relationship with annual air temperature (T, °C), annual precipitation (P, mm), volume of timber (V, m^3 ha^{-1}), and age (A, yr):

$$NPP = 0.0123P + 0.1017T - 0.026A + 0.114V + 1.233$$
$$(r = 0.8942, F = 7.978, n = 13, F(sig.) = 0.0068)$$

Furthermore, the potential for CO_2 fixation, oxygen release, and soil erosion were analyzed using an erosion module, the reaction equation of photosynthesis, and respiration. The results showed that the Chinese boreal forest currently stores 121.083 t ha^{-1} yr^{-1} of organic material. It could potentially store organic material 6.52 t ha^{-1} yr^{-1}, fix 2.89 t C ha^{-1} yr^{-1}, release 7.8 t O_2 ha^{-1} yr^{-1}, and decrease soil erosion by 4.65 x 10^9 t. The value of ecosystem services of the Chinese boreal forest is about US$ 4500 million per year, of which 58% is the estimated value of climate control and water conservation services and 25% is associated with the value of raw materials and food production. The value of ecosystem services indicates that the Chinese boreal forest ecological service should draw more and more attention in the future.

[1] Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Academia Sinica, P.R. China.

Insect Responses to Climate Change and their Impact on Boreal Forests: An Overview of Research

W. Jan A.Volney[1], Richard A. Fleming[1], David A. MacLean[2], and David R. Gray[1]

Natural disturbances are fundamental processes in the succession, functioning, and carbon cycling that occurs in many of the world's boreal forests. Insects cause more losses to the merchantable forest volume than any other natural disturbance agent, and during outbreaks trees are often killed over vast areas.

Most research on natural disturbances and climate change in boreal forests is directed towards sustaining current benefits and maximizing carbon storage. Achieving these goals involves both preparatory activities which anticipate the future, and the development of reactive management plans to deal with the unforeseen surprises that are certain to arise as the climate changes. Specific research on insect responses to climate change and their impact focuses on a number of fundamental questions: (1) How might individual insects, species, and outbreak systems respond and with what impacts? (2) What are the likely temporal and spatial characteristics of this response? (3) How will carbon storage, forecasts of timber volume losses, pest hazard rating procedures, and long-term planning for harvest queues and pest control requirements be affected? (4) Will changes to insect disturbance regimes aggravate the impacts of other disturbance regimes and vice-versa? (5) Could climate-induced changes to insect outbreak dynamics either directly or indirectly accelerate net rates of natural disturbance enough to accelerate climate warming? (6) What are the likely consequences of various alternative strategies to managing forest insect disturbance regimes in a changing climate?

Emerging evidence directed at answering these questions suggests that an understanding of processes over a variety of temporal and spatial scales will be critical in forecasting and manipulating behavior of forest insect outbreak systems. Current carbon budget models permit some projections on the consequences of uncontrolled insect outbreaks. Nevertheless, to be useful in assessing the consequences of feedbacks and direct pest mitigation efforts, these models will have to incorporate effects of outbreak behavior at forest/grassland and forest/tundra ecotones. This approach forces investigators to look at conditions and situations that have not been traditionally investigated in forest insect research. It is thus critical to obtain historical information on interactions of insect populations with forests at the extremes of their ranges and in extreme weather conditions over at least the past century. A final consideration is that this approach may be useful in anticipating responses of pests inherent in initiating new land-use policies and intensive forest management practices, possibly involving exotic tree species, in efforts to mitigate the effects of climate change.

[1] Canadian Forest Service, Natural Resources Canada, Canada; [2] University of New Brunswick, Canada.

Carbon Balance of the Alaskan Taiga Forest

John Yarie[1] and Sharon Billings[2]

Forest biomass, rates of production, and carbon dynamics are a function of climate, plant species present, and the structure of the organic and mineral soil layers. The estimated boreal forest area in Alaska is 17,244,098 hectares. There were seven primary ecosystem types used by the United States Forest Service Inventory Unit to classify the stands sampled during the inventories of Alaska's boreal forest. They were white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) B.S.P.), quaking aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* March.), and poplar (*Populus* spp.) (a combination of balsam poplar (*Populus balsamifera* L.) and black cottonwood (*Populus trichocarpa* Torr. and Gray)). The mixed species combinations from the south-west inventory unit include mixed spruce (white and black spruce), mixed hardwoods (aspen, birch, and poplar) and mixed species (a potential for all six species but at least one conifer and one deciduous species).

The total aboveground biomass within Alaska was estimated to be 815,330,000 metric tons. The CENTURY model was used to estimate the maximum net ecosystem production (NEP). The NEP values for individual forest stands of aspen, birch, poplar, white spruce, and black spruce were 137, 88, 152, 65, and 99 g C m^{-2} yr^{-1}. These values were predicted at stand ages of 75, 60, 45, 100, and 75 years, respectively. A five-degree increase in mean annual temperature applied through the entire year resulted in an increase in predicted production and decomposition in all ecosystem types, resulting in an increase of NEP. The indication is that biomass production increased at a higher rate than forest floor decomposition.

It was predicted that the total NEP would increase for Alaska's white spruce ecosystems from 3.25 to 3.73 Mt C yr^{-1}. Total NEP will increase for Alaska's black spruce ecosystems from 2.18 to 2.40 Mt C yr^{-1}. It will increase for birch ecosystems from 1.47 to 2.22 Mt C yr^{-1}. The current vegetation absorbs approximately 9.65 Mt C yr^{-1} within the boreal forest of Alaska. If there is a five degree increase in the mean annual temperature with no change in precipitation we estimated that NEP for the boreal forest in Alaska would increase to 16.95 Mt C yr^{-1}.

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Assessment by Remote Sensing of Carbon Emissions from Forest Fires

Alexander S. Isaev[1] and George N. Korovin[1]

A remote sensing survey method was developed to map local fire impacts on forest ecosystems of Siberia and to calculate post-fire carbon emissions. The survey-based methods may also be used to assess the dynamics of forest cover and carbon balance in boreal forests. One technique involves analysis of satellite imagery (SPOT and RESURS) taken at different times. The method, based on the calculation of change in normalized difference in vegetation indices before and after fire, can be used to differentiate burned areas from dead stands, to estimate area burned by fire, and to classify the fire impact severity. Satellite-based remote sensing provide important instrumental tools for mapping of fire areas and fire-frequency index for boreal forests over extensive areas.

Results confirm that remote sensing can be useful for the assessment and mapping of forest vegetation damage from fire. It can provide detailed information on fire intensity, and the structure and stocks of forest-fuel materials before and after fire within each sector of burned area. Detailed characteristics of forest-fuel materials are determined from pre-fire inventory data. The structure of forest-fuel materials allows the identification of zones of potential crown fires, while the degree of forest stand injury can be used to estimate the relative fire severity. Superimposing potential crown and ground fire zones with zones of different forest stand injury reveals the fire characteristics and intensity, and allows the mapping of fire carbon emissions. Development of remote sensing methods for managing forest conditions, thereby influencing its carbon budget, will play an important role in the fulfillment of anticipated obligations under the Kyoto Protocol and the United Nations Framework Convention on Climate Change concerning the establishment of national systems for assessment of greenhouse gas emissions by sources and removals by sinks.

[1] International Forest Institute, Russia.

Peat Covered Lands of Russia as a Sink of Atmospheric Carbon

S.E. Vompersky[1], O.P. Tsyganova[1], A.G. Kovalev[1],
T.V. Glukhova[1], and N.A. Valyaeva[1]

Accumulation of carbon (C) in mire and paludified forests ecosystems is an atmospheric carbon sink. Such systems are widely distributed over the boreal zone, but existing estimates of their contribution to regional and global biotic carbon cycles vary considerably. There is little accurate data available on the total area of peatlands, and good methods for evaluating their mean carbon accumulation rate at the regional and national level have not been developed.

The present study aims: 1) to estimate the area of peat-covered lands, their distribution across Russia, and the amount of peat stored; 2) to evaluate mean peat growth rate for different regions; 3) to study the relation between peat layer depth and peat growth rate; and 4) to make a draft estimate of mean long-term carbon accumulation rate by the mires of Russia. It used the Soil Map of Russia (Scale 1:2.5 million), "Torfgeologija" Service data on the proved peat resources, generalized data of C^{14} datings from Russian mires, and the analysis of information on peat depth and peatland age from different countries over the boreal zone.

In Russia, 139,109 ha are mires with peat to a depth > 30 cm, and 230,109 ha are paludified with < 30 cm of peat. Peat storage in mires and paludified lands equals 113.5 10^9 t dry weight. A map of mire distribution over Russian territory for each 1-degree latitude to 2-degree longitude parcel was compiled. Mean peat growth rate during the Holocene period (calculated for the deepest points of peat deposits) varied from 0.55 to 0.85 mm yr^{-1} in European Russia and Central Siberia to 0.1 mm yr^{-1} in northern regions and East Siberia (areas with permafrost).

It was established that within regions with approximately equal natural conditions, peat depths were adequately related to mean peat growth rates taken for the whole peat profile. Linear relations between them were established for 6 regions of Russia, Canada, and Finland. Carbon accumulation rate estimates should be consistent with representative depths of peat deposits within a region. This type of analysis was not made before, therefore mire contribution to the biotic carbon cycle have previously been over-estimated.

In this new approach the whole Russian territory was divided into 10 regions, each with a different peat depth. Mean carbon accumulation rate by mires with peat depth over 0.5 m was found to be 13.5 to 14.6 g C m^{-2} yr^{-1}, and to first approximation, annual carbon accumulation rate by Russian mires (with peat depth > 30 cm) equals 17.7 to 19.1 Mt C yr^{-1}. These estimates need further refinements, as several regions lack accurate data on peat-covered area, mean peat depth, and mire age.

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The Role of Peatlands in the Carbon Budget of the North American Boreal Forest

Peter Lafleur[1] and Nigel Roulet[2]

There is between 100 to 200 Pg of carbon stored in North American boreal and sub-arctic peatlands, many of which are forested. This estimate represents 5 to 10% of the total global standing biomass and soil carbon pools. Although this carbon has accumulated over the last 8,000 years, the exchange of carbon from these systems plays a significant role in the biome level carbon budget of the boreal region and in the global scale. This paper discusses what is known about the contemporary carbon exchange and cycling of carbon dioxide (CO_2) in boreal peatlands.

Existing literature indicates that boreal peatlands can be either a source or a sink for carbon. However, these estimates are based on short-term (weeks to growing season) measurements of net ecosystem exchange (NEE). The range in growing season maximum day-time CO_2 uptake for peatland types is small (0.3 to 0.6 mg m^{-2} s^{-1}) and overall only slightly less than for many boreal forest types. The most important factors controlling the net growing season exchange are phenology, water table (or soil moisture content), and nutrient availability.

As part of the Peatlands Carbon Study we have been taking continuous measurements of the NEE and the loss of carbon via runoff from the Mer Bleue peatland in eastern Ontario. This peatland is representative of raised, shrub bogs found in the boreal region. We have concluded the first ever full-year's measurement on carbon exchange for a peatland and found a larger than expected net annual sink for CO_2 of between 200 to 300 g CO_2 m^{-2} yr^{-1} (0.55 to 0.80 t C ha^{-1} yr^{-1}). Winter-time respiration offsets almost 25% of the total growing season uptake. Explanations for this large uptake are lacking, but if our results are applicable to other peatlands, then the role of peatlands in the boreal carbon budget is being significantly underestimated.

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Estimating Biomass and Net Primary Production of Chinese Boreal Forests Based on Forest Inventory Data

Guangsheng Zhou[1], Yuhui Wang[1], Yanling Jiang[1], and Zhenyu Yang[1]

Forest inventory data include the areas and volumes of timber, and are important resources for compiling accurate information of forest volume at landscape and regional scales. It is important for forest ecologists to effectively use these data in order to understand the dynamics of forest biomass, net primary production (NPP), and carbon cycling. This is necessary for the scientific management of forest ecosystems, and for use in global climate change studies in order to comply with the Kyoto Protocol on greenhouse gas reduction. In 1984, Brown & Lugo suggested a volume-driven method for estimating the biomass of tropical forests, however as the ratio of forest biomass and volume were treated as a constant, this method is not suitable for all forest types. In particular the method cannot be used directly to calculate biomass of forests of different ages.

Based on field and literature data, a new volume-driven biomass production model for boreal forests was developed, taking into account the change in the ratio of forest biomass and volume with the age of forest. The new volume-driven biomass equation for the boreal forest was:

$$B=[0.524+0.562\, e^{-0.00665V}]\, V \qquad (R = 0.83)$$

where B is biomass (t DM ha^{-1}), and V is the volume of timber (m^3 ha^{-1}).

The NPP (t DM ha^{-1} yr^{-1}) and biomass (B, t DM ha^{-1}) of the boreal forest has a close relationship:

$$NPP = 0.543\, B\, e^{-0.02B} \qquad (R = 0.90)$$

Based on the developed models and Chinese forest inventory data (1973 to 1976, 1984 to 1988, and 1989 to 1993), the dynamics of biomass and NPP in the Chinese boreal forest were examined. The results indicated that biomass and NPP per hectare decreased from 1973 to 1993, however total biomass and total NPP increased from 1973 to 1993 because the total area of the boreal forest increased during this time. The contribution of boreal forests of different ages to total biomass and NPP was also analyzed. The analysis of the contribution of Chinese boreal forests to the global carbon balance showed that the amount of accumulated carbon has greatly increased since 1973.

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Productivity of Forests in the Eurosiberian Boreal Region and Their Potential to Serve as a Carbon Sink

Ernst-Detlef Schulze[1]

The carbon relations of coniferous and broad-leafed forests were studied along a north-south transect through Europe, and coniferous forests were studied along a west-east transect along the 60^{th} latitude from Europe to central Siberia. The European transect allows a process-oriented estimate of net primary productivity (NPP) and net ecosystem productivity (NEP) using inventory and soil decomposition data. The European forests were found to sequester large quantities of carbon in the soils. It appears that the rate of carbon sequestration increases with nitrogen deposition. The role of stemwood increment will be discussed in view of quantifying NEP, because stemwood will be harvested in managed forests and, depending on wood products, it may not contribute to global carbon sequestration.

NPP decreased along the west-east transect. Despite its much larger area, the NPP of the Siberian forest was not much larger than that of Europe. However, the low productivity pine (*Pinus* spp.) forest in Siberia had the same NEP as the high productivity spruce (*Picea* spp.) forest in Germany due to a reduced rate of respiration. It was shown for European forests that the ecosystem carbon balance was determined by respiration rather than by assimilation.

The pattern of carbon sequestration is altered by natural and human disturbances, such as windthrow, fire, and harvesting. The effects of these disturbances will be quantified. Windthrow resulted in massive respiratory losses and a decay of wood over about 80 years. Fire, depending on intensity, will result in a flush loss of carbon bypassing respiration, but will also result in a contribution to charcoal production. Based on charcoal, net biome productivity (NBP) will be estimated. Harvesting increased respiration so that NEP will be negative of balanced NEP for at least 14 years. Respiratory losses were also due to drainage of peat soils. Besides forests, wetlands emerged as major carbon sink, but were less affected by disturbance than forests, except when drained.

In summary, we were able to estimate NEP across large regions, but the observations were biased towards stable conditions. More emphasis is needed to study processes across the life cycle of trees (chronosequence approach) and to include natural and human induced disturbances. The role of managed forests in view of the Kyoto Protocol will be discussed.

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POSTER LOCATOR NO. 132

Determination of Biochemical Photosynthesis Model Parameters for Betula *Pendula*

Tuula Aalto[1] and Eija Juurola[2]

Gas exchange of one-year-old silver birch (*Betula pendula* Roth.) seedlings of boreal habitat was studied under laboratory conditions. Seedlings were exposed to stepwise changes in carbon dioxide (CO_2) concentration and irradiance under five constant temperatures ranging from 9 to 33°C. The Farquhar et al. (1980) biochemical model was fitted to the response curves. Values for the photosynthesis parameters J_{max} and V_{cmax} as well as their temperature dependencies were derived from the measurements. Following characteristics of the boreal growth conditions, the response curves were also determined at temperatures below 20°C. This was, indeed, reflected to photosynthesis parameters, though results showed relatively large variation due to differences among leaves. The gas exchange rates of separate leaves could vary by 40% and also the temperature dependencies were slightly different. The slope and curvature of the light response curve were relatively constant above 19°C and decreased at low temperatures.

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Variability and Uncertainty in Estimating Regional Scale Carbon Stocks in Boreal Forest Ecosystems: Results From Central Alberta

G.E. Banfield[1], J.S. Bhatti[1], M.M. Uddin[1], R. Phan[1], H. Jiang[2], and M.J. Apps[1]

Biomass, forest floor, and mineral soils in Canadian boreal forests contain approximately 200 Pg of carbon (C), which represents approximately 15% of the total carbon stored in the terrestrial biosphere. The dynamics of these carbon pools are highly connected; the organic carbon content of the forest floor and the mineral soil is the result of an interaction between climate, soil moisture, temperature, nutrient availability, soil texture, and disturbance regimes. These interactions control the primary processes of production and decomposition, and in turn regulate net ecosystem carbon dynamics. Understanding the interacting processes, and the quantitative relationships amongst them, are keys to improved projections of carbon budget responses with climate change and potential management interventions.

Aboveground biomass, forest floor, and soil carbon stocks were estimated for a 9 Mha region in west-central Alberta using available forest inventory data, model simulation, point data, and soil polygon information from the Canadian Soil Organic Carbon Database (CSOCD). This large region contains diverse mixed forests of deciduous and coniferous trees. Total precipitation ranges from 400 to 600 mm annually, with growing season average temperature around 10°C. For the three carbon pools investigated, model simulation provided a regional estimate, while forest inventory, point data, and soil polygon data provided an estimate of the spatial variation. These data were used to examine the variation of the carbon estimates, in both temporal (e.g., climate change) and spatial (e.g., soil physical characteristics) dimensions.

Using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2) the regional average aboveground biomass was estimated at 4.9 kg C m^{-2}. Preliminary small-scale simulations showed variations from 2.0 to 6.7 kg C m^{-2} associated with different site characteristics. Regional estimates of forest floor carbon using aggregated point data, CSOCD (forested area only) data, and CBM-CFS2 simulations were in close agreement, yielding preliminary values of 2.5, 3.4, and 3.6 kg C m^{-2}, respectively. Regional estimates of soil carbon using the three methods appear to be more divergent (14.5, 8.3, and 15.6 kg C m^{-2}, respectively). Smaller scale estimates of forest floor and soil carbon pools using spatially referenced data are being compared with these regional estimates. The observed variations in biomass, soil, and forest floor carbon are being examined in terms of site characteristics, including vegetation type, disturbance history, soil texture, and drainage status.

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Estimating Soil Organic Carbon Stocks in Central Canada Using Different Approaches

J.S. Bhatti[1], M.J. Apps[1], and C. Tarnocai[2]

Globally, soil reservoirs account for about three times as much carbon (C) as terrestrial vegetation. Soil carbon stocks are characterized by long residence times relative to the other biological carbon pools. This is particularly true in boreal and cold temperate zones where the soils and dead organic matter have high carbon content. Understanding the role of soil and dead organic matter carbon in the global cycle requires knowledge of its amount and spatial pattern of distribution. Estimates vary considerably, however, and the uncertainties associated with these estimates are difficult to determine.

This study compared three estimates of carbon contained in the surface horizon and total soil pools at regional and polygon scales, and the spatial pattern of distribution in forested areas of the three prairie provinces in western Canada. The approaches were: 1) analysis of pedon data from both the Boreal Forest Transect Case Study area and from a national-scale soil profile database; 2) the Canadian Soil Organic Carbon Database (CSOCD), which uses expert estimation based on soil characteristics; and 3) model simulations with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS2).

These three approaches yielded consistent regional estimates for upland forest soils, ranging from 1.4 to 7.7 kg C m^{-2} for the surface (0 to 30 cm) and 6.2 to 27.4 kg C m^{-2} for the total soil column. The CSOCD yielded carbon content values for peatland soils that were significantly higher than for upland forest soils, ranging from 14.6 to 28 kg C m^{-2} for the surface and 60 to 181 kg C m^{-2} for the total peat soil column. All three approaches indicated higher soil carbon content in the boreal zone than in other regions.

When organic soils associated with peatlands were excluded from the CSOCD regional estimates, soil carbon estimates from all three approaches were comparable. The agreement between the simulated values (method 3) and the values obtained using the two more empirical approaches (methods 1 and 2) provided an independent test of CBM-CFS2 soil simulations for upland forests. The soil simulations in CBM-CFS2, based primarily on vegetation dynamics and forest inventory data, were only weakly constrained by empirical soil profile data. At the soil-polygon level (sub-regional scale), total soil carbon values estimated from the CSOCD (method 2) were lower than those obtained from averaged site pedon values (method 1). However, good agreement was found between the CSOCD and pedon (method 1) total ($r^2 = 0.92$) and surface ($r^2 = 0.64$) soil carbon values. Higher total soil carbon values obtained using pedon data (method 1) may be related to micro- and mesoscale geomorphic and microclimate influences that are not accounted for in the CSOCD data set.

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Moss Species as Indicators of Carbon Cycling in a Boreal Black Spruce Forest in Central Saskatchewan, Canada

Kari Bisbee[1], Tom Gower[1], and John Norman[2]

The objective of this study was to compare net primary production (NPP) and carbon distribution for two dominant, but contrasting, boreal black spruce (*Picea mariana*) forest communities in the southern old black spruce study area of the BOReal Ecosystem-Atmosphere Study (BOREAS) in central Saskatchewan, Canada. The two communities included open-canopy stands with sphagnum groundcover on poorly-drained sites, and closed-canopy stands with feathermoss groundcover on well-drained sites.

There was a significant positive relationship ($R = 0.62$) between percent ground coverage by sphagnum and light availability, and a significant negative relationship ($R = -0.62$) between percent ground coverage by feathermoss and light availability. The contrasting relationships reflect distinct strategies of the two types of mosses to maintain adequate hydration levels, and the variations in canopy structure of the two black spruce ecosystems; the leaf area index (LAI) was significantly lower ($p = 0.001$) for the black spruce–sphagnum (2.8) than the black spruce-feathermoss ecosystem (8.2).

Despite the almost three-fold difference in LAI between the two black spruce ecosystems, the NPP was not significantly different in the two communities. The NPP of the black spruce-feathermoss and black spruce–sphagnum ecosystems were 194 and 175 g C ha^{-1} yr^{-1}, respectively. However, the NPP of the groundcover was significantly greater ($p = 0.025$) for the black spruce–sphagnum than black spruce-feathermoss ecosystem (66 *versus* 19 g C m^{-2} yr^{-1}).

Soil temperature was lower for most of the year in the black spruce–sphagnum than in the black spruce-feathermoss ecosystem. The colder soil temperature and greater NPP of the sphagnum over the feathermoss ecosystem contributed to the observed two-fold greater soil carbon content in the black spruce–sphagnum (8435 g C m^{-2}) than black spruce-feathermoss ecosystem (3349 g C m^{-2}). The large differences in environmental and stand structural characteristics between the two ecosystems, but small differences in NPP, emphasize the need to accurately measure and model carbon dynamics of the groundcover of boreal forests, and better understand the factors that influence the composition of the groundcover.

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POSTER LOCATOR NO. 80

Spruce Budworm Defoliation and Climate: Analysis of Historical Data and Projections under Climate Change Scenarios

Jean-Noël Candau[1] and Richard A. Fleming[2]

Natural disturbance is a major component of forest dynamics when human intervention is limited. One of the greatest effects of climate change on Canada's forests will be a change in natural disturbance patterns. Spruce budworm (*Choristenuera fumiferana*) was used as a case study because it constitutes the largest and most damaging disturbance caused by insects in boreal forests. In this study, the relation between climate variables and spruce budworm defoliation regimes in Ontario were analyzed using historical data.

Three distinct zones of spruce budworm defoliation frequency between 1941 and 1996 were mapped. Each zone was characterized by an area of high defoliation frequency surrounded by areas of decreasing frequencies. North-south corridors of low defoliation frequency separated these zones. In the south, defoliation was limited by the absence of host species whereas in the north climatic conditions were the limiting factor. The northern border of the area of defoliation seemed to be defoliated only when the outbreak was close to its maximum and when climatic conditions were most favorable. During the 56 year period studied, occasional extreme weather such as late frosts appear to have had only a limited and temporary effect on the course of outbreaks.

Climate change will likely affect spruce budworm defoliation dynamics both directly through changes in the parameters of the population dynamics and indirectly through feedback and interactions with other species and abiotic factors. Direct effects include changes in insect phenology, changes in the spatial extent of the populations, and changes in the frequency and duration of outbreaks. Indirect effects comprise changes in the distribution and phenology of host species, in the population dynamics of natural enemies, and in the interaction between fire and spruce budworm. Finally, analysis of potential effects of climate change on the dynamics of spruce budworm defoliation is complicated by the possibility that individual components of the ecosystem may migrate separately. Such phenomenon could modify or destroy current interactions among these components and de-stabilize current ecosystems.

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POSTER LOCATOR NO. 4

Coupling a Three-Dimensional Regional Atmospheric Model to a Biospheric CO_2 Flux Model

Douglas Chan[1], Ken Yuen[1], Jane Liu[2], Kaz Higuchi[1], Jing Chen[2], and Josef Cihlar[2]

The main reservoirs of carbon dioxide (CO_2) are the atmosphere, biosphere, and ocean. Exchange processes between the reservoirs determine the allocation of anthropogenic CO_2. To study these exchange processes and their governing factors on a daily to annual basis at the landscape (mesoscale) scale, an atmospheric model was coupled to a biospheric CO_2 flux model.

The Mesoscale Compressible Community (MC2) model is a full-elastic non-hydrostatic atmospheric model. It solves a full set of Euler equations on a limited area with time-dependent nesting of the lateral boundary conditions supplied by a large-scale model. Currently, the initialization fields and the lateral boundary conditions are obtained from the Canadian Meteorological Centre analyses. The nesting capability of MC2 allows the study of processes over a wide spectrum of scales.

The Boreal Ecosystem Productivity Simulator (BEPS) is a biospheric CO_2 flux process model that uses the principles of forest biogeochemical cycles (FOREST-BGC) for quantifying the biophysical processes governing ecosystem productivity, with modifications to better represent canopy radiation processes and canopy photosynthesis. The processed remote sensing data required by the model are the leaf area index (10-day interval) and land cover type (annual). The meteorological data include hourly air temperature, incoming short-wave radiation, precipitation, and humidity. The soil data input is the available water holding capacity of the soil.

Initially, the model will use data collected near Fraserdale, Ontario, during intensive field and aircraft measurement campaigns. Currently the MC2 and BEPS models are coupled in the offline mode. Preliminary model results computed with BEPS at Fraserdale for the intensive campaign period of June 1999 showed that net ecosystem productivity ranged diurnally from ~ -0.02 mg C m^{-2} s^{-1} to $+0.04$ mg C m^{-2} s^{-1}. The CO_2 concentration computed by MC2 had a diurnal amplitude of ~ 6 ppm. More simulations will be performed to allow detailed comparisons of the model results with intensive field measurements at Fraserdale.

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The Inert Carbon Pool in Boreal Soils: Char-Black Carbon Stocks in Pristine Siberian Scots Pine Forests

C.I. Czimczik[1], M.W.I. Schmidt[2], B. Glaser[3], and E.D. Schulze[1]

Vegetation fires occur frequently in boreal forests, producing large amounts of thermally altered organic matter, here called char-black carbon (CBC). CBC is thought to resist microbial and photochemical breakdown because of its highly condensed molecular structure. As an inert part of the soil organic carbon pool, CBC could act as a long-term sink for photosynthetically fixed atmospheric carbon dioxide (CO_2). Studies on CBC dynamics in savanna and tropical rain forest soils, however, resulted in ambiguous findings. To elucidate the potential role of CBC in carbon sequestration, we studied the effect of fire on the long-term behavior (0 to 100 years) of organic carbon stocks in boreal soils.

We quantified CBC and total organic carbon (TOC) stocks of sandy, podzolic soils in pristine Siberian Scots pine (*Pinus sylvestris*) forests with a lichen dominated understory. The average burning frequency of these forests was 25 to 40 years. The study area was located 40 km west of the Yenesei River (60°43'N, 89°08'E) in Central Siberia. To elucidate the development of CBC stocks after fire, a chronosequence of 8 fires, occurring 6 to 100 years ago, was sampled. CBC was quantified via a gas-chromatography/ flame ionization detector using benzenepolycarboxylic acids as molecular markers. TOC was detected with an elemental analyzer. Standard deviations were ±1 to 4 mol m^{-2}.

Initial results obtained from 6, 35, and 50 years after fire showed a consistent decrease (21 to 26 mol m^{-2}) of CBC stocks in the organic layer (0 to +0.03 m) with time, while TOC stocks increased (144 to 292 mol m^{-2}). In the mineral layers (0 to 0.25 m depth), CBC stocks were highest after 35 years (22 mol m^{-2}), but lower after 6 years (2 mol m^{-2}) and 50 years (3 mol m^{-2}). The same was true for TOC stocks, which were highest after 35 years (134 mol m^{-2}), but lower after 6 years (50 mol m^{-2}) and 50 years (41 mol m^{-2}). Deeper horizons (0.25 to 2 m depth, all sites) showed only small CBC stocks (5 mol m^{-2}).

A CBC decrease in the organic layers of forest soils was detected from 6 to 50 years after fire. This could be explained by *in situ* CBC degradation or by CBC relocation with depth. Underlying horizons, however, did not reveal unambiguous evidence for CBC relocation. The number of samples analyzed so far is too small to draw firm conclusions; thus further results will be included and discussed at the conference.

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POSTER LOCATOR NO. 95

Comparison of High Latitude Large Scale Flux Estimates From Ecosystem Models and an Inversion of Atmospheric CO_2 Measurements

Roger Dargaville[1], A. David McGuire[2], Peter Rayner[3], and CCMLP Participants[4]

We examined the high latitude regional fluxes estimated from four global terrestrial biosphere models (TBMs): Terrestrial Ecosystem Model (TEM), High Resolution Biosphere Model (HRBM), Integrated Biosphere Simulator (IBIS), and Lund-Potsdam-Jena Dynamic Vegetation Model (LPJ) for the period 1980 to 1992. The TBMs are each driven with the same observed carbon dioxide (CO_2) concentrations, climate, and land-use change data sets.

An atmospheric transport model with these surface fluxes was run, and the modeled CO_2 values at the monitoring sites were compared with the observations from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL) network at Mould Bay (Northwest Territories, Canada), Barrow (Alaska, United States) and Ocean Station M (Norway). The modeled fluxes generally underestimated the amplitude of the seasonal cycle in the high latitudes, with LPJ closest to the observations and IBIS having the smallest seasonal cycle. It is important to note that the TBMs do not represent all mechanisms that may contribute to the seasonal cycle amplitude, such as nitrogen deposition, and that some mechanisms with seasonal cycles, such as fire disturbance, were modeled on annual rather than monthly timescales.

The fluxes were independently estimated using a time-dependent synthesis inversion of the atmospheric observations. This comparison also indicated that the underestimation of the atmospheric seasonal cycle in the models was due to terrestrial fluxes in the high latitudes, with the inversion requiring a larger seasonal cycle in Europe, northern Asia, and northern North America than the TBMs estimate. There was good agreement between the interannual variability of the ecosystem models and the inversion in northern North America, but poor agreement in northern Asia, possibly due to the inversion being poorly constrained in Asia. Averaged over the period 1980 to 1992, the inversion estimated a larger net uptake in the northern high latitudes compared with the ecosystem model estimates.

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POSTER LOCATOR NO. 103

Simulation of Altered Fire Regimes and Impacts on Boreal Carbon Dynamics

W.J. de Groot[1], P.M. Bothwell[1], and K. Logan[1]

Climate-induced changes in fire regime are expected to have a significant effect on boreal carbon dynamics. Future fire regimes will likely result in greater carbon release by fire. Carbon sequestration may also be affected by the influence of fire on forest composition. This is because boreal species have adapted to fire in different ways, so a change in fire regime will favor some species over others. If fire regimes are significantly changed, the result could be a shift in species composition and carbon sequestration rate of some forest stand types.

This study examined the influence of altered fire regimes on boreal carbon dynamics using a forest fire effects model and estimates of future fire regimes under increased atmospheric carbon dioxide (CO_2) conditions. The model was based on the fire ecology and growth characteristics for six major boreal tree species. Basic stand types for the western Canadian boreal region were identified and simulated in the model using various species combinations. Fire was incorporated as a stochastic event using fire regime criteria calculated from Canadian General Circulation Model (GCM) output for 1975 to 1995 and 2080 to 2100, in order to compare current and future conditions. Each stand type was simulated separately for a 400-year period using three different fire frequencies, and each simulation scenario was repeated 25 times. The model recorded carbon storage in live and dead plant material for aboveground and belowground compartments, and species composition of the stand. Changes in carbon pools and tree species were summarized for each stand type. These results were applied to current forest stands in several areas of western and northern Canada to provide a spatial estimate of future change in forest composition and carbon pools.

The model results indicate that future fire regimes will promote greater carbon loss during fire, primarily because of increased fire severity. This was due to the forest floor becoming very dry on a more frequent basis, which led to a greater occurrence of deeper burning fires. Fire severity increased in all regions, but there was a much greater increase in the north where current fire severity is considerably lower than in southern areas. Fire intensity also increased in all regions, but the influence on carbon loss was not as great. Carbon sequestration increased in some stand types where there was a shift in species composition towards aspen (*Populus tremuloides*). Conditions that promoted stand conversion are presented, and the effects of fire regime and stand type change on carbon dynamics are discussed.

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POSTER LOCATOR NO. 84

Coarse and Fine Root Respiration of Aspen (*Populus tremuloides*)

Annie DesRochers[1], Simon Landhäusser[1], and Victor J. Lieffers[1]

Coarse and fine root respiration rates of aspen (*Populus tremuloides*) were measured at 5, 15, and 25°C. In order to discriminate between maintenance and growth respiration, rates were measured during the dormant and growing periods. An additional measurement was made for the coarse roots during spring leaf flush to evaluate the increased root respiration caused by the mobilization of resources for leaf expansion.

Fine roots respired at much higher rates than coarse roots, at an average rate at 15°C of 1289.04 µmol CO_2 m^{-3} s^{-1} during the growing period (growth + maintenance respiration), compared to 662.64 µmol CO_2 m^{-3} s^{-1} during the dormant period (maintenance respiration). The temperature response of fine root respiration was not linear, with an average Q_{10} (ratio of respiration rate at a temperature t on the respiration rate at t - 10) of 3.90 between the 5 to 15°C increase, and an average Q_{10} = 2.19 between the 15 to 25°C increase. Surprisingly, coarse root respiration rates measured in late fall (dormant season) were higher than rates from the roots collected at leaf flush and early summer, the latter two not significantly different. Rates at 15°C were 372.83 µmol CO_2 m^{-3} s^{-1} in the fall and averaged 204.82 µmol CO_2 m^{-3} s^{-1} in spring and early summer. These higher respiration rates, accompanied by lower total non-structural carbohydrate (TNC) levels suggest that respiration rates in late fall comprised growth expenditures, reflecting recent radial growth. Bud flush and shoot growth of the trees did not cause an increase in coarse root respiration nor a decrease of TNC levels, suggesting a limited role of the coarse roots as reserve storage organs for spring growth. Average Q_{10} for coarse roots was 2.15. Nitrogen content did not vary within the seasons in the coarse and fine roots, but explained 65% of respiration when data of fine and coarse roots were pooled

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Impact of Catastrophic Boreal Forest Fires on the Carbon Budget: Russian Far East Case Study, 1998

D.F. Efremov[1], M.A. Sheshukov[1], and A.Z. Shvidenko[2]

This paper considers specific features of catastrophic forest fires over large boreal regions, and their impact on the condition and function of forest cover as well as on the carbon (C) budget. Catastrophic forest fires: 1) envelope vast territories; 2) stipulate extremely severe fire threat that causes a wide distribution of crown and peat fires as well as a high level of fuel consumption and post-fire dieback; 3) lead to a change in the environment and ecological conditions of forest landscapes as a whole; 4) significantly deteriorate quantitative and qualitative characteristics of post-fire recovery of landscapes and regeneration of forests, and often initiate the green desertification; 5) impact the gaseous composition of the emission; and 6) generate a high level of fire threat for future decades due to the accumulation of a large amount of fuel.

In 1998, forest fires in the Khabarovsk Kray (Russian Far East) were observed on an area amounting to 2.4 million hectares (conservative estimate based on official statistics; an expert estimate of the actual area is about 1.5 to 2-fold higher). These fires resulted in direct losses of stem wood of about 150 million m^3 and direct fire emissions of about 60 Tg C. The post-1998 fire biogenic flux for the next three decades is expected to be at the rate of 20 Tg C annually.

