Salem State College

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ESTIMATING SOIL CARBON STOCKS AND FLUXES IN A BOREAL FOREST LANDSCAPE

A Thesis in Geo-Information Science

by

Gloria Rapalee

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The undersigned have examined and approved the thesis by Gloria Rapalee entitled "Estimating soil carbon stocks and fluxes in a boreal forest landscape."

Robert H. Arnold
Co-Chair of Thesis Committee
Professor of Geography
Salem State College

March 4, 1999
Date

John T. Hayes
Co-Chair of Thesis Committee
Assistant Professor of Geography
Salem State College

March 4, 1999
Date

Stephen S. Young
Assistant Professor of Geography
Salem State College

March 12, 1999
Date

Hugo Veldhuis
Senior Pedologist
Agriculture & Agri-Food Canada
Brandon Research Centre
Manitoba Land Resource Unit
University of Manitoba
Winnipeg, Manitoba
Canada

May 5, 1998
Date

C. Dana Tomlin
Professor of Landscape Architecture and Regional Planning
University of Pennsylvania

May 5, 1998
Date

The earth beneath the feet of all runners and walkers
Declares the glory of God, our Cherisher!
The roots of trees and grasses, the sole
And all organisms in the rich realm of darkness...
These are God's handiwork.
Our life in the realm of sunlight
Is upheld by the vital earth. God made it so.
All creatures that live on the land depend on the soil,
which is like a strong parent,
Providing for all peoples and
All creatures that live above the waters.
Praise be to the holy ground that is softly under our feet!
Praise be to God who has blessed the living carpet
That He has spread for our walking,
In the days of our living in the flesh,
And into which our residues will return.

-- Francis D. Hole
An Original "Psalm" Inspired by Psalm 19

Each soil is an individual body of nature, possessing its own character, life history, and powers to support plants and animals.

-- Hans Jenny

I believe there's only one conflict, and that's between the short-term and the long-term thinking. In the long term, the economy and the environment are the same thing. If it's unenvironmental, it is uneconomical. That is a rule of nature.

-- Mollie Beattie

Abstract

Boreal forests and wetlands are currently thought to be significant carbon (C) sinks in global carbon budgets and they could become net carbon sources as the Earth warms, likely effects of greenhouse gas-induced global warming. Most of the carbon of boreal forest ecosystems is stored in the moss layer and in the soil. Carbon budgets of several boreal forest and wetland ecosystems were studied intensively at the plot scale during the 1994 and 1996 field seasons of the BOReal Ecosystem-Atmosphere Study (BOREAS). The objective of my study was to estimate soil carbon stocks and fluxes at a larger spatial scale for a 733 km^2 area of the BOREAS study site in northern Manitoba, Canada. I used a simple, process-based model developed from carbon and radiocarbon measurements to relate soil C storage and dynamics to soil drainage and forest stand age. Benefiting from use of a geographic information system (GIS) and application of spatial analytical techniques, I then estimated soil carbon stocks and fluxes for the study area using the model together with regional maps of drainage and forest stand age properties. Soil carbon stocks correspond to soil drainage class, with the largest C stocks occurring in poorly drained sites. In the imperfectly and poorly drained sites, a large carbon pool composed of highly decomposed humic material and a charred layer derived from fire residues lies exists at the base of the moss layer. Calculations of net flux of carbon are sensitive to the estimated decomposition rates for this large pool of deep soil C. While the upper moss layers regrow and accumulate carbon after fires, the estimated deep C flux in years between fire events varies across the landscape, ranging from a small net sink to a significant source. Estimated net soil carbon accumulation, averaged for the entire 733 km^2 area, was 20 g C m^{-2} yr^{-1} (28 g C m^{-2} yr^{-1} accumulation in surface mosses offset by

8 g C m^{-2} yr^{-1} lost from deep C pools) in 1994, a year with no fire. Data from the field studies and results derived from the model indicate that most of the C accumulated in poorly and very poorly drained soils (peatlands and wetlands). A fire in any year across only 1% of the area covered by uplands would release enough carbon to offset the amount of carbon stored in the remaining 99% of the area. Significant interannual variability in carbon storage is expected due to the irregular occurrence of fire in space and time. The effects of climate change and management on fire frequency and on decomposition of immense deep soil C stocks are key to understanding future carbon budgets in boreal forests. My study demonstrates the need of large-scale studies such as BOREAS to include spatial analysis of landscape properties to better comprehend the interactive processes within the atmosphere and biosphere.

KEY WORDS: Soil carbon dynamics, boreal forests, climate change, modeling, GIS.

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Jim Wilkinson, Linda Matteson, and Lynn Levine, fine foresters and finest friends, have encouraged me all along to branch out as a forester. I am thankful for their encouragement. None of us could have foreseen how far and wide a Vermont forester might branch out. In many ways I have come a far piece from Camel's Hump.

I thank my four co-authors and BOREAS colleagues for taking a chance and sticking by me. Eric Davidson and Sue Trumbore offered me the greatest of opportunities when they invited me to join their project. While I am grateful for her financial and scientific support, I am most especially thankful for the unique opportunity Jennifer Harden arranged for me to drive "Blue" from Thompson back to Menlo Park. What a fine trip. I am grateful for the support and advice Hugo Veldhuis has offered me in his dual role as colleague on this project and as member of my thesis committee.

This thesis is based on work supported by the National Aeronautics and Space Administration (NASA) under prime grant NAG5-2306, The Regents of the University of California, and the U.S. Geological Survey Global Change Program. Financial support from the USGS during the summer of 1997 enabled me to write the first draft of our paper [*Rapalee et al.*, 1998c], from which this thesis evolved. I also acknowledge additional support during 1998 from grants NAG5-31752 and NAG5-7301 that enabled me to finalize our paper and this thesis.

I thank my colleagues at The Woods Hole Research Center, most especially Peter Schlesinger who provided invaluable expertise, advice, assistance, and consultation about all phases of this project. I thank my friends at the MBL and at the USGS in Quissett for maintaining their good humor and helping me out at the very beginning of this project.

Kathy Newkirk patiently lent her expertise on soil genesis and taxonomy. Greg Winston helped with locating sites on the soils maps. Greg and I continue to swap stories of our separate, and respective, thru-hikes on the AT and LT in the 70s and our trips in Blue in the 90s.

I thank my colleagues and all the BOREAS staff at the Goddard Space Flight Center (GSFC) who work very hard to keep the project running. I especially thank my officemates for their good humor day after day; Dave Knapp who made available an essential gridded data layer; Dave Landis who helped me polish up the final maps and figures for this project and who also suggested the idea for and helped me finalize our "electronic" poster [*Rapalee et al.,* 1998b]; Fred Huemmrich who enlightened me as to the "swamp" that is graduate school (for me, another "swamp" of many, though this one has been particularly wide); and Alexis Conley who relatively recently got to the other side of the "swamp," hauled herself out, and offered me encouragement for the same. I thank Elissa Levine who, in 1996, sponsored me for a month's stay as a visiting scientist at GSFC and who offers me support and encouragement and is a colleague on our BOREAS follow-on project. Denise Dunn and Mike Kalb, from Universities Space Research Association (USRA), arranged all the logistical details for my stay in Greenbelt. I thank Lou Steyaert for helping me get started with the moss cover mapping project. I thank Jon Ranson for providing the opportunity for me to travel to Duluth and participate in the boreal forest conference in August 1997. Forrest Hall sponsored me for my interim position until the new grant kicked in. I am grateful for the opportunity to have looked at the "big picture" and to have been paid at the same time.

See 3_POSTER.PDF, this CD.

Many BOREAS investigators helped me along the way. I especially thank Jill Bubier and Steve Frolking. Jill is the moss expert and helped me with moss identification and classification. Steve patiently offered helpful comments and suggestions about modeling and poster papers.

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I thank the five "official" members of my graduate committee who have challenged me all along. Bob Arnold, John Hayes, and Steve Young are dedicated teachers. I thank

Bob and John for co-chairing this diverse committee and Steve for his insights. Dana Tomlin encouraged me several years ago to believe that my (then evolving) decision to combine work at a larger research site with graduate school at a small state college several miles down the road would, in fact, work. From his office in Winnipeg and from the north country of Canada's boreal forests, Hugo Veldhuis taught me most of what I know about soils and all along the way has helped me remain on track and keep my perspective with his diligent, detailed, and organized responses to my many queries.

My good fortune is that I have a sixth "unofficial", but equally important committee member. Francis Hole, committee member *emeritus*, inspired me to look past the trees to the soil. The soil, as Francis says, is "the realm of lively darkness beneath our feet."

Since selling my trees and leaving my house on the Hump, I've become a peripatetic researcher and have ended up at the right house to live at precisely the right time. I am thankful for and grateful to each of my many housemates and landlords, who have welcomed and encouraged and supported me at every stop. I thank Delight; Sally; the Coombes family; Pam and Greg and Mark; Kathy and Jeff and Julia; the Bruces; Alison; Judy and Len and all the residents of the House of Hamburg; and the Nelsons.

In each town I found my way to one music group and sometimes two. Our rehearsals and concerts have been the greatest joy, challenge, and inspiration. We would "lift every voice and sing" and, for a brief time each week, we shed our busy lives. In Petersham I learned to treasure the strong Welsh hymns and the lasting genius of Vaughn Williams. I learned to sing in Latin in New Salem. One summer Sunday evening in Athol a group of us learned 500 years of hymnody, singing one tune after another without words or accompaniment. The Yuletide Festival was the highpoint of my year in Salem. One spring in Waquoit, where our numbers were small, but our voices strong and clear, I learned a new song every week. On warm summer evenings next to the water I sang in the Woods Hole Cantata Consort, a blend of scientists, summer people, and locals. And in Glenn Dale I learned new sets of words to old Celtic tunes. I am thankful for my New England and Maryland friends in music -- each place, each group, and each person a gift of serendipity.

Camel's Hump will always be my home. My friends and neighbors, who have known me forever, always welcome me back as if I've been in town just for the day. Instead of (now) the big city for months at a time. I still think running water (hot and cold) in the winter is a downright miracle.

My family has stuck by me on this long, long journey. I am grateful and thankful for and am blessed by their abiding love and support. Thanks to my folks, Katherine and Bill, and all my various siblings and their families -- Brian, Amy, Ben and Leah; Amy, Tim, and Julia; Steve, Hannah (The Pumpkin), and Kayla; and Billy.

My project and thesis are dedicated to Craig Whiting whose gentle spirit is always in my heart.

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NOTATION

°C	degrees Centigrade.
^{14}C	radioactive carbon, radiocarbon, Carbon 14.
AES	Atmospheric Environment Service.
AFM	airborne fluxes and meteorology.
BD	bulk density, mass of dry soil per unit bulk volume, g cm^{-3}.
BOREAS	BOReal Ecosystem-Atmosphere Study.
BORIS	BOREAS Information System.
BP	beaver pond.
BS	black spruce.
C	organic carbon mass, kg C m^{-2}.
Ca	calcium.
CanSIS	Canadian Soil Information System.
CCRS	Canadian Centre for Remote Sensing.
CDIAC	Carbon Dioxide and Information Analysis Center.
CD-ROM	compact disk-read only memory.
CH_4	methane.
CMDL	Climate Monitoring and Diagnostics Laboratory.
CO_2	carbon dioxide.
$C_{surface}$	carbon inventory of surface soil layers, kg C m^{-2}.
dbh	diameter (cm) at breast height, 1.3 m.
DAAC	Distributed Active Archive Center.
DIC	dissolved inorganic carbon.
DOC	dissolved organic carbon.
FEN	fen.
GIS	geographic information system.
GPP	gross primary production, 10^{15} g C yr^{-1}, g C yr^{-1}.
GSFC	Goddard Space Flight Center.
Gt	gigatonne, 10^{12} kg, 10^{15} g.
HW	hardwoods.
HYD	hydrology.
I	input rate, kg C m^{-2} yr^{-1}.
I_{deep}	input rate of deep soil layers, kg C m^{-2} yr^{-1}.
$I_{surface}$	input rate of surface soil layers, kg C m^{-2} yr^{-1}.
JP	jack pine.
k	decomposition rate constant, yr^{-1}.
$k_{surface}$	decomposition rate constant of surface soil layers in $year^{-1}$.
ln	natural logarithm.
M	mass of a carbon reservoir, kg C m^{-2}.
MAAT	mean annual air temperature, °C.
MAST	mean annual soil temperature, °C.
Mg	manganese.
MNR	Manitoba Natural Resources

MSA	modeling subarea.
MSST	mean summer soil temperature, °C.
n	number of samples.
Na	sodium.
N_2O	nitrous oxide.
NAD83	North American Datum, 1983.
NASA	National Aeronautics and Space Administration.
NEP	net ecosystem production, 10^{15} g C yr^{-1}, g C yr^{-1}.
NMHC	nonmethane hydrocarbon.
NOAA	National Oceanic and Atmospheric Administration.
NPP	net primary production, 10^{15} g C yr^{-1}, g C yr^{-1}.
NSA	northern study area.
NTS	National Topographic System.
OA	old aspen.
OBS	old black spruce.
OJP	old jack pine.
ORNL	Oak Ridge National Laboratory.
ppm	parts per million.
ppmv	parts per million by volume.
R_D	heterotrophic respiration.
R_P	plant respiration.
R_T	total respiration.
RSS	remote sensing science.
S	total rate of removal of carbon from a reservoir, kg C m^{-2} yr^{-1}.
SOM	soil organic matter.
SSA	southern study area.
SST	supersite.
t	number of years since last stand-killing fire, yrs.
T	turnover, mean residence time, yrs.
TA	trembling aspen.
TE	terrestrial ecology.
TF	tower flux.
TGB	trace gas biogeochemistry.
TM	technical memoranda.
UBS	upland black spruce.
USRA	Universities Space Research Association.
YJP	young jack pine.

1. Introduction

The global climate has stayed relatively stable during the last 10,000 years since the last glaciation, with global temperature changes of less than 1° Centigrade (°C) over a century [*Watson et al.*, 1996]. During that time our modern society has evolved. Now, however, human activities are increasing the atmospheric concentrations of greenhouse gases that tend to warm the atmosphere and the Earth's surface, and aerosols, which tend to cool the atmosphere. Next to water vapor, carbon dioxide (CO_2) is the most abundant of the greenhouse gases. Other important greenhouse gases include methane (CH_4) and nitrous oxide (N_2O).

While concern about global atmospheric changes has intensified recently -- the Kyoto Summit [*The Kyoto Protocol*, 1999], held in December 1997, is a recent example -- over 100 years ago, the Swedish chemist Svante August Arrhenius was the first to make a quantitative link between changes in carbon dioxide levels and changes in climate [*Arrhenius,* 1896]. Arrehenius reported that increased atmospheric levels of 'carbonic acid' (carbon dioxide) was created by increased use of fossil fuel associated with the Industrial Revolution. *Arrhenius* [1906] predicted that "...any doubling of the percentage of carbonic acid in the air would raise the temperature of the Earth's surface by 4 °C ..." and concluded that the "...percentage of carbonic acid in the atmosphere may by the advances of industry be changed to a noticeable degree in the course of a few centuries."

Arrhenius's calculations are close to the range of present estimates. For example, *Watson et al.* [1996] report that since 1750, around the beginning of the Industrial Revolution, carbon dioxide levels have increased by 30%, CH_4 by more than 100%, and N_2O by about 15%. The sharp rise in CO_2 shows up well in Figure 1. *Houghton et al.* [1996] predict at the present rate the Earth's temperature will increase 1.5 to 4.5° C, and atmospheric CO_2 will double between 2050 and 2100.

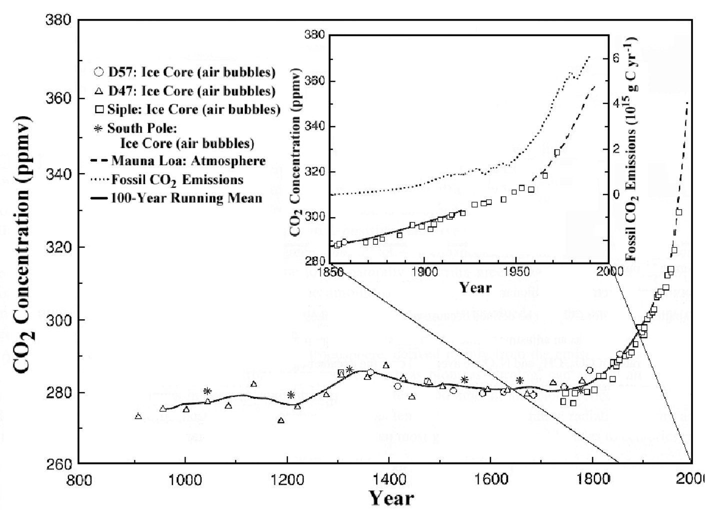

Figure 1. Long-term atmospheric CO_2 concentration. Data are from ice core records in Antarctica (D57, D47, Siple, and South Pole) and (since 1958) from the Mauna Loa Observatory, Hawaii. The smooth curve is based on a 100-year running mean. Inset shows CO_2 concentration from 1850 to present. Modified from *Houghton et al.* [1996].

1.1. Physical Climate

The period since 1980 has been the warmest in the past 200 years [*Fung*, 1997]. The greatest recent changes have been observed in the middle and high latitudes of the Northern Hemisphere where the seasonal CO_2 cycle varies in timing and amplitude. In the first direct observation using satellite imagery, *Myneni et al.* [1997] found that photosynthesis increased between 1981 and 1991 in the regions between 45° N and 70° N. A 30-year record (1961-1990) of annual and seasonal temperature variations in the northern latitudes show that warming dominates in the spring and winter, annual summer temperatures remained steady, and recent warming, reaching 1.25° C per decade, is strongest in the 50-60° N zone over the subpolar land areas of Alaska, northwestern Canada, and northern Eurasia [*Chapman and Walsh*, 1993]. *Myneni et al.* [1997] suggest that temperature increases in the spring are associated with a lengthening active growing season in the northern latitudes. *Keeling et al.* [1996] analyzed a 40-year record (1955-1995) of atmospheric CO_2 concentrations and found that warming in the higher latitudes may have led to an increase of about 6 days to the 150-day growing season.

A 24-year record (1973-1997) of data collected at the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) continuous monitoring stations, including Mauna Loa, Hawaii (19° N), and Point Barrow, Alaska (71° N), shows two trends (Figure 2A) [*Tans,* 1997; *Conway et al.,* 1994]:

(1) Both sites showed a steady annual increase in atmospheric CO_2 concentrations from an average level of about 330 parts per million (ppm) in 1973 to about 360 ppm in 1997.

(2) The greatest annual amplitude, or seasonal variation, occurred at the sites in the more northerly latitudes [*Keeling et al.*, 1996; *Tans and Conway*, 1997]. This biospheric oscillation in the data for the middle and upper latitudes is a result of the seasonal photosynthetic cycle of summer plant growth and winter dormancy.

CO_2 concentrations at NOAA's Cold Bay station (55° N) on coastal Alaska (showing trends 1 and 2 listed above) are representative of conditions at a study site in inland Canada at the same latitude (S. Wofsy, unpublished data, personal communication, 1998). Further, a 10-year record of latitudinal distribution of atmospheric CO_2 shows consistently that the highest annual concentrations are greatest in the high northern latitudes (Figure 2B) [*Tans and Conway*, 1997; *Conway et al.,* 1994].

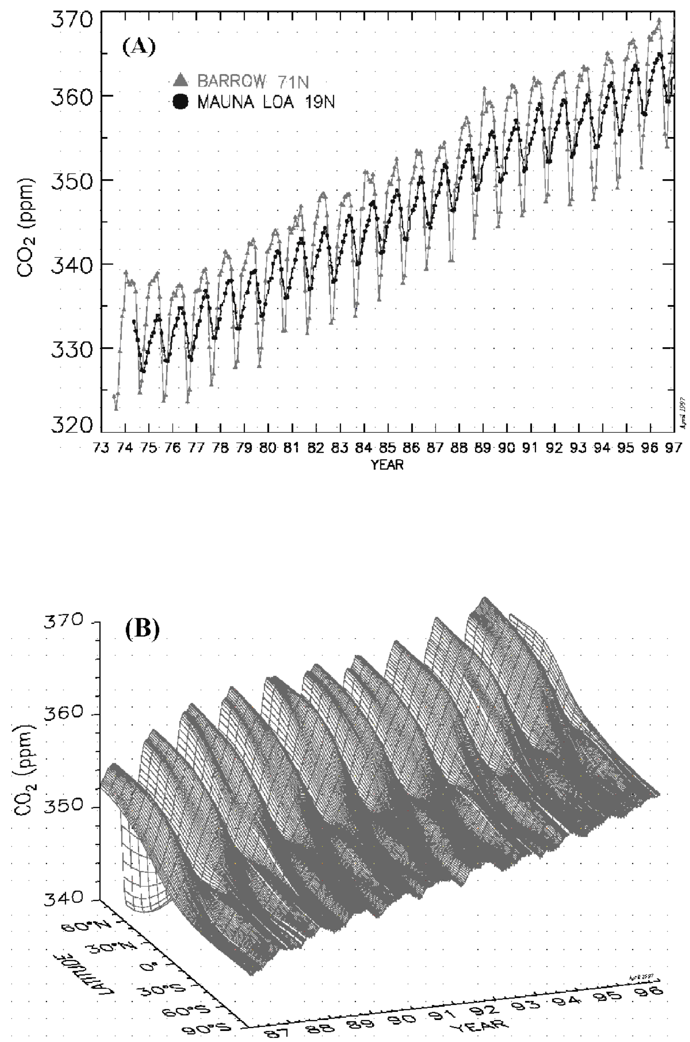

Figure 2. (A) Monthly observations of atmospheric CO_2 concentration from the continuous monitoring stations at Barrow, Alaska, and Mauna Loa Observatory, Hawaii. 1973-1997. Modified from *Tans* [1997]. (B) Latitudinal distribution of atmospheric CO_2 in the marine boundary. 1987-1996. The surface represents data smoothed in time and latitude. Modified from *Tans and Conway* [1997]. Source data for A and B are from the NOAA CMDL cooperative air sampling network.

1.2. Global Carbon Cycle

Physical climate is strongly linked with the global carbon (C) cycle. Global carbon is stored in and travels through several reservoirs, or pools, interconnected by many pathways of exchange. The major pools and the flows in the carbon cycle are shown in Figure 3 and listed in Tables 1 and 2. One important aspect of the carbon cycle is

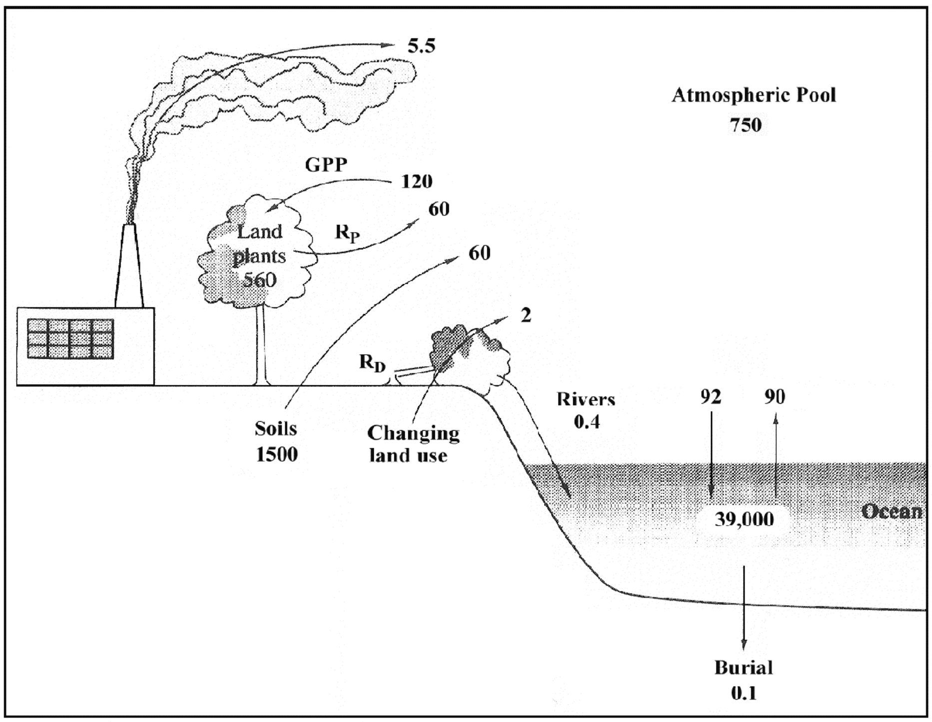

Figure 3. The global carbon cycle, showing the reservoirs (10^{15} g C) and fluxes (10^{15} g C yr^{-1}). Gross primary production (GPP); plant respiration (R_P); heterotrophic respiration (R_D). Modified from *Schlesinger* [1991], with average annual C fluxes from the 1980-1990 global carbon budget [*Houghton et al.,* 1998; *Reeburgh,* 1997]. (See also Tables 1 and 2.)

turnover (mean residence time). Turnover (T), the length of time in years that C stays in a particular pool before moving to another, is the ratio of the mass (M) of a reservoir to the total rate of removal from the reservoir (S) (where $T = M / S$) [*Schlesinger,* 1991].

