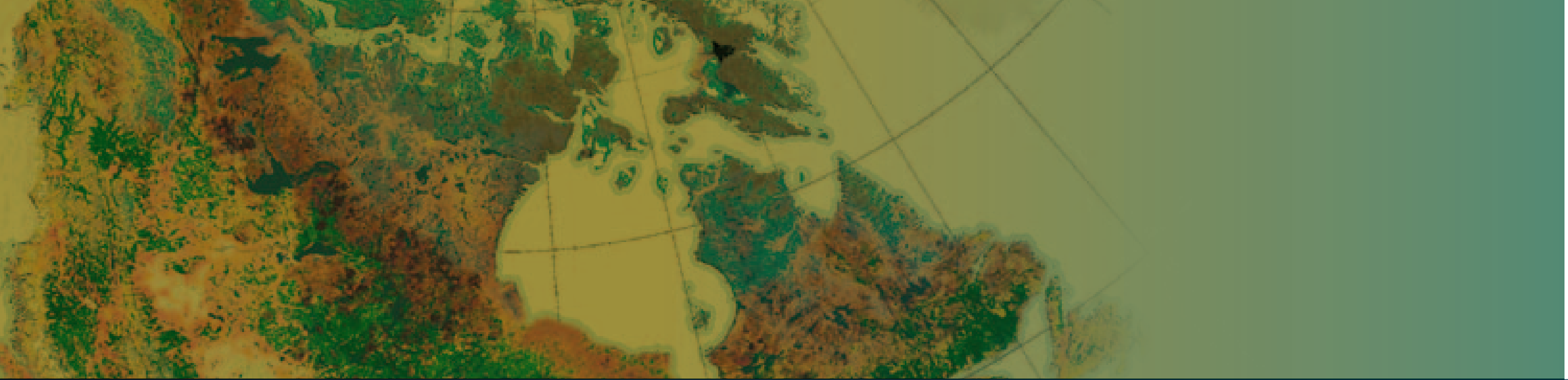

Ecosystems in Flux: Carbon, Climate, and Disturbance in Northern Forests and Peatlands

Perspectives from the Fluxnet-Canada and Canadian Carbon Program Research Networks (2001-2011)

CANADIAN CARBON PROGRAM
PROGRAMME CANADIEN DU CARBONE

Fluxnet Canada

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Message from the Program Leader

IMAGE A CHOISIR

IMAGE A CHOISIR

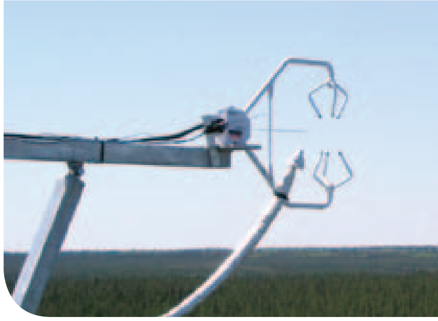

IMAGE A CHOISIR

The Fluxnet-Canada Research Network (FCRN) was inaugurated in 2002 to study and understand the carbon cycle of Canadian forests and peatlands. Funding for university scientists was provided by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the Natural Sciences and Engineering Research Council of Canada (NSERC) and BIOCAP, Canada and by Natural Resources Canada (NRCan) and Environment Canada for government scientists. After an initial five-year period, the work that began under FCRN was continued and expanded by the Canadian Carbon Program Research Network (CCP) through funding provided to university scientists by CFCAS, NRCan and BIOCAP Canada and with the continued participation of scientists from NRCan and Environment Canada.

From 2002 to 2011, the FCRN and CCP provided a dynamic and collaborative environment for more than 50 scientists and 120 graduate students to conduct research on a diverse set of topics related to the carbon cycle and climate. Our funding has enabled us to hold annual general meetings bringing together scientists, students and staff from North America and Europe. Students have been able to attend conferences, workshops and training courses all over the world and we have held two Carbon Cycle Science Short Courses in Prince Albert National Park, Saskatchewan. Some of the work carried out by our scientists and students is highlighted in this document.

Our research networks brought people together from across Canada around a common research theme. We accomplished much more together than we ever could alone. Our legacy is the scientific advances we achieved, the students we trained, the ecosystem models we developed, and a standardised, long-term data set that documents the carbon cycle of Canadian forests and peatlands at the beginning of the 21st century. Our data are openly available and will advance our science for many years into the future. I sincerely thank all of those who participated and all of those who provided financial and/or moral support.

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Who are we, what do we do?

Increasing concentrations of atmospheric carbon dioxide and other greenhouse gases, as a result of fossil fuel emissions and changing land use, have led to concerns about climate change. Natural ecosystems are a major component of the global carbon cycle and their response to climate and to human interventions needs to be considered when we evaluate different policy options about climate change and our use of energy. Integrating natural ecosystems into the policy discussion requires an enhanced scientific understanding of how natural ecosystems currently respond to climate and how this response might change in the future.

In 2002 nearly 50 Canadian university and government researchers came together in a coordinated national-scale effort to better understand the carbon cycle of Canada's vast forest and peatland ecosystems and their role in climate change. We united around the idea that advancing terrestrial carbon cycle science in Canada required the establishment of a coordinated set of standardised, continuous, long-term observations across the country that would be closely linked to the development of mathematical ecosystem models. Our idea was to furnish the critical carbon cycle measurements necessary to develop and test process models that describe and predict how our ecosystems respond to changes in climate and ecological disturbances (e.g., fires, insects and forest harvest) as well as how this response might feed back to either exacerbate or modulate future climate change.

The Fluxnet-Canada Research Network (2002-2007) was designed as a proof-of-concept of a carbon monitoring and observation system centered on the establishment of a network of eddy covariance flux towers (Figure 1). Data collection at these towers include fluctuations in wind speed and atmospheric gas concentrations, allowing us to calculate the exchange of carbon, water and energy between the land surface and the atmosphere for entire ecosystems over an area of (a *footprint* of) approximately one square kilometre. We make these measurements in 30-minute time steps – 24 hours per day, 365 days per year over multiple years. The towers were strategically located in different forest and peatland types across the country and placed in areas that capture the effects of ecological disturbance and landscape spatial variability. When combined with satellite remote sensing and climate and soil information, we can start to piece together how our major ecosystems respond to changing climate at local, regional, national, continental and global scales. In 2007, the Fluxnet-Canada concept was expanded by integrating other greenhouse gas measurements and forest inventory data to develop ever more sophisticated models. This new effort, known as the Canadian Carbon Program, was in operation until early 2011.

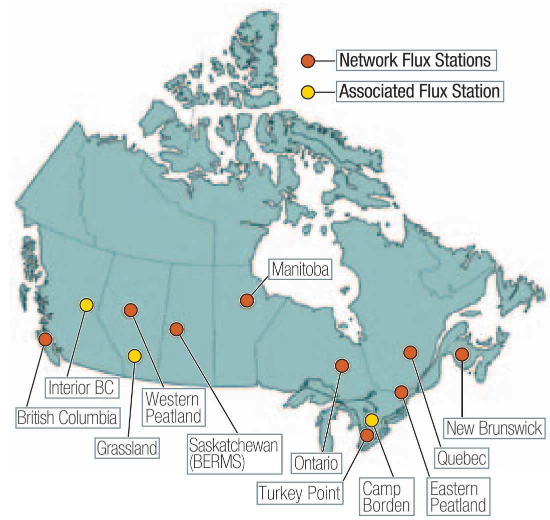


Figure 1. Ecosystem flux measurements were conducted at more than 25 different flux tower sites located at 12 different FCRN/CCP flux stations in seven provinces. Flux tower sites were located in mature and disturbed stands in both boreal and temperate forests, as well as in peatland ecosystems.

We have been able to combine our data with data from other similar measurement networks across the world to establish a global data base that has advanced our understanding of the global carbon cycle significantly. We have also produced an archived data set that will be an important part of the network's scientific legacy and serve as the foundation for long-term monitoring of Canada's carbon cycle over subsequent decades. Over 120 graduate students and post-doctoral fellows were trained within FCRN/CCP. We expect these talented researchers will carry the networks' mandate onward into the future. Finally, more than 200 peer reviewed journal articles and a special issue of *Agricultural and Forest Meteorology* were published as a result of FCRN/CCP research activities.

How Does Carbon Cycle Science Inform Public Policy?

Increasing concentrations of atmospheric carbon dioxide and other greenhouse gases from fossil fuel emissions and land use change are affecting the climate. The global carbon cycle is a complex system in which terrestrial ecosystems play a major role. There are five major reasons why we need to better understand the terrestrial carbon cycle that are directly pertinent to climate change policy:

1. The movement of carbon dioxide back and forth between terrestrial ecosystems and the atmosphere within a given year exceeds fossil fuel emissions by more than ten-fold. Thus, relatively small changes in the balance of these fluxes can have a very large effect on the overall carbon budget. We need to understand the mechanisms and nature of these changes (feedbacks) in the terrestrial carbon cycle so that we can better assess the ultimate effectiveness of different emission reduction strategies.
2. We have good evidence that terrestrial ecosystems sequester, on average, 30% of fossil fuel CO2 emissions each year, carbon that would otherwise remain in the atmosphere if these sinks were to stop sequestering carbon. However, understanding what determines the sink/source status of terrestrial ecosystems, and how to quantify it at large spatial scales, remains a complex scientific challenge.
3. Forests could potentially play a significant role in a carbon mitigation portfolio, but the quantity, stability, and cost of the carbon sequestered needs to be better understood.
4. Climate change will have an impact on the capacity of terrestrial ecosystems to provide continued goods and services to society in addition to the sequestration of CO2. We need to better understand the sensitivity of our ecosystems to a changing climate if we are to develop effective strategies for adapting to climate change.
5. Given the importance of climate change to our society and our economy, Canada needs to improve its capacity to integrate all available information about the carbon cycle, including the contribution of Canada's forests and peatlands, into a coherent analytical framework. This should be designed to support Canada's existing carbon monitoring and prediction system.

The Fluxnet-Canada Research Network and the Canadian Carbon Program were designed to contribute to these five scientific issues in a way that is directly pertinent to Canada. We are a scientific enterprise devoted to providing the high-quality measurements, analytical framework, and robust scientific collaboration necessary to move the science forward in a significant way and thereby provide a Canadian contribution to understanding this global problem. Given Canada's large land area and the distribution of its carbon stocks, our efforts are focused on the country's forests and peatlands.

FCRN/CCP have provided scientific support to help address Canada's domestic and international policy goals with respect to its forest and peatland carbon, including its reporting needs and the assessment of forest- and peatland-based mitigation options. In doing so, we have contributed to the following Canadian policy goals:

1. Demonstrating climate-responsible forest and peatland stewardship within an increasingly global economy and global scientific environment;
2. Satisfying domestic and international greenhouse gas reporting needs and requirements and anticipating possible future needs;
3. Assuring that domestic and international forest carbon policies and rules reflect Canada's circumstances; and
4. Potentially using forest carbon to help achieve Canada's mitigation objectives.

01 Forests and the Carbon Cycle

Selected Publications

Amiro, B.D., A.G. Barr, J.G. Barr, T.A. Black, R. Bracho, M. Brown, J. Chen, K.L. Clark, K.J. Davis, A.R. Desai, S. Dore, V. Engel, J.D. Fuentes, A.H. Goldstein, M.L. Goulden, T.E. Kolb, M.B. Lavigne, B.E. Law, H.A. Margolis, T. Martin, J.H. McCaughey, L. Misson, M. Montes-Helu, A. Noormets, J.T. Randerson, G. Starr, J. Xiao. 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. Journal of Geophysical Research 115, G00K02, doi:10.1029/2010JG001390.

Amiro, B.D., A.L. Orchansky, A.G. Barr, T.A. Black, S.D. Chambers, F.S. Chapin III, M.L. Goulden, M. Litvak, H.P. Liu, J.H. McCaughey, A. McMillan, J.T. Randerson. 2006. The effect of post-fire stand age on the boreal forest energy balance. Agricultural and Forest Meteorology 140: 41-50.

Arain, M.A., N. Restrepo-Coupe. 2005. Net Ecosystem Production in an Eastern White Pine plantation in southern Canada. Agricultural and Forest Meteorology 128: 223-241.

Barr, A.G, T.A. Black, E.H. Hogg, T. Griffis, K. Morgenstern, N. Kljun, A. Theede, Z. Nesic. 2007. Climatic controls on the carbon and water budgets of a boreal aspen forest. Global Change Biology 13: 561-576.

Bergeron, O., H.A. Margolis, T.A. Black, C.C. Coursolle, A.L. Dunn, A.G. Barr, S.C. Wofsy. 2007. Comparison of CO2 fluxes over three boreal black spruce forests in Canada. Global Change Biology 13: 89-107, doi:10.1111/j.1365-2486.2006.01281.x.

Bernier, P.Y., P. Bartlett, T.A. Black, A. Barr, N. Kljun, H. McCaughey. 2006. Drought constraints on transpiration and canopy conductance in mature aspen and jack pine stands. Agricultural and Forest Meteorology 140: 64-78.

Brown, M, T.A. Black, Z. Nesic, V.N. Foord, D.L. Spittlehouse, A.L. Fredeen, N.J. Grant, P.J. Burton, J.A. Trofymow. 2010. Impact of mountain pine beetle on the net ecosystem production of lodgepole pine stands in BC. Agricultural and Forest Meteorology 150: 254–264.

Cai, T., L.B. Flanagan, R.S. Jassal, T.A. Black. 2008. Modeling environmental controls on photosynthesis and the carbon isotope composition of ecosystem respired CO2 in a coastal Douglas-fir forest. Plant Cell and Environment 31: 435-453.

Chasmer, L., H. McCaughey, A. Barr, A. Black, A. Shashkov, P. Treitz, T. Zha. 2008. Investigating light-use efficiency across a jack pine chronosequence during dry and wet years. Tree Physiology 28: 1395-1406.

Chen, J.M., A. Govind, O. Sonnentag, Y. Zhang, A. Barr, B. Amiro. 2006. Leaf area index measurements at Fluxnet-Canada forest sites. Agricultural and Forest Meteorology 140: 257-268.

Coursolle, C., H.A. Margolis, A.G. Barr, T.A. Black, B.D. Amiro, J.H. McCaughey, L.B. Flanagan, P.M. Lafleur, N.T. Roulet, C. P.-A. Bourque, M.A. Arain, S.C. Wofsy, A. Dunn, K. Morgenstern, A.L. Orchansky, P.-Y. Bernier, J.M. Chen, J. Kidston, N. Saigusa, N. Hedstrom. 2006. Late-summer carbon fluxes from Canadian forests and peatlands along an east-west continental transect. Canadian Journal of Forest Research 36: 783-800.

Flanagan, L.B., T. Cai, T.A. Black, A.G. Barr, J.H. McCaughey, H.A. Margolis. 2011. Measuring and modeling ecosystem photosynthesis and the carbon isotope composition of ecosystem-respired CO2 in three boreal coniferous forests. Agricultural and Forest Meteorology (in press, special issue in honour of Andrew Black).

Giasson, M.-A., C. Coursolle, H.A. Margolis. 2006. Ecosystem-level carbon fluxes from a boreal cutover in eastern Canada before and after scarification. Agricultural and Forest Meteorology 140: 23-40 doi:10.1016/j.agrformet.2006.08.001.

Hermle, S., M.B. Lavigne, P.Y. Bernier, O. Bergeron, D. Paré. 2010. Component respiration and net primary production of a mature black spruce forest in northern Québec. Tree Physiology 30: 527-540.

Humphreys, E.R., T.A. Black, K. Morgenstern, T. Cai, G.B. Drewitt, Z. Nesic. 2006. Carbon dioxide fluxes in three coastal Douglas-fir stands at different stages of development after harvesting. Agricultural and Forest Meteorology 140: 6-22.

Jassal, R.S., T.A. Black, B. Chen, Z. Nesic, R. Roy, D. Spittlehouse, A.J. Trofymow. 2008. N2O emissions and carbon sequestration in a nitrogen-fertilized Douglas-fir stand. Journal of Geophysical Research-Biogeosciences doi:10.1029/2008JG000764.

Krishnan P., T.A. Black, A.G. Barr et al. 2008. Factors controlling the interannual variability in the carbon balance of a southern boreal black spruce forest. Journal of Geophysical Research 113, D09109, doi:10.1029/2007JD008965.

Krishnan, P., T.A. Black, R.S. Jassal, Z. Nesic. 2009. Interannual variability in the carbon balance of three different-aged Pacific Northwest Douglas-fir stands. Journal of Geophysical Research-Biogeosciences 114, G04011, doi:10.1029/2008JG000912.