Detailed data on the description of the fire season, origin and distribution of fires, and the impact on regional forests and forest landscapes were examined. Quantitative estimates of direct fire carbon emissions and a modeling prediction of future post-fire carbon biogenic fluxes were determined. Based on historical analysis, it was concluded that there has been an increase in the frequency of the seasons involving catastrophic forest fires in the Northern Eurasian boreal zone during the last few decades. The large inter-seasonal variability of major regional indicators of forest fires defines specific requirements for modeling the future vegetation fire carbon budget in the boreal zone, in particular with respect to climate change. Deterministic models could generate significant uncertainties in the predictions. Some methodological aspects of the stochastic approach to the regional boreal forest fire carbon models are discussed.

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POSTER LOCATOR NO. 81

Exploratory Retrospective Analysis of the Interaction Between Spruce Budworm and Forest Fire Activity

Richard A. Fleming[1], Jean-Noël Candau[2], and Rob S. McAlpine[3]

The dominant natural disturbances in Canada's boreal forests are wildfire and outbreaks of spruce budworm (*Choristoneura fumiferana* (Clem.)). Carbon budget studies show that changes in these disturbance regimes that may be greatly influenced by climate warming are critical influences on the net atmospheric carbon exchange. The fire-spruce budworm (SBW) interaction under climate warming is also important because: 1) the tendency for SBW-killed stands to burn is expected to increase in warmer, drier climates; 2) in much of Canada's boreal forest, SBW outbreaks occur over much greater spatial extents than do fires; and 3) SBW outbreak frequency and extent, and thus the availability of SBW-killed stands, may increase as the climate warms. These three factors, when considered together, suggest that as climate warms, the interaction of SBW and wildfire disturbance regimes may substantially accelerate carbon releases from the boreal forest.

A retrospective analysis of Ontario's historical records from 1941 to 1995 was conducted as a pre-requisite to developing models for forecasting, and as a baseline for future monitoring. These results begin to quantify the interaction between SBW outbreak and wildfire disturbance regimes, and how climate has influenced this interaction in the past. Spatio-temporal analyses suggest that fires burned less than 10 Mha while SBW caused whole tree mortality within 33 Mha. Within the 41 Mha defoliated by SBW at least once since 1941, the proportion burned was significantly greater ($P = 0.00021$) in areas that suffered moderate frequencies (9 to 11 years) of SBW defoliation. Randomization tests revealed that fires over 200 ha occurred more often than would be expected by chance alone ($P < 0.05$) 3 to 9 years after a SBW outbreak, and that SBW outbreaks generally occurred less often than expected by chance alone ($P < 0.05$) between 1 year before and 16 years after fire. This 'time-window' of disproportionately high fire prevalence appears to have started later after SBW outbreak and to have been wider in western than in eastern Ontario. Possible climatic explanations for such differences were investigated.

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Climate Change Effects on Net Carbon Exchange of Boreal Aspen and Spruce Forests: Estimates from the Mathematical Model *Ecosys*

R.F. Grant[1], T.A. Black[2], P.G. Jarvis[3], and J.A. Berry[4]

There is much uncertainty about the net carbon (C) exchange of boreal forest ecosystems, although this exchange may be an important part of global carbon dynamics. To resolve this uncertainty net carbon exchange has been measured using eddy correlation techniques at several sites in the boreal forest of Canada as part of the BOReal Ecosystem-Atmosphere Study (BOREAS). These measurements were used to test hourly simulations of mass and energy exchange using a detailed ecosystem model *Ecosys* under short-term changes in weather.

Daily totals of net carbon exchange in these tests indicated that boreal forests lost carbon under low day-time radiation or high night-time temperature. Aggregations of measured and simulated carbon fluxes to annual time scales suggested that under current climates, boreal aspen (*Populus tremuloides*) and black spruce (*Picea mariana*) forests are net sinks of 100 to 200 g C m^{-2} yr^{-1} and 50 to 100 g C m^{-2} yr^{-1}, respectively. Long-term simulations indicated that these sinks might be larger during cooler years and smaller during warmer years because carbon fixation in the model was less sensitive to temperature than was respiration.

Ecosys was then used to evaluate possible changes in ecosystem carbon exchange and accumulation under changes in atmospheric carbon dioxide concentration (C_a) and accompanying changes in air temperature and precipitation proposed in emissions scenario IS92a. Under these changes in climate, a mixed aspen-hazelnut (*Corylus* spp.) stand in central Saskatchewan would accumulate an additional 8.5 kg C m^{-2} over 120 years, largely through higher rates of carbon dioxide fixation and longer growing seasons under higher C_a and temperature. Similarly a black spruce-moss stand in northern Manitoba would accumulate an additional 4.8 kg C m^{-2} over 150 years. This additional carbon accumulation would be almost entirely as aspen or spruce wood, while soil organic matter would change little. This accumulation would therefore be vulnerable to losses from fire and insects.

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POSTER LOCATOR NO. 46

Characterizing Carbon Assimilation of Black Spruce Following Frost: Implications for Carbon Cycle Modeling

David G. Guay[1], Hank Margolis[1], and Francine Bigras[2]

The boreal forest occupies approximately 11% of Earth's terrestrial surface. Thus, understanding how environmental constraints such as frost influence net photosynthesis (A_n) in this biome is key to the development of realistic physiologically based models of the global carbon cycle.

The phenological development of how A_n responds to frost was examined for the most common boreal tree species, black spruce (*Picea mariana* Mill.). Two-year-old black spruce seedlings from northern and southern provenances were exposed to artificial frosts of different intensities four times during spring de-hardening and five times during autumn hardening. Light-response curves were measured at various times over the three weeks following treatment. Seedlings were exposed to natural conditions both before and after frost treatment. As a function of growing degree-days and levels of frost hardiness, we evaluated: 1) the threshold sensitivities of A_n and apparent quantum use efficiency (α'); 2) the impact of different frost intensities on A_n and α'; and 3) the recovery of A_n and α' following frost applications. These data will be integrated into an algorithm that can be used to model photosynthesis as a function of different frost intensities over different parts of the growing season. This model will eventually be tested against data from various boreal forest field sites.

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Recovery of Photosynthesis of Boreal Conifers During Spring: A Comparison of Two Models

Heikki Hänninen[1], Koen Kramer[2], and Ilkka Leinonen[2]

Reduced photosynthetic capacity of conifers during late winter and early spring is a major factor affecting the carbon budget of stands in boreal conditions. Overestimates of up to 40% in net primary production (NPP) have been documented for simulations where the winter reduction of photosynthetic capacity has not been taken into account. Two models for the spring-time recovery of photosynthetic capacity were compared with respect to three aspects: 1) ecophysiological assumptions inherent in the logical structure of the models; 2) predicted spring-time development of photosynthetic capacity in years and locations with different climatic conditions; and 3) implications for the annual NPP of forest stands.

In order to study the implications of reduced winter photosynthetic capacity on predicted annual NPP, the ecophysiological models were included, one at a time, into the process based stand model FORGRO. The differences between the predictions of the two models were analyzed with reference to their ecophysiological assumptions.

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Carbon Dynamics in Northern Ontario Jack Pine and Black Spruce Plantations

Shelley L. Hunt[1], A.M. Gordon[1], and Dave M. Morris[2]

With the continued advent of intensive forest management in many regions of North America, large tracts of natural forest are being converted to conifer plantations, a trend that is likely to continue. It is therefore increasingly important to understand the carbon (C) and nutrient budgets of these plantations, especially in the boreal forest of Canada.

In the current study, carbon storage and fluxes are being documented in 14 well-established jack pine (*Pinus banksiana*) and 6 black spruce (*Picea mariana*) plantations, ranging in age from 10 to 53 years, in the Lake Nipigon region of northern Ontario (49.5°N, 88°W). Tree, understory and forest floor biomasses have been determined and analysis of these components in conjunction with sampling in mineral soil horizons is on-going. Carbon flux in litterfall is also being measured in 9 of the 20 stands.

Preliminary estimates of carbon storage suggest that jack pine plantations aged 12, 35, and 50 years have accumulated 24, 65, and 71 t C ha^{-1}, respectively, in living tree biomass, 21, 41, and 37 t C ha^{-1}, respectively, in the forest floor, and 25, 14, and 12 t C ha^{-1}, respectively, in the top 15 cm of mineral soil. Corresponding sequestration rate estimates for these components in total are 5.8, 3.4, and 2.4 t C ha^{-1} yr^{-1}, for jack pine plantations aged 12, 35, and 50 years, respectively.

The slower growing black spruce plantations, aged 14 and 35 years, have 10 and 50 t C ha^{-1}, respectively, in living tree biomass, 14 and 31 t C ha^{-1}, respectively, in the forest floor, and 14 and 25 t C ha^{-1}, respectively, in the top 15 cm of mineral soil. These values correspond to total sequestration rates of 2.7 t C ha^{-1} yr^{-1} and 3 t ha^{-1} yr^{-1}, respectively, for black spruce plantations aged 14 and 35 years. Carbon in understory biomass averaged less than 2% of total tree carbon.

Forthcoming studies and results will document carbon contents of litterfall, the soil respiration flux, and carbon in coarse woody debris for the complete range of sites. Results are being compared with those from a chronosequence of natural fire-generated stands in the area, ranging in age from 15 to 105 years.

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POSTER LOCATOR NO. 44

Modeling Carbon Dynamics in Coniferous Forest Soils

Riitta Hyvönen[1] and Göran I. Ågren[1]

Climatic change and changes in land use will alter the stores and turnover of soil organic matter. Combinations of conventional forest yield tables and a theory for carbon cycles were used to analyze the consequences for coniferous forest soils. The yield tables provided growth and litter production data in different forest stands. The litter production was then fed into a decomposition model from which time-series of soil carbon development were obtained. The decomposition model was developed on the basis of the continuous quality theory. The central concepts are a continuously changing substrate quality, a constant decomposer efficiency, and a climatically controlled decomposer growth rate.

This approach was applied to examine consequences for the national carbon (C) budget of Sweden as a result of increased use of biomass from forests and an increasing temperature. Swedish forest soils are estimated to contain 1700 Tg C and the annual Swedish emission from fossil fuel use is 16 Tg C. Removing needles, branches, and tops, which are normally left during harvesting operations, will only change the carbon budget a few percent. Leaving needles, which should also be done to retain nutrients, will almost imperceptibly affect the carbon budget. A temperature increase of 4°C can, on the other hand, have an impact that corresponds to an emission of about 1 Tg C per year. Increasing forest production will decrease this loss, but not enough to balance it. There is a general trend within the country towards larger soil carbon stores with increasing site temperature as a consequence of a shift in the balance between production and decomposition. However, it is not certain that such a shift will also occur under a climate change, because the productivity of a site is the result of a long history of build-up of nutrient capital and not only the result of current temperature.

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POSTER LOCATOR NO. 105

Lightning Fire in Siberian Forests

Valery A. Ivanov[1]

Lightning induced fires occur annually in the forests of Siberia, and account for 30 to 70% of forest fires. They make a considerable contribution to the global carbon budget. Storm activity varies widely along the Yenisei meridian of Siberia, increasing from north to south. Most storms (up to 45%) occur in July. During day-time storms, most lightening strikes occur between noon and 6:00 p.m. The annual average duration of storms is 58 hours. Localized storms occur most often, accounting for 93% of storms.

The number of cloud-to-ground charges and lightning fires were found to increase with increasing intensity of geomagnetic anomalies. Lightning fires can occur in any forest type, but mostly in stands dominated by light-needled species. Scots pine (*Pinus sylvestris*) and Siberian pine (*Pinus sibirica*) stands account for 55% and 30% of all lightning fires, respectively. Lightning fire occurrence is determined by storm frequency and extent, and by site conditions, and is non-uniformly distributed across the region. There are areas where lightning fire potential is considerably higher than in the rest of central Siberia. In these areas, fuel-related fire danger is high and storms are frequent. Accurate identification of these areas will improve lightning fire detection and control. Storms are especially dangerous in that they can ignite several fires simultaneously over a large area in a short period of time. Lightning fires can be in a stage of decay within several days. Most areas where lightning fires are common are inaccessible, so that even with early detection, they cannot be contained quickly and can grow to extreme sizes. Therefore, developing methods of storm prediction and early detection is a key issue. This problem can be approached through predicting and rating lightning-induced forest fire danger.

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Impact of Fires on Carbon Balance in Pine Forests of Siberia

Dr. Galina A. Ivanova[1] and Dr. Valentina D. Perevoznikova[1]

Siberian boreal forests are a major contributor to the global carbon (C) balance. Pine (*Pinus sylvestris* L.) stands comprise 30% of the total conifer forests, where one-third of carbon is stored. Fire is a key agent controlling the carbon budget of the boreal forest. Types of Siberian pine forests are determined by site conditions. Pine stands with green moss groundcover are found in a wide range of ecological conditions and grow in sites optimal in terms of soil peat and water content.

Aboveground biomass of living groundcover varies from 1.5 to 2.5 t ha^{-1} (dry weight), or 0.75 to 1.25 t C ha^{-1}. Green mosses amount to 40 to 70% of the living groundcover layer. Pine stands with grass-dominated groundcover are also prevalent, and occur most often as a result of pine-green moss forest succession after high intensity fires. Aboveground grass biomass is 2 to 2.2 t ha^{-1} (1.25 t C ha^{-1}) in these forests. Pine stands with groundcover made up by lichens are intrazonal and limited to dry and oligotrophic sites. Lichens contain 0.1 to 0.35 t C ha^{-1}.

Carbon budget components are relatively stable in climax communities. However, the situation is very different in ecosystems that experience fires. Green mosses and lichens suffer the most from fire. Living groundcover carbon losses are 90% under a high-intensity fire, and 70% and 10 to 20% under moderate and low intensity fires, respectively. In pine-grass forest types, spring fires of low intensity promote grasses and this, eventually, compensates for carbon losses. Periodic surface fires of varying intensity are common in pine stands. The mean fire return interval decreases from north to south and ranges from 25 to 10 years. Forest fire emission increases drastically during extreme fire seasons that occur 2 to 3 times a decade. Boreal forest fire emissions depend on fire intensity that changes both spatially and temporally. Emissions from high intensity surface fires in pine stands are several times higher than emissions from low intensity fires. Fire intensity and seasonality also impact post-fire biogenic emissions. Therefore, estimating the contribution of emissions from Siberian pine forests to the global carbon balance requires an understanding of mechanisms of fire behavior and the influence of fire intensity influence on emissions released in different types of pine forests.

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POSTER LOCATOR NO. 9

Evaluating the Carbon Dynamics of Canadian Boreal Forests by Estimating NPP, NEP, and NBP

Hong Jiang [1], Michael J. Apps[2], Jag Bhatti[2], Yanli Zhang[1], and Changhui Peng[3]

Net primary production (NPP), net ecosystem production (NEP), and net biome production (NBP) are the fundamental indicators of the contribution made by forest ecosystems to the carbon cycle. In central Canada, the boreal forests can be divided into three eco-climatic zones: high boreal, mid-boreal, and low boreal zones. In all three types, wildfire is the primary disturbance agent.

Site-specific estimates of NPP and NEP in the three types of boreal forest ecosystems in central Canada were simulated using the terrestrial ecosystem process-based model (CENTURY 4.0). An algorithm for estimating NBP was developed for use with the simulation results. The influence of different fire regimes (return interval and fire intensity) on NPP, NEP, and NBP was also examined.

The simulation results show that fire disturbances significantly influence NPP, NEP, and NBP in the boreal forests of central Canada, and modify the net nitrogen mineralization rates. A decrease in the disturbance interval increases the net nitrogen mineralization rate and ultimately the NPP and NEP in each zone. Comparison of changes in NPP, NEP, and NBP under different fire disturbance regimes provided important insights on the potential changes in carbon source-sink relationships in boreal forests under a changing climate.

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POSTER LOCATOR NO. 126

Man-made and Natural Disturbances along the Siberian IGPB Transect

Viacheslav I. Kharuk[1] and Kenneth J. Ranson[2]

The anthropogenic and natural disturbance impacts on the carbon balance of key sites along the Siberian International Geosphere-Biosphere Project (IGBP) transect were investigated using remote sensing in microwave and optical bands, on-ground observations, and historical data. The disturbed areas were classified under three to four grades of impact.

The Norilsk zone has experienced the largest anthropogenic catastrophe in the sub-arctic, caused by approximately 2 Mt yr^{-1} of sulphur dioxide (SO_2) emissions. Forest mortality was observed approximately 120 km from smelters, and forest damage occurred over 200 km from smelters. The winter-acquired images show a 'pollution footprint' on the snow background. Correlation of the snow to soil heavy metal content and the level of pollution in run-off water is clear. The concentrations of the heavy metals exceeded the background level by 3 to 4 orders of magnitude. The temporal record of satellite images allows the detection of the decline in forest productivity. Its maximal speed correlates with construction of new industries at the end of the 1970s and beginning of the 1980s. Today the area of dead forest is about 0.5 million hectares, with a wood volume of approximately 3.4 million m^3. The total affected forested area is approximately 7 million hectares. The zone of forest damage is still spreading at a rate of 2 to 3 km per year.

Pest impacts were analyzed using the case of the Siberian silkmoth (*Dendrolimus sibiricus*) outbreak in 1993 to 1996. The total affected area of 'black needle' taiga (composed of Siberian fir (*Abies sibirica*), Siberian pine (*Pinus sibirica*), and spruce (*Picea obovata*)) stands was estimated to be ~0.7 Mha. Winter-acquired images were used for delineation of the northern border of the outbreak region. Since this border will move to the north with climate change, the potential zone of outbreaks was delineated.

Since all disturbance types caused biomass decrease, special emphasis was made to apply microwave remote sensing techniques (SIR/SAR and ERS data). The wood biomass of stands could be estimated in the range of up to 200 t ha^{-1} by analysis of spectral signatures and polarization in C and L bands. Approximately 90% of Siberian forests are within this range of biomass values. Good agreement was found between on-ground and radar-derived fire scars and clearcut parameters. The post-disturbance successions (with respect to the types of disturbances, forests, soils, and topography) were analyzed.

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Nutrient Use Efficiency: Coupling Plant and Soil

Magnus F. Knecht[1]

Since its introduction, the concept of nutrient use efficiency (NUE) has been subject to disagreement among ecologists with respect to the definition of the term and its interpretation in an empirical context. Following some recent discussions in the literature, Pastor and Bridgeham presented a thorough analysis of the properties of NUE that should leave little room for further confusion.

Plant production is one of the fundamental properties of an ecosystem, but decomposition must be considered as important. The purpose of this study was to weave these two properties together in a simple model on the basis of the ecosystem theories of Ågren and Bosatta, which consider NUE in the way described by Pastor and Bridgeham. For convenience the system was assumed to be limited solely by nitrogen. The model consists of a plant with size W growing with a nitrogen productivity P_N and a turnover rate μ of tissue. A minimum nitrogen concentration, c_{Nmin} in the plant is required to enable plant growth. At lower concentrations no plant production will occur. The relative growth rate increases with increasing nitrogen concentration. At a nitrogen concentration of c_{Nopt}, the relative growth rate has reached its maximum.

(1) $$\frac{dW}{dt} = P_N \cdot (N - c_{N\min} \cdot W) - \mu \cdot W$$

The soil part of the model describes soil carbon ($C(t)$) and soil nitrogen ($N(t)$), as functions of time t, according to the equations:

(2) $$C(t) = C_0 \cdot e^{-\frac{1-e_0}{e_0} \cdot f_C \cdot u \cdot t}$$

(3) $$N(t) = C_0 \cdot \left[\frac{f_N}{f_C} - \left(\frac{f_N}{f_C} - r_0 \right) \cdot e^{-f_C \cdot u \cdot t} \right] \cdot e^{-\frac{1-e_0}{e_0} \cdot f_C \cdot u \cdot t}$$

Here e_0 is the decomposer efficiency, u the decomposer growth rate per unit of carbon, and f_C and f_N the carbon and nitrogen concentrations in the decomposer biomass. C_0 is the initial amount of carbon and r_0 is the initial nitrogen to carbon ratio in the litter.

General patterns were studied starting with the simplest scenario of one plant in a system closed to nitrogen. The addition of another plant species provided an opportunity to analyze the impact of the various plant properties on competition. The suggestion that litter decomposability could be an important component of plant fitness was analyzed. Steady state solutions to these systems can be derived analytically, making it possible to analyze steady state properties more in-depth.

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POSTER LOCATOR NO. 28

Forecast of Carbon Pools and Streams in Siberian and Far Eastern Forests

George N. Korovin[1] and Alexander S. Isaev[1]

A forecast of carbon stock dynamics and annual carbon sequestration by forest vegetation is based on modeling of long-term forest cover dynamics. Temporal changes in the structure of forested lands, tree-species composition, and age structure are considered to be the result of biological processes of forest growth and evolution under present management and disturbance impacts. Disturbance impacts include forest fires, pests, and other natural factors, while management impacts include clearcut harvesting, forest protection, and regeneration activities.

Processes of forest stand growth are described by curves of average phytomass stock as a function of the biological age of forest stands. Transition matrices for predominant tree species with changing forest stand age are used to describe processes of natural succession. Disturbance impacts are characterized by matrices of stand death due to forest fires and other disturbance factors, and the transition into another category of wooded lands.

Dynamics of forest cover, carbon pools, and increments were predicted for different types of forest management strategies. Each was determined by its own regime of forest-resource use, regeneration, and level of forest protection. The influence of forest-use activity, forest protection level, and silviculture methods on the dynamics of carbon stocks and carbon deposition were analyzed for different test regions of Siberia and the Far East. The curves of carbon stock dynamics and annual sequestration were examined under different scales of management and disturbance impacts on the forests. The qualitative estimates of carbon pools and fluxes in forest vegetation for every twenty years during the 200-year prognostic period, and for the quasi-stationary forest land base, were also obtained within the test regions.

It was established that increased forest use decreased the carbon stock in the forest while increasing the annual sequestration rate by forest vegetation. This was a result of the gradual replacement of mature and over-mature forest stands by young and middle-aged stands with higher phytomass increments. Harvesting increased the area of young to middle-aged stands in the total forest land base. Forest protection practices reduced fire and post-fire carbon emissions and reduced the area of young and middle-aged forest stands in the total composition of the forest land base.

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Impacts of Clearcut Logging on the Terrestrial Carbon Budget of a Watershed in Northwestern Ontario

Blake Laporte[1], Mark Johnston[2], and Margaret Donnelly[3]

The study area is part of the Coldwater Lakes Experimental Watershed site located 70 km NW of Atikokan in northwestern Ontario (longitude 92°18'W and latitude 49°18'N). The forest region is Great Lakes-St. Lawrence, and the forest type is predominantly jack pine (*Pinus banksiana*)/Aspen (*Populus tremuloides*) mixedwood on shallow to moderately deep and sandy Brunisols or Podsols. Two watersheds were experimentally clearcut from 1996 to 1998.

Study parameters included the vertical distribution of carbon (C) in soil and vegetation within three experimental lake basins before and after harvest. Plot sampling was a square, nested sampling design in a 100 m grid. Carbon was indexed using organic matter (OM) content for soils and allometric biomass equations for vegetation. Removed carbon was indexed using merchantable bole volume. Harvesting occurred on only 59% of sample plots due to operational limitations (rough terrain). Mean soil carbon totals (t C ha^{-1}) increased from 126.4 (± 61.2) to 135.1 (± 58.0) after harvest. OM percent in the organic soil decreased by 28.6%, while OM percent in upper mineral soil (top 25 cm) increased 15.2%. Mean root carbon total (t C ha^{-1}) was 20.5 (± 10.3). Mean carbon totals (t C ha^{-1}) for aboveground vegetation (understory and tree layers) decreased from 61.9 (± 26.6) to 29.5 (± 11.2) after harvest due to the removal of merchantable boles. While harvesting had a major impact on the herbaceous and shrub layers, the removal of merchantable boles caused the largest decrease in vegetation carbon totals. Disturbance (especially scarification) caused a mixing of the organic layer and the upper mineral soil resulting in a change in soil carbon location.

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Soil Respiration Responses to Climatic Warming will not Reduce Net Ecosystem Exchange of Carbon in Balsam Fir Ecosystems

M.B. Lavigne[1], R. Foster[1], R. Boutin[1], G. Goodine[1], and G. Robitaille[1]

To enhance our understanding of the environmental and ecosystem controls over net ecosystem exchange of carbon, soil respiration (*R*) was measured with a portable infrared gas analyzer between 1997 and 1999 at three balsam fir (*Abies balsamea*) ecosystems on a latitudinal transect in eastern Canada.

Annual total *R* increased from south to north on the transect, however this trend was not due to temperature-dependent rate of soil carbon turnover. Results of trenching experiments suggested that root respiration rates were largely responsible for greater annual total *R* at more southerly locations. Temperature-corrected *R* was greatest late in the growing season; this seasonal pattern was consistent with the notion that root respiration was the largest contributor to *R*, because root growth was greatest late in the growing season. There were differences in annual total *R* between years that could not entirely be explained by interannual differences in climate. Other factors, possibly including variation in the quantity of photosynthates allocated to root growth, also contributed to interannual variability. Taken together, these results suggest that roots were largely responsible for differences in *R* between ecoclimatic provinces in balsam fir ecosystems. Since root respiration uses recently acquired carbon, these differences in *R* do not imply that net ecosystem productivity will necessarily decline as the climate warms.

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Phenology as a Key Factor in Determining the Carbon Sequestration Potential of Boreal Forests under Climate Change

Ilkka Leinonen[1] and Koen Kramer[1]

The timing of phenological events, such as leaf unfolding and leaf fall in deciduous trees, and the spring recovery and autumn cessation of photosynthetic capacity in conifers, strongly affects the overall carbon budgets of boreal forests. The importance of these phenomena was demonstrated with the aid of a process-based forest growth model. In the model simulations, the gross primary production (GPP), net primary production (NPP), and net ecosystem exchange (NEE) of boreal coniferous (pine) and deciduous (birch) forest stands were predicted in the present climate and in the future climate, where the rise of temperature was predicted by a global climate model. The change in phenology was taken into account in the case of pine by applying a temperature-dependent model, which predicted the spring recovery of photosynthesis from winter-time depression, and its cessation in autumn caused by low temperatures. In the case of birch, the timing of bud burst was predicted by using a model based on the cumulative temperature sum. In the analyses, the effects of phenological events were separated from other processes affecting the carbon sequestration.

The results show that a major part of the changes in the carbon sequestration potential caused by climatic warming in boreal coniferous and deciduous forests were due to the changes in the timing of phenological events. The increased temperature caused a prolonged photosynthetically active period and thus increased the annual GPP. The results indicated that change in phenology needs to be taken into account to accurately assess carbon budgets of boreal forests in the future.

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POSTER LOCATOR NO. 100

The Loss of Carbon during Smoldering Combustion Fires in Northern Wetland Permafrost Soils

Michael J. Liston[1] and Ross W. Wein[1]

During the summers of 1979 to 1981 (very hot and dry summers), fires burned almost 20% of the 43,560 km² area of Wood Buffalo National Park. Shortly after the 1981 fire, deep ash deposits were noted in some of the wetlands; evidence of these fires is readily apparent today in soil profiles. Ash beds of 20 cm or more in depth typically have a dark organic surface layer, white ash, brown/red brick-like aggregate, orange mottled white ash, hard brick-like aggregate, and then a thin layer of charcoal at the surface of the fine textured gray mineral soil.

The objective of the study was to estimate the temperatures reached and the carbon loss from these peat deposits during these smoldering fires. Profiles were taken from a range of sites with differing depth of burn, using a 15 cm diameter steel tube, and subdivided into homogeneous layers based upon color and texture. In the laboratory, percent organic content was determined by loss on ignition procedures, at a range of temperatures up to 55°C for four hours. Laboratory analysis indicated that ash color and temperature were strongly related and carbon loss varied strongly by depth. The work will be discussed in light of the fire-climate change scenarios.

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Modeling Carbon Stock and Dynamics in Boreal Forests of China

Jinxun Liu[1], Hong Jiang[2], Yanli Zhang[2], Changhui Peng[1], and Michael J. Apps[3]

The boreal forests of China, geographically distributed in the Daxinnanling Mountains of northeastern China, are the most southern part of the global boreal forest. Dominant vegetation in these forests are larch (*Larix gmelinii*), birch (*Betula platyphylla*), pine (*Pinus sylvestris* var. *mongolica*), and oak (*Qurcus mongolica*). In this study, a terrestrial ecosystem process model, CENTURY 4.0, was used to investigate the effects of different ecosystem disturbance regimes (fire and harvest) and disturbance cycle and intensity on carbon stocks and dynamics. Ground-based data were assembled for three sites, Xinlin, Tahe, and Mohe, representing the northern, middle, and southern parts of the Chinese boreal forest. The simulated carbon stocks from CENTURY 4.0 for these sites were consistent with measured data.

Biomass and soil carbon were found to decline markedly after fire and harvest disturbances, and the decreases were positively correlated with disturbance interval and intensity. Net primary production (NPP) and net ecosystem production (NEP) were negatively correlated with fire and harvest disturbances. Ecosystem carbon stocks (in biomass and soil), and NPP and NEP in the southern region were higher than those in the mid- and northern regions. Throughout the entire region, younger forests had higher NPP and NEP than older forests, but lower carbon stocks. As a whole forest system indicator, net biome production (NBP) was also estimated. The carbon stocks in boreal forests of China were compared with those of Canada and Russia.

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Carbon Budget of the Georgian Forests: On the Way from Boreal to Tropical Forest Ecosystems

Ioseb I. Mamukashvili[1] and Vladislav A. Alexeyev[2]

Forests of Georgia occupy 2.76 million ha (39% of the territory). The forested area consists of hardwood forests (67.2%), conifer forests (16.4%), deciduous softwood forests (10.7%), and scrub (5.7%). Most of the forests are located in the Great Caucasus Mountains, with 20% in the Colkheti lowland and some plains and valleys. Subtropical forests of the lowlands and foothills are heavily changed by human activity.

Spectra of forests in mountains differ considerably over the country. Well distinguished are oak (*Quercus* spp.), beech (*Fagus orientalis*), and spruce–fir (*Picea orientalis – Abies nordmaniana*) belts. The area of these belts equals 2.3 million ha; and the growing stock amounts to 390.4 million m^3. The carbon storage of forest stands is 148 Mt; the carbon of forest ecosystems equals 308.4 Mt. Most of forest communities retain their natural composition and structure. The average carbon density of the conifer ecosystems is 165 Mg C ha^{-1}. Carbon of their litter, coarse woody debris (CWD), and soil amounted to 46% of the total value. The distribution of carbon in hardwood ecosystems is similar.

In comparison with boreal forests of European Russia, the carbon in live vegetation in the Georgian forests is much higher whereas litter shows low absolute and relative values. The proportion of CWD in Georgian forests is also much lower, especially in hardwood ecosystems. Forest soils of Georgia are richer in organic matter than soils of the boreal zone in Russia. The reasons and role of the observed peculiarities in the carbon budget of these systems are discussed.

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Carbon and Water Exchanges in a Boreal Black Spruce Stand

Jonathan M. Massheder[1], Paul G. Jarvis[1], and John B. Moncrieff[1]

Eddy covariance fluxes of carbon dioxide (CO_2), momentum, sensible heat, and latent heat were measured from 25 March to 28 November 1996 over a black spruce (*Picea mariana* (Mill.) BSP) stand as part of the BOReal Ecosystem-Atmosphere Study (BOREAS). BOREAS was a multi-scale study using satellites, aircraft, tower, and leaf-scale measurements of the major vegetation types of the Canadian boreal forest. The measurements were made at the BOREAS Southern Study Area Old Black Spruce Site in mid-Saskatchewan.

When upper soil temperature was less than 0°C, the ecosystem was a carbon (C) source with losses averaging 0.8 g C m^{-2} d^{-1}. On hot cloudy summer days, the ecosystem was also a net carbon source. Net ecosystem uptake reached a maximum of 14 μmol m^{-2} s^{-1} and nighttime efflux reached a maximum of 10 μmol m^{-2} s^{-1}. The optimum temperature for CO_2 assimilation was 30°C, close to the maximum air temperature observed at 26 m. Quantum efficiency of assimilation (α) reached a maximum of 0.066 in July. Assimilation by the canopy followed incident photosynthetic photon flux density closely when $\alpha > 0.0$ and decreased when the vapor pressure deficit exceeded 1.3 kPa. Over the year temperature was the most important environmental variable limiting carbon uptake. Respiration estimated from nighttime fluxes showed an exponential response to temperature, the sensitivity of which varied with season.

Carbon exchange in the winter, when fluxes were not measured, was estimated using a respiration model driven by soil temperature. The estimated annual carbon uptake for the stand was 15 g C m^{-2} (0.15 Mg ha^{-1}). The annual evaporation was estimated as 271 mm.

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POSTER LOCATOR NO. 110

Carbon Storage and Climate Change in the Boreal Forests of China: Local Perspective

Jian Ni[1]

The boreal forests of China are distributed in the northeastern and northwestern regions (approximately 41 to 54°N latitude). Both maritime-humid and continental-arid climates affect these regions. Annual mean temperatures range from –7.3°C to 6.2°C, and annual precipitation ranges from 403.4 to 630.8 mm in the east and from 162.4 to 180.8 mm in the west.

The carbon storage (C) of boreal forests in China was estimated using a mapping system for vegetation patterns combined with carbon density estimates for vegetation and soils. The BIOME3 model, with current climate conditions and carbon dioxide (CO_2) concentrations of 340 ppm, was used to estimate total carbon storage of the boreal forests of this area. For current boreal forests, excluding agricultural vegetation and using median carbon storage estimates, total carbon storage was calculated at 1.83 Pg C in biomass and 2.77 Pg C in soils. For potential boreal forests under present climatic conditions, including agricultural vegetation, the carbon storage increased to 2.76 Pg C in vegetation and 4.16 Pg C in soils.

Changes in climate and CO_2 concentration would change the carbon storage capacity of boreal forests in China. However, climate change with or without CO_2 enrichment would lead to a large decrease in total carbon storage (by about 6.5 Pg C). This is due to a reduction in the total area of boreal forests in China as a result of climate change. In the absence of climate change, assuming that the total area of boreal forest remained the same, CO_2 concentrations of 200 ppmv (low estimate) to 500 ppmv (high estimate) would result in a very small decrease in total carbon storage. The effect of climate change is more significant than the effect of a change in CO_2 concentration on the boreal forests of China.

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Contribution to Carbon Cycle and Climate Stability via Expansion of Azonal Boreal Forests in the Ukrainian Carpathians

Maria Nijnik [1]

The communist regime that was established in the western territories of the Ukraine after the Second World War subjected the Carpathian forests to disastrous overexploitation. Until the early 1970s, harvesting in these forests exceeded annual allowable norms by 2 to 2.5 times. Due to excessive felling, the vitality of forests, their age structure, density, and forest stand productivity have decreased considerably. The upper border of the Carpathian forests has become lower with the contraction of the azonal boreal forests of the Ukraine. Forests of the Carpathian Mountains have become less powerful with respect to their shelter functions, including those of climate stabilization.

Forest distribution in the mountains could be expanded via afforestation and reforestation of wasteland and highly-eroded unwooded lands within the State Forest Fund, and marginal agricultural lands locally used as pastures. The objective of the study was to assess the potential possibilities to contribute to carbon cycle and climate stability via the expansion of azonal boreal forests in the Carpathians, and to estimate the policy implementation costs. The first step of the research was to consider a "storage option", where trees are planted for a period of 40 years. The study did not consider future use of wood and land after this period.

The results of the research have shown that afforestation and reforestation in the Carpathian Mountains for the single objective of carbon uptake would not be beneficial. However, we highly recommend expanding the wooded area of azonal boreal forests of the Ukraine for other purposes, such as for soil and water protection. Thus, besides certain contribution to climate stability, the afforestation program would significantly enhance the environmental role of the Carpathian forests. In future studies, we intend to employ a dynamic optimization model (an optimal control tool) to indicate optimal expansion of azonal boreal forests in the Carpathians.

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Effect of Temperature on the Mineralization of Carbon and Nitrogen from Soil Organic Matter across a Latitudinal Gradient of Forest Sites in Eastern Canada

D. Paré[1] and R. Boutin[1]

The dynamic of soil organic matter is controlled in a large measure by the nature of soil organic matter and by temperature. Long-term laboratory incubation techniques were used to investigate the effect of temperature on the mineralization potential of different soils representing a gradient in climate and forest productivity. Three forest types were studied: sugar maple (*Acer saccharum*), balsam fir (*Abies balsamea*), and black spruce (*Picea mariana*) forests. The fraction of soil nitrogen and carbon available to soil microorganisms increased with soil temperature in sugar maple and balsam fir sites. However, on black spruce sites, an effect of temperature was only found at high temperatures and this effect was much weaker than in the other soils especially for nitrogen mineralization. This information suggests that the nature of the soil organic matter of black spruce forests makes this ecosystem resistant to alterations in its function upon warming, while temperature could have an important effect on the cycling of nitrogen and carbon in the other ecosystems studied.