Another aspect of the carbon cycle is carbon flux, or the rate of exchange of carbon between reservoirs. A reservoir may be a sink or a source of carbon. A pool that absorbs or takes up carbon released from another part of the carbon cycle is a sink. A pool that releases carbon to another part of the carbon cycle is a source. If the sink is greater than the sources of carbon, then its concentration will decrease; if the source is greater than the sink, C concentration will increase.

In the carbon cycle, photosynthesis removes carbon from the atmosphere when green plants capture energy from the sunlight and change it into chemical energy in the form of carbohydrates. Then, that energy is released through respiration and combustion. Microbial respiration of decomposing organic matter restores carbon to the atmosphere. Residues of organic matter from plants buried in geologic deposits have been transformed into hydrocarbons (commonly known as fossil fuels). Combustion of those deposits in the form of coal, oil, and natural gas, for example, also releases carbon to the atmosphere [*Rosenzweig and Hillel*, 1998].

The annual cycle of CO_2 in the atmosphere arises from the differences in timing of photosynthesis and respiration. In tropical rainforests, for example, there is little seasonal variation in the annual carbon cycle. Rates of photosynthesis and respiration are great but largely cancel each other out over a day or a month [*Fung,* 1997]. In the northern latitudes, however, where the growing season is short, photosynthesis and respiration are asynchronous, and the greatest amplitude of the CO_2 cycle is found (Figure 2A) [*Fung,* 1997].

1.2.1. Global carbon reservoirs and turnover times. The largest carbon reservoir is the ocean, which covers about 70% of the Earth's surface. Including the surface and deep ocean, marine biota, and ocean sediments, the ocean is thought to store about 39,000 gigatonnes (1 Gt = 10^{15} g)[1] of carbon. Turnover time in the deep ocean, the largest pool of C (38,000 Gt), is about 2000 years, while turnover times of C in the other oceanic pools range from <1 year to decades [*Reeburgh*, 1997].

The three smallest and most active carbon reservoirs -- the atmosphere, terrestrial biomass, and the soil -- are about the same size (Table 1, Figure 3) [*Reeburgh,* 1997]. The atmosphere stores an estimated 750 Gt C, with a residence time of 3 to 5 years. Somewhat smaller is the terrestrial biomass reservoir, storing an estimated 550-680 Gt C, with a turnover time of about 50 years (Table 1) [*Reeburgh*, 1997]. The living biomass actively exchanges with the atmospheric pool through photosynthesis and respiration. Soils are thought to store about 1500 Gt C [*Reeburgh*, 1997]. Upland forested soils and wetlands together store an estimated 380-740 Gt of C in soil organic matter (SOM, the fraction of the soil consisting of plant and animal residues at various stages of decomposition) [*Gorham*, 1991; *Post et al.*, 1982], an amount that represents about 20% to 35% of the total carbon stored in the terrestrial biosphere [*Schimel*, 1995]. The turnover times of soil carbon range from <10 to 10^5 years [*Reeburgh*, 1997].

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2.1 Gt C = 1 ppm atmospheric CO_2.

Table 1. Global Carbon Reservoirs and Turnover Times

Reservoir	Gt C[a]	Turnover Time
Sediments, rocks	77×10^6	$>>10^6$ yrs.
Deep ocean (DIC) [b]	38000	2000 yrs.
Soils	1500	$<10 - 10^5$ yrs.
Surface ocean	1000	decades
Atmosphere	750	3 - 5 yrs.
Deep ocean (DOC) [c]	700	5000 yrs.
Terrestrial biomass	550 - 680	50 yrs.
Surface sediments	150	0.1 - 1000 yrs.
Marine biomass	2	0.1 - 1 yrs.

Information in this table is from *Reeburgh* [1997].

[a] 1 Gt = 10^{15} g.

[b] Dissolved inorganic carbon.

[c] Dissolved organic carbon.

1.2.2. Global carbon budget. The global carbon budget is the balance of the exchanges of C between carbon pools or between a specific loop (*e.g.* atmosphere ⇔ soil). (See Figure 3.) The amount of C in various pools, particularly the atmosphere, and the amount of movement between various pools can have an effect on the global climate. Because of its small size and the relatively slow equilibration with the ocean reservoir, the atmospheric carbon reservoir is presently out of balance [*Reeburgh*, 1997].

Table 2. 1980 - 1990 Global CO_2 Budget (Gt C yr^{-1})

Sources	
Fossil fuel	5.5 ± 0.5
Net emissions from changes in land use	1.6 ± 1.0
Total	7.1 ± 1.5
Sinks	
Atmospheric storage	3.3 ± 0.2
Oceanic uptake	2.0 ± 0.8
Total	5.3 ± 1.0
Imbalance	
Residual terrestrial sink "The Missing Sink"	1.8 ± 1.5

Note: 2.1 g Carbon ⇔ 1 ppm atmospheric CO_2,
where 1 Gt = 10^{15} g.

Information in this table is from *Houghton et al.* [1998].

The global carbon budget for 1980-1990 (Table 2) [*Houghton et al.,* 1998] shows the difference between the sum of the average annual C sources to the atmosphere of 7.1 ± 1.5 Gt C (atmospheric C sources of net emissions from changes in land use (1.6 ± 1.0 Gt) plus fossil fuel combustion (5.5 ± 0.5 Gt)) is greater than the sum of the C sinks of atmospheric storage (3.3 ± 0.2 Gt) and oceanic uptake (2.0 ± 0.8 Gt). This imbalance of 1.8 Gt, required to balance the carbon budget, is the so-called "missing sink."

Several studies have shown that carbon is accumulating in terrestrial ecosystems [*Tans et al.,* 1990; *Ciais et al.,* 1995; *Keeling et al.*, 1996, *Denning et al.,* 1995]. This 'residual terrestrial sink' (Table 2) includes atmospheric carbon from fossil fuel emissions as well as other anthropogenic sources [*Houghton et al.,* 1998]. These recent studies indicate that the carbon unaccounted for (*i.e.* the "missing sink") may be in the latitudes north of 40° N and likely in boreal forests and the tundra region (F. Hall, personal communication, 1998) [*Sellers et al.,* 1997].

1.3. Role of Boreal Forests in the Global Carbon Budget

Boreal forests play an important role in the global carbon budget. Seasonal variations of CO_2 concentrations are greatest in the northern latitudes (Figures 2A, 2B). Models that calculate the latitudinal distribution of CO_2 sources and sinks from observed latitudinal distributions of atmospheric CO_2 concentrations suggest that boreal regions may be significant carbon sinks [*Tans et al.*, 1990; *Ciais et al.*, 1995].

The total area of the Earth's boreal ecosystem is vast, estimated to be between 13 million km^2 [*Post et al.,* 1982] and 20 million km^2 [*Sellers et al.,* 1997][2]. The boreal forest represents about 13% of the total terrestrial area and about 40% of the world's

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Sellers et al. [1997] computed the latter figure from the land classification of *DeFries and Townshend* [1994], published by *Meeson et al.* [1995] and described by *Sellers et al.* [1995b].

forests. About one-third of the residual terrestrial carbon sink (0.6 ± 0.5 Gt C yr^{-1}) has been observed in the northern forests, although the mechanisms responsible for this increased uptake are unclear [*Houghton,* 1998]. Given the global "missing sink" of 1.8 ± 1.5 Gt C yr^{-1} (Table 2) [*Houghton et al.,*1998], *Sellers et al.* [1997] and F. G. Hall (personal communication, 1998) calculate that, on average, sequestering 50-80 g C m^{-2} yr^{-1} would account for a 1 Gt C yr^{-1} global sink.

1.3.1. Role of boreal forest soils. Responses of boreal forest soils to warming, changes in drainage, or changes in fire frequency have all been proposed to be important for terrestrial carbon storage [*Bonan*, 1993; *Moore and Knowles*, 1990; *Gorham*, 1991; *Kasischke et al.*, 1995; *Kurz and Apps*, 1995]. Of the 1500 Gt of C stored in soils globally and 600 Gt of C in aboveground biomass [*Reeburgh*, 1997], about one-third of this global terrestrial C is found in the biomass, detritus, soil, and peat pools of the boreal forest biome, with about three-fourths of the C in boreal forest biome stored belowground [*Apps et al.*, 1993; *Peng et al.*, 1998].

1.3.2. Boreal forests of Canada. Clearly, the boreal forest plays an important role in the possible effects of global climate change on the carbon cycle. The Canadian boreal forests and peatlands occupy about 4 million km^2 [*Apps et al.,* 1993], about 20-30% of the world's total, and represent a significant portion of the world's total carbon (an estimated 709 Gt C), storing about 190 Gt C [*Apps et al.,* 1993]. Since the early 1990s the boreal forest of Canada has been the focus of study of a major international research program, described below. My study, briefly summarized in Section 1.5, concentrates on examining the carbon dynamics of boreal forest soils in Canada.

1.4. BOReal Ecosystem-Atmosphere Study (BOREAS)

The BOReal Ecosystem-Atmospheric Study (BOREAS) is a large-scale, international, interdisciplinary project focused in the boreal forests of Canada. The goal of BOREAS is to improve the breadth of knowledge and understanding of the boreal forests -- how they interact with the atmosphere, how much CO_2 they can store, and how climate change will affect them [*Sellers et al.,* 1994, 1995a, 1997]. To help researchers anticipate the effects of global changes in temperature and precipitation patterns as a result of greenhouse gas-induced climate change, BOREAS has two principal objectives:

(1) to collect data needed to improve computer models that would simulate the processes controlling these interactions;

(2) to then apply those models over larger spatial scales using remote sensing and other integrative modeling techniques.

1.4.1. BOREAS project research design. The research design of BOREAS is one of nested multiple-scale measurements designed to integrate observations and models over spatial scales ranging from <1 m^2 at the plot (local) scale to 1000 km^2, an area covering the BOREAS Study Region in Saskatchewan and Manitoba (Figure 4A). This region is the focus of meteorological and satellite data and large-scale modeling.

Two smaller study areas were established in the northern and southern portions of the region to examine the processes associated with factors (temperature in the north and moisture in the south) expected to control and influence any changes in the boreal forest itself [*Sellers et al.*, 1997]. The Northern and Southern Study Areas (NSA and SSA) are the focus of satellite and airborne remote sensing studies and airborne flux measurements as well as modeling on an intermediate scale. The NSA (8000 km^2) is located west of Thompson, Manitoba, and the SSA (11,700 km^2) lies north of Prince Albert, Saskatchewan (Figure 4A).

Within each study area is a test area known, interchangeably, as a modeling subarea (MSA) or Supersite (SST), designated for intensive modeling using gridded map layers as well as airborne remote sensing studies and flux measurements. The modeling subareas cover areas of 40 km $\times$ 30 km in the NSA and 50 km $\times$ 40 km in the SSA.
Within the MSAs are 10 tower flux (TF) sites, situated within relatively homogenous forest cover that is representative of the vegetation types at the sites. Each tower site occupies 1 km^2, at the center of which is/was a tower extending above the forest canopy and measuring radiation, heat, water, CO_2, methane (CH_4), and other trace gas[3] fluxes. The towers themselves operated almost continuously during the growing season from 1994 through 1996. Two of the towers (at the NSA Old Black Spruce (OBS) and the SSA Old Aspen sites) operated almost continuously from the fall of 1993 through 1996.

3

So named because the gases are present in small, or "trace," concentrations.

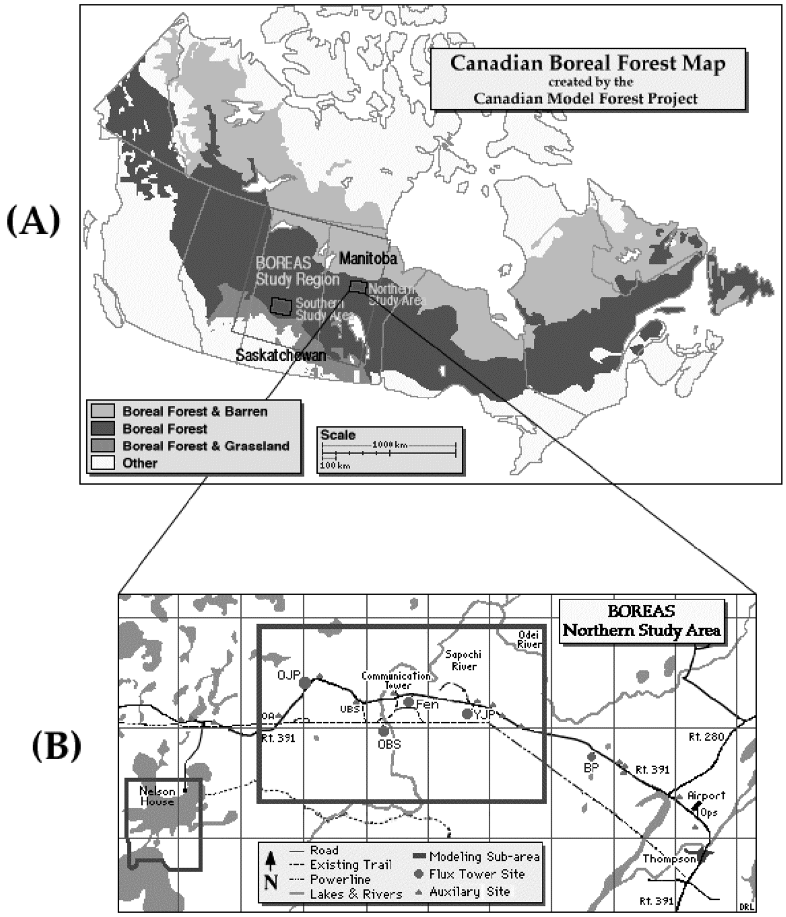

Figure 4. (A) Map of Canadian boreal forests showing the BOREAS study region and the northern and southern sites; (B) Map of BOREAS Northern Study Area. The 733 km^2 study area is drawn in black. The eddy flux tower sites are: Old Jack Pine (OJP), Old Black Spruce (OBS), Fen (FEN), Young Jack Pine (YJP), and Beaver Pond (BP). The canopy access towers at the auxiliary sites are: Upland Black Spruce (UBS) and Old Aspen (OA). These maps were modified from those publicly available courtesy of BOREAS, http://daacl.esd.ornl.gov/BOREAS/bhs/BOREAS_Home.html.

Both towers are expected to be in continuous operation for the foreseeable future. (TF sites in Northern Study Area are shown on Figure 4B.)

Eighty smaller study sites (called auxiliary or process study sites), some within the TF sites, were located throughout the study region. Measurements here were at the plot-, or local scale, covering areas from several cm^2 to 1000 m^2. The focuses in these sites were correlative studies of remote sensing measurements as well as a biometric survey that characterized vegetation dynamics of the region and carbon cycle studies that measured leaf physiology, litterfall, and soil carbon flux.

1.4.2. BOREAS science groups. From 1993 through 1996 field campaigns and monitoring measurements were undertaken by over 300 researchers from 85 science teams in six disciplinary groups plus the staff science and support teams. Most of the researchers were from the United States and Canada, although some were also from the United Kingdom, Australia, France, Russia, and Japan.

The Airborne Fluxes and Meteorology (AFM) group undertook local and regional scale flux measurements and established a network of meteorological monitoring stations within the Study Region. Several scientists from this group studied ground surface--atmospheric interactions using global-scale atmospheric models.

The primary objective of the Tower Flux (TF) group was to quantify the exchanges of energy between the atmosphere and the various boreal forest vegetation types to investigate the processes that control those fluxes. The work of the TF group was designed to complement smaller-scale ground measurements within the 1 km^2 sites surrounding the towers.

The Terrestrial Ecosystem (TE) group examined the biophysical controls on carbon, nutrient, water, and energy fluxes within the major forest types in the boreal forest landscape. Models developed from these studies scale from chamber measurements at the plot level to stand, landscape, and regional levels.

The Remote Sensing Science (RSS) group focused on vegetation, surface, and soil properties at leaf, canopy, and regional levels by using field, aircraft, and satellite sensors. The TE and RSS groups collaborated in gathering a wide range of biometric and radiometric data at the auxiliary sites.

The Hydrology (HYD) group characterized the storage of moisture at and near the land surface, in both solid and liquid states, and the fluxes of moisture to and from the land surface. The science teams focused on snow processes, hydrological modeling, and soil moisture measurements.

The Trace Gas Biogeochemistry (TGB) group, of which this study is a part, used chamber measurements and other field techniques to characterize the flow of gases, which included CO_2, CH_4, and nonmethane hydrocarbons (NMHCs), between the soil and the atmosphere. The group also quantified long-term accumulation of carbon in boreal forest soils.

The staff science and support teams have been responsible for operations management, logistical support, monitoring, infrastructure installation and maintenance, calibration of radiometric instruments, aircraft operations, and satellite data acquisition. Staff scientists and support contractors are from the National Aeronautics and Space Administration (NASA); Atmospheric Environment Service (AES), Canada; the Canadian Centre for Remote Sensing (CCRS); the School of Forestry, University of

Wisconsin; and the Canadian Forest Service. The NASA staff is also responsible for the BOREAS Information System (BORIS), which serves as the data organization, distribution, and short-term archiving center for the project. BORIS has implemented and maintained the BOREAS web site (http://daacl.esd.ornl.gov/BOREAS/bhs/BOREAS_Home.html), which describes the project and distributes data among the BOREAS science teams.

1.4.3. BOREAS data publication and distribution. The Distributed Active Archive Center (DAAC) at the Oak Ridge National Laboratory (ORNL) serves as the long-term archive for BOREAS data. BOREAS data are available on the World Wide Web at the ORNL DAAC (http://www-eosdis.ornl.gov/). By 2000 an estimated 300 data sets from BOREAS will be archived and available to the public through a set of compact disks (CD-ROM) produced by the BORIS staff [*Newcomer et al.,* 2000]. In addition, the staff is preparing a series of NASA Technical Memoranda (TM) of the data set documentation.

1.5. Using Models to Predict Regional C Fluxes

Predicting how the vast stores of organic carbon in the boreal forest biome will be affected by possible future global warming requires an understanding of the factors controlling the production, decomposition, and storage of organic C in boreal ecosystems. Inverse models that calculate the latitudinal distribution of CO_2 sources and sinks from observed CO_2 distributions suggest that boreal regions may be significant C sinks [*Tans* *et al.*, 1990; *Ciais et al.*, 1995]. However, according to David Schimel, forest inventories and land use studies do not explain where all the carbon is sequestered, perhaps because these approaches do not fully account for the soils, which may store as much as two-thirds of the missing carbon [*Kaiser*, 1998].

An alternative approach to determining C fluxes at the landscape or regional scale is to develop models that examine the processes of C dynamics and to use those models, together with a knowledge of the spatial distribution of important controlling factors (such as precipitation, temperature, and soil drainage), to extrapolate C fluxes from the plot-scale of observations to larger regions. Because it is process-based, this latter approach may also be used to predict the response of the landscape to changes in controlling parameters.

For example, models developed in each of the following four studies examined the processes of C dynamics in the soil, moss, and trees. In a study of boreal forest soils in Finland, *Liski and Westman* modeled the effects of a temperature gradient [1997a] and site productivity [1997b] to estimate and determine regional patterns of soil carbon storage. *Burke et al.* [1989] examined the effects of the major controls over soil organic matter content and predicted regional patterns of C storage in grasslands by modeling relationships between soil C and soil texture and differing precipitation and temperature conditions. *Bonan and Korzuhin* [1989] examined the ecological significance of interactions among site conditions, tree growth, and moss layer development in boreal forests of interior Alaska by simulating different climatic and forest canopy conditions.

Responses of boreal forest soils to warming, changes in drainage, or changes in fire frequency have all been proposed to be important for terrestrial C storage [*Bonan*, 1993;

Moore and Knowles, 1990; *Gorham*, 1991; *Kasischke et al.*, 1995; *Kurz and Apps*, 1995]. To confirm these inferences based on atmospheric CO_2 concentrations and to better understand the geophysical and biophysical factors, a better understanding of the surface biogeochemical processes expected in carbon cycling is needed.

To examine these processes in the boreal forest soils, I used field studies of C input, storage, and turnover in the northern region of the boreal forest, made as part of the BOReal Ecosystem-Atmosphere Study, to develop simple models linking soil C storage and rates of accumulation to two major factors -- soil drainage class and the time since last fire [*Trumbore and Harden*, 1997; *Harden et al.*, 1997]. These models have previously been combined with a soil drainage map for a 120-year-old black spruce (*Picea mariana*) stand at the BOREAS NSA Old Black Spruce (OBS) site (1 km^2), to compare the soil component of net C storage with tower-based eddy-covariance measurements of **net ecosystem production**[4], the rate at which carbon from the atmosphere is accumulated in the biosphere [*Harden et al.,* 1997].

In this study, I expand this scaling approach at a 1 km^2 site to estimate the soil C storage and flux for a 733 km^2 area within the BOREAS NSA Supersite. More specifically, I used plot-scale data from several intensive BOREAS field studies:

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4 See Glossary (Appendix E) for detailed descriptions of terms highlighted in bold type throughout the text.

(1) to estimate total C stocks (inventory) by horizon for common **soil series** on the basis of soil survey data and analyses of data from individual **soil profiles** [*Veldhuis,* 1998; *Veldhuis and Knapp,* 1998 ; *Trumbore et al.,* 1998];

(2) to estimate rates of soil C accumulation and loss on the basis of C stocks and a simple model of C turnover derived from field radiocarbon (^{14}C) studies [*Trumbore and Harden*, 1997] (see Appendix A for detailed discussion on radiocarbon dating);

(3) to relate patterns of soil C stocks and flux to patterns of drainage, moss cover, and fire history;

(4) to generate maps of soil C stocks and flux across the 733 km^2 study area in 1994, the year in which most BOREAS field studies were conducted;

(5) to identify areas of greatest sensitivity (the degree to which the system will respond to a change in conditions) and greatest uncertainty in these estimates;

(6) to demonstrate the utility of using a geographic information system (GIS) for landscape studies of atmospheric-biospheric interactions.

2. Approach

2.1. Study Area

The BOREAS Northern Study Area, an area surrounding Thompson and Nelson House, Manitoba, is near the northern limit of the closed-crown boreal forest (Figure 4A) [*Sellers et al.,* 1994]. The area includes: well-drained[5], upland jack pine (*Pinus banksiana*) stands on sandy deposits with Brunisolic soils (Inceptisols)[6]; black spruce-dominated stands with feather moss (*Pleurozium, Hylocomium* spp.) ground cover on moderately well- to imperfectly drained Luvisolic soils (Boralfs) developed on lacustrine clay; black spruce stands with abundant sphagnum moss (*Sphagnum* spp.) ground cover on more poorly drained soils developed on clayey sediments with Gleysolic and shallow Organic soils (Humaquepts and shallow Histosols); peatlands with permafrost (perennially frozen ground) with Organic Cryosols (Cryohemists); and low-lying peatlands with Organic soils (Histosols). Forest stand ages range from 13 to 140 years or more on uplands, marking the period elapsed since the last fire.

5

See section on **soil drainage** in the Glossary (Appendix E) for detailed descriptions of drainage classes used in this study.

6

Canadian soil classification [*Soil Classification Working Group,* 1998] (H. Veldhuis, personal communication, 1998) followed (in parentheses) by the U.S. soil taxonomy [*Soil Survey Staff*, 1975, 1998] (H. Veldhuis and E. Levine, personal communication, 1998).

The Supersite (SST) is an area of 1200 km^2 located within the NSA (Figure 4B), identified as a region of focus for remote sensing and modeling efforts in the BOREAS project [*Sellers et al.*, 1994, 1995a, 1997]. The study area consists of a 733 km^2 area within the Supersite (Figure 4B), for which a soil survey map was generated during the 1994 BOREAS field season [*Veldhuis and Knapp,* 1998]. Corner coordinates of the study area in latitude/longitude are: 56.00° N, 98.69° W; 56.00° N, 98.17° W; 55.80° N, 98.18° W; and 55.80° N, 98.69° W.

2.1.1. Physiography and surficial deposits. Part of the Kazan Upland, a part of the Kazan Region, which itself is part of the Canadian Shield [*Bostock,* 1970], the study area is underlain by fine- and coarse-grained bedrock of Precambrian origin that is blanketed by thick surficial deposits. During glaciation the entire area was covered by two ice sheets (Labradorean in the east and Keewatin in the west), and was subjected to scouring of bedrock and the removal and deposition of unconsolidated materials. Glacial deposits here are sandy, gravelly and, to a lesser extent, silty.

During deglaciation Glacial Lake Agassiz developed in front of the receding ice sheets, covering what is now most of southern and central Manitoba, reaching to about 59° 30' N [*Teller et al.*, 1983]. Large amounts of sediments were deposited in the deep water sections and in lines about the fluctuating shore lines. Glacial Lake Agassiz disappeared about 7500 years ago [*Klassen*, 1983] from all of northern Manitoba, and probably somewhat earlier from the study area [*Veldhuis,* 1995].

Because the landscape is a relatively young one [*Veldhuis and Rapalee,* 1999], drainage is not yet well-developed. The terrain is characterized by many depressions that lack drainage or are linked by slow moving brooks [*Veldhuis,* 1995]. As a result, development of organic deposits is widespread throughout the region. Most low-lying areas contain organic deposits of varying thicknesses and origin, the oldest of which date about 6500 years (H. Veldhuis, personal communication, 1998), some 1000 years after the time of the glacier. Adjacent gentle sloping uplands are often covered with thin peat, though these peat deposits are not as permanent as those that developed in the depressions [*Veldhuis,* 1995].

