ESTIMATING SOIL CARBON STOCKS AND FLUXES IN A BOREAL FOREST LANDSCAPE

by

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Thesis Defense Presentation

3 April 1998

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Click Here

PREFACE

The following is a digital version of the talk with slides that I presented as my thesis defense on 3 April 1998 at Salem State College.

Each page is numbered and sources for the slides are credited on pages 51 and 52. Many of the slides are publicly available on the World Wide Web, and their URLs are listed in the credits.

This file has two features that will help you navigate through my presentation -- a green "button" on the bottom left of each page and "thumbnails" down the left-hand side of the screen. The buttons are programmed to advance to the next page, from start to finish. When you click the button, you will advance to the next slide or page. The thumbnails, which are small "pictures" of each page, are especially useful for locating a particular page. To bring up a page to the screen, click on its thumbnail.

Each page fits entirely in the window on your screen, with thumbnails down the left side of the screen. To look more closely at a particular portion of a page, adjust the view on your monitor by zooming in or out by using the "View" menu or by clicking on the "magnifying glass -- zoom-in tool" in the menu bar. To return to seeing the entire page, and before clicking to the next page, go to "View" and click "Fit in Window."

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You may prefer to view this document so that the pictures and text are larger. One option is to "hide" the thumbnails by clicking "Hide Thumbnails" in the "Windows" menu in the toolbar at the top of the screen. To reopen the thumbnails, go again to "Windows" and click on "Show Thumbnails."

A second way is to view the pages so that they cover the entire screen, and will therefore be the largest possible on your screen. To change to this option, go to "View" on the menu bar and click "Full Screen." To advance to the next page, either click the green button on the page or press "Enter" on the keyboard. To return to the regular menu, press the "Escape" (ESC) key.

To start with the first slide, click on the green "button" at the bottom of the page.

22 February 2000

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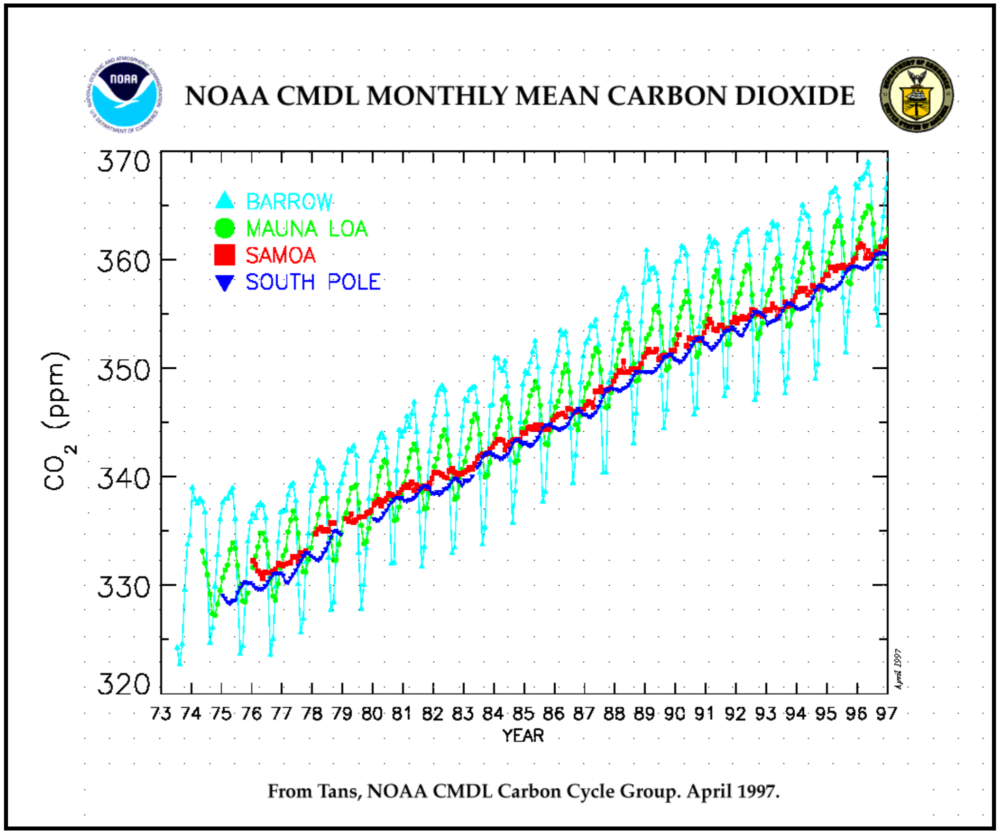
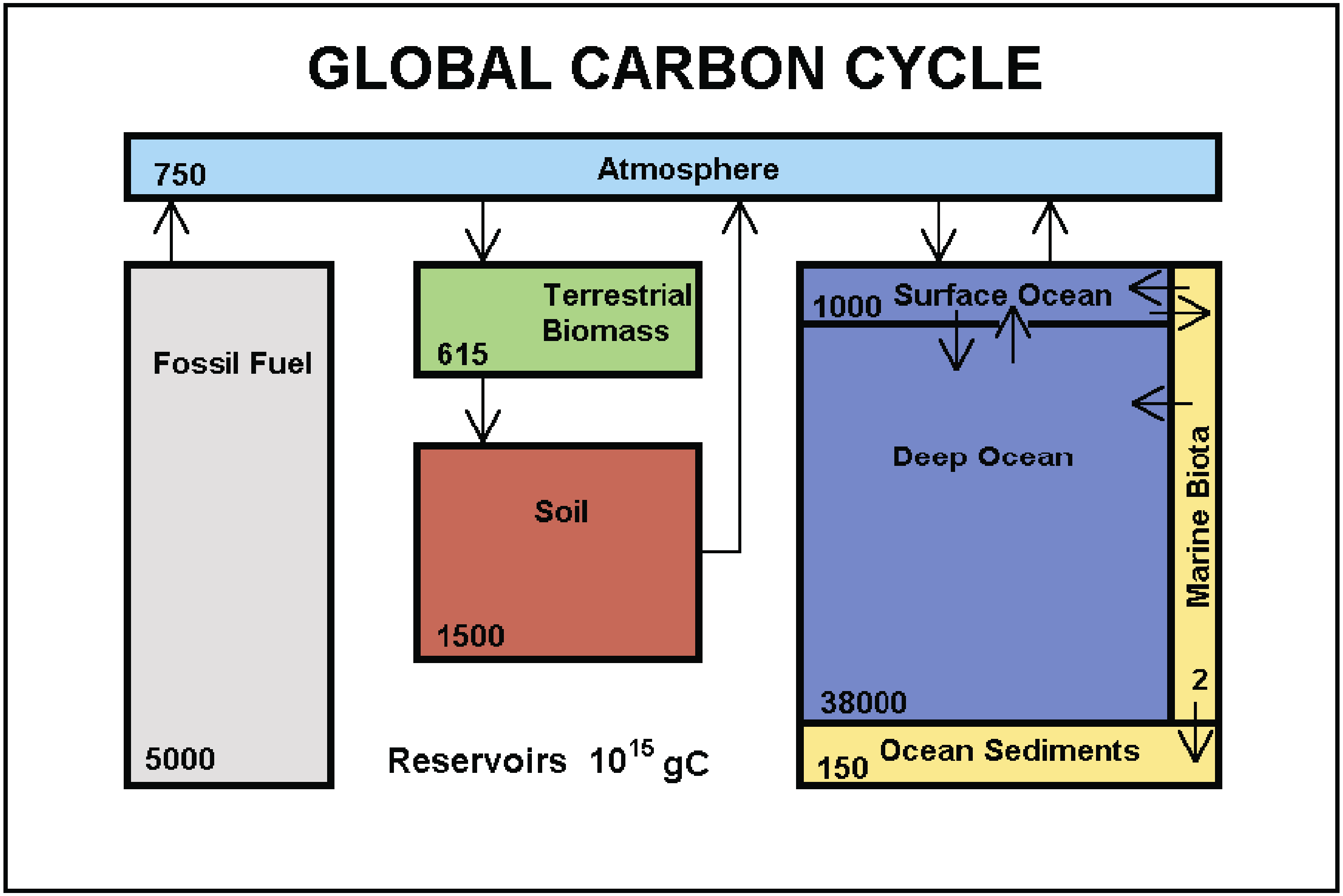
My topic is a small and important piece of the larger global picture ...

... and one that you hear on the news and read about in the papers. Global warming, climate change, earlier spring, and lengthening growing season are in the news.



Global levels of carbon dioxide (CO_2) are increasing, as this graph shows. The graph plots 25 years of annual monthly mean levels of CO_2 monitored at different locations -- Mauna Loa and Samoa near the Equator, the South Pole, and Barrow in the northern latitudes. In all cases levels are rising. And in the northern latitudes annual variation is greatest. That is, the annual highs and lows are greatest.



Carbon moves in and out of several reservoirs (or pools), the largest of which is the ocean. Here, I concentrate on terrestrial reservoirs.

As Freeman Dyson says ...

> **...the three smallest and most active reservoirs (of carbon in the global carbon cycle), the atmosphere, the plants and the soil, are all of roughly the same size. This means that large human disturbance of any one of these reservoirs will have large effects on all three. We cannot hope either to understand or to manage the carbon in the atmosphere unless we understand and manage the trees and soil too.**
>
> **Freeman J. Dyson**
> ***From Eros to Gaia,* 1993**

By "active" Dyson refers to turnover times of carbon in the reservoirs.