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Poster Locator No. 49

Heterotrophic Respiration in Organic and Mineral Soil Layers in Boreal and Temperate European Forests

Tryggve Persson[1], Patrik S. Karlsson[1], R. Michael Sjöberg[1], and Anna Rudebeck[1]

Effects of climate, tree species, and nitrogen status on heterotrophic respiration (carbon mineralization) rate were studied in 8 stands of *Picea abies* and 6 stands of *Fagus sylvatica* in a transect from northern Sweden to central Italy. Organic and mineral soil layers were quantitatively sampled to a depth of 50 cm. Carbon mineralization rate was determined in the laboratory on freshly sieved samples at 15°C and optimum moisture during 150 days.

The carbon mineralization rates declined with increasing soil depth, from 990 ± 70 (mean ± SE) $\mu g\ C\ g^{-1}$ C in the litter layer to 34 ± 6 $\mu g\ C\ g^{-1}$ C at 30 to 50 cm depth in the mineral soil. For comparable stands, carbon mineralization rate had a tendency to be higher in the topsoil under *Picea* than under *Fagus*. In the L- and FH-horizons, carbon mineralization rate was positively correlated with the carbon-to-nitrogen ratio, implying that boreal forests with low nitrogen deposition can have high carbon mineralization despite low temperature. When extrapolated to the field, taking soil pools, soil temperature, and soil moisture into consideration, heterotrophic respiration was estimated to be 1900 ± 180 (range 900 to 3000) kg C ha^{-1} yr^{-1}. Mean contribution of the L, FH, 0 to 10, 10 to 20, 20 to 30, and 30 to 50 cm soil layers to total respiration was 32, 32, 18, 9, 4, and 5%, respectively. Total heterotrophic respiration was positively, although not very strongly, correlated with the soil carbon pool and mean air temperature. Mean residence time (MRT) estimated as mineralized C ha^{-1} yr^{-1} divided by soil-layer C ha^{-1} was often shorter than 50 years in the organic layers. Below a depth of 10 cm in the mineral soil, MRT was normally 100 to 400 years, indicating that this carbon originated from former tree stands rather than the present ones.

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What Controls Carbon Sequestration? Characterization of Carbon and Nitrogen on the Canadian Boreal Forest Transect

Caroline M. Preston[1], Jagtar S. Bhatti[1], and R.M. Siltanen[1]

Despite its recognized importance, little is known about carbon (C) quality in boreal forest soils. To understand factors controlling carbon sequestration in boreal ecosystems we must isolate and characterize soil organic matter fractions corresponding to the conceptual pools of slow- to fast-turnover carbon, and their associated organic nitrogen (N). The amount and chemical nature of soil carbon and nitrogen were investigated at paired sites (three upland forested, three lowland non-forested) along the Boreal Forest Transect Case Study (BFTCS). The transect is oriented southwest to northeast, covering approximately 1000 by 100 km of generally flat topography in central Saskatchewan and northern Manitoba. Organic horizons (LFH from forest sites, 0 to 10 cm from peatlands) were separated into 2000 to 250 μm and <250 μm size fractions. Mineral soil (<2 mm) was separated by sonication and wet-sieving into water-floatables, 2000 to 250 μm, 250 to 63 μm and <63 μm for A- and B-horizons of two sandy soils and a combined A+B-horizon for a silty clay soil with a thin and discontinuous Ah-horizon.

Recoveries were over 95% of starting mass, with the sandy soils having the greatest recovery in the 2000 to 250 μm fraction and the silty clay in <63 μm. Whole soils and fractions will be further analyzed for total carbon and nitrogen, and ^{13}C and ^{15}N enrichment. Solid-state ^{13}C nuclear magnetic resonance (NMR) spectroscopy will be used to characterize carbon components in organic horizons, floatables, and mineral fractions, where possible.

Carbon and nitrogen exhibited lower concentrations in the LFH layer in upland forest sites as compared to lowland sites. Accumulation of carbon and nitrogen is related to factors such as climate, soil texture, drainage class, nutrient regime, quality of plant inputs (especially woody material), and preservation of charcoal, which may constitute a very slow, passive pool of soil carbon. Climatic gradients had a substantial influence on carbon and nitrogen stocks with larger pool sizes on northeastern sites as compared to southwestern sites along the transect. Upland forested sites with higher clay content had higher carbon and nitrogen accumulation.

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Carbon Sequestering in Northern British Columbia Clearcuts: Is a 5-Year-Old Sub-Boreal Spruce Clearcut a Source or Sink of CO_2?

Thomas G. Pypker[1] and Arthur L. Fredeen[1]

It is often assumed that after timber harvesting, clearcuts remain a source of carbon dioxide (CO_2) for many years. However, few studies have actually measured the *in situ* fluxes of CO_2 from very young clearcuts. This lack of information, and the questions surrounding rising atmospheric CO_2 levels and the missing carbon sink, prompted an investigation into when forests switch from a carbon source to a carbon sink.

To begin tackling the question, a Bowen ratio system was deployed in a 5-year-old clearcut approximately 80 km east of Prince George, British Columbia. Between June 10 and September 4, 1999, fluxes of water and CO_2 were measured. To further augment the results of the Bowen ratio system, and to provide insight into the components of the fluxes, an Li-6200 was used from May until September to measure CO_2 fluxes from the soil, spruce seedlings (*Picea glauca*), and deciduous plants (*Lonicera involucrata, Spirea douglasii, Calamagrostis canadensis,* and *Epilobium angustifolium*).

The component approach allows for the scaling up from the leaf and soil levels to the clearcut and will provide insight during times when the tower based instruments function poorly (i.e., dusk/dawn and many nights). During the summer period the clearcut was a source for CO_2 on 49% of the days. Carbon emissions were greatest early in the summer prior to leaf-out in the deciduous plants. Furthermore, the soil remained a large contributor to the overall carbon flux.

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POSTER LOCATOR NO. 7

Moss Cover at Local and Regional Scales in the Boreal Forests of Canada

Gloria Rapalee[1,2], Louis T. Steyaert[2,3], and Forrest G. Hall[2,4]

Mosses are important components of boreal upland and wetland plant communities, contribute significantly to annual plant productivity, store significant amounts of carbon, and alter surface runoff and energy balance. Decomposition of moss is slow enough that carbon accumulates between fires, and can be an important local carbon sink. At the regional scale, the carbon sink in growing moss layers in any year depends mostly on areas of burn and regrowth. For several days following rainfall, moss surface water storage and evaporation can significantly alter runoff and surface energy balance, and can humidify the atmospheric boundary layer.

To provide continuous gridded moss coverage across the BOReal Ecosystem-Atmosphere Study (BOREAS) region of Canada's boreal forest, we mapped surface moss type at three scales (10 m, 30 m, and 1 km). Our classification was based on observed associations (at 10 and 30 m scales) between four broad classes of ground cover (feather, sphagnum, and brown mosses, and lichen) and land cover type. From the results of our detailed analyses at the finer scales of 10 and 30 metres, we made inferences on moss type and distribution at the regional level (1 km).

Our major objective was to develop a previously unavailable regional moss cover classification at 1 km (re-aggregated to scales of 2 km, 10 minute by 5 minute, and one-half degree) for modeling at regional and global scales. By including images at finer scales (10 m and 30 m) we demonstrate spatial variability of moss within 1 km land cover pixels and account for smaller wetland areas not detected at this scale.

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POSTER LOCATOR NO. 93

The Carbon Balance of a Boreal Forest Ecosystem

M.B. Rayment[1] and P.G. Jarvis[1]

There are many uncertainties in our understanding of how changes in global climate might lead to changes in the contribution by boreal forest ecosystems to the global carbon (C) budget. By individually measuring the components of the carbon budget, a better understanding of the carbon-related physiology of an ecosystem may be gained.

In 1996, carbon fluxes were measured using gas exchange chambers, and carbon stocks were measured using inventory data, at the Old Black Spruce (*Picea mariana*) site, Southern Study Area (SSA-OBS) of the BOReal Ecosystem-Atmosphere Study (BOREAS) in Saskatchewan, Canada. With this data, a complete carbon budget was constructed for the site for that year. By using process-based models of each component flux, parameterized from data acquired at the site, the temperature sensitivity of each component flux and of the carbon budget of the whole ecosystem were investigated.

In 1996, the estimated annual net carbon uptake for the ecosystem was 0.33 Mg C ha^{-1} yr^{-1}. This was the small difference between a large inward flux (total gross photosynthesis, 12.19 Mg C ha^{-1} yr^{-1}) and a large outward flux (total respiration, 11.63 Mg C ha^{-1} yr^{-1}). Because both photosynthesis and respiration are sensitive to temperature, the carbon source/sink strength of this ecosystem was found to be very sensitive to changes in environmental conditions.

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Carbon of Litter in Boreal Forest Ecosystems of European Russia

Boris Ryabinin[1], Vladislav Alexeyev[1], Michael Tarasov[1], and Richard Birdsey[2]

Forest litter is a multi-functional part of forest ecosystems. It is an extremely mobile organic-producing layer that determines the type of soil humus. Density of litter carbon (C) ranges on average from 2 to 97 Mg C ha^{-1} in various boreal forest ecosystems. Much data is available on the density of litter in forests of Russia, especially for European Russia. However, these data have not been summarized in a systematic way. Since this causes difficulties for correct estimates of litter carbon in large forest areas, a model was developed to determine the most probable estimates of litter carbon for the main types of forests in Russia and Scandinavia. The model is based on a literature database of average densities of litter in different forest types, data on climatic conditions in ecoregions, and statistical data from the Russian national forest inventory on the distribution of forested areas by forest type and age. The results of the model were verified with regional data for different forest types. The litter model has been adopted as part of the ecosystem approach for estimation of carbon in boreal and temperate forests.

The litter model provided more detailed data than earlier studies. A simplified example of the model output showed the average density of litter carbon in premature Scots pine (*Pinus sylvestris*) forests of Leningrad Oblast (southern subzone of boreal zone) was 6 Mg C ha^{-1} in the *Pinetum lichenosum* type, 16 Mg C ha^{-1} in the *P. vaccinosum* type, 25 Mg C ha^{-1} in the *P. myrtillosum* type, 30 Mg C ha^{-1} in the *P. polytrihosum* type, and 72 Mg C ha^{-1} in the *P. sphagnosum* type of forest. Carbon density of litter in the *P. vaccinosum* ecosystem was 4 Mg C ha^{-1} in young stands developing after clearcutting, 14 Mg C ha^{-1} in middle-aged stands, 16 Mg C ha^{-1} in premature stands, and 18 Mg C ha^{-1} in mature stands. Rates of litter decomposition varied among forest types of the same region. The proposed model and detailed information for forest ecoregions of European Russia will be discussed.

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POSTER LOCATOR NO. 59

The Role of Nutrient Availability in the Carbon Budget of Boreal Forests

Nagwa Salih[1] and Göran I. Ågren[1]

Availability of nutrients is recognized as an important key factor controlling plant growth and vitality anywhere on the globe. Other important factors include water availability, light, and climatic conditions. According to the law of minimum (Liebig 1840) the factor that is in shortest supply determines the ecosystem production rate. In many boreal forests nitrogen has traditionally been the most limiting factor for forest growth, though increasing atmospheric nitrogen deposition has improved the availability of the element.

We investigated the relationship between the production of Norway spruce (*Picea abies* L. Karst.) forests, established under different fertilization regimes and environmental conditions in the Nordic countries, and different levels of nutrient availability. The investigation was done by coupling the plant carbon and nutrients using a carbon-nutrient theory. The theory in its general form connects plant growth to any limiting mineral nutrient through nutrient productivity. Nutrient release in the soil is connected to carbon mineralization. Different components of the biogeochemical cycling through vegetation and soil were analyzed.

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POSTER LOCATOR NO. 121

Fire Severity and Carbon Release During the *FROSTFIRE* Boreal Fire Experiment

D.V. Sandberg[1], Roger Ottmar[1], and Ernesto Alvarado[1]

FROSTFIRE is a major field experiment and modeling effort to study the role of fire in boreal forests as a global change feedback, and to simultaneously provide fire managers with an improved capacity to predict fire severity based on meteorological conditions. The centerpiece of the experiment was the July 1999 ignition and continued observation of a boreal watershed near Fairbanks, Alaska. The experiment is being conducted on an LTER site by the USDA Forest Service Research Pacific Northwest Station, the University of Alaska Fairbanks, the Bureau of Land Management Alaska Fire Service, and many other collaborators. In total, the experiment will study and model three feedback mechanisms in relation to boreal fire: 1) changes in carbon stocks caused by immediate off-site transfer during the fire, and by changes in decomposition and production following fire; 2) changes in energy budgets caused by fire; and 3) changes in the structure of the ecosystem, with associated changes in carbon or energy budgets.

This poster presents our first results in measuring the extent of organic material consumption and vegetation mortality in a mostly black spruce (*Picea mariana*) forest burned in 1999. We related the measured consumption to the fuel moisture, forest characteristics, and meteorology using a methodology consistent with one we have developed for experimental fires elsewhere in temperate and tropical forests.

Fire severity was measured in three ways: 1) intensive biomass inventories were completed before and after the burn at selected sites within the watershed, including duff, moss, litter, woody fuels, herbs, shrubs, and trees; 2) extensive inventories were completed on a 200-metre grid on the entire watershed; and 3) vegetation and fire severity was mapped and classified from 1:6000 aerial photography flown before and after the burn. Data collected on the intensive sites and extensive inventory were used to assess the change in carbon pools in each cover type and fire severity class, and the photography was used to integrate the data across the watershed.

Numerous experiments continue on-site to follow the secondary effects of the fire on carbon pools and fluxes. Additional burning may be done in 2000 or subsequent years to expand the forest cover types and forest floor compositions affected by the fire.

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Post-Fire Decomposition Dynamics of Coarse Woody Material in the Western Canadian Continental Boreal Forest

Barbara Sander[1] and Ross W. Wein[1]

Forest fires release carbon that has been stored in the forest biomass. Usually the biomass fixed in the stem wood of trees is not consumed by fire, but exposed to subsequent decomposition processes. The decomposition of fire-killed *Populus tremuloides*, *Pinus banksiana*, and *Picea mariana* was measured quantitatively as wood density loss over time in Saskatchewan, Alberta, and the Northwest Territories. Wood density loss was calculated as one minus the relative density of the downed trees (= density of the downed log/ density of undecayed wood). The number of years since the fires ranged from 7 to 56 years.

Standing dead trees (9 years for *Populus tremuloides,* 16 years for *Pinus banksiana*, and 34 years for *Picea mariana*) showed no significant density loss. Height above ground was identified as a critical factor for the decomposition process: the density losses for logs on or close (< 10.5 cm) to the ground were significantly higher ($p < 0.001$) than for those elevated over the ground (> 10.5 cm). All species showed no significant density loss during the first 8 years after the fire. *Populus tremuloides* showed a significant decrease ($p < 0.001$) in density starting 9 years after the fire. *Pinus banksiana* did not display a clear trend of density loss during the next 20 years; only a few sites showed a significant density loss ($p < 0.01$) and some showed a significant increase ($p = 0.001$) in density. Sites that burned more than 30 years ago all showed a significant density loss ($p < 0.001$). *Picea mariana* did not display a significant density loss during the first 20 years after the fire. For the following 20 years a clear pattern was absent; in some sites density losses were significant ($p < 0.001$), but most sites showed no significant density loss. Sites that burned more than 50 years ago all showed a significant decrease in density ($p = 0.001$ or $p < 0.001$).

This slow initial wood density loss indicates that the decomposition dynamics in the boreal forest do not follow the negative exponential function. The negative exponential function was compared to a linear and a negative sigmoidal function as descriptions of decay over time. A linear model might describe the actual decomposition dynamic better when limiting factors control the decomposition. A negative sigmoidal function might describe the overall decomposition process better allowing for low decomposition rates during the first decade(s).

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POSTER LOCATOR NO. 20

Assessment of the Carbon Balance and Forest Dynamics over Large Territories as Influenced by Forest Fires and Other Disturbances

M.A. Sofronov[1], A.V. Volokitina[1], and D.I. Nazimova[1]

The carbon budget of boreal forests is a result of complicated interrelations of different sources and sinks. Disturbances such as fire can influence estimates of the carbon budget due to post-fire dieback and the long decomposition period of fire-killed trees. Post-fire restoration of forests is slow, from 5 to 40 years, and carbon sink from forest regrowth could be smaller than the carbon release due to decomposition. The usual methods of carbon budget evaluation are based either on differences in carbon stocks or on estimates of carbon fluxes. The stock-based method operates with a rather small difference of two large approximate values, and the uncertainty of the difference can be significant. For large territories, estimates of fluxes (sources and sinks) are very approximate. Therefore, it is sometimes difficult to judge not only the magnitude of the carbon balance, but even its sign over large territories.

A different approach for examining the carbon budget, based on the estimation of biomass dynamics in succession, is suggested. However, it is difficult to describe and quantify all the numerous succession lines and their interconnections within a region. We suggest a modal approach, in which all vegetation plots within the region are distributed according to a small number of modal (i.e., prescribed *a priori*) successions, and the dynamics of the biomass by the phases and stages of the successions are investigated. The modal successions could be most suitably combined with forest inventory data. The quantitative description of the biomass dynamics should be carried out by the major phytocenoses' components. A method for linear description and measurements in field investigations was developed. The information, aggregated in the described way, together with the forest inventory data, generate a regional information base for the assessment and prediction of the carbon budget over large territories.

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POSTER LOCATOR NO. 34

Role of Coarse Woody Debris in the Carbon Balance of Boreal Forest Ecosystems in European Russia

Michael E. Tarasov[1]

Coarse woody debris (CWD) comprises 10 to 20% of total aboveground biomass in boreal forests. A balance between mortality and decay rates determines the amount of CWD. While there are some sparse observations of mortality in forests of European Russia, very little is known about decay rates and storage of CWD. A model of CWD dynamics was developed based on: 1) the data of the National Forest Inventory, 2) the local tables of forest growth and mortality, and 3) the rates of CWD decomposition.

Carbon dioxide (CO_2) evolution from CWD represents the main mechanism of mass loss. This process was studied under natural and laboratory conditions using a LiCor CO_2 analyzer. The effect of temperature and moisture on CO_2 efflux was estimated by applying data from two years of observations of CO_2 flux from CWD in the forest, and measurements of CO_2 flux from macro-samples of CWD in a phytotron. Using these dependencies along with climatic characteristics of the study territory, decay rates of CWD were evaluated for the south, middle, and north taiga of the boreal zone. Calculated rates were in good agreement with field estimations of CWD decomposition in the Leningrad Oblast. The results of field estimations showed significant correlation between the diameter of CWD and rate of decay. This allowed the description of density loss by two-parameter functions, dependent on the decomposition period and diameter of wood.

For the Leningrad Oblast, the model revealed an asymmetric U-shaped temporal distribution of CWD storage in forests of pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) Karst.) and a nearly negative exponential pattern in birch (*Betula* spp.) and aspen (*Populus tremula* L.) forests. CWD mass in mature stands of average productivity was highest in pine and spruce forests (21 Mg C ha^{-1} and 17 Mg C ha^{-1}, respectively), moderate in the aspen forest (10 Mg C ha^{-1}), and lowest in the birch forest (7 Mg C ha^{-1}). The ratio of CWD to live phytomass was 0.32, 0.22, 0.15, and 0.13 in mature pine, spruce, birch, and aspen forests, respectively. Average annual CO_2 flux from CWD was 0.9 Mg C ha^{-1} in the mature pine stand. Assessed efflux is comparable to that observed in the forest.

CWD storage in the boreal part of European Russia was estimated by ecoregions. Generally, the CWD model represents a part of the ecosystem approach for estimation of carbon in boreal forests.

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Relationships between Vegetation and Climate Change in Transbaikalia, Siberia

N.M. Tchebakova[1] and E.I Parfenova[1]

Vegetation and live phytomass within the Lake Baikal basin, Transbaikalia, were modeled based on climatic parameters at orobiome and forest stand levels. Both models were coupled with a climate change scenario to predict vegetation and tree species redistribution and phytomass change over the territory under a new climate.

In our regional correlative vegetation model, an orobiome was predicted from temperature sums, base 5°C (TS), and dryness index (DI). Data from one hundred weather stations was used to model TS and DI distribution from physiography (latitude, longitude, and elevation). Orobiome distribution was modeled by coupling the vegetation model to TS and DI layers. Total phytomass was calculated as a sum of products of each orobiome area multiplied by phytomass density.

Tree species composition and phytomass of climax conifer forests consisting of dominant species *Pinus sylvestris* (pine) and *Pinus sibirica* (Siberian cedar) with an admixture of *Larix sibirica* (larch) and *Abies sibirica* (fir) across a mountain range in Central Transbaikalia were predicted using the same climatic parameters. Data on stand characteristics of 500 permanent inventory plots were employed. Climatic indices for each inventory plot were calculated with respect to topography (elevation, aspect, and slope). Multiple piece-wise linear regressions were used to predict forest composition and stocking for a plot based on local climate. Total stand phytomass was calculated based on stocking and local conversion coefficients. The combination of TS and DI explain up to 90% of the variation in forest composition and 75% of the variation in stocking.

Under a 2°C increase in summer temperature and a 20% increase in annual precipitation (a most reliable scenario for this area), tundra, subalpine, and currently prevailing pine-larch (light-leaf) taiga would be drastically reduced. Taiga would be mostly replaced by less productive sub-taiga/forest-steppe, resulting in a 40% phytomass loss. Siberian cedar-fir (dark-leaf) taiga would expand 1.5-fold. In the south, numerous habitats favorable for the most productive dark-leaf (chern) taiga with maximum phytomass and rich biodiversity would develop. Under elevated temperature balanced by precipitation, phytomass of dark-leaf taiga would increase 5-fold. Total phytomass over the entire area would not change (2.5 Pg predicted compared to 2.3 Pg current). At the stand level, the pine component of forest composition is not predicted to change, with stocking increased by some 30 t ha^{-1}. The Siberian cedar component of the forest composition is predicted to increase by 10% with the same gain in phytomass.

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Predicting Biomass Accumulation in Boreal Forest Stands under Variable Climate Conditions

Mafiz M. Uddin[1], Michael J. Apps[1], George E. Banfield[1] and Jagtar S. Bhatti[1]

Forest biomass accumulation is a function of biochemical and physiological processes, vegetation species, and the influence of the environment. Process representation in models that operate at a point-scale (typically 1/10 ha in gap models such as FORSKA) is well established, but there remains a need to model the carbon dynamics of forest biomass at the landscape scale using a less data-intensive approach. A semi process-based model was developed to estimate the biomass accumulation in a forest stand and was calibrated on a regional scale with observed data.

An initial growth curve was assigned to each stand in the region based on species characteristics (but not limited by climate and nutrient availability) and described by an analytical extension of the Chapman-Richards growth function. Parameters were constrained by process representation of climate and nutrient limitations under local stand conditions. These stand growth curves were aggregated to obtain a theoretical landscape (simulation) growth curve that was then compared to an empirical growth curve (inventory data). The stand growth curves were then repeatedly modified until a close agreement was found between the empirical and simulation growth curves.

Aboveground biomass was simulated for individual stands in a 9 Mha region in west-central Alberta containing more than 75,000 stands (inventory data). Stands were grouped into 36 categories using forest type, site quality, stocking, and dominant species as classification criteria. Empirical regional growth curves for each category (n = 36) were obtained by fitting area-weighted biomass to a function of age class.

For stands classified as "softwood" stands, the mature biomass of softwood species was 80 to 150 t ha^{-1} (empirical, n = 12) and 60 to 200 t ha^{-1} (simulated, n = 36,500). The mature biomass of hardwood species in these "softwood" stands was 5 to 15 t ha^{-1} (observed, n = 12) and 5 to 20 t ha^{-1} (simulated, n = 36,500). For stands classified as "hardwood" stands, the mature biomass of hardwood species was 60 to 80 t ha^{-1} (observed, n = 12) and 50 to 100 t ha^{-1} (simulated, n = 14,400). The mature biomass of softwood species in these "hardwood" stands was 25 to 30 t ha^{-1} (observed, n = 12) and 20 to 35 t ha^{-1} (simulated, n = 14,400). Similar relative variation was observed for other maturity classes. The simulated growth curves for 15 softwood and 10 hardwood stands were within ±1% of the growth curves derived from FORSKA. Since it combines readily available site information with extensive inventory data, the new simulation model approach will be useful for modeling forest ecosystems dynamics on a large scale.

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Reserves and Density of Organic Carbon in Russian Forests

Anatoly Utkin[1,2], Dmitry Zamolodchikov[1], Georgy Korovin[1], and Olga Chestnykh[1]

Reserves of organic carbon (C) were assessed for phytomass ($C_{phytomass}$), soil without wood debris (C_{soil}), and as totals (C_{total}). Data from 59 ecoregions in the Asian part and from 56 federal districts in the European part of Russia were used in the estimation. These data include: 1) state forest inventory; 2) phytomass estimations for forest stands; 3) phytomass estimations for meadows, peat bogs, and other non-forest areas; and 4) reserves of C_{soil} for stands of dominant tree species and non-forest lands.

The total land area in the Russian Forest Fund is 1110.5 x 10^6 ha, consisting of 64% forests, 10% altered forests (burned areas, clearcuts, etc.), and 26% non-forest lands. The total reserve of $C_{phytomass}$ (34.35 x 10^9 t C) is distributed between forests (98%), altered forests (1%), and non-forest areas (1%). The total reserve of C_{soil} (172.43 x 10^9 t C) is distributed between forests (61%), altered forests (8%), and non-forest areas (31%). The C_{total} (206.78 x 10^9 t C) is distributed between forests (66%), altered forests (8%), and non-forest areas (26%).

The area of the Forest Fund is distributed between the northern (42%), middle (35%), and southern (23%) landscape subzones. Distribution of $C_{phytomass}$ between these subzones is 25% (northern), 39% (middle), and 36% (southern). The distribution of C_{soil} is 45% (northern), 32% (middle), and 23% (southern). The distribution of C_{total} is 42% (northern), 33% (middle), and 25% (southern).

Within the forested area, 72% is coniferous, 2% is hardwood deciduous, 16% is softwood deciduous, and 10% is other tree and shrub species. The distribution of $C_{phytomass}$ in the forested area is 77% coniferous, 4% hardwood deciduous, 15% softwood deciduous, and 4% other. The distribution of C_{soil} is 69% coniferous, 3% hardwood deciduous, 15% softwood deciduous, and 13% other. The distribution of C_{total} is 71% coniferous, 3% hardwood deciduous, 15% softwood deciduous, and 11% other. Larch stands have the most $C_{phytomass}$ (11.37 x 10^9 t C) among all forests.

The density of C_{total} is 179 to 202 t C ha^{-1} for the three landscape subzones. Biomass carbon ($C_{phytomass}$) is 18 to 48 t C ha^{-1} in the three subzones, increasing in eastward and northward directions. The ratio of C_{soil} to $C_{phytomass}$ changes analogously for forest stands from 2.6 to 5.5 for the subzones. The low density of C_{total} (150 to 175 t C ha^{-1}) is typical for pine stands.

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Assessment of Carbon Emissions by Wildland Fires Based on Vegetation Fuel Maps

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The amount of carbon per unit of area that is directly emitted in boreal forest wildfires is determined by the amount of biomass consumed by fire. The biomass consumption depends on: 1) the distribution of the biomass stock by vegetation fuel classification categories; 2) the period of the season when the fire occurs, and the severity of the drought; and 3) the fire development as induced by wind, topography, and humidity.

A method was developed for producing maps of biomass stock based on a vegetation classification of fuels and a computer-based version produced using forest inventory data.

The season and weather at the time of the wildfire influences the complex dynamics of the processes of humidifying/drying of vegetation residues, mosses, and lichens. The direct dependence of the amount of burned biomass on seasonal and weather factors was investigated for different categories of vegetation fuel classification. The possibility of combustion of more large-sized vegetation residuals (fallen branches, wind-thrown trees) as related to weather conditions can be estimated with the use of the National Fire Danger Rating System (NFDRS). An estimation of duff and peat burning in relation to drought severity can be done either with the PV-2 Index or with the DC Index of the Canadian Forest Fire Danger Rating System (CFFDRS). The above estimates relate to biomass burning in ground fires, which constitute more than 80% of all wildfires by area in this region.

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Influence of Fire on Carbon Content and Distribution Of Boreal *Larix gmelinii* Forests in Northeastern China

C.K. Wang[1,2], S.T. Gower[1], Y.H. Wang[2], H.X. Zhao[2], P. Yan[2], and B. Bond-Lamberty[1]

Larix gmelinii is the dominant forest ecosystem in the southern region of the Siberian boreal forest. Although poorly understood, the fire ecology of these ecosystems is an important factor in their contribution to the carbon budget of global boreal forests.

To explore the effects of fire on ecosystem structure and function, we compared the carbon (C) content and distribution for three of the major *Larix gmelinii* forest ecosystems: *ledum-larix* forests on mesic toe slopes, grass-*larix* forests on fertile mid-slopes, and *rhododendron-larix* forests on dry, infertile steep slopes. The forests were located in Tahe, Daxing'anling, China (52.7°N, 123.6°E), and were burned in a large wildfire in 1987. Three replicate plots were established in each of lightly burned (mostly living trees), heavily burned (mostly dead trees), and old-growth stands in each of the larch forest ecosystems, except for the *rhododendron-larix* old growth that only has one plot. We measured the overstory leaf area index and the carbon distribution in the soil, forest floor, understory, and overstory.

Total ecosystem carbon content was 140, 130, and 157 t C ha^{-1} for the *ledum-larix*, grass-*larix*, and *rhododendron-larix* forests, respectively. The impact of fire on total carbon content was the most significant for grass-*larix* forest among the three forest types. Fire tended to shift carbon allocation from aboveground to belowground pools. The grass-*larix* forest had the highest productivity of the three *Larix* ecosystems, of which the total overstory (above- and belowground) net primary production (NPP) was 1.9 t C ha^{-1} for the old growth stand. The total overstory NPP for the lightly burned stands was 1.1 t C ha^{-1}, 1.7 t C ha^{-1}, and 1.4 t C ha^{-1} for *ledum-larix*, grass-*larix*, and *rhododendron-larix stands,* respectively. Total NPP of the overstory for the heavily burned stands was lower because fire killed most of the trees.

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POSTER LOCATOR NO. 23

Modeling Water, Carbon and Nitrogen Dynamics of the Boreal Forests in the Canadian Land Surface Scheme

Shusen Wang [1], R.F. Grant [1], T.A. Black [2], and D. Verseghy [3]

The Canadian Land Surface Scheme (CLASS) was a "second-generation" land surface model developed in the late 1980's for the Canadian general circulation model (GCM). We have developed the "third-generation" land surface scheme based on the current version of CLASS V2.6. This new generation model physiologically couples plant water and carbon dynamics, implements plant litter and soil carbon biogeochemical cycles, and emphasizes the role of nitrogen in land surface energy, water, and carbon processes. The CLASS model has been improved by including carbon exchanges between the atmosphere and ecosystems, and feeding back dynamically based vegetation parameters to the GCM.

Simulations were implemented on two vegetation types: deciduous and coniferous. Data from the Old Aspen (*Populus tremuloides*) site in the Southern Study Area (SSA-OA) and the Old Black Spruce (*Picea mariana*) site in the Northern Study Area (NSA-OBS) of the BOReal Ecosystem-Atmosphere Study (BOREAS) were used for the model initializations and tests. Comparisons were made of energy, water, and carbon dioxide (CO_2) fluxes between the model output and eddy correlation measurements.

For the SSA-OA site, annual root mean square error (RMSE) and correlation coefficient between model output and measurements for daily evapotranspiration were 0.71 mm H_2O d^{-1} and 0.87, and for carbon exchange were 1.10 g C m^{-2} d^{-1} and 0.93. The model predicted this aspen ecosystem was a net carbon sink of 163.6 g C m^{-2} yr^{-1} and 203.2 g C m^{-2} yr^{-1} for 1994 and 1996, respectively. It accounted for about 16.7% of the total gross primary production (GPP) on average for the two years. For the NSA-OBS site, annual RMSE for hourly evapotranspiration and carbon exchange were 0.03 mm H_2O h^{-1} and 0.07 g C m^{-2} h^{-1}, respectively. Annual RMSE for daily evapotranspiration and carbon exchange were 0.45 mm H_2O d^{-1} and 0.6 g C m^{-2} d^{-1}, respectively. The model predicted this spruce ecosystem was a net carbon sink of 79, 7, and 45 g C m^{-2} yr^{-1} for 1994, 1995, and 1996, respectively. This represented about 5.7% of the GPP on average for the three years.

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POSTER LOCATOR NO. 66

How Fire Exerts Control over Carbon Balances in Siberian Scots Pine Forests

Christian Wirth[1], Ernst-Detlef Schulze[1], and Barbara Lühker[1]

Ecosystem carbon (C) pools and net primary production (NPP) were compared along four chronosequences of Siberian Scots pine (*Pinus sylvestris*) forests representing different levels of fire impact and site quality. Twenty-five stands were investigated with stand ages ranging from 2 to 380 years. The long-term carbon balance (> 250 years) was close to zero. The overlapping dynamics of the two dominant processes, 1) decay of initial coarse woody debris (CWD) and 2) accumulation of biomass, created a characteristic pattern of total carbon pool reduction (6 to 10 mol C m^{-2} yr^{-1}; range represents different site types) and restoration (8 to 10 mol C m^{-2} yr^{-1}) during the first 100 years. This was followed by a lower carbon sequestration (0.8 to 2.5 mol C m^{-2} yr^{-1}) until high stand ages. Recurrent surface fires prolonged the restoration phase due to increased mortality.

Based on data of actual NPP, stem analysis, and mortality, the dynamics of total carbon input (biomass + mortmass) into the ecosystem was modeled. The total woody carbon input along the unburned and the moderately burned chronosequences were comparable because increased NPP of surviving trees was able to compensate for fire related mortality. Cumulative woody mortmass production without fire impact over 95 years was only 80 mol C m^{-2} compared to 600 mol C m^{-2} of woody biomass accumulation. Under a moderate fire regime the corresponding partitioning was 390 versus 350 mol C m^{-2} at age 67 years, and 730 versus 680 mol C m^{-2} at age 380 years. Under heavy fire impact both mortmass and biomass production were strongly reduced. Needle NPP was about half of the total wood NPP. Although the rate of litter production (needles + CWD) was lower in the unburned sequence (3.6 mol C m^{-2} yr^{-1}) compared to the burned sequence (5.7 mol C m^{-2} yr^{-1}), the organic layer carbon pool in the sequence without fire reached 216 mol C m^{-2} compared to 160 mol C m^{-2} under fire influence. Comparing pools and input we calculated that recurring surface fires reduced the turnover time of the organic material on the forest floor from 59 to 30 years and therefore also lowered the long-term carbon balance.

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POSTER LOCATOR NO. 21

Modeling the Effects of Global Climatic Change on the Forest at the Ecotone of the Boreal Larch Forest and Mixed Coniferous/Broad-Leafed Forest in Northeast China

Chen Xiongwen[1] and Wang Fengyou[2]

Two short-term modeling experiments were conducted to assess the effect of doubled carbon dioxide (CO_2) concentration on the biomass of seedlings of Korean pine (*Pinus koraiensis*) and Changbai larch (*Larix olgensis*). At a CO_2 concentration of 700 ppm, the mean biomass of larch increased 12.2% in the first experiment and 14.2% in the second experiment, while the mean biomass of pine was reduced 3.9% and 12.8% in the first and second experiments, respectively. The change in mean biomass of other tree species at the ecotone of the boreal larch forest and mixed coniferous/broad-leafed Korean pine forest under a 700 ppm concentration of CO_2 was taken from the literature. Based on these results and the biophysical limits of the tree species, the dynamics of the forest at the ecotone was modeled using a gap model BKPF (Chen Xiongwen andWang Fengyou) under global climatic change (GFDL scenario) and a doubling CO_2 concentration over 50 years.

The results show that under GFDL scenario and doubled CO_2 concentration for 50 years (annual temperature, annual precipitation, and CO_2 concentration increase linearly), the stand density of a forest growing from bare land would be slightly lower than one grown under the current climate conditions. Stand productivity would increase about 4%, leaf area index (LAI) would increase 8%, and stand biomass would increase 15%, but the stand dead biomass would be doubled.

However, the current forest stand growing for 50 years under GFDL scenario and doubled CO_2 concentration (annual temperature, annual precipitation, and CO_2 concentration increase linearly) would experience a 20% reduction in stand density and a 90% reduction in stand biomass with those growing for 50 years under no climate change. The stand would be dominated by oak (*Quercus* spp.), aspen (*Populus* spp.), birch (*Betula* spp.), and other broad-leafed trees, with oak constituting about 50% of the total stand density and about 57% of the total stand biomass. The stand productivity would increase 4%, but it would be comprised mainly of oak, aspen, and birch. The current stand height would decrease from about 35 m to 32 m, and LAI would decline dramatically.