2.1.2. Climate. The area is characterized by long, cold winters and short, cool summers. Climatic records (1961-1990) [*Atmospheric Environmental Service*, 1992] from the Thompson Airport, the nearest meteorological station, indicate that the mean annual air temperature (MAAT) is –3.4° C and mean annual precipitation is 535.6 mm. Though both are highly variable, the mean frost-free period averages 93 days and number of growing degree days (days >5° C) averages 1038 [*Atmospheric Environmental Service*, 1992].

2.1.3. Soil climate. In the spring, soils in the study area are slow to warm. Fine-textured and wet soils and heavily shaded soils may remain cold throughout the growing season (Veldhuis, personal communication, 1998). Additionally, soils in older forest stands are colder. Soil climate data collected by *Veldhuis et al.* [1990] indicate that mean annual soil temperatures (MAST) at 50 cm depth range from 2.1° to 3.7° C on well-drained clay, about 2.8° C on poorly drained clay, and about 3.7° C on well-drained sandy soils. The mean summer soil temperatures (MSST) at 50 cm range from 5.7° to 8.9° C on well-drained clay, about 5.2° C on poorly drained clay, and 9.2° to 10.5° C on well-drained sands. Organic soils are colder than mineral soils; at a depth of 50 cm MAST is < 2° C and MSST is < 5°C [*Veldhuis,* 1995]. In a study of winter CO_2 fluxes at the BOREAS NSA, *Winston et al.* [1997] found that minimum monthly mean winter soil temperatures during the winter of 1993-1994 in two well-drained sandy sites ranged from about -5° to -15° C and at a poorly drained black spruce site from about -3° to -15° C. The winter of 1994-1995 was warmer with lowest measured temperatures 3° to 8° C higher than in the winter of 1993-1994.

Soil temperatures are influenced by vegetation characteristics. *Veldhuis* [1995] indicates MAST and MSST of an upland clay soil may be several degrees lower than reported above. MAST and MSST of upland clay areas tend to be low on sites with closed-crown spruce stands with feather moss ground cover.

2.1.4. Wetlands classification. Boreal wetlands are classified in several ways depending on their origin and nutrient status. For this study I differentiate between **fens** and **bogs**, and further differentiate among palsas and collapse scar, veneer, and peat plateau bogs. Fens are wetlands fed by groundwater that is relatively nutrient-rich, compared to the precipitation that is largely the water source for bogs. Vegetation of the fens is characteristically sedge (*Carex*, *Eriophorum* spp.) and brown moss (*Depranocladus, Tomenthypnum* spp.).

Bogs are **oligotrophic**, having their upper peat layer (rooting zone) above the groundwater flow, if present, and therefore have a rooting zone largely dependent on precipitation for its water and nutrient supply. Since productivity of wetlands depends on nutrient supply, fens are more productive than bogs. Sphagnum and/or feather mosses occur in bogs. Surrounded by frozen peatland and with no connection to the nutrient-rich waters of the fens, a **collapse scar bog** is a nutrient-poor circular or oval depression caused by subsidence of the peatland surface due to thawing of permafrost [*Rubec,* 1988; *Veldhuis and Knapp,* 1998]. A **veneer bog** occurs on gentle sloping terrain that is underlain by discontinuous permafrost with drainage predominantly below the surface except during high runoff [*Rubec,* 1988; *Zoltai et al.,* 1988a; *Veldhuis and Knapp,* 1998]. **Palsas** are mounds of upland peat underlain by perennially frozen peat and mineral soil, with rough and uneven surfaces, and are characterized by having domed surfaces. When a number of palsas coalesce, they form a bog with several highs and lows (hummock topography), where the surface itself may or may not be characterized by sphagnum hummocks [*Rubec,* 1988; *Zoltai et al.,* 1988b; *Veldhuis and Knapp,* 1998]. **Peat plateau bogs**, also underlain by continuous permafrost, rise abruptly from surrounding unfrozen fens, and are characterized by having relatively flat and even surfaces [*Rubec,* 1988; *Veldhuis and Knapp,* 1998].

2.1.5. Site description. Much of the region is underlain by poorly drained, **varved** clay deposited by Glacial Lake Agassiz and interspersed with frequent bedrock outcrops, but only few and minor exposures of well-drained sandy glacial till. Extensive areas of the clayey deposits are overlain by deep and shallow organic deposits. Most depressions are peat-filled, but shallow peat is often present on gentle, lower slopes and flat topped uplands. Permafrost occurs sporadically and at variable depths in clayey, upland soils and in veneer bogs [*Sellers et al.*, 1994; *Rubec,* 1988; *Veldhuis and Knapp,* 1998], and is continuous in collapse scar and peat plateau bogs and palsas [*Rubec,* 1988; *Veldhuis and Knapp,* 1998]. The area is undulating with long gentle slopes.

Drainage is poor as a result of interacting factors of climate, landscape form, and soil materials in this relatively young landscape in which the drainage pattern is not yet fully developed. Thus, moisture condition is a function of precipitation, modified by **evapotranspiration**, which itself is a function of vegetation type and temperature, the clayey soil, the formation of peat that impedes drainage, and surface and subsurface drainage.

In the eastern part of the study area, two major hills composed of sand and gravel (kame deposits) run north-south with relief up to 60 m [*Sellers et al.*, 1994]. Soils on these deposits tend to be well-drained, with predominantly jack pine vegetation as forest cover**.** (See Figures 5A and 6B.) Organic matter storage in these sandy sites is low compared to more poorly drained soils with clay **parent material**.

Soils contain C primarily in organic form, with only minor amounts associated with mineral material. The clay soils within a depth of <50 cm usually contain large amounts of calcium (Ca) and manganese (Mg) carbonates. Thus, although clayey soil surface horizons contain C primarily in organic form, with only minor amounts in the form of mineral C, exceptions occur where, through disturbance (windthrow and water erosion, for example) or frost action (cryoturbation), calcareous subsurface material is found at or near the surface (H. Veldhuis, personal communication, 1998).

Carbon storage in soils ranges from <5 kg C m^{-2} on well-drained sandy deposits, 10-25 kg C m^{-2} in clay soils with moderate to poor drainage, and >75 kg C m^{-2} in palsas, fens, and collapse scar bogs. Increased C storage in wetter areas is primarily in the form of moderately to highly decomposed organic matter (humics) and charred material

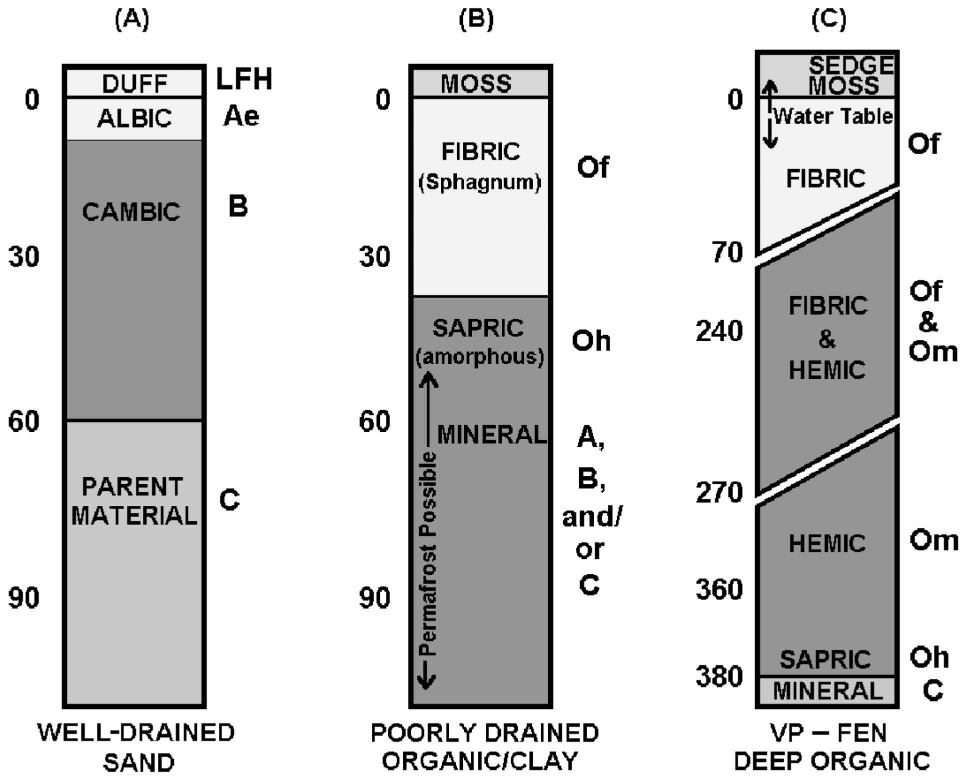

Figure 5. Typical boreal forest soil profiles from three sites: (A) well-drained sand, (B) poorly drained organic materials and clay soil, and (C) very poorly drained fen with deep organic material. Profile depths are in centimeters. Soil profile nomenclature is from the Canadian system [*Soil Classification Working Group,* 1998] and the U.S. soil classification [*Soil Survey Staff,* 1975 and 1998]. (See Appendix B for detailed descriptions of the soil horizons depicted in these profiles.) From *Rapalee et al.* [1998c].

(Figures 5B and 5C) and is linked to slowed decomposition rates associated with waterlogging and cold soil temperatures.

2.1.6. Drainage class/land cover type. Stratifying the study area by drainage class is an effective means of identifying vegetation type because land cover type (both forest and surface vegetation) is predictable by soil drainage. Six broad land cover types were identified on the basis of similarities in landform, drainage, depth of organics (peat), and dominant forest and moss cover [*Harden et al.*, 1997] (J. Harden, H. Veldhuis, and S. Trumbore, personal communication, 1997):

(1) upland, well-drained, sandy Eluviated Dystric Brunisols (Cryochrepts) with jack pine cover;

(2) upland, moderately well-drained, clayey Orthic Gray Luvisols (Cryoboralfs) with mixed black spruce and deciduous forest stands with feather moss as the dominant ground cover;

(3) transitional, imperfectly to poorly drained, clayey Gleyed Gray Luvisols and Luvic Gleysols (Cryoboralfs) with land cover of black spruce and a mixture of feather and sphagnum mosses;

(4) poorly to very poorly drained, level to gently sloping, clayey, peaty Luvic Gleysols and Terric Mesic Fibrisols (Cryoboralfs and Cryofibrists) with vegetation cover of black spruce and sphagnum moss mixed with feather and other mosses;

(5) peatlands consisting of varying peat materials that are well- to poorly drained at the surface, and have frozen peat and/or mineral material at depth (palsas and peat plateau bogs) with Fibric and Mesic Organic Cryosols (Cryofibrists and Cryohemists), and black spruce and sphagnum/feather moss vegetation cover;

(6) very poorly drained fens and permafrost collapse scar bogs with deep Typic Fibrisols (Cryofibrists), and sedge and brown moss vegetation.

2.1.7. Controls. Drainage and incidence of fire are the two factors most important in controlling annual accumulation rates of soil carbon in the boreal forest [*Bonan*, 1993; *Moore and Knowles*, 1990; *Gorham*, 1991; *Kasischke et al.*, 1995; *Kurz and Apps*, 1995]. Drainage affects the severity of fires, the kind of vegetation, and the rate of regeneration. For example, feather moss cover on moderately well- to imperfectly drained soils (often underlain by permafrost in mature black spruce stands) tends to dry out in summer because it does not overlie saturated soils, and hence will burn completely to mineral soil in an intense fire. In contrast, sphagnum moss cover is associated with imperfectly and poorly drained soils that tend to stay moist at depth and therefore burn less completely. Wetlands burn only infrequently, typically down to the water table (S. Trumbore, personal communication, 1996, 1997).

In addition to drainage, incidence of fire is an important feature controlling variations in C storage across the landscape. In the northern region of the boreal forest most fires are caused by lightning. Fire can burn dried-out organic material, such as relatively undecomposed litter (duff) and mosses on the surface of the soil. Thick organic mats of moss developed in older forest stands may store up to 4-5 kg C m^{-2} [*Harden et al.*, 1997], much of which may burn in the periodic fires that characterize the northern boreal region. A 1981 fire [*Peterson,* 1998] burned about 128 km^2 of the predominantly spruce-forested southern part of the study area. (See Figure 6A.) Smaller burns totaling about 33 km^2 occurred in 1956 and 1964 [*Peterson,* 1998] along the north-south ridge near the eastern boundary where primarily jack pine has regenerated. In 1989 large areas burned in the western and northern sections of the NSA, outside of the study area. None of the study region burned in 1994.

2.2. Soil Carbon Storage

Models of soil C dynamics were developed using data on C inventories and radiocarbon dating as part of the BOREAS field effort during 1993 to 1995 [*Trumbore and Harden*, 1997; *Harden et al.*, 1997; *Trumbore et al.,* 1998]. Upland soil profiles were divided into two layers (Figures 5A and 5B[7]) that are distinctly different in their C dynamics: (1) a surface detrital or moss layer, made up of relatively undecomposed organic material, and (2) a deep layer consisting of more highly decomposed organic matter (humic layer) in which macrofossils (fossil remains in the form of tree stumps, leaves, and seeds) are rare, and where minor amounts of organic matter are incorporated into the mineral soil A horizon. To include the soil profile to just above the parent material (Figures 5A and 5B), and therefore nearly all soil carbon, this study also includes the mineral B horizon (as per J. Harden, personal communication, 1997). Carbon dynamics differed for the two layers among each of the six identified major drainage classes.

2.2.1. Upland surface soil layers. The dynamics of C in upland surface layers is thus one of net accumulation in between fire events. Organic C is input directly to the

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7 See also Appendix B for detailed descriptions of soil profiles depicted in Figure 5 and for a general discussion of boreal forest soil horizons.

surface layer as detritus from trees and mosses. Decomposition rates are slow (with mean residence times of the order of decades), so that thick organic mats accumulate in the surface layers before losses through decomposition offset annual additions. Feather moss cover on moderately well- to imperfectly drained soils tends to dry out in summer because it does not overlie saturated soils and hence will burn nearly completely to mineral soil in stand-killing fires. In contrast, sphagnum moss cover is associated with imperfectly and poorly drained soils that tend to stay moist at depth and therefore burn less completely.

Within a spreadsheet I modeled soil C accumulation of the surface layers between fires as a simple balance of C inputs and first-order decomposition using the following equations from *Jenny et al.* [1949] and *Harden et al.* [1992, 1997]:

$$dC/dt = I - (k \times C) \tag{1}$$

Solving for C in Equation (1) yields:

$$C_{(t)} = (I \div k) \times \left(1 - e^{-k \times t}\right) \tag{2}$$

where C is carbon mass in units of mass per unit area,

t is number of years since the last stand-killing fire,

I is input rate of carbon in mass per unit area per year,

k is a decomposition coefficient in units of years^{-1}.

This model assumes that the C stock in surface moss and detritus is zero immediately following fire and that input rates and decomposition constants do not change over time as moss layers regrow and accumulate C after fire. The rate of accumulation is rapid at first, as inputs are much greater than decomposition, then slows as enough C accumulates so that decomposition losses nearly offset C inputs [*Harden et al.,* 1997].

To recognize the complexity of the effects of fire and drainage on soil C accumulation and decomposition in the study region, I examined the modeling approaches of two other studies of boreal wetlands [*Clymo*, 1984; *Frolking et al.*, 1996]. Here, both studies assumed the decomposition rates decline over time, with the decline estimated to be linear over time, as the *Frolking et al.* [1996] equations show:

$$dC/dt = I \div (1 + kt) \qquad (3)$$

Solving for C in Equation 3 yields:

$$C_{(t)} = (I \div k) \times \ln (1 + kt) \qquad (4)$$

In each method the underlying assumption is that net change in storage (dC/dt) represents a balance between annual C input (I) and decomposition (k). My approach in modeling has many assumptions and simplifications. I chose the simpler model (Equations 1 and 2) to be consistent with the purposes expressed by *Trumbore and Harden* [1997] to contrast decadal and millennial decomposition rates and to determine how those factors vary over the landscape of the study area. The rationale in using the simpler method is also closer to that of the *Harden et al.* [1997] study examining moss and soil contributions to carbon flux in a black spruce forest, at a site chosen as representative of the abundant black spruce-feather moss forests of the study area. *Harden et al.* [1997] found that allowing the value of *k* to change with time did not significantly improve the fit to their field data over that of a fixed *k* value.

Input (*I*) rates and decomposition (*k*) constants (Table 3) were determined using two approaches. First, vertical accumulations of moss were obtained using radiocarbon analyses to determine the age of accumulated C [*Trumbore and Harden,* 1997]. Second, surveys of the C inventory in organic matter above the most recent charcoal layer in the deep **soil profile** were made across a series of sites (chronosequence) that differed in time since last fire [*Harden et al.*, 1997; *Trumbore et al.,* 1998]. As noted by *Harden et al.* [1997], in upland soils C accumulates not only vertically, but laterally, as moss spreads over burned areas. For my extrapolation of upland moss, I used the estimates of *I* and *k* based on the chronosequence studies for upland sites with feather and sphagnum mosses on clay parent material [*Harden et al.*, 1997] to represent both vertical and lateral accumulation. The radiocarbon-derived *I* and *k* values were used for jack pine sites on sandy soils and for wetlands, where no chronosequence data are available [*Trumbore and Harden*, 1997]. This approach was found to be consistent with a two-component approach in which vertical and lateral accumulation were modeled independently [*Harden et al.*, 1997].

Table 3. Input (*I*) Rates and Decomposition (*k*) Constants for Surface and Deep Soil Layers

Soil Horizon	Drainage Class	*I*, kg C m^{-2} yr^{-1}	*k*, yr^{-1}
Surface	Well	0.06	0.07
	Moderately well	0.08	0.013
	Imperfect	0.07	0.0105
	Poor		
	Sphagnum moss	0.06	0.008
	Palsa	0.08	0.013
	Very poor		
	Fen	0.0324[a]	0.02[a]
	Collapse scar bog	0.0324[a]	0.02[a]
Deep	Well	0.015	0.01
	Moderately well	0	0.003
	Imperfect	0	0.002
	Poor		
	Sphagnum moss	0	0.0007
	Palsa	0	0
	Very poor		
	Fen	0.064	0.0004
	Collapse scar bog	0.064	0.0004

Information in this table is from *Trumbore and Harden* [1997].

[a] These values are fixed for a C inventory of 13 kg C m^{-2}, so as to give 0.064 kg C m^{-2} yr^{-1}, the input to the deep layers.

From *Rapalee et al.* [1998c].

Although the various components of litter layers, such as leaves, moss, and roots, decompose at different rates, the use of a single *k* value does a reasonable job of describing the decadal process of accumulation of C in regrowing moss and detritus in the BOREAS Northern Study Area [*Trumbore and Harden*, 1997; *Harden et al.,* 1997]. The majority of the mass of C in the slow-growing detrital layer is dead moss, and the *k* values derived from field studies largely describe decomposition of moss rather than the other litter components, which constitute a smaller fraction of the total C in the layer and which do not continue to accumulate substantially over decades.

2.2.2. Upland deep soil organic layers. The deep soil layers are composed of decomposed organic matter and the mineral A and B horizons. In contrast to the surface layers, which are made up of recognizable plant fragments, deep soil organic matter consists of humified material (dark-colored organic matter not associated with minerals in which pieces of moss and litter are no longer identifiable), charcoal, and mineral-associated carbon. The deep soil is derived from organic matter that was originally added as surface detrital and moss layers but was later transferred to deep organic layers through the accumulation of charred remnants of fires and the downward percolation of soluble organic material. Radiocarbon measurements show that most of the C in the deep organic layers has turnover times of centuries or millennia [*Trumbore and Harden*, 1997] and that these layers have accumulated slowly, influenced by many fire events over the millennia since the drying of Glacial Lake Agassiz (S. Trumbore, personal communication, 1997). (See also Appendix A for discussion on application of radiocarbon dating to soil C turnover.)

From the findings that *Harden et al.*[1997] report, for this study I assume that deep C pools in upland soils gain carbon immediately following fire and experience net C loss between fire events through decomposition. One exception to this assumption was made for the jack pine sites, where *Trumbore and Harden* [1997] found radiocarbon in the deep sandy soils from atmospheric thermonuclear weapons testing during the 1950s and 1960s. Hence C inputs must have occurred to these **soil horizons** during the last 30 years, probably from sources other than fire residues, such as inputs of C from pine roots and inputs from dissolved organic C. Pine and spruce roots are found in soil B horizons in well-drained sands and in the more poorly drained clay sites, respectively. However, roots in the black spruce sites do not normally penetrate into permanently saturated or frozen mineral soils.

Drainage has two effects on the deep organic material. First, inputs of charred material to the deep soil after burning are greater in the more poorly drained soils because the surface moss is less efficiently consumed in the fire (S. Trumbore, personal communication, 1997). Second, poorly drained soils have slower decomposition rates because diffusion of oxygen is slower in water than in air [*Clymo,* 1984]. Together, these two factors account for greater inventories of deep soil C in the more poorly drained soils.

Input (*I*) rates and decomposition (*k*) constants used in this study (Table 3) were derived using the accumulation of C and ^{14}C since deglaciation [*Trumbore and Harden*, 1997]. The *I* and *k* values for deep soil were used in Equation 1 along with estimates of deep soil C stocks from a soil inventory to simulate annual fluxes of C in or out of the deep soil.

2.2.3. Wetland soils. Wetland soils can also be split into two layers with distinctly different C dynamics [*Clymo*, 1984]: (1) the surface layers, which include the acrotelm (the aerobic portion of the soil profile above the water table in which the rate of decomposition is relatively high) and the upper portion of the catotelm (the submerged, anaerobic portion below the water table, where the decomposition rate is slow) where organic material is still recognizable, and (2) the deep horizons of the catotelm where organic matter is more decomposed (Figure 5C).

The surface layer of the wetland can dry out or grow above the water table. Decomposition rates of mosses in this upper zone are comparable to those in upland surface layers (Table 3). For fens and collapse scar bogs, I assume that the surface layer is at steady state (S. Trumbore, E. Davidson, personal communication, 1997) and that any C not decomposed is pushed below the water table to be added to the deeper layers. In contrast, on the frozen uplands (*e.g.* palsas) the frost table moves up with the rising surface stopping decomposition of those layers.

Trumbore and Harden [1997] found that the inventory of the surface layers of fens ranged from 6 to 13 kg C m^{-2}. For this study, I chose the inventory of the surface layer to be 13 kg C m^{-2}, because this is the C inventory required to calculate the observed deep input value of 0.064 kg C m^{-2} yr^{-1} [*Trumbore and Harden,* 1997], using surface values of I and k given in Table 3 (and $I_{deep} = I_{surface} - (k_{surface} \times C_{surface})$). This inventory corresponds to a depth of approximately 70 cm (Figure 5C), where the organic matter is visibly more decomposed (S. Trumbore, personal communication, 1997) and where bulk density (a measure of the compactness of the soil) increases. The top 70 cm increment includes C that has been fixed over roughly the last 50-100 years [*Trumbore and Harden*, 1997].

Below the water table, oxygen limitation slows decomposition rates [*Clymo*, 1984]. Unlike upland soils, where inputs to the deep soil are tied to fire, C is added continuously to deep layers of wetlands as the growing surface layer of moss pushes organic matter below the water and as the water table rises with the accumulation of the peat material. Decomposition in the deep wetland soils is affected by surface drainage and the presence or absence of permafrost. Carbon inputs and decomposition coefficients (Table 3) were determined from radiocarbon analyses and C inventory data for both surface and deep layers [*Trumbore and Harden*, 1997]. For the palsas and peat plateau bogs, I set deep decomposition rates to zero, because these layers are frozen solid year-round. Wetlands burn only infrequently, typically down to the water table.

In summary, my approach to scaling up the Supersite region was to: (1) combine soil survey data of drainage class and the historical record of time since fire with Equation 1 to calculate the stocks and 1994 fluxes of C into surface moss layers using I and k values determined for the six drainage classes (Table 3); (2) use data collected in soil surveys on C inventory to determine the deep C inventory for each polygon of the soil map; and (3) determine the fluxes of C lost from the deep C pool using the deep C soil stock estimates and I and k values (Table 3). As part of (2), I also show a relationship between deep soil carbon inventory and drainage class that may be useful for scaling to areas for which soil maps are not available.

3. Data Sources and Methods

The spatial base for my analyses is a soil polygon map from *Veldhuis and Knapp's* [1998] extensive and detailed 1994 soil survey of the 733 km^2 study area within the Supersite. The map is at 30 m resolution, in raster form, and uses the BOREAS grid coordinate system (on the basis of the Albers Equal-Area Conic projection) in the 1983 North American datum (NAD83).

Soils of the NSA Supersite were mapped using aerial photography flown in 1978 at 1:50,000 scale and field work along foot traverses at the site. The geo-referenced digital base map (used in this study) was generated using 1:50,000 scale National Topographic System (NTS) of Canada maps.

Accompanying the soil polygon raster image is an attribute table that describes in detail each component of each respective soil polygon. (See Appendix C for sample data table and list of soil attributes used in this study.) Spatial variation is indicated by estimates of the percent area of the total polygon occupied by the dominant soil series and each of the minor soil series inclusions within each map polygon. An inclusion is a soil type found within a soil polygon that is not extensive enough to be mapped separately or as part of a complex of soils. In the *Veldhuis and Knapp* [1998] survey, an inclusion covers <15% of the soil polygon, though the combined area of inclusions may total up to 25%.