This table lists global carbon storage and turnover times. Turnover time is the length of time (here in years) that carbon stays (or resides) in a pool before moving to another.

GLOBAL CARBON RESERVOIRS AND TURNOVER TIMES

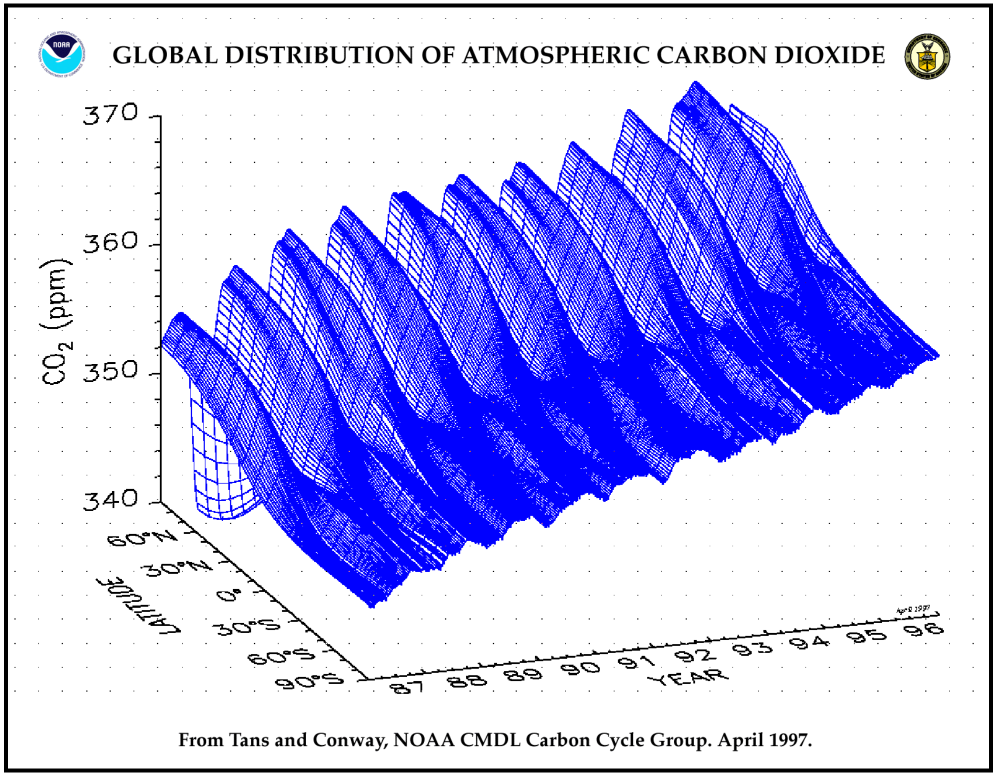
	10^{15} g C	Turnover Time
Sediments, rocks	77×10^{6}	$>>10^{6}$ y
Ocean, marine biomass	40,000	0.1 m -- 5000 y
Soils	1500	<10 -- 10^{5} y
Atmosphere	750	3 -- 5 y
Terrestrial biomass	550 -- 680	50 y

Adapted from *Reeburgh,* 1997

You can see that in each of the active pools, turnover is a short enough span that affects us and that we can track. Turnover time in soils, in particular, ranges from less than 10 years to times that date back to the glaciers.

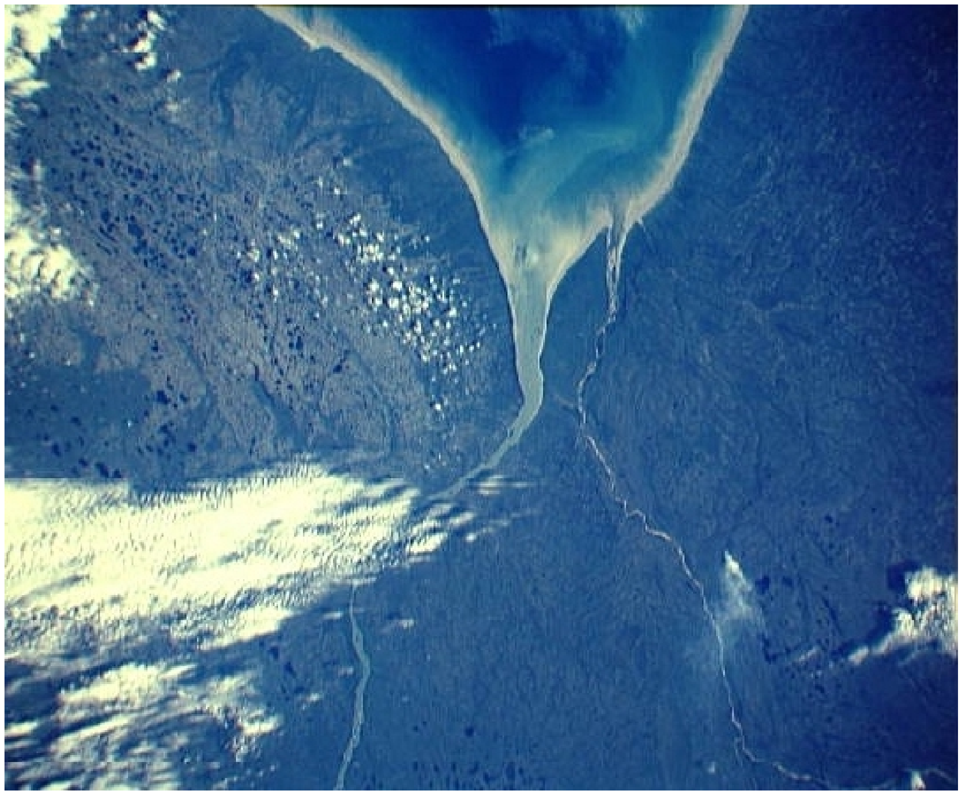
My focus is the soil, the largest of the three active reservoirs. And, in particular, soil in the northern latitudes...

... especially, since as this graph shows so well, CO_2 concentrations are highest in the northern latitudes.

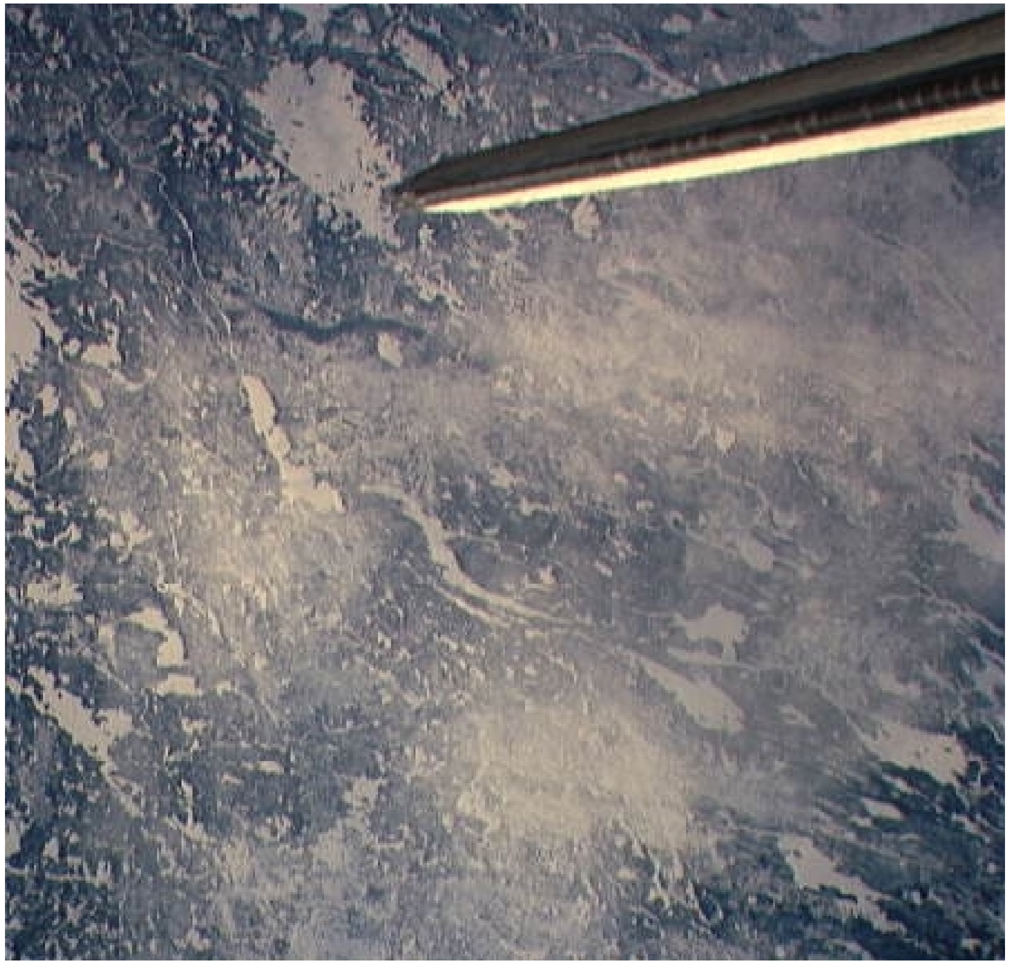


So, I have examined the distribution and flow of carbon in the soil in the northern latitudes. Through space and time. And a GIS lends itself to spatial analysis -- tracking the spatial and data components of my study.