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Simulating the Effects of Harvesting Regimes on Carbon and Nitrogen Dynamics of Boreal Forests in Central Canada

Yanli Zhang[1], Changhui Peng[2], Hong Jiang[1], and Michael J. Apps[1,3]

There is growing concern about the effects of intensive forest management and timber harvesting on the sustainability of forest ecosystems. Intensive forest management practices based on short rotations and high levels of biomass utilization (e.g., whole-tree harvesting) may significantly reduce forest site productivity, soil organic matter, and nutrient availability on some sites.

The effects of different harvesting intensities and rotation lengths on the long-term carbon and nitrogen dynamics of boreal forests in central Canada were simulated using the process-based ecosystem model CENTURY 4.0. Three harvesting intensities and four rotation lengths were investigated.

Results suggest that intensive harvesting regimes (e.g., whole-tree harvesting) would decrease total ecosystem carbon, soil carbon storage, and nitrogen availability, compared to conventional harvesting. Harvested biomass would increase with increasing harvesting intensity. Net loss of forest productivity (measured by aboveground biomass) would be higher in low boreal ecoclimatic regions with higher productivity stands. Extremely short rotations (i.e., 30 year) would reduce boreal forest productivity by as much as 65%. Total ecosystem carbon and nitrogen availability would be highest with long rotations (120 years) and lowest under short rotations (60 and 30 years).

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THEME 2

Monitoring and Measuring Boreal Forest Carbon Fluxes and Stocks

THEME 2: KEYNOTE ADDRESS

Towards a Better Understanding of the Carbon Budgets of Boreal Forests

Stith T. Gower[1], Paul G. Jarvis[2], and Sune Linder[3]

Biospheric models, based on ecophysiological principles and driven by remotely sensed products, are an important tool for quantifying the role of boreal forests in the global carbon cycle. However, a better understanding of the environmental and ecological controls on species composition, structure, and function of boreal forests is needed to resolve the uncertainty of the role of boreal forests in the global carbon budget.

The growing season of the boreal forest is short and the timing of soil thaw in spring, vapor pressure deficit in the summer, and soil freeze-up in fall strongly influence net primary production, light use efficiency, and net ecosystem production of boreal forests. Soil carbon dynamics are also influenced the timing of soil thaw in the spring and soil thaw in the fall.

Species composition of the overstory, understory, and ground-cover vegetation influence the carbon budget of boreal forests. Leaf area index (LAI), net primary production (NPP), and carbon allocation patterns differ consistently between boreal evergreen and deciduous forests; LAI, NPP, and above-to-total NPP ratio are greater for needle-leaf evergreen than broad-leaf deciduous boreal forests. Nitrogen-fixing shrubs such as *Alnus* spp. stimulate NPP and carbon accumulation in the soil. The percent cover and species composition of the ground cover vegetation affects the soil microclimate, net primary production and decomposition, and thus the overall carbon accumulation rate. Net primary production of ground cover ranges from near zero for many boreal aspen (*Populus* spp.) stands to greater than 100 g C m^{-2} yr^{-1} – a value that exceeds the NPP of overstory trees in poorly drained conifer stands.

Net ecosystem production (NEP) of boreal forest varies by five-fold and does not appear to be correlated to NPP. Many of the components of the carbon budget that determine NEP change during succession following disturbance and this effect may be the single largest contributor to observed variations in NPP and NEP for individual stands, and an important contributor of net biome productivity. NPP often varies amore among stands in an age-sequence than for similar aged stands of boreal forests. Changes in microclimate and resource availability during succession are complex, and poorly understood.

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Monitoring and Measuring Boreal Carbon Fluxes: Regional To Global Extrapolations

Steven W. Running[1]

The boreal region presents a particular challenge for carbon flux calculations. Due to its remoteness and difficult climate, the density of any type of measurements, from forest cover to weather is extremely low, necessitating greater reliance on modeling and remote sensing. Basic principles of terrestrial carbon flux dynamics are represented in many competent models, however most were developed from lower latitude science. These models are adequate in representing carbon flux processes, but may miss certain key features, such as permafrost or surface moss layers that are peculiar to boreal forests. However, even good models are limited by critical data to initialize and drive the model, such as meteorological data. Extrapolating the sparse weather station network to complete coverage of boreal climatic conditions is challenging.

Remote sensing confronts different problems, primarily lack of solar input in the winter, and persistent cloud cover during other times of the year. Consequently an interesting mixture of optical and radar remote sensing has developed to provide the regular complete coverage of the boreal landscape required for comprehensive carbon flux calculations. Although in some ways the boreal ecosystem has low biological diversity, it has high diversity in land/water interfaces and in disturbance dynamics, particularly wildfire. Accurately characterizing the boreal vegetation cover thus poses unique problems.

This presentation will focus on progress in spatially explicit, boreal terrestrial carbon balance modeling, and the array of remote sensing that is being used to generate the regular, full coverage needed for that modeling. I will begin by addressing the adequacy of existing boreal ecosystem models, including validation studies against flux tower data from the BOReal Ecosystem-Atmosphere Study (BOREAS). Next I will discuss progress in building initializing data layers for regional scale modeling, primarily using remotely sensed biophysical variables. Then I will discuss techniques for generating the required surface meteorological data for driving the models. Finally, I will illustrate the current state of regional to global scale calculations of carbon balances for the boreal region.

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Carbon Sequestration in Swedish Forest Soils

Agnetha Alriksson[1], Hillevi Eriksson[1], Erik Karltun[1], Lars Lundin[1], Behnaz Mazogi[2], Mats T. Olsson[1], and Dietrich von Rosen[2]

Forests cover about 22.9 million hectares of the total 42 million hectares of land in Sweden. Most (14.8 million ha) are on naturally well-drained soils with a groundwater level of more than 1 m, while about 7.5 million hectares are on well-drained to moist soils, and about 0.5 million hectares are on moist to wet soils.

A nation-wide soil survey (Swedish National Survey of Forest Soil and Vegetation) was conducted twice (1983 to 1987 and 1993 to 1996). A comparison of the results from the two surveys showed a regional increase, predominantly in southwestern Sweden, in the amount of carbon in the O-horizons of naturally well-drained soils. The southwestern region of Sweden receives the highest nitrogen deposition, which is one likely explanation for the carbon pool increase in the soil. Another explanation may be changes in land use and forest management practices.

This study examined the difficulties with repeated large-scale inventories, including sampling techniques, method of analyses, and statistical methods.

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Influence of Interacting Elevated Atmospheric CO_2 and O_3 on Carbon Sequestration in a Regenerating Northern Hardwood Forest

J.G. Isebrands[1], Kurt S. Pregitzer[2], George R. Hendrey[3], Kevin E. Percy[4], Richard E. Dickson[1], Asko Noormets[2], Anu Sober[5], Jaak Sober[2], Eric L. Kruger[6], Evan McDonald[1], and David F. Karnosky[2]

Because atmospheric carbon dioxide (CO_2) and tropospheric ozone (O_3) are concomitantly increasing on a global basis, vast areas of forest ecosystems will be exposed to elevated levels of these two greenhouse gases in the next century. Since these gases act in diametrically opposite ways (CO_2 inducing generally positive growth responses and O_3 inducing generally negative growth responses), it is difficult to predict how forest ecosystems will respond to simultaneous exposure to these two pollutants. In a large free-air CO_2 and O_3 enrichment (FACE) project we examined the impacts of elevated atmospheric CO_2 and/or O_3 on a regenerating trembling aspen/paper birch/sugar maple (*Populus tremuloides/Betula papyrifera/Acer saccharum*) stand in northern Wisconsin, United States.

Early results suggest that there is a 35 to 40% increase in aboveground and belowground growth with elevated CO_2 for trembling aspen and paper birch. In contrast, elevated O_3 has resulted in a 13 to 17% decrease in aboveground growth and a 25 to 30% decrease in fine root growth. For the interacting pollutants, O_3 dominated the response, with decreasing aboveground and belowground growth in the CO_2 + O_3 treatments for both aspen and birch. Our results have implications for global carbon sequestration models of forests and tree plantations, as these models generally project substantial increases in tree growth in elevated CO_2, but do not take into account that these increases may be offset by the occurrence of other stresses such as O_3. Ozone is increasing globally with increasing population and its impact on growth must be considered in future carbon budget models of forest ecosystems.

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Carbon Balance of Swedish Forests: Upscaling Based on Net Ecosystem Exchange Measurements and Modeling

Anders Lindroth[1], Harry Lankreijer[1], and Achim Grelle[2]

In this study, the carbon balance of Swedish forests was estimated and the changes in the carbon balance during the last decade were assessed. The estimation was based on multi-annual measurements of net ecosystem exchange (NEE) in three different coniferous forests in Sweden, corresponding data from a EUROFLUX site in Finland, and simulations with a dynamic carbon balance model.

Two of the measurements sites were mature mixed pine and spruce stands closely situated in central Sweden, while the third site was a young spruce stand located in northern Sweden. All stands were growing on till. The net fluxes were measured using identical eddy correlation systems specially designed to function under harsh winter conditions. Two of the sites, one in central Sweden and one in the northern Sweden, had multi-annual (5 to 7 years) records of net ecosystem exchange while the measurements at the third site only represented two growing seasons. Response functions to different climatic parameters were estimated for the analysis. The fluxes were separated into uptake and respiration components in order to determine the differences between the sites. The comparison assessed how representative single flux sites were for determining carbon balances in the same geographic region.

The carbon balance model used age-yield and age-allocation tables, which can be easily applied to different forest types. Annual NEE data was used to test the model. Carbon fixation by the forest stands was estimated from the yearly stem yield in m^3 wood ha^{-1} yr^{-1}. Prescribed age-allocation relations were used to estimate the growth of needles, branches, and roots from the stem increase. Litter fall, needle mass, branches, and roots were directly related to stem volumes.

The soil module used five compartments of soil carbon with different decomposition rates and consequently different resident times. The last compartment represented the stable carbon. In the model, only the decomposition rate of young and new carbon in the 'first' compartment was dependent on the mean annual temperature. For the other compartments, a constant fraction was used for the total volume annually decomposed to carbon dioxide. The applied average decomposition rates included the decomposition of needles and wood. The model roughly simulated the total carbon content down to a 1 m depth. Scaling parameters were soil carbon content, age, and species distributions of forests in different geographic regions in Sweden.

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Coarse Woody Debris in Forest Regions of Russia: Estimation Methods and Role in Forest Management for Carbon Sequestration

Olga N. Krankina[1], Yurii A. Kukuev[2], Rudolf F. Treyfeld[2], Mark E. Harmon[1], Nikolai N. Kashpor[2], Vladimir G. Kresnov[2], Victor M. Skudin[2], Nikolai A. Protasov[2], Mikhail A. Yatskov[1], Gody Spycher[1], and Ewgenii D. Povarov[2]

To assess the regional stores of coarse woody debris (CWD), data collected as part of the Russian Forest Inventory were combined with measurements from 1084 sample plots and density sampling of 739 dead trees. Six forest regions (i.e., Oblasts) spread across the territory of Russia were selected, and in each region a stand-level database for 5 to 7 forests that represent the local variation in site conditions and successional patterns was used. These stand-level databases were processed using a system of expansion and correction factors derived from measurements in the sample plots. The volumes of logs and snags in each species' age grouping were converted to biomass and carbon. In all the groupings the average density of snags (0.280 to 0.415 Mg m^{-3}) was greater than the density of logs (0.110 to 0.316 Mg m^{-3}).

The stores of CWD varied among the regions and among the dominant tree species. Regions with intensive forest management (Northwest and Central regions) had lower average stores of dead wood (15 to 25 m^3 ha^{-1}) than the East Siberian and Far Eastern regions (30 to 50 m^3 ha^{-1}). Lower decomposition rates may also have contributed to greater accumulation of CWD in the east. The store of CWD was highest on recently disturbed forest lands and depended primarily on the type of disturbance. The amount of CWD declined with age among young forests and reached the minimum in stands 20 to 50 years old, depending on species and region. In older forests the amount of CWD and the CWD to live wood ratio generally increased. Stand development patterns, disturbance, and management history in the regions strongly influenced the changes in CWD stores with forest age. Forest management policies that favor longer harvest rotations and retention of CWD material on the site would increase the regional stores of CWD. Consideration of CWD is important for the development of strategies to increase carbon stores in forest ecosystems.

[1] Oregon State University, United States; [2] Russian Federal Forest Service, Russia.

Net Ecosystem Fluxes of Carbon Dioxide in Boreal Forests

P. G. Jarvis[1]

With few exceptions, boreal forests are annual carbon sinks in the range of 0.5 to 2.5 t C ha^{-1}. Daily, seasonal, and annual ecosystem fluxes will be compared for several boreal and temperate forest sites in North America, Europe, and Russia. The features of the boreal climate that constrain the fluxes are timing of thaw in spring and freeze-up in fall. How long the current carbon sink capacity of the terrestrial biosphere is likely to be maintained into the future is a matter of conjecture, and several hypotheses have been proposed as the basis for quantitative explanation.

Since the last glaciation, carbon has accumulated in the boreal forest ecosystems as transfer from the atmosphere, via the vegetation, to the soil organic carbon pool (SOC). Experimental addition of nutrients has demonstrated the large capacity of these ecosystems for additional tree growth and production of detritus and SOC. This accumulation of carbon seems to have been constrained since the retreat of the ice by slow concurrent accumulation of nutrients, particularly nitrogen, in the ecosystem. The small size of the trees and their low nitrogen contents suggest that the capacity of the system to store carbon will not by itself limit the transfer of carbon from the atmosphere to the tree and soil pools in the immediate future, particularly as increasing atmospheric inputs may enhance the availability of nitrogen. However, short-term increases in photosynthesis resulting from the rise in atmospheric carbon dioxide (CO_2) concentration diminishes at higher CO_2 concentrations, whereas autotrophic and heterotrophic respiration increase exponentially with increasing temperature. It has been hypothesized that as climate changes, the overall capacity to take up additional carbon from the atmosphere will progressively diminish so that at some point respiration will exceed photosynthesis and carbon sinks will become sources. This argument assumes that acclimation to higher CO_2 concentrations and temperatures does not occur, that respiration is independent of photosynthesis, and that there are no feedbacks involving nutrition between the processes.

The ecosystem model (G'Day), which treats interactions and feedbacks between the effects of CO_2 and temperature on pools and fluxes of carbon and nitrogen within vegetation and soil compartments, has been parameterized for a boreal coniferous forest in northern Sweden. In contrast to the above, with temperature and CO_2 concentration increasing gradually according to the IPCC IS92a scenario, the model indicates that NPP consistently exceeds heterotrophic respiration and the carbon sink rises to an asymptotic maximum and remains there for 100 years without significant decline. On the other hand, sinks may disappear if climate change or deforestation lead to widespread tree mortality and this can be as important as the physiological effects discussed.

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An Integrated Analysis of Canada's National Forest Carbon Budget And its Carbon Management Implication

Wenjun Chen[1], Jing M. Chen[1], Josef Cihlar[1], Jane Liu[1], and David T. Price[2]

Disturbances (i.e., fire, insect-induced mortality, and harvesting), planting, climate, atmospheric carbon dioxide (CO_2) concentrations, and nitrogen (N) deposition affect forest carbon cycling through various ecosystem processes operating at different spatial and temporal scales. To estimate their integrated effects on the national carbon budget of Canada's 417.6 Mha forests, we developed an Integrated Terrestrial Ecosystem Carbon Budget model (InTEC). The model inputs include mean leaf area index (LAI) and net primary production (NPP) derived from satellite data, as well as historical data for disturbances, climate, atmospheric CO_2 levels, and nitrogen deposition rates.

From 1800 to 1998, the estimated carbon balance of Canada's forests varied appreciably. There was a sink of 40 ± 20 Tg C yr^{-1} in the early 19th century, changing to a source of -131 ± 65 Tg C yr^{-1} by the 1870s. It increased thereafter to a maximum sink of 200 ± 80 Tg C yr^{-1} in the 1930s, but this sink decreased again to 57 ± 29 Tg C yr^{-1} during the 1990s. It is estimated that from 1800 to 1998, the aboveground biomass of Canada's forests increased by approximately 19%, while the soil carbon stock increased by roughly 2%.

Using InTEC, we attempted to estimate the maximum carbon offset potentials of four alternative forest management strategies in Canada under different climatic and disturbance scenarios. These were: 1) afforesting in 1999 all of the estimated 7.2 Mha of marginal agricultural lands and urban areas available for tree planting; 2) implementing a program of afforesting all disturbed areas within one year of disturbance; 3) nitrogen fertilization of the 125 Mha of semi-mature forests at the low rate of 5 kg N ha^{-1} yr^{-1}; and 4) increasing forest harvest 20% above current average rates and using the extra wood products to substitute for fossil energy after 1999. If implemented to the maximum extent, the combined net carbon offset potential, after subtracting the carbon costs of implementing these strategies, could be as much as 100 ± 50 Tg C yr^{-1} in 2010, increasing to 160 ± 80 Tg C yr^{-1} by 2050. The simulations indicated that nitrogen fertilization and reforestation strategies would be the two largest contributors to the combined net carbon offset potential.

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A Blast From a Boreal Forest: Interannual Variability of Carbon Balance in Relation to Climate and Groundwater Level

Achim Grelle[1] and Anders Lindroth[2]

Six years of continuous net ecosystem flux measurements have been done using eddy-correlation over a mature boreal forest in central Sweden. The data gap fraction was only 2% of the time. The forest's carbon balance showed large interannual variations. During most of the observation period, this forest was an atmospheric carbon dioxide (CO_2) source rather than a sink. The large CO_2 release was mainly attributed to soil respiration. Particularly at this site, with a CO_2 balance close to zero, it is clear that net carbon balance usually is the small difference between two large terms, namely CO_2 uptake and CO_2 release by the ecosystem. Relatively small climate-induced changes in either of these terms may lead to large changes in the net carbon flux. Therefore, carbon uptake and release in relation to external driving variables must be treated separately to provide an accurate view of processes controlling the net carbon balance.

The annual CO_2 uptake is controlled both by phenology and uptake rates. The spring-time onset of photosynthesis varied between years and was the main factor controlling the annual CO_2 budget. During late summer, on the other hand, daily rates of CO_2 uptake varied substantially between different years, and caused differences in integrated annual uptake. Differences in the annual amount of CO_2 released by the ecosystem were mainly due to time shifts in the beginning and end of the warm season. Although these time variations caused large differences in intra-annual distribution of CO_2 release, the observed annual sums were quite similar. That means that the overall duration of the "respiration season" was approximately the same during the observed years, but it was to some extent shifted in time.

The main driving variables controlling both CO_2 uptake and release are soil frost and thaw, groundwater level, temperature, and cloudiness. Measurements of these variables during the observation period were compared with a 30-year record of regional climate data to determine indications of global change. In combination with knowledge about the processes controlling the carbon balance, new understanding of feedback effects that relate global change and CO_2 fluxes was gained.

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Airborne Atmospheric Measurements of Carbon Dioxide over a Mixedwood Boreal Forest in Northern Ontario

Alexander Shashkov[1], Kaz Higuchi[1], Lin Huang[1], Darrell Ernst[1], Senen Racki[1], Michele Ernst[1], and Robert Kessler[1]

Vertical profiles of carbon dioxide (CO_2) over a mixedwood boreal forest region in northern Ontario were measured during 3 intensive field campaigns in June, July, and September of 1999. The CO_2 measurements were made using a Li-Cor NDIR system installed in a Cessna 172 aircraft. The accuracy of the measurement was estimated to be better than 0.5 ppm based on frequent in-flight calibrations. In addition, continuous in-flight measurements of air pressure, temperature, humidity, aircraft position, and wind vector as well as flask samples were taken simultaneously with airborne CO_2. The flask samples were analyzed for CO_2, CH_4, N_2O, CO and SF_6 concentration and for ^{13}C and ^{18}O in CO_2.

The observed changes in atmospheric CO_2 vertical distribution (due to exchange with sources/sinks at the surface and to the convective boundary layer development) provided insight into the CO_2 exchange dynamics on diurnal time scales. The magnitude of the exchange flux of CO_2 was estimated by integrating over height between two profiles measured at two different times within the day. The ^{13}C and ^{18}O stable isotopic data revealed isotopic discrimination of the source/sink processes that influence the atmospheric CO_2 content. This information has the potential to partition the net estimated flux into the major individual contributing components.

Comparing the results from all three campaigns revealed the seasonal variations in the above estimates. In addition, the aircraft measurement-profiling program aided in the interpretation of the on-going continuous surface CO_2 measurements at the remote continental monitoring station at Fraserdale, Ontario (49°53'N 81°34'W). Together, the surface and aircraft measurements provided a more comprehensive understanding of the CO_2 exchange processes and mixing dynamics within and above the boundary layer.

One of the main goals of the measurement program was aimed at contributing to the development of the experimental and modeling framework for studying CO_2 mesoscale exchange between the boreal forest and the atmosphere. The objective of the whole project was to develop adequate modeling tools in coordination with properly scaled experimental measurements to create a consistent framework for studying the principal processes in mesoscale (1 to 100 km) CO_2 exchange flux between the boreal forest and atmosphere. The modeling component is described briefly in an accompanying poster presentation at this conference.

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Carbon Budget of Forests in Western Europe: Past, Present, and Future

Jari Liski[1], Daniel Perruchoud[2], Ari Pussinen[1], and Timo Karjalainen[1]

The carbon (C) budget of trees, soil, and wood products between 1950 and 2040 was estimated for 15 European Union countries plus Norway and Switzerland. The analysis was based on forest inventory data for 1950 to 1990, a forest resource scenario for 2000 to 2040, biomass allocation data, and dynamic soil carbon and wood product models.

The carbon sink of trees was estimated to have increased from 5 Tg C yr^{-1} in 1950 to 60 Tg C yr^{-1} in 1990. It was expected to increase to 70 Tg C yr^{-1} by 2040. The sink increased when the growth of trees increased more than litter production and harvesting. The increased production of litter and harvest residues induced a carbon sink in soil. This sink was estimated at 30 Tg C yr^{-1} in 1990 and 40 Tg C yr^{-1} by 2040. Carbon removed from forests in harvested wood was estimated to have increased from 50 Tg C yr^{-1} in 1950 to 60 Tg C yr^{-1} in 1990, and expected to increase to 80 Tg C yr^{-1} by 2040. The consequent carbon sink of wood products depended on how the wood was used. The carbon sink of trees and soil was about 10% compared with anthropogenic carbon dioxide emissions in the region in 1990.

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Rates of Litter Decomposition after Six Years in Canadian Forests: Influence of Litter Quality and Climate

J.A. Trofymow[1] and CIDET Working Group[2]

The Canadian Intersite Decomposition Experiment (CIDET) is a 10-year study of litter decay, started in 1992, involving 15 site cooperators and the placement of 11 different litter types at 21 sites across Canada. The effect of litter quality and climate on decomposition rates of plant tissues were examined using the remaining mass of 10 foliar litters after 6 years exposure at 18 upland forest sites. Litter qualities were determined by analysis of initial nutrient content (nitrogen, phosphorus, sulphur, potassium, calcium, and magnesium) and carbon (C) fractions (sugars, cellulose, hemi-cellulose, Klason lignin, and tanin by ^{13}C nuclear magnetic resonance spectroscopy (NMR) and wet chemical proximate analysis). Climate normal variables used included mean annual temperature, precipitation, and potential evapotranspiration.

Amongst sites, mass remaining was strongly related to mean annual temperature and precipitation, and amongst litter types the ratio of Klason lignin-to-nitrogen in the initial tissue was the most important litter quality variable. When combined into a multiple regression, mean annual temperature, mean annual precipitation, and Klason lignin-to-nitrogen ratio at 3 years explained 64% of the variance in mass remaining for all sites and tissues, and at 6 years explained 58% of the variance. An exponential decay model was fit to the six-year data for each litter type for each site. Model fit was generally good for most foliar litters with R^2 ranging from 0.64 to 0.98, though poorest for cold sites with low litter quality materials (e.g., $R^2 = 0.35$ for the western red cedar Inuvik site, $R^2 = 0.64$ for the Whitehorse site). Multiple regression of the fitted exponential decay model k values with litter quality and climatic variables confirmed the importance of the Klason lignin-to-nitrogen ratio and mean annual temperature ($R^2 = 0.64$). The best three-variable model ($R^2 = 0.69$) included ^{13}C NMR measures of litter quality (total carboxylic or phenolic C) and was marginally better than a model with annual precipitation ($R^2 = 0.66$). Potential influences of site-specific edaphic factors and other climatic variables will be discussed.

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POSTER LOCATOR NO. 1

Global Observation of Forest Cover and Carbon: Coordinating an International Effort

Frank Ahern[1], Robert Stewart[2], Tim Perrott[1], and Jacques Trencia[2]

Although forests play a major role in the global carbon cycle, there is currently great uncertainty regarding the magnitude of forest carbon sources and sinks. Satellite observations can reduce this uncertainty by providing relevant, globally consistent information on key components of carbon budget estimates. To expand the use of space-borne data, the Committee on Earth Observation Satellites initiated Global Observation of Forest Cover (GOFC) as one of six pilot projects within the Integrated Global Observing Strategy. GOFC is working to improve the quality and availability of space-borne and near-earth observations of forests at global and regional scales, concentrating on three strategic areas: 1) Forest Fire Monitoring and Mapping; 2) Forest Cover Characteristics and Changes; and 3) Forest Biophysical Processes.

Through GOFC, international cooperation in daily hotspot monitoring and estimation and mapping of annual burned area has increased. Additional research is required to refine burn area estimates, to quantify intensity of the burns, and to derive carbon emission estimates from current products. With respect to forest cover, a strategy has been developed that combines various data types (coarse/fine resolution optical, radar, and lidar) acquired using optimized revisit schedules. Key space observational variables needed to estimate forest biophysical productivity have also been identified. These include leaf area index, photosynthetically active radiation and its absorbed fraction, and aboveground biomass. GOFC is establishing multi-national networks to carry out coordinated regional projects in each of the three areas. It is also acting as a communications channel between users and suppliers to ensure the continuity of critical data and to promote easier access to data and derived products.

There remain significant obstacles to more widespread use of satellite data. Acquisition and processing costs for satellite data can be high, especially for fine resolution data. Satellite and airborne observations cannot be used alone; in-situ data are still needed to calibrate and validate image-based models. Unfortunately, existing ground-based data sources are generally fragmented in time and space and are not always representative of the area under observation. Furthermore, different parameters are measured within different jurisdictions. The Canadian Forest Service is working with the GOFC project office and the Canada Centre for Remote Sensing to help produce forest remote sensing products relevant to Canada and other major forest nations. To facilitate this process, Canada is making a number of strategic investments including: designing and implementing an extensive national plot-based monitoring network covering all major forest ecosystems and climatic conditions; developing more automated information extraction methods; and producing accurate nationwide digital elevation models.

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Scots Pine Growth Trends in Northwestern Kola Peninsula as an Indicator of Positive Changes in the Carbon Cycle

Alexander S. Alekseev[1]

When the carbon cycle is analyzed the focus is usually on carbon pools and flows. The carbon cycle is not in steady state, however, but instead has continuous significant fluctuations. Therefore, an analysis of the direction and size of changes in carbon flow is important in estimating the future evolution of the size of carbon flows and the pools themselves.

Growth trends of Scots pine (*Pinus sylvestris*) at its northernmost extent may be an indicator of changes in the carbon cycle of terrestrial forest ecosystems. Using a method which removed age trends from the data, a time-series analysis of annual radial increment in wood over the last few decades was performed. Comparison of radial increment to that observed during the period of the last registered warming period (1930 to1940), revealed elevated growth of 78% for trees 0 to 20 years old (0.016 mm yr^{-1}), 56% for trees 21 to 40 years old (0.012 mm yr^{-1}), 21% for trees 41 to 60 years old (0.005 mm yr^{-1}), and 10% for trees more than 101 years old (0.006 mm yr^{-1}). The increment for trees 61 to 80 and 81 to 100 years old remained the same. This increased growth occurred despite a decrease in temperature after about 1940 and significant air pollution. These growth trends are unstable in time and exhibit growing oscillations of Scots pine trees' radial increment.

The most probable reasons for a marked increase in radial increment growth of Scots pine in this region are climate warming and higher levels of carbon dioxide. Together these may produce a synergetic effect. Theoretically, an increase in the average radial increment of Scots pine trees at its northernmost extent indicates the beginning of positive changes in the carbon cycle resulting from higher accumulations of carbon in forest biomass. This generally may be considered as an indicator of a response by the biosphere to counteract the greenhouse effect and global environmental changes.

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Whole-Ecosystem Measurements of Carbon Fluxes Following Fire in the Canadian Boreal Forest

B.D. Amiro[1], J.I. MacPherson[2], R.L. Desjardins[3], J.M. Chen[4], and J. Liu[4]

Fire is the most important stand-renewing disturbance in the Canadian boreal forest, and its occurrence is estimated to drive much of the net carbon balance. Many models assume that about half of the carbon lost to the ecosystem from fire occurs indirectly through decomposition following the event. However, there are few measurements to substantiate these assumptions. Recently, we have measured post-fire carbon fluxes at three spatial scales in the Canadian boreal forest.

First, simultaneous measurements of carbon fluxes were compared from towers over burned and unburned forest stands. Second, day-time carbon fluxes were measured from an aircraft along a 500 km transect to compare burned areas of different ages at the landscape scale. And thirdly, a combination of remote sensing and mechanistic modeling was used to estimate net primary productivity (NPP) following fire for Canadian ecoregions.

The data show that fire caused a decrease in the forest carbon sink for a period of typically 20 to 30 years, although some sites recovered more quickly. For example, paired-tower measurements showed no significant difference in the daily-integrated flux between a ten-year-old burn site and a more mature site. However, the day and night amplitudes of the flux were less at the ten-year-old burned site. Day-time net carbon fluxes at the landscape scale showed a sink for burned areas greater than one year old, with the sink strength increasing with time since fire. However, newly burned areas were a day-time carbon source. In severely burned areas, revegetation can be slow and respiration dominates the carbon balance. NPP increased almost linearly for the first 15 years following a fire, but the rate of increase varied with ecoregion. This multiple scale approach provides evidence to support national carbon-balance models.

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POSTER LOCATOR NO. 67

Uptake and Respiration Rates of CO_2 in Three Northern Boreal Ecosystems Using the Eddy Covariance Method

Mika Aurela[1], Tuomas Laurila[1], Juha-Pekka Tuovinen[1],
Juha Hatakka[1], and Timo Vesala[2]

Northern Fennoscandia is an ecologically important area as it contains the boundary zone between two major biomes, the boreal coniferous forest, and the arctic tundra. It includes a tree line, but in contrast to the typical situation, the deciduous mountain birch (*Betula pubescens* ssp. *czerepanovii*) extends further north than the coniferous Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) forest owing to the relatively maritime climate.

Measurements of carbon dioxide (CO_2) exchange were conducted in three different forest ecosystems in northern Finland using the eddy covariance method. The mountain birch forest at Petsikko (69°28'N 27°14'E, 280 m above mean sea level), 350 km north of the Arctic circle, consists mainly of 4 metre high multi-stemmed trees. A total leaf area index (LAI) of 2.5 was estimated for the site during the time of maximal biomass in August. The Pallas site (67°58'N 24°14'E, 330 m above sea level) is a mixed birch-spruce forest close to the alpine tree line with a mean tree height of 13 m and a LAI of 5. The third site, Sodankyla (67°22'N 26°39'E, 180 m above sea level), is a 50-year-old Scots pine forest with a typical tree height of 13 m.

Due to the northern location, the growing season is relatively short. The mountain birch site acted as a net sink of carbon for only about two months. The sink period for the coniferous forest is somewhat longer due to the presence of full foliage biomass at the beginning of the growing season. The highest net photosynthesis rates at Petsikko were observed in late July, with a mean daytime maximum of about –0.2 mg CO_2 m^{-2} s^{-1}. At the Sodankyla and Pallas sites, the typical daily maxima during that period were higher, –0.3 and –0.4 mg CO_2 m^{-2} s^{-1}, respectively. The corresponding mean nocturnal net respiration rates were 0.1, 0.2, and 0.2 mg CO_2 m^{-2} s^{-1} at the mountain birch, mixed birch-spruce, and Scots pine forest sites, respectively. The levels of the observed photosynthesis and respiration rates were in accordance with the estimated biomass, with the highest fluxes at Pallas and the lowest fluxes at Petsikko.

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Comparing the Carbon Balances of Mature Boreal and Temperate Deciduous Forest Stands

Alan G. Barr[1], T. Andrew Black[2], Xuhui Lee[3], Ralf M. Staebler[4], Jose D. Fuentes[5], and Zhong Chen[2]

Boreal and temperate deciduous forests at northern mid-latitudes play an important role in the global carbon (C) cycle. However, the processes that govern their carbon budgets are not fully understood, particularly with respect to climatic variability and change. To increase our understanding of these processes and their climatic controls, we measured carbon dioxide (CO_2) flux over three complete annual cycles (1996 to 1998) from two mature deciduous forests: a temperate mixedwood (TM) stand in southern Ontario, Canada and a boreal aspen (*Populus tremuloides*) (BA) stand in central Saskatchewan, Canada. The boreal stand is part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program, at sites that began as part of the Canada-USA collaborative BOReal Ecosystem-Atmosphere Study (BOREAS).

The two stands have similar ages (TM = 90 years, BA = 80 years) and leaf area indexes (TM = 4.1, BA = 4.5 (2.5 aspen, 2.0 hazel (*Corylus spp.*))), but differ in climate (mean air temperature: TM = 6.7 ^{o}C, BA = 0.5 ^{o}C; annual precipitation: TM = 858 mm, BA = 406 mm), species composition (TM dominated by red maple (*Acer rubrum*) and aspen in one canopy layer, BA with an aspen overstory and hazel understory), and stem density (TM = 3400 stems ha^{-1}, BA = 830 stems ha^{-1}).

Net ecosystem production (NEP) for 1996, 1997, and 1998 was 80, 270 and 200 g C m^{-2} (TM) and 80, 160 and 290 g C m^{-2} (BA), respectively. In this presentation, we will compare and contrast the two stands with respect to NEP and its seasonality, gross ecosystem production, and ecosystem respiration. We will also investigate the key climatic controls on forest-atmosphere CO_2 exchange.

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Impact of Spring Temperature on Carbon Sequestration by a Boreal Aspen Forest

T.A. Black[1], W.J. Chen[2], A.G. Barr[3], M.A. Arain[1], Z. Chen[1], E.H. Hogg[4], and Z. Nesic[1]

Over the past 100 years, the temperature of the Northern Hemisphere has increased significantly. There is strong evidence of an associated increase in biosphere activity because of increased growing season length. However, we do not fully understand how the boreal forest is responding. Previous studies have suggested that early thaws due to warmer spring temperatures can result in the loss of carbon from boreal black spruce (*Picea mariana*) forests and tundra. Here we report progress in our investigation of the effect of spring weather conditions on carbon sequestration by a boreal aspen (*Populus tremuloides*) forest in Prince Albert National Park in northern Saskatchewan, Canada. Sequestration or net ecosystem productivity (NEP) was estimated by measuring the carbon dioxide (CO_2) flux above the forest year-round using eddy covariance instrumentation. These measurements are part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) program, which is a follow-on to the Canada-USA collaborative BOReal Ecosystem-Atmosphere Study (BOREAS).

In 1994, 1996, 1997, and 1998, NEP was approximately 144, 80, 116 and 290 g C m^{-2} yr^{-1}, respectively. The primary climatic control on NEP was spring air temperature; warm springs caused early leaf emergence and increased ecosystem photosynthesis, but had little effect on respiration. The high carbon sequestration in 1998 was coincident with one of the strongest El Niño events of that century. Spring (April and May) air temperature (24-hour average) at the site was 9.9 °C, which was 3.2, 5.7 and 4.0 °C higher than in 1994, 1996, and 1997, respectively.

The first day of the year when photosynthesis was detectable occurred 2 to 3 weeks after the beginning of overstory aspen leaf emergence and 4 to 6 weeks after snow melt. The aspen leaf emergence date was highly correlated ($r^2 = 0.99$) with spring air temperature and was predictable using accumulated growing degree-days. One reason that ecosystem photosynthesis increased with earlier leaf emergence is that the latter resulted in higher absorbed photosynthetically active radiation during the growing season. Implications for stand water use as well as the effect of soil moisture on carbon sequestration will be discussed. Results for 1999 will be included in the presentation.

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Early Results of the Effects of Wildfire on Microclimate, Structure, and Function of Boreal Black Spruce Forests in Northern Manitoba

B.P. Bond-Lamberty[1], S.T. Gower[1], and C.K. Wang[1]

Fire is the dominant natural disturbance in boreal forests, but its effects on ecosystem structure and function remain poorly understood. A chronosequence of seven sites differing in time since their most recent fire event was established in the black spruce (*Picea mariana*) forests near Thompson, Manitoba. Attempts were made to match site characteristics (soil type, drainage, etc.) as closely as possible. The sites burned in 1998, 1995, 1989, 1981, 1964, 1930, and approximately 1870. The oldest site is located at the BOReal Ecosystem-Atmosphere Study – Northern Old Black Spruce site. Multiple replicate plots were established at each site in poorly- and well-drained areas. Campbell CR10X dataloggers recorded continuous data on soil temperatures (from 0 to 100 cm), soil moisture, soil heat flux, incident photosynthetically active radiation, air temperature, and humidity. Eleven months of data were recorded to date.