3.1. Map of Forest Stand Age

My strategy in constructing the forest stand age map (Figure 6A) was to first fill in those areas within the larger study area for which I had definitive information on known incidence of disturbance or age of stand. Then, using that knowledge coupled with other site characteristics, such as vegetation type, drainage class, and soil type, I made some inferences so that I could fill in the rest. As with all maps generated in this study, my spatial base is *Veldhuis and Knapp's* [1998] soil polygon map to which I assigned an age or range of ages for each polygon.

Using a classified Landsat Thematic Mapper image (30 m resolution) from August 20, 1988 [*Hall and Knapp,* 1998] (image source is the Canadian Centre for Remote Sensing), I identified the burn scar of the large 1981 fire that encompassed most of the southwestern portion of the study area. Using the "Digitize" module of IDRISI for Windows Version 2.0 [*Eastman,* 1997], the perimeter of the regeneration area was screen-digitized and saved as a polygon vector image. Then using IDRISI's "Polyras" module, the vector image was converted to a raster image, and overlaid ("Overlay" module) onto *Veldhuis and Knapp's* [1998] soil polygon map. Using 1994 as the reference year for my study, I assigned a stand age of 13 years to those polygons and portions of polygons within the burn. I assumed any inclusion classified in the soil survey [*Veldhuis and Knapp,* 1998] as a fen or collapse scar bog did not burn in this or any other fire. Figure 6A shows those polygons for which 50% or more of the total area in the soil survey is delineated as fen and/or collapse scar bog.

From the series of Manitoba forest fire history maps (1:50,000 scale) that date from 1937 to 1995 [*Peterson,* 1998], I determined approximate locations of the major burns of 1964 and 1956. I then used digital maps (30 m resolution; original data was digitized from 1:15,840 scale maps) from the Manitoba Natural Resources (MNR) 1988 forest inventory, which includes three data layers: species cover, cutting class, and site class (which includes age ranges for the three major forest cover types) [*Knapp and Tuinhoff,* 1998; *Becker et al.*, 1996], I generated three additional data layers: (1) a consolidated forest cover layer consisting of three major forest cover types: black spruce, jack pine, and aspen (*Populus tremuloides*); (2) an age-class layer in which each polygon (forest stand) was coded by forest cover, cutting class, and site class; and (3) a stand age-class layer derived from (2) that assigns an age or age range for each forest stand. (See Appendix D for a detailed description of the MNR forest cover map layers.) I used the age-class data layer to isolate 30- to 40-year-old upland jack pine stands which occupy the north-south ridge in the eastern portion of the study area and that correspond to the sites identified on the Manitoba fire history maps [*Peterson*, 1998] as the 1964 and 1956 burns.

To establish age(s) of forest stands along Highway 391 (see Figure 4B), essentially an east-west transect through the study area, I used tree core data collected in the *Halliwell and Apps* [1996] extensive biometric survey of the BOREAS Northern Study Area. The *Halliwell and Apps* [1995] tie-in points were overlaid with the soil polygon map to identify the location of each sample point by soil polygon. From the tree core data I then calculated a mean forest stand age for all soil polygons along Highway 391 (except for one younger and one older jack pine stand for which I calculated separate averages) for which tree core data were available. Where trees were cored at breast height (1.3 m), I added 10 years for spruce and 5 years for jack pine and aspen (as per G. Peterson, personal communication, 1997) to the number of rings recorded. For all others I used the number of rings or whorls as recorded. I assumed that the mean stand age of the forest stands within the soil polygons was the mean stand age of the entire soil polygon.

To estimate stand ages for the remaining areas where there were neither fire scars nor tree core data, I relied on the stand age data layer (which gives a range of stand ages) derived from the Manitoba Natural Resources 1988 forest inventory [*Knapp and Tuinhoff,* 1998]. Noting that the more site-specific ages derived from the fire scar and tree core data were at the high end of the age ranges in the 1988 inventory, I used the high end of the MNR age ranges for all other areas. For areas that were not inventoried in the 1988 MNR survey, because of their unproductive wetland status, I assumed stand ages were the same as contiguous stands with similar characteristics for which data were available.

Thus, the forest stand age map (Figure 6A) is a compilation from several sources. Finite ages were assigned to the burn areas. I assumed that fires occur infrequently in fens and collapse scar bogs (as per S. Trumbore, personal communication, 1997) and did not assign stand ages in the model (rather assuming that surface layers remain in steady state). For all others I represent those stands/soil polygons with a range of probable ages and use the midpoint of that range for model input.

The resulting forest stand age map was used to model input. To run the model an age or age range was assigned to each inclusion of each soil polygon, except as noted above for the fens and collapse scar bogs.

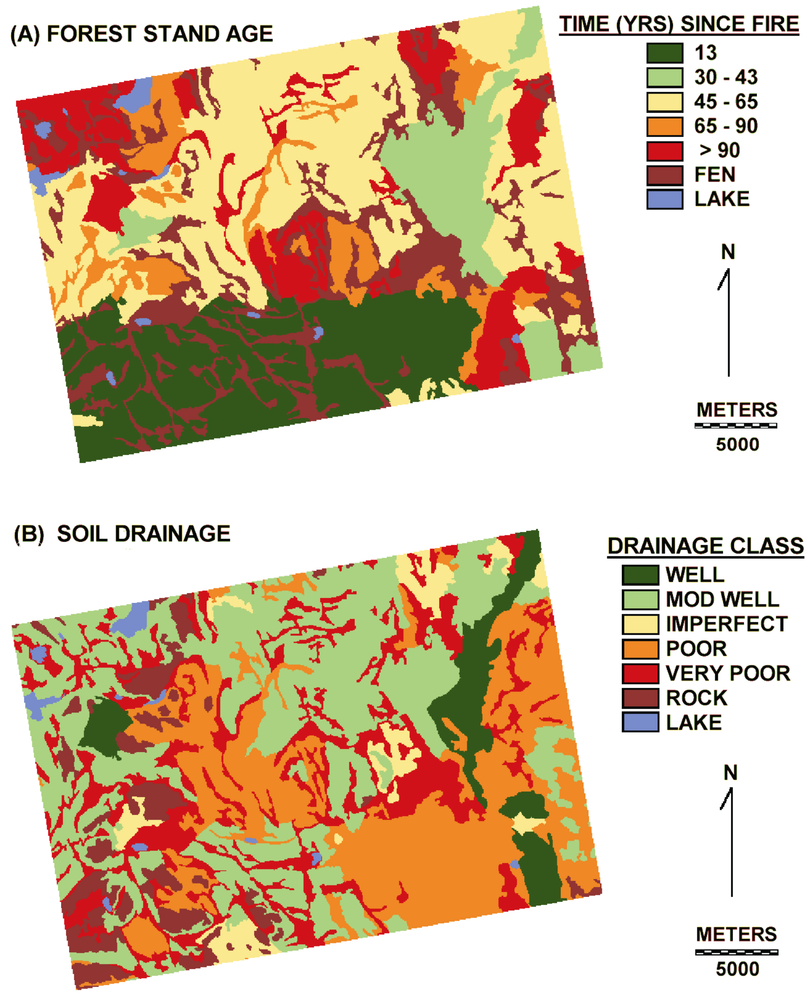

Figure 6. (A) Forest stand age map of the 733 km^2 study area compiled from satellite images, fire history maps, forest inventory, and tree core data. Age ranges represent time since last fire. The reference year is 1994. Fens are those soil polygons from the *Veldhuis and Knapp* [1998] soil survey for which 50% or more of the area is classified as fen and/or collapse scar bog and is assumed not to have burned. (B) Soil drainage map of the 733 km^2 study area. The map represents soil drainage by the dominant mapped soil series of soil polygons based on field observations of the *Veldhuis and Knapp* [1998] soil survey. Drainage classes are those from the Canadian soil classification and described in *Veldhuis* [1995]. Areas mapped as "rock" represent bedrock and exposed rock outcrops. From *Rapalee et al.* [1998c].

3.2. Map of Soil Drainage

The map of soil drainage (Figure 6B) represents the drainage class of the dominant soil series of each mapped soil polygon, all based on field observations from the 1994 soil survey [*Veldhuis and Knapp,* 1998]. The areas mapped as rock are those polygons with the greatest extent identified in the soil survey as bedrock and exposed rock outcrops.

Soil drainage classes listed here are those of the Canadian Soil Information System (CanSIS) [*Agriculture Canada Expert Committee on Soil Survey,* 1983 (also available on the World Wide Web at http://res.agr.ca/CANSIS/PUBLICATIONS/MANUALS/)]. In this classification drainage is described as the rapidity and extent of removal of water from the soil by runoff and flow downward through the soil to underground spaces and the frequency of and duration of periods when the soil is free of saturation [*Veldhuis,* 1995].

Soils in the study area range from dry and well-drained to wet most of the year. At well-drained sites the water source is precipitation and excess water moves readily downward or laterally. In moderately well-drained soils, however, water is removed somewhat slowly in relation to supply because of low perviousness, a shallow water table, lack of gradient, or a combination of these conditions. Imperfectly drained soils are wet for a significant portion of the growing season because the water is removed from the soil sufficiently slowly enough in relation to supply, the source of which may be precipitation or subsurface water or groundwater. Soils in poorly drained sites remain wet for a comparatively large portion of the year when the soils are not frozen because water is removed slowly enough in relation to supply, which may be subsurface flow and/or groundwater, or precipitation. In the very poorly drained sites, where groundwater flow and subsurface flow are the major water sources, the water table remains at or near the surface for the greater part of the time the soil is not frozen. (See section on soil drainage in Appendix E for more detailed descriptions of the five drainage classes shown on Figure 6B and described above.)

The purpose of Figure 6B is to show only general spatial patterns of soil drainage within the 733 km^2 study area. Not represented on this map are the minor inclusions of other soil series within each polygon. These accompanying data on the spatial extent of each soil series that was used in model calculations are described in Section 3.3.

Many of the soil polygons are composed of more than one component (or inclusion). Thus, Figure 6B is a result of reclassifying *Veldhuis and Knapp's* [1998] soil polygon map so that each polygon is now assigned the drainage class that was delineated for the map component(s) classified as dominant, or totaling ≥50% of polygon's total area. (See Appendix C for a sample data record (Table 8) from the soil survey and brief descriptions of each soil variable. For detailed descriptions of the variables in the soil survey, see *Veldhuis and Knapp* [1998] and *Rapalee et al.* [1998a].)

3.3. Soil Carbon Stock and Flux Maps

For generating the soil carbon stock (inventory) and flux maps (Figures 7 and 8) I followed the methods outlined by *Davidson* [1995] and *Davidson and Lefebvre* [1993] with a few adaptations to account for differences in the BOREAS data sets. The carbon stock and flux maps employ area-weighted estimates for soil polygons, numerically accounting for spatial variations in inclusions of unnamed soil series within each named soil polygon.

By using data in a GIS, mean C stocks and fluxes can be calculated for each land cover type for surface soil layers and for each soil series for the deep layers. Then those stocks and fluxes can be area-weighted (weighted according to their respective estimated areal coverage within the soil polygons).

As *Davidson and Lefebvre* [1993] show, mapping in this way recognizes the presence of soils that are relatively unimportant spatially but that may make significant contributions to soil carbon stocks. Because the surface and deep soil layers accumulate C at different rates and by different mechanisms, I estimated C stocks and fluxes independently for each. Total C stocks and fluxes are the sums of surface and deep C stocks and fluxes.

3.3.1. Surface soil carbon stock map. Data from soil pits were not used to calculate soil C stock of the surface layers because the depth of the surface layers is influenced more by time since last fire than it is a characterization of a given soil series. Instead, surface layer C stocks (kg C m^{-2}) were calculated for each fractional component (*i.e.* soil series inclusion) of each soil polygon, using *I* and *k* values appropriate to each drainage class (Table 3) and *t* values from the forest stand ages of the fire history map (Figure 6A). [See also *Rapalee et al.,* 1998a.] I calculated an area-weighted average of moss layer and surface layer C stock for each soil polygon by multiplying the C stock by the percent area covered by each respective component and then computing a sum for the entire polygon. Figure 7A shows area-weighted averages for the entire study area.

3.3.2. Deep soil carbon stock map. The average deep C inventory for each soil series was calculated from field observations of bulk density (BD), C content, and thickness of individual soil horizons made in 1994 by *Trumbore et al.* [1998] and *Veldhuis* [1998] for humic and mineral horizons (below the layer of charred material). These averages were used to calculate area-weighted deep carbon stocks for each polygon (Figure 7B). Twelve percent of the study area was mapped as being covered with soil series for which I had no profile data on depth, bulk density, and carbon concentrations. In these cases, I identified similar soil series, as indicated in *Veldhuis* [1995], and applied their deep soil C inventories to the soil series with missing data.

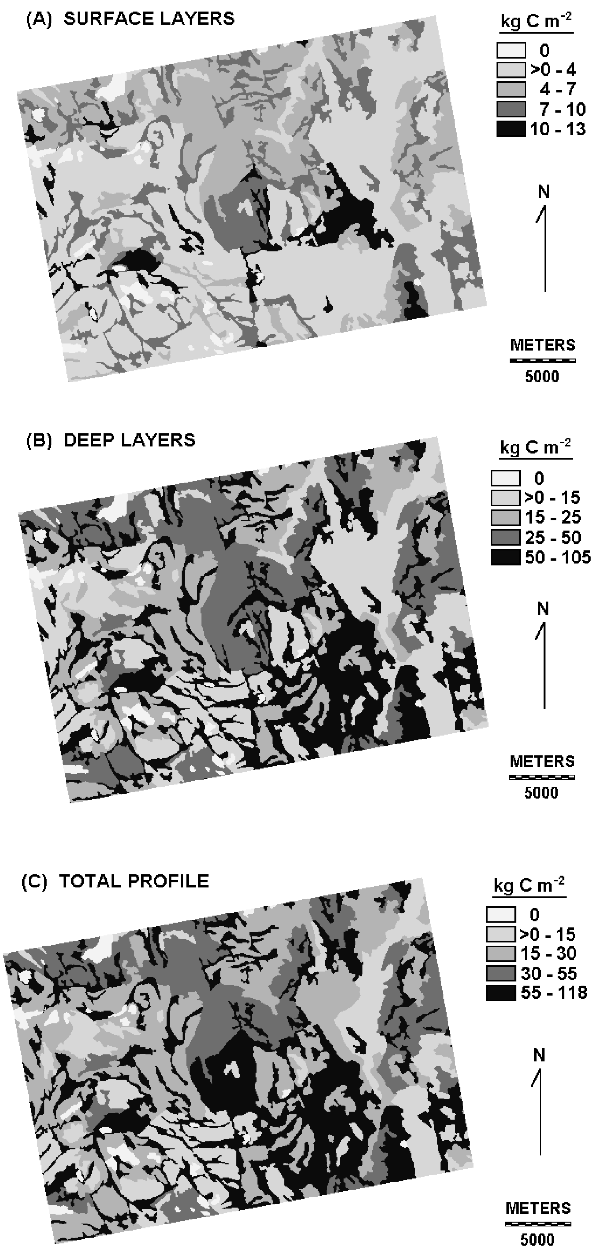

Figure 7. Soil carbon stocks of the 733 km^2 study area. The values represent area-weighted averages in kg C m^{-2} of (A) surface layers (including moss), (B) deep layers, and (C) total profile. Average C inventory for deep soils from similar soil series, as indicated in *Veldhuis* [1995], was applied for the 12% of the study area where no data were available for the mapped soil series. Depths varied among soil series. See text for discussion of surface and deep soil layers. From *Rapalee et al.* [1998c].

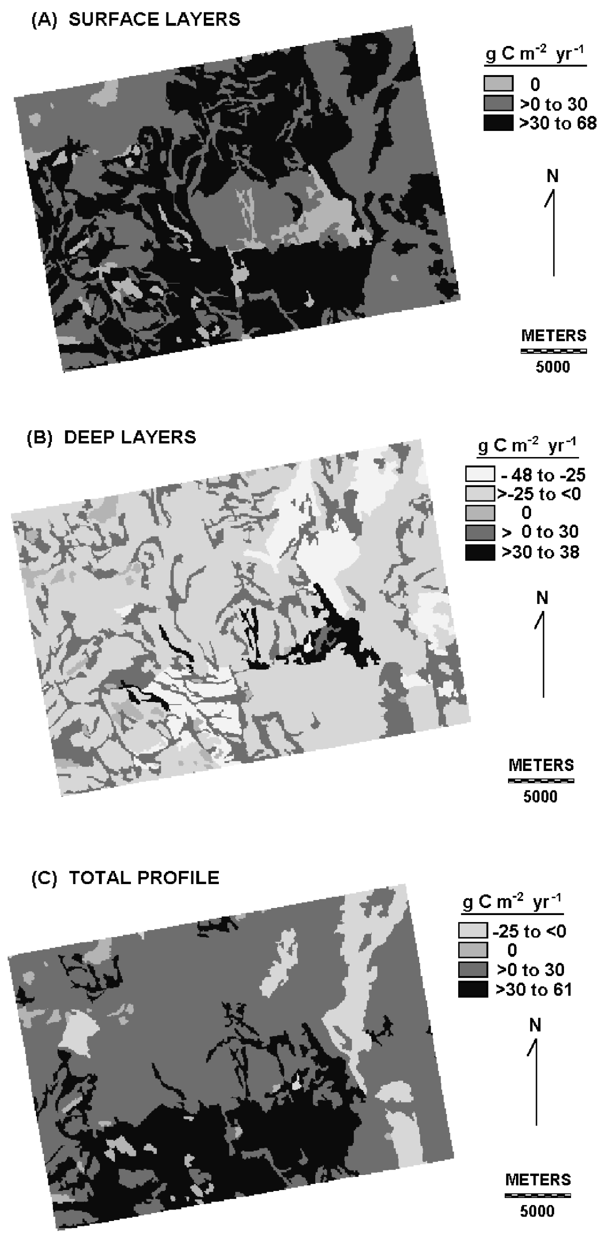

Figure 8. Soil carbon flux of the 733 km^2 study area. The values represent area-weighted averages in g C m^{-2} yr^{-1} of (A) surface layers (including moss), (B) deep layers, and (C) total profile. See text for discussion of surface and deep soil layers. From *Rapalee et al.* [1998c].

3.4. Bulk Density

Bulk density, which affects the capacity of soil to sustain plant life [*Anderson,* 1998], provides an overall picture of the soil's physical conditions. Bulk density is the measure of the mass of a unit volume of dry soil, commonly expressed as g cm^{-3}. This measure of compactness includes both the solids and the pores in the soil. The compactness of a soil is known to be related to its content of water and air, and to the temperature and the supply of nutrients [*Saini,* 1966]. As the literature [*Curtis and Post,* 1964; *Gosselink et al,* 1984; *Alexander,* 1989; *Huntington et al.,* 1989; *Federer et al.,* 1993; *Homann et al.,* 1995] and Figure 9 show, there is an inverse relationship between bulk density and the content and amount of soil organic matter, and thus organic carbon. Thus, bulk density is lower in loosely packed soils that are more aerated, are better drained, and have low C content. Bulk density is higher in those soils that are rich in organic matter and that also are denser and more poorly drained.

3.4.1. Estimating missing bulk density values. Because many soil profile descriptions of the study area had missing data on bulk density, I developed nonlinear regressions relating bulk density to carbon content for the soil profile descriptions that had both. Several published regressions for predicting bulk density from C concentrations [*Alexander,* 1989; *Huntington et al.,*1989; *Curtis and Post,* 1964] could not be used because my data sets included organic soils with high C content and mineral soils with very low C content (<1%), which extend beyond the valid range of these reported regressions. Instead, I developed two separate regressions on all of the soil data in both data sets used in this study:

Veldhuis [1998] (Figure 9):

$$\ln(\mathrm{BD}) = 0.271 - 0.066 \times \%\mathrm{C} \quad (R^2 = 0.91) \qquad (n = 29) \qquad (5)$$

Trumbore et al. [1998]:

$$\ln(\mathrm{BD}) = 0.132 - 0.072 \times \%\mathrm{C} \quad (R^2 = 0.77) \qquad (n = 35) \qquad (6)$$

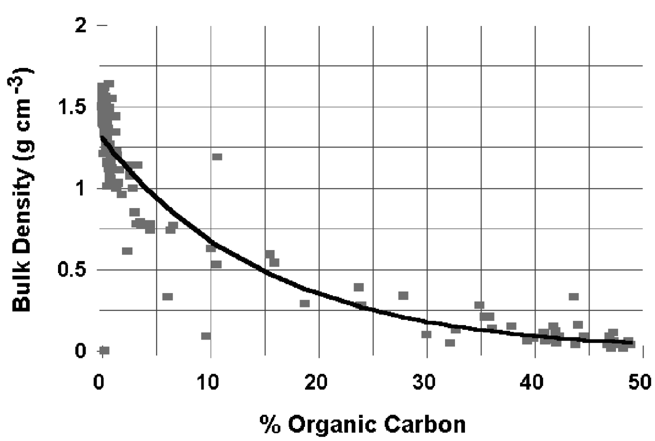

Figure 9. Bulk density (BD) versus percentage of organic carbon for all soil horizons of the *Veldhuis* [1998] data, where: $\ln(\mathrm{BD}) = 0.271 - 0.066 \times \%$ C. $R^2 = 0.91$. Curve for *Trumbore et al.* [1998] data [$\ln(\mathrm{BD}) = 0.132 - 0.072 \times \%$ C. $R^2 = 0.77$] is similar. From *Rapalee et al.* [1998c].

Missing bulk density data for horizons of soil series in both data sets were estimated from these equations. Carbon stocks of each deep horizon of each profile were calculated by multiplying bulk density by percent C and depth, and the products were summed for each deep soil series profile, including B horizons, when present [*Davidson and Lefebvre*, 1993]. Soil depth varied among soil series from 23 cm for the most shallow sandy soil profile to 495 cm for the deepest reported profile of a bog soil [*Veldhuis,* 1998]. The average C content of each soil series was multiplied by the percent area of the polygon covered by the respective soil series, and these products were summed for the each polygon, providing an area-weighted estimate of deep soil C stocks for each polygon (Figure 7B).

4. Results

4.1. Spatial Distribution

Table 4 shows the age and drainage class distribution of the 733 km^2 study area. The study site is a mosaic of drainage classes and stand ages, with no one class comprising more than 28% of the area.

The age ranges[8] in Table 4 represent time in years since the last fire. The results indicate that recent incidence of fire is a key factor in the age distribution of the site. About one-quarter of the total area is 43 years old or younger, having burned in 1956 and 1964 (10%) and in 1981 (18%). Another 28% is within the 45-65 year range and 6% in the 65-90 year range. Only 11% of the total area is greater than 90 years old, mostly at the NSA Old Black Spruce site. (See Figures 4B and 6A.)

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[8] The "reference year" for this study is 1994, the year when most of the field work was conducted. Therefore, ages and age ranges discussed here represent the age class distribution of the study area in 1994.

Table 4. Percent of Total Study Area by Forest Stand Age and Drainage Class / Land Cover Type

Drainage Class/	Time Since Fire, years					
Land Cover Type	13	30-43	45-65	65-90	>90	Total
Well						
Jack pine	0	5	< 1	0	1	6
Moderately well						
Black spruce/Feather moss	5	2	10	2	2	21
Imperfect						
Black spruce/Mixed mosses	3	1	6	1	1	12
Poor						
Black spruce/Sphagnum moss	4	2	9	2	3	20
Palsa	6	< 1	3	1	4	14
Very poor						
Fen						18
Collapse scar bog						1
Other						
Rock, water, lake						8
Total	18	10	28	6	11	100

Note: The reference year for this study is 1994, the year when most of the field work was conducted. Therefore, ages and age ranges shown here represent the age class distribution of the study area in 1994.

From *Rapalee et al.* [1998c].

Black spruce is the dominant forest cover, occupying 53% of the landscape in three drainage types. About half of the black spruce occurs in the 45-65 year age class, and the rest is distributed throughout the other age classes. Of the area dominated by black spruce sites, 21% of the area is moderately well-drained with feather moss ground cover, 20% is poorly drained sphagnum moss area, and 12% of the area is imperfectly drained with a mixture of sphagnum and feather mosses. In contrast, jack pine sites occupy about 6% of the total area, which is well-drained and mostly in the 30-43 year age range along the north-south ridge in the eastern section (Figure 6B), burned in 1964 and 1956.

Wetlands and palsas occupy about one-third of the total area. Poorly drained palsas cover 14% of the study area, about half (6%) of which is within the 1981 burn (13 year old stands) (Figure 6A). The very poorly drained fens and collapse scar bogs cover 18% of the total area distributed in the low-lying areas throughout the study area (Figure 6B).

4.2. Soil Carbon Stocks

4.2.1. Surface soil carbon stocks. Figure 7A and Table 5 show the amount of C in the surface soil layer in kg C m^{-2}. Moss and surface soil C stocks vary with forest stand age and drainage class, with lowest stocks in the well-drained, recently burned sites and highest in the very poorly drained and unburned wetlands (Figure 7A and Table 5). Averaged over the entire study area, surface C stocks are 4 kg C m^{-2}, but variability ranges from 13 kg C m^{-2} for the very poorly drained fens and collapse scar bogs to a mean of 3 kg C m^{-2} for the uplands.