We started out with Apollo 17's view of Earth from space and the larger global picture. Next, we'll narrow the focus to my study site...



looking from the Space Shuttle flying over Hudson Bay and the mouth of the Nelson River ...



... and then over the frozen lakes while flying toward Thompson, Manitoba.

Changing aircraft and flying over the boreal forest west of Thompson, ...

... and over a mature black spruce forest at one of the project's study sites.

Finally, on the ground ...

... and looking at the soil, the focus of this study.

I’ll be talking about estimating soil carbon stocks and fluxes in a boreal forest landscape from the soil pit to the regional scale.

ESTIMATING SOIL CARBON STOCKS AND FLUXES IN A BOREAL FOREST LANDSCAPE

Gloria Rapalee

The Woods Hole Research Center
Salem State College
Goddard Space Flight Center

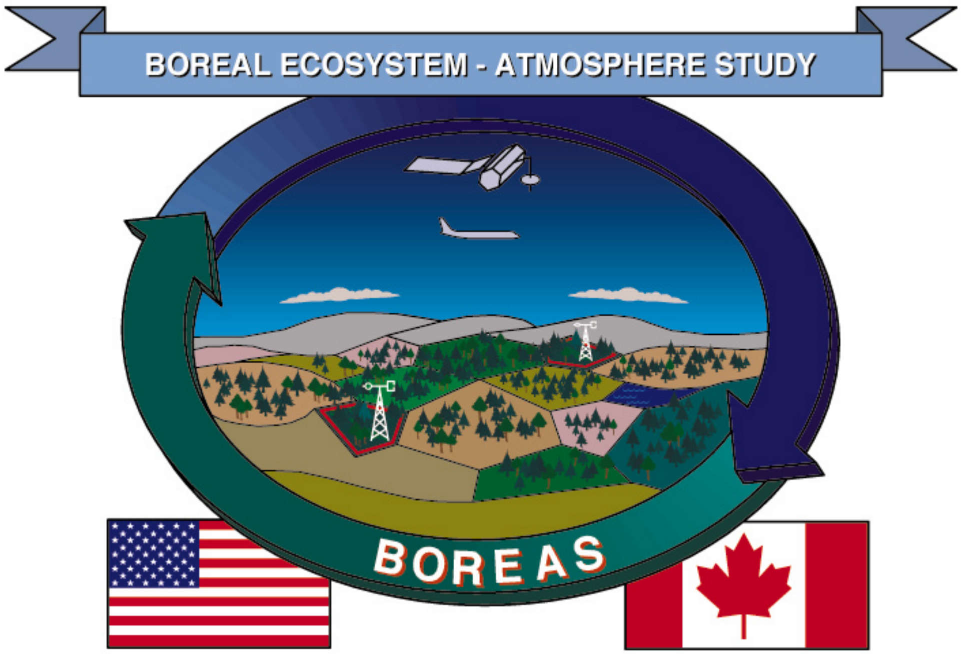
Supported by:
NASA
The Regents of the University of California
U.S. Geological Survey Global Change Program

Dedicated to Craig Whiting

My work is supported by NASA, The Regents of the University of California, and the U.S. Geological Survey Global Change Program.

My talk and this project are dedicated to Craig Whiting.

My project is part of BOREAS. NASA's BOReal Ecosystem-Atmosphere Study is a large-scale, international, interdisciplinary project in the boreal forests of Canada.



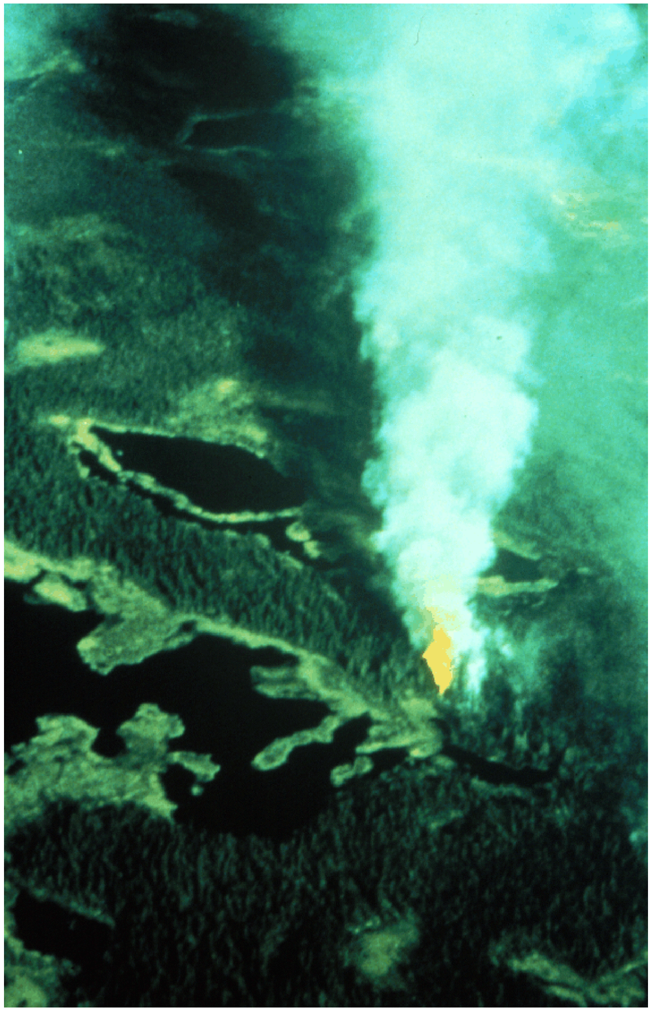
The goal of BOREAS is to improve our understanding of the boreal forests -- how they interact with the atmosphere, how much CO_2 they can store, and how climate change will affect them.

My project concentrates on the carbon cycle in boreal forest soils -- carbon coming in and going out of the soil, how much and where in the soil profile the carbon is stored -- and presents one method of quantifying all this.

Boreal forests and wetlands are currently thought to be significant carbon sinks in global C budgets and they could become net C sources as the earth warms.

Most of the C of boreal forest ecosystems is stored in the soil and moss.

My project examines incidence of fire ...

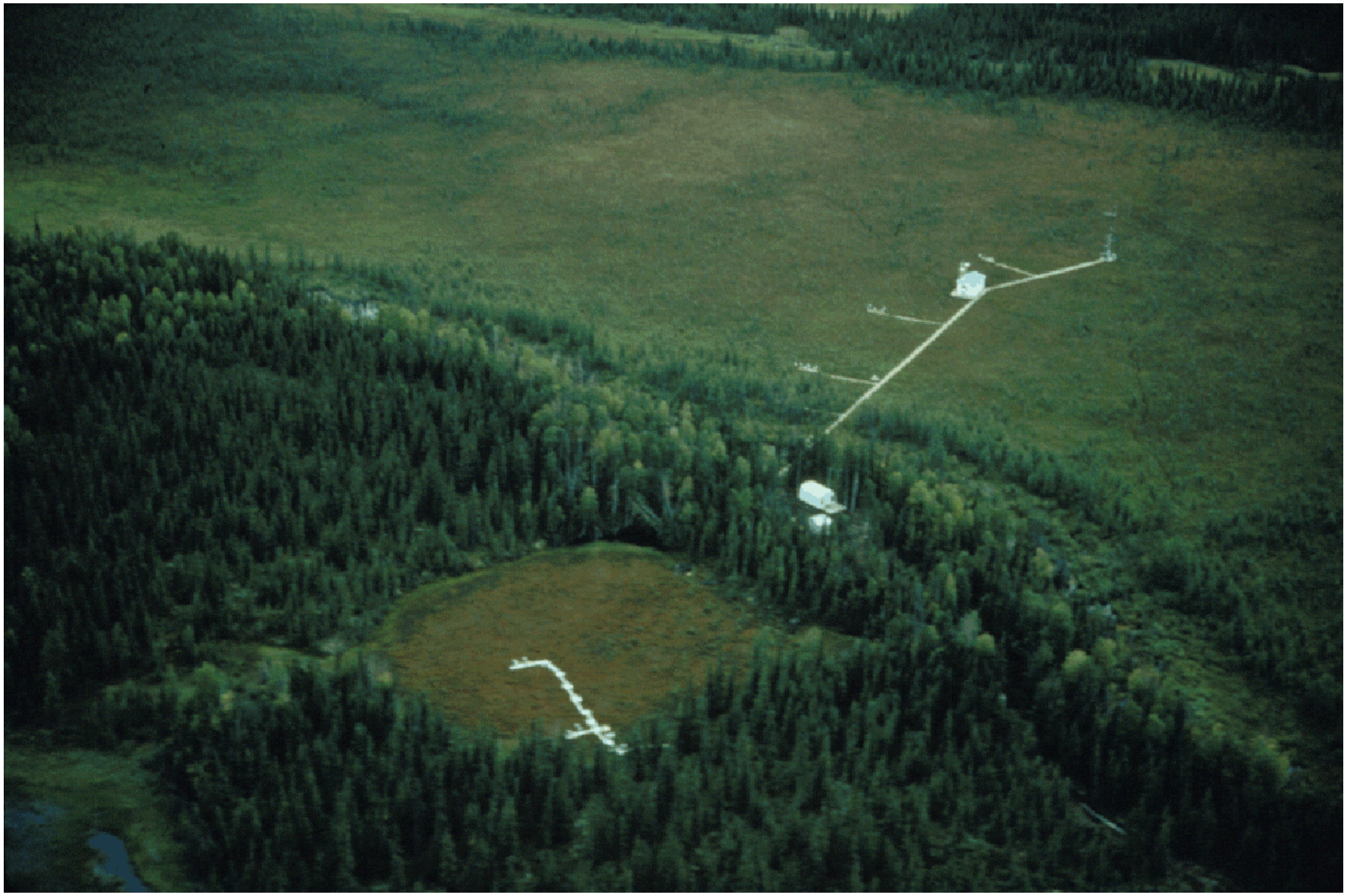


... and the influence of drainage,

... the two factors thought to be most important in controlling annual accumulation rates of soil carbon.