Average soil temperature increased sharply immediately after burning and then decreased slowly with stand age as leaf area index and surface organic layer increased. In general, the soil temperature was colder in the poorly-drained than well-drained black spruce ecosystems.

Biomass accumulation and distribution patterns varied markedly within each chronosequence, and carbon accumulation rates differed significantly between poorly- and well-drained stands. Across edaphic conditions, sapling density peaked about 10 years post-burn and then declined, basal area increased with stand age, and black spruce comprised a greater proportion of aboveground biomass.

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POSTER LOCATOR NO. 50

Carbon Storage in Forest Soils in the Nordic Countries: Effects of Climate and Soil Type

I. Callesen[1], J. Liski[2], K. Raulund-Rasmussen[1], A. Alriksson[3], M.T. Olsson[3], L. Tau-Strand[4], and C.J. Westman[5]

A new database (NORDSOIL) increases the knowledge of soil carbon in the boreal zone. The soil profiles extend from latitude 54 to 70° N and longitude 6 to 30° E, with mean annual temperatures ranging from -2 to 8.5 °C, and precipitation from 300 to 2300 mm yr^{-1} increasing from east to west. The data covers soil profiles in the boreal coniferous forest zone, but also extends into mixed and temperate-nemoral deciduous forest, where leaves are shed as an adaptation to the cold season.

Mean carbon storage in the organic layer plus 0 to 50 cm mineral soil was 10.4 kg m^{-2} (N = 266, range 1.8 to 30.5 kg m^{-2}). The carbon storage (C_{t50}) was positively correlated with T, mean annual temperature ($r \sim 0.31$), and P, mean annual precipitation ($r \sim 0.58$). This positive trend in carbon accumulation with temperature contrasts with some other studies. In ANOVA log (C_{t50}) depended on soil type, temperature, and precipitation. The fine, medium, and coarse soil types were defined by horizon-thickness weighted average percentages of clay (0 to 2 μm), silt (2 to 20 μm), and fine sand (20 to 200 μm) in depth 0 to 100 cm. Main effects of soil type, temperature, and precipitation, and the interaction between soil type and temperature, were highly significant ($p < 0.0001$). Consequently, the data were analyzed by soil type. In coarse-textured (<5% clay or silt, <50% fine sand) and medium-textured (>5% clay and >5% silt or >50% fine sand) soils, log (C_{t50}) increased linearly with T and log (P). In fine-textured soils (>10% clay, N = 24) there was no relationship between log (C_{t50}), and temperature and precipitation.

Coarse-textured soils:

$$\log (C_{t50}) = -7.27 + 0.135\, T\, [°C] + 1.31 \log P\, [mm\, yr^{-1}] \qquad (r^2 = 0.59, N = 96).$$

Medium-textured soils:

$$\log (C_{t50}) = -2.66 + 0.045\, T\, [°C] + 0.705 \log P\, [mm\, yr^{-1}] \qquad (r^2 = 0.37, N = 92).$$

Distribution of carbon within profiles varied with soil type. Coarse-textured soils generally accumulated carbon in organic layers and in Bhs-horizons contrary to fine-textured soils, in which thin organic layers and deeper mixing of organic matter in A-horizons prevailed.

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Successional Changes in Carbon, Water, and Energy Exchange after Fire in Alaskan Boreal Forests: Measurements and Potential Climate Feedbacks

Scott Chambers[1], Michelle Durant[1], and F. Stuart Chapin, III[1]

We measured the carbon dioxide (CO_2), energy, and water exchange by eddy covariance in black spruce (*Picea mariana*) forests during summer for 1 month, and 4, 8, 12, 15, and 80 years after fire. In addition, we measured these parameters before and after an experimental burn.

The albedo of black spruce (0.08) was initially reduced by fire (0.04), then increased to levels higher than those observed in unburned stands (0.12 to 0.15) until black spruce replaced deciduous shrubs and trees in late succession. Throughout post-fire succession, there was a reduction of 5 to 15% in the partitioning of incident short-wave radiation into net radiation at the surface. Initially this was due to the high surface temperatures of the dark flat surface, but the influence of increasing albedo and transpiration soon dominated. Initially there was a large relative partitioning of net radiation into atmospheric and ground heating at the expense of evapotranspiration. The emphasis then changed from sensible to latent heating as the successional deciduous canopy developed, although increased ground heating persisted until the moss mat was re-established. This resulted in a short-term (1 to 3 year) increase in atmospheric heating following wildfire, followed by a period of 20 to 70 years of dominance by deciduous woody species, during which atmospheric heating was less than in unburned black spruce stands. Consequently, at a regional level, an increase in area burned would act as a negative feedback to regional warming.

Fire severity, as determined by the amount of organic material overlying the mineral soil horizon, was observed to strongly influence the surface thermal and hydraulic properties. Severely burned regions promoted more rapid permafrost retreat, and the mineral soils underwent less dramatic diurnal temperature changes. Consequently, severely burned regions provided a superior substrate for regrowth, causing revegetation to occur faster and more homogeneously following a severe fire. Furthermore, severe fire promoted the growth of deciduous species (e.g., aspen (*Populus tremuloides*)) that will develop a deep successional canopy. Preliminary analysis of the data on carbon exchange suggested that during the mid-summer growing season, a severe fire led to a net efflux of carbon for less than 5 years, after which the rapidly regrowing deciduous vegetation had a higher rate of carbon gain than did the unburned black spruce stands.

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Spatial Distribution of Carbon Sinks and Sources in Canada's Forests Based on Remote Sensing and Climate, Inventory, and Tower Flux Data

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In order to determine the role of Canada's forests in the global carbon balance, it is necessary to map the spatial distribution of carbon sinks and sources, and to understand their temporal dynamics. Using satellite, climate, inventory, and tower flux data, we developed a method of mapping leaf area index (LAI), land cover, net primary production (NPP), fire-scar age, and net ecosystem production (NEP).

An optical instrument recently developed at the Canada Centre for Remote Sensing (CCRS) has become a new international standard for ground-based measurements of LAI. A process-based daily canopy NPP model with sunlit/shaded leaf separation was validated using two-level carbon dioxide (CO_2) tower flux data. This new model avoids problems of widely used big-leaf models for regional applications. Spatial forestry inventory data were co-registered with images from the VEGETATION sensor, and an algorithm for detecting fire-scar age up to 50 years was developed. An Integrated Terrestrial Ecosystem Carbon Budget Model (InTEC) was developed to describe the long-term effects of disturbance (fire, insect, harvest) and non-disturbance (climate warming, CO_2 concentration, nitrogen deposition) on the forest carbon cycle and to simulate post-disturbance dynamics of various carbon pools in vegetation and soil.

In mapping NEP, a grid of half-degree climate data for the last 100 years was bi-linearly interpolated to each pixel at 1 km resolution, and 1994 NPP and stand age data were used. A 1200 km x 1200 km NEP map covering most of Saskatchewan and Manitoba was compared against the tower flux data acquired between 1994 and 1996 during the BOReal Ecosystem-Atmospheric Study (BOREAS).

Using the same methodology, Canada-wide NEP maps were produced, showing south-north gradients in the sink/source strength in addition to large spatial variability. These maps are to be validated using tower flux and other data currently being acquired in different regions of Canada.

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POSTER LOCATOR NO. 107

Estimating and Monitoring Effects of Fire Severity and Area Burned on Carbon Cycling and Emissions in Siberia

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The Russian boreal forest contains about 25% of the global terrestrial biomass. Fire burns large areas of the Russian boreal forest each year, but there is little data on the amount of area burned, the severity of the fires, or the impact of fire on the forest. Changes in land use, forest cover, and disturbance patterns such as those predicted by global climate change models have the potential to greatly alter current fire regimes in boreal forests and to significantly impact global carbon budgets. The extent and global importance of fires in the boreal zone have often been greatly underestimated.

Preliminary analysis of remote sensing data (1 km NOAA-AVHRR) indicated that official estimates of burned areas for Russia are low by as much as an order of magnitude. For the 1998 fire season, we estimated that about 10 to 12 million ha of forest burned in Siberia. This remote-sensing estimate does not include some large areas burned in low-severity ground fires, yet it is still much higher than the estimate of about 2.7 million ha of burn in 1998 given by the Russian Aerial Forest Protection Service.

The available data suggest that the relative percentage of area burned in surface versus crown fire varies tremendously both in space and time, yet few data are available on the impacts of fires of different severity on carbon storage and emissions. We estimate that fires in the Russian boreal forest may constitute 5 to 8% of direct global carbon emissions from biomass burning, but lack of accurate data and models introduces large potential errors into this estimate. Improved monitoring and understanding of the landscape extent and severity of fires, and the effects of fire on carbon storage, air chemistry, vegetation dynamics and structure, and forest health and productivity, are essential to provide inputs into global and regional models of carbon cycling and atmospheric chemistry.

In 1996, a research project was initiated to: 1) refine and validate methods for remote-sensing based estimates of fire extent and severity in the boreal forests of Siberia; 2) quantify and model the effects of fire intensity and severity on fire and post-fire carbon emissions; and 3) develop regional estimates of fire extent and severity, and the impact on carbon balance, emissions, and forest health. This project takes a multi-scale approach, integrating data from intensively monitored prescribed fires of varying severity, ground sampling of wildfires, and airplane- and satellite-based remote sensing, in order to extrapolate the results over larger areas.

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Carbon Pools of the Korean Pine-Spruce-Fir Forest in the Changbai Mountain Region of China

Dai Limin[1], Sun Weizhong[1], and Deng Hongbing[1]

The biomass carbon (C) pool is a basic component of ecosystems, and its assessment is essential for studies on carbon cycling. The Korean pine-spruce-fir forest is one of the typical forest types in northeastern China. A 4 ha quadrat was established in the Changbai Mountain region to assess the forest ecosystem biomass. The results showed that the total carbon storage of this forest ecosystem was 174.3 t C ha^{-1}, with 144.3 t C ha^{-1} in trees, 0.018 t C ha^{-1} in shrubs, 4.2 t C ha^{-1} in herbs, 25.45 t C ha^{-1} in roots, and 0.332 t C ha^{-1} stored in the rest.

Underground carbon storage was almost 15% of the total carbon storage in the forest. Among the main trees of this ecosystem, the carbon storage of larch (*Larix olgensis*) was the highest at 54.2 t C ha^{-1}, followed by Korean pine (*Pinus koraiensis*) at 39.9 t C ha^{-1}, and spruce (*Picea koyamai* var. *koraiensis*) at 37.2 t C ha^{-1}. The carbon storage of fir (*Abies nephrolepis*) was the lowest at 8.25 t C ha^{-1}. For forest floor litter, carbon storage was 0.925 t C ha^{-1} in needles, 0.442 t C ha^{-1} in branches, and 0.072 t C ha^{-1} in broadleaf litter.

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Carbon Dioxide Exchange Rates from the Forest Floor and Lower Canopy in a Black Spruce Ecosystem

L.B. Flanagan[1], R.V. Swanson[1], and T.G. Williams[1]

Carbon dioxide (CO_2) flux measurements were made from the forest floor (moss and underlying soil) using a chamber system. Flux measurements in the lower canopy were made using an eddy covariance system located 2.1 metres above ground. Forest floor measurements showed maximum rates (6 µmol m^{-2} s^{-1}) of CO_2 efflux in July. In feather moss dominated areas, moss photosynthesis never exceeded total forest floor respiration so there was always a net efflux of CO_2. In sphagnum moss dominated areas during July, moss photosynthesis did exceed total respiration with average net uptake of 1.5 µmol m^{-2} s^{-1}. Eddy covariance measurements in July showed a net loss of CO_2 (average 2.3 µmol m^{-2} s^{-1}) over the day. Below canopy measurements made during dark periods (respiration) were strongly correlated ($r = 0.76$) with air temperature. The respiration rate to temperature relationship was used with day-time net CO_2 exchange to estimate photosynthesis by vegetation in the lower canopy. These measurements suggest that total photosynthesis by lower canopy vascular plants and moss had an average rate of 6 µmol m^{-2} s^{-1} during the day. These measurements are being used to develop models for calculating the contribution of moss photosynthesis to the annual carbon budget of the forest ecosystem.

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Preliminary Assessment of the Impact of Fire on Surface Albedo using Remote Sensing

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Wildfire causes extreme changes in energy dynamics and has a profound impact on the structure and function of ecosystems. Although it has long been recognized that fire plays an important and immediate role in modifying boreal forest ecosystems, detailed studies on the impact of fire on available energy and energy flow have been few. Measurements of energy flux in fire-disturbed boreal sites are underway. Remote sensing is being investigated as a tool for estimating energy budget model parameters and for extrapolation of field-based measurements to broader scales.

Landsat imagery and tower-based and hand-held instruments were used to measure surface albedo at sites in interior Alaska. Spectral reflectance in the imagery and of surface material lab samples was also measured. These measurements were used to study the impact of fire on surface albedo, a fundamental measurement for estimating net radiation. Results of the image analysis show that after a fire, spectral reflectance in the short-wave infrared region (1.5 to 3.0 μm) increased from 12 to 25% and remained higher than the surrounding unburned forest for many years. In the visible and near infra-red (IR) region of the spectrum, spectral reflectance decreased 3 to 9% (0.4 to 1.5 μm) in the burned area. Preliminary results of total albedo estimated with both field and image data show that fire typically reduced albedo directly following the burn. In the case of severe burn conditions, however, albedo could be higher following burning due to a combination of higher albedo surface material and fewer shadows from standing dead trees.

Additional research showed that following the typical initial decrease in albedo due to charring, albedo will increase at a site due to the re-establishment of light-leafed deciduous primary successional plant species. Further analysis is underway to develop methods of modeling the changes in albedo over time (diurnal and multi-year) to understand the impact of fire on net radiation in both space and time.

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Paleoclimatic and Paleovegetation Changes and Peat-Carbon Accumulation Dynamics in the West Siberian Plain

F.Z. Glebov[1], L.V. Karpenko[1], and I.S. Dashkovskaya[1]

A vast ridge-hollow-lake complex is situated between the Ob' and Vasyugan Rivers. Characteristic of the middle taiga subzone of the West Siberian Plain, this region is one of the largest northern wetland areas in the world. A peat profile at 60°31'N 77°41'E on the Ob'-Vasygan watershed was investigated. The peat samples were taken every 25 cm down the column. Botanical, pollen spores, and continuous layer-to-layer radiocarbon analyses of the vertical peat profiles were carried out according to traditional peat-land science methods. The age of the peat profile was 9510 years, and the depth of peat was 550 cm.

The profile illustrated the succession dynamics of bog and upland vegetation through the Holocene era. Bog vegetation in the Holocene changed in following sequence: eutrophic swampy-mare's tail; swamp-subor forest; mesotrophic woody–hypnum–sphagnous facies; oligotrophic hummock–ridge complex. Upland woody species changed as follows: spruce and larch – tundra –forest; cedar, spruce, larch–taiga; spruce, fir, birch–taiga; cedar, birch, pine-taiga.

The climate was reconstructed with the help of a statistical analysis of the general structure, wood components, and pollen-spore spectrum. Paleoclimatic curves of annual, January, and July temperatures, and quantity of precipitation were reconstructed. The extreme of the moist warm climatic optimum began in the Ob'-Vasuygan watershed 5500 years ago. The data suggests that warming periods took place about 10,000, 9100, 9000, 8500, 7100, 6700, 6000, 5500, 4600, 3500, 2200, 2000, 1800, and 1000 years ago. On the whole, the peaks of warming and the decrease of temperature coincided with available data on other regions of Russia.

Decreases in temperature occurred 9500, 8800, 8300, 6900, 6400, 5800, 5100, 4200, 2500, 1900, and 1500 years ago. Peat-carbon accumulation was the most intensive at the border of the second Pre-Boreal and Boreal period, but later decreased sharply and continues to decrease in Atlantic, Subboreal, and Subatlantic periods.

Modeling, based on the data of continuous radiocarbon dating of peat, has shown that the change of peat-carbon accumulation increment is well approximated by exponential functions. The analysis indicates that the process of peat-carbon accumulation is presently decreasing and will almost stop in 1000 years. The study of the connection between peat-carbon accumulation and paleotemperature enables us to predict the change of carbon accumulation with climatic changes.

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Fine Root Growth and Turnover in Spruce and Beech Forests at Different Soil Acidity

Douglas L. Godbold[1], Heinz-Werner Fritz[1], Kehong Wu[2], and Georg Jentschke[1]

Root biomass and production were determined at four approximately 40-year-old spruce (*Picea* spp.) stands differing in soil acidity, and two 120-year-old beech (*Fagus* spp.) stands, one growing on acid brown soil and the other on calcareous soil. Measurements were taken over three growing seasons from 1995 to 1997, using sequential coring, in-growth cores, and a root net method.

In the spruce stands, the vertical distribution of fine roots was strongly dependent on soil chemistry. With increasing soil acidity, a higher proportion of the fine roots were found in the organic soil horizons. Root biomass decreased with increasing soil acidity, and tended to have a shorter life span. Fine root production was higher in the stands with the highest soil acidity. At stands with a high base cation supply, lower fluctuations in root biomass were found. Estimations of root production using sequential coring, in-growth cores, and the root net method produced similar results.

In the beech stands, a higher root biomass was found at the acid brown soil site compared to the calcareous soil site. However, the longevity of the roots was shorter on the calcareous site; this was attributed to higher biological activity in the soil. The results showed that root biomass and root turnover are strongly influenced by soil parameters. This must be taken into account in estimating carbon fluxes in forest ecosystems.

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Determination of Aboveground Carbon in Northern Forests

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The Kyoto Protocol requires Canada to report on carbon stocks and changes in carbon stocks with time. Canada has 10% of the world's forests (418 million hectares) which account for a significant proportion of global terrestrial carbon fluxes. Reporting commitments include a baseline estimate of forest carbon stocks in 1990, and the capacity to monitor changes in carbon stocks leading up to the reporting period 2008 to 2012. In the current pilot study involving the test site at Hinton, Alberta (0.26 Mha in size), remote sensing has been used to generate aboveground estimates of carbon and their changes over the time period 1985 to 1996.

Multi-temporal Landsat TM imagery acquired in 1985, 1990, and 1996 (for leaf-on and leaf-off conditions) was used in conjunction with geographic information system (GIS) and field data to compute aboveground biomass from which the aboveground carbon content was determined. Topographic data at 1:20,000 (provincial) and 1:250,000 scales (national) were compared and impacts of horizontal and vertical accuracies on carbon estimation described. This data fusion approach helps to address key factors that play a role in the determination of carbon stocks such as species distribution, age classes, and forest structure.

For our test site at Hinton, Alberta, we discuss the analytical methods used to spatially segment, classify, measure timber volume, and convert to carbon. We identified the problems with estimating national carbon from remote sensing and the requirement for addressing site-specific spatial patterns, allometric equations, and biomass relationships. Summary tables and images showing carbon change over time are presented. These carbon estimates are compared with estimates from a Carbon Budget Model. We discuss how our methodology for computing aboveground carbon can be integrated into intelligent information systems in order to automatically and efficiently create Kyoto products for Canada, and manage large volumes of information for rapid data interchange and analysis.

We also present issues that impact the computation of aboveground carbon nationally for Canada. Production methods and systems are addressed in the context of local, national, and international linkages and reporting requirements for Canada. At the national level, the relevance of aboveground carbon to forest area and forest cover change is addressed along with periodic national assessments, such as criteria and indicators of sustainable forest development. At the local level, aboveground carbon, forest regeneration assessment, inventory profiles, and updates as well as other environmental issues provide information for compliance at the national level.

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Consequences of Changed Growth for the Estimation of Forest Carbon Stocks

R. Joosten[1] and A. Schulte[1]

Most national forest inventories only measure the volumes of merchantable stem mass and don't consider the residual non-commercial biomass. These tree components are commonly estimated with stem volume expansion factors of yield or stand tables dependent on diameter at breast height (DBH) or age. Schoene and Schulte (1999) demonstrated the enormous variation in the applied expansion factors. Precise and practicable inventory methods are needed to assess the whole tree biomass.

In this study we analyzed the North Rhine-Westphalia (NRW) forest inventory data and found several enormous deviations from the yield tables:

- the yield class of younger trees is higher than the older age classes;
- the number of trees per hectare is lower;
- the DBH is significantly larger;
- the ratio of height/ DBH is up to 30 points lower than in the model forests of the yield tables.

Further comparison of previous studies with actual forest growth has shown that today the crown ratio of Norway spruce (*Picea abies*) is considerably higher than in strongly thinned forest stands in the past.

In a pilot study we determined the aboveground fresh weight of 15 trees (*Picea abies*), separated into stem weight (larger than 7 cm diameter-over-bark) and the residual crown mass. One to 3 stem disks from each tree and crown chip samples from 6 trees were taken to determine the moisture content of the tree components. The oven-dry biomass of each sample tree was computed.

Our results suggest that: 1) the additional consideration of height of crown base and diameter at crown base improved the estimation of crown mass; and 2) the moisture of the stem wood was about 3% higher than the moisture of the logging slash.

This shows the set of difficulties in using the volume factors of the brush yield tables without considering the differences between fresh weight and oven-dry weight. Our results confirm that there is a high correlation ($r = 0.99$) between DBH and aboveground biomass. This method seemed to be more effective than the estimation of carbon stocks with expansion factors. The aim of further biomass studies is to test the most reliable method.

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The Influence of Secondary Succession on Boreal Forest CO_2 and Energy Exchange

M.E. Litvak[1] and M.L. Goulden[1]

A portable, fully autonomous eddy flux system was used to measure fluxes of carbon dioxide (CO_2), latent heat, and sensible heat in a 70-year-old black spruce (*Picea mariana*) forest in central Manitoba from August 12 to September 9, 1999. These fluxes were directly referenced to continuous measurements made over this same time period in a nearby 150-year-old black spruce forest at the BOReal Ecosystem-Atmosphere Study Northern Study Area Old Black Spruce (BOREAS-NSA OBS) site.

The 70-year-old forest accumulated on average 8 kg C m^{-2} more per day than the 150-year-old forest. A five-year record of fluxes at OBS indicated that this forest is at carbon balance, implying that the 70-year-old forest is accumulating as much as a ton of carbon per year. Night-time half-hourly averages of CO_2 efflux were comparable between the two sites. Day-time CO_2 uptake was 30% higher in the 70-year-old forest compared to OBS. We found no difference in the response of CO_2 uptake to vapor pressure deficit between the two sites. A 10 day side-by-side comparison of the two eddy flux systems used to make these measurements found no significant instrumental bias, establishing that the differences in CO_2 exchange observed between the sites reflects differences in forest physiology.

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The Boreal Ecosystem Research and Monitoring Sites (BERMS) Initiative: Scientific Accomplishments

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The BOReal Ecosystem-Atmosphere Study (BOREAS) was an international, regional-scale study to evaluate the contribution of the Canadian boreal forest to the global carbon budget and climate system. After intensive field campaigns in 1994 and 1996, this phase of BOREAS ended in April 1997. Key elements of BOREAS field research and monitoring have been continued at three sites in what was the BOREAS Southern Study Area in central Saskatchewan, as part of the follow-on Boreal Ecosystem Research and Monitoring Sites (BERMS) initiative.

There is a crucial need to provide long-term, continuous climatological and flux data (heat, water, and carbon) from target ecosystems in Canada. Such data are necessary to explore basic questions regarding carbon and water cycling in forests, and to provide the data essential to parameterize and test models of ecosystem carbon exchange. BERMS will add a long-term perspective to the BOREAS research findings, and will examine the role of interannual climate variation and site disturbance on forest-atmosphere interactions (water and energy) and carbon sequestration (seasonal and annual basis). The BERMS database will serve as a test-bed for the development of Land Surface Parameterization (LSP) schemes, specifically the Canadian Land Surface Scheme (CLASS).

Studies are being conducted at three tower flux sites situated within pure, mature stands of aspen (*Populus tremuloides*), black spruce (*Picea mariana*), and jack pine (*Pinus banksiana*). Preliminary analyses of carbon and water fluxes, and an assessment of their relevance to large-scale responses of the Canadian boreal forest to climate change, have been completed. The BERMS project is monitoring the immediate and long-term effects of ecosystem disturbance on the forest's net carbon balance. The length of time a forest takes to change from a net carbon source to a carbon sink following disturbance is a key component in understanding boreal carbon dynamics. Within one year following burning, a jack pine forest and an aspen forest both became net sources of carbon. However, after ten years the impact of burning appeared to be minimal. Data from a mixed forest region show that the diurnal carbon flux from a recovering burned site is very similar in pattern and magnitude to that from an undisturbed mixed forest.

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Carbon and Water Exchanges of Regenerating Forests in Central Siberia

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Direct measurement of carbon dioxide (CO_2) and water vapor of regenerating forests after fire events (secondary succession stages) are needed to determine the role of such disturbances in the functioning of biome carbon and water cycles. The relative importance of burned areas is also needed in order to quantify net biome productivity (NBP), a variable that includes large-scale carbon losses bypassing heterotrophic respiration (such as fire).

The study area is located near Zotino (60°44'N 89°09'E) east of the Yenisey River of Central Siberia (Krasnoyarsk region). A stand of 48-year-old birch (*Betula* spp.) naturally regenerating after a fire was selected for analysis. Eddy covariance measurements of CO_2 and water vapor were taken continuously from July to September of 1999.

The maximum rate of net ecosystem carbon exchange (NEE) exceeded -30 $\mu mol\ m^{-2}\ s^{-1}$ (net flux was negative indicating CO_2 uptake by vegetation) and the partitioning of the available energy was mostly dominated by latent heat flux.

A preparatory remote sensing analysis of a Landsat-5 Thematic Mapper (TM) scene has been done to select sites in the dark taiga region, extending for one hundred km east of the Yenisey River. Dark taiga is a forest mainly composed of Siberian fir (*Abies sibirica*) and spruce (*Picea obovata*), tree species with dark green needles. In order to determine the magnitude of burned area and the extension of broadleaf regenerating forests, a supervised classification of a TM image was performed. Training and testing of the supervised classification for the forest areas studied used standard field ecology methods. Forest structure, age, and composition were analyzed to understand the dark taiga secondary successional stages. Analysis of the spatial frequency of burned areas and carbon exchanges of the regenerating forest underline the importance of considering large area disturbances for full carbon accounting.

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Dependence of Photosynthetic Capacity and Photosynthetic Pigment Allocation on Foliar Nitrogen Levels in Aspen Stands

Elizabeth M. Middleton[1], Joseph H. Sullivan[2], and Andrea J. Papagno[3]

The boreal forest is a critical component of the global carbon cycle. Photosynthetic uptake of atmospheric carbon dioxide (CO_2) can be limited by availability of nitrogen, an important component of photosynthetic enzymes. We examined the photosynthetic capacity (A_{max}), photosynthetic pigment content (Chl *a*), and nitrogen (N) content of leaves of aspen trees (*Populus tremuloides*) and the associated hazelnut shrubs (*Corylus* spp.) at two differently aged aspen stands (15 years old and 60 years old) in Saskatchewan during the 1994 and 1996 growing seasons.

Photosynthetic capacity (μ mol O_2 m^{-2} s^{-1}) and photosynthetic pigment content (μ g cm^{-2}) of leaves were dependent on the seasonal, site, and vertical canopy variability of the foliar nitrogen content (% N: μ g N g^{-1} dry weight). The initial nitrogen levels observed in emerging and expanding young leaves (2.8 to 4.8% N) decreased to lower levels in mature leaves. Optimal values for photosynthesis (~2.6% N) were attained in early summer and thereafter declined through senescence. Well-defined vertical profiles for A_{max} and Chl *a* as a function of percent nitrogen were observed at both sites throughout the growing season. However, differences were apparent between the closed canopy "old" site (OA) and the more open canopy "young" site (YA). Aspen leaves at OA had higher A_{max}, Chl *a*, and total photosynthetic pigment content (Chl *a* + Chl *b* + carotenoids) than did aspen leaves at YA or hazelnut leaves at either site. Higher A_{max} was achieved in aspen leaves, as compared to hazelnut, throughout the growing season. A_{max} was strongly dependent on the *relative* amount of Chl *a*, or percent Chl *a* content, rather than the Chl *a* content alone, when examined over all groups and canopy layers ($r^2 = 0.88$, n = 259). This demonstrated that the relative allocation to Chl *a* versus allocation to accessory pigments (Chl *b* and carotenoids) is important in determining the photosynthetic capacity of leaves in aspen stands. Although A_{max} was higher in aspen leaves at OA, assimilation in the field was higher in aspen leaves at YA, and was dependent on the total pigment content rather than percent Chl *a* content. These results may have implications for remote sensing estimates of carbon uptake by boreal landscapes comprised of a mosaic of aspen stands of different ages.

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POSTER LOCATOR NO. 96

Soil Carbon Pools in a North-South Gradient in Sweden

Torbjörn Nilsson[1], Agnetha Alriksson[1], and Mats Olsson[1]

Soil organic carbon to a depth of 1 metre in upland soils was measured at 18 forest sites along a north-south gradient in Sweden. The study sites were selected to represent a national range in geochemical properties, temperature regimes, and site fertility. They were relatively similar with respect to podzolic properties, with glacial loamy sandy to loamy till soils and naturally drained conditions. The pedogenic age was in the range of 8,000 to 13,000 years, due to deglaciation from south to north.

The results showed that the amount of carbon was in the range of 4 to 11 kg m^{-2}. Carbon increased from north to south and was well correlated with the temperature sum during the growing season ($R^2 = 0.64$) as well as the site capacity ($R^2 = 0.63$). In northern sites, most of the carbon occurred in the B-horizon. In southern sites a larger part of the carbon was present in the O+A horizons. The variation in carbon content to 1 metre depth was considered to reflect differences in long-term biomass production. The high amount of carbon in A-horizons in southern Sweden was interpreted as being a result of the historical use of land for agriculture.

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Poster Locator No. 58

New Design of an Open Chamber System for Measuring Soil Surface CO_2 Efflux

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T. Pohja[3], T. Vesala[2], and P. Hari[1]

An open chamber is a widely used method for soil carbon dioxide (CO_2) efflux measurements. However, uncontrolled airflow between the inside and outside of the chamber can cause errors in soil CO_2 efflux measurements. To avoid these problems a new type of open chamber system was designed. The magnitude of errors caused by airflows between the inside and the outside of the chamber was studied with this system. Furthermore, a comparison was made between the efflux measurements of this system and a closed static system.

A system was constructed in which compensation air of known CO_2 concentration was introduced into the chamber and the CO_2 concentration of the air sucked from the chamber was measured. The airflows into and out of the chamber were controlled by two separate mass flow controllers, and the pressure difference between the chamber and the ambient air was measured. For testing the effect of flow rate differences on the measured CO_2 efflux and the pressure difference, the inflow rate was adjusted to be higher and lower than the outflow rate.

When the inflow was larger than the outflow, the measured CO_2 efflux decreased, whereas when the inflow was smaller than the outflow the efflux increased. The significance of this error depended on the CO_2 efflux. Differences in flow rates caused larger errors during high CO_2 efflux than during low CO_2 efflux. During low efflux (0.1 g m^{-2} h^{-1}) this error was statistically significant ($p < 0.05$) when the difference between the flow rates was larger than 30%. The open chamber measurements described here were compared to closed static measurements based on syringe samples taken manually from this chamber. The CO_2 efflux rates measured with these two methods differed less than ±15% from each other.

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Stochastic Simulations of Footprints and Analysis of a Mixed Douglas-fir/Beech Forest Flux

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The evaluation of carbon dioxide (CO_2) concentration and fluxes due to localized sources, equivalent to a footprint estimation, was performed using a simulation of ensemble of fluid parcel trajectories. Flow inside the forest and the vertical distribution of sources and sinks inside the canopy were taken into account in an analysis of source contribution to measured fluxes and concentrations above the forest.

Numerical simulations have shown that due to relatively slow turbulent transport inside the forest, the influence of the forest canopy on the footprint is important only for observation levels up to few times the forest height. The influence of along-wind turbulent diffusion, which analytical atmospheric surface layer footprint models do not take into account, can be significant even for higher levels. An analysis was performed to observe the sensitivity of crosswind integrated footprint function on flow parameterization.

The footprint simulations were performed to predict the contribution of distinctive sub-plots of mixed forest to flux above the forest. The Vielsalm site (Belgian Ardennes) consists mainly of Douglas-fir (*Pseudotsuga menziesii*) and beech (*Fagus* spp.), with grass areas some distance from the measurement tower. During the pre-leaf periods of beech in spring, the site constitutes a good experimental ground for footprint analysis. The eddy-covariance CO_2 flux measurements under high radiation conditions were combined with footprint analysis to deduce the CO_2 uptake by the Douglas-fir canopy.

The systematic variation of deduced Douglas-fir canopy flux with wind direction, with remarkable scatter, suggests that there were considerable uncertainties in the footprint prediction. The sensitivity analysis reveals that footprint estimates above the heterogeneous forest could be biased mainly because of lack of information on flow statistics, especially inside the forest, and the inability to account for horizontally inhomogeneous turbulence in a heterogeneous forest. These factors limit the quantitative accuracy of footprint simulation over a heterogeneous forest. The footprint analysis is useful for estimating the qualitative effect of the forest canopy on footprint function.

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Estimation of Net Primary Production at the Landscape Level in the Boreal Forest of Eastern Canada

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Net primary production (NPP) was modeled across a 2,100 km^2 region of boreal and sub-boreal forest north of Quebec City, Canada. The model used is a version of 3-PG modified to take into account the strong dependence on climatic variables of forest growth at northern latitudes. Monthly climatic inputs for each pixel were interpolated from permanent climate stations taking elevation, slope, and aspect into account. Forest type was interpreted from a Landsat-TM image. Stand attributes were estimated from forest type classification and forest-inventory-derived relationships. The fraction of absorbed radiation was estimated from the satellite image. The model was used to produce a map of NPP across the landscape under a climatic regime derived from 40 years of climate records.

Preliminary results show biomass estimates over the pilot region ranging from 30 Mg ha^{-1} to 165 Mg ha^{-1}, and NPP varying from 3.3 Mg ha^{-1} yr^{-1} to 14.3 Mg ha^{-1} yr^{-1}. Although differences in productivity are associated with changes in climate, most of the variability is captured by changes in vegetation types, going from sugar maple (*Acer saccharum* Marsh.) in the southern valleys to balsam fir (*Abies balsamea* [Mill.] B.S.P.) stands in the northern highlands. The results show that substantial region-level errors in productivity are caused by the lack of up-to-date information on changes in stand status through fire, harvesting, thinning, or insect defoliation, a type of information readily available from satellite imagery. The NPP allocation algorithm used in 3-PG requires several input data that are difficult to obtain at the landscape level (e.g., aboveground biomass and number of stems per hectare).

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Coarse Woody Debris as a Component of the Carbon Cycle in Boreal Old-Growth Spruce Forests

Ekaterine V. Shorohova[1] and Alexey A. Shorohov[2]

Coarse woody debris (CWD) carbon dynamics were studied in a series of permanent sample plots established in old-growth spruce (*Picea abies* (L.) Karst.) forests of different age structures (even-aged, uneven-aged, and all-aged) and dynamic phases (increasing, stabilization, and digression of the total biomass). The study aimed to: i) estimate the total CWD carbon (C) stores; ii) estimate the percentage of CWD in the total wood; and iii) explore the carbon balance of CWD as the difference between the flows to CWD (stand mortality) and flows from CWD (decay).

Field experiments were carried out in the "Veppsky Les" reserve (middle boreal zone, Russia). Twenty-one sample plots ranging from 0.1 to 0.2 ha were established, and an inventory of all not-buried CWD was taken. Each CWD unit was aged and classified among 1 to 5 decay classes (with given bulk density) on the basis of permanent plot records (data from St. Petersburg Forestry Research Institute), wood characteristics (volume, type, and stage of rot), and other features.

CWD carbon stores ranged from 3.3 to 51.0 Mg C ha^{-1}, depending on the dynamic phase of the stand. Percentage of CWD carbon in the total wood carbon varied from 3.5 to 39.5%, depending on the dynamic phase of stand. The average annual spruce mortality input was 0.2 to 0.8 Mg C ha^{-1}. This value accounted for 0.3 to 0.9% of the carbon of spruce living biomass. The calculated annual carbon loss of CWD averaged 1.6%, assuming that the decay rate of CWD over the 25 year period is linear.

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Impact Studies on Nordic Forests: Effects of Elevated CO_2 and Fertilization on Gas Exchange

B.D. Sigurdsson[1], P. Roberntz[1], M. Freeman[1], H. Saxe[2], M. Naess[3], H. Thorgeirsson[4], and S. Linder[1]

The likely effects of rising carbon dioxide (CO_2) concentration on key growth processes of four tree species on high and low nutrient sites in the five Nordic countries: *Picea abies* (Sweden), *Pinus sylvestris* (Norway and Finland), *Fagus sylvatica* (Denmark) and *Populus trichocarpa* (Iceland) were examined using branch bags (SE, NO, FI, DK) or whole-tree chambers (IS). Results are presented on changes in light-saturated rate of net photosynthesis (A_{sat}), carboxylation efficiency (max dA/dC_i, termed α), stomatal conductance (g_s), and stomatal limitation of photosynthesis (L_s) after two (DK), three (IS), and four (NO and SE) years of treatment. The age of the field-grown trees ranged between 7 and 34 years.