McCaughey, H., M.R. Pejam, M.A. Arain, D.A. Cameron. 2006. Carbon dioxide and energy fluxes from a boreal mixedwood forest ecosystem in Ontario, Canada. Agricultural and Forest Meteorology 140: 79-96.

McLaren, J.D., M.A. Arain, M. Khomik, M. Peichl, J. Brodeur. 2008. Water flux components and soil water-atmospheric controls in a temperate pine forest growing in a well-drained sandy soil. Journal of Geophysical Research-Biogeosciences, 113: G04031, doi:10.1029/2007JG000653.

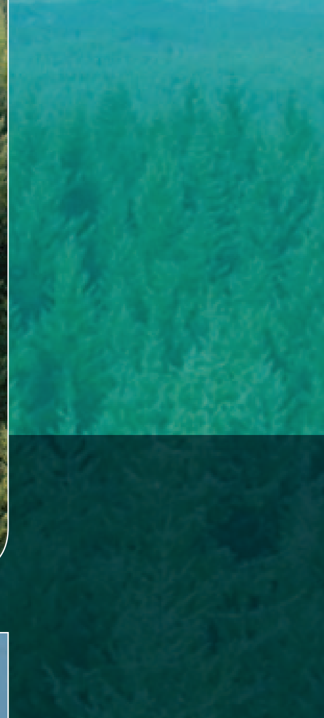
Mkhabela, M.S., B.D. Amiro, A.G. Barr, T.A. Black, I. Hawthorne, J. Kidston, J.H. McCaughey, A.L. Orchansky, Z. Nesic, A. Sass, A. Shashkov, T. Zha. 2009. Comparison of carbon dynamics and water use efficiency following fire and harvesting in Canadian boreal forests. Agricultural and Forest Meteorology 149: 783-794.

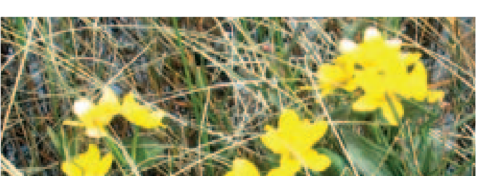
Peichl M., J. Brodeur, M. Khomik, M.A Arain. 2010. Biometric and eddy-covariance based estimates of carbon fluxes in an age-sequence of temperate pine forests. Agricultural and Forest Meteorology 150:952-965, doi:10.1016/j.agrformet.2010.03.002.

Thomas, V., D.A. Finch, H. McCaughey, T. Noland, L. Rich, P. Treitz. 2006. Spatial modelling of the fraction of photosynthetically active radiation absorbed by a boreal mixedwood forest using a lidar-hyperspectral approach. Agricultural and Forest Meteorology 140: 287-307.

Thomas, V., P. Treitz, J.H. McCaughey, T. Noland, L. Rich. 2008. Canopy chlorophyll concentration estimation using hyperspectral and lidar data for a boreal mixedwood forest in northern Ontario, Canada. International Journal of Remote Sensing 29: 1029-1052.

Zha, T., A.G. Barr, T.A. Black, J.H. McCaughey, J. Bhatti, I. Hawthorne, P. Krishnan, J. Kidston, N. Saigusa, A. Shashkov, Z. Nesic. 2009. Carbon sequestration in boreal jack pine stands following harvesting. Global Change Biology 15: 1475-1487.





Are mature forests in Canada carbon sinks?

Before the advent of flux tower measurements, classic ecological theory predicted that older forest stands would tend towards carbon neutrality, neither sequestering nor emitting carbon. This was because the processes of photosynthesis and respiration would reach a balance over the longer term in the absence of a major disturbance. If this were true, the carbon sequestration benefits of conserving older forests would be lower, although the standing carbon stocks in these forests would still be a significant pool of carbon. However, these carbon stocks are vulnerable to ecological disturbances such as fire or insect attack, particularly in the boreal forest of Canada.

In Canada, we have been making measurements of the annual carbon balances of different temperate and boreal forest stands. These measurements have provided insight into the role of Canada's mature forests in the global carbon cycle. The boreal forest represents more than half of Canada's forest area. Analyses have shown that older Canadian forests tend towards being significant carbon sinks, with average annual sequestration rates ranging from 0.1 to 0.8 t C/ha for boreal black spruce and jack pine stands to as high as 4.2 t C/ha for a west coast temperate Douglas-fir stand (Figure 1). A mature mixedwood boreal stand in northern Ontario sequesters on average 0.9 t/ha annually and a temperate white pine plantation stand is an average carbon sink of 1.6 t/ha (Figure 1).

> Analyses have shown that older Canadian forests tend towards being significant carbon sinks

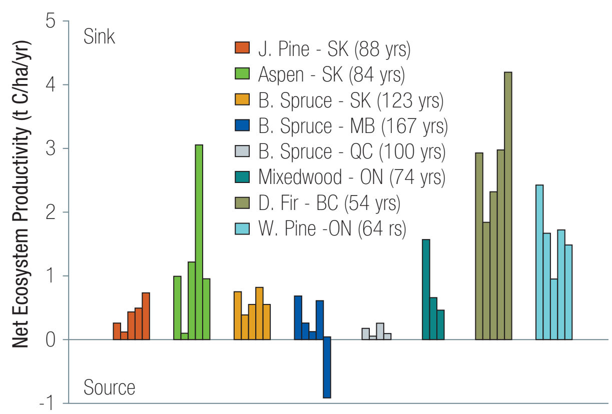


Figure 1. Annual carbon sequestration or emission (net ecosystem productivity) from 2003 to 2007 by the mature boreal jack pine, aspen, black spruce and mixedwood stands in Saskatchewan, Manitoba, Quebec and Ontario and by the temperate Douglas-fir and white pine stands in British Columbia and Ontario. Each vertical bar represents the total amount of carbon sequestered by a given site in one year. Positive values indicate carbon sequestration (sink) and negative values indicate carbon emissions (source).

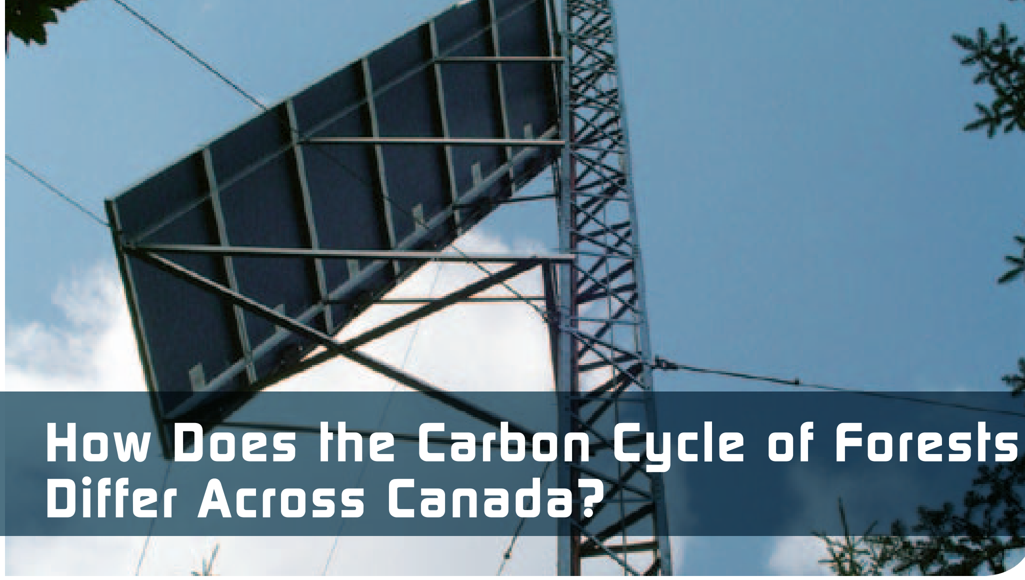
Our studies have also shown that the hydrological balance is an important factor in determining the sink-source status of northern mature black spruce forests. Periods with abundant precipitation and high water tables tend to suppress soil respiration and thereby increase the strength of the carbon sink. For example, a northern black spruce stand went from emitting 0.40 t C/ha to sequestering 0.25 t C/ha annually after an increase in annual precipitation in 1999. In a southern boreal aspen stand, a 3-year long drought significantly reduced carbon sequestration, although it had little effect on carbon sequestration in nearby black spruce and jack pine stands, species that are more drought tolerant. The depth of the boreal

snow pack can also be an important factor, with higher snow depths being related to higher soil temperatures and greater losses of carbon through respiration during winter. Finally, extended periods of cloudiness during the long days of late spring in the boreal region can suppress light levels and photosynthesis, leading to reductions in annual carbon sequestration. Warm, early springs on the west coast tend to increase carbon sequestration of Douglas-fir forests, while warm summers decrease it.

The source-sink status of mature forests is an important issue for national climate policy. Although forests were not considered in the 1997 Kyoto Protocol, there has been an increasing recognition of their importance in more recent negotiations leading to the recent decision at the 2010 United Nations sponsored negotiations in Cancun to establish a Green Fund to help poorer countries reduce deforestation and forest degradation. However, it should also be recognized that half of the world's primary forests are located in the boreal and temperate regions of the Northern Hemisphere. Even though they are highly vulnerable to ecological disturbance, these northern forests are also important for both carbon storage and as continuing carbon sinks.

For additional information, please contact Dr. Hank Margolis (hank.margolis@sbf.ulaval.ca)

How Does the Carbon Cycle of Forests Differ Across Canada?



The carbon cycle of a forest is affected by climate and the plant species present. As a result, the carbon cycle of forests in Canada varies regionally. We have been making long-term measurements of carbon fluxes across the country to gain insights into the variability of the carbon cycle across Canada.

Carbon flux measurements made in the temperate forests of British Columbia and Ontario and in the boreal forests of Saskatchewan and Quebec show that mature temperate forests sequester between 1.0 and 4.2 t C/ha annually and boreal forests sequester between 0.1 and 0.8 t C/ha/yr (Figure 1a). A more favourable climate in temperate forests leads to a longer period of carbon capture through photosynthesis compared to boreal sites. On average, the temperate Douglas-fir and white pine stands photosynthesize for 12 and 9 months of the year, respectively, while the boreal jack pine and black spruce stands photosynthesize for 7 months of the year (Figure 1b).

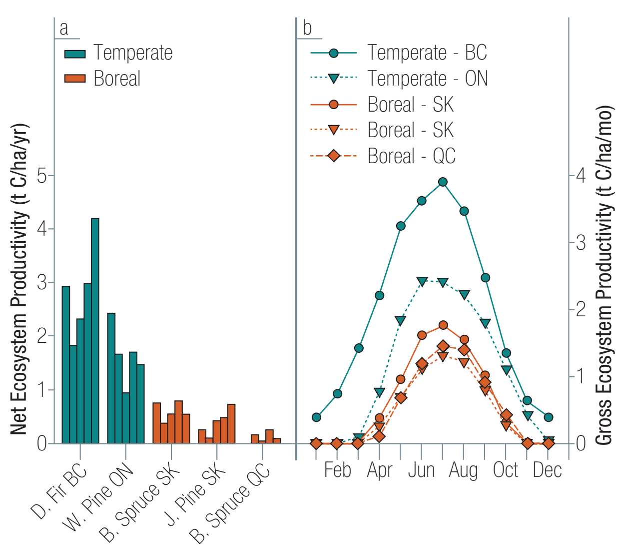


Figure 1. (a) Total annual net carbon sequestration (net ecosystem productivity) from 2003 to 2007 by the temperate Douglas-fir and white pine stands in British Columbia and Ontario, respectively, and by the boreal jack pine and black spruce stands in Saskatchewan and Quebec. Each vertical bar represents the net amount of carbon sequestered in one year. (b) Average total carbon captured through photosynthesis (gross ecosystem productivity) per month for the same stands. Each symbol represents the average capture for that month for the 2003 - 2007 period.

A more favourable climate in temperate forests leads to a longer period of carbon capture through photosynthesis compared to boreal sites. On average, the temperate Douglas-fir and white pine stands photosynthesize for 12 and 9 months of the year, respectively, while the boreal jack pine and black spruce stands photosynthesize for 7 months of the year (Figure 1b).

Comparisons between western and eastern boreal black spruce stands illustrate the effects of differing amounts of winter precipitation. In the winter, the western boreal site emits less carbon than the eastern site (Figure 2a). Winter emissions account for 8% of annual emissions at the western site and 12% at the eastern site. These higher emissions can be linked to a thicker snowpack which insulates the soil and keeps it from freezing for most of the winter in the east. Soils remained frozen for at least 80% of the winter at the western site during the study period. We estimate that, if the carbon losses (0.3 t C/ha) attributable to the thicker snowpack (Figure 2b, gold bars) are removed from the annual carbon budget of the eastern black spruce site, the total amount of carbon sequestered would then approach the levels of carbon sequestration attained at the western site (Figure 2b).

The quantities of carbon sequestered, as well as the year-to-year variability, will also depend on the forest ecosystem type (deciduous, coniferous, mixed species). The amount of carbon sequestered annually by the aspen forest site tends to be greater than for the coniferous black spruce and mixedwood forests, despite the fact that the deciduous aspen canopy is photosynthetically active for only five months of the year, compared to seven months at the other two sites (Figure 3a,b). Year-to-year variability in climate tends to have a greater effect on carbon sequestration at the deciduous aspen site compared to the other two sites. For example, a drought lasting several years caused a reduction in the deciduous leaf area in 2004, leading to carbon sequestration levels similar to those at the eastern black spruce site and a more favourable climate in 2006 (end of the drought) led to similar carbon sequestration levels at the aspen and Douglas-fir sites (Figures 1a, 3a). On the other hand, the Saskatchewan black spruce site has lower photosynthetic rates because of its coniferous physiology (Figure 3b). The mixedwood site in Ontario exhibits traits of both coniferous and deciduous forests. It tends to have higher photosynthetic rates and more year-to-year variability in the levels of carbon sequestration relative to the black spruce stand but lower photosynthetic rates than the aspen stand (Figure 3b).

The quantities of carbon sequestered, as well as the year-to-year variability, will also depend on the forest ecosystem type (deciduous, coniferous, mixed species).

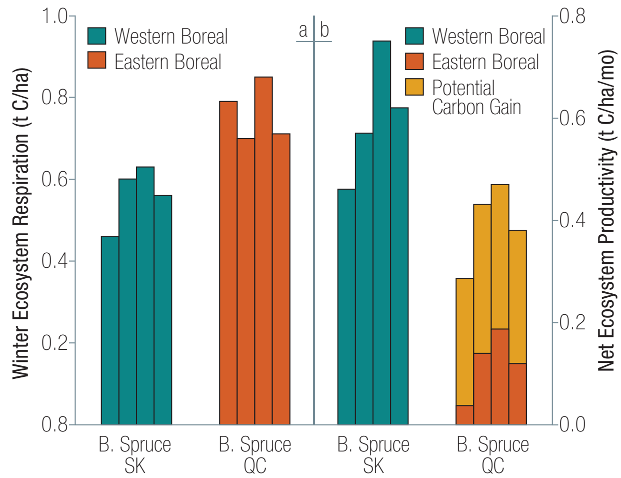


Figure 2. (a) Total amount of carbon emitted through respiration during the winter from November 2003 to October 2007 for the western and eastern boreal black spruce stands in Saskatchewan and Quebec. Each vertical bar represents the total amount of carbon emitted during one winter. (b) Total annual net carbon sequestration from November 2003 to October 2007 by the same stands. The teal and orange bars represent the actual amount of carbon sequestered and the gold bars represent the potential amount of additional carbon that would have been sequestered at the eastern boreal site if its winter respiration rate had been similar to the western site.

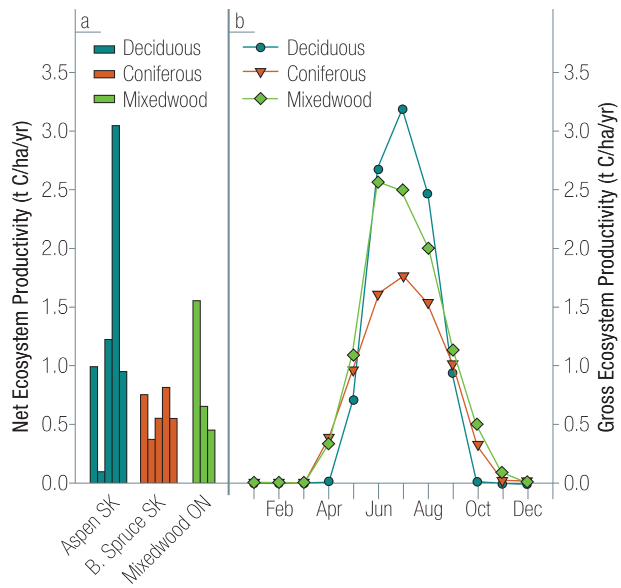


Figure 3. (a) Total annual net carbon sequestration from 2003 to 2007 by the deciduous aspen, coniferous black spruce and mixedwood boreal stands in Saskatchewan, and Ontario. Each vertical bar represents the net amount of carbon sequestered in one year. (b) Average total carbon captured through photosynthesis (gross ecosystem productivity) per month for the same stands. Each symbol represents the average capture for that month for the 2003-2007 period.