I scale up from the soil pit ...

... to a regional scale.

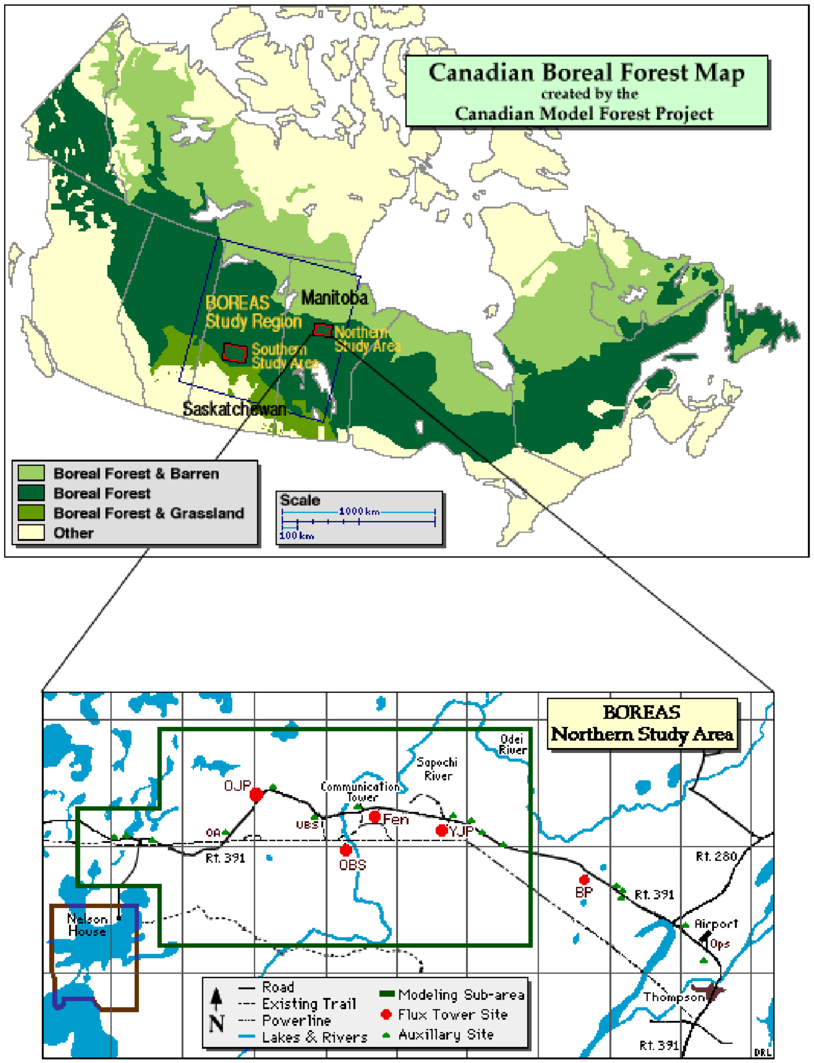


The goals of my project were to:

PROJECT GOALS

- **Estimate total carbon stocks by horizon for common soil series.**
- **Estimate soil carbon flux based on C stocks and simple model of C turnover derived from radiocarbon studies.**
- **Generate area-weighted maps of soil carbon stocks and flux.**
- **Relate patterns of carbon stocks and flux to patterns of drainage, moss cover, and fire history.**

STUDY AREA



The study area is located in northern Manitoba, close to the northern limit of the closed-crown boreal forest, shown in dark green on the top map.

The study area occupies 733 square kilometers, the area enclosed in the box on the lower map.

The study area includes:

well-drained upland jack pine stands ...

on sandy soils; ...

and black spruce stands ...

... on imperfectly and poorly drained soils developed on clay.

The study area also includes low-lying wetlands consisting of fens, as shown in this slide, and bogs and palsas.

To accomplish my goals, I:

METHODS

- **Stratified study area by drainage class.**
- **Determined time since last fire.**
- **Separated the soil profile into two broad layers -- *surface and deep* -- with distinctly different C accumulation rates.**

This slide shows well the delineation between surface and deep soil layers.

Surface layers include moss and soil that is recognizable as organic material.

The deep layers include highly decomposed organic matter, charred material, and mineral horizons.

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.

Continuing with methods --

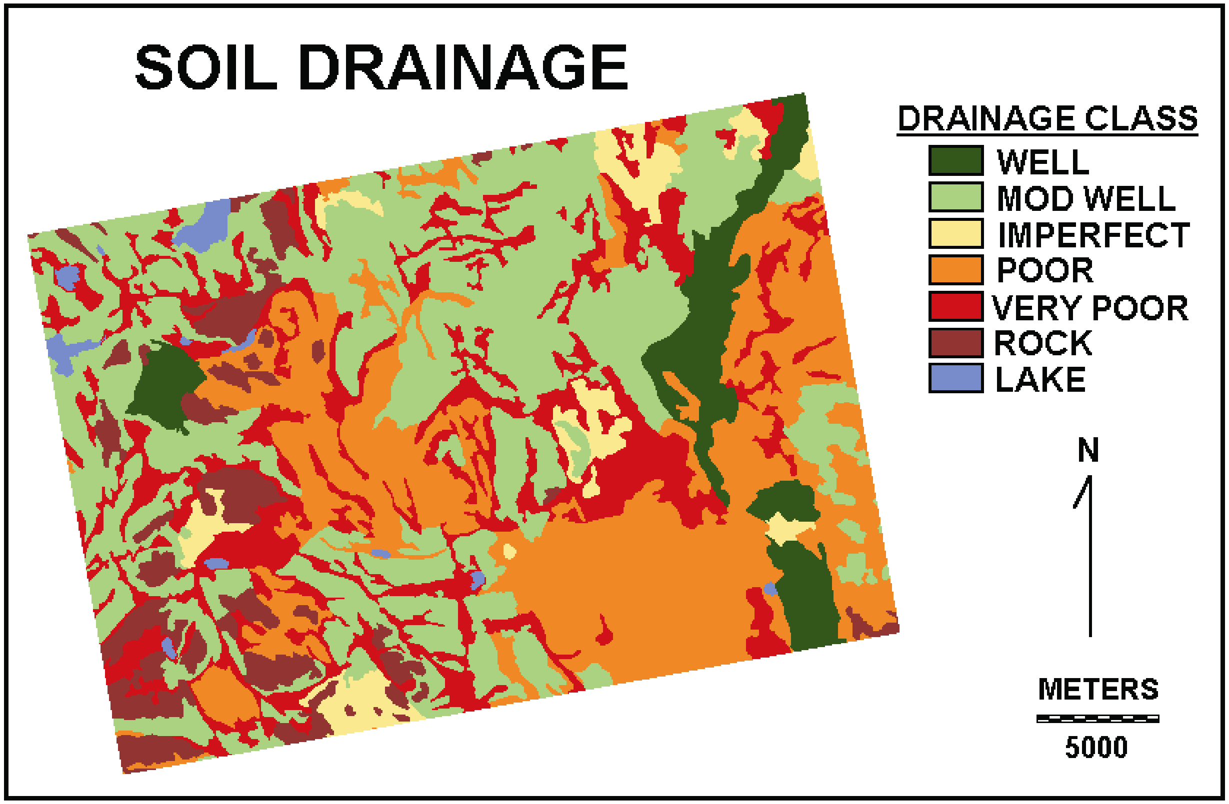
METHODS (cont.)

- **Estimated C stocks for surface layers based on a time-dependent model of moss growth after fire.**
- **Estimated deep soil C stocks from profile data and soil series map.**
- **Estimated annual C fluxes from a simple model of input (*I*), decomposition constants (*k*), and carbon stocks (C) from radiocarbon studies: Net Flux = *I* - *k*C.**

My model has 3 inputs: soil drainage, forest stand age -- time since fire --, and soil carbon stocks.