Fertilization did not change A_{sat}, α, g_s or L_s significantly for any species. At the present CO_2 concentration A_{sat} was 15.9, 12.2, 12.0, and 8.4 µmol m^{-2} s^{-1} for *P. trichocarpa, P. abies, P. sylvestris,* and *F. sylvatica*, respectively. *P. trichocarpa* had almost three times higher g_s than the other species, 410 compared to 140 to 170 mmol m^{-2} s^{-1}. *P. trichocarpa* had also significantly ($p < 0.001$) lower L_s, 17% compared to 33% (*P. abies*), and 40 to 41% (*F. sylvatica* and *P. sylvestris*). *F. sylvatica* had, however, the highest α of 0.12 mol m^{-2} s^{-1} ($p < 0.02$), while the other species were not significantly different from each other, with 0.09 to 0.10 mol m^{-2} s^{-1}.

Long-term CO_2 elevation increased A_{sat} significantly ($p < 0.001$) by 46, 52, 102, and 123% for the *P. trichocarpa, P. abies, F. sylvatica, and P. sylvestris*, respectively. No significant CO_2-effect was detected for g_s, α or down regulation of A_{sat} in any species, but L_s was significantly ($p < 0.001$) decreased as an effect of higher internal CO_2 concentration for all species. The relative CO_2-effect on A_{sat} increased linearly with temperature for all species, which was the main reason for the difference in the CO_2-effect between species. Application of such a simple linear relationship between CO_2-effect and temperature could improve predictions of future tree growth, and may be essential when predicting growth responses to elevated CO_2 at higher latitudes.

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Linkages between Microbial Carbon Transformations and Carbon Chemical Structure in the Humus Layer of Coniferous Forests

R. Michael Sjöberg[1], Tryggve Persson[1], and Heike Knicker[2]

We studied the relationship between microbial carbon (C) transformations and carbon chemical structure, obtained by solid state ^{13}C nuclear magnetic resonance spectroscopy (^{13}C-CPMAS-NMR), in the humus layer of coniferous forests. Intact soil cores were sampled from control and nitrogen fertilized plots in a pine (*Pinus sylvestris*) and a spruce (*Picea abies*) forest and incubated in darkness at 15 °C and 3.5 °C for up to 147 days. CO_2 evolution, chemical variables, and ^{13}C-CPMAS-NMR were determined during incubation. The results were examined using the partial least squares (PLS) method to probe the relationships between different sample properties and to test the predictive efficiency of the models obtained.

The prediction of CO_2 evolution rates, by using chemical variables and normalized NMR-spectra, was satisfactory (r^2 = 0.94 to 0.98) for each PLS analysis performed. Score plots from the PLS-models separated the soils from the pine and the spruce forest along the first principal component. The second and third principal component described the time of incubation and the fifth principal component separated the effect of fertilization. By generating subspectra constructed from loading weights of the principal components, a more distinct chemical interpretation was obtained of which carbon species were affecting CO_2 evolution. For instance, differences in CO_2 evolution rates between humus from the pine and the spruce forest could be assigned to variation in incubation temperature, total carbon content, organic matter content, total nitrogen content, inorganic nitrogen, and certain carbon chemical structures. Methylene groups in alkyl rings and chains, CH(OH) groups (C-2, C-3, C-5) in cellulose, anomeric carbon (C-1) in polysaccharides, CH_2OH groups (C-6 of polysaccharides), syringyl lignin or oxygen-substituted aromatic carbon in tannins and carboxyl, and amide or ester carbon had a large impact on differences in CO_2 evolution rates.

This study demonstrated that ^{13}C-CPMAS-NMR and multivariate data analyses have a potential for use in exploring the relationship between microbial carbon transformations and carbon chemical structure in forest soils.

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CO_2 and Winter Temperature Effects on White Birch and Norway Spruce

Oddvar Skre[1] and Marius Naess[2]

Three-year-old Norway spruce seedlings (*Picea abies* (L.) Karst.) from three latitudinal populations (Norway subarctic, Norway southern, and Iceland) were transplanted in March 1992 under two nutrient regimes, equivalent to 1 and 10 g Nitrogen m^{-2} yr^{-1} and two temperature regimes (ambient and 4 °C above ambient). The seedlings were kept in a greenhouse during the winter and in the spring moved into open top chambers under two levels of carbon dioxide (CO_2) (350 and 650 μmol mol^{-1}). The experiment was repeated in 1993, and supplemented with one-year-old seedlings of white birch (*Betula pubescens* Ehrh.) from the three populations. The shoot elongation rates were measured each summer, and shoot and root biomass were sampled at the end of each season. Measurements of carbohydrate content and CO_2 exchange rates were taken at intervals. Light and photoperiod were close to ambient conditions.

At the higher CO_2 level (650 μmol mol^{-1}), birch from subarctic and southern populations in Norway strongly increased their shoot elongation rates and biomass, but a similar increase did not occur in the Icelandic population. Elevated winter temperature promoted earlier budbreak and provided a longer growth period for the southern Norway birch, positively influencing shoot and biomass growth. However, this treatment had a slightly negative effect on plants from the two northern populations. In spruce seedlings, only slight or insignificant increases in growth and photosynthesis rates could be found as a result of elevated CO_2 levels. On the other hand, there was a significant increase in photosynthesis rates at elevated *versus* low CO_2 levels in white birch, except from the Icelandic population, where this positive CO_2 effect on photosynthesis was only found at late season. Growth rates were strongly increased in both species as a result of increased nutrient levels, regardless of population.

In spruce seedlings, carbon exchange measurements during the winter, supplemented with carbohydrate analysis, showed a strong reduction of the carbon pool in seedlings grown at elevated *versus* normal winter temperatures. The observed negative carbon balance indicated an observed growth reduction and corresponding premature needle loss in the high temperature regime relative to plants grown under ambient temperatures. In birch seedlings the influence of winter temperatures on the carbon balance was insignificant, due to the absence of leaves in winter and the relatively low carbon exchange rates.

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POSTER LOCATOR NO. 73

Carbon Budgets for Jack Pine Forests along a Climate Gradient

Sarah J. Steele[1], Stith T. Gower[2], Jason G. Vogel[3], and John M. Norman[4]

The carbon content, net primary production (NPP), and respiration components of the carbon budgets of four mature boreal jack pine (*Pinus banksiana*) forests were estimated along a climate gradient that spanned the species latitudinal natural distribution. The sites are part of the BOReal Ecosystem-Atmospheric Study (BOREAS), and extend from Sayner, Wisconsin, United States (latitude 46°N) to Gillam, Manitoba, Canada (latitude 57°N), with intermediate sites near Prince Albert, Saskatchewan, Canada and Thompson, Manitoba, Canada. Site-specific allometric equations were used to estimate above- and belowground biomass, and temperature driven respiration equations were used to estimate autotrophic and heterotrophic respiration.

NPP and autotrophic respiration decreased with increasing latitude, but heterotrophic respiration increased with latitude. Net ecosystem production (NEP), estimated as the difference between NPP and heterotrophic respiration, was negative for the Prince Albert and Gillam sites, and was strongly correlated with annual precipitation on all sites. NPP was positively correlated to potential evapotranspiration (PET), except for at the extremely water limited site near Prince Albert. An ecosystem process model was used to quantify environmental limitations on canopy photosynthesis and net ecosystem exchange for boreal jack pine forests.

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POSTER LOCATOR NO. 63

Airborne Laser Altimetry as a Powerful Tool for Monitoring the Carbon Budget in Boreal Forests

T. Sweda[1], T. Kusakabe[1], H. Tsuzuki[1], and A.R.G. Emmanuel[1]

Climate warming due to increasing atmospheric carbon dioxide and other anthropogenic greenhouse gasses is expected to cause vegetation change. It can take place anywhere on the globe, but is expected to be most conspicuous in higher latitudes of the northern hemisphere, where warming is considered most prominent.

In this work, extensive, continuous distributions of forest biomass and leaf area index (LAI) were estimated using airborne laser altimetry over a 600 km transect along a latitudinal gradient from Edmonton, Alberta to Cluff Lake, Saskatchewan. This transect was used as a baseline to monitor possible changes in vegetation and carbon budget. Coupled with a global positioning system (GPS) receiver, the airborne laser altimetry system provides latitude- and longitude-coordinated clearance between the aircraft and objects on the ground at an interval as close as a couple of centimeters along the flight pass. By calibrating with the GPS-monitored flight altitude, the continuous series of clearance measurements can then be converted into a high-resolution vegetation profile.

A series of ground truth surveys at over 50 plots directly under the flight course revealed a significant correlation between the integral of vegetation profile and standing timber stock. This in turn showed significant correlation with the aboveground forest biomass as well as with LAI, enabling the establishment of a series of regressions relating the vegetation profile with the estimates of aboveground biomass and LAI. The geographical distributions of biomass and LAI showed similar trends. In both distributions, the boundary between the aspen parkland to the south and the boreal forest to the north showed clearly at around 150 km from Edmonton. The distribution centers of both biomass and LAI for the boreal forest appeared further south than its geographical center at around 200 km from Edmonton, declining rather sharply southward but rather gradually northward.

Qualitative aspects of vegetation change such as shift in biome boundary and change in species composition are difficult to detect, but the quantitative aspects of latitudinal distributions of biomass and LAI are much easier to measure, and thus easier to detect.

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Predicting and Monitoring Forest Growth at Local to National Scales

Philip Tickle[1,2], Nicholas Coops[3], Susan Hafner[1,2], and Joe Landsberg[4]

With government commitments to sustainable forest management and climate change initiatives such as the Montreal Process, the United Nations Framework Convention on Climate Change (UNFCCC), and the Kyoto Protocol, there is increasing demand for precise estimates of standing biomass, potential productivity, and forest growth rates at local to global scales. Process-based ecosystem models designed to predict and monitor forest productivity at national to global scales have been widely accepted by the scientific research community for some time, but have suffered from a lack of rigorous calibration and validation at the local scale. At the scale of operational forestry, there has been little adoption of process models, due largely to their complexity, the lack of output variables of relevance to forest managers, the lack of available spatially explicit information to run the models, and user-friendly modeling systems. In order to bridge this gap we require locally relevant model outputs that are capable of being scaled up for calibrating and validating national and global scale models.

To address some of the above issues, the Australian Bureau of Rural Sciences (BRS) and CSIRO Forestry and Forest Products have developed the 3PG-SPATIAL model. This model is a further development of the process-based 3PG model developed by Landsberg and Waring (1997), which has been fully integrated into a geographic information system (GIS) framework. To demonstrate the capacity to predict forest growth variables of relevance to forest managers using a simplified process model, we implemented 3PG-SPATIAL over 50,000 hectares of diverse native eucalypt forest in southeastern Australia. Forest stands ranged in age from 16 to 87 years old, and had undergone a range of typical natural and management related disturbances.

Using contemporary environmental information, satellite data, and a small number of calibration plots, we were able to predict forest variables at levels of accuracy applicable to operational forest management. Key results include accounting for 86, 86, 59, and 76% of the variance in predictions of standing volume, stocking, mean diameter at breast height, and current annual increment, respectively.

The results demonstrate that generalized physiological growth models, when implemented within a GIS environment, can be used to predict forest growth variables at fine scales over large areas. Having such capacity further enhances our ability to provide transparent and operationally relevant information and increases our ability to calibrate and validate national and global modeling of forest growth.

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Simple Models for Using Survey Data to Estimate Organic Carbon Stocks in Forest Floor and Mineral Horizons of Forest Soil

Sylvie Tremblay[1], Rock Ouimet[1], and Daniel Houle[1]

Soil organic carbon is an important component in carbon dynamics, and an indicator of sustainable forest management. Predictive models of organic carbon stocks (t ha^{-1}) (Q) were developed for forest floor and mineral horizons of forest soils. These models used basic soil survey variables as input variables, as these are the most important source of information for forest soils.

The forest floor model explained 75% of the variation in soil organic carbon stocks, with forest floor thickness as the explicative variable. The mean relative error of a new prediction is 28%. The mineral horizons model was composed of two equations: 1) organic carbon concentration as a function of horizon color; and 2) density as a function of the estimated carbon concentration obtained from the first equation. The mineral horizons model explained 56% of Q variation, with a mean relative error of 28%.

These simple models could rapidly and inexpensively evaluate carbon stocks in forest soils when chemical analyses are lacking. In a further step, the models will be used to estimate carbon stocks at a provincial scale (from the data of 8000 pedons) and to identify ecological variables influencing carbon stocks in forest soils.

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Fire Scars Provide Annual Resolution of Fire History for Evaluation of Carbon Emission in Siberian Forests

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The history of fires in Siberia has not been studied extensively. The reconstructed fire history of stands, combined with stand age-structure dynamics, provides the basis of quantitative analysis of the effect of fire on the carbon cycle in forest ecosystems. Fire frequency, spatial patterns, and within seasonal distribution can be recorded in tree rings. One of the main characteristics of fire regimes is mean fire interval (MFI), and the most accurate record of MFI is derived by cross-dating fire scars on wood discs taken from trees periodically affected by fires.

We examined the lichen-pine forests of the middle taiga (20 sites) and the moss-shrub larch forests of the northern taiga (12 sites) in Central Siberia. The average MFI in pine forests of the middle taiga is 29.5 years, and in larch forests is 82 years. To transform MFI data in the burned area they must be combined with a corresponding spatial probabilistic model of fire occurrence. The model showed that over a period of more than 400 years in pine forests, fire burned about 2% of the area annually. In extremely warm years this reached 4.5% of the area. In the northern larch taiga, fire burned on average 1.2% of the area annually, and in extremely warm summers it burned 2.8%.

These data can be used to evaluate the portion of annual net primary production (NPP) of the forested area that is returned to the atmosphere by the direct impact of fires. Ground fires in the pine forests burned from 1 to 1.8 kg m^{-2} of organic material (OM) which, in combination with the area burned annually, resulted in combustion of 0.03 kg OM m^{-2}. Taking into account that annual productivity of those pine forests is about 0.27 kg m^{-2}, 9% of annual NPP (and carbon) returned to the atmosphere as a direct result of forest fires. In extremely warm summers this increased up to 20%. MFI became 2.5 to 3 times shorter in forests under strong anthropogenic impact other than systematic forest management, so in extreme years carbon turnover could reach 60%. Similar calculations for larch forests showed that on average 11% (or taking crown fires into account, 16%) of carbon in NPP was returned to the atmosphere due to forest fires (in warm summers up to 25%). If we add the percentage of indirect turnover due to decomposition of organic material in the post-fire period, we find that a single factor - forest fires - can change the vast forested territory from a carbon sink to a carbon source.

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POSTER LOCATOR NO. 19

Role of Soil Organic Matter in the Carbon Cycle in Forest Ecosystems of the Krasnoyarsk Region

Estella F. Vedrova[1] and Ludmila V. Mukhortova[1]

In forest ecosystems, organic matter is mineralized to inorganic carbon when carbon is released during the decomposition of leaf-fall litter, dead roots, and soil microbe biomass, and forms resistant humus fractions of soil organic matter. In soils of mature stands the young humus compounds renew the peripheral part of the soil humus molecule and therefore additional carbon accumulation in the soil is not observed. In young stands biologically resistant, new-formed compounds of a specific nature are fixed in soil, not only renewing part of the molecule of the soil-humus acids, but also enlarging the humus store in the soil. It is not the amount of stored carbon, but the biochemical structure of the material being decomposed, which determines the intensity of the carbon return to the atmosphere under a close combination of hydrothermic indexes.

In the Krasnoyarsk region, carbon accumulation in coarse woody debris (t ha^{-1}) is greatest in larch (*Larix sibirica* and *L. gmelinii*) stands, followed by cedar (*Pinus sibirica*), pine (*Pinus sylvestris*), spruce (*Picea obovata*), fir (*Abies sibirica*), aspen (*Populus tremuloides*), and birch (*Betula pendula*) stands. In coniferous stands, carbon accumulation is highest in the northern and the southern taiga. In deciduous stands, carbon accumulation changes slightly from the north to the south of the region. Coniferous stands store three to four times more coarse woody debris than deciduous stands due to the faster rate of decomposition of deciduous materials. This larger storage capacity results in a greater carbon dioxide (CO_2) output when decomposition occurs, yet the amount of carbon released to the atmosphere was found to be similar in aspen, birch, and cedar (*Pinus sibirica*) stands.

Newly formed humus accounts for 8 to 26% of carbon loss at decomposition. It is equivalent to 3 to 6% of the organic matter stored in residues being decomposed or 0.2 to 0.6% of the carbon stored in the top 50 cm of forest soil. The total mineralized carbon flux in the Krasnoyarsk region was 75.8 million t C yr^{-1}. Larch stands accounted for more than 90% of CO_2 released to the atmosphere in the pre-tundra and northern taiga forests, and almost 50% of CO_2 released in middle taiga forests. Birch stands contributed 17%, with their share in the total carbon flux to the atmosphere increasing in the latitudinal direction.

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POSTER LOCATOR NO. 30

On the Inaccuracies of Net Ecosystem Exchange Estimates using the Eddy-Covariance Technique

Timo Vesala[1], Yllar Rannik[1], Tiina Markkanen[1], and Petri Keronen[1]

The most common approaches to measuring the carbon balance of forests include micrometeorological techniques, biomass inventories, inversion from atmospheric gas concentrations, and remote sensing. Among the micrometeorological techniques, eddy-covariance measurements have recently become a widely used tool.

Eddy-covariance is based on the determination of the statistical correlation of the fluctuations in the wind and concentration, to deduce the vertical flux. However, the net carbon balance is the relatively small net sum of opposite day-time and night-time or summer-time and winter-time fluxes. There are several interacting circumstances which may lead to random or systematic uncertainties either in the short- or long-term or both: non-stationary turbulence and intermittency, the stochastic nature of turbulence, footprint (flux source area) and its reliable estimation, calm and stable nights, determination of storage fluxes, and gap filling. Caution is required when, for example, the annual carbon budget is estimated. We give an overview of these issues, discuss them, and suggest remedies.

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Effects of Landscape Structure on Phytomass Estimates in Tundra and Northern Forest Vegetation Communities: Examples from Northern Russia

Tarmo Virtanen[1], Kari Mikkola[1], and Ari Nikula[1]

We have compiled a geographic information system (GIS) database of major landscape and vegetation units with associated aboveground phytomass for the Usa River catchment in Komi, Russia (about 93,000 km^2). Vegetation zones in the area range from taiga in the south to forest-tundra and tundra plateau in the north. The Ural Mountains restrict the area in the southeast. Vegetation classification was based on a spectrally adjusted Landsat TM image-mosaic constructed from 8 images taken between 11 July and 3 August in 1988. Ground truthing, phytomass measurements, and sampling were conducted on four sub-catchment areas (each covering 2.5 to 5% of the basin) during the summers of 1998 and 1999. Over 20 landscape - vegetation units were distinguished from images, and average aboveground phytomass and carbon content for each was estimated from our measurements and literature data.

The average carbon (C) content of the different vegetation communities varied from about 4 kg C m^{-2} in spruce-dominated northern taiga forests to about one-third of that in the sparse tree-line forests, and to about one-tenth or even less of that in the shrub tundra. However, in the open bogs between taiga forests, phytomass corresponded to the values in the tundra areas. In the willow-dominated areas of the tundra, the amount of phytomass was as high as in the taiga forests. If the phytomass estimates were calculated based only on the most common vegetation type within larger grids, the effect of the most fragmented vegetation classes would be mainly overlooked (for example, willow-dominated areas in tundra).

Generally, the spatial structure of the vegetation communities was more fragmented in the tundra, where the size of the different vegetation patches was often only hundreds and sometimes even tens of square meters, but in the forested areas vegetation patches were usually much larger. Thirty metre pixel Landsat TM images allow the classification of the unmixed vegetation types in the taiga, but not in the many areas of the tundra. To achieve more precise phytomass estimates of vegetation, different spatial structures of the different vegetation types should be taken into account.

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POSTER LOCATOR NO. 65

Measurement and Modeling of Post-Winter Recovery of Photosynthetic Capacity in Boreal Norway Spruce

Göran Wallin[1], Johan Bergh[2], Mats Räntfors[1], and Sune Linder[2]

Carbon sequestration in boreal ecosystems is to a large extent constrained by soil freezing and sub-zero air temperatures leading to winter damage of the photosynthetic apparatus of plants. A modified version of the process-based model BIOMASS postulated a 34 to 44% reduction of the annual potential gross photosynthetic production caused by the boreal climate, with the largest reduction during spring and early summer.

In order to validate the modified version of BIOMASS, the net carbon dioxide (CO_2) exchange of shoots on 35-year-old Norway spruce (*Picea abies*) trees was measured continuously for three years (1997 to 1999). The study was performed at the Flakaliden nutrient optimization experimental site in northern Sweden (64°07' N, 19°27' E). Trees from a control plot and a plot that had been irrigated and fertilized since 1987 were used. The shoot CO_2 exchange was monitored by means of an automatic gas exchange system for semi-continuous measurements consisting of 36 temperature-controlled shoot cuvettes. The measurements were made on one- to three-year-old shoots in the fifth whorl on three trees per plot.

Results from the measurements are compared with modeling results on the seasonal course of photosynthesis, focussing on the post-winter recovery.

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POSTER LOCATOR NO. 26

Soil CO_2 Efflux and Root Respiration in a Boreal Forest: Seasonal and Diurnal Variation

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Soil carbon dioxide (CO_2) efflux, consisting of belowground autotrophic and heterotrophic respiration, is an important component of the carbon cycle in boreal forests. To develop accurate carbon budgets for forest ecosystems, precise estimates of the relative contributions of root and heterotrophic respiration in relation to site characteristics are required.

In three stands of different age and species composition at the Norunda research site (60°05'N 17°30'E), soil CO_2 efflux and fine-root (< 5 mm) respiration were measured with a closed dynamic system (Li-6200) on five occasions from May to October in 1999, both day and night. Climatic variables such as soil and root temperature, soil moisture, and soil CO_2 concentration were monitored, and respiration of excised roots was measured at ambient root temperature and soil CO_2 partial pressure. The roots were later analyzed for nitrogen content. Root density data from soil cores taken in September 1998 were used to estimate fine-root respiration per square metre. Coarse-root respiration was estimated from stand data, literature data, and allometric relationships.

Both soil CO_2 efflux and fine-root respiration differed significantly between the sites ($P < 0.01$). There was no diurnal variation in soil CO_2 efflux or in root respiration. Soil CO_2 efflux ranged from 2.8 to 7.5 μmol m^{-2} s^{-1} and was only correlated to soil temperature. Similarly, fine-root respiration was only correlated to root temperature and ranged from 0.2 to 2.5 μmol m^{-2} s^{-1} (0.4 to 3.4 nmol g^{-1} s^{-1}), with the highest rates in July. Soil CO_2 partial pressure ranged between 668 to 1263 ppm. Even though fine-root respiration was affected by CO_2 partial pressure, the correlation was most probably concealed by an increase in growth respiration at times of high soil CO_2 concentration. The variation in root nitrogen content between sites and time of year was not large enough to cause any significant effect on fine-root respiration. The percentage of total respiration originating from roots was 50% in May (47% from fine roots), thereafter decreasing to 15% in October (9% from fine roots). Considering that fine-root respiration was twice as sensitive to changes in temperature than was bulk soil CO_2 efflux, the seasonal variation in root respiration would be enough to cause a seasonal variation in the temperature response of soil CO_2 efflux.

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Classification and Discrimination of Landscape Features with JERS-1 SAR: Preliminary Results from the Global Boreal Forest Mapping Project

Cynthia L. Williams[1], Kyle McDonald[2], and Bruce Chapman[2]

Ecologists have used Synthetic Aperture Radar (SAR) imagery at boreal sites in Alaska and Canada to classify forest types and successional stages, to estimate vegetation biomass, to estimate regrowth after logging and wildfires, and to detect seasonal patterns of inundation. These results, coupled with the capacity of SAR to image through cloud cover, its moderate resolution (8 to 100 m), its ability to penetrate vegetation canopies and to image vegetation structure, suggest that SAR will make an important contribution to on-going monitoring and modeling of carbon budgets.

We are now assembling 100 m resolution winter and summer SAR mosaics of North American boreal forests as one node of the Global Boreal Forest Mapping Project. We are using L-band HH-polarization imagery collected primarily from 1997 to 1998 by the Japanese Earth Resources Satellite (JERS-1). Within Alaska and Canada we will also be assembling a number of multi-temporal regional and local mosaics. These mosaics and our derived products will contribute to the on-going forest monitoring efforts of the Committee on Earth Observation Satellites (CEOS) Global Observations of Forest Cover (GOFC) program.

Our preliminary classifications and image interpretations demonstrate that the imagery provides baseline information about the distribution and extent of woodlands, inundation, seasonal and perennial wetland distribution, arctic and alpine treelines, and short-term landscape changes driven by fire, flooding, forest pathogens, and permafrost. We distinguished up to five biomass classes; over 80% of the land area of our interior Alaskan sites falls below JERS-1 sensor saturation. Specific structural classes, such as those in GOFC protocols in remote sensing based classifications and in ecologically based classifications, are distinguishable with this imagery. We expect that the specific applicability of the JERS-1 imagery and that of future sensors (especially ALOS) to modeling of carbon fluxes in boreal ecosystems will be through the estimation of biomass, burning, regrowth, inundation, soil exposure, and growing season length. The challenge for widespread use of the entire mosaics is to determine the generality of classification methods and predictive algorithms. We are now testing the generality of algorithms designed to distinguish physiographic regions, structural classes, biomass, inundation, wetlands, and wetland origins.

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Spatial and Temporal Characteristics of Historic Fire Weather and Fire Danger in Canada

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Forest fires are an important disturbance in Canadian forests, burning an average of approximately 3 million hectares annually, and as such also exert a major influence on the forest's carbon sink/source strength. Climate change projections from General Circulation Models (GCMs) and Regional Climate Models (RCMs) suggest a strong increase in the frequency and severity of weather conditions conducive to forest fires across much of Canada. This translates directly into increased fire activity, shortened fire return intervals, a shift in forest age class distribution, and a decrease in biosphere carbon storage. In this work we investigated historical fire danger trends for indications that fire severity increases projected from GCMs and RCMs might already be observable; annual area burned by wildfire has increased in some regions of Canada in recent decades. The Canadian Forest Fire Danger Rating System (CFFDRS) is a set of fire weather indices that are based on daily weather observations (noon air temperature, 24-hour precipitation, relative humidity, and wind speed) designed to serve as indicators of wildfire occurrence and behavior. We studied the spatial and temporal variability of the daily fire weather and danger observed over a 43 year period (1953 to 1995) at 65 Atmospheric Environment Service hourly synoptic meteorological stations located across Canada, for evidence of trends in the frequency and/or magnitude of severe fire weather events.

Using the CFFDRS we developed yearly outputs for a number of basic indicators of fire danger as well as frequencies of passing critical fire severity thresholds. The parameters studied, which were compared individually at each station, and then spatially across Canada, were: basic seasonal weather means and 90th percentile levels; fire season start dates; seasonal and monthly means and 90th percentile levels of CFFDRS moisture codes and the daily severity ratings; frequency of exceeding each station's 90th percentile level in daily severity rating; frequency of exceeding various fuel moisture levels necessary for vigorous spread; and frequency of exceeding a number of fire behavior thresholds (fire intensity, crown fraction burned, etc) in 2 standard boreal fuel types.

Significant trends, both positive and negative, were observed in a number of variables at individual stations, and these trends were examined across the country for their spatial consistency. Basic comparisons of means and 90th percentiles lacked strong significant spatial consistency. The frequency of exceeding critical fire spread thresholds such as levels of fine fuel moisture seemed to be consistently increasing across the entire boreal region of Canada.

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Reforestation Influence on a Boreal Soil System in the Russian Forest Zone

E.Y. Yakimenko[1]

To understand soil dynamics under forest vegetation, several forest ecosystems of different age, type, and history of prior treatment were studied in the Russian forest zone. All forest ecosystems studied were secondary successions on arable lands or natural regeneration after felling. The forest sites did not undergo any treatment. Soil changes in time depended on whether the forest appeared on arable land or was renewed just after felling

Soil evolution of naturally reforested sites was studied in Fir-Spruce (*Abies-Picea* spp.) forests of 50, 100, 150, 180, 250, and 300 years of age in the Middle Ural region of Russia. The oldest forest ecosystem stored the highest amount of organic carbon (about 80 t C ha^{-1}) in the soil profile, compared to the others (no more than 65 t C ha^{-1}).

Reforestation of cultivated lands in Moscow and St. Petersburg provinces caused rapid changes in soil properties, including carbon content; it favored the development of podzolic features obliterated during cultivation of this area, in the first 80 to 90 years of afforestation. Forest establishment increased the spatial variability of carbon and nutrient contents in the upper soil horizon, and changed their prior gradual profile distribution to a sharp decrease down the soil profile. Large aggregate fractions (>1 mm) contributed the most significant input into total organic carbon content in the A1-horizon of the forest soil, while 0.25 to 1 mm aggregate fractions contributed most to the E-horizon. Examination of secondary birch (*Betula* spp.), oak (*Quercus* spp.), and pine (*Pinus* spp.) woodlands within the Moscow and St. Petersburg regions revealed that rates of soil change under forest establishment and development depended on the forest type and level of prior soil cultivation.

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THEME 3

Forestry Practices for Carbon Management

Managing Forests for Carbon: An Industry Perspective

George Weyerhaeuser Jr.[1]

Forward thinking forest product firms should begin now to understand their carbon stocks and mitigate their emissions. Most of their choices today are straight forward even in the absence of a definitive international protocol. Firms focused on improving their energy efficiency or maximizing the utilization of their forest harvest are not going to find that their decisions are radically altered by carbon considerations. Their mitigations today can be guided by assumptions about the characteristics of an ideal future framework.

In the end, we are concerned about carbon dioxide accumulation in the atmosphere; any sound framework will motivate decision makers to minimize the life cycle contributions of their activity to the net carbon flux. The cost to society will be minimized if the global protocol is flexible enough to always encourage the cheapest mitigation. Forest products firms can prudently anticipate a large market for certified tradable offsets. Depending on the frame of reference finally agreed to, commercial boreal forest activities may be reported as a net source or sink. Either way, firms should be ready to consider trading off the carbon impacts of their forestry *versus* the larger market. The market price will stimulate them to maximize forest regrowth through practices such as early regeneration and careful stocking control. There will be incentives to minimize forest waste while still maintaining soil productivity. Pest and fire management will be even more valuable practices than today.

Until the world settles on the accounting protocol for forest commodity exports and long lived forest products in a country's stock, some forestry activities will have uncertain incentives. We will not know how to set the optimum economic rotation age for the boreal forest until we know both the market price for offsets and the life cycle impacts of our customers' alternative products. There may be incentives to fertilize and shorten our rotations if our customers' storage of our products are taken into account or if their other choices of materials have even higher costs.

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Impact of Forest Management and Climate Change on the Forest Sector Carbon Budget in the Nordic Countries

Timo Karjalainen[1], Gert-Jan Nabuurs[1,2], Ari Pussinen[1], Jari Liski[1], Markus Erhard[3], and Frits Mohren[4]

A European Union funded project "Long-term regional effects of climate change on European forests: impact assessment and consequences for carbon budgets" (LTEEF-II) is investigating the impacts of climate change on the long-term growth and development of European forests. The main focus in this project is on carbon fluxes between the forests and the atmosphere, and on the long-term carbon budget of the forest sector.

In the LTEEF-II project, regional impacts of climate change on forest growth are assessed using process-based models. These responses are then scaled up to the country and continental level using national forest inventory data in a large-scale scenario model EFISCEN (European Forest Information Scenario Model).

This assessment covers 49.1 million hectares of forests in Finland, Sweden, and Norway, about 48% of the total land area in these countries. Forests in these countries are regularly managed, and forest fires are less common than in Canada or Russia. Two forest management scenarios were applied: a business as usual scenario, which assumes continuation of early 1990s harvesting levels; and a multi-functional scenario, which assumes that the current trend toward more nature-oriented forest management will continue in the future. With this latter scenario, we assessed whether the predicted rise in harvesting levels of around 0.5 to 1% per year can be sustained in the future. Both forest management scenarios have been run under the current climate conditions and under changing climatic conditions. We assessed the carbon pool dynamics in tree biomass, soil and wood products between 1990 and 2050.

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Potential and Economic Efficiency of Carbon Sequestration by Changing Management Practices in a Boreal Forest*

Hans Fredrik Hoen[1] and Birger Solberg[1]

The potential and the economic efficiency of carbon sequestration by changing forest management practices were studied for a boreal region consisting of 695,000 ha of productive forests. The analysis was based on data from the National Forest Inventory sample-plots in Norway. Economically optimal timber management scenarios with a time horizon of 30 years were calculated and production possibilities frontiers of commercial timber and carbon sequestration were investigated.

Compared with previous studies, the analysis was based on a far more detailed representation of the forest data, more realistic modeling of regeneration and natural mortality, and a sensitivity analysis of the effects of an increase in natural mortality for old, dense stands. The analyses also provided results with the flow of carbon dioxide (CO_2) out of and into the atmosphere valued by a price derived from the 'carbon-tax' on fossil fuels in Norway, which were included in the cashflow of each timber management schedule.

The results confirm earlier findings that in boreal forests a considerable increase in carbon sequestration can be achieved by changing forest management practices. Furthermore, the more detailed data and assumptions for timber management and especially for regeneration applied in this study gave considerably higher differences in carbon sequestration between an alternative which maximizes the economic return and an alternative which maximizes the net carbon sequestration discounted over time. Given the price-level for sequestering and emitting CO_2 equal to the 'carbon-tax' on fossil fuels in Norway, the solutions with both timber and the CO_2-flow valued in monetary terms were quite close to the solutions when CO_2 only was optimized.

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Effects of Management on Carbon Pools in Swedish Forests During the 21st Century

Hillevi M. Eriksson[1], Anders Lundström[2], and Tomas Thuresson[3]

Changes in carbon (C) pools in forest biomass and soils 10, 50, and 100 years into the future were estimated under three forest management scenarios: "Present trends", "More bioenergy" and "Higher ambitions" for four Swedish regions. The scenarios vary in the extension of measures to preserve biodiversity, silvicultural methods, and in levels of tree harvesting and resulting tree growth and tree species distribution.

Stand growth was calculated using the Hugin model. The effect on the carbon pool of the soil from harvesting stems and branches, and not only stems, was estimated using the q model. Conclusions from a literature review contributed to the basis for the calculations. For example, an addition of 150 kg of nitrogen fertilizer will cause an increase of 1.3 t C ha^{-1} in the topsoil within 10 years. Harrowing reduces the carbon pool of the topsoil by an average of 9% within 15 years. In relation to non-treated areas, these effects will fade with time unless the measure is repeated. Scots pine (*Pinus sylvestris*) store on average 2.5 t C ha^{-1} less in the humus layer than other common tree species.

For all scenarios, the increase in the carbon pool of the forest biomass will continue during almost all of the 21st century, however at a decreasing rate. The calculated net effect of silvicultural measures applied in the scenarios is a reduction in the carbon pool of the soils at various degrees.

Scenarios with high intensity harvesting will induce smaller carbon pools than scenarios with less intensive harvesting. However, decreased emissions due to fossil fuel replacement with wood fuels are potentially, but not necessarily, larger in the former scenarios. The longer the time perspective of the study, the more important is the bioenergy potential compared to the potential for carbon pool changes.

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Organic Matter, Carbon, and Nutrient Changes after Whole Tree and Conventional Harvesting on Boreal White Birch Sites of Different Quality in Newfoundland, Canada

B.A. Roberts[1] and K.W. Deering[2]

Whole-tree harvesting (WTH) and conventional stem-only harvesting (STO) of white birch (*Betula papyrifera*) on a range of soil and site conditions were compared in 9 stands at 3 sites. This study examined litter, organic matter, and carbon production, and changes in nutrient concentrations in soil solution pre-harvest, and 3 and 6 years post-harvest.

Pre-harvest litter production ranged from 1.25 t ha^{-1} to 5.75 t ha^{-1} dry matter, but averaged 2.0 to 2.4 t ha^{-1}. Litter depth significantly decreased ($p = 0.05$) 3 years post-harvest at all sites and treatments with the exception of one WTH treatment. Total forest floor depth significantly decreased ($p = 0.05$) at all sites in the STO treatment, but decreased only at one site in the WTH treatment.