Highest total surface C stocks are in the 45-65 year old black spruce sites that occupy the greatest total area of their respective drainage classes. Moderately well-drained feather moss sites cover 10% of the total study area storing 0.24×10^{12} g C. Similarly, poorly drained sphagnum moss sites occupying 9% of the total area store 0.19×10^{12} g C and imperfectly drained mixed moss sites (6 %) store 0.14×10^{12} g C.

4.2.2. Deep soil carbon stocks. The bulk of C is stored in the deep soil layers (Figure 7B), with C inventory ranging from 3 kg C m^{-2} in well-drained jack pine stands to 88 kg C m^{-2} in the very poorly drained fens and 131 kg C m^{-2} in the collapse scar bogs, with an average of 37 kg C m^{-2} for the entire study area (Table 5).

Deep C inventory is controlled by drainage class and is unaffected by recent fire history. As Table 5 shows, area-weighted averages of deep C stock in each drainage class vary only slightly among their respective age ranges. This is in contrast with surface C stocks, which are lowest shortly after fire and increase as the forest stands age. In the imperfectly drained sites, for example, deep C stocks are 20 and 19 kg C m^{-2} in the 13 and >90 year sites, respectively, but surface C stocks at the same sites increase from 1 to 5 kg C m^{-2}, respectively.

Table 5. Areal Coverage, Organic Carbon Stocks and Fluxes by Drainage Class, Vegetation Type, and Age Class for 733 km^2 Study Site Within the BOREAS Northern Study Area

Drainage Class	Vegetation Type	Age Class	Area		Carbon Stock: Area-Weighted Average			Carbon Stock: Total for Study Area				Carbon Flux: Area-Weighted Average			Carbon Flux: Total for Study Area		
					Surface	Deep	Total	Surface	Deep	Total	Total	Surface	Deep	Total	Surface	Deep	Total
			km^2	%	kg C m^{-2}			10^{12} g C			%	g C m^{-2} yr^{-1}			10^9 g C yr^{-1}		
Well	Jack pine	13	0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		30-43	33	4.5	0.8	2.8	3.6	0.03	0.09	0.12	0.4	6.6	-13.1	-6.4	0.2	-0.4	-0.2
		45-65	2	0.3	0.8	3.7	4.6	0.00	0.01	0.01	<0.1	0.9	-22.2	-21.3	<0.1	-0.1	<0.0
		65-90	0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		>90	11	1.4	0.9	3.1	4.0	0.01	0.03	0.04	0.1	0.1	-16.0	-15.9	0.0	-0.2	-0.2
Moderately well	Black spruce	13	37	5.0	1.0	9.6	10.6	0.04	0.35	0.39	1.4	67.6	-28.8	38.7	2.5	-1.1	1.4
	Feather moss	30-43	12	1.7	2.1	12.7	14.8	0.03	0.16	0.18	0.6	52.8	-38.0	14.8	0.7	-0.5	0.2
		45-65	71	9.6	3.3	11.0	14.3	0.24	0.78	1.01	3.6	36.7	-32.9	3.8	2.6	-2.3	0.3
		65-90	12	1.7	3.7	11.6	15.3	0.04	0.14	0.19	0.7	32.2	-34.9	-2.7	0.4	-0.4	< 0.0
		>90	15	2.1	4.4	9.8	14.2	0.07	0.15	0.22	0.8	22.7	-29.5	-6.8	0.4	-0.5	-0.1
Imperfect	Black spruce	13	21	2.8	0.8	19.6	20.4	0.02	0.41	0.43	1.5	60.8	-39.2	21.7	1.3	-0.8	0.5
	Mixed mosses	30-43	6	0.8	1.9	15.6	17.5	0.01	0.09	0.10	0.4	49.7	-31.2	18.5	0.3	-0.2	0.1
		45-65	46	6.2	3.1	19.7	22.8	0.14	0.90	1.05	3.7	36.9	-39.5	-2.6	1.7	-1.8	-0.1
		65-90	8	1.1	3.4	15.3	18.7	0.03	0.13	0.16	0.6	33.2	-30.6	2.6	0.3	-0.3	0.0
		>90	8	1.1	4.8	19.4	24.2	0.04	0.16	0.20	0.7	25.3	-38.9	-13.6	0.2	-0.3	-0.1
Poor	Black spruce	13	26	3.6	0.7	11.7	12.5	0.02	0.31	0.33	1.2	54.1	-8.2	45.9	1.4	-0.2	1.2
	Sphagnum moss	30-43	14	1.9	1.7	14.1	15.8	0.02	0.20	0.22	0.8	46.5	-9.8	36.7	0.7	-0.1	0.5
		45-65	68	9.3	2.9	12.0	14.9	0.19	0.82	1.01	3.6	37.1	-8.4	28.7	2.5	-0.6	2.0
		65-90	12	1.6	3.2	11.7	15.0	0.04	0.14	0.18	0.6	34.3	-8.2	26.1	0.4	-0.1	0.3
		>90	24	3.3	4.2	14.3	18.4	0.10	0.35	0.45	1.6	26.7	-10.0	16.7	0.7	-0.2	0.4
Poor	Palsa	13	44	6.0	1.0	69.9	70.9	0.04	3.06	3.10	11.0	67.6	0.0	67.6	3.0	0.0	3.0
		30-43	<1	<0.1	2.6	55.9	58.5	<0.01	0.01	0.01	0.1	45.7	0.0	45.7	<0.1	0.0	<0.1
		45-65	23	3.1	3.3	60.8	64.1	0.08	1.39	1.47	5.2	36.7	0.0	36.7	0.8	0.0	0.8
		65-90	8	1.1	3.7	65.3	68.9	0.03	0.51	0.54	1.9	32.2	0.0	32.2	0.3	0.0	0.3
		>90	31	4.2	4.8	70.3	75.1	0.15	2.16	2.31	8.2	21.6	0.0	21.6	0.7	0.0	0.7
Very poor	Fen	N/A	131	17.9	13.0	88.0	101.0	1.7	11.6	13.3	47.0	0.0	28.8	28.8	0.0	3.8	3.8
	Collapse scar bog	N/A	9	1.2	13.0	130.6	143.6	0.1	1.1	1.2	4.4	0.0	11.7	11.7	0.0	0.1	0.1
All soils			673	91.7	4.7	37.3	42.0	3.2	25.1	28.2	100	30.9	-9.2	21.8	20.8	-6.2	14.7
Other	Rock, water, lake	N/A	61	8.3	0.0	0.0	0.0					0.0	0.0	0.0			
Total area			733	100	4.3	34.2	38.5					28.4	-8.4	20.0			

N/A = Not applicable

From *Rapalee et al.* [1998c].

4.2.3. Total soil carbon stocks. Figure 7C shows the total soil C stocks calculated for the region, the sum of surface and deep layers. Total soil C stocks covary with drainage classes and are dominated by the deep soil layers, with the largest C stocks occurring in the more poorly drained sites. Table 5 shows that although the very poorly drained fens and collapse scar bogs together occupy only about one-fifth of the total area (18% and 1%), they account for a little over half of the total carbon stocks (47% and 4%, respectively). Poorly drained palsas cover 14% of the landscape and account for 26% of total C stocks. Table 5 shows that the entire study area is storing 3×10^{12} g C in the surface soil layers and 25×10^{12} g C in the deep layers, for a total of 28×10^{12} g C.

4.3. Soil Carbon Fluxes

4.3.1. Surface soil carbon flux. Fluxes for surface layers were calculated using Equation (1), with *I* and *k* values from Table 3 for the forest stand ages and six drainage class types from Figures 6A and 6B. [See also *Rapalee et al.,* 1998a.] Calculated annual fluxes in the surface layers range from an average of 64 g C m^{-2} yr^{-1} in the 1981 burn site (13-year-old stands) to 21 g C m^{-2} yr^{-1} in sites >90 years, and with an average of 28 g C m^{-2} yr^{-1} for the entire 733 km^2 study area (Table 5 and Figure 10A). Not shown in Figure 10A are the fens and collapse scar bogs, where surface C stocks are assumed to be at steady state (zero annual flux). In the uplands, forest stand age influences surface C storage rates more than does soil drainage (Figure 10A). Total annual accumulation of atmospheric carbon in the surface soil layers is an estimated 21×10^9 g C (Table 5).

4.3.2. Deep soil carbon flux. Deep C fluxes represent net C losses (releases) from upland soils to the atmosphere, and were calculated in the same way as for surface layers (Equation 1), but with the *I* and *k* values for inputs and decomposition constants for the deep soil layers indicated in Table 3. Modeled net deep soil losses for the entire 733 km^2 study area are losing 9 g C m^{-2} yr^{-1}, with an estimated total annual release to the atmosphere of 6×10^9 g C (Table 5). Losses for upland soils range from 0 in the palsas to about 40 g C m^{-2} yr^{-1} from imperfectly drained soils (Figure 10B). Although decomposition rates are faster in moderately well-drained upland soils, the C inventory is lower, so fluxes are smaller than for imperfectly drained soils. For poorly drained soils, decomposition rates are very slow (Table 3), so that fluxes are smaller even though C inventories are large. I have assumed that deep C losses are zero for the perennially frozen deep soils in the palsas, and that jack pine sites on well-drained sandy soils are at steady state (C inputs from pine roots equal C losses) [*Trumbore and Harden*, 1997].

In the fens and collapse scar bogs, however, deep soil layers are accumulating C, because the input values (*I*) exceed losses ($k \times$ C; Equation 1). The model estimates that the fens are storing on average 28.8 g C m^{-2} yr^{-1} in deep layers (Table 5). This is in accord with *Gorham's* [1991] estimated annual accumulation rate of 29 g C m^{-2} yr^{-1}, derived from synthesizing results of several studies of undrained and unmined boreal and subarctic peatlands.

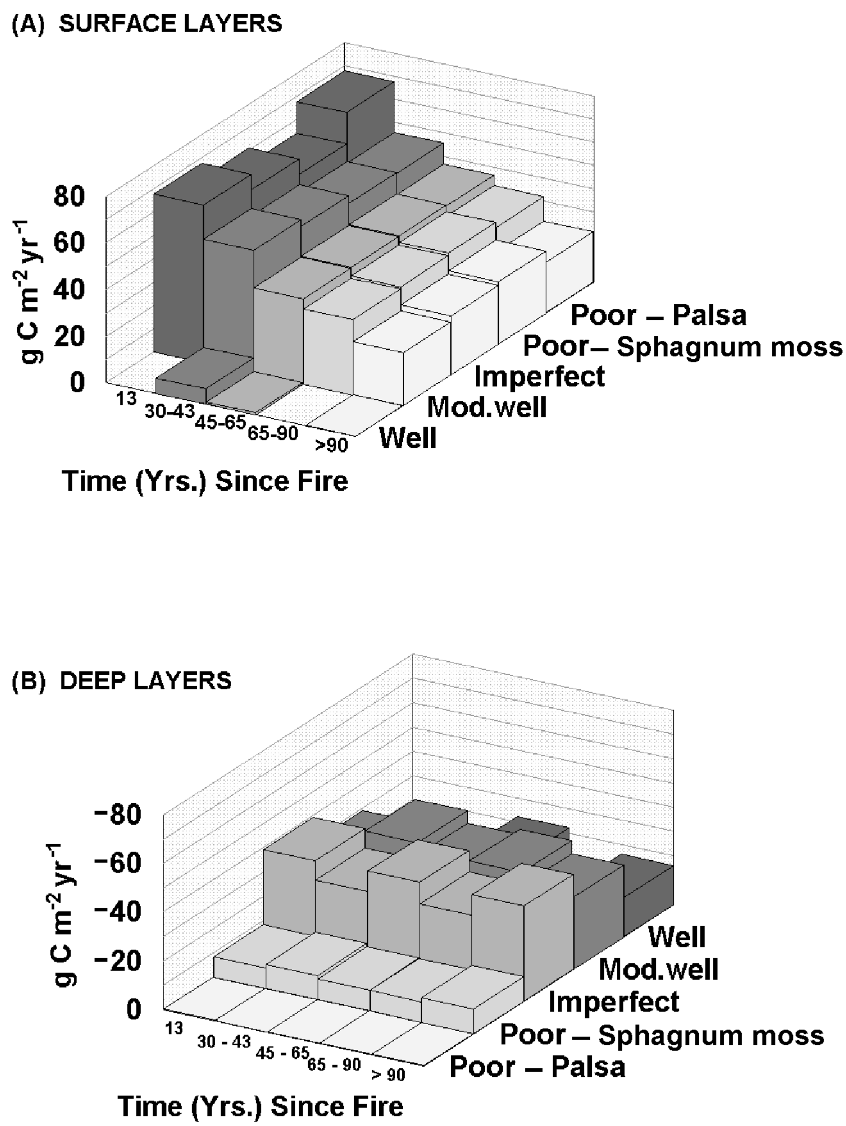

Figure 10. (A) Rates of C accumulation (positive values) in surface layers (including moss) for drainage class and time since fire (forest stand age). (B) Rates of C loss (negative values) from deep organic layers (below moss) and mineral soil as a function of soil drainage and time since fire. Fens and collapse scar bogs (not shown) are gaining an estimated 29 and 12 g C m^{-2} yr^{-1}, respectively, in the deep layers. From *Rapalee et al.* [1998c].

4.3.3. Net soil carbon flux. Losses of C from the deep soil of uplands in years between fire events partly cancel the rate of accumulation of C in the upper moss layers, resulting in a net change of nearly zero for the entire soil-moss profile. Soil C fluxes in the total profile depend on both drainage class and time since last fire, with the largest rates of soil C accumulation in fens and in the surface mosses of recently burned sites (Figure 8C). (Compare with Figure 6A.)

These results indicate that the study site was a small net sink of atmospheric C in 1994, with gains in regrowing surface moss layers largely offset by decomposition in deep, humic soil layers. Estimated rates of C storage are 20 g C m^{-2} yr^{-1} averaged over the 733 km^2 study area, and they sum to 15×10^9 g C for the entire study area (Figure 11 and Table 5). Most of the accumulation occurs in the poorly drained black spruce-sphagnum moss sites (4×10^9 g C), the palsas (5×10^9 g C), and the very poorly drained fens and collapse scar bogs (4×10^9 g C). Only the well-drained jack pine sites are showing a small net annual C loss (-0.4×10^9 g C) (Figure 11).

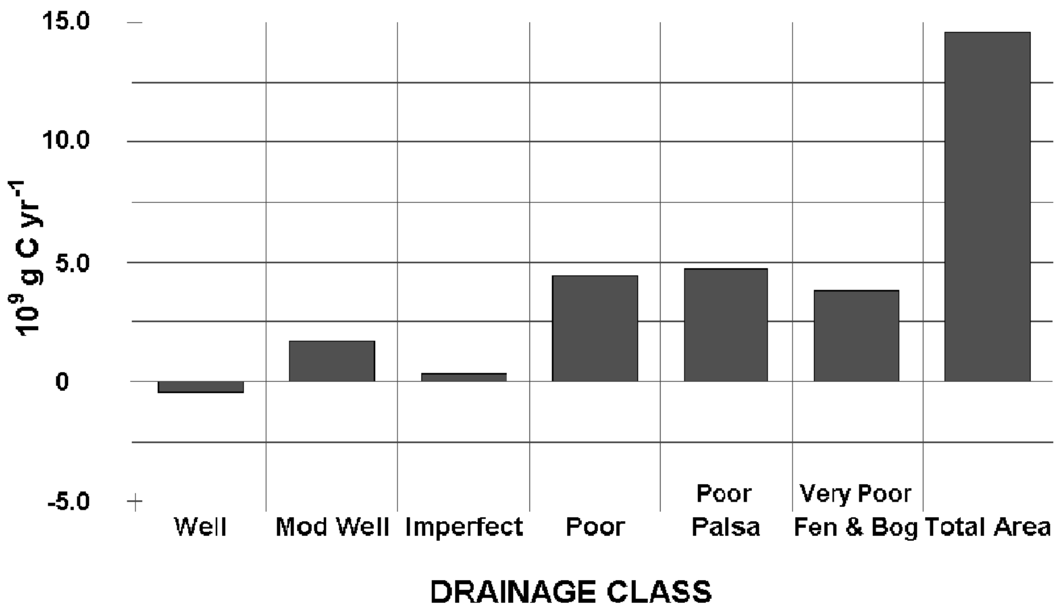

Figure 11. Total annual C soil flux (10^9 g C m^{-2} yr^{-1}) by drainage class for entire 733 km^2 study area. From *Rapalee et al.* [1998c].

5. Sensitivity Analyses

Sensitivity analysis of a model is a method of testing the degree to which a system will respond to a change in conditions. The purpose is to evaluate the effects of the model performance by altering its parameter, coefficient, or input values to determine which parameters most control the results and at what level. A widely used technique to test the effects is to vary the model input, thus narrowing down the range of possible input. For example, each of the following six studies compares conditions of the "reference," or "standard," case with results from changing input variables that represent a range of observed values.

Frolking et al. [1996] modeled daily carbon balance of a black spruce-feather moss site and compared the results with preliminary data from the 1994 BOREAS field work at the Old Black Spruce site in the NSA. The authors then carried out a series of model runs, where, in each case, a single parameter was raised or lowered by 20%. The purpose of the test runs was to evaluate the sensitivity of the model by comparing results of each test run with the standard to determine which parameter(s) most control carbon balance.

In a study simulating climatic effects on hydrologic output in a watershed, *Curd* [1996] systematically varied 15 model parameters by 9 percentages and applied those changes to three years -- the median, and the years with the lowest and the highest recorded streamflow. Then, calibrated parameters were used to simulate a controlled streamflow for each year.

In a simulation of carbon and nitrogen cycling in an alpine tundra ecosystem, *Hartz* [1997] and *Conley et al.* [1999] altered site and species specific characteristics by −50%, +50%, and +100% to determine their effect on key model outputs. These key model outputs served to define ecosystem function and included total soil carbon, **net primary productivity (NPP)**, net nitrogen mineralization, and plant nitrogen uptake.

Parton et al. [1987] analyzed factors controlling soil organic C and nitrogen (N) levels by modeling the effects of climatic gradients and grazing intensity on soil organic matter (SOM) and plant productivity at 24 sites in the Great Plains. The modeled, or simulated values, were then compared with field data. To test sensitivity to climatic factors, observed maximum and minimum monthly temperature and monthly precipitation were used. To determine how sensitive SOM levels could be to changes in grazing intensity, *Parton et al.* [1987] varied grazing levels from 0 to 50% of annual plant production.

McGuire et al. [1997] evaluated the sensitivity of global and regional responses of NPP and C storage at doubled atmospheric CO_2 levels to changes in nitrogen concentration in vegetation. The authors conducted simulations of their model in which they compared their reference case of doubled CO_2 concentration with (1) simulations where N concentration was reduced without influencing decomposition dynamics and (2) simulations where reduced nitrogen concentration did influence decomposition. The simulations (1 and 2) were run with three different concentrations of N.

Harrison et al. [1993] examined a strategy to estimate the impact of CO_2 fertilization on global soil carbon storage by developing estimates of carbon turnover rates. Their sensitivity analysis compared an estimated turnover time of 25 years and its corresponding fertilization rate with turnover times of 20 and 30 years.

The results presented in my study represent estimates of the conditions for a particular year (1994), a year in which there was no fire. Following the approach used in the studies mentioned above, I investigated the effects (sensitivity) of the model under different scenarios when, for example: (1) climate changed and air temperatures increased, the soil dried and decomposition rates increased; (2) fire frequency increased; or (3) a lightning fire swept through the entire area.

I tested the sensitivity of the modeled soil C dynamics to two factors: (1) assigned values for deep (k) decomposition constants and (2) estimates of forest stand age, as these are the two inputs to the model with the greatest uncertainty. The first test compared results using a range of deep layer decomposition constants, including the "reference case" of values reported in Table 3 and high and low k values that are within the ranges *Trumbore and Harden* [1997] report to be consistent with their radiocarbon data (Table 6). Using faster decomposition rates for deep soil organic layers, individual soil series may become C sources rather than C sinks as losses of deep soil C more than offset C gains in surface moss layers. Presented in Table 6 are estimates of mean area-weighted C flux (g C m^{-2} yr^{-1}) for 92% of the study area (673 km^2), excluding areas mapped as rock, water, and lakes. These results show that the deep C flux averaged over the entire area ranged from a small sink (+5 g C m^{-2} yr^{-1}) using the lowest k values to a source (−22 g C

m^{-2} yr^{-1}) using the highest *k* values. The calculated deep soil C loss using the high *k* values is large enough to almost completely counter the surface layer sink. The results highlight the potential importance of deep soil C in the net budget of the system and the importance of narrowing uncertainties in the estimates of deep soil C decomposition rates.

Table 6. Sensitivity Analysis of the Effects of Deep Soil C Decomposition Constants on Simulated Carbon Fluxes

	Scenario Decomposition Constants, yr^{-1}		
Drainage Class/Vegetation Type	Reference	Low	High
Well-drained sand Jack pine	0.01	0.007	0.012
Moderately well-drained clay Black spruce/feather moss	0.003	0.0006	0.006
Imperfectly drained clay Black spruce/mixed mosses	0.002	0.0006	0.003
Poorly drained Black spruce/sphagnum moss	0.0007	0.0005	0.0009
Very poorly drained Fen and collapse scar bog	0.0004	0.0002	0.0005

	Mean Area-Weighted C Flux for Total Study Area[a], $g\ C\ m^{-2}\ yr^{-1}$		
Soil Horizon	Reference	Low	High
Surface	30.9	30.9	30.9
Deep	– 9.1	+ 4.9	– 21.5
Total profile	21.8	35.8	9.4

[a] Values cover 673 km^2, total area mapped as soils (Table 5).

From *Rapalee et al.* [1998c].

The second sensitivity analysis estimated changes in annual soil C flux if the entire study area (except fens and collapse scar bogs) had burned 13, 30, 60, and 120 years ago (Table 7). In effect, each of these simulations assumes the 1981 fire, the 1964 fire, and two older fires, which correspond to average stand age and the age of the Old Black Spruce tower site, had each uniformly burned the entire study area. As with the previous analysis, the estimates represent mean area-weighted C flux (g C m^{-2} yr^{-1}) for 92% of the study area. Total simulated C flux for the surface layers is 46 g C m^{-2} yr^{-1} in the scenario where the entire site burned 13 years ago and decreases to 14 g C m^{-2} yr^{-1} at 120 years after fire (Table 7). Using a uniform stand age of 120 years, the total calculated C flux is near zero (5 g C m^{-2} yr^{-1}), with release of C by the deep layers (−9 g C m^{-2} yr^{-1}) nearly offsetting annual uptake of atmospheric CO_2 by the surface layers (14 g C m^{-2} yr^{-1}).

Table 7. Sensitivity Analysis of C Accumulation in Moss and Surface Soil Layers, Assuming Entire Area (Except Fens and Collapse Scar Bogs) Burned 13, 30, 60, or 120 Years Ago

	Mean Area-Weighted C Flux[a], g C m^{-2} yr^{-1}		
Time Since Fire, years	Surface Layers	Deep Layers	Total Profile
Reference case (1994)	30.9	− 9.1	21.8
13	46.4	− 9.1	37.3
30	37.9	− 9.1	28.8
60	26.8	− 9.1	17.7
120	13.9	− 9.1	4.8

[a] Values cover 673 km^2, total area mapped as soils (Table 5).

From *Rapalee et al.* [1998c].

6. Discussion

The model estimates that average net soil C storage was about 20 g C m^{-2} yr^{-1} over the 733 km^2 study area of northern boreal forest in 1994 (Table 5), which is a modest sink of atmospheric CO_2. Using an eddy-covariance method, *Goulden et al.* [1998] estimated that the 120-year-old Old Black Spruce study site had net ecosystem productivity (NEP) ranging from a loss of 70 g C m^{-2} yr^{-1} to a gain of 10 g C m^{-2} yr^{-1}.

Woody biomass was accumulating 20-40 g C m^{-2} yr^{-1}, thus indicating that the moss and soils were losing 10 to 100 g C m^{-2} yr^{-1}. The average forest stand age across the 733 km^2 area, however, is 45-65 years, and this analysis shows that stand age is an important factor in soil C accumulation rates, especially for surface soils and moss layers in upland sites. Stands like the 120-year-old OBS tower site occupy <10% of the NSA map area. Scaling fluxes measured by eddy-covariation techniques at a few towers (compare Figures 4B, 6A, and 6B) in this mosaic landscape of drainage class and stand age could be misleading. Even so, the modeled estimate of 20 g C m^{-2} yr^{-1} sequestered by soils is modest and is within the range of error and interannual variation reported by *Goulden et al.* [1998]. Interannual variation is a measure of fluctuation about a long-term measured mean of such factors as temperature, precipitation, and rates of carbon decomposition and accumulation. *Gower et al.* [1997] compute interannual variation as (annual maximum – annual minimum) ÷ number of years of observations.