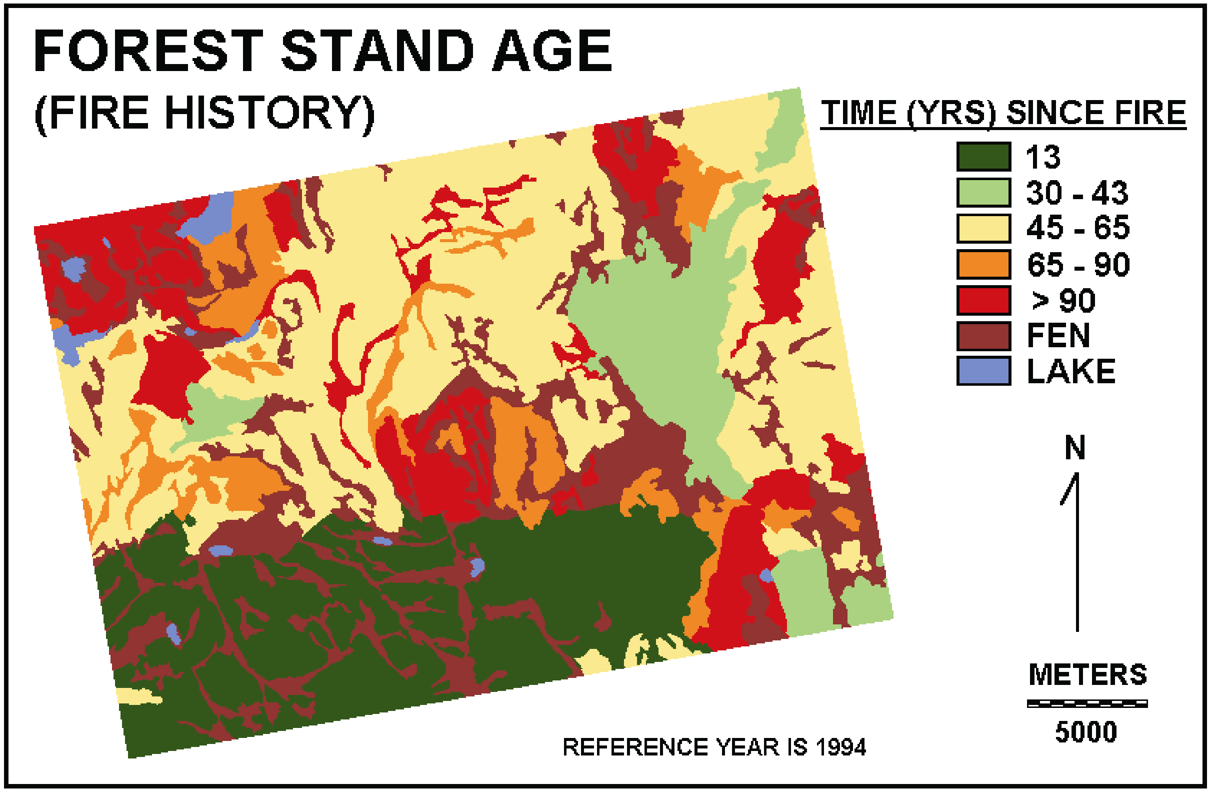
MODEL INPUT

- **Soil Drainage**
- **Forest Stand Age**
- **Soil Carbon Stocks**



I compiled the drainage map from the soil survey conducted by Hugo Veldhuis of Ag-Canada.

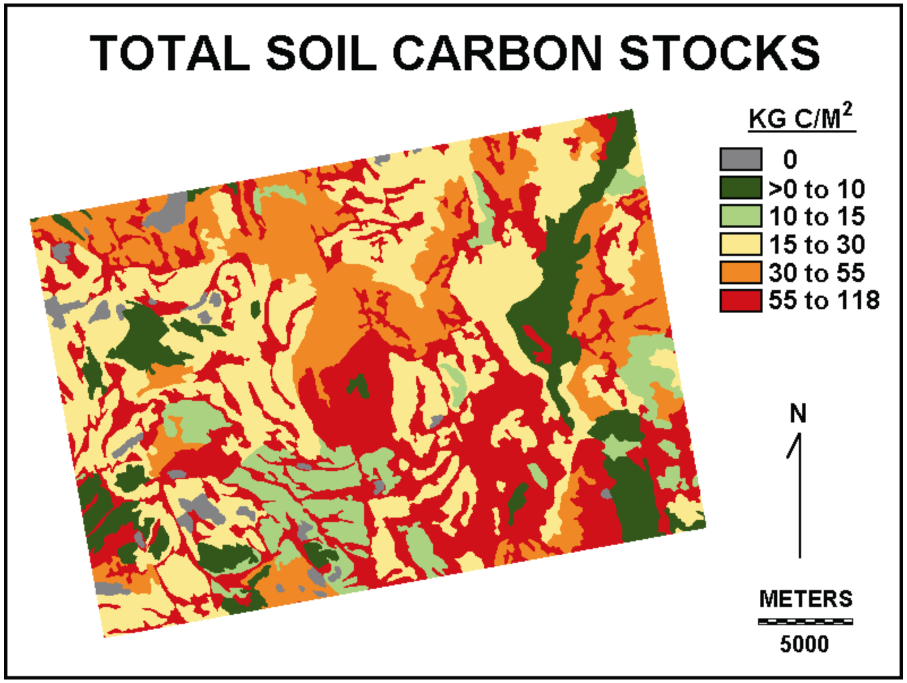
Note that the red and orange areas are wetter palsas, bogs, and fens.



I compiled the fire history map from fire scars detected on satellite imagery and fire maps, as well as tree core and forest inventory data. The age ranges represent time since last fire. The reference year is 1994.

Note the dark green area in the southwest section burned in 1981. The brown areas are predominantly fens, which burn infrequently.

THE THIRD INPUT... CARBON STOCKS



This map shows total carbon stocks calculated from soil survey data. The numbers are area-weighted averages in kg C/m^2.

My calculations indicate that soil C stocks correspond to drainage. The largest C stocks occur in the more poorly drained areas, shown in red and orange on this map.

NOW FOR THE RESULTS:

The study area is a mosaic of drainage classes and forest stand ages. This table shows the distribution by vegetation type/drainage class and age range of the entire study area. The numbers are percents of the total area.

PERCENT OF TOTAL STUDY AREA BY STAND AGE AND DRAINAGE CLASS/VEGETATION TYPE

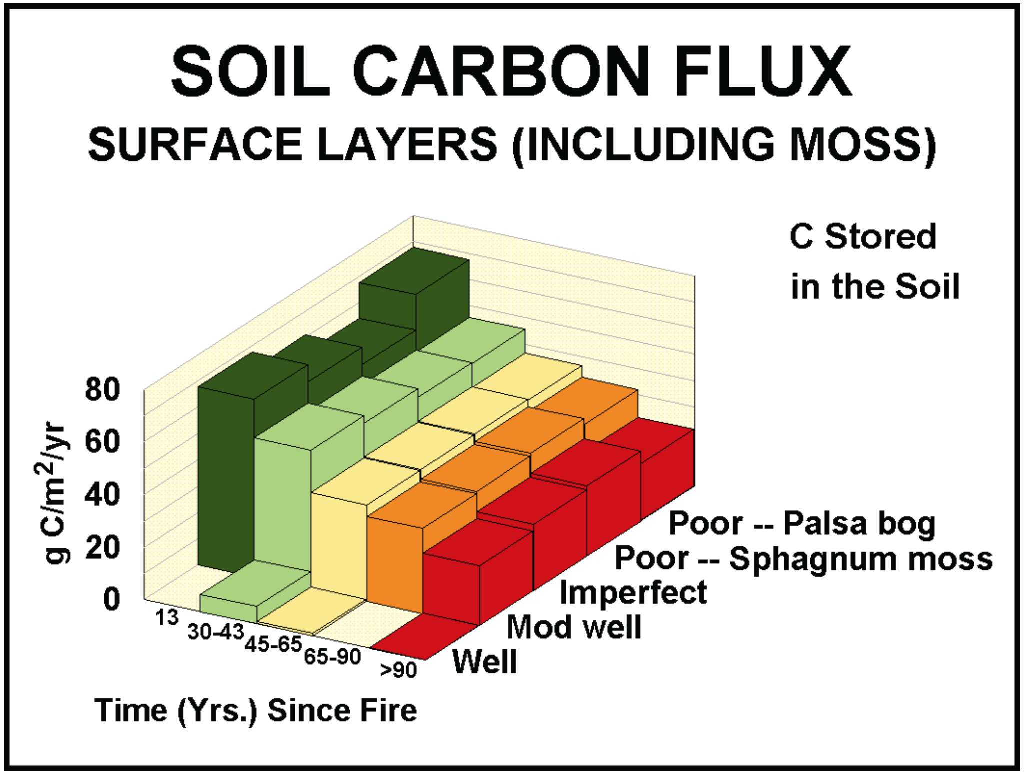
	TIME (YRS.) SINCE FIRE					
DRAINAGE CLASS	**13**	**30-43**	**45-65**	**65-90**	**>90**	**TOTAL**
WELL-DRAINED						
Jack Pine	0	5	<1	0	1	6%
MODERATELY WELL-DRAINED						
Black Spruce/Feather Moss	5	2	10	2	2	21%
IMPERFECT						
Black Spruce/Mixed Mosses	3	1	6	1	1	12%
POOR						
Black Spruce/Sphagnum Moss	4	2	9	2	3	20%
Palsa	6	<1	3	1	4	14%
VERY POOR						
Fen & Bog Collapse						19%
ROCK, WATER, LAKE						8%
TOTAL	18	10	28	6	11	100%

Reference year is 1994.