The change in nutrients in the forest floor 3 and 6 years post-harvest was variable, but there was a significant decrease ($p = 0.05$) in available calcium in both treatments (WTH & STO) at the two least productive sites. Post-harvest leachate nutrient concentrations were related to physical disturbance and increased post-harvest residue. STO on the richest site resulted in the highest leachate ammonium concentrations, but nitrate concentrations were decreased. Phosphorous concentrations were not greatly affected by harvesting, but potassium and calcium concentrations were elevated for four to five years. Losses of nutrients in biomass were proportionally greater with WTH, as tree components with higher concentrations (branches and foliage) were removed. WTH led to a 19% increase in biomass removal as compared to STO harvest, and an increase in nutrient removals of 127% for nitrogen, 138% for phosphorous, 151% for potassium, 72% for calcium, and 90% for magnesium. STO removed nitrogen (126 kg ha^{-1}), phosphorous (9 kg ha^{-1}), potassium (51 kg ha^{-1}), calcium (126 kg ha^{-1}), and magnesium (23 kg ha^{-1}) in the harvested biomass.

Nutrient losses in leachate solution below the B-horizon (50 cm) in the first 3 years post-harvest were generally greater following STO harvesting than WTH. This can be attributed to increased leaching from the slash and the retardation of successional vegetation acting as a nutrient sink. Leaching losses 3 years post-harvest were small compared to losses in biomass. Aspects of the slash dynamics and their role in the organic matter cycle will be discussed.

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Effects of Silvicultural Treatments on Carbon Stores in Forest Stands

Mark E. Harmon[1]

This study uses a new model, STANDCARB, to examine the effects of silvicultural treatments on the dynamics of living, detrital, and forest product carbon pools of forest stands. The model simulates the accumulation of carbon over succession in mixed species, mixed aged forest stands and is currently parameterized for the Pacific Northwest of the United States.

Simulation experiments, with 5 replicates of each treatment, were used to investigate the effects of initial conditions, tree establishment rates, rotation length, tree utilization level, site preparation, and partial cutting on total and forest product carbon stores. Simulations were run until carbon stores reached a carbon steady-state for a uniform age-class distribution at the landscape level and were then rescaled relative to the maximum amount of carbon stored in a landscape comprised only of old-growth forests (>200 years old).

Our simulation experiments indicated that agricultural fields stored the least (15% of the maximum) and forests protected from fire stored the greatest (93% of the maximum) amount of carbon on the landscape level. Conversion of old-growth forests to any other management system or disturbance regime resulted in a net loss of carbon to the atmosphere, whereas conversion of agricultural systems to any type of forest system had the opposite effect. The three factors, in order of importance, that appeared to be most crucial in developing an optimum silvicultural system for storing carbon were: 1) rotation length; 2) amount of live mass harvested; and 3) amount of detritus removed by site preparation. Carbon stores increased with rotation length, but decreased as the fraction of trees harvested and detritus removed increased. Our simulation experiments indicate that some non-traditional silvicultural systems, such as partial harvest, with minimum use of site preparation fires, may provide as much timber harvest as traditional systems. They also appear to increase carbon stores far above the level that can be maintained in a traditional system (65 to 79% of the maximum *versus* 31%). This study therefore suggests that an adequate supply of wood products may not be incompatible with a silvicultural system that maximizes carbon stores.

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Strategies in Swedish Forestry for Reducing Net CO_2 Emissions

Mats Olsson [1]

In Sweden, where 52% or approximately 23 M ha of the land area is forest, and with the second largest forestland area per capita in Europe, forest management plays a profound role in reducing net greenhouse-gas emissions. Forestland in Sweden is presently a substantial sink for carbon dioxide (CO_2) with an annually increasing amount of carbon sequestered in both biomass and soils. The total stock of carbon in total tree biomass amounts to approximately 1000 Mt. Growth exceeds harvests and the annual growth of the carbon stock is in the range 6 to 9.5 Mt yr^{-1}. Factors that govern growth and carbon sequestration are effective management and atmospheric nitrogen deposition. However, the annually increasing carbon stock in forest biomass is considered to be vulnerable.

The main proposed strategy for reduction of net emissions of greenhouse gases is: 1) a more intensive use of woody biomass and harvest residues for fossil fuel substitution; and 2) soil carbon conservation and sequestration. The supply of harvest residues may increase following climate change and following intensified forestry with optimized fertilization. Afforestation with short-rotation species for biomass fuel production may also contribute to reducing net emissions. In addition, mitigation of scarification may decrease losses of soil carbon. In total, substitution and soil carbon conservation and sequestration can reduce net emissions in Sweden by approximately 12 to 24 M t C yr^{-1}, representing 75 to 150% of present emissions from fossil fuels. However, the total reduction might amount to 130 to 225% of present emissions if, in addition, the carbon sequestration in forest biomass is included in the estimates. Special precaution is needed to minimize emissions of CO_2 and nitrous oxide (N_2O) from the high proportion of wet and fertile forestland in Sweden. The emission of CO_2 from drained wet forestland is estimated to 2.5 M t C yr^{-1}, whereas the amount of N_2O emission is unknown, but suspected to be high and increases following nitrogen deposition and fertilization.

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Managing Terrestrial Ecosystems to Offset Rising Atmospheric CO_2: A Feasibility Analysis of Reforestation and Restoration Options

Thomas W. Steele[1] and Stith T. Gower[2]

Atmospheric carbon dioxide (CO_2) concentrations are predicted to increase dramatically over the next fifty years. If this unprecedented increase is realized, the ecological, economic, and social systems of boreal regions and the world may be greatly affected. Numerous mitigation strategies have been proposed, however initiatives to mitigate CO_2 emissions have been hampered by a lack of information on their efficacy and cost effectiveness. In this study we evaluated the ecological and economic feasibility of reforestation and restoration of fallow land as a means to offset rising CO_2 concentrations. Specifically, we quantified the amount of carbon sequestered and the associated costs of five mitigation alternatives: red pine (*Pinus resinosa*) reforestation with and without subsequent timber management; pine (*Pinus* spp.) barrens restoration; prairie restoration; and oak (*Quercus* spp.) savanna restoration. Carbon sequestration and timber volume estimates were generated for a 150-year time horizon using ecosystem process and forest growth and yield models for two contrasting sites in Wisconsin, United States. Average sequestration costs were calculated by dividing the net present value of the management alternative by the amount of carbon sequestered.

Carbon sequestration rates differed between and among the management alternatives. Reforestation practices sequestered considerably more total carbon (C_T) than barrens, prairie, or savanna restoration over the 150 year period (82 to 184 t C_T ha^{-1} versus 36 to 61 t C_T ha^{-1}, respectively). Intensive timber management increased C_T sequestration by 69 to 84% over the no-management option. Sequestration costs ranged from 4 to 8 US$ t^{-1} for the reforestation practices to 14 to 40 US$ t^{-1} for the restoration alternatives. The larger sequestration costs for non-forested ecosystems were directly due to the lack of timber revenue to offset establishment costs. However, C_T sequestration costs associated with reforestation must be interpreted cautiously as they make implicit assumptions regarding the ultimate fate and mean residence time of carbon stored in forest biomass. Soil carbon (C_S) may provide a more accurate measure of the long-term efficacy of sequestration strategies. When C_S is considered, restoration options substantially outperformed reforestation alternatives, sequestering 4 to 10 times more carbon at 12 to 40% of the cost.

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Comparison of Emissions from Forest Operations in Finland and Sweden

S. Berg[1] and T. Karjalainen[2]

The authors of this study have published studies of environmental loads from forest operations in Sweden and Finland. They compared findings regarding emissions from logging operations, transport of timber to industry, and from some silvicultural activities. The proportion of volumes harvested in thinning and final felling was similar in both countries. There were resemblances concerning machine types used in logging and also regarding methods used for soil preparation and stand treatment. Terrain difficulty was different and also the level of mechanization in thinning.

We recognized differences between countries in carbon dioxide (CO_2), carbon monoxide (CO), and NO_x emissions. These were attributed to the actual variations in operations and technologies, and to the quality of fuel used. It was also clear that some of the variation observed was due to the origin of data as well as methods used in collecting data. This illustrates the importance of being confident about the origin and quality of data. In forest operations usually two types of data are available; these are either time study data or data from follow-up of routines. Our study revealed that the unreflected use of data from varying origin might cause mistakes in calculating energy consumption.

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Poster Locator No. 6

Increasing the Productivity of Forests: Nitrogen Fertilizer and its Echo Effect on Biomass Growth

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To improve the carbon budget of forest ecosystems, there must be an increase in the productivity. This can be gained through an increase in the efficiency of carbon dioxide (CO_2) cycling, solar energy, or other resources that influence photosynthesis—a complex set of factors that influence the productivity of forest components and the forest ecosystem as a whole. One method of increasing the productivity of forest stands is the use of fertilizers. Fertilizer application must be optimized to provide the greatest possible increase in wood production with the minimum possible expense.

To study this, the effects of different amounts of nitrogen fertilizer (Carbamid) on even-age pine stands were examined (*Pinus silvestris*, 15 to 90 years old, lichen and green-moss forest floor). The stands (11 permanent sample plots) were located in two study areas in the Middle Priangarye (Siberia, 55°15'N 101°30'E and 57°20'N 96°45'E).

An analysis of the long-term dynamics of radial growth revealed an "echo effect" associated with the nitrogen fertilizer application. Large amounts of fertilizer increased the biomass of trees in the first three years, followed by a second peak of growth 7 to 8 years later. Results showed a 1.8 to 2.2-fold increase in biomass in forest stands 2 to 3 years following fertilization and a 1.2 to 1.5-fold increase in biomass 7 to 8 years after this first peak. With this "echo effect" a single application of nitrogen fertilizer in Siberian pine stands will result in a steady increase in biomass increment (radial growth) for up to 10 years.

A mathematical model describing the dependence of increment change on fertilizer dose that takes into account this "echo-effect" was developed. The model represents the integral equation that describes the biomass response M(t) at time t to fertilizers applied as a dose $D(t-\tau)$ at the time $(t-\tau)$:b

$$M(t) = \int A \tau \exp(-\alpha\tau) D(t-\tau)d\tau + B M(t-\theta) \exp(-\beta t)$$

where A, α, B, and β are coefficients and θ is the characteristic delay time. The first term in the right hand side of the equation describes direct influence of fertilizers, and the second term the "echo effect" which depends on the tree's response $M(t-\theta)$ at the time $(t-\theta)$. The exponential damping factor $\exp(-\beta t)$ characterizes the loss of mineral matter after several cycles of use by the tree.

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Interaction of Vegetation and Human Controls over Fire Regime in the Alaskan Boreal Forest

F. Stuart Chapin, III[1], Marie Louise Gotholdt[1], Scott Rupp[2], Erika Zavaleta[3], Roz Naylor[4], Anthony M. Starfield[2], David McGuire[5], and David Verbyla[6]

In the Alaskan boreal forest, human activities account for 80 to 90% of the ignitions, but only 10 to 20% of the area burned. The annual area burned is governed primarily by climate. It is broadly distributed through interior Alaska, and most area burned is concentrated in a few hot dry years. Therefore, climatic warming may affect fire regime as much through changes in variance as through changes in mean summer temperature. Fire ignition is concentrated close to roads and river transportation corridors, but exhibits an interaction between climate and population density. Fire control effort is governed more strongly by number of ignitions than by fire size and therefore responds to both population density and climate. Fire-control priorities are established by landowners rather than by control agencies, and are therefore sensitive to the opinions of landowners about the costs and benefits of fire.

A simple model of fire policy showed that fire suppression activity is sensitive to both climate and changing socio-economic conditions. Model simulations of vegetation changes suggest that there would be substantial cost to fire suppression that would significantly reduce the warming-induced increase in fire frequency. The switch to less flammable early successional vegetation resulting from increased fire frequency would have greater impact than fire suppression in minimizing the warming-induced increase in area burned. Three distinct communities (native villages, dispersed homesteads along road networks, and urban communities) differ in the economic impacts, in the ecosystem services that they derive from fire regimes, and in their influence on fire policy. We discuss the implications of these scenarios for regional carbon storage.

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Soil CO_2 Fluxes and Temperatures of Harvested and Fire-origin Sites in Boreal Black Spruce Ecosystems

Marie R. Coyea[1], Alison Munson[1], Ken Smith[2], Hank Margolis[1], and Raynald Paquin[3]

Soil carbon dioxide (CO_2) respiration is an index of the metabolic activities of roots, mycorrhizae, decomposers, and other soil organisms, and it can contribute substantially to a general understanding of the turnover rates that characterize and regulate an ecosystem. Management practices can have significant effects on the magnitude of soil CO_2 flux, although neither the nature of the effects nor changes with stand age are well understood.

To better understand the effects of fire and harvesting on soil nutrients and carbon, the diurnal and seasonal variations of soil surface CO_2 fluxes were compared among a recently burned site, an old burned site (mature stand), and a recently cut-with-protection-of-regeneration-and-soils (CPRS) harvested site near Chibougamau, Quebec (50°N 72°W).

Diurnal soil CO_2 respiration rates were higher at the old fire-origin site than recently disturbed sites for periods that were sampled. Fluxes of soil surface CO_2 were generally higher on the uncompacted areas than the compacted harvest trails of the recently harvested site. Diurnal soil CO_2 respiration rates responded positively to soil temperature.

Complementary microclimate data were also obtained on these three site types as well as on an old harvested site. Average 1998 to 1999 organic and mineral soil (10 cm depth) temperatures increased in the following order: old harvested site, old burned site, recently burned site, and a recently harvested CPRS site. Spring thaw in the mineral soil was approximately 15 days later at the old harvested site compared to the old burned site. Spring thaw was approximately 25 days earlier at the recently disturbed sites (burned or harvested) than at the old harvested site.

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POSTER LOCATOR NO. 60

Nitrogen Constraints on Carbon Accumulation by a Jack Pine Stand

N.W. Foster[1] and I.K. Morrison[1]

Aboveground carbon accumulation in a semi-mature fire-origin jack pine (*Pinus banksiana*) stand in northeastern Ontario was examined for thirty years after fertilization. Nitrogen (N) was applied at five levels (0, 56, 112, 224, and 448 kg N ha^{-1}) in a Latin-square design in May 1970. Net stand biomass was estimated at five year intervals from local biomass equations and tree diameters, heights, and density. Year-to-year growth response was quantified by comparing pre- and post-treatment diameter-at-breast-height increments on five trees per plot.

Results were interpreted with respect to ecosystem carbon and nitrogen pools and fluxes. Possible phosphorus, potassium, calcium, and magnesium limitations to carbon accumulation by jack pine were assessed in the same stand by examining short-term (10 year) response to additions of each nutrient alone or in combination with each other and nitrogen.

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Effectiveness of Fuels Management at Reducing Carbon Loss from Wildfires

K. Hirsch[1], V. Kafka[1], B. Todd[1], and B. Amiro[1]

Wildfires are a significant natural disturbance in most of Canada's forest ecosystems and play an important role in the carbon budget. Within Canada's managed forest there is an opportunity to reduce wildfire size and potential carbon loss by incorporating fuels management (e.g., fuel reduction and fuel conversion) into forest management activities. In this study the impact of strategically located fuels treatments on wildfire size and carbon loss in a 200,000 ha area in central Alberta was assessed.

A set of almost 100 wildfires was independently simulated on both the existing land base and a "fire-smart" land base that was developed in consultation with forest managers. Ignitions points were determined using a systematic grid, and fire spread was modeled using a cellular propagation, hourly time-step fire growth model. Inputs consisted of a 100 m by 100 m fuels grid and a constant set of extreme fire weather conditions derived from an analysis of historic fire occurrence and fire weather data. Selected fire behavior characteristics (e.g., fire size, fire intensity, surface fuel consumption, crown fraction burned) were calculated for each simulated wildfire based on the Canadian Forest Fire Behaviour Prediction System, and this information was used to estimate carbon loss.

The results suggest that fuels management targeted at spatially critical locations on the landscape could cause a major change in the distribution of large wildfires and therefore reduce the overall burn rate of the area. Application of fire-smart forest management strategies in Canada's industrial forest could help determine whether Canadian forests are a carbon sink or source.

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Effects of Logging Activity on Components of the Carbon Budget in a Canadian Jack Pine (*Pinus banksiana*) Forest

Erica A. Howard[1,2], Stith T. Gower[1], and Jonathan A. Foley[2]

Logging is growing in importance as an agent of disturbance in the world's boreal forests. The extent of timber harvest is increasing in central Canada's boreal zone in response to a higher demand for pulpwood. This demand has implications for changing local ecosystem dynamics from the natural disturbance regime, which is dominated by fire and insects.

We are entering the second year of this two-year study, and will attempt to extend results of previous studies examining carbon cycling in central Saskatchewan, Canada, to include the effects of logging. We have established a chronosequence of four previously clearcut jack pine sites in the area encompassed by the BOReal Ecosystem-Atmosphere Study (BOREAS) Southern Study Area, including the BOREAS Southern Young Jack Pine (SYJP) site. The BOREAS Southern Old Jack Pine (SOJP) site, a 72 to 77-year-old mature stand of wildfire origin, has been included as a fifth site as an example of pre-harvest conditions. Preliminary results from data collected in May through October 1999 will highlight differences among sites in surface carbon dioxide (CO_2) efflux, above- and belowground biomass, coarse woody debris, soil and air temperatures, and soil moisture. We will also compare some of the results to data collected from SOJP and SYJP during the BOREAS field campaigns of 1994 to 1996.

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The Carbon Cycle of the *Larix gmelinii* Forest Ecosystem and the Impact of Management Practices in the Great Khingan Mountains

Yanling Jiang[1] and Guangsheng Zhou[1]

The *Larix gmelinii* (larch) forest in the Great Khingan Mountains at the northeastern edge of China is a major component of the world boreal forests. It dominates about 15.6×10^6 ha and comprises 13.2% of the total forested area in China. It provides about US$ 4700 million or 4% of the gross annual forest ecosystem services of China. It is uncertain if this boreal forest is an atmospheric sink or source of carbon (C). To better understand its global role, the carbon cycle of the Chinese boreal forest and the effect of different management practices and climate change conditions on it were examined using the CENTURY model.

Results indicate that the *Larix gmelinii* forest served as a net carbon sink, sequestering about 2 t C ha^{-1} yr^{-1}. Climatic change and a doubling of carbon dioxide increased its net primary production and produced a net carbon sink even when ecosystem respiration was taken into account. Different forestry management practices produced different impacts on the forest carbon sink capacity. Low harvest levels were favorable for growth and regeneration. Fire had a severe impact on the forest, but a light surface-burn fire was beneficial for regeneration and stimulating the forest carbon cycle. Accumulated forest litter improved the growth of the established forest, but was unfavorable for regeneration and increased the potential and severity of wildfire.

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Carbon Budget of Pine Stands in the Middle Zavolgie, Russia

Eldar Kurbanov[1]

The rapid increase in atmospheric carbon dioxide (CO_2) concentration since the industrial revolution continues to cause concern about long-term global climate change. Pine (*Pinus sylvestris*) forests of Middle Zavolgie are large reservoirs of carbon (C), and occupy an important position among Russian forests in the global carbon cycle. The Middle Zavolgie is located in the eastern part of the Russian plain where it occupies 28.7 Mha. Under the Russian Federation Economy Republic classification scheme, this region was subsumed to the Volgo-Vyatski and Povolzskij economic regions. Administrative units in this territory are the Republics of Mari El and Tatarstan, and the Nizegorodskaya and Kirovskaya Oblasts.

The aim of this study was to estimate the carbon budget for pine biomass at the stand level in Middle Zavolgie of Russia. The assessment was based on carbon sequestration. This approach considered the remaining amount of carbon in vegetation, litter, and soil organic matter (SOM) after carbon released from respiration and decay processes has been taken into account. Sample plots were established in normal (full stocked) and modal (managed) pine stands of medium to high productivity within a relatively homogeneous area. Pine stands were selected to represent the full range of stand age groups, tree species composition, and structure typically occurring in these ecosystems.

The total carbon budget during a 120 year period for the I site modal pine stands was 160 Mg C ha^{-1}, which consisted of carbon storage in vegetation (107 Mg C ha^{-1}), litter (28 Mg C ha^{-1}), and SOM (28 Mg C ha^{-1}). The largest total carbon storage (254 Mg C ha^{-1}) occurred in normal pine stands at the first site.

The total regional carbon budget of the pine forests was 128.4 Tg C. Kirovskaya Oblast contains the largest proportion of this total carbon storage in Middle Zavolgie (70 Tg C), while Tatarstan has only 5.2 Tg C. Pine stands of Nizegorodskaya Oblast and Republic Mari El have 37.4 Tg C and 15.8 Tg C of stored carbon, respectively.

These stand level analyses form the basis for further methods of regional assessment. Research results demonstrated that the effectiveness of forest management as a driving force for reducing net carbon emissions to the atmosphere largely depends on the site, age, and basal area of the stand, and the efficiency with which the forest harvest is used.

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The Role of Thinning Operations in Carbon Management

Evgeny N. Kuznetsov[1]

The effect of thinning operations on total productivity was examined by comparing long-term observations from natural and thinned stands. Experimental plots were established from 1928 to 1933 at the experimental forest station Siverskaya of the St. Petersburg Forest Research Institute (70 km south of St. Petersburg) in the south taiga zone. Various levels of thinning were implemented in several forest stands, with some natural stands retained as control plots. Measurements were taken every five years for 65 to 70 years on the main stand characteristics and other components of the forest ecosystem. The plots were established in enough high productivity sites, in the *Piceetum Oxalidosum* and *Piceetum Myrtillosum* forest types. Six series of permanent plots (a total of 14 plots) were analyzed. Five plots were natural stands retained as control plots. Measurements of the following parameters were carried out in the stands every five years: mean diameter, mean and highest height, growing stock, basal area, mean increment, mortality, stand density, and total productivity. The herb cover and composition of herbs and mosses species, upper soil layers, and undergrowth were also studied.

At high productivity sites, there was a 1 to 3-class increase in site index during stand development. This increase was not taken into account in growth tables and prognosis of stand growth, which led to errors in forecasting stand productivity. Growth increments were variable over time. Thinning initially increased the amplitude of variability, and then growth increment decreased until the next thinning. This characteristic change is evidence of the resilience and self-regulatory nature of forest ecosystems. Peak growth increments in pure spruce (*Picea* spp.) stands occurred at 50 to 60 years of age. On thinned plots, the maximum increment during this period was greater in absolute terms than on the control plots. In mature stands, there was an observed increase in annual growth increment in growing stock at 90 to 100 years of age, and it is possible that changed climatic conditions (greenhouse effect) led to this increased growth increment.

Stand density did not affect total productivity. The total productivity on the permanent plots was 1019, 1040, and 1162 $m^3 ha^{-1}$, for 457, 298, and 198 trees per hectare, respectively. At maturity, stands consisted of 90 to 95% of trees, which at 40 to 45 years of age had a relative diameter close to or greater than the mean. Those trees that lagged in growth were, as a rule, the ones that died. Thinning permitted an almost complete elimination of mortality.

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Effects of Thinning on Canopy Transpiration and Photosynthesis in a Boreal Forest: Model Application and Measurements

Harry Lankreijer[1], Fredrik Lagergren[2], Ann-Sofie Morén[2], and Anders Lindroth[1]

This study analyzed how stand thinning affected canopy transpiration and carbon uptake in a boreal forest. The thinning experiment was performed in a 50-year-old mixed Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) forest near Uppsala in central Sweden. Sap flow was measured on 30 trees on two plots in 1998. One plot was then thinned in November 1998, reducing basal area by 25%. Measurements continued through 1999 on both the thinned and un-thinned stands. Tree position, stem diameter, tree height, crown length, crown diameter, and leaf area index for all trees was used as input in the MAESTRA-model. Leaf area index was obtained from an extensive destructive tree sampling in an adjacent stand. MEASTRA is an array-based model, estimating radiation absorption, photosynthesis, and transpiration by individual trees in a stand. Gas exchange measurements at the branch level were used to parameterize the model.

The two measurement years, 1998 and 1999, had contrasting weather; 1998 was wet and cool while 1999 was dry and warm. The 1999 drought was very strong and affected the sap flow considerably. Measurements showed that the transpiration at the thinned plot was higher than at the control plot during the period with water limitation. Soil water content between sites did not differ significantly during this period. The MAESTRA model was tested at the individual tree and stand levels with respect to simulated *versus* measured transpiration, and was subsequently used to estimate the effect of thinning on the total canopy fluxes of water and carbon dioxide.

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Post-Fire Forest Floor Development along Toposequences of White Spruce - Aspen (*Picea glauca – Populus tremuloides*) Mixedwood Communities in West-Central Alberta

T.I. Little[1], D.J. Pluth[1], I.G.W. Corns[2], and D.W. Gilmore[3]

After wildfire, storage of organic carbon (C) begins again with the accumulation of forest floor material. Our central hypothesis is that slope position does not influence the amount of accumulated organic carbon. This is important because organic carbon trends in post-fire forest floor and soil development may correspond to mixedwood site productivity. Forest floor and mineral soil organic carbon, carbon to nitrogen ratios (C/N), and other soil properties of grey luvisols were studied to determine the differences in development along three toposequences. Toposequences varied from 0.15 to 0.5 km in length and up to 24 m relief in the Lower Foothills Natural Subregion of west-central Alberta.

Within the studied toposequences, the mean maximum tree age was 90 ± 10 years. Typically aspen trees were the oldest and occupied higher slope positions. Organic carbon and C/N in the forest floor, A- and B-horizons increased from crest to toe slope position. Total organic carbon values for 1.2 m soil profiles ranged from 14.1 kg m^{-2} at the crest to 21.2 kg m^{-2} at the toe of the slope. The forest floor contributed 2.0 ± 1.2 (standard deviation) kg C m^{-2} at the crest to 3.5 ± 1.6 kg C m^{-2} at the toe. Differences in the C/N ratio between crest and toe were detected only for the A-horizon, *i.e.*, 12 for crest and 16 for toe. Differences for ***in situ*** net nitrogen mineralization rates between the toe and crest slope positions were not detected. Tree and shrub layer leaf area index (LAI), used as a proxy for net primary productivity, was significantly greater ($p = 0.034$) at the toe slope position (3.5 ± 0.7) compared to the crest slope position (2.8 ± 0.6).

LAI results from the stands approximately 90 years after the last major fire disturbance indicate greatest potential productivity at lower and toe slope positions. Forest floor at the toe slope of these mixedwood stands accumulated approximately 1.5 kg m^{-2} more organic carbon than the crest position. These data suggest slower nutrient turnover at the toe position, which does not reduce site productivity. A portion of the difference in accumulated organic carbon along the toposequences may result from variation in tree age and composition of forest litter.

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POSTER LOCATOR NO. 25

Challenges in the Application of Existing Process-Based Models to Predict the Effect of Climate Change on Carbon Pools in Forest Ecosystems

Nancy Luckai[1] and Guy R. Larocque[2]

Process-based models used to investigate forest ecosystem response to climate change were not necessarily developed to include the effect of carbon dioxide (CO_2) and temperature increases on physiological processes. Simulation of the impacts of climate change with such models may lead to questionable predictions. It is generally believed that significant shifts in the performance of black spruce (*Picea mariana* Marsh.) will occur under climate change. This species, which accounts for 64% of Ontario's coniferous growing stock and 80% of the annual allowable cut, represents important economic activity throughout the boreal forest region. Forest management planning requires relatively accurate productivity estimates. Thus, it is imperative to ensure that process-based models realistically predict the effect of climate change.

In this study, CENTURY and Forest-BGC models were calibrated for a high productivity black spruce stand in northwestern Ontario. Simulations indicated that the representation of critical processes in these two forest ecosystem models is incomplete. For instance, the interactive effects of CO_2 and temperature increases on physiological processes at the stand and soil level, particularly for sites differing in fertility, are not well documented nor are they easily identifiable in the models. Their incorporation into the models is therefore problematic. Practitioners must consequently be wary of assumptions about the inclusion of critical processes in models.

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Response of Fine Roots to Nitrogen Availability and Temperature in Norway Spruce Stands in Sweden

Hooshang Majdi [1]

The longevity of fine roots (<1 mm in diameter) in the first 0 to 20 cm of forest soil was examined at two sites in Norway spruce *(Picea abies)* stands in southern and northern Sweden. The growing season at the southern site was 220 days, with an average monthly soil temperature of 7.5 °C. The growing season at the northern site was 110 days, with monthly soil temperature ranging from -8.7 to 14.4 °C. Using the minirhizotoron technique, the longevity of fine roots was measured in response to liquid fertilization (IL) at the southern site, and to soil warming with liquid fertilization (HIL) at the northern site. Soil in the HIL plots was warmed 5 °C to 15 cm depth during the snow free period at northern site. Soil was warmed using electrical heating cables under the humus layer giving heating capacity of 65 W m^{-2}. Nitrogen concentrations in fine roots in the LFH and mineral soil layers were also measured.

Median fine root longevity in the control plots at the southern site was lower (280 days) than at the northern site (430 days). At the southern site, there was no significant difference ($p < 0.05$) in fine root longevity between the IL and control plots. At the northern site, IL treatment lowered root longevity (350 days) relative to the control plots. In the HIL plots, soil warming significantly decreased ($p < 0.05$) median fine root longevity to 120 days, which was less than the longevity in the control and IL plots.

The nitrogen concentration of fine roots in the control plots at the southern site was higher than in the IL plots at northern site. The nitrogen concentrations of IL plots at both sites were lower than their respective control plots.

Results show that significant ($p < 0.05$) root mortality occurred at the end of the growing season and that temperature was a major factor in fine root mortality. Increased temperature associated with global warming resulting from increased atmospheric carbon dioxide and other greenhouse gases will cause higher fine root mortality.

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The Spruce Budworm Decision Support System: Modification for Use in Predicting Climate Change Effects

Kevin B. Porter[1], Wayne MacKinnon[1], Mark Budd[1], Kathy Beaton[1], and David A. MacLean[2]

Spruce budworm (*Choristenuera fumiferana*) outbreaks are natural disturbances that cause significant growth loss and mortality in spruce-fir (*Picea-Abies*) forests in eastern Canada and thereby result in large uncertainty in forest structure, productivity, and carbon dynamics. Building upon the results of scientific research studies on spruce budworm impacts, the Canadian Forest Service developed the Spruce Budworm Decision Support System (SBW DSS). The SBW DSS integrates the ARC/INFO and ArcView geographic information system (GIS) products, a stand growth and yield model, and a forest planning model to determine marginal timber supply benefits (m^3 ha^{-1}) and forest structure consequences of alternative management actions. This facilitates incorporating the effects of insect damage into forest management planning.

Spatial data representing forest inventory, historical budworm defoliation, predicted defoliation, and future harvest plans were utilized along with non-spatial forest management information. SBW DSS is being operationally implemented in New Brunswick, Quebec, Saskatchewan, and Alberta. With Canada Climate Change Action Fund support, the SBW DSS is being modified to predict effects of climate change scenarios on insect outbreaks and the carbon sink potential of Canada's forests. This involves "scaling up" the DSS to use National Forest Inventory data and linkage to the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) to convert insect-caused volume changes to carbon.

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Methods of Estimating Forest Ecosystem Carbon Balance Dynamics: Natural and Anthropogenic Interaction

A.P. Sapozhnikov[1]

Carbon balance and flux dynamics are a reliable indicator of the status of terrestrial ecosystems. The "supernormative" carbon dioxide accumulation in the atmosphere testifies to the destabilization of the global ecological situation. Estimated at the global level, surplus carbon accumulation and the formation in the atmospheric layer of the "greenhouse effect" are viewed as a warning.

The great bulk of carbon fluxes is in carbon deposition within forest ecosystems, and in carbon emissions associated with industrial and other anthropogenic factors, and with decomposition. These processes do not coincide either temporally or spatially; emissions are not necessarily and adequately compensated by absorption. Therefore, all global calculations have a definite assumption. Most carbon balance calculations involve site observations that are then extrapolated to the local, continental, or even global level. The stability of the carbon balance is usually taken as an indicator of the "positiveness" of an ecological situation, and regarded as the standard functioning of ecosystems.

Any disturbance of a regional ecological situation, connected with or accompanied by carbon emission at the global level, is also accompanied with a definite time lag. At the same time, active control of the carbon fluxes and an implementation of well-timed measures for their regulation in order to prevent negative consequences, are possible only on the regional or even the local ecoregional level. Therefore, global calculations can have no more than an informative value. For control, it is necessary to elaborate an epicyclical system of the constant monitoring representative points. They should be ranked on levels of generalization as follows: group of biogeocenoses types - facies - sub-formation - formation - vegetative (forest vegetative) zone - climatic zone. The first two to three levels are implemented within the ecoregions. This system can be easily implemented within a project of meridional transects.

The soil component part of the balance is not sufficiently taken into account in the usually adopted methods of carbon dynamics estimations. The process vector of the vegetative mortmass transformation in humus formation is very important, and is one of the leading elementary soil formation processes. Carbon accumulates under humus formation, however carbon emission occurs in various forms at the same time, including the output of water-soluble carbon compounds. Soil carbon emission must be considered as a factor in current carbon cycle dynamics, and its preservation by humus accumulation should be viewed as a sign of ecosystem condition in the long-term perspective.

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Modeling the Long-Term Impacts of Stand-Level Management Strategies on Carbon Sequestration in Boreal Forest Ecosystems

Brad Seely[1], Clive Welham[1], and Hamish Kimmins[1]

Regional and national analyses of forest ecosystem carbon budgets are typically reliant upon a set of relatively simple vegetation growth curves to estimate forest productivity across large and diverse landscapes. Similarly, it is common for Life Cycle Assessments (LCA) of forest products to focus primarily on post-harvest fates and energy costs of production and transportation while using a simple "carbon shadow" assumption to represent a constant pattern of carbon sequestration on the forest side of the equation. While such simplifications of forest productivity may be necessary for large-scale analyses, they are unlikely to be sensitive to the impacts of alternative stand-level management strategies on long-term forest productivity and carbon sequestration.

In this study, we examined the application of the stand-level forest ecosystem model *FORECAST* for projecting the long-term impacts of a series of alternative management scenarios on carbon sequestration in a boreal mixedwood forest in northeastern British Columbia, Canada. The output of the *FORECAST* model was evaluated for a selection of variables related to stand-level productivity and ecosystem carbon sequestration for each management scenario. Finally, results of the stand-level modeling are discussed in the context of large-scale carbon budget analyses.

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POSTER LOCATOR NO. 88

Soil Carbon Recovery and Site Productivity Changes following Harvesting and Site Preparation of a Sub-boreal Forested Wetland

C.T. Trettin[1], M.F. Jurgensen[2], and M.R. Gale[2]

Most information on the effects of timber harvesting on soil carbon pools and processes in non-drained, forested wetlands are for relatively short time periods (2 to 3 years). While many of these studies have found significant soil carbon losses after harvesting, little is known about soil carbon recovery rates, and if these soil carbon changes have influenced long-term site productivity. Therefore, a study was established to determine long-term response of soil carbon pools and site productivity to clearcut harvesting and various site preparation treatments (bedding, trenching) in a conifer wetland in northern Michigan, United States. The study site is characteristic of sub-boreal, histic-mineral, forested wetlands in this region, which are dominated by jack pine (*Pinus banksiana*), black spruce (*Picea mariana*), and larch (*Larix laricina*). Previous measurements 18 months and five years after harvesting showed considerable losses of soil carbon, the extent of which depended on site preparation treatment. This paper will present the results of a re-sampling of this study site in 1999 (11 years after harvest), which focused on the recovery of soil carbon pools, and the possible effects of soil carbon loss on site productivity.

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Soil Carbon Sequestration Following Afforestation of Former Arable Land

Lars Vesterdal[1], Per Gundersen[1], and Eva Ritter[1]

Following the Kyoto Protocol there has been renewed interest in the issue of carbon sequestration in forest biomass and forest soils. Denmark is currently implementing a plan to double its forested area within the next 80 to 100 years by afforestation of arable land. Carbon is being sequestered in the biomass of the new forests, but the question remains as to what extent the former arable soils will contribute as sinks for carbon dioxide. The study explored changes in soil carbon stores following afforestation of former arable land with oak (*Quercus robur*) and Norway spruce (*Picea abies*). Seven stands of each tree species on similar nutrient-rich soils (Alfisols) made up a chronosequence ranging from 1 to 30 years. Soil sampling included organic layers and the mineral soil to a depth of 30 cm.

Developing forest floors sequestered most of the carbon in spruce stands. While oak stands had reached a steady-state level in forest floor carbon at around 2 Mg C ha^{-1}, spruce forest floors had sequestered approximately 9 Mg C ha^{-1} after 30 years and were still in the accretion stage. There was no overall increase in mineral soil carbon storage with increasing stand age, but the carbon stores appeared to be undergoing redistribution following afforestation. In both tree species, there was a significant increase in carbon concentration and content in the upper 5 cm of the mineral soil, while carbon concentrations and contents were unchanged or decreased in the 5 to 15 cm and 15 to 30 cm soil layers. This pattern of redistribution led to fairly similar total soil carbon stores of around 60 Mg ha^{-1} along the 30 year chronosequence. In comparison, biomass carbon sequestration during 30 years was estimated at 90 Mg ha^{-1} for spruce stands and 60 Mg ha^{-1} for oak stands. However, the on-going redistribution of mineral soil carbon suggests that nutrient-rich afforestation soils may become greater sinks for carbon over a longer time perspective.