While studies on interannual variability of C fluxes in boreal forests have concentrated on extrapolating stand-level responses of photosynthesis and respiration to differences in climatic conditions [*e.g. Frolking et al.*, 1996; *Frolking,* 1997; *Goulden et al.*, 1998], results from this study show that significant interannual variability in regional C exchange rates may also result from interannual differences in the occurrence of fire. For example, the 1981 fire burned approximately 17% of the study area (128 of 733 km^2). The average soil C accumulation rate in 1981 is estimated by the model to have been 27 g m^{-2}. Assuming that burning of the moss layer in this 128 km^2 fire released 2000 g C m^{-2}, then the net soil C flux in 1981 was a net *loss* of 317 g C m^{-2} yr^{-1} (27 g C m^{-2} yr^{-1} $\times$ 0.83 – 2000 g C m^{-2} yr^{-1} $\times$ 0.17). For comparison, *Frolking* [1997] estimated that interannual differences in C storage at the OBS tower site varied between 0 and 125 g C m^{-2} yr^{-1} because of physiological response to interannual anomalies in weather. Hence, averaged over large regions, interannual variability in C exchange may result from changes in the lateral extent of fire as much or more than direct responses of the vegetation to climatic conditions.

Putting the importance of fire another way, the release of C from the moss layer by a fire covering only 1% of the area in any year would offset the amount of C stored in soils of the rest of the area (20 g C m^{-2} yr^{-1} $\times$ 0.99 – 2000 g C m^{-2} yr^{-1} $\times$ 0.01). The fire return interval (the number of years between two successive fires in a given area) for Alaskan boreal forests has been estimated to be 150 years [*Kasischke et al.*, 1995], with a range in various North American boreal forest types of 70-500 years [*Payette,* 1993]. If the fire cycle (the number of years necessary to burn at least one time an area equal to the total area) were about 100 years, then the carbon budget in this study area for a year with no fire might suggest that the soil C stock may be roughly at steady state over large areas and long time scales. Over millennial time scales, soil C storage rates since the drying of Glacial Lake Agassiz are of the order of only a few g C m^{-2} yr^{-1} [*Trumbore and Harden*, 1997; *Harden et al.*, 1997]. However, the incidence of fire is variable over space and time and could be changing in response to climate change and management practices. For an annual C budget of a local site, the time since the last fire is critical. For decadal or centennial scale budgets over the region, fire frequency (the number of fires per unit time in a given area) and its variability over the landscape are clearly important.

A major uncertainty in determining the present and future role of soils as C sources or sinks is the role of the deep organic matter in the C budget of upland soils. Decomposition rates of deep organic layers are an order of magnitude slower than those in surface layers (Table 3), which might lead to the assumption that the deep soil is not important in C cycling. However, large stores of C are present in the deep layers, so even at slow rates of decomposition, losses on an annual basis are significant, and interannual differences in decomposition of deep soil C can affect the C balance of a whole forest stand [*Goulden et al.*, 1998]. I have assumed that the deep soil C pools show net losses of C in between fire events. Comparison of soil C balance with eddy-covariance measurements of NEP [*Harden et al.,* 1997], evidence of increases in late summer soil respiration [*Goulden et al.*, 1998], and radiocarbon measurements in soil CO_2 [*Winston et al.*, 1997] all support this hypothesis.

Considerable uncertainties remain about the origin and dynamics of this important deep soil C pool. The radiocarbon data used by *Trumbore and Harden* [1997] to calculate inputs and decomposition constants may have been influenced more by the frequency and severity of burning than by actual decomposition rates of the humic materials. Incubation measurements [*Fries et al.*, 1997; *Moore and Knowles*, 1990] show that deep organic C decomposes rapidly if warmed and dried. These findings suggest that the slow decomposition rates inferred from radiocarbon studies are constrained by physical conditions (cold and wet) within the soil, rather than by the ability of the organic matter itself to decompose. I cannot, therefore, necessarily predict decomposition rates for this pool should global warming occur. Although deep soil C has accumulated slowly over millennia, the dynamics of this large C pool may dominate the response of northern boreal forest to future changes in fire frequency or climate.

7. Summary

High and mid-latitude ecosystems would be expected to experience the largest temperature changes if the Earth warms. Boreal forest soils, where most soil carbon accumulates in the moss layer and organic and humic horizons, are both an important source of and sink for atmospheric carbon. Therefore, responses of boreal forest soils to warming could have important effects on the interactions between climate change and terrestrial carbon storage. This study examined the present patterns of soil C distribution and the soil properties that correspond with soil carbon. Understanding these present interactive processes is essential for projecting future changes.

Part of BOREAS, an interdisciplinary project which examines how the boreal forests of Canada interact with the atmosphere, how much CO_2 the forests can store, and how climate change will affect the boreal forests, my study concentrated on the carbon cycle in boreal forest soils and presented one method of quantifying soil carbon dynamics over a regional scale. I examined the movement of carbon in and out of the soil, how much and where in the soil profile carbon is stored, and annual rates of carbon accumulation and loss.

The goals of this study were to estimate total carbon stocks by horizon for common soil series; estimate soil carbon flux based on C stocks and a simple model of C turnover derived from radiocarbon studies; generate area-weighted maps of soil carbon stocks and flux; and relate patterns of carbon stocks and flux to patterns of drainage, moss cover, and fire history. Another goal was to identify areas of greatest sensitivity and the greatest uncertainty in these estimates.

The focus of study was a 733 km^2 area, located in northern Manitoba, close to the northern limit of the closed-crown boreal forest. Soils in the study area had been surveyed and mapped in 1994 and 1996 at both the soil pit and regional scales. This study also incorporated data from several other BOREAS studies.

The boreal forest landscape is complex. Soil carbon dynamics differ in time and space according to depth and location in the soil profile, drainage, and time since the last disturbance -- most often caused by lightning fire. The study area includes well-drained upland jack pine stands on sandy soils, mixed black spruce and deciduous stands on moderately well-drained soils developed on lacustrine clay, and black spruce stands on imperfectly and poorly drained soils developed on clay. The study area also includes low-lying wetlands consisting of fens and bogs. Forest stands range in age from 13 to 140 years, the time elapsed since the last fire.

Drainage and incidence of fire are the two factors thought to be most important in controlling annual accumulation rates of soil carbon in the boreal forest. Drainage affects the severity of fires, the kind of vegetation, and the rate of regeneration. Periodic fires characterize the northern boreal region, controlling variations in C storage across the landscape. Using data from the soil surveys I stratified the study area by drainage class, which also corresponds to vegetation type. From fire scars detected on satellite images and fire history maps as well as forest inventory and tree core data, I determined the age of the forest stands in the study area.

I divided the upland soil profiles into two layers that are distinctly different in their carbon dynamics: (1) a surface layer that includes moss and soil that is recognizable as organic material, and (2) a deep layer consisting of more highly decomposed organic matter (humic material), charred material, and the mineral A horizon where minor amounts of organic matter are incorporated. The mineral B horizon was also included in this deep layer. Surface layers accumulate C between fires and turnover times are about 10 times shorter than for deep layers in which C accumulates slowly, integrating over many fire cycles.

Because carbon dynamics are different in surface and deep soil layers, I estimated total C stocks using a different method for each layer. Carbon stocks for surface layers were estimated based on a time-dependent model of moss growth after fire. For the deep soil layers I estimated C stocks by common soil series based on soil survey data and analyses of data from individual soil profiles. I estimated surface and deep soil carbon flux for 1994, the year in which most of the field studies were conducted, based on C stocks and a simple model of carbon turnover derived from radiocarbon field studies.

Finally, I tested the sensitivity of the modeled soil carbon accumulation and loss to two separate broad scenarios to account for the range of uncertainty of the C flux estimates and to simulate effects of changes in the fire cycle. In the first test I modified the fire cycle over 120 years, and in the second I varied decomposition rates of the deep soil based on findings of radiocarbon dating studies conducted in the study area.

The results show that the study area is a mosaic of drainage classes and stand ages. No one class comprises more than about one-third of the total area, and black spruce is the dominant forest cover. Variation in soil C stocks across the landscape mainly reflects the amount of deep C present as slowly decomposing humic and mineral organic matter and is clearly related to soil drainage. Carbon stocks are greatest in the poorly drained areas and lowest in well-drained upland jack pine sites. The very poorly drained fens and collapse scar bogs occupy about 20% of the total area but store about 50% of the total carbon, most in the deep organic soil layers. The deep soil layers are an important source of carbon, storing about 90% of the total soil carbon across the study area.

Variation in rates of soil C accumulation and loss is due to both drainage and forest stand age. Largest C accumulations are in the surface mosses of recently burned sites and in the deep soils of the very poorly drained fens, which rarely burn. In a year with no fire, the deep soils in the rest of the study area, however, are releasing C to the atmosphere, with greatest releases in the moderately well and imperfectly drained sites. Estimated net soil C storage averaged over the entire 733 km^2 study area was about 20 g C m^{-2} yr^{-1} (28 g C m^{-2} yr^{-1} accumulation in fens and surface soil layers (including mosses) offset by 8 g C m^{-2} yr^{-1} lost from deep soil pools) in 1994, a year when none of the area was affected by fire.

Significant interannual variability in C storage is expected because of the irregular occurrence of fire in space and time. The future C balance for the region may depend largely on how fire frequency is affected by changing climate and management.

This study helps to emphasize the importance of drainage and fire in potentially changing the carbon balance of boreal forest ecosystems and, rather than offering predictions, presents a range of possibilities. The sensitivity analyses show that assumptions about fire history are important and that they can change the sign of the estimated net soil carbon fluxes, from a small carbon sink to a significant source over the landscape of this study.

The turnover of deep soil C in these ecosystems deserves more attention, because of the large C stocks present in deep layers, uncertainties in the estimated decomposition constants, and the possibility that decomposition rates in the deep soil could increase as soils warm and become drier. The effects of expected warming and altered drainage patterns on the fate of the immense stores of C in the deep soil of boreal forests must be understood to determine how climate change will affect the global carbon budget.

8. Future Studies

Scaling plot-level measurements to landscape level patterns is a difficult and important task. This study makes an important contribution to this gap in the BOREAS effort, in particular, and to the fields of biogeochemistry and geography, in general. However, this study also concludes with recognizing the uncertainties in the simple model and of the assumption that the deep soils are experiencing net C losses between fire events. I have emphasized in the discussion and summary that uncertainty in the decomposition *k* constants is an important knowledge gap that needs filling. The rates of decomposition are subject to change if global warming leads to changes in soil drainage patterns.

Future studies, three of which are described below, might examine refining the model by determining and applying *I* and *k* values that are more sensitive to conditions in the BOREAS region, expanding the sensitivity analyses, and incorporating more complex models that are capable of examining varying conditions within the soil profile that affect soil dynamics on a landscape level. Finally, since this study could be looked upon as a prototype for modeling soil carbon dynamics over a relatively small area within the boreal forest, the methods applied here and with the more refined approaches listed above could then be expanded to a larger region of the boreal forest.

The first study (as suggested by D. Tomlin, personal communication, 1998) examines a different approach to the sensitivity analyses described in Section 5. Although several maps were generated from the inputs and results (Figures 6-8) described in this thesis, this work was spatially insensitive. With each grid cell assigned a set of attributes -- drainage class, age, C stock and C flux --, the results would be the same had the pixels been located differently spatially. To introduce the element of spatial autocorrelation to this study, a different approach in the sensitivity analyses could be employed by varying the spatial locations --rather than attribute values -- of individual grid cells. A simple way to do this would be to transform each of the input images -- soil drainage, forest stand age, and surface and deep carbon stocks -- by replacing each grid cell value with the maximum (and then the minimum) value within its immediate neighborhood.

To expand on the approach and findings of this and two other BOREAS studies [*Goulden et al.,* 1998; *Frolking et al.,* 1996], two new projects will further assess the role of fire and soil drainage in determining net carbon fluxes in boreal forest ecosystems. The first is a two-year BOREAS follow-on study (Principal Investigators -- S. E. Trumbore, E. R. Levine, and F. G. Hall) for which the focus is twofold: (1) to expand the spatial extrapolation of soil and vegetation C fluxes across landscapes to the BOREAS Southern Study Area (SSA) in Saskatchewan (Figure 4A) and the area covered in a transect between the NSA and SSA [*Halliwell et al.,* 1995]; and (2) to predict how organic matter decomposition is likely to change following fire or drainage changes by combining existing data on radiocarbon in soil organic matter and soil-respired CO_2 with models of soil respiration for the major vegetation and soil types found in the boreal forests.

In the second study Adam Hirsch, a graduate student in the Department of Earth System Science, University of California, Irvine, will (1) test the *Goulden et al.* [1998] hypothesis that the Old Black Spruce site in the NSA is in net carbon balance because loss of deep soil C is offsetting gain of carbon in growing trees and moss layers; (2) answer the question of whether it is the deep soil organic carbon that decomposes or more modern roots or dissolved components that have been transported down through the soil profile; and (3) compare data collected in (1) and (2) with output from the *Frolking et al.* [1996] model of C cycling at the OBS in the Northern Study Area to estimate the rate of CO_2 production as a function of depth in soil that can be compared to Frolking's model. Critical in (3) is understanding the temperature dependence of CO_2 production from decomposition of organic matter in the deep soils. If decomposition rates increase significantly if deep soils warm up (and dry out), then the potential for C loss in boreal forest soils with warming climate can be large.

The modeling efforts of the two studies will parallel each other. Of particular interest in both studies is examining the following questions:

(1) How does the amount of CO_2 derived from decomposing soil organic matter change across the burn chronosequence in the NSA [*Harden et al.,* 1997; *Trumbore et al.,* 1998; also described in Section 2.2.1, this paper]? (*i.e.* Does the soil become a

net source of carbon to the atmosphere for the decade or so immediately following the fire as my simple *I* and *k* model predicts?)

(2) How does the makeup and age of soil respiration differ between the jack pine and black spruce tower sites and in the fen sites in the Northern and Southern Study Areas?

(3) How does the seasonal course of soil respiration differ at the same sites given the climatic data that are available?

(4) How can models developed under (3) that predict soil respiration for different soil types (drainage classes) and that link soil physical changes (warming and drying) following fire be applied across the chronosequence?

Maps of forest stand age and soil drainage (for both the NSA and SSA) can then be used to make regional estimates of soil respiration and to improve on the estimates of net C storage and loss based on the simple *I* and *k* models presented in this study. The objective here is to develop models that can be applied not only in the NSA and SSA of BOREAS but also in other regions of the boreal forest.

9. References

Agriculture Canada Expert Committee on Soil Survey, The Canadian soil information system (CanSIS) manual for describing soils in the field, 1982 revised, edited by J. H. Day, *Land Resource Research Institute Contribution 82-52,* 175 pp., Research Branch, Agriculture Canada, Canadian Government Publishing Centre, Ottawa, Ontario, 1983.

Alexander, E. B., Bulk density equations for southern Alaska soils*, Canadian Journal of Soil Science, 69,* 177-180, 1989.

Anderson, D., BOREAS TE-01 soils data over the SSA tower sites in raster format (part of "Soils of Tower Sites in the Southern Study Area"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 4: HTML_PAGES/GROUPS/TE/TE01/TE01_SSA_SOIL_LAB.HTML. Published on CD-ROM by NASA, 2000. Also on-line at, http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.

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

Arrhenius, S. A., On the influence of carbonic acid in the air upon the temperature of the ground, *Philosophical Magazine, 41,* 237-276, 1896.

Arrhenius, S. A., *Verldarnas Utveckling,* Gerbers, Stockholm, Sweden, (English translation by H. Berns, *Worlds in the Making: The Evolution of the Universe,* Harpers, New York, 1908), 1906.

Atmospheric Environmental Service, *Canadian Climate Normals 1961-1990,* Environment Canada, Downsview, Ontario, Canada, 1992.

Baum, S. K., *Glossary of oceanography, climatology and the related geosciences with references*, http://www-ocean.tamu.edu/~baum/paleo/paleogloss/paleogloss.html, Texas Center for Climate Studies, College of Geosciences and Maritime Studies, Texas A & M University, College Station, Texas, (last updated 20 Jan 97) 1996.

Becker, G., C. Elliott, G. Peterson, R. Bell, R. Frank, G. Daudet, M. Szmigelski, F. Houston, W. Hamilton, D. Bagot, D. Acres, D. Van de Vyvere, *et al.*, Forest Inventory Field Instruction Manual, 79 pp., Forest Resource Surveys, Natural Resources Manitoba, Winnipeg, Manitoba, 1996.

Bonan, G. B., Physiological controls of the carbon balance of boreal forest ecosystems, *Canadian Journal of Forestry Research, 23* (7), 1453-1471, 1993.

Bonan, G. B. and M. D. Korzuhin, Simulation of moss and tree dynamics in the boreal forests of interior Alaska, *Vegetatio, 84,* 31-44, 1989.

Bostock, H. S., Physiographic subdivisions of Canada, in *Geology and economic minerals of Canada, Economic Geology Report No. 1,* 5th edition, edited by R. J. W. Douglas, Geological Survey of Canada, Ottawa, Ontario, 1970.

Buol, S. W., F. D. Hole, and R. J. McCracken, *Soil Genesis and Classification,* 3rd edition, Iowa State University Press, Ames, Iowa, 1989.

Burcholdze, A. A., M. Chudy, I. V. Eristavi, S. V. Pagava, P. Povinec, A. Sivo, and G. I. Togonidze, Anthropogenic ^{14}C variations in atmospheric CO_2 and wines, *Radiocarbon, 31*, 771-776, 1989.

Burke, I. C., C. M. Yonker, W. J. Parton, C. V. Cole, K. Flach, and D. S. Schimel, Texture, climate, and cultivation effects on soil organic matter in U.S. grassland soils, *Soil Science Society of America Journal, 53* (3), 800-805, 1989.

C-1 Forest Ecology Working Group, *C-1 Forest Ecology Working Group Terminology*, Society of American Foresters, http://soilslab.cfr.washington.edu/S-7/index.html, edited by R. Harrison, University of Washington, Seattle, 1996.

Chapman, W. L. and J. E. Walsh, Recent variations of sea ice and air temperature in high latitudes, *Bulletin of the American Meteorological Society, 74* (1), 33-47, 1993.

Ciais, P., P. P. Tans, M. Trolier, J. W. C. White, and J. R. Francey, A large northern hemisphere CO_2 sink indicated by $^{13}C/^{12}C$ of atmospheric CO_2, *Science, 269*, 1098-1102, 1995.

Clymo, R. S., The limits to peat growth, *Philosophical Transactions, Royal Society of London Series B, 303*, 605-654, 1984.

Conley, A. H., E. A. Holland, T. R. Seastedt, and W. J. Parton, Simulation of carbon and nitrogen cycling in an alpine tundra ecosystem, *Arctic, Antarctic, and Alpine Research* (in press), 1999.

Conway, T. J., P. P. Tans, L. S. Waterman, K. W. Thoning, D. R. Kitzis, K. A. Masarie, and N. Zhang, Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network, *Journal of Geophysical Research, 99* (D11), 22,831-22,855, 1994.

Curd, S. L., Simulation of climate effects on watershed hydrologic output, M.S. thesis, 65 pp., Frostburg State University, Frostburg, Maryland, December 1996.

Curtis, R. O. and B. W. Post, Estimating bulk density from organic matter content in some Vermont forest soils, *Soil Science Society of America Proceedings, 28*, 285-286, 1964.

Davidson, E. A., Spatial covariation of soil organic carbon, clay content, and drainage class at a regional basis, *Landscape Ecology, 10* (6), 349-362, 1995.

Davidson, E. A. and P. A. Lefebvre, Estimating regional carbon stocks and spatially covarying edaphic factors using soil maps at three scales, *Biogeochemistry, 22*, 107-131, 1993.

DeFries, R. S. and J. R. G. Townshend, NDVI-derived land cover classification at a global scale, *International Journal of Remote Sensing, 15,* 2567-3586, 1994.

Denning, A. S., I. Fung, and D. A. Randall, Strong simulated meridional gradient of atmospheric CO_2 due to seasonal exchange with the terrestrial biota, *Nature, 376,* 240-243, 1995.

Eastman. J. R., *IDRISI for Windows, User's Guide,* Version 2.0, The Clark Labs for Cartographic Technology and Geographic Analysis, Clark University, Worcester, Massachusetts, Revision 5, December 1997.

Federer, C. A., D. E. Turcotte, and C. T. Smith, The organic fraction -- bulk density relationship and the expression of nutrient content in forest soils, *Canadian Journal of Forest Research, 23,* 1026-1032, 1993.

Fries, T. L., J. W. Harden, T. G. Huntington, S. E. Trumbore, and P. M. Crill, Partitioning soil CO_2 flux between shallow and deep sources of organic matter, paper presented at Symposium on Controls on Soil Respiration: Implications for Climate Change, Soil Science Society of America, Anaheim, California, Oct. 1997.

Fritton, D. D. and K. L. Butler, *Soil observations -- soil monoliths and soil samples. Background information*, http://www.cas.psu.edu/docs/casdept/agronomy/courses/soils101/Labs/monolith.html, Department of Agronomy, College of Agricultural Sciences, Pennsylvania State University, State College, Pennsylvania, (last updated 4 Feb 98), 1998a.

Fritton, D. D. and K. L. Butler, *The soil around us. Background information*, http://www.cas.psu.edu/docs/casdept/agronomy/courses/soils101/Labs/monolith.html, Department of Agronomy, College of Agricultural Sciences, Pennsylvania State University, State College, Pennsylvania, (last updated 7 Apr 98), 1998b.

Frolking, S., Sensitivity of spruce/moss boreal forest net ecosystem productivity to seasonal anomolies in weather, *Journal of Geophysical Research, 102* (D24), 29,053-29,064, 1997.

Frolking, S., M. L. Goulden, S. C. Wofsy, S.-M. Fan, D. J. Sutton, J. W. Munger, A. M. Bazzaz, B. C. Daube, P. M. Crill, J. D. Aber, L. E. Band, X. Wang, K. Savage, T. Moore, and R. C. Harriss, Modeling temporal variability in the carbon balance of a spruce/moss boreal forest, *Global Change Biology, 2*, 343-366, 1996.

Fung, I., A greener north, *Nature, 386,* 659-660, 1997.

Gorham, E., Northern peatlands: role in the carbon cycle and probable responses to climate warming, *Ecological Applications, 1* (2), 182-195, 1991.

Gosselink, J. G., R. Hatton, and C. S. Hopkinson, Relationship of organic carbon and mineral content to bulk density in Louisiana marsh soils, *Soil Science, 137* (3), 177-180, 1984.

Gower, S. T., J. Vogel, J. Norman, C. Kucharik, S. Steele, and T. Stow, Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada, *Journal of Geophysical Research, 102* (D24), 29,029-29,041, 1997.

Goulden, M. L., S. C. Wofsy, J. W. Harden, S. E. Trumbore, P. M. Crill, S. T. Gower, T. Fries, B. C. Daube, S.-M. Fan, D. J. Sutton, A. Bazzaz, and J. W. Munger, Sensitivity of boreal forest carbon balance to soil thaw, *Science, 279*, 214-217, 1998.

Hall, F. and D. Knapp, BOREAS TE-18 Landsat TM maximum likelihood classification image of the NSA (part of "BOREAS TE-18 Regional Scale Carbon Flux from Modeling and Remote Sensing"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 4: HTML_PAGES/GROUPS/TE/TE18/TE18_NSA_CLASS_MAX.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.

Halliwell, D. and M. J. Apps, BOREAS biometry and auxiliary sites: Locations and descriptions, Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Version 2.0, July 1995. [Updated version (v. 3.03, March 1997) in *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 1: HTML_PAGES/GROUPS/TE/TE13/TE13_BIOMETRY_PDF.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.]

Halliwell, D. and M. J. Apps, BOREAS biometry and auxiliary sites: Overstory & understory data, Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Version 2, January 1996. [Updated version (v. 3.03, March 1997) in *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 1: HTML_PAGES/GROUPS/TE/TE13/TE13_BIOMETRY_PDF.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.]

Halliwell, D., M. J. Apps, and D. T. Price, A survey of the forest site characteristics in a transect through the central Canadian boreal forest, *Water, Soil, and Air Pollution, 82,* 257-270, 1995.

Harden, J. W., E. T. Sundquist, R. F. Stallard, and R. K. Mark, Dynamics of soil carbon during deglaciation of the Laurentide ice sheet, *Science, 258*, 1921-1924, 1992.

Harden, J. W., K. P. O'Neill, S. E. Trumbore, H. Veldhuis, and B. J. Stocks, Moss and soil contributions to the annual net carbon flux of a maturing boreal forest, *Journal of Geophysical Research, 102* (D24), 28,805-28,816, 1997.

Harrison, K., W. Broecker, and G. Bonani, A strategy for estimating the impact of CO_2 fertilization of soil carbon storage, *Global Biogeochemical Cycles, 7* (1), 69-80, 1993.

Hartz, A. A., Simulation of carbon and nitrogen cycling in an alpine tundra ecosystem, M.S. thesis, 71 pp., University of Colorado, Boulder, 1997.

Homann, P. S., P. Sollins, H. N. Chappell, and A. G. Stangenberger, Soil organic carbon in a mountainous, forested region: Relation to site characteristics, *Soil Science Society of America Journal, 59,* 1468-1475, 1995.

Houghton, J. T., L. G. Meiro Fihlo, B. A. Callander, N. Harris, A. Kattenburg, and K. Maskell (Eds.), Technical summary, in *Climate Change 1995 -- The science of climate change*, pp. 9-97, Working Group I of Second Assessment Report, Intergovernmental Panel on Climate Change, Cambridge University Press, New York, 1996.