The left side of the table shows drainage classes from well-drained at the top to poorly drained fens and collapse bogs at the bottom. Along the top, from left to right, the columns show age ranges of time since last fire.

Note the column on the right and the bottom row. The totals show that no one class occupies more than about one-third of the total area.

TURNING TO FLUXES -- THE ANNUAL CHANGE IN C...

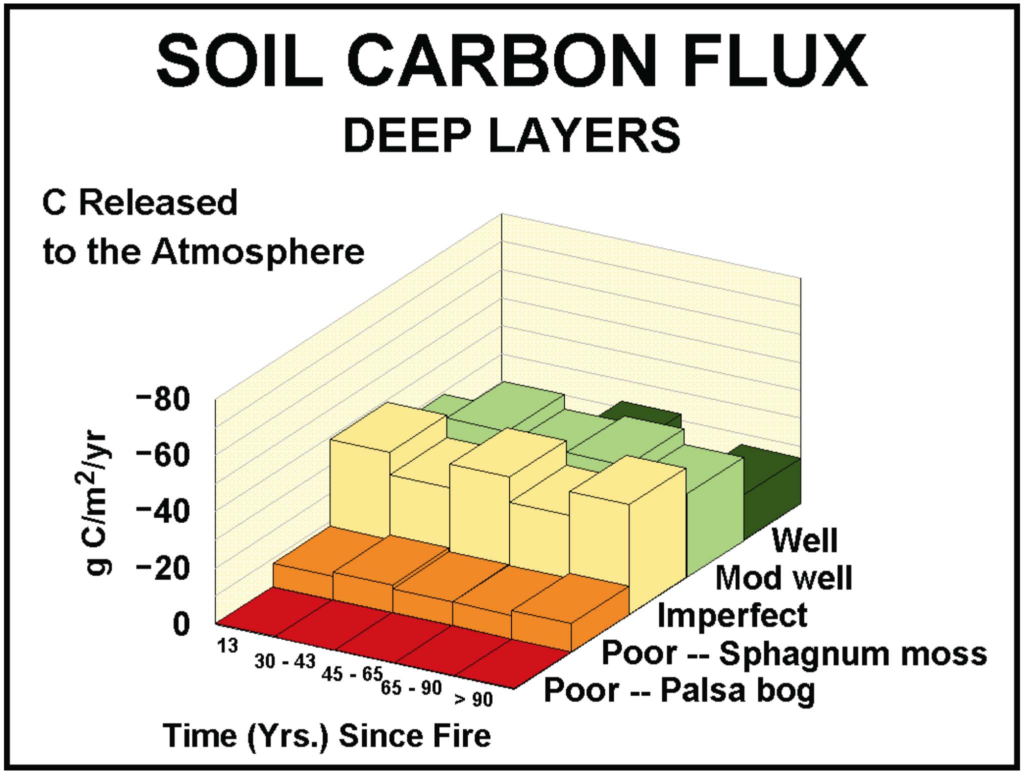


This graph shows the **net annual uptake of C by the soil of the surface layers.** So that the soil is a **sink.**

Values are in $g/m^2/yr$ on the vertical axis. I plotted time in years since last fire and vegetation/drainage class from driest to wettest.

The graph shows that time since fire is an important factor in the fluxes of the surface layers. The greatest annual rates of increase are in the more recently burned sites, and progressively decrease over time.

The story in the deep layers is different, however, as this graph shows. I plotted at the same scale as the previous graph, but notice that the numbers are negative.



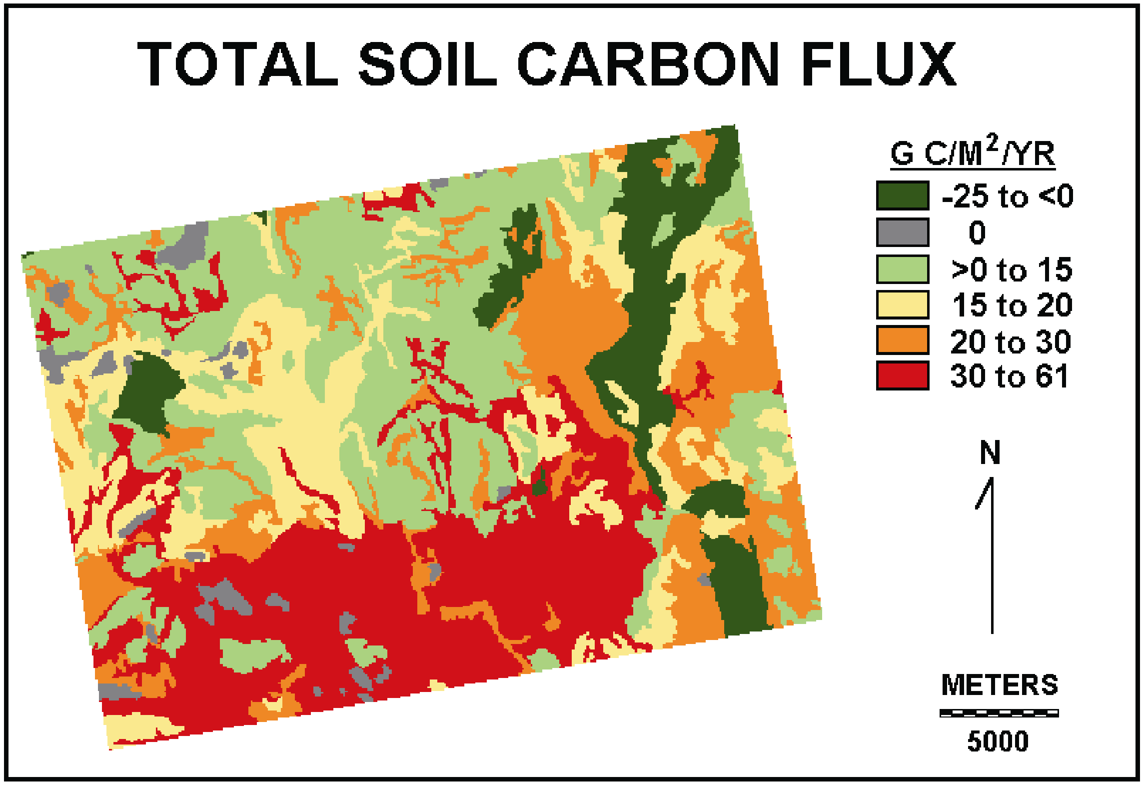
In the deep layers, **in a year with no fire**, the flux is a **net release into the atmosphere** -- a **net loss** of deep C.

And you can see that the factor here is **not** time, but rather drainage.

Greatest releases are in the moderately well and imperfectly drained sites, shown in light green and tan.

Not shown on either slide are the wetlands, which are at steady state in the surface layers but are **STORING** carbon at a slow and steady rate in the deep soil layers. In fact, my analysis indicates that the fens, while occupying about 1/5 of the total area, store about 1/2 of the total carbon stocks, most in the deep soil layers. Annual carbon flux in the fens is about 30 $g/m^2/yr$, all in the deep layers.

Adding together flux from the surface and deep layers -- this map shows total annual C flux for the study area.

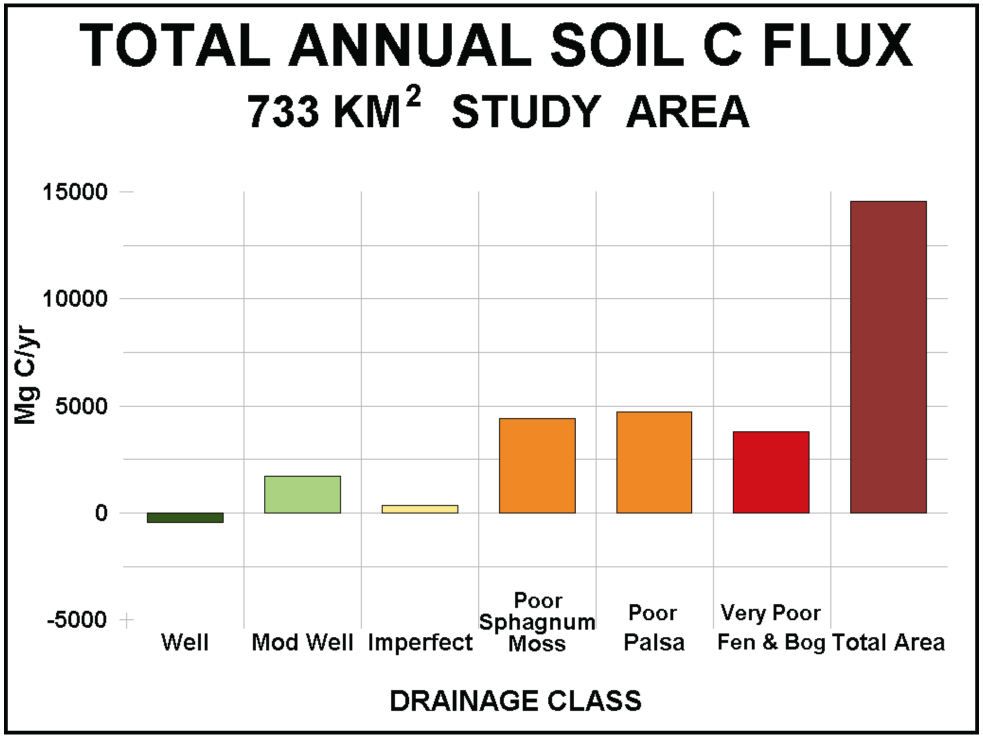


The numbers here are area-weighted averages of total C flux in g $C/m^2/yr$. While the range is not all that great, it is important to note the dark green areas -- jack pine stands, for the most part -- are showing **losses** to the atmosphere. The greatest uptake is in the red area, site of the 1981 burn.