For additional information, please contact Dr. Carole Coursolle (carole.coursolle@sbf.ulaval.ca)

What happens to a forest after it is harvested?

Forests provide commercial timber and non-timber forest products, wildlife habitat, climate regulation, soil and water protection, and recreational benefits. They also store 1,640 Pg of carbon that might otherwise be in the atmosphere as carbon dioxide (CO_2). Approximately 70% of this carbon is stored in the soil and litter. As they grow, forests take up atmospheric CO_2 during the process of photosynthesis, a portion of which is stored in wood, while the remainder is lost in growth and maintenance respiration. Whether harvesting is done to produce timber, or to clear land for development or agriculture, it initially results in the loss of carbon stocks, reduced wildlife habitat aesthetic and landscape value, increased runoff of precipitation and a decrease in evapotranspiration.

After harvesting, photosynthesis sharply decreases because of a reduction in leaf area. Growth and maintenance respiration also decrease. However, the microbial decomposition component of soil respiration, which is a large fraction of ecosystem respiration, could rise following soil disturbance and the accompanying increases in soil temperature and soil water content that result from the absence of a tree cover. Furthermore, stem-only harvesting removes carbon from the forest, storing it in wood and paper products off site. The branches, foliage and other logging residue that are left on site decompose over time, releasing carbon in the form of CO_2 back into the atmosphere.

Whether harvesting is done to produce timber, or to clear land for development or agriculture, it initially results in the loss of carbon stocks, reduced wildlife habitat aesthetic and landscape value, increased runoff of precipitation and a decrease in evapotranspiration.

Table 1. Percent reduction in gross ecosystem productivity (GEP, photosynthesis) and ecosystem respiration (ER) following harvesting of boreal black spruce and jack pine and temperate Douglas-fir stands compared to pre-harvest rates.

	Black Spruce (%)	Douglas-Fir (%)	Jack Pine (%)
GEP	52	73	94
ER	21	37	60

Table 2. Total annual net ecosystem sequestration/emission (net ecosystem production) before and after harvesting of black spruce, jack pine and Douglas-fir stands. Positive values indicate that the stand is sequestering carbon (sink) and negative values indicate that the stand is emitting carbon (source) to the atmosphere.

	Black Spruce	Douglas-Fir	Jack Pine
Before (t C/ha)	0.2	3.5	0.2
After (t C/ha)	-1.4	-6.0	-1.9

Our measurements show that forest harvesting reduces gross ecosystem productivity (GEP) by 52%, 73% and 94%, in boreal black spruce, temperate Douglas-fir and boreal jack pine stands, respectively (Table 1). However, ecosystem respiration (ER) in these stands decreases by only 21, 37 and 60%, respectively. Greater reductions in GEP than in ER result in annual carbon emissions of 1.4, 6.0 and 1.9 t/ha, respectively in the first few years after harvesting (Table 2). Harvested stands continue to lose carbon until the uptake of carbon by new growth matches ecosystem respiration, which occurs at approximately 10, 17 and 10 years of age, in black spruce, Douglas-fir and jack pine stands, respectively. Moreover, by this time, the stands will have lost approximately 4 to 50 t C/ha, depending on species. These losses will not be offset until the trees reach approximately 19 to 40 years of age. Carbon uptake beyond this age and until harvest represents the total net Carbon sequestered by the stand over its management rotation.

In Canadian forests, annual evapotranspiration (*E*) generally does not exceed 500 mm. For a Douglas-fir stand, where *E* is about 400 mm, harvesting has been found to cause a *E* of 30%. This would result in an additional 120 mm of water draining into streams and ground water. Full recovery of *E* occurs by the time the new forest stand is 12 years old. Harvesting also alters other hydrologic variables such as snow accumulation, timing of snow melt, interception losses and soil hydraulic characteristics. These changes alter the dynamics of streamflow as well as the water balance of the watershed.

Harvesting activities such as establishing landings, access roads, and main skid trails may cause soil compaction and significantly reduce water percolation thereby increasing runoff and soil erosion. Changes in soil compaction, soil organic matter decomposition and the soil water regime are expected to affect soil surface methane (CH_4) and nitrous oxide (N_2O) fluxes. The increased emissions of CO_2, (and possibly CH_4 and N_2O) following harvesting increase radiative forcing and hence global warming. However, removal of the canopy cover and the ensuing greater accumulation of snow, which results in increased albedo, can neutralize some of the global warming effect.

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How does fire affect the carbon balance of forests?

The Role of Fire in Canadian Forests

Fire is a major agent for renewing Canadian forests. All of our forests experience fire, but the frequency is much higher in the boreal forest and in some western forest types. The period between fires at any given location, the fire return interval, can vary from just a few years to many hundreds of years. Over the past few decades, the average time between fires has been about 140 years in Canada, but this period may be decreasing. A greater area burned is expected in the future because of a changing climate. Carbon dynamics are controlled by the life cycle of the forest between disturbances. Vegetation type has adapted to the fire cycle, thus affecting carbon exchanges, especially in the boreal forest. In the Canadian Carbon Program, we have been studying this life cycle effect on carbon because most fires in the boreal forest kill trees and remove organic matter from the forest floor. Furthermore, forests quickly regenerate, and this balance between carbon loss and gain needs to be quantified to calculate the net effect. We can divide the main effects into direct carbon emissions during the fire combustion, and a recovery period as the new forest grows.

Figure 1. A fire in a young pine forest in northern Manitoba. The photograph was taken a few days after the fire. Note how all the vegetation has been killed and some bare rocks show where the forest floor has burned.

Carbon Emissions Through Combustion

Fire immediately causes a large carbon emission during the combustion process. The amount of carbon emitted to the atmosphere in a fire can be highly variable, and depends on the forest type, the moisture conditions, and the nature of the fire itself. Typically, the shallow top of the forest floor (dry organic matter) is combusted, as are leaves and small twigs on the trees. Although trees are killed, living tree trunks usually do not burn and can remain standing for many years (Figure 1). In Canada, we estimate that forest fires combust an average of about 15 t C/ha, but this can be much higher for individual fires in areas of deep organic soils under dry conditions. Fires in late summer usually result in greater carbon emissions compared to those in the spring because conditions are drier.

In Canada, we estimate that forest fires combust an average of about 15 t C/ha

Carbon Dynamics in Young Post-Fire Forests

Following a fire, killed vegetation will decompose, emitting carbon through respiration. This respiration, by heterotrophic organisms, surpasses any carbon gains made through photosynthesis by newly growing vegetation. However, vegetation recovers rapidly in many forests with the invasion of colonizing species or growth of plants that have strategies to be successful following fire. The speed of carbon recovery is dependent on the severity of the fire, the forest type and environmental conditions. In the boreal forest, we have been measuring annual carbon fluxes on chronosequences of forests following fire. The flux-tower data indicate that the forest emits carbon for perhaps the first 5 to 10 years, but can be a net carbon sink after this (Figure 2). However, we have also found that there could be a second period of carbon loss when the fire-killed trees finally fall over and start to decompose (Figure 3). If we integrate the average curve shown in Figure 2, we find that we could get a net accumulation of 15 t C/ha at about 30 years for boreal sites, which would balance the average carbon loss from direct combustion. Although this implies that forests that experience a fire at a frequency of greater than 30 years should be net carbon sinks, more frequent fire will change the structure of the forest landscape and its recovery, creating a very different environment from the one where the flux measurements were made.

The flux-tower data indicate that the forest emits carbon for perhaps the first 5 to 10 years, but can be a net carbon sink after this .

Figure 3. A young forest in Saskatchewan recovering from a severe fire. The photo was taken seven years following the fire, and the vigorous growth of young jack pine trees can be seen within a forest of dead standing and fallen tree trunks.

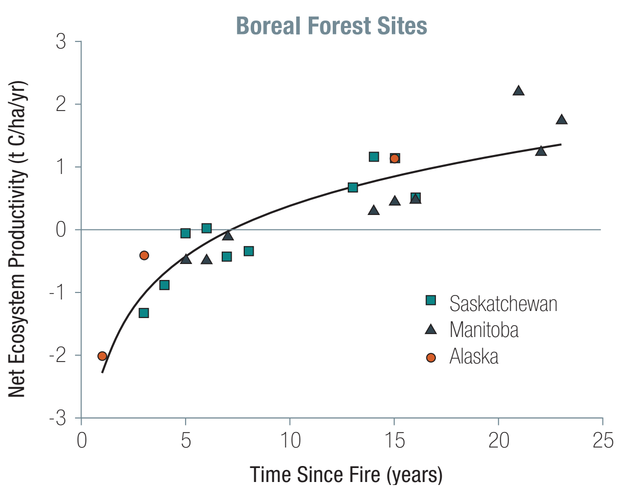
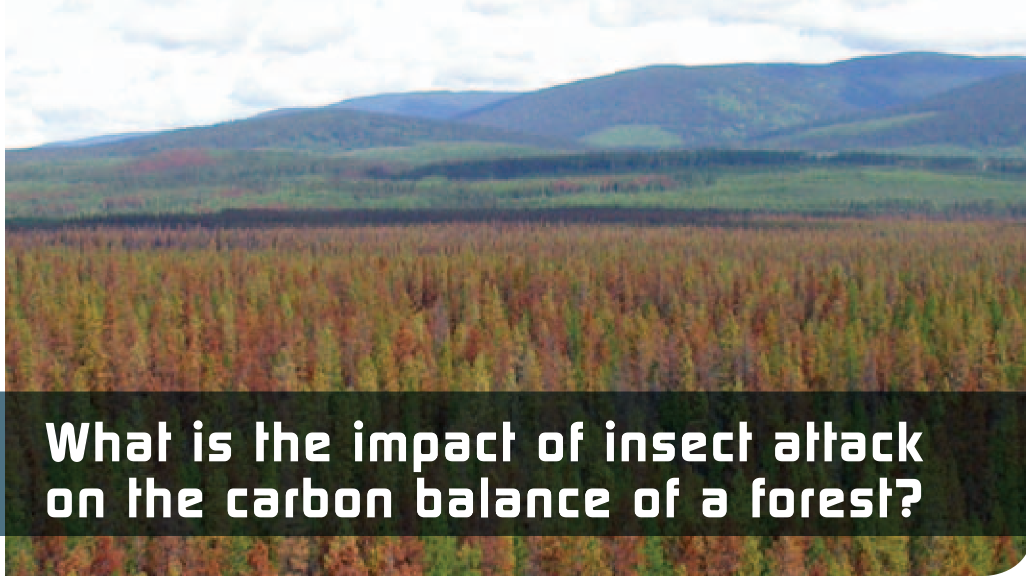


Figure 2. Net annual carbon sequestration/emission (net ecosystem productivity) for boreal forest chronosequences following fire. Positive values indicate net carbon sequestration and negative values indicate net carbon emissions. The curve is a best-fit line for the data shown.

For additional information, please contact Dr. Brian Amiro (brian_amiro@umanitoba.ca)



What is the impact of insect attack on the carbon balance of a forest?

Insects play a key role in forest ecosystems but they can also alter wildlife habitat, cause serious economic damage and affect the forest carbon balance. Insect attacks influence carbon sequestration by the forest, by decreasing ecosystem photosynthesis (GEP) and increasing ecosystem respiration (ER). In Canada, mountain pine beetle (MPB), tent caterpillar and spruce budworm are implicated in the majority of insect infestations, which result in greater annual tree mortality than either fires or harvesting. The recent MPB outbreak in British Columbia (BC) is unprecedented in terms of tree mortality and area affected and could severely impact the carbon balance of BC's forests and potentially those east of the Rocky Mountains if the infestation spreads. Lodgepole pine, the main host of the beetle, is found throughout the BC interior. A 2009 aerial survey reported about 9 million ha of forests showing some beetle impact, down from the peak infestation of 10 million ha in 2007.

> In Canada, mountain pine beetle, tent caterpillar and spruce budworm are implicated in the majority of insect infestations, which result in greater annual tree mortality than either fires or harvesting.

Carbon flux measurements were made in two lodgepole pine stands located in the northern BC interior. The first stand, MPB-06, which was 85 years old, was first attacked in 2006. By 2010, approximately 16% of the trees remained healthy (Figure 1). The second stand, MPB-03, which was 110 years old with understory and subalpine fir trees, was first attacked in 2003 and by 2007 had > 95% pine canopy mortality. Both these stands demonstrated considerable resilience to MPB attack. MPB-06 went from emitting 0.8 t C/ha the year following the attack to sequestering 0.6 t C/ha three years later, while MPB-03 oscillated between sequestering and emitting small amounts of carbon depending on the year (Table 1). While MPB-06 was a moderate carbon source for the first two years following attack, the surviving trees and vegetation showed increased vigour in the third and fourth years resulting in an increase in GEP (photosynthesis) and a net sequestration of carbon. At MPB-03, measurements were not made until the fourth year following attack, a year in which the site was a moderate carbon source. Although the site sequestered slight amounts of C in the following two years, it became a carbon source in the seventh year after attack (2010), as a result of drought. Despite a rapid decrease in the fraction of healthy trees at MPB-06

Table 1. Annual net carbon sequestered/emitted (net ecosystem productivity) by two mountain pine beetle-attacked lodgepole pine stands in interior British Columbia. Positive values indicate carbon sequestration and negative values indicate carbon emissions.

	Net Ecosystem Production (t C/ha/yr)	
Year	**MPB-06**	**MPB-03**
2007	-0.8	-0.60
2008	-0.5	0.03
2009	0.1	0.06
2009	0.6	-0.30

in 2007 and 2008, and nearly complete canopy mortality at MPB-03, the surviving trees and vegetation appeared to benefit from a reduction in competition for nutrients and soil water and an increase in solar radiation reaching the lower levels of the canopy and understory. Other studies suggest that the surviving trees will experience rapid growth for decades, until the canopy begins to close and competition suppresses annual growth. It takes many years for the dead trees to fall, get into contact with the soil, and start decomposing, which can result in an increase in ER, negating the positive effects of enhanced GEP on carbon sequestration.

Estimates of the regional impact of the MPB attack in BC differ somewhat from our findings. A modelling study by the Canadian Forest Service showed the impact of insects peaking in 2009 with regional emissions of 0.005 t C/ha/yr, compared to a slight sequestration prior to attack. Remote-sensing-based estimates of GEP over the infestation area from 2002 to 2005 showed a 10-20% decrease in GEP from pre-outbreak levels, with more severely attacked stands having a greater reduction. Contrasting results from these different approaches highlight the importance of making direct carbon flux measurements at the stand scale, as well as using other techniques, such as remote sensing and modelling, to study the landscape scale recovery from MPB outbreak.