Houghton, R. A., Historic role of forests in the global carbon cycle, in *Carbon Dioxide Mitigation in Forestry and Wood Industry,* edited by G. H. Kohlmaier, M. Weber, and R. A. Houghton, pp. 1-24, Springer-Verlag, New York, 1998.

Houghton, R. A., E. A. Davidson, and G. M. Woodwell, Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance, *Global Biogeochemical Cycles, 12* (1), 25-34, 1998.

Huntington, T. G., C. E. Johnson, A. H. Johnson, T. G. Siccama, and D. F. Ryan, Carbon, organic matter, and bulk density relationships in a forested spodosol, *Soil Science, 148* (5), 380-386, 1989.

Jenny, H., S. Gessel, and F. T. Bingham, Comparative study of decomposition rates of organic matter in temperate and tropical regions, *Soil Science, 68,* 419-432, 1949.

Kaiser, J., New network aims to take the world's CO_2 pulse, *Science, 281,* 506-507, 1998.

Kasischke, E. S., N. L. Christensen, and B. J. Stocks, Fire, global warming, and the carbon balance of boreal forests, *Ecological Applications, 5,* 437-451, 1995.

Keeling, C. D., J. F. S. Chin, and T. P. Whorf, Increased activity of northern vegetation inferred from atmospheric CO_2 measurements, *Nature, 382,* 146-149, 1996.

Klassen, R. W., Lake Agassiz and the late glacial history of northern Manitoba, in *Glacial Lake Agassiz, Special Paper No. 26*, edited by J. T. Teller and L. Clayton, pp. 97-116, Geological Association of Canada, University of Toronto Press, Toronto, Ontario, 1983.

Knapp, D. and M. Tuinhoff, BOREAS forest cover data layers of the NSA in raster format (part of "BOREAS Staff Science GIS Data Collection Program"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 4: HTML_PAGES/GROUPS/RSS/RSS_STAFF_GIS_MAP/RSS_STAFF_NSA_FOREST_COV.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.

Kurz, W. A. and M. J. Apps, An analysis of future carbon budgets of Canadian boreal forests, *Water, Air, and Soil Pollution, 82*, 321-331, 1995.

Liski, J. and C. J. Westman, Carbon storage in forest soil of Finland 1. Effect of thermoclimate, *Biogeochemistry, 36* (3), 239-260, 1997a.

Liski, J. and C. J. Westman, Carbon storage in forest soil of Finland 2. Size and regional patterns, *Biogeochemistry, 36* (3), 261-274, 1997b.

McGuire, A. D., J. M. Melillo, D. W. Kicklighter, Y. Pan, X. Xiao, J. Helfrich, B. Moore III, C. J. Vorosmarty, and A. L. Schloss, Equilibrium responses of global net primary production and carbon storage in vegetation to doubled atmospheric carbon dioxide: Sensitivity to changes in vegetation nitrogen concentration, *Global Biogeochemical Cycles, 11* (2), 173-189, 1997.

Meeson, B. W., F. E. Corprew, J. M. P. McManus, D. M. Myers, J. W. Closs, K.-J. Sun, D. J. Sunday, and P. J. Sellers, *ISLSCP Initiative I - Global Data Sets for Land-Atmosphere Models, 1987-1988, Volumes 1-5,* published on CD-ROM by NASA (USA_NASA_GDAAC_ISLSCP_001 -- USA_NASA_GDAAC_ISLSCP_005), 1995.

Mintzer, I. M. (Ed.), *Confronting climate change: Risks, implications, and responses,* Cambridge University Press, New York, 1992.

Moore, T. R. and R. Knowles, Methane emissions from fen, bog, and swamp peatlands in Quebec, *Biogeochemistry, 11*, 45-61, 1990.

Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asra, and R. R. Nemani, Increased plant growth in the northern latitudes from 1981 to 1991, *Nature, 386,* 688-702, 1997.

Newcomer, J., D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers (Editors), *Collected Data of the BOReal Ecosystem-Atmosphere Study*, *Volumes 1-12,* published on CD-ROM by NASA, 2000.

O'Hara, F. Jr. (Ed.), *Glossary: Carbon dioxide and climate, 1990, ORNL/CDIAC-39,* http://cdiac.esd.ornl.gov/, Carbon Dioxide and Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, (last revision 28 June 1996), 1990.

Parton, W. J., D. S. Schimel, C. V. Cole, and D. S. Ojima, Analysis of factors controlling soil organic matter levels in Great Plains grasslands, *Soil Science Society of America Journal, 51* (5), 1173-1179, 1987.

Payette, S., Fire as a controlling process in the North American boreal forest, in *A Systems Analysis of the Global Boreal Forest,* edited by H. H. Shugart, R. Leemans, and G. B. Bonan, pp. 144-169, Cambridge University Press, Cambridge, England, 1993.

Peng, C., M. J. Apps, D. T. Price, I. A. Nalder, and D. H. Halliwell, Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in central Canada 1. Model testing, *Global Biogeochemical Cycles, 12,* 381-392, 1998.

Peterson, G., Manitoba Forest Fire History Map Index 1997, 12 pp., Manitoba Natural Resources, Forestry Branch, Winnipeg, Manitoba, Canada, (last updated April 1998), 1998.

Post, W. M., W. R. Emanuel, P. J. Zinke, and A. G. Stangenberger, Soil carbon pools and world life zones, *Nature, 298* (July 8), 156-159, 1982.

Rapalee, G., E. A. Davidson, J. W. Harden, S. E. Trumbore, H. Veldhuis, and D. Knapp, BOREAS TGB-12 soil carbon and flux data of NSA-MSA in raster format (part of "Input, Accumulation, and Turnover of Carbon in Boreal Forest Soils: Integrating ^{14}C Isotopic Analyses with Ecosystem Dynamics"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 4: HTML_PAGES/ GROUPS/TGB/TGB12/TGB12_SOIL_CARBON_MAP.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998a.

See 3_POSTER.PDF, this CD.

Rapalee, G., E. A. Davidson, J. W. Harden, S. E. Trumbore, and H. Veldhuis. Scaling soil carbon stocks and fluxes at the BOREAS northern study area (part of "Input, Accumulation, and Turnover of Carbon in Boreal Forest Soils: Integrating ^{14}C Isotopic Analyses with Ecosystem Dynamics"). An electronic poster. In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volumes 1-12: HTML_PAGES/GROUPS/TGB/TGB12/TGB12_POSTER.PDF. Published on CD-ROM by NASA, 2000. Also on-line at http://daacl.esd.ornl.gov/BOREAS/bhs/ Groups/TGB/ tgb12_poster.pdf, (last updated 4 Jan 1999), 1998b.

Rapalee, G., S. E. Trumbore, E. A. Davidson, J. W. Harden, and H. Veldhuis, Soil carbon stocks and their rates of accumulation and loss in a boreal forest landscape, *Global Biogeochemical Cycles, 12* (4), 687-701, 1998c.

Reeburgh, W. S., Figures summarizing the global cycles of biogeochemically important elements, *Bulletin of the Ecological Society of America, 78*, 260-268, 1997.

Rosenzweig, C. and D. Hillel, *Climate Change and the Global Harvest,* Oxford University Press, Inc., New York, 1998.

Rubec, C. D. A. (Ed.), *Wetlands of Canada, Ecological Land Classification Series, No. 24*, Sustainable Development Branch, Environment Canada, Ottawa, Ontario, and Polyscience Publication, Inc., Montreal, Quebec, 1988.

Saini, G. R., Organic matter as a measure of bulk density of soil, *Nature, 210,* 1295-1296, 1966.

Schimel, D. S., Terrestrial ecosystems and the carbon cycle, *Global Change Biology, 1*, 77-91, 1995.

Schlesinger, W. H., *Biogeochemistry, An analysis of global change,* Academic Press, Inc., San Diego, California, 1991.

Seastedt, T., *EPO biology 3010, ecology course material for fall 1997*, http://culter.colorado.edu:1030/~tims/index.html, Department of Environmental, Population, and Organismic Biology, University of Colorado, Boulder, Colorado, 1997.

Sellers, P. J., F. G. Hall, D. Baldocchi, J. Cihlar, P. Crill, J. Den Hartog, B. Goodison, R. D. Kelly, D. Lettenmeier, H. Margolis, J. Ranson, and M. Ryan (Eds.), *Experiment Plan, BOReal Ecosystem-Atmosphere Study, Version 3.0,* NASA, Goddard Space Flight Center, Laboratory for Terrestrial Physics, Biospheric Sciences Branch, Code 923, Greenbelt, Maryland, 1994.

Sellers, P., F. Hall, H. Margolis, B. Kelly, D. Baldocchi, G. Den Hartog, J. Cihlar, M. G. Ryan, B. Goodison, P. Crill, K. J. Ranson, D. Lettenmaier, and D. E. Wickland, The BOReal Ecosystem-Atmosphere Study (BOREAS): An overview and early results from the 1994 field year, *Bulletin of the American Meteorological Society, 76* (9), 1549-1577, 1995a.

Sellers, P. J., B. W. Meeson, J. Closs, J. Collatz, F. Corprew, D. Dazlich, F. G. Hall, Y. Kerr, R. Koster, S. Loss, K. Mitchell, J. McManus, D. Myers, K.-J. Sun, and P. Try, An overview of the ISLSCP Initiative I global data sets, in *ISLSCP Initiative I - Global Data Sets for Land-Atmosphere Models, 1987-1988, Volumes 1-5.* Volume 1: USA_NASA_GDAAC_ ISLSCP_001, OVERVIEW.DOC. Published on CD-ROM by NASA (USA_NASA_GDAAC_ISLSCP_001 -- USA_NASA_GDAAC_ISLSCP_ 005), 1995b.

Sellers, P. J., F. G. Hall, R. D. Kelly, A. Black, D. Baldocchi, J. Berry, M. Ryan, K. J. Ranson, P. M. Crill, D. P. Lettenmaier, H. Margolis, J. Cihlar, J. Newcomer, D. Fitzjarrald, P. G. Jarvis, S. T. Gower, D. Halliwell, D. Williams, B. Goodison, D. E. Wickland, and F. E. Guertin, BOREAS in 1997: Experiment overview, scientific results, and future directions, *Journal of Geophysical Research, 102* (D24), 28,731-28,769, 1997.

Soil Classification Working Group (Eds.), The Canadian system of soil classification, 3rd edition, *Agriculture and Agri-Food Canada Publication 1646*, 187 pp., Research Branch, Agriculture and Agri-Food Canada, National Research Council of Canada, Ottawa, Ontario, 1998.

Soil Survey Staff, Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys, *Agricultural Handbook No. 436*, U.S. Department of Agriculture, Soil Conservation Service, Washington DC, 1975.

Soil Survey Staff, *Keys to Soil Taxonomy,* 8th edition, U.S. Department of Agriculture, Natural Resources Conservation Service. Also online at http://www.statlab.iastate.edu/soils/index.html/, Statistical Laboratory, Iowa State University, Ames, Iowa, (last updated 30 Aug 99), 1998.

Tans, P. P., NOAA CMDL monthly mean carbon dioxide, http://www.cmdl.noaa.gov/ccg/figures/figures.html, edited by K. A. Masarie, National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostics Laboratory, Carbon Cycle Group, Boulder, Colorado (last updated 5 Nov 1997), 1997.

Tans, P. P., I. Y. Fung, and T. Takahashi, Observational constraints on the global atmospheric CO_2 budget, *Science, 247*, 1431-1438, 1990.

Tans, P. P. and T. Conway, Three dimensional representation of the latitudinal distribution of atmospheric carbon dioxide in the marine boundary layer for the period 1987 through 1996, http://www.cmdl.noaa.gov/ccg/figures/figures.html, edited by K. A. Masarie, National Oceanic and Atmospheric Administration, Climate Monitoring and Diagnostics Laboratory, Carbon Cycle Group, Boulder, Colorado (last updated 5 Nov 1997), 1997.

Teller, J. T., L. H. Thorleifson, L. A. Dredge, H. C. Hobbs, and B. T. Schreiner, Maximum extent and major features of Lake Agassiz, scale 1:3,000,000, in *Glacial Lake Agassiz: Geological Association of Canada Special Paper 26*, edited by J. T. Teller and L. Clayton, 1983.

The Kyoto Protocol, http://www.whrc.org/globalwarming/warmingearth.htm, edited by M. Ernst, The Woods Hole Research Center, Woods Hole, Massachusetts (last modified 1 Sept 1999), 1999.

Trumbore, S. E. and J. W. Harden, Accumulation and turnover of carbon in organic and mineral soils of the BOREAS northern study area, *Journal of Geophysical Research, 102* (D24), 28,817-28,830, 1997.

Trumbore, S. E., J. W. Harden, E. T. Sundquist, and G. C. Winston, BOREAS TGB-12 soil carbon data over the NSA (part of "Input, Accumulation, and Turnover of Carbon in Boreal Forest Soils: Integrating ^{14}C Isotopic Analyses with Ecosystem Dynamics"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 1: HTML_PAGES/GROUPS/TGB/TGB12/TGB12_SOIL_CARBON.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.

Veldhuis, H., Soils of tower sites and super site, northern study area, Thompson, Manitoba, Canada. A report. In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1995.

Veldhuis, H., BOREAS TE-20 NSA soil lab data (part of "Soils of Tower Sites and Super Site, Northern Study Area, Thompson, Manitoba, Canada"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 1: HTML_PAGES/GROUPS/TE/TE20/TE20_NSA_SOIL_LAB.HTML . Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.

Veldhuis, H. and D. Knapp, BOREAS TE-20 soils data over the NSA-MSA and tower sites in raster format (part of "Soils of Tower Sites and Super Site, Northern Study Area, Thompson, Manitoba, Canada"). In *Collected Data of the BOReal Ecosystem-Atmosphere Study, Volumes 1-12.* Edited by J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. Volume 4: HTML_PAGES/GROUPS/TE/TE20/TE20_NSA_SOILS_RASTER.HTML. Published on CD-ROM by NASA, 2000. Also on-line at http://www-eosdis.ornl.gov/, Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1998.

Veldhuis, H., G. F. Mills, and R. G. Eilers, Thermal regimes of clay soils in Manitoba, Proceedings of 33rd Annual Manitoba Soil Science Society Meeting, Winnipeg, Manitoba, 33-46, 1990.

Veldhuis, H. and G. Rapalee, Soil carbon stocks and distribution in soil and landscapes of the Glacial Lake Agassiz basin, north-central Manitoba, Proceedings of 42nd Annual Manitoba Soil Science Society Meeting, Winnipeg, Manitoba, 181-188, 1999.

Watson, R. T., M. C. Zinyowera, and R. H. Moss (Eds.), Technical summary: Impacts, adaptions, and mitigation options, in *Climate Change 1995 -- Impacts, adaptions and mitigation of climate change: Scientific--technical analyses*, pp. 19-53, Working Group II, Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, New York, 1996.

Winston, G. C., E. T. Sundquist, B. B. Stephens, and S. E. Trumbore, Winter CO_2 fluxes in a boreal forest, *Journal of Geophysical Research, 102* (D24), 28,795-28,804, 1997.

Zoltai, S. C., C. Tarnocai, G. F. Mills, and H. Veldhuis, Wetlands of subarctic Canada, in *Wetlands of Canada, Ecological Land Classification Series, No. 24*, edited by C. D. A. Rubec, pp. 55-96, Sustainable Development Branch, Environment Canada, Ottawa, Ontario, and Polyscience Publication, Inc., Montreal, Quebec, 1988a.

Zoltai, S. C., S. Taylor, J. K. Jeglum, G. F. Mills, and J. D. Johnson, Wetlands of boreal Canada, in *Wetlands of Canada, Ecological Land Classification Series, No. 24*, edited by C. D. A. Rubec, pp. 97-154, Sustainable Development Branch, Environment Canada, Ottawa, Ontario, and Polyscience Publication, Inc., Montreal, Quebec, 1988b.

APPENDICES

APPENDIX A

Radiocarbon (^{14}C) Dating

The following discussion of radiocarbon dating is from *Trumbore et al.* [1998].

Carbon inventories and radiocarbon (^{14}C) give information that are needed to determine C storage, as well as to determine the accumulation rate of C (in non-steady state systems) or the turnover rate of C (in systems where C turnover rate is less than soil or disturbance age). These data are checked using the isotopic composition of respired CO_2 (which will reflect the ^{14}C content of root respiration and decomposing organic matter), and by a knowledge of soil C inputs and losses.

Theory of measurements. ^{14}C is produced in the stratosphere by the ^{14}N (n, p) ^{14}C reaction. The ^{14}C atom is oxidized rapidly to ^{14}CO, which has a lifetime of months before it is oxidized to $^{14}CO_2$. Most ^{14}C production occurs in the stratosphere, but the long lifetime of CO_2 enables $^{14}CO_2$ to become well-mixed throughout the troposphere. The steady state ^{14}C content of the atmosphere is determined by the exchange of carbon in CO_2 with that in ocean and biospheric reservoirs. Because of the relatively rapid cycling of carbon between the atmosphere and living biomass, most plants maintain a ^{14}C specific activity (or $^{14}C/^{12}C$ ratio corrected for mass-dependent isotope fractionation effects) that equals that of atmospheric CO_2. Similarly, animals reflect the $^{14}C/^{12}C$ of the plants (or animals) they consume. Upon the death of an organism, the ^{14}C in its tissues is no longer replenished, and decays with a half-life of 5730 years. If the tissue remains intact and isolated from exchange, the $^{14}C/^{12}C$ ratio may be used to indicate the time since the death of the organism. This is the basis for radiocarbon dating.

Calculation of a radiocarbon age requires the assumption that the ^{14}C content of the carbon originally fixed in plant tissues equaled that of the atmospheric CO_2 in 1950 (0.95 times the activity of oxalic acid, or Modern). In fact, the ^{14}C content of the atmosphere has varied with time because of changes in the production rate of ^{14}C (cosmic ray flux and magnetic field variations) and because of changes in the distribution of carbon among oceanic, biospheric, and atmospheric reservoirs. These variations, deduced from the ^{14}C content of cellulose of known age taken from the annual growth rings of trees, are generally less than 10% over the past 7000 years. More recent changes in the ^{14}C content of atmospheric CO_2 have resulted from dilution by ^{14}C-free fossil-fuel-derived carbon and by the production of ^{14}C during atmospheric testing of thermonuclear weapons ("bomb ^{14}C"). The latter effect dominates other natural and fossil fuel effects, as the atmospheric burden of ^{14}C was approximately doubled in the few years preceding the implementation of the Nuclear Test Ban Treaty in 1964. This isotopic spike in the global carbon system provides a means for radiocarbon to be a useful tracer of carbon cycle processes on time scales of decades.

We express ^{14}C data in the geochemical D notation, the deviation in parts per thousand (per mil) from an absolute standard (95 times the activity of NBS oxalic acid measured in 1950). In this notation, zero equals the ^{14}C content of 1895 wood, positive values indicate the presence of "bomb" radiocarbon, and negative values indicate the predominance of C fixed from the atmosphere more than several hundred years ago.

One important correction made in calculating the D ^{14}C value is the ^{13}C concentration is needed to account for isotopic fractionation effects. For example, consider that the D ^{13}C difference between atmospheric CO_2 and carbon fixed during photosynthesis by C3 plants is approximately 20â. Since the mass difference between 12 and 14 is twice that between 12 and 13, the fractionation of ^{14}C will be roughly twice that of ^{13}C. The ^{14}C contents of a tree and the CO_2 that it is fixing through photosynthesis will differ by approximately 40%. To account for fractionation effects, the sample (with d ^{13}C of d) and standard are corrected to a constant ^{13}C content. The standard oxalic acid is corrected in the same way, to −19 per mil. (For more detail see references in Section 17 in *Trumbore et al*. [1998].)

For seeds and deciduous leaves that represent a single year's growth, the ^{14}C content of recent samples may be used to determine the age of a sample to within a year or two. The ^{14}C content of the sample is compared to the ^{14}C record of atmospheric C in the Northern Hemisphere. [For an example see *Burcholadze et al.,* 1989.] Evergreen needles, that may average several years' growth, will be less easily interpreted.

For samples prior to 1960, radiocarbon ages in years may be calculated from the given Delta (Δ) values as -8033 H (ln(Delta $\times$ 0.995/1000 +1)). The conventional radiocarbon age must be converted to a calibrated age using the tree-ring-based calibration curves that correct for known variations in atmospheric ^{14}C over time. Both ages are usually rounded to the nearest decade or pentad.

One application of radiocarbon to soil science lies in the ^{14}C dating of charcoal and plant macrofossils to determine the accumulation rate of C in vertically aggrading soils (peat or moss). Unlike the closed systems represented by intact macrofossils, such as seeds or pollen, bulk Soil Organic Matter (SOM) is a heterogeneous reservoir with a variety of turnover times, to which carbon is continuously added (as new plant matter) and lost (as leached organic carbon or CO_2). The radiocarbon content of SOM can not be interpreted as a 'date,' but represents the average age of a carbon atom in this reservoir.

Note: Section 2.2.1 (Upland surface soil layers), this paper, discusses three approaches to determining the breakdown of C into faster and slower cycling pools.

APPENDIX B

Soil Horizons

The following information describes the soil profiles depicted in Figure 5.

From: *Veldhuis* [1995] and *Soil Classification Working Group* [1998].

The definitions of classes in the Canadian system are based mainly on the kinds, degrees of development, and the sequence of soil horizons and other layers in pedons. Therefore, the clear definition and designation of soil horizons and other layers are basic to soil classification. A soil horizon is a layer of mineral or organic soil or soil material approximately parallel to the land surface that has characteristics altered by processes of soil formation. It differs from adjacent horizons in properties such as color, structure, texture, and consistence, and in chemical, biological, and mineralogical composition. The other layers are either nonsoil layers such as rock or water or layers of unconsolidated material considered to be unaffected by soil-forming processes. For the sake of brevity these other layers are referred to simply as layers, but it is recognized that soil horizons are also layers.

The major mineral horizons are A, B, and C. The major organic horizons are L, F, and H, which consist mainly of forest litter at various stages of decomposition, and O, which is derived mainly from bogs, marsh, or swamp vegetation. Subdivisions of horizons are labeled by adding lower case suffixes to some of the major horizons symbols as with Ah or Ae. Well-developed horizons are readily identified in the field. However, in cases of weak expression or of borderline properties, such as between Ah and H, laboratory determinations are necessary before horizons can be designated positively.

Soil Horizon Designations

Organic horizons. Organic horizons are found in Organic soils, and commonly at the surface of mineral soils. They may occur at any depth beneath the surface in buried soils, or overlying geologic deposits. They contain more than 17% organic carbon (approximately 30% organic matter) by weight. Two groups of these horizons are recognized, O horizons and the L, F, and H horizons.

O This is an organic horizon developed mainly from mosses, rushes, and woody materials.

Of The fibric horizon is the least decomposed of all the organic soil materials. It has large amounts of well-preserved fiber that are readily identifiable as to botanical origin. A fibric horizon has 40% or more of rubbed fiber by volume and a pyrophosphate index of 5 or more. If the rubbed fiber volume is 75% or more, the pyrophosphate criterion does not apply.

Om The mesic horizon is the intermediate stage of decomposition with intermediate amount of fiber, bulk density, and water-holding capacity. The material is partly altered both physically and biochemically. A mesic horizon is one that fails to meet the requirements of fibric or humic.

Oh The humic horizon is the most highly decomposed of the organic soil materials. It has the least amount of fiber, the highest bulk density, and the lowest saturated water-holding capacity. It is very stable and changes very little physically or chemically with time unless it is drained. The humic horizon has less than 10% rubbed fiber by volume and a pyrophosphate index of 3 or less.

LFH These organic horizons developed primarily from leaves, twigs, woody materials, and a minor component of mosses under imperfectly to well-drained forest conditions.

L This is an organic horizon characterized by an accumulation of organic matter in which the original structures are easily discernible.

F This is an organic horizon characterized by an accumulation of partly decomposed organic matter. The original structures in part are difficult to recognize. The horizon may be partly comminuted by soil fauna as in moder, or it may be a partly decomposed mat permeated by fungal hyphae as in mor.

H This is an organic horizon characterized by an accumulation of decomposed organic matter in which the original structures are indiscernible. This material differs from the F horizon by its greater humification chiefly through the action of organisms. It is frequently intermixed with mineral grains, especially near the junction with the mineral horizon.

Master mineral horizons. Mineral horizons are those that contain less than 30% organic matter by weight as specified for organic horizon.

A This is a mineral horizon or horizons formed at or near the surface in the zone of leaching or removal of materials in solution and suspension or of maximum *in situ* accumulation of organic matter, or both. Included are:

1. horizons in which organic matter has accumulated as a result of biological activity (Ah);

2. horizons that have been eluviated of clay, iron, aluminium, or organic matter, or all of them (Ae);

3. horizons having characteristics of 1) and 2) above, but transitional to underlying B or C (AB or A and B);

4. horizons markedly disturbed by cultivation or pasture (Ap).

B This is a mineral horizon or horizons characterized by one or more of the following:

1. an enrichment in silicate, clay, iron, aluminum, or humus, alone or in combination (Bt, Bf, Bfh, Bhf, and Bh);

2. a prismatic or columnar structure that exhibits pronounced coatings or stainings and significant amount of exchangeable sodium (Na) (Bn);

3. an alteration by hydrolysis, reduction, or oxidation to give a change in color or structure from horizons above or below, or both, and does not meet the requirements of 1) and 2) above (Bm, Bg).