Net annual flux for the entire area is a slight gain. Remember, that none of these fluxes are very large, so the system is near steady state.

So, what does this mean for the total picture??

This graph shows my estimate of **TOTAL** annual soil C flux in **MEGAGRAMS** for the entire study area.



The graph plots C on the vertical axis and drainage along the bottom, from upland well-drained sites (left) to very poorly drained fens and collapse bogs (right).

The graph shows that each drainage type contributes to the total, with the more poorly drained sites contributing the most.

So far the results you've seen are for one year (1994), a year without fire. Because this is a model, we can test the model's sensitivity to different conditions.

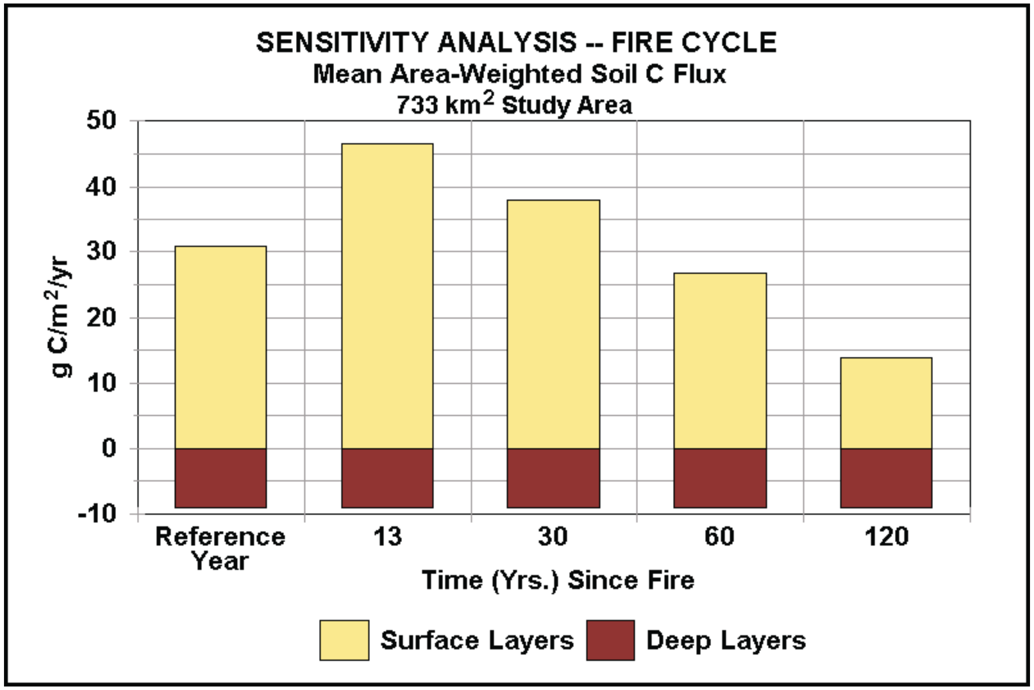
So,

TESTING THE MODEL

We tested the sensitivity of the modeled soil C dynamics to two separate broad scenarios to account for the range of uncertainty of our C flux estimates and to simulate effects of changes in the fire cycle:

- ***by modifying the fire cycle over 120 years.***
- ***by varying decomposition rapes of the deep soil based on Trumbore and Harden's (1997) radiocarbon studies.***

The first test…



This graph shows the effect of fire on annual C flux. In this sensitivity analysis I tracked changes in annual soil C flux if the entire study area (except fens and collapse bogs) burned 13, 30, 60, 90, 120 years ago, to simulate uniformly for the whole region the 1981 burn, the 1964 burn, a burn that would predate existing fire maps (60 years), and the conditions at the oldest forest stand in the study area (120 years).

The numbers represent mean area-weighted C flux (g C/m^2 /yr) for the entire study area. I compare those results with the reference year of 1994. Here, as the graph shows, total C flux for the surface layers initially is highest shortly after fire, then decreases in the older areas. 120 years after fire total net flux for the total profile is nearly zero, with annual uptake by the surface layers nearly offsetting the release of C by the deep layers.

The second test is a bit different, as you will see. First, I offer a little background.

Decomposition of deep soil C is a source of CO_2 to the atmosphere. The magnitude of the deep soil C source depends on the assumed decomposition constant (*k*).

DEEP SOIL C DECOMPOSITION CONSTANTS (*K*) (YR^{-1})

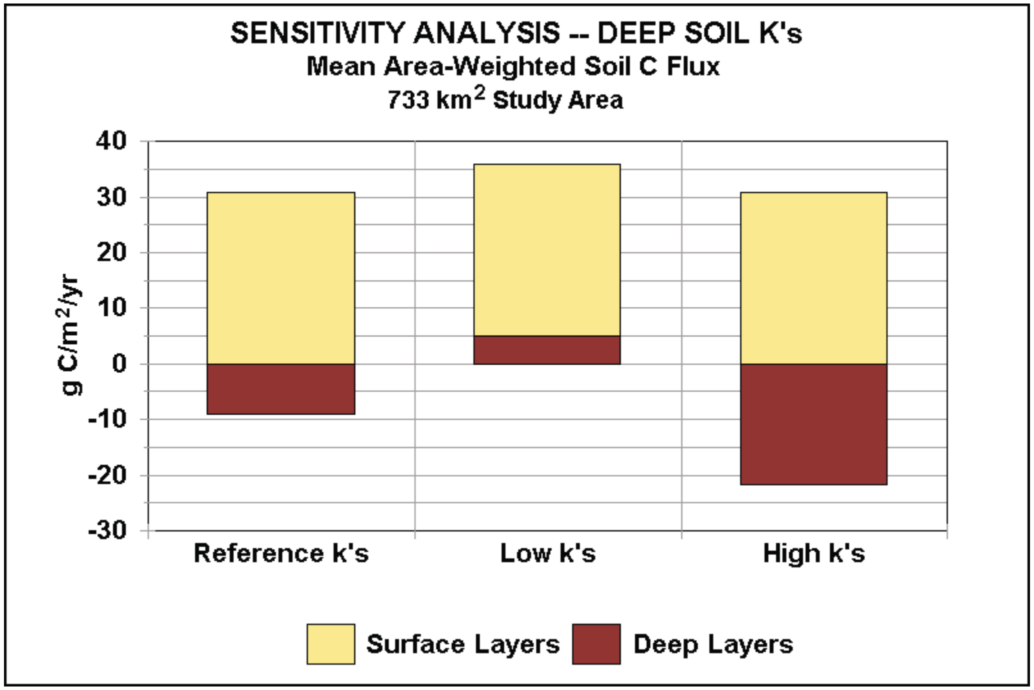
DRAINAGE CLASS	REFERENCE	LOW	HIGH
Well	0.01	0.007	0.012
Moderately Well	0.003	0.0006	0.006
Imperfect	0.002	0.0006	0.003
Poor	0.0007	0.0005	0.0009
Very Poor	0.0004	0.0002	0.0005

From *Trumbore and Harden,* 1997

The second test compared results of changes in decomposition in the deep layers using the reference *k*'s with high and low *k*'s that Sue Trumbore and Jennifer Harden report to be consistent with their radiocarbon data.

These low and high *k* values are really the ranges of uncertainty. Using faster decomposition rates for the deep soil organic layers, individual soil series may become carbon sources rather than C sinks as losses of deep soil C more than offset C gains in surface moss layers.

The results of the second test ...



Here, as in the previous bar graph, the numbers in the graph represent mean area-weighted C flux (g C/m^2/yr) for the entire study area.

My results show that the deep C flux averaged over the entire area can range from a small sink to a source that is large enough to almost completely counter the surface layer sink.

The results of this sensitivity analysis show that the decomposition rate of the large pools of deep soil C is the largest uncertainty in my calculation of net C flux.

So, in effect, the sensitivity analysis of the deep soil *k* values becomes the main message.

Here, as Sue points out so well, my **MAIN** message is that the deep soils are important and uncertainty is limiting our understanding of the ability of boreal ecosystems to act as present sources or sinks of C. The biggest uncertainty is the assumption that the deep soils are experiencing net losses of C between fire events.

MAIN MESSAGE

"... deep soils are important and uncertainty is limiting our understanding of boreal ecosystems to act as present sources or sinks of carbon. The biggest uncertainty is the assumption that the deep soils are experiencing net C losses between fire events."

S. E. Trumbore
June 1997

That uncertainty is limiting our understanding of the ability of the boreal forest ecosystems to act as present sources or sinks of C.

To summarize:

SUMMARY

- Study site is a mosaic of drainage classes and stand ages, with no one class comprising more than 28% of the area.
- Soil C stocks correspond to drainage classes with the largest stocks in poorly drained areas.
- Soil C fluxes depend on both drainage class and stand age, with the largest accumulations of soil C in fens and in the surface mosses of recently burned sites.