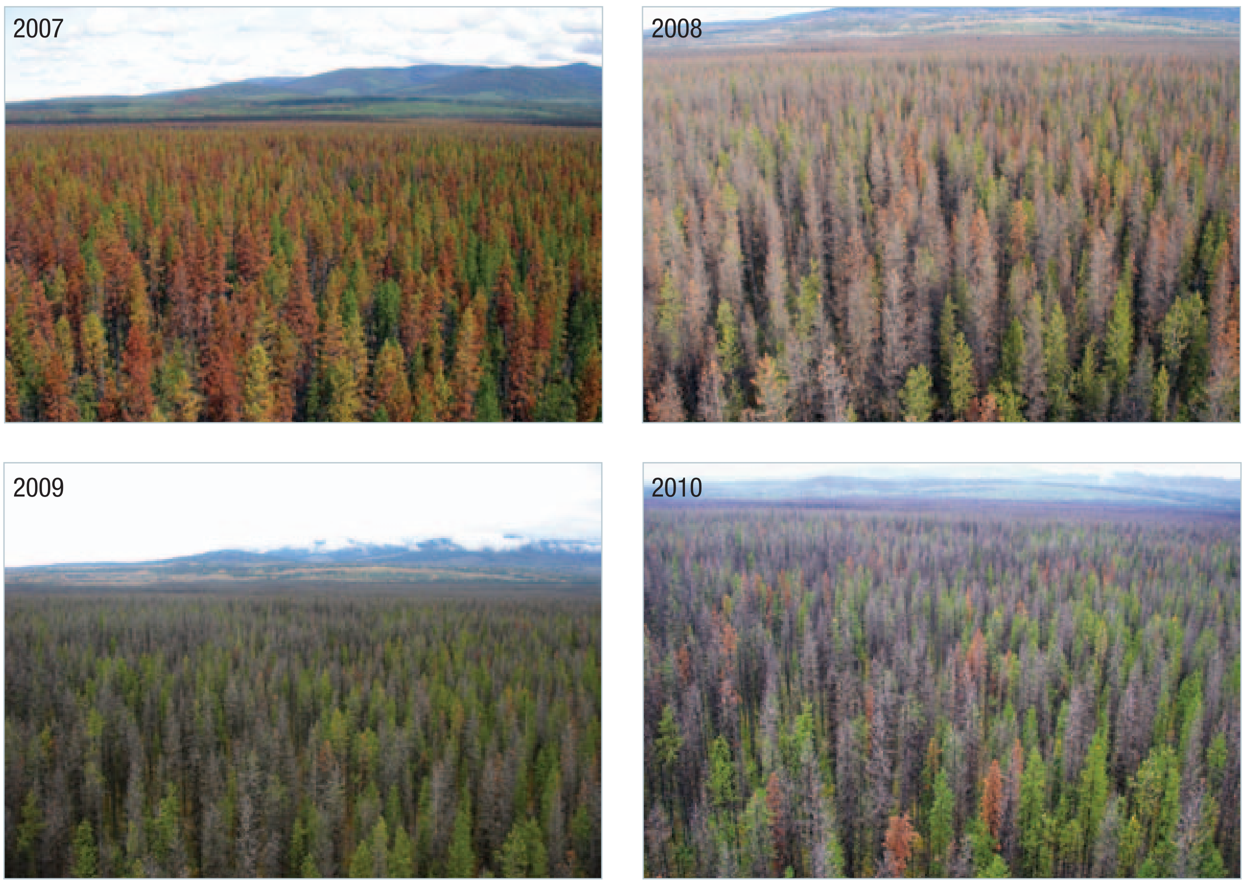


Figure 1. Photographs of the forest canopy showing the progression of the MPB attack at the MPB-06 in interior British Columbia. The attack began in Aug 2006 with the stand entering the green-attack stage. The red-attack stage was in 2007, red-grey-attack stage in 2008 and the grey-attack stage (dead trees) in 2009 and 2010.

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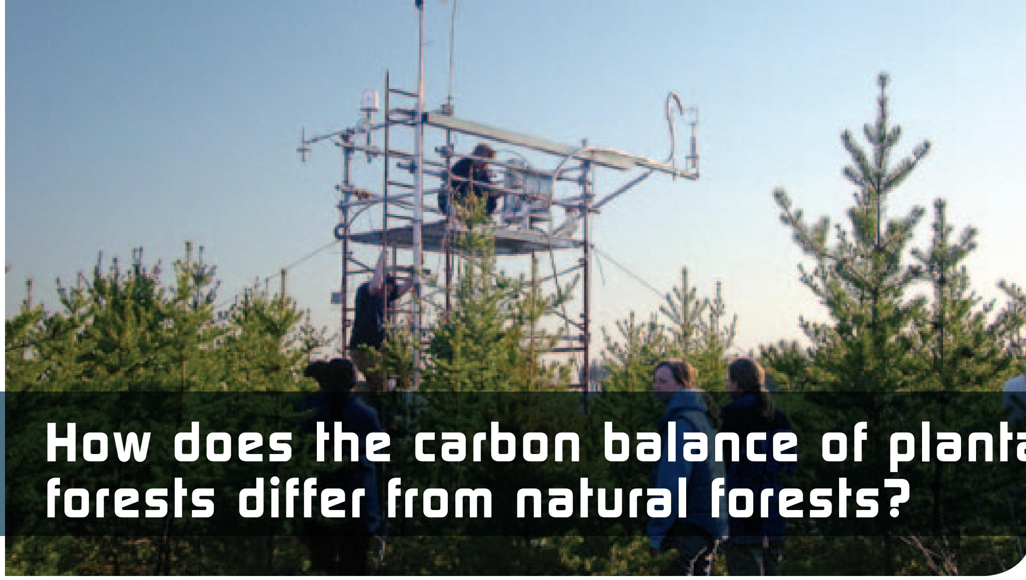

How does the carbon balance of plantation forests differ from natural forests?

A large portion of northeastern forests in both Canada and the United States are regenerated or plantation forests on former agricultural or abandoned lands. Most of these forests are in different stages of re-growth and their carbon sink and source status is different from that of naturally regenerated forests. Sink/source (sequestration/emission) status is dependent on developmental stage, tree species, soil nutrient status, management regime, and most importantly, the climate of the region where the forest is growing. Carbon flux measurements conducted in different-aged (7-, 20-, 35-, and 70-year old) temperate pine (*Pinus strobus* L.) plantation forests at Turkey Point, in southern Ontario, suggested that annual carbon sequestration peaks about three decades earlier in plantation stands than in naturally regenerated stands, where sequestration commonly peaks at between 50 to 70 years of age (Figure 1). These plantation forests sequestered 0.66, 7.36, 3.92 and 1.24 t C/ha in the 7-, 20-, 35-, and 70-year old stands, respectively, between 2005 and 2008. Integrating this carbon uptake across all four ages results in a total net carbon sequestration of 229 t C/ha over the initial 70 years of the plantation.

Carbon flux measurements conducted in different-aged (7-, 20-, 35-, and 70-year old) temperate pine (*Pinus strobus* L.) plantation forests at Turkey Point, in southern Ontario, suggested that annual carbon sequestration peaks about three decades earlier in plantation stands than in naturally regenerated stands, where sequestration commonly peaks at between 50 to 70 years of age

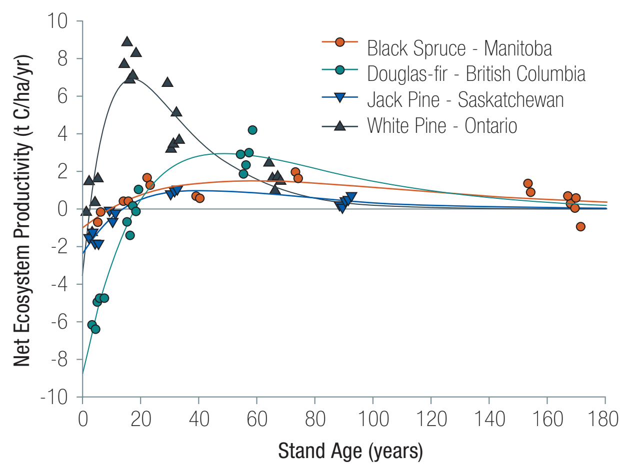

Figure 1. Annual net ecosystem productivity (NEP) of natural (black spruce, Douglas-fir, jack pine) and plantation forest (white pine) chronosequences with respect to their age. Positive values indicate net carbon sequestration and negative values indicate net carbon emissions on a yearly basis.

Carbon allocation to leaf, stem and root components in plantation forests changes rapidly as stands grow older. Tree dimension and annual stem growth measurements indicated that stem wood production was 27% of total tree biomass in the 7-year old stand as compared to 55% in the 70-year stand (Figure 2a). Similarly, the contribution of foliage production decreased with stand age from 34% in the youngest stand to 2% in the oldest stand. Branch biomass production was considerable in the two middle-aged forests, accounting for 33% and 27% of production in the 19- and 35-year olds stands, respectively. The contribution of aboveground tree biomass production to net primary productivity (NPP, the total annual biomass production) decreased with stand age from 51% in the 7-year old stand to 21% in the 70-year

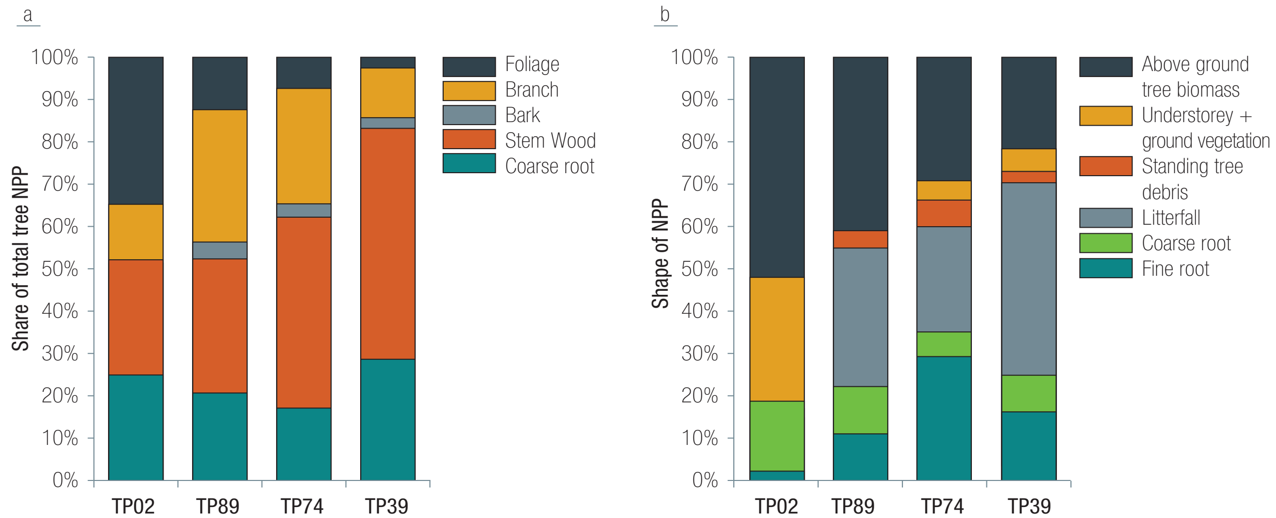

Figure 2. Mean relative contribution of (a) individual tree biomass components and (b) above and belowground biomass production to net primary productivity (NPP) in the 7- (TP02), 20- (TP89), 35- (TP74) and 70-year old (TP39) stands at Turkey Point.

old stand (Figure 2b). Growth of ground vegetation in the 7-year old stand (30% of NPP) and litterfall at the three older sites (25-46% of NPP) were additional important components of NPP.

Flux measurements at Turkey Point suggest that, contrary to other northern Canadian forests, the rate of carbon sequestration decreases with an increase in growing season temperature.

Changes in climate may severely impact the carbon sequestration of both planted and natural forests. Flux measurements at Turkey Point suggest that, contrary to other northern Canadian forests, the rate of carbon sequestration decreases with an increase in growing season temperature. The simultaneous occurrence of early growing season drought and extreme summer heat events reduced net carbon uptake by approximately 0.5 to 1.5 t C/ha in both mature and young forests, making mature stands carbon neutral. An experimental drought study suggested that severe early growing season drought in the absence of heat stress alone may cause a 40% reduction in net carbon sequestration at the mature 70-year old site (Figure 3). Both drought and heat stress predominantly affected photosynthesis, rather than ecosystem respiration.

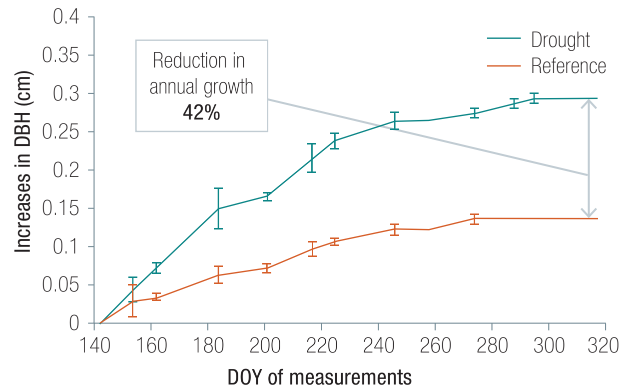

Figure 3. The reduction in cumulative growth rates in drought plots (turquoise line) relative to reference plots (orange line) as a result of an induced severe drought where 90% of rainfall was excluded between April 1 and July 3, 2009 in the 70-year old Turkey Point plantation stand. The standard error for each measurement is also shown.

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02 Peatlands and the Carbon Cycle

Selected Publications

Adkinson, A.C., K.H. Syed, L.B. Flanagan. 2011. Contrasting responses of ecosystem CO2 exchange to variation in temperature and water table depth in two peatlands in northern Alberta, Canada. Journal of Geophysical Research-Biogeosciences 116, G01004, doi: 10.1029/2010JG001512.

Dimitrov, D.D., R.F. Grant, P.M. Lafleur, E. Humphreys. 2010. Modelling the effects of hydrology on ecosystem respiration at Mer Bleue bog. Journal of Geophysical Research-Biogeosciences 115, G04043, doi:10.1029/2010JG001312.

Dimitrov, D.D., R.F. Grant, P.M. Lafleur, E. Humphreys. 2010. Modelling subsurface hydrology of Mer Bleue bog. Soil Science Society of America Journal 74: 680-694.

Dimitrov, D.D., R.F. Grant, P.M. Lafleur, E. Humphreys. 2010. Modelling peat thermal regime of an ombrotropic peatland with hummock-hollow microtopography. Soil Science Society of America Journal 74: 1406-1425.

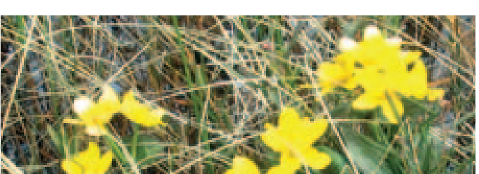
Flanagan, L.B., K.H. Syed. 2011. Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. Global Change Biology 17, doi: 10.1111/j.1365-2486.2010.02378.x.

Long, K.D., L.B. Flanagan, T. Cai. 2010. Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. Global Change Biology 16: 2420-2435, doi:10.1111/j.1365-2486.2009.02083.x.

Roulet N.T., P.M. Lafleur, P.J.H. Richard, T.R. Moore, E.R. Humphreys, J. Bubier. 2007. Comparison of a six year contemporary carbon balance and the carbon accumulation for the last 3,000 years for a northern peatland. Global Change Biology 13: 397-411.

Sonnentag, O., J.M. Chen, N.T. Roulet, W. Ju, A. Govind, 2008. Spatially explicit simulation of peatland hydrology and carbon dioxide exchange: The influence of topography. Journal of Geophysical Research-Biogeosciences 113, G02005, doi: 10.1029/2007JG000605.

Wu. J., N.T. Roulet, T.R. Moore, P. Lafleur, E. Humphreys. 2011. Dealing with microtopography of an ombrotrophic bog for simulating ecosystem-level CO2 exchanges. Ecological Modelling 222: 1038-1047.



Are Canada's Peatlands Gaining or Losing Carbon?

Peatlands occupy about 13% of the Canadian landmass and are mainly distributed throughout the boreal and subarctic regions. Despite their relatively small total land area, they contain approximately 60% of the total carbon stored in Canadian soils. Radiocarbon dating of the basal sediments shows that this carbon (in the form of decomposed vegetation) has been accumulating slowly over the past 5,000 to 8,000 years. We know that northern peatlands have been a long-term sink for atmospheric carbon dioxide. Yet, recent climate warming may be influencing these ecosystems and we need to ask the question – are peatlands still a sink for carbon, and further, how will they function in the future as the climate continues to change?

The Eastern and Western Peatland Flux Stations (EPFS and WPFS, respectively) were established to investigate peatland-atmosphere carbon exchange in Canada. The WPFS, located in central Alberta, is a treed fen habitat, where the water table is relatively close to the surface and water moves laterally through the site transporting nutrients. In contrast, the EPFS is an ombrotrophic bog (Mer Bleue near Ottawa, ON), receiving nutrients from rainfall only and has a comparatively deep water table below the moss and shrub surface. Multiple years of measurements at these sites reveal that both peatlands are typically carbon sinks on an annual basis, with the EPFS being more variable, ranging from near carbon neutral to a sink of 1.5 t C/ha/yr. Between 2004 and 2009, the western peatland fen sequestered a total of 11.3 t C/ha and the Mer Bleue bog 6.9 t C/ha (Figure 1). The substantial difference between these two peatlands is probably due to the differences in nutrient status and the dominant vegetation at the sites. The WPFS site is less acidic and has a dense tree cover (comprised of spruce and tamarack) making this site more productive than EPFS. In the past 50 years vegetation succession has been taking place at the site, possibly in response to decadal warming and drying, which has produced a more favorable environment for tree growth,

> Multiple years of measurements at these sites reveal that both peatlands are typically carbon dioxide sinks on an annual basis.