C This is a mineral horizon or horizons comparatively unaffected by the pedogenic processes operative in A and B, except for (i) the process of gleying, and (ii) the accumulation of calcium and magnesium carbonates and more soluble salts (Cca, Csa, Cg, and C). Marl and diatomaceous earth are considered to be C horizons.

Other terms relating to the soil profiles depicted in Figure 5:

Descriptions are from: *Veldhuis* [1995]; *Soil Classification Working Group* [1998]; *Buol et al.* [1989].

Albic layer. A zone from which clays and iron oxides have been eluviated and in which very little organic matter has accumulated.

Cambic layer. A subsurface horizon of very fine sand, loamy fine sand, or finer texture, showing some evidence of accumulation (color changes, structural development, etc.) but not enough to qualify for any other horizon.

Parent material. The unaltered or essentially unaltered mineral or organic material from which the soil profile develops by pedogenic processes.

Organic layers:

Organic layers are characterized here by the amount of fiber and its durability, reflecting on the degree of decomposition of the material.

Fibric soil material. The least decomposed of all organic materials; there is a large amount of well-preserved fiber that is readily identifiable as to botanical origin. Fibers compose over two-thirds of the mass of soil.

Hemic soil material. One-third to two-thirds of the total mass is composed of fibers (intermediate in decomposition between fibric and sapric horizons).

Sapric soil material. Less than one-third of the mass is composed of identifiable fibers.

APPENDIX C

Sample Data Record

The following table is excerpted from the soil polygon spreadsheet that is the database of this study. Because the records are so long, they are presented here in two groups. Short descriptions of each soil attribute follow. The first 31 attributes are from the *Veldhuis and Knapp* [1998] soil survey; the remaining records (32 to 42 -- in bold type) were generated for this study [*Rapalee et al.*, 1998a]. For detailed descriptions of soil attributes, see *Veldhuis and Knapp* [1998] and *Rapalee et al.* [1998a].

Table 8. Sample Data Record

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
POLYNUM	GRIDLOC	COMPONT	RANKNUM	PERCENT	KINDMAT	LANDFRM	PMDEPO1	TXTURE1	TXTMOD1	PMDEPO2	TXTURE2	TXTMOD2	PMDEPO3	TXTURE3	TXTMOD3	COFRAGS	SLOPE	DRAINGE	DEPTHWT	PFDISTR	DPTHACT	ICECTNT	DPTHLFH	DPTHORG
1	F1	D	1	65	R2	h	RK	#	#	#	#	#	#	#	#	#	C	#	#	#	#	#	#	#
1	F1	D	2	20	SO	vh	GL	HC	-	RK	-	-	-	-	-	A	B	MW	-	-	-	-	1	#
1	F1	I	1	15	SO	bh	GL	HC	-	-	-	-	-	-	-	A	B	I	125	-	-	-	1	#
2	F1	D	1	90	R2	h	RK	#	#	#	#	#	#	#	#	#	E	#	#	#	#	#	#	#
2	F1	I	1	10	OR	Bv	B	F	-	GL	HC	-	-	-	-	#	B	P	50	-	-	-	#	1
3	F1	D	1	90	R2	h	RK	#	#	#	#	#	#	#	#	#	C	#	#	#	#	#	#	#
3	F1	I	1	10	OR	Bv	B	F	-	GL	HC	-	-	-	-	#	B	P	50	V	50	H	#	1
4	F1	D	1	60	SO	hb	GL	HC	-	-	-	-	-	-	-	A	D	MW	125	-	-	-	1	#
4	F1	D	2	15	OR	Bv	B	F	-	GL	HC	-	-	-	-	#	B	P	50	V	50	H	#	1
4	F1	S	1	15	OR	Ba	B	M	-	GL	HC	-	-	-	-	#	C	P	*	D	50	H	#	2
4	F1	I	2	10	OR	Fc	FN	F	-	GL	HC	-	-	-	-	#	A	VP	10	-	-	-	#	2

Table 8. (cont.)

1	26	27	28	29	30	31	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**
POLYNUM	SOILDEV	VARIANT	SERIES1	SERVAR1	SERIES2	SERVAR2	**TOTLAREA**	**COMPAREA**	**DR CLASS**	**STND AGE**	**ST AGE GRP**	**C SURFACE**	**C DEEP**	**C TOTAL**	**FL SURFACE**	**FL DEEP**	**FL NET**
							hectares					**kg C m^{-2}**			**g C m^{-2} yr^{-1}**		
1	#		$AR				**7.7**	**5.0**	**1**	**86**	**90**	**0**	**0**	**0**	**0**	**0**	**0**
1	OGL	L	WRL				**7.7**	**1.5**	**5**	**86**	**90**	**0.85**	**1.97**	**2.82**	**4.97**	**-5.90**	**-0.93**
1	GLGL		ROK		LPR	p	**7.7**	**1.1**	**6**	**86**	**90**	**0.61**	**2.97**	**3.58**	**4.05**	**-5.95**	**-1.90**
2	#		$AR				**68.1**	**61.3**	**1**	**86**	**90**	**0**	**0**	**0**	**0**	**0**	**0**
2	TF		NIC		ROK		**68.1**	**6.8**	**7**	**86**	**90**	**0.38**	**1.17**	**1.56**	**2.92**	**-0.82**	**2.10**
3	#		$AR				**14.2**	**12.8**	**1**	**86**	**90**	**0**	**0**	**0**	**0**	**0**	**0**
3	TF		NIC		ROK		**14.2**	**1.4**	**7**	**86**	**90**	**0.38**	**1.17**	**1.56**	**2.92**	**-0.82**	**2.10**
4	OGL		WBW		ROK		**963.3**	**578.0**	**5**	**86**	**90**	**2.55**	**5.90**	**8.45**	**14.90**	**-17.70**	**-2.80**
4	TF		NIC		LPR	p	**963.3**	**144.5**	**7**	**86**	**90**	**0.58**	**1.76**	**2.34**	**4.38**	**-1.23**	**3.15**
4	TMEOC		PLT				**963.3**	**144.5**	**7**	**86**	**90**	**0.64**	**10.94**	**11.58**	**3.72**	**0**	**3.72**
4	TMEF		TFN	w			**963.3**	**96.3**	**8**	**199**	**1**	**1.30**	**10.43**	**11.73**	**0**	**2.23**	**2.23**

Note: Negative (<0) flux denotes carbon released from the soil or surface horizons to the atmosphere (source). Positive (>0) flux denotes carbon stored in the soil or surface horizons (sink).

Key Soil Attributes

The following key soil attributes of this data set are those listed in Table 8. The polygon numbers in this table correspond to the pixel values in the gridded soils map [*Veldhuis and Knapp,* 1998]. The value of each pixel in the soil map can link to the table in order to extract these parameters.

1 POLYNUM = Polygon number
2 GRIDLOC = Grid location
3 COMPONT = Polygon component (landscape element)
4 NUMBER = Component rank number
5 PERCENT = Percentage distribution of components
6 KINDMAT = Kind of rock outcrop or other material at the surface
7 LANDFRM = Local surface form
8 PMDEPO1 = Mode of deposition or origin of first (upper) parent material
9 TXTURE1 = Texture of first (upper) parent material
10 TXTMOD1 = Texture modifier of first (upper) parent material
11 PMDEPO2 = Mode of deposition or origin of second (middle) parent material
12 TXTURE2 = Texture of second (middle) parent material
13 TXTMOD2 = Texture modifier of second (middle) parent material
14 PMDEPO3 = Mode of deposition or origin of third (lower) parent material
15 TXTURE3 = Texture of third (lower) parent material
16 TXTMOD3 = Texture modifier of third (lower) parent material
17 COFRAGS = Coarse fragment content in control section of mineral soils
18 SLOPE = Slope gradient class
19 DRAINGE = Drainage class
20 DEPTHWT = Depth to water table, average
21 PFDISTR = Permafrost distribution or occurrence
22 DPTHACT = Depth of active layer (average)
23 ICECTNT = Ice content of permanently frozen layer
24 DPTHLFH = Thickness of humus layer (L, F, H)

25 DPTHORG = Average thickness of peat deposit
26 SOILDEV = Soil development (soil classification)
27 VARIANT = Classification variant or phase
28 SOILTP1 = Dominant soil type associated with polygon component
29 SOILPH1 = Soil phase or variant associated with dominant soil type
30 SOILTP2 = Subdominant soil type associated with polygon component
31 SOILPH2 = Soil phase or variant associated with subdominant soil type
32 TOTLAREA = Total area (hectares) of each soil polygon
33 COMPAREA = Area (hectares) of each polygon component
34 DR_CLASS = Drainage class (numerical code)
35 STND_AGE = Stand age; time since last fire
36 ST_AGE_GRP = Stand age; age ranges since last fire
37 C_SURFACE = Area-weighted carbon stocks of surface layers, including moss
38 C_DEEP = Area-weighted carbon stocks of deep soil horizons
39 C_TOTAL = Area-weighted total carbon stock for entire profile (C_SURFACE + C_DEEP)
40 FL_SURFACE = Area-weighted carbon fluxes of surface layers, including moss
41 FL_DEEP = Area-weighted carbon fluxes of deep soil horizons
42 FL_NET = Area-weighted carbon fluxes for entire profile (FL_SURFACE + FL_DEEP)

APPENDIX D

Forest Cover Map Layers of the BOREAS Northern Study Area

Appendix D describes the forest cover map layers used to generate the stand age class map layer, for which each polygon (forest stand) was assigned a 3-digit map code identified as forest cover (X00), cutting class (X0), and site class (X). In combination with forest cover and cutting class, site class determined the age range of each polygon. The resulting stand age class map layer is one data set used to compile the forest stand age map (Figure 6A) used in the soil carbon analysis.

Information in this appendix is from *Becker et al.* [1996] and *Knapp and Tuinhoff* [1998], describing Manitoba Natural Resources (MNR) forest inventory specifications.

Variable

1. Forest Cover
2. Cutting Class
3. Site Class

Variable Description/Definition

1. **Forest Cover** -- Forest cover by predominant overstory tree species.

Table 9. Forest and Land Cover Types

Map Code	Dominant Overstory Species
100	Jack pine (JP)
200	Black spruce (BS)
300	Trembling aspen/Hardwoods (TA/HW)

Map Code	Nonproductive Land
400	Treed muskeg
500	Treed rock
600	Clear muskeg

Note: For this study I simplified the *Knapp and Tuinhoff* [1998] forest cover map layer, which included 66 classes, by reclassifying to the three major forest cover types plus three categories of nonproductive land listed in Table 9.
Note: Forest cover categories (JP, BS, TA) are also listed as Subtypes (Table 11) and Working Groups (Table 12).

2. Cutting Class -- Cutting class is based on size, vigor, state of development, and maturity of a stand for harvesting purposes with designations such as 'Unproductive,' 'Not restocked,' 'Immature,' and 'Mature.'

Table 10. Cutting Class

Cutting Class	Map Code	Description
	0	No original data over the area.
	60	Unproductive stands. No cutting class given.
0	60	Forest land not restocked following fire, cutting, windfall, or other major disturbances (hence, potentially productive land). Some reproduction or scattered residual trees (with net merchantable volume <20 m^3 ha^{-1}) may be present.
1	10	Stands that have been restocked either naturally or artificially. There may be scattered residual trees present as in Cutting Class 0. The average height of the stand must be <3 m.
2	20	Advanced young growth of post size, with some merchantable volume. The average height of the stand must be >3 m.
3	30	Immature stands with merchantable volume growing at or near their maximum rate, which definitely should not be cut. The average height of the stand should be >10 m and the average diameter should be >9.0 cm at dbh (1.3 m).
4	40	Mature stands, which may be cut as they have reached rotation age ± 10 years on Site 1 or ± 20 years on Site 2.
5	50	Overmature stands, which should be given priority in cutting.

Note: Map code 60 includes stands identified as unproductive and not restocked (Cutting Class 0).

3. Site Class -- The type of site on which the forest is growing.

Site class is based on site characteristics including: landform, drainage, and indicator plants.

Note: The site class descriptions that follow were taken from page 16 of the Forest Inventory Field Instruction Manual [*Becker et al.,* 1996]. The manual indicates that the site classification is applicable to the Interlake section of Manitoba. Although the BOREAS NSA near Thompson is not included geographically in the Interlake section, Manitoba Natural Resources used the Interlake site classification for the 1988 forest inventory of the area of this study (G. Peterson, personal communication, 1997).

The land types and associated indicator plants are described for each moisture regime (Table 11). The moisture regime in return denotes the site class for each tree species. Because height, growth, and stand density are reflections of site, these factors should be considered when evaluating the growth of timber types. A site class was assigned to each subtype on the basis of its major species.

In general terms, Site Class 1 is associated with moist, very moist, and wet moisture regimes, regardless of the dominant tree species. Site Class 2 is associated with the saturated moisture regime when black spruce or tamarack (*Larix laricina*) is the dominant species. Site Class 2 is also associated with the dry moisture regime when jack pine or trembling aspen is the dominant species. Site Class 3 is generally associated with various tree species in the arid or dry moisture regime.

Although the plants generally reflect the moisture regime of the area, they become important site indicators only when they occur in abundance throughout the entire type. Localized elevations and depressions in the timber stand can reflect entirely different plant indicators than those throughout most of the type. Mineral and nutrients strongly influence tree growth but may not affect the presence of minor vegetation. Most of the soil in the Interlake area of Manitoba consists of strongly calcareous till. Although this high calcareous content does not affect the growth of indicators of Site Class 1 jack pine sites, it seriously inhibits the growth of jack pine. On the other hand, *Sphagnum* spp. do not tolerate high lime conditions. For this reason, feather moss rather than sphagnum is found on much of the deep organic terrain in the Interlake section.

Because most of the indicator plants grow over a range of moisture regimes, they generally become important only when they occur in abundance and when a variety of plants are present. In isolated cases, however, the mere presence of a certain indicator plant throughout the type can denote site class. A good example of this is when bunchberry or twinflower occurs in association with jack pine. These plants do not occur on dry moisture regimes and therefore denote Site Class 1.

Indicator Plants

Reindeer lichen (*Cladonia mites*)
Reindeer moss (*Cladonia rangiferna*) B a lichen
Creeping savin (*Juniperus horizontalis*)
Bearberry (*Arctostaphylos uva-ursi*)
Mountain (slender) rice (*Orzopsis pungens*)
Common juniper (*Juniperus communis*)
Buffaloberry (*Shepardia canadensis*)
Twinflower (*Linnaea borealis*)
Rough-grained mountain rice (*Oryzopsis asperifolia*)
Bunchberry (*Cornus canadensis*)
Red-ozier dogwood (*Cornus stolonifera*)
Low wild gooseberry (*Ribes hirtellum*)
Skunk currant (*Ribes glandulosum*)
Naked miterwort (*Mitella nuda*)
Creeping snowberry (*Gautheria hispidula*)
Speckled alder (*Alnus rugosa*)
Bog cranberry (*Oxycoccus quadrialus*)
Marsh marigold (*Calth palustris*)
Sphagnum moss (*Sphagnum* spp.)

Table 11. Site Classification by Moisture Regime, Landform, and Indicator Plants

Moisture Regime	Landform	Indicator Plants		Subtype and Site Class		
		Abundant	Scattered	JP	BS	TA
Arid	Rock outcrop, higher gravel beach ridges	Reindeer moss, Creeping savin	Bearberry	2	--	3
Dry	Higher beach, outwash, and moraine ridges	Bearberry, Creeping savin, Reindeer moss, Slender mountain rice	Common juniper, Soapberry	2	3	2
Fresh	Lower beach, outwash, and moraine ridge, slopes, and intermediate terraces	Twinflower, Buffaloberry, Common juniper, Rough-grained mountain rice	Bearberry, Bunchberry	1	1	1
Moist (groundwater and vadose water types)	Low positions and flaring-out margins OR Till plains, lacustrine flats, and higher flood plains	Red-ozier dogwood, Bunchberry, *Ribes* spp., Naked miterwort, Creeping snowberry	Buffaloberry, Common juniper, Rough-grained mountain rice, Alder	1	1	1
Very Moist	Depressional positions on beach and outwash and lacustrine deposits	Red-ozier dogwood, Naked miterwort, Bunchberry, *Ribes* spp., Alder	Bog cranberry	1	1	1
Wet	Depressional positions on till and lacustrine material	Alder, Marsh marigold, Bog cranberry		--	1	1
Saturated	Deep organic terrain	*Sphagnum* spp., Labrador tea, Marsh marigold		--	2	--

Note: Arid sites are generally devoid of tree cover.

Table 12. Age Range by Cutting Class and Working Group

	Cutting Class				
	1	2	3	4	5
Working Group	Age Range, years				
Jack pine -- all sites	5 ± 5	18 ± 7	48 ± 22	80 ± 10	91+
Black spruce					
Site 1	7 ± 7	23 ± 7	50 ± 20	80 ± 10	91+
Site 2	15 ± 15	53 ± 22	98 ± 22	140 ± 20	161+
Hardwoods -- all sites	7 ± 7	23 ± 7	50 ± 20	80 ± 10	91+

Note: Tables 11 and 12 show how cutting class and site class tie with forest cover in determining age ranges for the stand age class map layer. For example, the age distribution of a Site 2 black spruce stand in Cutting Class 3 is 98 ± 22 years, where 98 represents the mid-point of the age range. The ranges listed in Table 12 represent forest age distribution in 1988, the year of the MNR forest inventory. Because the reference year for this study is 1994, I added 6 years to the mid-points in Table 12 for data used from the MNR inventory that were incorporated into the forest stand age map (Figure 6A).

APPENDIX E

Glossary

Bog. A peatland, generally with the water table at or near the surface. The bog surface, which may be raised or level with the surrounding terrain, is virtually unaffected by the nutrient-rich groundwaters from the surrounding mineral soils and is thus generally acid and low in nutrients. The dominant materials are weakly to moderately decomposed *Sphagnum* and woody peat, underlain at times by sedge peat. The soils are mainly Fibrisols, Mesisols, and Organic Cryosols (permafrost soils). Bogs may be treed or treeless, and they are usually covered with *Sphagnum* spp. and ericaceous shrubs. [From *Rubec*, 1988.]

Collapse scar bog. A circular or oval-shaped wet depression in a perennially frozen peatland. The collapse scar bog was once part of the perennially frozen peatland, but the permafrost thawed, causing the surface to subside. The depression is poor in nutrients, as it not connected to the minerotrophic fens in which the palsa or peat plateau occurs. [From *Rubec*, 1988.]

Evapotranspiration. The process of water vapor transfer from vegetated land surfaces into the atmosphere; an essential part of the global hydrologic cycle. Evapotranspiration includes evaporation (the change of liquid water, from bodies of water and wet soil, into water vapor) and transpiration (in which water is drawn from the soil into plant roots, transported through the plant, and then evaporated from leaves and other plant surfaces into the air). [From *Mintzer*, 1992.]

Gross primary production (GPP). The carbon fixed by plants during the process of photosynthesis. ($GPP = NPP + R_P$). [From *Schlesinger,* 1991.]

Heterotrophic respiration (R_D). Decomposition. The process by which organic matter is converted back into CO_2, mainly by soil micro-organisms. [From *Baum,* 1996.]

Net ecosystem production (NEP). The net difference between how much carbon (energy) the vegetation can fix versus the amount of carbon (energy) that animals and microbes use. Or, the rate at which carbon from the atmosphere is accumulated in the biosphere ($NEP = GPP - R_T$). If NEP >0, the system is storing carbon (energy). If NEP = 0, the system is at equilibrium (steady state) so that carbon (energy) in = carbon (energy) out. If NEP <0, losses of carbon from plant, microbial, and animal respiration exceed the amount fixed by the plants. [From *Seastedt*, 1997; *Schlesinger,* 1991.]

Net primary production (NPP). The carbon that remains stored in the vegetation. ($NPP = GPP - R_P$). [From *Schlesinger,* 1991.]

Oligotrophic. A condition describing habitats low in basic nutrients, usually characterized by a low accumulation of dissolved nutrient salts, supporting only limited plant and animal life, and having a high oxygen content owing to the low organic content. [From *C-1 Forest Ecology Working Group,* 1996.]

Palsa. A mound of perennially frozen peat and mineral soil, up to 5 m high, with a maximum diameter of 100 m. The surface is highly uneven, often containing collapse scar bogs. [From *Rubec*, 1988.]

Palsa bog. A bog composed of individual or coalesced palsas, occurring in an unfrozen peatland. [From *Rubec*, 1988.]

Parent material. Solid matter, usually weathered rocks and minerals but sometimes decomposed organic matter, that becomes soil after the other soil forming factors have acted upon it. [From *Fritton and Butler*, 1998a.]

Peat plateau bog. A bog comprised of perennially frozen peat, rising abruptly about 1 m from the surrounding unfrozen fen. The surface is relatively flat and even, and often covers very large areas. The peat was originally deposited in a non-permafrost environment and is often associated with collapse scar bogs and fens. [From *Rubec*, 1988.]

Plant respiration (R_P). The carbon that plants release to the atmosphere.

Soil drainage. (1) The rapidity and extent of the removal of water from the soil by runoff and flow through the soil to underground spaces. (2) As a condition of the soil, it refers to the frequency and duration of periods when the soil is free of saturation [*Veldhuis*, 1995].

Drainage in the *Veldhuis* [1995] soil report and *Agriculture Canada Expert Committee on Soil Survey* [1983] is described on the basis of actual moisture content in excess of field capacity and length of the saturation period within the plant root zone. [See also *Veldhuis and Knapp,* 1998.] The terms are as follows:

> Well-drained -- Water is removed from the soil readily but not rapidly. Excess water flows downward readily into underlying pervious material or laterally as subsurface flow. Soils have intermediate available water storage capacity (4-5 cm) within the control section, and are generally intermediate in texture and depth. Water source is precipitation. On slopes subsurface flow may occur for short durations but additions are equalled by losses. These soils are usually free of mottles within 100 cm of the surface but may be mottled below this depth. Soil horizons are usually bright colored.
>
> Moderately well-drained -- Water is removed from the soil somewhat slowly in relation to supply. Excess water is removed somewhat slowly

due to low perviousness, shallow water table, lack of gradient, or some combination of these. Soils have intermediate to high water storage capacity (5-6 cm) within the control section and are usually medium to fine in texture. Soils are commonly mottled in the 50 to 100 cm depth. Colors are dull brown in the subsoil with stains and mottles.

Imperfectly drained -- Water is removed from the soil sufficiently slowly in relation to supply to keep the soil wet for a significant part of the growing season. Excess water moves slowly downward if precipitation is major supply. If subsurface water or groundwater, or both, is the main source, flow rate may vary but the soil remains wet for a significant part of the growing season. Precipitation is the main source if available water storage capacity is high; contribution by subsurface flow or groundwater flow, or both, increases as available water storage capacity decreases. Soils have a wide range in available water supply, texture, and depth, and are gleyed phases of well-drained subgroups. These soils generally have mottling below the surface layers and generally have duller colors with depth, generally brownish gray with mottles of yellow and gray.

Poorly drained -- Water is removed so slowly in relation to supply that the soil remains wet for a comparatively large part of the time the soil is not frozen. Excess water is evident in the soil for a large part of the time. Subsurface flow or groundwater flow, or both, in addition to precipitation are main water sources; there may also be a perched water table, with precipitation exceeding evapotranspiration. Poorly drained soils have a wide range in available water storage capacity, texture, and depth, and are gleyed subgroups, Gleysols, and Organic soils.

Very poorly drained -- Water is removed from the soil so slowly that the water table remains at or on the surface for the greater part of the time the soil is not frozen. Excess water is present in the soil for the greater part of the time. Groundwater flow and subsurface flow are major water sources. Precipitation is less important except where there is a perched water table with precipitation exceeding evapotranspiration. These soils have a wide range in available water storage capacity, texture, and depth, and are either Gleysolic or Organic.

Soil horizon. A layer approximately parallel to the soil surface which differs from adjacent layers in properties such as texture, color, structure, and chemical composition. [From *Fritton and Butler*, 1998b.]

Soil profile. A vertical section of a soil, including all of its horizons. [From *Fritton and Butler*, 1998b.]

Soil series. A group of soils developed from similar parent material under similar formative processes, and with similar profiles. Soils within the same series have similar physical, chemical, and morphological characteristics. [From *Fritton and Butler,* 1998b.]

Total respiration (R_T). Total respiratory loss of CO_2 from the ecosystem. [From *Schlesinger,* 1991.]

Varve. A distinct band representing the annual deposit in sedimentary materials regardless of origin and usually consisting of two layers, one thick light colored layer of silt and fine sand laid down in the spring and summer, and the other a thin, dark-colored layer of clay laid down in the fall and winter [*Veldhuis*, 1995]. Thus, the layers can be counted and measured. In a complete series, the number of layers gives the date on which the ground was vacated by the retreating ice [*O'Hara*, 1990].

Veneer bog. A bog occurring on gently sloping terrain underlain by generally discontinuous permafrost. Although drainage is predominantly below the surface, overland flow occurs in poorly defined drainage-ways during peak runoff. Peat thickness is usually less than 1.5 m. [From *Rubec*, 1988.]