SUMMARY (cont.)

- "The deep soil can range from a small sink to a source that is large enough to almost completely counter the (surface) moss layer sink. Our 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."
  E. A. Davidson (July 1997)

- Turnover of deep soil C in these ecosystems and its response to expected warming and altered drainage patterns deserve more attention.

THE GLOBE AND MAIL

SCIENCE & ENVIRONMENT

DEER MOUSE

A small, delicately built rodent found from Alaska to South America; large eyes and ears; nocturnal; often used as a laboratory animal

D8 ■ Saturday, August 3, 1996 ■

EMISSIONS

Where has all the carbon gone?

Of the billions of tonnes of carbon released into the atmosphere every year, a large chunk cannot be accounted for. A study of the boreal forest may shed light on the mystery

BY MICHAEL SMITH
Special to The Globe and Mail
Toronto

IF you look at Toronto from a distance, you'll notice the air seems to be thicker and browner over the downtown core. Part of the smog is dust kicked up by a few million people and vehicles; another part is carbon, emitted in the form of oxides by those fossil-fuel-using vehicles, by the furnaces of skyscrapers and homes and by steam plants and incinerators.

The main form of carbon dumped into the air by these human activities is carbon dioxide, a so-called "greenhouse gas" that many scientists believe contributes to

The Boreal Ecosystem Atmosphere Study is monitoring the carbon intake of a huge area of

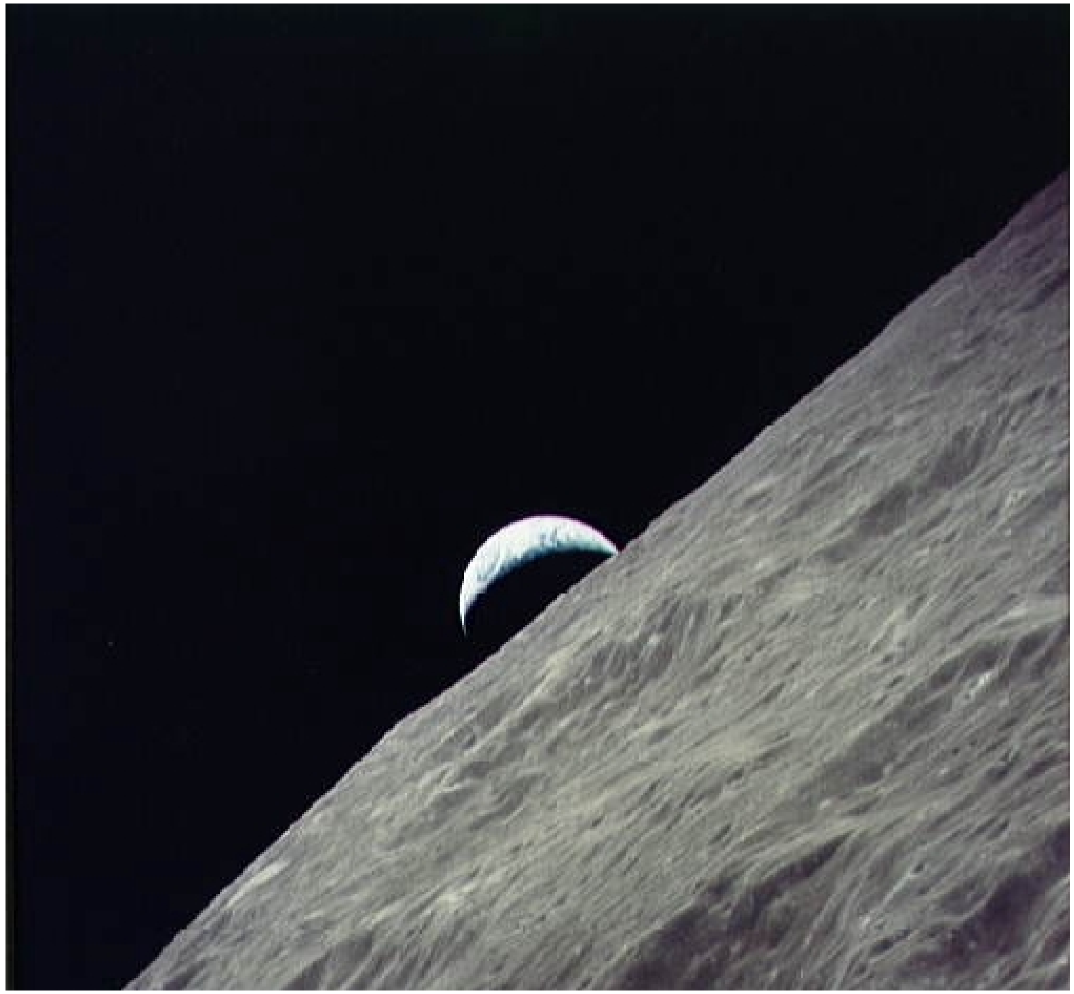
However, the BOREAS data on the lost carbon are preliminary: Results from a large environmental prairie study concluded a decade ago in Kansas are still being analyzed and producing scientific papers, Dr. Hall says, and there's no reason to believe BOREAS won't take at least as long to analyze in detail. The missing sink may be lurking in reams of unstudied information.

And the study sites in Manitoba and Saskatchewan — areas featuring black spruce on the high ground and peat bogs on the lower — may not be as typical of the boreal forest as researchers had thought.

"What we've learned in the three or four

In partial answer to the question posed in the Toronto Globe & Mail in early August 1996 ......

We still don't know where **ALL** the carbon has gone. But the results of this study indicate that the deep soil of the boreal forest holds one answer.



Slide Credits

1 NASA, Johnson Space Center Digital Image Collection. View of the Earth seen by the Apollo 17 crew traveling toward the moon during NASA's final lunar landing mission in the Apollo program. Photo taken 7 December 1972. NASA Photo ID: AS17-148-22727. Available online at: http://images.jsc.nasa.gov/images/pao/AS17/10075945.jpg and http://images.jsc.nasa.gov/images/pao/AS17/10075945.htm.

3 Tans, P. P., NOAA CMDL monthly mean carbon dioxide, http://www.cmdl.noaa.gov/ccg/figures/figures.html (CO_2 Monthly Means). 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.

4 Global carbon reservoirs from Schlesinger, W. H., *Biogeochemistry, An analysis of global change,* Academic Press, Inc., San Diego, California, 1991; 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; Reeburgh, W. S., Figures summarizing the global cycles of biogeochemically important elements, *Bulletin of the Ecological Society of America, 78*, 260-268, 1997.

5 From Dyson, F. J., *From Eros to Gaia*, Penquin Books, 1993. Paperback re-issue edition (April 1995), Penguin USA (Paper); ISBN: 0140174230.

6 Modified from Reeburgh, *ibid*. Also available online at: http://www.ess.uci.edu/~reeburgh/figures.html (last updated 30 May 1997).

7 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 (CO_2 Rug). 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.

8 NASA, Johnson Space Center Digital Image Collection. The Nelson River (larger, westerly) and the Hayes River (smaller, southwesterly) form a small peninsula that extends into the southwest side of Hudson Bay in Manitoba. Photo taken in August 1989 on Space Shuttle Mission STS 028. NASA Photo ID: STS028-152-149. Available online at: http://images.jsc.nasa.gov/iams/images/earth/STS028/html/10009235.htm and http://images.jsc.nasa.gov/iams/images/earth/STS028/lowres/10009235.jpg.

9 NASA, Johnson Space Center Digital Image Collection. Frozen lakes near Thompson, Manitoba. Photo taken in January 1992 on Space Shuttle Mission STS 042. NASA Photo ID: STS042-81-097. Available online at: http://images.jsc.nasa.gov/iams/images/earth/STS042/html/10066462.htm and http://images.jsc.nasa.gov/iams/images/earth/STS042/lowres/10066462.jpg.

10,18 Photos courtesy of Forrest G. Hall.

11,12,13,16,17,20,21,24,25,26,27,28,30,39 Photos courtesy of Hugo Veldhuis. Available online at: http://ltpwww.gsfc.nasa.gov/globe/index.htm and http://www.globe.gov/.

15,23 Courtesy of BOREAS. 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/ ARTWORK.HTML. Published on CD-ROM by NASA, 2000. Also available online at: http://daacl.esd.ornl.gov/BOREAS/bhs/BOREAS_Home.html.

19 Photo courtesy of Jeffrey A. Newcomer.

33,34,35,36,37,38,40,41,44 From 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, 1998. Used with permission of the American Geophysical Union.

43,45 Modified from Rapalee *et al., ibid*. Used with permission of the American Geophysical Union.

49 From *The Globe and Mail*, Toronto, Ontario, 3 August 1996. Online at: http://www.theglobeandmail.com/.

50 NASA, Johnson Space Center Digital Image Collection. The crescent Earth rises above the lunar horizon in this photograph taken from the Apollo 17 spacecraft in lunar orbit during NASA's final lunar landing mission in the Apollo program. Photo taken 14 December 1972. NASA Photo ID: AS17-152-23274. Available online at: http://images.jsc.nasa.gov/images/pao/AS17/10075989.jpg and http://images.jsc.nasa.gov/images/pao/AS17/ 10075989.htm.