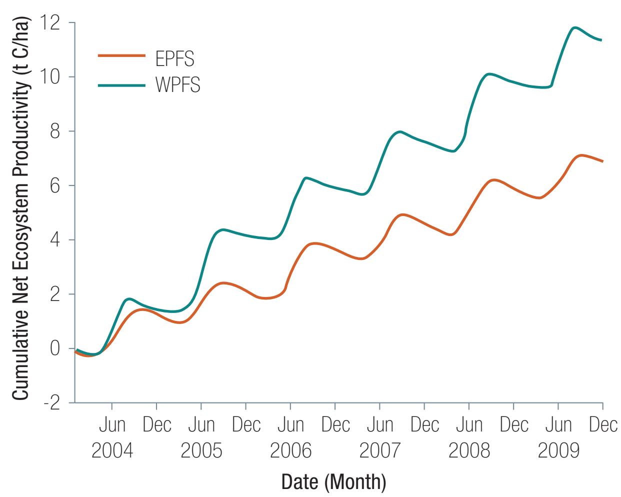


Figure 1. Cumulative net carbon sequestration (NEP, net ecosystem productivity) from 2004 to 2009 at the Western Peatland site in Alberta (WPFS) and at the Eastern Peatland site (EPFS) in Ontario. The patterns of increase and slight decrease represent carbon sequestration by the ecosystem during the growing season and carbon emissions during the dormant (winter) season. Overall, both peatlands showed the ability to sequester carbon over this time period.

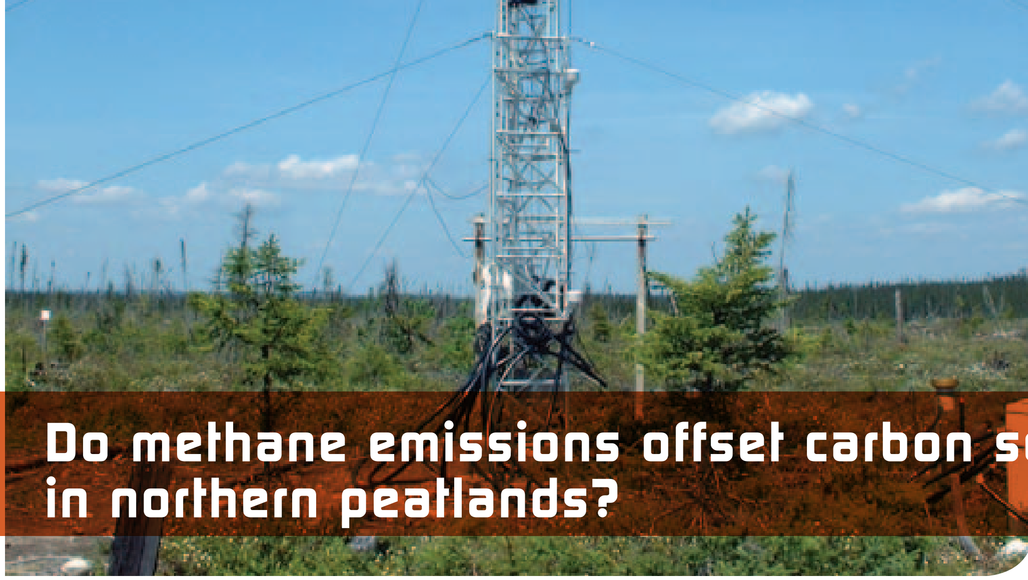
thereby enhancing productivity and carbon sequestration. On the other hand, peat core analysis from the EPFS indicates that it has existed in its current form, relatively undisturbed, for centuries. Its low shrubs and moss cover are adapted to a harsh chemical environment of high acidity that limits invasion of more productive vegetation types. This behavior tends to make the site resistant to external changes.

Between 2004 and 2009, the western peatland fen sequestered a total of 11.3 t C/ha and the Mer Bleue bog 6.9 t C/ha.

Inter-year variability in carbon sequestration provides some clues as to the possible future of these carbon dioxide sinks. At EPFS, droughts which occur every 5 to 7 years reduce carbon sequestration to near zero. Increased frequency of droughts in the future will have a dramatic effect on carbon accumulation at this site. Conversely, a steadily declining water table at WPFS did not result in less carbon sequestration. To the contrary, both productivity and ecosystem respiration increased, with no overall change in sequestration, over a four year period. Climate change impacts at this site will likely be more complex and depend upon future vegetation succession and the trajectory of the water table (stabilizing, continued decline or increasing). Similar processes at treed fens and ombrotrophic bogs across Canada may contribute to maintaining peatlands as strong carbon sinks.

For additional information, please contact Dr. Larry Flanagan (larry.flanagan@uleth.ca) or Dr. Peter Lafleur (plafleur@trentu.ca).

Figure 2. Western Peatland (top) and Eastern Peatland (bottom) Flux Station eddy-covariance towers.



Do methane emissions offset carbon sequestration in northern peatlands?

Methane (CH_4) emissions from natural sources worldwide (wetlands, termites and oceans) contribute about 225 Tg CH_4/yr to the atmosphere, which amounts to approximately 37% of total sources in the global methane budget. Wetland ecosystems in northern latitudes have been estimated to release between 6 and 40 Tg CH_4/yr. The magnitude of net methane emissions can have a significant influence on the total carbon budget in some northern wetland and peatland ecosystems. On a per-molecule basis, CH_4 has 25 (g g^{-1}) or 9.1 (mol mol^{-1}) times more global warming potential (GWP) compared to carbon dioxide (CO_2), when considered over a 100-year time frame. Therefore, it is important to measure and understand the relative rates of carbon dioxide and methane exchange when calculating the carbon budget of peatland ecosystems.

The rates of methane emission measured at both the Western and Eastern Peatland Flux Stations (WPFS and EPFS, respectively) were relatively low in comparison to both simultaneous net carbon dioxide sequestration rates and the methane emissions measured in other boreal peatlands. For example, at the WPFS fen the seasonal total of carbon released as methane from late May to late September 2007 was 0.024 t/ha. By contrast, the rate of net carbon sequestration was relatively high (2.2 t C/ha) during the same time period. However, 2007 was a relatively dry year

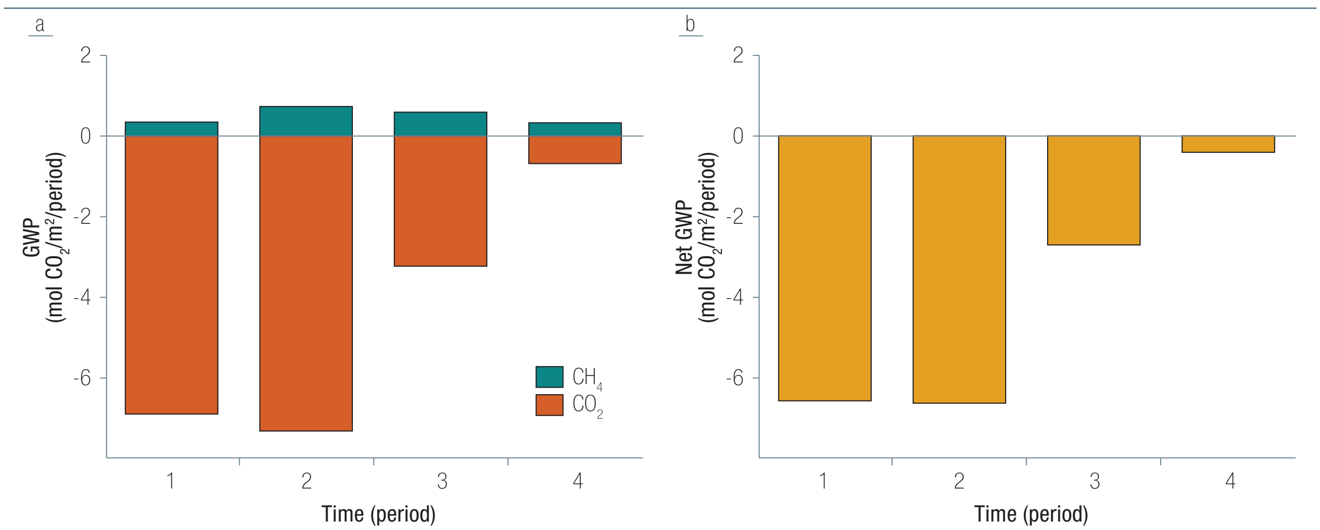


Figure 1. Comparison of seasonal variation in: (a) the global warming potential (GWP) for methane and carbon dioxide, and (b) the net GWP, at the Western Peatland Flux Station during 2007. The net GWP flux represents the sum of the GWP fluxes for CH_4 and CO_2, a positive flux is a loss from the peatland. The global warming potential fluxes were expressed in CO_2 equivalents and were calculated from the CH_4 flux data for a 100-year time horizon (where CH_4 equals 9.1 times the effect of CO_2 (on a molar basis)). Time periods represent the following intervals: (1) late May through June (days 144-180); (2) July (days 181-215); (3) ~ August (days 216-244), (4) September (days 245-269).

at the WPFS site and carbon loss via methane emission may contribute more in years when the water table is higher. At the EPFS bog, the average loss of carbon due to the emission of methane was 0.037 t/ha/yr. This methane loss rate is much lower than the average annual carbon sequestration rate of 0.6 t/ha/yr measured at EPFS during 1998-2009. In addition, significantly higher rates of methane emission (0.09 to 0.14 t C/ha/yr) have been recorded in peatlands in northern Sweden.

The cooling effect of peatlands is proportional to the total amount of carbon accumulated in the peatland (thickness of peat) during its entire development (thousands of years), while the warming effect is proportional to the rate of methane emissions only during the previous several decades (approximately 50 years).

The methane emission rate at the Western Peatland site, when expressed in CO_2-equivalent units, by taking into account the different effectiveness of carbon dioxide and methane as greenhouse gases, offset 10% of the carbon dioxide sequestration that occurred during the entire May to September growing season (Figure 1). GWP calculations for peatlands need to consider that they are both persistent sources of methane and persistent sinks for carbon dioxide. A comprehensive analysis shows that the cooling effect of peatlands is proportional to the total amount of carbon accumulated in the peatland (thickness of peat) during its entire development (thousands of years), while the warming effect is proportional to the rate of methane emissions only during the previous several decades (approximately 50 years) since methane has a shorter lifetime in the atmosphere. After about 50 years the methane impact stabilizes but the cooling effect of persistent carbon sequestration continues, offsetting the initial effect of methane-induced warming.

At WPFS it has been estimated that the total methane emission by the peatland over the last 50 years (3.2 t CH_4/ha) would have produced a warming effect of approximately 42 x 10^{-15} W/m^2. By contrast, the total amount of carbon that has accumulated in the peatland over the last 2200 years is approximately 510 t C/ha, and this would have produced a cooling effect of 101 x 10^{-15} W/m^2. So this approximate calculation shows that the cooling effect of CO_2 sequestration would have easily countered the warming effect of methane emission resulting in a net cooling effect of 59 x 10^{-15} W/m^2 during the development of the western peatland.

For additional information, please contact Dr. Larry Flanagan (larry.flanagan@uleth.ca)

03 Carbon Cycling at Regional, National and Global Scales

Selected Publications

Arain, M.A., F. Yuan, T.A. Black. 2006: Soil–plant nitrogen cycling modulated carbon exchanges in a western temperate conifer forest in Canada. Agricultural and Forest Meteorology 140: 171-192.

Beer, C., M. Reichstein, E. Tomelleri, P. Ciais, M. Jung, N. Carvalhais, C. Rödenbeck, M.A. Arain, D. Baldocchi, G.B. Bonan, A. Bondeau, A. Cescatti, G. Lasslop, A. Lindroth, M. Lomas, S. Luyssaert, H.A. Margolis, K.W. Oleson, O. Roupsard, E. Veenendaal, N. Viovy, C. Williams, F.I. Woodward, D. Papale. 2010. Terrestrial gross carbon dioxide uptake: global distribution and co-variation with climate. Science 329: 834-838.

Bernier, P.Y., L. Guindon, W.A. Kurz, G. Stinson. 2010. Reconstructing and modelling 71 years of forest growth in a Canadian boreal landscape: a test of the CBM-CFS3 carbon accounting model. Canadian Journal of Forest Research 40: 109-118.

Govind, A., J.M. Chen, H. Margolis, W. Ju, O. Sonnentag, M. Giasson. 2009. A Spatially Explicit Hydro-Ecological Modeling Framework (BEPS-TerrainLab V2.0): Model Description and Test in a Boreal Ecosystem in Eastern North America., Journal of Hydrology 367: 200-216.

Grant, R.F., A.G. Barr, T.A. Black, H.A. Margolis, J.H. McCaughey, J.A. Trofymow. 2010. Net ecosystem productivity of temperate and boreal forests after clearcutting – a Fluxnet-Canada synthesis. Tellus B. 62: 475-496.

Grant, R.F., R.S Jassal, T.A. Black, C. Bruemmer. 2010. Changes in net CO2 and N2O exchange with fertilization of Douglas fir: mathematical modelling in ecosys. Journal of Geophysical Research 115, G04009, doi:10.1029/2009JG001094.

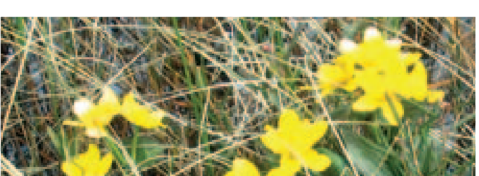
Ju, W., J.M. Chen, T.A. Black, A.G. Barr, H. McCaughey, N.T. Roulet. 2010. Spatially explicit modelling of coupled water and carbon cycles in Canada's forests and wetlands. Tellus doi:10.1111/j.1600-0889.2010.00459.x.

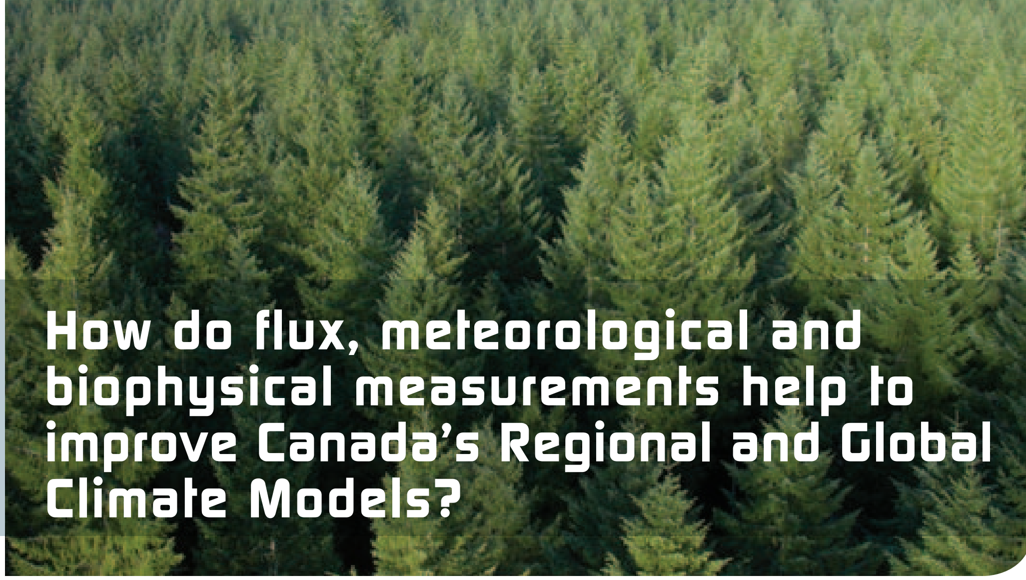
Piao, S., P. Ciais, P. Friedlingstein, P. Peylin, M. Reichstein, S. Luyssaert, H. Margolis, J. Fang, A. Barr, A. Chen, A. Grelle, D. Hollinger, T. Laurila, A. Lindroth, A. Richardson, T. Vesala. 2008. Net carbon dioxide losses of northern ecosystems in response to autumn warming. Nature 451: 49-53.

Ponton, S., L.B. Flanagan, K.P. Alstad, B.G. Johnson, K. Morgenstern, N. Kljun, T.A. Black, A.G. Barr. 2006. Comparison of ecosystem water-use efficiency among Douglas fir forest, aspen forest and grassland using eddy covariance and carbon isotope techniques. Global Change Biology 12: 294-310.