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THEME 4

Social and Economic Issues, Including Implications of the Kyoto Protocol

Boreal Forests: Social, Economic, and Environmental Considerations

J.S. Maini[1]

Boreal forests, characterized by coniferous species, short growing season, discontinuous and continuous permafrost, and podzolic soils, are composed of closed canopy forest and open wooded lands encircling the northern latitudes.

This region includes both "forest rich" and "forest poor" countries as well as developed and developing countries where boreal forests play an important but diverse economic, social, cultural, and environmental role. This forest type is shared by 13 countries which represent the microcosm of the world in terms of population and economic development as well as per capita forest cover, income, purchasing power parity, and Gross Domestic Product – real growth rate.

Canada and the Russian Federation are examples of "forest rich" countries with 13.66 and 6.01 ha per capita of forest and other wooded lands, respectively, while in Lithuania and Japan, the per capita forest cover amounts to only 0.55 and 0.20 ha, respectively.

In the "forest rich" countries, forests make an important contribution to economic and industrial development. However, in developing countries with "low forest cover", forests are an important source of fuelwood and subsistence to people who live in and around forests, including thousands of indigenous people.

Understanding the implication of the Kyoto Protocol to countries in the boreal region would involve a recognition of the diverse interface between forests and human activities, in the context of a range of ecological, social, and economic conditions, particularly per capita forest cover and per capita income. While the implementation of the Kyoto Protocol may present potential economic opportunities in terms of financial compensation for the environmental services (e.g., carbon sequestration) and contribute to the cost of sustainable forest management, there would be potential opportunities to rehabilitate degraded forests, expand forest cover, and restore biological diversity particularly in "forest poor" countries. Forests and wooded lands should not be viewed simply as nature's factory that sequesters carbon and provides environmental services, but as an ecosystem that provides multiple benefits and meets diverse basic human needs. There could be potential opportunities to realize multiple benefits to meet diverse present and future social and economic needs. In some cases, there is a need to consider accepting lower rates of carbon sequestration as a trade-off for multiple social and environmental benefits.

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Projecting Impacts of Global Climate Change on the U.S. Forest and Agricultural Sectors and Carbon Budgets

Ralph J. Alig[1], Darius M. Adams[2], and Bruce A. McCarl[3]

We examined forest carbon, timber and agricultural production, price, and welfare impacts of global climate change on the United States' forest and agricultural sectors. We used four alternative scenarios arising from the application of two global circulation models (GCM's: Had! y and Canadian). To estimate climate change impacts on forest and agricultural yields, water availability, and irrigation water use, we used two ecological process models, a suite of crop growth simulators, and a hydrologic simulator. The resulting impacts from climate change were input into a production-based bio-economic model that projects forest and agricultural production, prices, economic welfare, and changes in forest carbon.

The yield projections, on net, suggested climate change would increase forest and agricultural yields. Thus, forest production and inventory levels, and agricultural output generally increased or changed little compared to a "base" case of no climate change. Increased supplies led to reduced product prices. In terms of welfare, climate change had a small positive impact in both sectors as measured by aggregate economic welfare (consumer's savings plus producer's profits). However, producer's welfare decreased while consumer's benefit increased. Both sectors demonstrated adaptive adjustment to climatic shifts, including changing mixes of products produced, land use shifts between the sectors, and alteration of the intensity of management among owners and across regions. The direction of net changes in total carbon inventories varied over the projection period, with migrations of land between forestry and agriculture as stimulated by climate change.

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Implications of a Market for Carbon on Timber and Non-Timber Values: Joint Production of Timber, Carbon, and Wildlife Habitat in an Uncertain World

Glen W. Armstrong[1], Wiktor L. Adamowicz[2], Grant K. Hauer[2], and Steven G. Cumming[3]

Significant interest has been generated in assessing the impact of climate change on the world's forest resources. Many of these studies examine the impact on timber and non-timber values arising from forest resources. There has also been considerable interest in the possibility of using forests for carbon sequestration to mitigate climate change. However, while there are proposals for using forests for carbon sequestration, there have been few studies of the impact of various carbon sequestration schemes on timber and non-timber values. Furthermore, there has been little analysis of these schemes in ecosystems that are characterized by relatively uncontrollable carbon-releasing disturbances such as wildfire. Since these schemes may come into being in the near future, their impacts will be more immediate, and perhaps more direct, than the impact of climate change itself. Furthermore, the structure of the actual market for carbon will probably result in different impacts on timber and non-timber values. For this reason, we examined the impact of alternative carbon market structures at a forestry firm level, and assessed the impacts on optimal harvesting of timber, and the resulting impact on non-timber elements.

We developed a modeling system comprised of an aspatial Monte Carlo simulation model and an optimization-based forest activity scheduling model. The simulation model was used to develop 100-year forecasts of the probability distributions of habitat area for five vertebrate species in a forest subject to a stochastic natural disturbance (stand-replacing wildfire) regime. These probability distributions were used to construct habitat area constraints for use in an optimization model that will allow for quantification of the trade-offs between timber values and the "degree of naturalness" maintained in the forest. The outcomes provide information on the implications of carbon sequestration schemes in general, and on the effect of different carbon market designs.

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CO_2 Sequestration through Bioconversion of Residual Wood to Ethanol: What is the Technical and Economic Feasibility?

Donald V. O'Connor[1], Ali R. Esteghlalian[2], David J. Gregg[2], and John N. Saddler[2]

Greenhouse and non-greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2), nitrous oxide, methane, sulphur oxides, and particulate matter, have a discernible impact on global climate and various aspects of human life on earth. The transportation sector is one of the main contributors to greenhouse emissions, especially in the United States and Canada. Alternative energy sources, such as wood-derived ethanol, can play a major role in reducing such emissions by sequestering the atmospheric CO_2 during photosynthesis and providing highly oxygenated fuels for near-complete combustion in road vehicle engines. Moreover, production of ethanol fuel from the vast amounts of wood waste available in British Columbia and other parts of Canada can reduce CO_2 and particulate matter by eliminating the need for wood residue incinerators. Canada currently produces 18.8 Mt (Bone Dry) of wood residues (sawdust, shavings, bark, etc.), 73% of which is used for production of energy and other value added products, while 27% remains unutilized. Disposal of surplus wood residues by landfilling or burning results in air pollution or contamination of groundwater and surface run-off.

The GHG emissions model developed and recently (1998) modified by Delucchi calculates CO_2-equivalent emissions of carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, nitrogen oxides, carbon monoxide, non-methane organic compounds weighted by their ozone-forming potential, sulphur oxides, and particulate matter from most stages of the life cycle of fuels and vehicles. The full-cycle GHG emissions (carbon dioxide, methane, and nitrous oxide) for ethanol fuel derived from agricultural as well as forest product residues were calculated using the Canadian version of Delucchi's model. The results of our modeling show that a 70 to 80% reduction in GHG emissions can be achieved by substituting ethanol derived from corn stover or wheat straw for gasoline. Similar reductions are likely to be gained from using wood-derived ethanol. There are a number of variables that impact this reduction. These include distance that the wastes must be transported to the processing plant, conversion efficiency, source of electricity displaced by co-product electricity, and the type of waste processed.

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Forest Carbon Sinks and Economic Costs of the Kyoto Protocol

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Forest carbon sinks were included in the Kyoto Protocol as a mechanism to mitigate global climate change (i.e., net carbon sink arising from land-use changes and forestry between 2008 and 2012 can be credited and may substitute for the reduction of carbon dioxide emissions). However, the size of the carbon sink, and consequently its influence on economic costs, vary considerably depending on the definitions and accounting methods adopted.

National carbon sinks were estimated using three different approaches: Kyoto carbon sinks according to the Intergovernmental Panel on Climate Change (IPCC); carbon sinks according to United Nations Food and Agriculture Organization (FAO) terminology; and carbon sinks as currently reported to United Nations Framework Convention on Climate Change (UNFCCC). Using a computable general equilibrium model, we analyzed how carbon sinks of different sizes will affect the costs of the Kyoto Protocol in various countries.

Inclusion of the IPCC sinks have a minor effect on the economic costs of the Kyoto Protocol in every country except New Zealand. The amount of cost reduction due to the inclusion of the FAO sinks (assuming that carbon in harvested timber is excluded from calculations) or the UNFCCC sinks, depends on the credited amount. In both cases, the cost reductions were largest in New Zealand, Sweden, and Finland. According to preliminary estimates for Finland, if the credited amount were one fourth of the size of sink, the inclusion of the FAO sinks would reduce costs by 15%, while the inclusion of the UNFCCC sinks would reduce costs by 25%. The more restricted is the use of the other flexible mechanisms (e.g., ceilings on international emission trading) the larger is the benefit from sinks.

The reliability of carbon sink assessment needs to be analyzed in order to develop guidelines for transparent and verifiable reporting of national carbon sinks. National inventories of forest resources set basic limits on the accuracy and reliability of the carbon sink estimates. The most accurate estimates of carbon sink were obtained with inventories of annual growth and drain. In this case, analysis of sources of errors of different components showed that the relative standard error of carbon sink estimates is over 10%. The most accurate approach cannot be applied when carbon sinks of the Kyoto Protocol are considered, since there is need to distinguish human-influenced carbon sink into different activities. Thus, the errors related to estimates of Kyoto sinks are manifold compared with errors related to estimated changes in forest and other woody biomass stocks (carbon sink as currently reported to UNFCCC).

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Alberta's Boreal Landscape in Transition: Implications of Land-use Practices to Plant Community Structure and Carbon Pools

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Alberta's boreal forest is undergoing a rapid transition in response to human land uses including forestry, the energy sector, agriculture, transportation networks, and other human utilities. Using A Landscape Cumulative Effects Simulator (ALCES), we tracked historic land-use practices in northern Alberta and projected a future landscape based on conservative industry and government estimates of development trajectories. The anthropogenic footprint in boreal Alberta is not stationary, but growing at an exponential rate for many land-use variables. Industrial estimates of future annual rates of activity relating to the oil and gas, forestry, and transportation sector, as simulated by ALCES, suggest that net losses of 25 to 30% of the merchantable forest land base are likely to occur during the next forest rotation (100 years).

The trajectory in landscape phytomass and carbon is dependent on several factors, most noticeably land-use development trajectories, revegetation rates of anthropogenic footprints (seismic lines, wellsites, pipelines, and roads), and annual fire rate. A recurrent theme to all simulation trajectories is a future landscape where forest cover is reduced significantly, where forests are younger and contain less phytomass, and where area in non-vegetation cover and in herbaceous cover increases. Based on anticipated land-use growth patterns and phytomass trajectory curves for litter/soils, herbaceous, shrub, downwood, snags, and live tree pools for each landscape type in northeastern Alberta, ALCES simulated an approximate reduction in phytomass and carbon of 23% during the next 100 years.

Mitigation strategies that significantly reduce the loss of phytomass on the landscape of northeastern Alberta include a reduction in the width and lifespan of seismic lines and pipelines, revegetation of abandoned wellsites to conifer trajectories, and reduced fire rates through improved suppression.

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POSTER LOCATOR NO. 109

Russia as a Purveyor of Carbon Credits to the Global Community

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The Kyoto Protocol set 1990 as the reference point against which to measure compliance of the signatories. By 1997, unlike most of the developed world, Russia had undergone a 51% reduction in industrial output below levels existing in 1990. Russia's ability to meet the target reduction is based not so much on investment in newer technologies or a shift in economic output away from energy intensive industries, as on a sharp drop in overall industrial output.

Using publicly available Russian statistics, this study examined the decline in industrial output and estimated the rebound in activity that can be expected by 2008 to 2012. Using 1990 as the base period, indicators of physical output for each of the 12 major industrial groups in Russia were developed, linking the fall in output with the overall decline in the economy. Output of the different sectors was linked to changes in the Russian Gross National Product (GNP). Through a scenario analysis, different activity levels for the sectors in the period 2008 to 2012 are provided. An indication of the unused carbon credits that could be available to other countries to offset reductions mandated by the Protocol is provided.

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Deforestation in Boreal Saskatchewan: Monitoring a Frequently Neglected Source of Carbon Emissions

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Deforestation is a major cause of carbon fluxes from terrestrial ecosystems to the atmosphere, but no national long-term monitoring system exists to estimate temporal changes in the total area of Canadian forests. This study introduces a methodology for landscape-scale monitoring of changes in wooded area, defined as land at least 35% covered by trees or shrubs with a minimum height of 2 meters. Sequential editions of 1:50,000 topographic maps were digitized and analyzed with a geographic information system to quantify changes in wooded area over approximately three decades for the Waskesiu Hills landscape (53°45'N 106°15'W) and the Red Deer River landscape (52°45'N 103°00'W) of Saskatchewan. Both study areas are located within the boreal plain ecozone, which was predominantly boreal forest prior to the past century of agricultural land clearing.

In the 4570 km^2 Waskesiu Hills landscape, wooded area decreased by 164 km^2 between 1963 and 1990. In the 4692 km^2 Red Deer River landscape, wooded area decreased by 371 km^2 in between 1957 and 1990. Estimated mean annual rates of change in wooded area were -0.19% yr^{-1} and -0.43% yr^{-1} for the former and latter landscapes, respectively. Losses of wooded area were not proportional across three land-use classes. Rates of change for wooded areas were small in parks (+0.09 % yr^{-1} and -0.02 % yr^{-1}) and commercial forests (+0.10 % yr^{-1} and +0.22% yr^{-1}), and larger in predominantly agricultural zones (-1.27 % yr^{-1} and -1.21 % yr^{-1} for the Waskesiu Hills landscape and Red Deer River landscape, respectively).

These estimated declines in wooded area are conservative because the methodology does not account for losses due to roads, transmission lines, dugouts, and other features not represented on topographic maps in an area-proportional manner. The total length of roads increased by 96 km (0.27% yr^{-1}) in the Waskesiu Hills landscape and by 507 km (0.74% yr^{-1}) in the Red Deer River landscape. Expanding infrastructure networks were contrasted by negative rates of change for human population in both landscapes.

Within the two study areas, wooded lands that are unprotected by legislation remain vulnerable to future deforestation. Conversely, areas previously converted to crops and pasture could sequester atmospheric carbon in aboveground biomass if afforestation is initiated.

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POSTER LOCATOR NO. 127

Systems for Measuring and Reporting on Deforestation in Canada under the Kyoto Protocol

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A national system for determining and reporting on areas of deforestation is needed to fulfil Canada's Kyoto Protocol reporting commitments. An enhanced National Forest Inventory (NFI) forms a reasonable national framework on which to build a deforestation reporting system. The NFI consists, at its core, of a grid system of 2 x 2 km plots on a 20 km grid. The base design calls for forest parameters to be determined from aerial photo interpretation. Subsets of plots are sampled on the ground. This core can be enhanced with data from other sources. One possible enhancement is the integration of the NFI plot system, medium resolution satellite remote sensing data (e.g., Landsat TM), and existing land-use records to improve measurements of deforestation in the context of the Kyoto Protocol. Important in such a system is what data are available and how to integrate the data.

Key issues related to the appropriateness of public land-use records are: what records are available; from who; their content, coverage and reliability; are they spatially explicit; are they yearly; are they legislated, regulated or voluntary; and are there access restrictions. Questions related to the potential use of satellite remote sensing include: what types of deforestation can be detected, how accurately and at what minimum mapping unit; for what types of deforestation can you infer deforestation using only one image; how long a time interval do you need to prove deforestation or alternately disprove deforestation; and what information can one infer regarding remaining carbon stocks. Issues related to integration into a system within the National Forest Inventory structure are: sampling system design (random, systematic, focused); scaling; sampling interval; what to do when different sources give different answers; and how area and location of deforestation can be related to forest type, biomass, and remaining carbon on-site so that the impact on the carbon budget can be determined. These considerations are detailed and proposed integrated systems outlined.

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Potential for Carbon Sequestration through Afforestation in Saskatchewan: An Ecological-Economic Analysis

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Afforestation, i.e., planting trees in areas that were previously without forest cover, is recognized by the Kyoto Protocol as a carbon-sequestering process that countries can use in meeting their carbon dioxide emission reduction targets. Previous studies have identified the potential for afforestation and associated carbon sequestration in the prairie region of Canada. We estimated the area potentially available in Saskatchewan for afforestation, the carbon sequestration possible on this land base, the economic incentives and disincentives surrounding afforestation, and the policy regimes necessary to encourage the adoption of afforestation.

Our estimate of the area available for afforestation in Saskatchewan is 1.47 million ha, based on an analysis of soil type and Canada Land Inventory ratings for agriculture and forestry. We assumed that this area would be afforested with white spruce (*Picea glauca*), aspen (*Populus tremuloides*), and fast-growing hybrid poplars, with each species occupying one-third of the land base. Using species-specific yield curves and sequestration values from the literature, we estimated that the resulting gross carbon sequestration over 80 years would be approximately 391 Mt.

The economic value of this sequestered carbon ranges from CAD$ 16 to 74 million depending on pricing assumptions. Given these values, we investigated the economic feasibility of afforestation in Saskatchewan considering current limitations in infrastructure, existing land uses, low economic value of forests, and social considerations that currently prevent the wide-scale adoption of afforestation as a viable land use. Economic evaluation of such afforestation was undertaken from both farmers' and societal perspectives.

Finally, we examined the significance of government policy as a deterrent to landowners that may otherwise adopt afforestation as an alternative economic strategy to traditional grain and oilseed crops. We show that some provincial government policies, such as the setting of low Crown timber royalty rates, and the practice of allocating excess volumes of Crown timber to forest industry, adversely affect the demand for privately grown timber. In addition, we found that Federal policies, such as Revenue Canada tax interpretations, create significant disincentives for woodlot management.

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POSTER LOCATOR NO. 71

Climate Change Effects on Insect Outbreaks and Management Opportunities for Carbon Sequestration

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Outbreaks of forest insects and diseases in Canada cause timber volume mortality and growth losses of 80 to 110 million m^3 yr^{-1}, more than one-half of harvest rates. Attempts to influence carbon sinks must consider forest and pest management. Climate change will affect insect outbreak cycles and the extent and severity of insect damage, and may worsen the current situation. Well-developed methodologies for forecasting stand and forest-estate timber volume development were scaled up to the regional and national level and interpreted in terms of carbon dynamics, using the Spruce Budworm (*Choristoneura fumiferana*) Decision Support System (SBW DSS).

This project, supported by the Canada Climate Change Action Fund, has quantified the effect of insect disturbances on the carbon sink potential of Canada's forests by: 1) developing a modeling system to analyze effects of climate change on pest outbreak dynamics and carbon sequestration patterns at a large regional scale; 2) predicting the extent and impact of future insect disturbance regimes on forest carbon sink potential; 3) using scenario planning ("*what if?*") analyses to quantify effects of enhanced management and protection against pests on carbon sequestration; and 4) providing probable effects of climate change on pest outbreaks and carbon sequestration opportunities from enhanced management programs.

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Integration of Satellite Imagery and Stand Inventory Data for Mapping Carbon Stocks in Forest Ecosystems of Northwestern Russia

Thomas K. Maiersperger[1], Olga N. Krankina[1], and Warren B. Cohen[2]

Approximately 50% of the world's boreal forests are located in Russia, making this region an important focus for carbon budgeting. Previous studies in this area have produced widely varying estimates of carbon stocks, indicating that further methodological developments are needed to more accurately measure carbon pools in Russian forests. In response to this need, an approach was developed that combines forest inventory data with Thematic Mapper (TM) imagery to map the spatial distribution of carbon stocks across a 3 million hectare region of northwestern Russia. The objectives of this research are: 1) to characterize the association between TM data and several forest inventory variables, including species composition, stand density, age, and mean growing stock; 2) to map a set of selected forest attributes across the region; and 3) to perform a statistical assessment of mapping errors. More than 3000 stands inventoried during 1991-92 and registered to a coincident TM scene were used for the study. Image analysis was performed using a suite of multivariate techniques including canonical correlation analysis, clustering, and regression. The mapping strategy used a first-level classification of open canopy forest, closed canopy forest, bog, water, and other non-forest, and second-level continuous modeling of the closed canopy forest variables. Final maps were validated using an independent set of reference stands. Using derived conversion factors, carbon storage was calculated from the mapped forest variables, and carbon flux was modeled using a temporal sequence of TM images. Because standardized inventory data are available for a large proportion of Russian forests, this method has the potential for application throughout the entire territory. In a more general context, the use of satellite-based mapping and monitoring of carbon stocks can provide an independent tool for monitoring impacts of management decisions on carbon budgets.

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Fluxes of N_2O, CH_4, and CO_2 from Afforested Boreal Agricultural Peat Soils

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Natural boreal peatlands usually act as sinks for carbon dioxide (CO_2) and sources for methane (CH_4). Drainage of these soils can highly affect gas fluxes. After drainage, decomposition of organic material increases, and the sites may turn into a net source of CO_2. Drainage also increases nitrogen losses from the soil. Farmed peat soils are known to be remarkable sources of CO_2 and nitrous oxide (N_2O). Afforestation of peat soils is assumed to reduce CO_2 emissions to the atmosphere due to the storage of carbon in the above- and belowground biomass of trees. Furthermore, increased immobilization of nitrogen would decrease the N_2O emissions. Fluxes of CH_4, N_2O, and CO_2 from organic agricultural soil were measured one year (site 1), 6 years (site 2), and 23 years (site 3) after afforestation in northwest Finland (71°13'N, 33°87'E). Measurements were made in 1996 and 1997 from June to October using an opaque static chamber method, and samples were analyzed with a gas chromatograph.

All of the sites were sources of nitrous oxide. There was a great spatial and temporal variation in the N_2O fluxes. Highest emissions were measured from Site 3 in May 1997 during the spring thaw (29 mg N_2O m^{-2} d^{-1}). The mean N_2O emissions from Sites 1 and 2 were lower than that from Site 3. The N_2O emissions were equal or greater than those reported earlier for boreal organic forest or agricultural soils. The N_2O fluxes decreased towards autumn at all sites and were lowest in October.

The sites usually acted as a small sink or source for methane. The two youngest sites were sources of CH_4 whereas the oldest one acted as a sink for methane. The water table level was lower (0.44 m) in Site 3 than in the other two sites (0.31 to 0.38 m). The highest methane emissions, up to 154 mg m^{-2} d^{-1}, were observed from Sites 1 and 2 in the middle of August 1997. These emissions were high, similar to those reported for minerogenous natural peatlands in Finland.

Carbon dioxide from aerobic and anaerobic decomposition processes, respiration of soil animals, dark respiration of plants, as well as CO_2 from root respiration were included in the CO_2 fluxes measured with the opaque chambers. This CO_2 flux is called here community CO_2 production (cCO_2). Day-time cCO_2 was highest at Site 2 and lowest at Site 3, and was dependent on temperature. The mean day-time dark respiration was lower at the oldest forest site (9.6 g CO_2 m^{-2} d^{-1}) than at the younger sites (12.6 to 15.2 g CO_2 m^{-2} d^{-1}).

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POSTER LOCATOR NO. 117

Kyoto Protocol: Implications for Conservation Programs in the Western Boreal Forest of Canada

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The Kyoto Protocol is a consensus that the evidence for climate change can no longer be ignored. To some, climate change is a pollution control issue that must be resolved by strictly enforced regulations to reduce emissions. Others maintain that a balanced approach, including the sustainable use and management of landscape resources as sinks, offers the most viable long-term approach. To date, only forestry activities are recognized as sinks under the Protocol, however there is opportunity for negotiation of additional sinks. Canada is supporting additional sinks including agricultural soils and wetlands to promote conservation measures related to forestry, agriculture, and wetlands.

The Protocol will have implications for industry in the Western Boreal Forest (WBF) of Canada. The increased demand for natural gas (because it is the cleanest burning fossil fuel) within the U.S. and Canada will result in greater overall gas exploration and development activity in the WBF. Kyoto may also spur re-evaluation of hydroelectric projects that are currently cost prohibitive. The result for the WBF will be increased activity related to hydropower development and the environmental consequences of increased dam construction and river modification. These industry responses to Kyoto will result in increased pressure on the WBF landscape. On the other hand, there will be incentives to reforest areas deforested prior to 1990. There will be incentives for forest companies to put more effort into replacing trees in harvested areas. Cutting seismic lines during oil/gas exploration and not replacing the trees would be considered deforestation and subject to penalty. Clearing forestland for agricultural purposes will likely be reduced. These scenarios all have positive implications for conservation programs in the WBF. It has been suggested that changes in carbon stores due to wetland restoration, creation, and wetland destruction since 1990 be recognized under the Protocol. In the WBF, the opportunity for wetland restoration and creation may be limited; therefore the primary impact of the Protocol may be related to preventing further destruction of wetland habitats.

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Think Globally, Act Locally: Quantifying Ontario's Forest Carbon Budget

Changhui Peng[1,2], Jinxun Liu[2], Mike Apps[3], and Qinglai Dang[2]

Under the Kyoto Protocol, Canada has agreed to reduce its greenhouse gas (GHG) emissions by 6% from 1990 levels by 2008 to 2012. Canada's current forest and forest carbon (C) budget measurement systems will likely not be able to satisfy the measurement needs arising from the Kyoto Protocol. Canada is faced with three requirements: 1) an annual inventory of GHG emission and removals; 2) an account of 1990 carbon stocks on managed forest land; and 3) changes in carbon stocks associated with reforestation, afforestation, and deforestation activities since 1990.

In response, the Ontario Ministry of Natural Resources has developed a strategic approach to the design and implementation of climate change programs in support of the Ontario government's commitment. A total of 61 million ha, or 62%, of Ontario's total land area is forested land. Ontario must clearly define its needs, investigate detailed carbon budgets, and report on its carbon sinks and sources. We adapted the well-established Carbon Budget Model (CBM-CFS2) to estimate the carbon stocks and fluxes using extensive provincial databases, including forest inventory data and growth and yield plots. The preliminary results suggest that about 13.1 Pg C (including 2.1 Pg C in biomass and 11.0 Pg C in forest floor and soil) was stored in Ontario's forest ecosystems in 1990, which contributed to about 15% of the Canadian forest carbon budget in 1990. About 87.7% of total carbon is estimated in the boreal region of northern Ontario and only 12.3% total carbon is found in the temperate region of central-southern Ontario.

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Carbon Sequestration in Forest Plantations in Iceland

Arnor Snorrason[1] and Thorbergur Jonsson[2]

Iceland has been almost totally deforested and has suffered extensive soil erosion since the settlement of the country in the late ninth century (*ca.* 870 AD). This historical land degradation has created the large potential for carbon (C) sequestration by afforestation and restoration of anthropogenic deserts to productive ecosystems. Land is increasingly becoming available for afforestation and soil reclamation following the decline in free-range grazing of domestic animals.

The objective of this study was to elucidate the potential for carbon sequestration through afforestation and soil reclamation in Iceland, and to evaluate suitable methodologies of using the stock change approach to determine total site carbon sequestration above- and belowground. Total site organic carbon stocks were compared in forest plantations of known age to adjacent open pastures of the same site type and pre-planting land use history.

Total site organic carbon stocks in a 32-year-old plantation of *Larix sibirica* (larch) on thick (50 to 100 cm) Andisol soil in East Iceland were 267 t C ha^{-1} compared to 166 t C ha^{-1} in adjacent open pastures, indicating a mean annual carbon sequestration of 3 t C ha^{-1} yr^{-1} in the plantation. Aboveground carbon stocks of the plantation were 64 t C ha^{-1} in trees, 16 t C ha^{-1} in coarse tree roots, 10 t C ha^{-1} in litter and ground vegetation, 11 t C ha^{-1} in fine roots, and 166 t C ha^{-1} in organic soil. In the adjacent open pasture, carbon stocks were 6 t C ha^{-1} in litter and ground vegetation, 13 t C ha^{-1} in fine roots, and 144 t C ha^{-1} in organic soil. The additional carbon in the plantation compared to the pasture accumulated mainly in woody biomass and no significant change was observed in other components of the system. Similar results were obtained at other sites studied.

The soil has by far the biggest stock of carbon at the study sites. However, accurate estimates of carbon stock change are difficult because of great within-site variability, costly methods of study, and difficulties in obtaining representative samples, particularly in deep and stony soil. The study of parallel sites is useful in the absence of time-series data on carbon accumulation.

[1] Icelandic Forest Research, Iceland; [2] Icelandic Institute Of Natural History, Iceland. In addition to the authors, scientists from The Agricultural Research Institute and The Soil Conservation Service in Iceland participated in the project.

Carbon Mitigation Means in the Forestry Sector of Hungary: Big Possibilities in a Small Country

Zoltán Somogyi[1]

Due to a surplus of net growth over timber removal in the current forests, the carbon inventory of the forestry sector in Hungary shows a positive balance. A recently conducted carbon mitigation analysis found that afforesting large areas could dramatically increase the carbon-fixing capacity of the Hungarian forests in the future. Large areas will become available for various land-use forms in the country because agricultural activity has become unprofitable due to political and economic reasons. Afforesting much of these areas seems a viable option, and the multiple benefits of the forests seem attractive for various interested parties.

To assess the possible rate of sequestering carbon by afforestation, the COMAP model, developed by the U.S. Country Studies Team, was further developed and adapted to Hungarian conditions. This new model, CASMOR, is able to handle all significant processes and pools in the carbon cycle. Its time resolution is one year, which allows much more detailed analyses of the carbon cycle and the economics of carbon fixation than COMAP. All data required by this model were available from various research sources. By using the CASMOR model, several afforestation scenarios were analyzed. These scenarios differed in the amount of land available for afforestation, site conditions, and species composition. This latter was important to analyze, because a considerable part of the available land is private, and private landowners may have different preferences than the State for rotation age and the naturalness of the stand. The site conditions may vary from medium to poor, similar to the boreal conditions.

The potential technical scenario showed that by afforesting one million hectares of former agricultural land by 2050, some 40 Mt carbon could be sequestered, which is equivalent to annually offsetting 4% of the current annual emission in Hungary. The specific costs of sequestering carbon by afforestation are low, around US$ 8. The study also revealed that, even in the technical scenario which is characterized by the most intensive, although still feasible rate of afforestation, carbon sequestration only becomes intensive about 15 years after launching the program. The most important precondition of a large-scale afforestation program is joint financing; the county, currently in economic transition, needs the collaboration of various parties interested in sequestering carbon. The paper analyzes several further mitigation options using various forestry plans in Hungary.

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POSTER LOCATOR NO. 53

Potential for Afforestation Development in Canada: Some Preliminary Spatial Analyses of Economic Land Suitability

Michael Stephens[1] and Dan McKenney[1]

Afforestation for carbon sequestration has been identified as a potential policy option in the context of meeting greenhouse gas emission reduction targets under the Kyoto Protocol. The current state of knowledge regarding afforestation potential in Canada is reviewed, including estimates of land availability and carbon sequestration. A preliminary spatial analysis of afforestation potential is presented at the sub-provincial level for several case study areas.

The case study areas have been identified as having a base of cleared land potentially available for afforestation, and include southern Ontario and the Prairie regions of Alberta, Saskatchewan, and Manitoba. Agricultural census data by subdivision (e.g., rural county or municipality) were used to identify areas of marginal agricultural land with relatively low annual returns, or opportunity costs, compared to forestry or other land uses. Areas considered suitable for afforestation were identified taking into account the opportunity costs of the land for agriculture, forest growth and capability, and potential values from forest products and carbon storage. The results indicated that the area of land likely to be economically suitable for afforestation was lower than the total area of cleared land capable of supporting tree growth, due largely to the opportunity cost of high value agricultural uses on a proportion of those lands.

Further research is needed to spatially identify areas with high socio-economic potential for afforestation, including better information on plantation land capability and growth, private landholder attitudes, future markets and returns for biomass products, and the implications of potential carbon trading benefits. This information can be used to assist national afforestation policies and programs aimed at enhancing forestry sinks.

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POSTER LOCATOR NO. 115

Carbon in Soils of Land Cover Patterns of the Russia Forest Zone: Implementing the Kyoto Protocol through Land-Use Changes

Vladimir Stolbovoi[1]

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) identified specific human-induced land-use change activities (afforestation, reforestation, and deforestation) to be accounted. The Protocol Article 3.4 also focused on carbon emissions from agricultural soils, however it ignored changes in the soil carbon pool derived from land-use manipulations and, thus, making carbon budget incomplete. This gap has been greatly criticised by numerous scientific publications that suggest the urgency of introducing soil in carbon accounts. However, there is still a paucity of data to support this notion.

The effect of land-use change on carbon sequestration should be based on full carbon accounting, including soil as a major carbon reserve of terrestrial ecosystems. A map-overlap method has been used to create a consistent land cover mosaic of Russia. Land cover classes were characterized by soil spectrums related to the soil carbon content. Carbon density in soils was used as a basis for setting regional strategies for carbon management associated with land-use changes.

The forest zone is a mosaic of diverse land cover patterns. This complexity is a result of both natural and human-induced factors. The middle taiga zone consists of 67% forest, 20% meadow, 11% wetland, and 2% agricultural land. The temperate zone consists of only 42% forest, 9% meadow, and 5% wetland, while the agricultural land in this zone accounts for 44% of the total area. Each land cover type contains a certain amount of organic substances in solid, liquid, and gaseous phases, that are in a thermodynamic equilibrium with existing soil-forming factors. Land-use change dramatically affects the equilibrium, influencing carbon pools or enhancing the leaching or decomposition processes. The amount of carbon in the soil varies with land-use and land-cover pattern, from 3 to 4 kg m^{-2} in pine forests to 24 kg m^{-2} in wetlands. The agricultural land in many regions is organically richer (up to 4 to 5 kg m^{-2} for the 0 to 100 cm layer) than forest land, caused by differences in natural soil characteristics, cropping of grasses, application of organic fertilizers, liming, etc. Clearly, changes in land use by afforestation or reforestation will affect the soil-vegetation balance, and might result in either carbon release or carbon sequestration in soils. Therefore, the goal to sequester carbon might be achieved if soil carbon is accounted for in the ecosystem "soil-land cover" fashion.

Carbon density of soils under different land cover patterns of forest zones in Russia is greatly varied and has a geographically explicit dimension. Strategies for carbon sequestration based on land-use change, afforestation and reforestation should take into account soil-organic and soil-land cover associations.

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POSTER LOCATOR NO. 99

Carbon Tax Credits: A Case for Conservation Nets in Industrial Landscapes

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Our federal government, in response to the environmental pressures, has committed to rare and endangered species legislation, conserving more conservation areas, and promoting a better balance of greenhouse gases input and output. At the provincial level there are additional pressures, with the government committing to protecting more representative landscapes and a new Natural Heritage Act. Industrial sectors need to quantify the degree to which their landscapes conserve biodiversity and carbon in both the intensively and extensively managed parts of landscapes. It is suggested that conservation within industrial landscapes should consider the concept of Conservation Nets (CN), which consist of recognized conservation areas connected by corridors. These will ensure greater potential for species' daily movements, seasonal migration, and also longer-term movements caused by environmental stress.

Our working hypothesis is that most, if not all, rare and endangered species are located in the waterways and extensively managed landscapes, which can be protected with minimum negative impacts to intensive cropping operations. Waterways also have the greatest potential for carbon sequestration if protected. If CN were allowed to regenerate toward more mature ecosystems with native plant diversity, they should store carbon that could be claimed for carbon tax credits. This paper quantifies our understanding of carbon storage in waterways and less heavily managed landscapes.

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The Role of China's Temperate Forests in the Atmospheric Carbon Budget

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Though only 13.4% of China was under forest cover in 1990, more than 31 million hectares of tree plantations were established from 1949 to 1989. China's forests and plantations are therefore expected to have an important impact on the global carbon (C) budget.

A computer model (F-CARBON) was developed to calculate and project carbon emission and sequestration by temperate forests in the northern 12 provinces of China for 1990 to 2040. The calculations were based on data from national forest resource inventories conducted from 1984 to 1988 and from 1989 to 1993. The area harvested and planted in each region had to be estimated, using various assumptions, due to insufficient available data. Forests were grouped into five age classes, and differences in biomass density and growth rate among the age classes were considered in the model. Time differences in biomass oxidization and decay were also considered. Changes in soil carbon due to harvesting and forest development were estimated. The total accumulation of soil carbon was assumed to be 3% of the litterfall each year. Conversely, the total soil carbon released due to harvesting was assumed to be 3% of the soil carbon pool from the time of harvest to reforestation.

The F-CARBON model estimated that in 1990 the temperate forests in China took up 43.6 Mt C, and released 9.7 Mt C, resulting in a net sequestration of 33.9 Mt C.

The F-CARBON model can be used for projecting changes in forest carbon inventory and projections of carbon emission and sequestration were made for the next 50 years. However, the model may have underestimated net carbon uptake in the base year (1990) because it did not take into account changes in forest cover in prior years. To reduce the uncertainties in these calculations, improved data for land-use conversion, productivity of natural forests and plantations, and soil carbon dynamics in relation to forest harvesting and afforestation/reforestation are required.

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