Yuan F., M.A. Arain, A.G Barr, T. A. Black, C.P-A. Bourque, C. Coursolle H.A. Margolis, J.H. McCaughey, S.C. Wofsy. 2008. Modeling analysis of primary controls on net ecosystem productivity of seven boreal and temperate coniferous forests across an east-west continental transect in Canada. Global Change Biology 14: 1-20, doi: 10.1111/j.1365-2486.2008.01612.x.

Zhang, Q.-Y., E.M. Middleton, H.A. Margolis, G.G. Drolet, A.G. Barr, T.A. Black. 2009. Can a satellite-derived estimate of the fraction of PAR absorbed by chlorophyll (FAPARchl) improve predictions of light-use efficiency and ecosystem photosynthesis for a boreal aspen forest? Remote Sensing of Environment 113: 880-888.





How do flux, meteorological and biophysical measurements help to improve Canada's Regional and Global Climate Models?

Energy, water vapour and carbon fluxes and meteorological and biometric data collected at CCP/FCRN flux tower sites have been used to test and further develop the Canadian Land Surface Scheme (CLASS) model. CLASS describes land surface-atmosphere interactions of energy and water in the Canadian Global Climate Model (CGCM) and Canadian Regional Climate Model (CRCM). GCMs and RCMs are used to (i) predict past and future changes in the Earth's climate, (ii) evaluate the impact of future CO_2 emission scenarios or states under different socio-economic and population growth projections and (iii) generate data products for both research and public use purposes for those regions where measured data sets may not be available. GCMs and RCMs play an important role in policy development related to future climate change. The CGCM is the only Canadian model being used by the Intergovernmental Panel on Climate Change (IPCC). The IPCC provides a scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts.

Photosynthesis and plant and soil respiration models were incorporated into CLASS to enhance its capability to simulate carbon cycling in terrestrial ecosystems such as forests, grasslands and crops. Biogeochemical processes such as nitrogen uptake by plants and soil nitrogen processes were also incorporated in CLASS to develop a coupled carbon and nitrogen model, known as CN-CLASS. CN-CLASS has been used to study the role of climatic variables and site-specific carbon stocks in net ecosystem productivity (NEP) of seven CCP forest flux tower sites across Canada. Both observed and simulated data showed that, on an annual basis, boreal forest sites were either carbon-neutral or weak carbon sinks, sequestering from 0.3 to 1.8 t C/ha/yr; while temperate forests were either moderate or strong C sinks, sequestering from 1.5 to 5 t C/ha/yr, depending on forest age and climatic regime (Figure 1). Model sensitivity tests illustrated that air temperature and above-ground biomass were dominant factors impacting annual carbon sequestration, while precipitation had a minor effect. The results of this study helped to evaluate the impact of potential future climate changes and/or forest carbon stock variations on carbon sequestration and emission in forest ecosystems that grow in diverse environments across the vast Canadian landscape. CN-CLASS has been an effective tool for synthesizing and/or extrapolating measured carbon exchanges from individual sites to larger scales. For example, it was included in a North American Carbon Program collaborative study whose goal was to develop and validate process-based, dynamic, terrestrial ecosystem models that improve quantitative estimates of uncertainties in simulated regional and site-specific carbon and water cycles.

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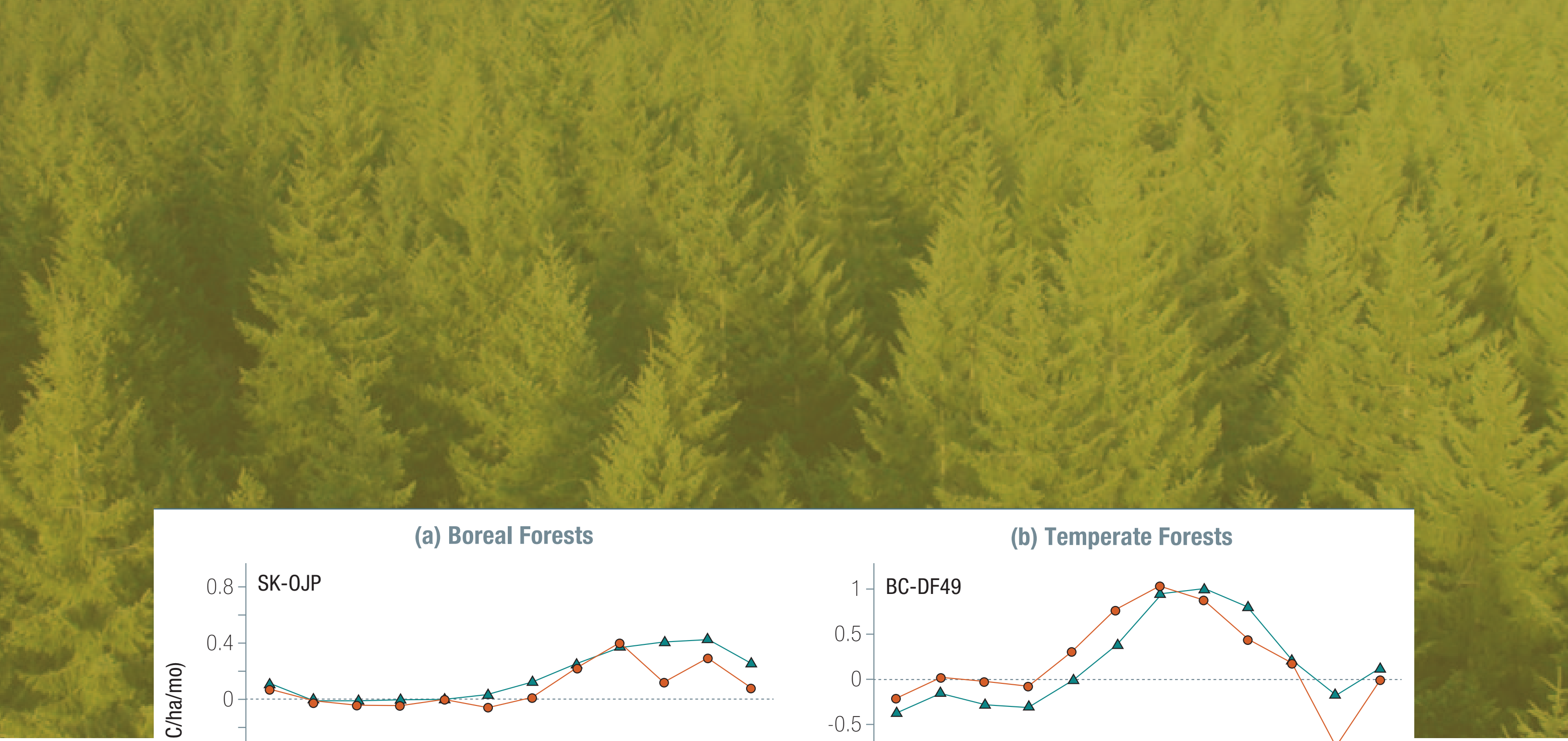

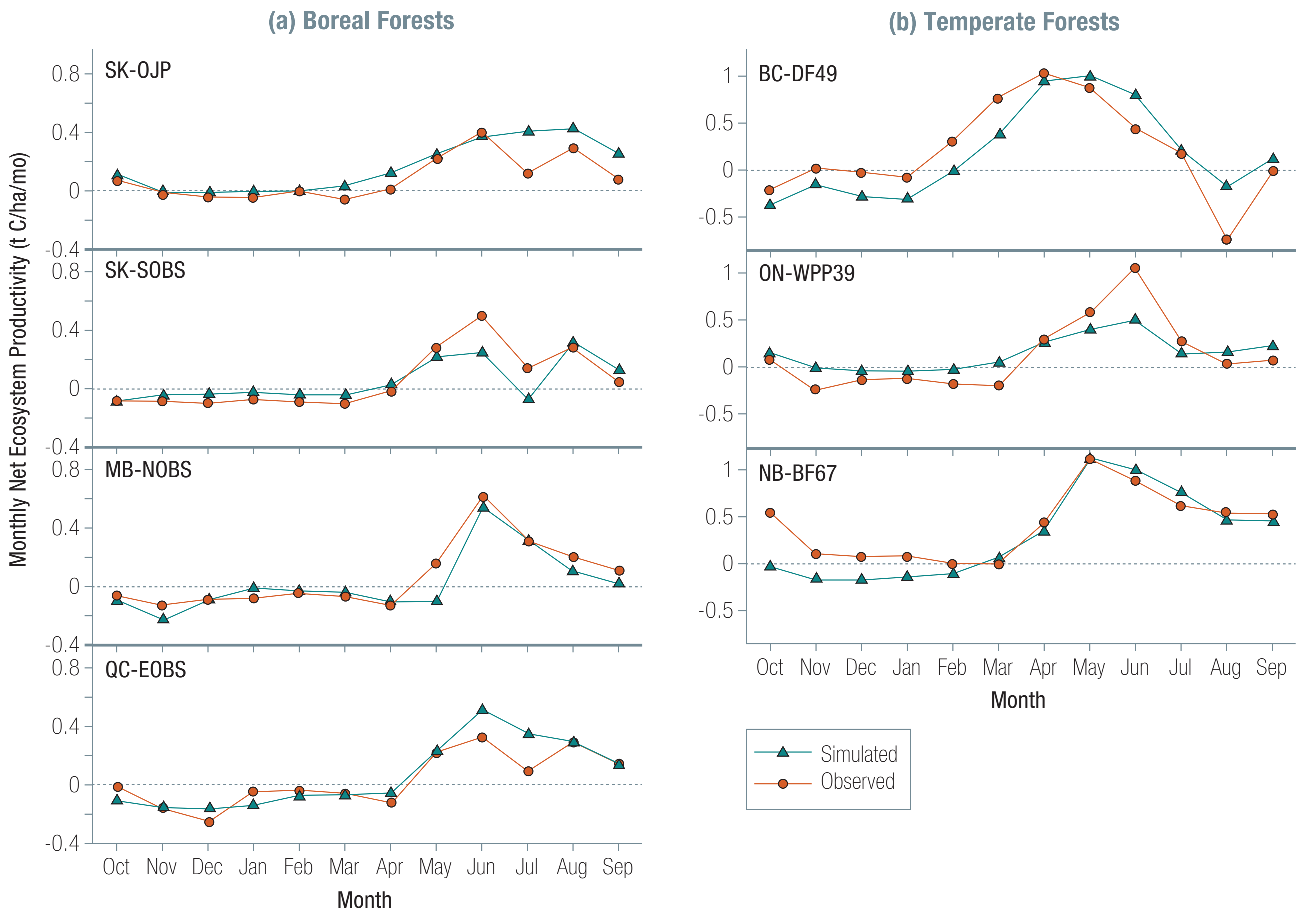

Figure 1. CN-CLASS simulated and observed monthly net ecosystem productivity (NEP) at seven coniferous forest sites across Canada. Positive values indicate net carbon sequestration and negative values indicate carbon emissions.

Recently, simplified versions of nitrogen and carbon algorithms used in the CN-CLASS model have been integrated into the Canadian Terrestrial Ecosystem Model (CTEM) to develop a next generation CTEM^{N+} model. CTEM is a dynamic vegetation model developed by the Canadian Centre for Climate Modeling and Analysis that simulates global and regional carbon cycles by the CGCM. The inclusion of a nitrogen modelling framework into the CGCM would help to evaluate the impact of nitrogen availability on terrestrial ecosystems and its feedback on the Earth's climate system. Nutrient (nitrogen) accessibility may become a serious issue for rapid plant growth and carbon uptake under the higher temperatures and atmospheric CO_2 concentrations currently predicted by field and modelling studies.

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What do atmospheric greenhouse gas (GHG) concentrations tell us about regional sources and sinks in Canada?

The CCP has contributed to the expansion of Environment Canada's network of greenhouse gases (GHG) measurements in the atmosphere over Canada. These "concentration" measurements reveal the number of molecules of GHG in a given amount of air in the atmosphere. Carbon dioxide (CO_2) and methane (CH_4) are two of the key species measured. A map of this network is shown in Figure. 1. The network provides a comprehensive picture of the GHG distribution in Canada, from coastal, interior and arctic regions. The arctic site at Alert is of particular international significance. Numerous countries measure GHG independently at this site and compare values to ensure that their GHG monitoring networks can be properly linked to piece together a coherent, global picture.

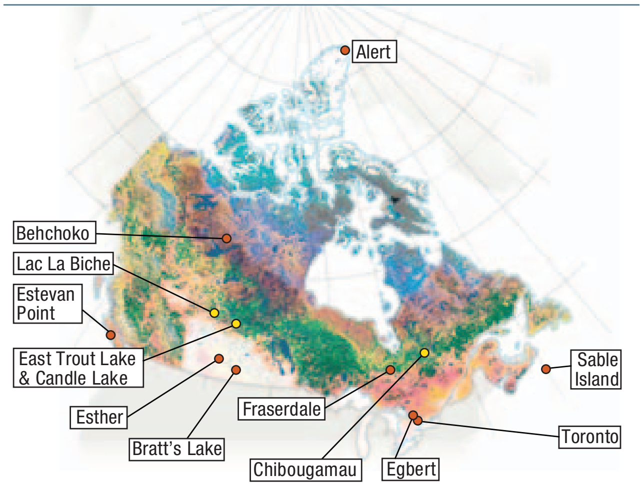

Figure 1. A map showing the location of Environment Canada's greenhouse gas observational stations, superimposed on a map of the vegetation coverage in Canada (courtesy of the Canadian Centre for Remote Sensing). The three stations shown with yellow dots were established with the participation of Fluxnet-Canada and the Canadian Carbon Program.

The GHG concentration data provide an important, large-scale perspective of carbon sources and sinks. As a result of winds and the associated mixing that takes place in the atmosphere, the increase and decrease of GHG concentrations in the lower atmosphere reflects the emission (source) and sequestration (sink) of carbon over a distance of several hundred kilometres. In other words, the atmosphere serves as a giant chamber in which the sources and sinks of GHG manifest themselves as concentration changes within this chamber. With sufficient measurement precision and surface coverage, a signature of individual surface source or sink regions can be detected and quantified. For example, the rise and fall of CO_2 concentrations shown in Figure 2 is a signature of the "breathing of the Earth", CO_2 concentrations decrease due to photosynthetic uptake during the summer growing season and are higher during the rest of the year. Differences in CO_2 concentrations among sites (Figure 2) document the spatial distribution and provide regional information on natural sources and sinks as well as emissions from fossil fuel combustion.

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An example of the "regional scale" perspective yielded by atmospheric GHG concentrations can be seen in Figure 3. The measured concentrations at the three CCP sites are linked to source regions covering air flow of up to five days back in time.

The results demonstrate that CO_2 sources have the potential to affect a large region covering distances of several hundred kilometres. At Lac La Biche and East Trout Lake, the higher CO_2 values are likely linked with emissions from southeast Alberta and southern Saskatchewan, respectively, which are areas of relatively high industrial activity. At Chibougamau, higher CO_2 values are observed during periods of southern transport, with emissions from the US accounting for the majority of this variability.

This “regional scale” perspective is difficult to obtain by other means. Flux towers only integrate flux measurements over an area of approximately one square kilometre. Likewise, ground based forest and ecological measurements are labour intensive and, hence, restricted to limited areas. An important research step of the CCP is to merge field measurements with atmospheric data using computer models to produce a detailed perspective of carbon and GHG sources/sinks at the “regional scale”.

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Knowing the regional scale of sources and sinks of GHG is important because:

- The regional scale is typically on the order of 10,000 km^2, so this knowledge aids provincial governments in monitoring natural changes in GHG emissions or sinks.
- It is at the biome scale (e.g. Prairies, boreal forests), a regional scale perspective provides a way to infer biome-level processes and responses.
- The large-scale, biome-level integration is necessary for understanding the impact of significant disturbances like the mountain pine beetle and drought.

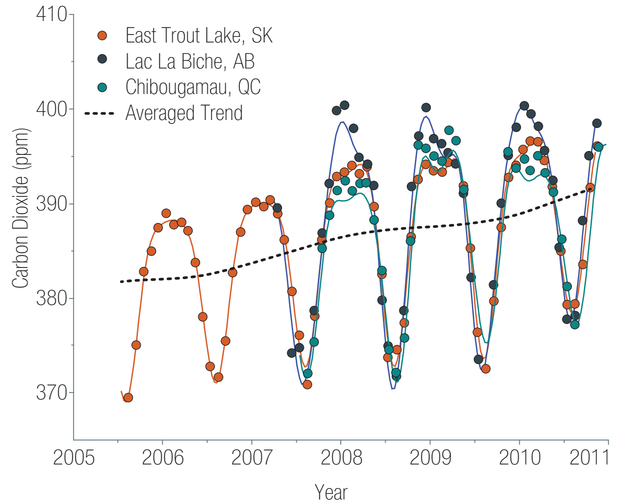


Figure 2. Monthly averaged CO_2 concentration (ppm) from continuous hourly observations at three sites in Canada. These measurements document the spatial and temporal distribution of CO_2 in the air and provide regional information on fossil fuel emissions and sequestration as well as emissions of carbon dioxide by vegetation and soils. In winter, observational sites located closer to urban centres, such as Lac Labiche, would be expected to see higher concentration levels, as a result of their proximity to high emissions from nearby industrial activities.

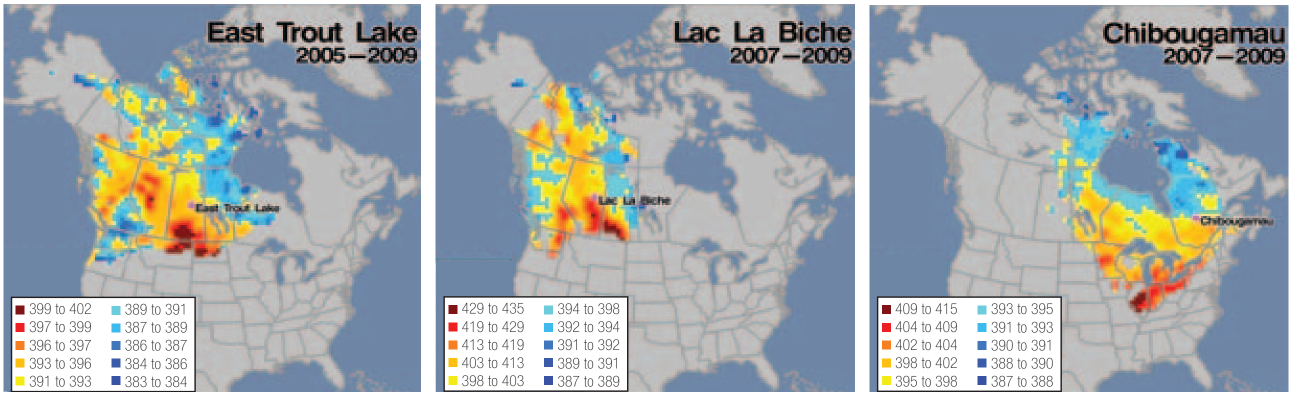
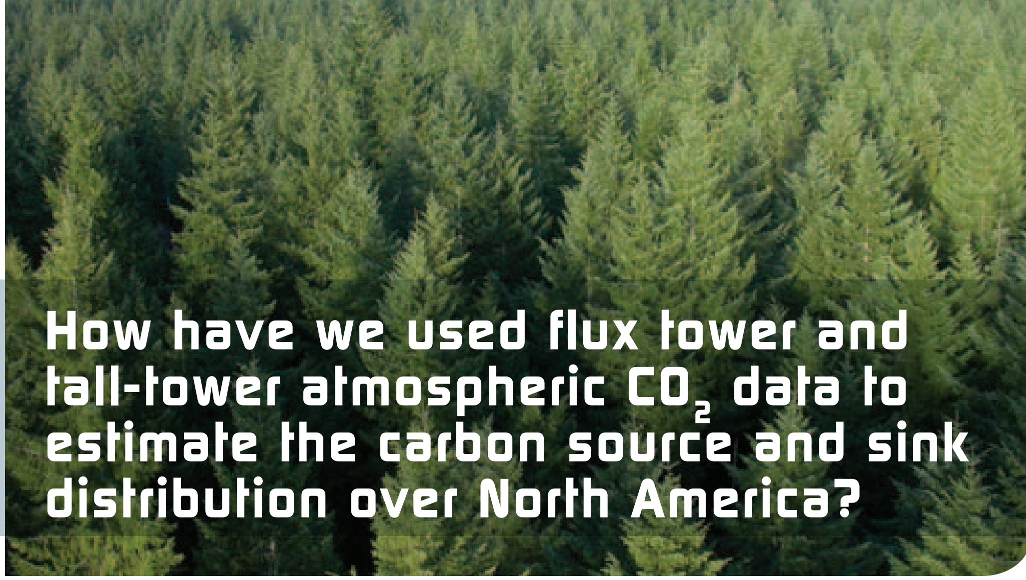


Figure 3. Air flow receptor analysis using measurements of surface CO_2 concentrations (ppm) during the winter months of November to February from the three CCP sites. The site locations are shown with circles.

For additional information, please contact Dr. John Lin (jcl@uwaterloo.ca) or Doug Worthy (doug.worthy@ec.gc.ca).



How have we used flux tower and tall-tower atmospheric CO_2 data to estimate the carbon source and sink distribution over North America?

Flux tower data and atmospheric CO_2 concentration data from tall towers differ greatly in the size of their "footprints" on land, which are approximately 1 km^2 and 10^4-10^5 km^2, respectively. These data, at the opposite ends of the spectrum, can be used in different ways to obtain the regional terrestrial carbon balance and its spatial distribution. Developing a scientific approach that can provide this information is integral to understanding the impact of climate change on terrestrial ecosystems at large spatial scales since these scales are very relevant to formulating and verifying the impacts of climate policy.

Flux towers may be considered to be the "pegs" supporting the spatially variable carbon flux field. Usually, process-based ecosystem models are used to calculate the carbon flux field based on gridded datasets and the calculated field is "pegged" at flux towers, meaning that model parameters are adjusted so that the modelled flux agrees with the measured flux at the towers. Using this method, flux data at a limited number of sites are mechanistically interpolated and extrapolated to a region. This process is usually referred to as bottom-up scaling. Figure 1 shows a carbon source and sink distribution for North American forests from 2000 to 2006 at a 1 km resolution derived using this bottom-up scaling approach. The modelled flux field is "pegged" at 37 flux tower sites in North America. The Integrated Terrestrial Ecosystem Carbon Cycle model (InTEC) is used for this upscaling and integrates both disturbance and non-disturbance (CO_2, nitrogen, climate) effects on the forest carbon cycle. Disturbance information required by the model is obtained by integrating data from the US Forest Inventory

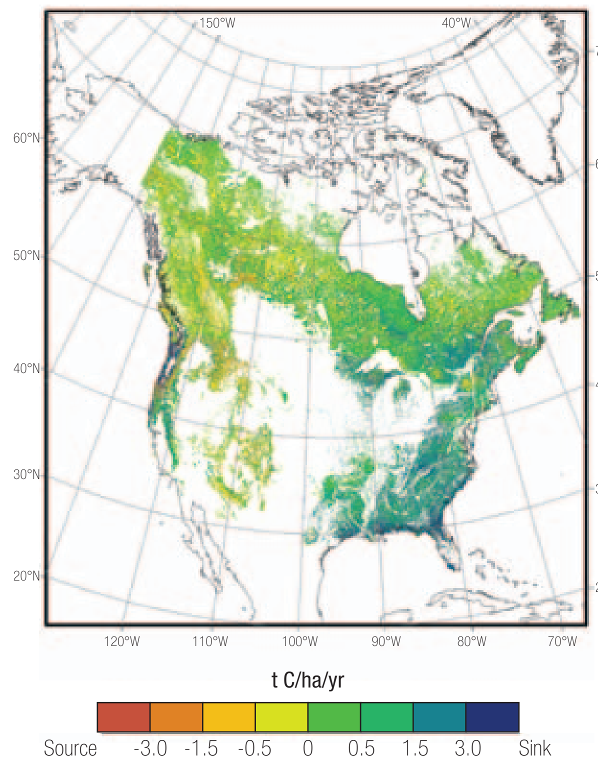


Figure 1. Carbon source and sink distribution (NBP) in North American forests upscaled from flux towers (bottom-up modelling) and based on gridded datasets of forest type, leaf area index, forest stand age, climate, GPP in 2000 (MODIS for USA and BEPS model for Canada), and soil texture. Non-forest areas are not included. Positive values indicate net carbon sequestration and negative values indicate net carbon emissions. R^2=0.71 and mean bias error= -0.48 t C/ha/yr

and Analysis (FIA) and Canadian Forest Inventory databases, the Large Fire Polygon database and satellite remote sensing sources. Other gridded datasets used in the bottom-up modelling include leaf area index and forest type from remote sensing sources, MODIS gross primary productivity (GPP) estimates, monthly climate data and soil texture data. The modelled average net biome productivity (NBP, which is GPP less carbon loss due to ecosystem respiration and disturbance) for the period from 2000 to 2006 was 32 Tg C/yr and 390 Tg C/yr for Canadian and conterminous US forests, respectively.

Atmospheric CO_2 data, collected globally over 200 sites and available from the GlobalView database, are greatly affected by the surface carbon flux within the footprint of each site, and therefore, can be used to estimate the surface flux through atmospheric inversion. This is often referred to as top-down modelling. Figure 2 shows a distribution of NBP from 2002 to 2006 separated into 30 regions for North America. In this top-down modelling approach, the influences of fossil fuel emissions and the ocean flux on atmospheric CO_2 are first removed. In addition to 196 marine sites, CO_2 concentration measured at 12 North American sites are used to make this inversion possible. Over this 5 year period, the inverted average NBP is 236 ± 130 Tg C/yr and 580 ± 140 Tg C/yr for Canada and the US, respectively. These estimates include large sinks in agricultural areas in the central US, which are not included in the bottom-up modelling estimates quoted above. The spatial pattern of inverted NBP is broadly similar to that shown in Figure 1, especially the large carbon sinks in the southeast USA, Ontario and Quebec.

Flux towers may be considered to be the "pegs" supporting the spatially variable carbon flux field. Usually, process-based ecosystem models are used to calculate the carbon flux field based on gridded datasets and the calculated field is "pegged" at flux towers, meaning that model parameters are adjusted so that the modelled flux agrees with the measured flux at the towers.

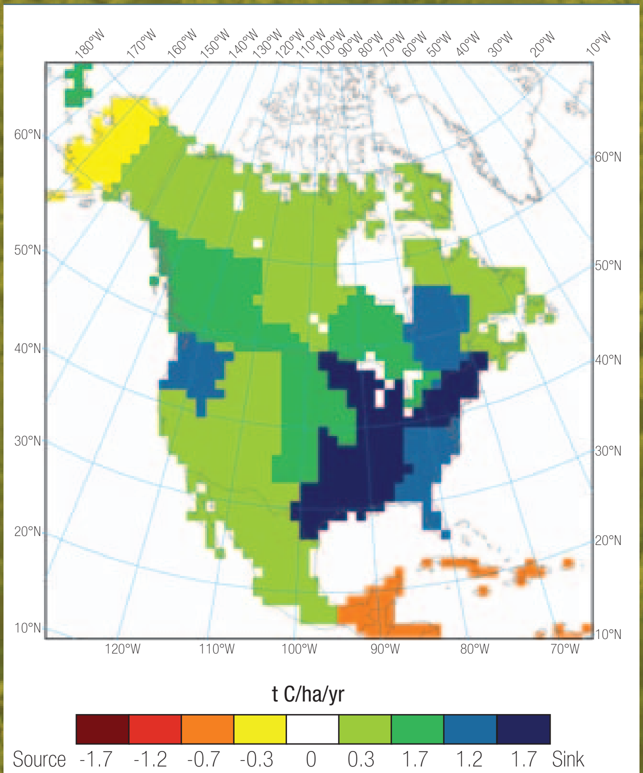


Figure 2. Carbon source and sink distribution (NBP) over North America, averaged for the period from 2002-2006 and separated into 30 regions. It is obtained through nested global inversion (top-down) modelling using CO_2 concentration data measured at 208 marine and continental sites. Positive values indicate net carbon sequestration and negative values indicate net carbon emissions.

For additional information, please contact Dr. Jing M. Chen (jing.chen@utoronto.ca)

How do flux towers help us understand the global carbon budget?

Data from our CCP/FCRN flux towers have been combined with those from other regions of the world to construct a global Fluxnet database for large-scale analyses. Data have been assembled from more than 400 sites across the planet representing more than 3,500 site-years of data. Canadian scientists have been collaborating closely with scientists in other countries to conduct these global analyses.

Since flux towers provide direct measurements of carbon, water and energy exchange, they can be considered as data benchmarks against which global models can be tested. "Artificial intelligence" approaches are used to establish relationships between measured site-level fluxes and an array of site-level explanatory data which are also available as spatially-explicit global data. The explanatory variables include meteorological variables and multi-spectral data from satellite-borne sensors from which we can derive land cover class and seasonal patterns of reflected radiation. The resulting statistical relationships can be used with the global datasets to calculate global fluxes. Given that global explanatory data vary over time and space, the predicted fluxes do as well.

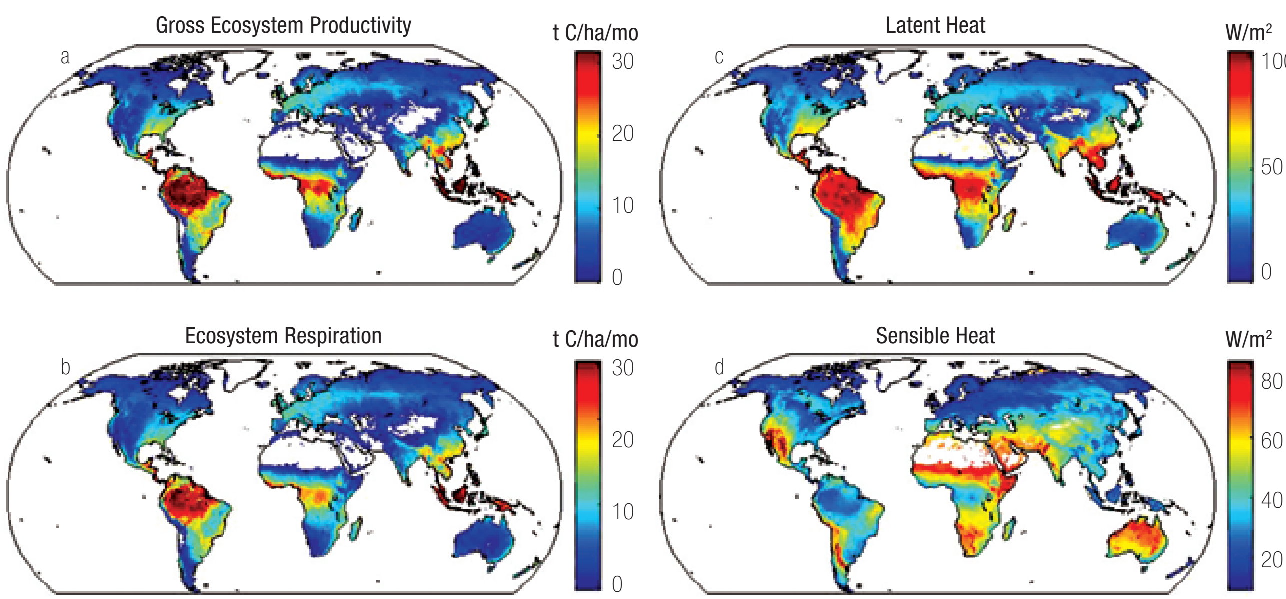


Figure 1. Average annual global fluxes of a) gross ecosystem productivity (photosynthesis), b) ecosystem respiration, c) latent heat (evapotranspiration) and d) sensible heat for the period 1982 to 2008.

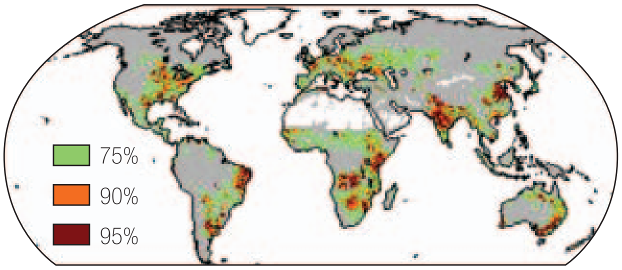


Figure 2. Hotspots of inter-annual variability in net ecosystem productivity. 75% indicates that the variability is greater than 75% of the mean value for the period 1982 to 1998.

These analyses have been used to make global maps of average annual photosynthesis, ecosystem respiration, evapotranspiration (latent heat) and sensible heat for the period 1982 to 2008[1] (Figure 1). Figure 2 shows where there were hotspots of inter-annual variability of net ecosystem productivity (NEP) during the same period and results have shown that for most areas of the world, NEP variability is more strongly related to variability in photosynthesis than to variability in respiration. Figure 3 illustrates the difference between the smallest and largest photosynthetic flux over the course of a year (the amplitude of the seasonal cycle) and the month when the largest photosynthetic fluxes occur[1]. These spatial products represent a valuable reference against which we can test vegetation process models. These process models attempt to represent detailed physiological and biophysical processes, while our data-driven reference maps are not based on any biological assumptions. Therefore, missing processes or other errors in the process models should be easier to detect.

Since flux towers provide direct measurements of carbon, water and energy exchange, they can be considered as data benchmarks against which global models can be tested.

This work uses eddy covariance data acquired by the entire Fluxnet community through the LaThuile data synthesis effort (www.fluxdata.org) and included the following networks and projects: AmeriFlux, AfriFlux, AsiaFlux, Canadian Carbon Program, CarboAfrica, CarboEurope-IP, CarboItaly, Carbomont, ChinaFlux, Fluxnet-Canada, GreenGrass, KoFlux, Large Scale Biosphere-Atmosphere Experiment in Amazonia, Nordic Centre for Studies of Ecosystem Carbon Exchange, OzFlux, TCOS SIBERIA, and the US-China Carbon Consortium.

1 Jung, M., Reichstein, M., Margolis, H.A., Cescatti, A., Richardson, A.D., Arain, A., Arneth, A., Bonal, D., Chen, J., Gianelle, D., Gobron, N., Kier, G., Kutsch, W., Lasslop, G., Law, B.E., Lindroth, A., Merbold, L., Montagnani, L., Moors, E.J., Papale, D., Sottocornola, M., Vaccari, F., Williams, C. 2011. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. Journal of Geophysical Research – Biogeosciences, (in press).

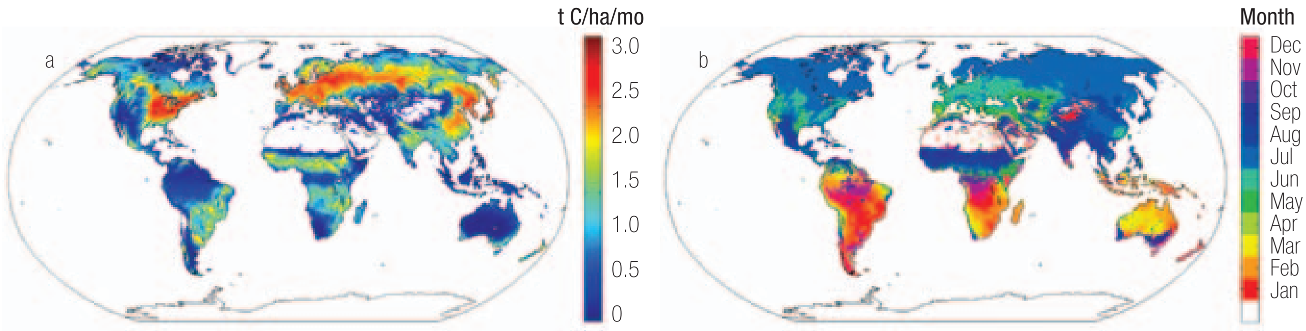


Figure 3. (a) The difference between the smallest and largest monthly photosynthetic flux (gross ecosystem productivity) over the course of a year, the amplitude of the seasonal cycle for the earth. Humid tropical forests have fairly uniform photosynthetic fluxes, whereas boreal forests have a large difference between winter and summer fluxes but the maximum summer fluxes, and therefore the amplitude, is modest. Temperate forests have low fluxes in winter when leaves are shed and very high maximums in summer, therefore they have the greatest amplitude. (b) The month when the largest photosynthetic fluxes occur, generally during the local summer or spring.

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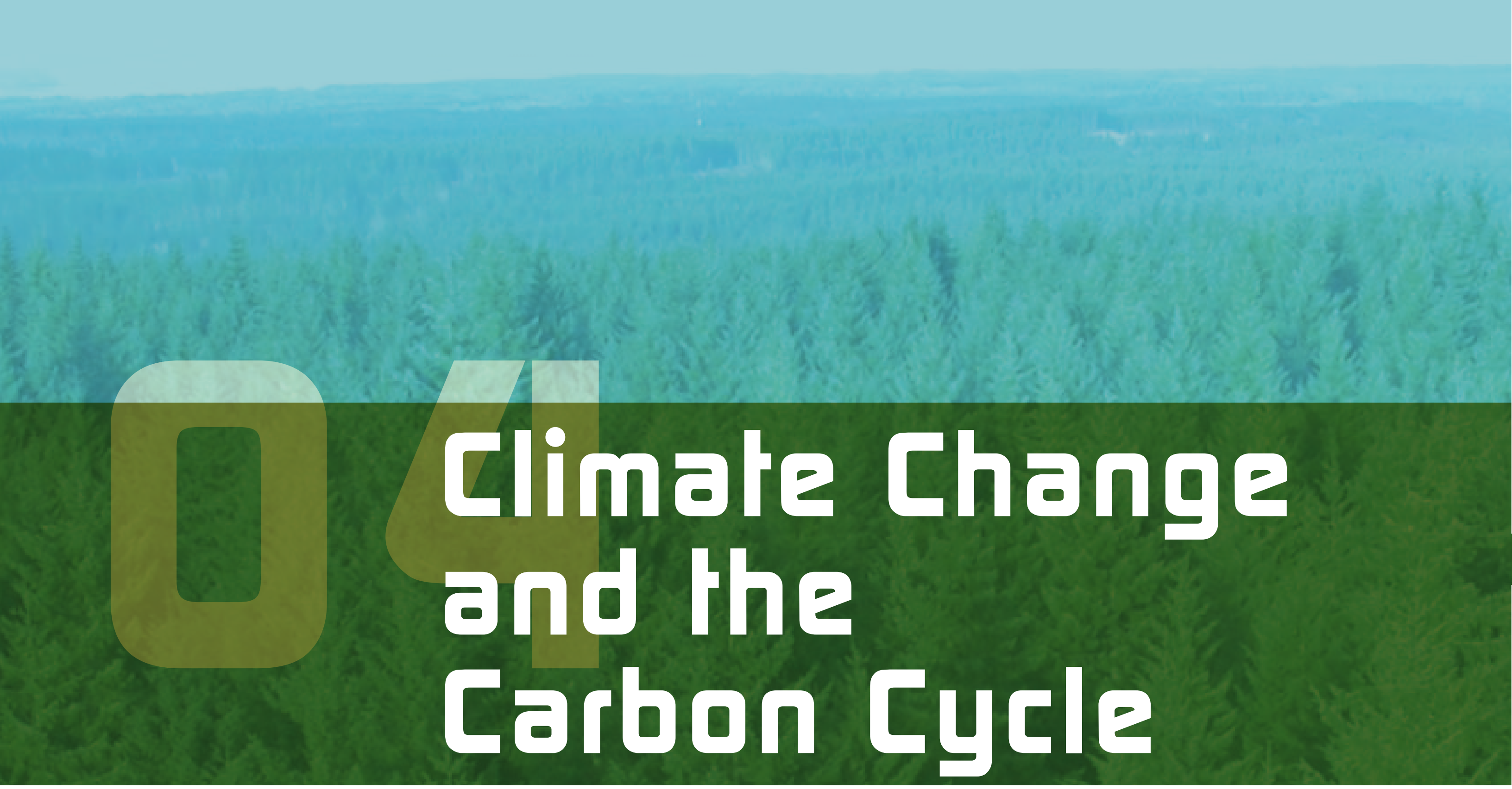


04 Climate Change and the Carbon Cycle

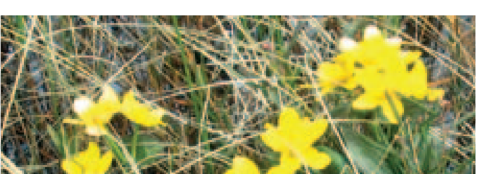
Selected Publications

Grant, R.F., A.G. Barr, T.A. Black, H.A. Margolis, A.L. Dunn, J. Metsaranta, S. Wang, J.H. McCaughey, C.P.-A. Bourque. 2009. Interannual variation in net ecosystem productivity of Canadian forests as affected by regional weather patterns – a Fluxnet-Canada synthesis. Agricultural and Forest Meteorology 149: 2022–2039.

Margolis, H.A., L.B. Flanagan, B.D. Amiro. 2006. The Fluxnet-Canada Research Network: Influence of climate and disturbance on carbon cycling in forest and peatlands. Agricultural and Forest Meteorology 140: 1-5; doi:10.1016/j.agrformet.2006.08.013.

Teklemariam, T., P.M. Lafleur, T.R. Moore, N.T. Roulet, E.R. Humphreys. 2010. The direct and indirect effects of inter-annual meteorological variability on ecosystem carbon dioxide exchange at a temperate ombrotrophic bog. Agricultural and Forest Meteorology 150: 1402-1411.

Yi S., M.K. Woo, M.A. Arain. 2007. Impact of peat and vegetation on permafrost degradation under climate warming. Geophysical Research Letters 34, L16504, doi: 10.1029/2007GL030550.



How studying year-to-year variations in forest productivity can help us to predict the effects of a changing climate

Our flux measurement records are not yet long enough to fully ascertain how climate change is affecting our forests, largely because productivity is greatly affected by year-to-year weather variation. Nonetheless, this variation can provide insight into how climate change may affect forest productivity in the future.

Year-to-year changes in temperature strongly affect forest productivity. For example, 2004 was a cool, wet year in central Canada and 2006 was a warm year. Increased photosynthesis during the warmer spring resulted in a Saskatchewan aspen stand sequestering almost 3 t C/ha in 2006, while in 2004, carbon sequestration was near zero (Figure 1). However, in coastal BC, we found that warming has a very different effect on forest productivity. For example, a Douglas-fir stand sequestered carbon during most of 1999, a particularly cool La Niña year, but emitted carbon during several short-term hot spells in the summer of 2004, a particularly warm El Nino year (Figure 2), thereby reducing carbon sequestration by 2 t/ha compared to 1999. We have found that sudden increased carbon emissions occur in all our coniferous forest sites whenever temperatures exceed 25 °C.

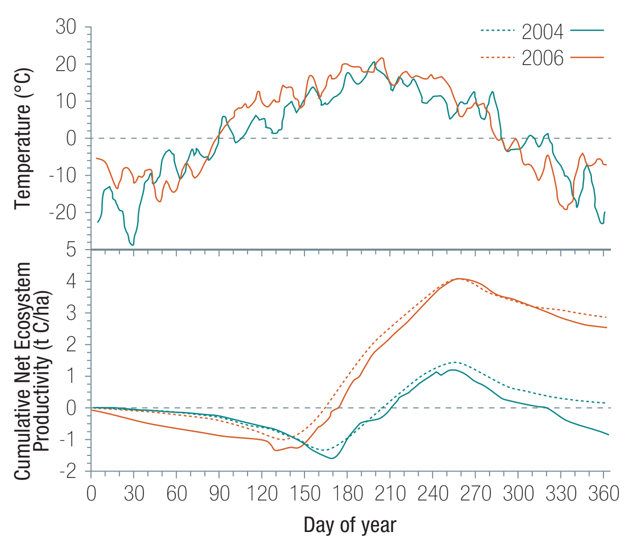


Figure 1. Mean air temperatures measured during 2004, a cooler year, and 2006, a warmer year, and cumulative net ecosystem productivity (NEP) measured (dashed lines) and modelled (solid lines) during these same years at an aspen site in Saskatchewan. Higher temperatures raised modelled and measured NEP at this site by approximately 3 t C/ha. NEP at day 365 indicates the total amount of carbon sequestered (positive value) or emitted (negative value) for that year.

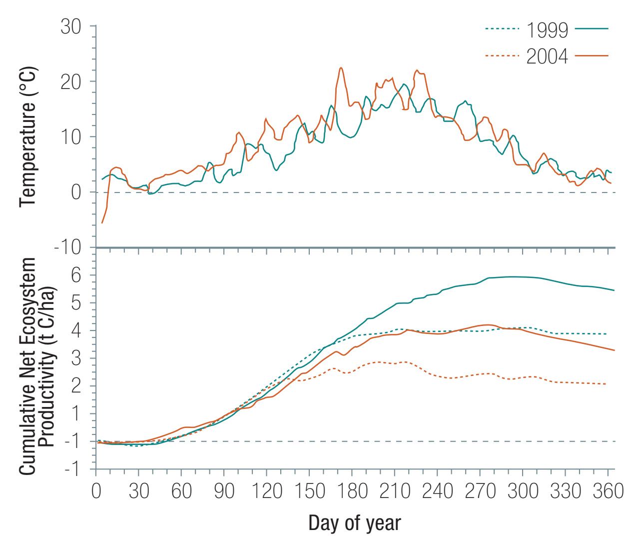


Figure 2. Mean air temperatures measured during 1999, a cooler year, and 2004, a warmer year, and cumulative net ecosystem productivity (NEP) measured (dashed line) and modelled (solid lines) during these same years at a Douglas-fir site in British Columbia. Higher temperatures lowered modelled and measured NEP by approximately 2 t C/ha. NEP at day 365 indicates the total amount of carbon sequestered (positive value) or emitted (negative value) for that year.

We also found that year-to-year changes in precipitation strongly affect forest productivity. A widespread drought in central Canada from 2001 to 2003 caused a decline in annual sequestration at the Saskatchewan aspen site from 3 t C/ha in 2001 to 1 t C/ha in 2003 (Figure. 3). Tree mortality also increased after the drought ended.

Our understanding of how year-to-year changes in weather affect present forest productivity can be used to predict how long-term changes in climate might affect future productivity by incorporating our understanding of ecosystem function into mathematical models. These models are then tested against actual measurements, such as those taken by the CCP. If our understanding is accurate, the model should simulate responses to weather seen in the measurements at CCP and other sites, from arctic tundra to tropical rainforests. The models may subsequently be used to predict ecosystem responses to long-term climate change.

Our understanding of how year-to-year changes in weather affect present forest productivity can be used to predict how long-term changes in climate might affect future productivity by incorporating our understanding of ecosystem function into mathematical models.

For example, the short-term carbon sequestration/emissions modelled in Figures 1 to 3 produce the long-term wood growth modelled in Figure 4. While rapid carbon sequestration at the Douglas-fir site (Figure 2) was associated with rapid wood growth since the last harvest in 1949 (Figure 4), shorter growing seasons at the boreal aspen site (Figures 1 & 3) caused slower wood growth following the last stand-replacing fire in the 1920s (Figure 4). Similarly, very slow carbon sequestration at the boreal black spruce and jack pine sites was associated with very slow wood growth in the years since the last stand-replacing fires of the early 1900s (Figure 4). The rates of wood growth modelled under the very different climates at these and other CCP sites have been verified against rates derived from inventory measurements.

How will rates of wood growth change in the future? Model projections of growth rates are being made for some of our CCP sites under a range of anticipated climate change scenarios for different regions in Canada. In general, these projections indicate increases in wood growth by undisturbed forests in the future, as a result of lengthening growing seasons and higher atmospheric CO_2 concentrations. However, these increases are vulnerable to disturbances such as drought, fire or pests, all of which may become more frequent and must be considered in comprehensive studies of the impacts of climate change on forest productivity.

For additional information, please contact Dr. Robert Grant (Robert.Grant@ales.ualberta.ca)

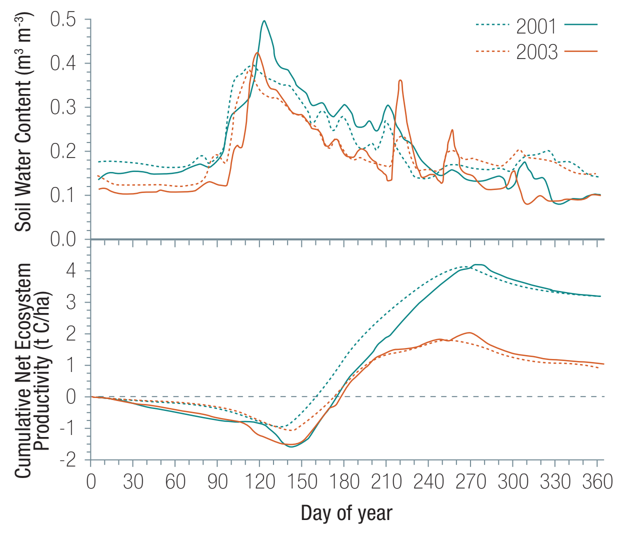


Figure 3. Near-surface (7.5 cm depth) soil water content (SWC) and net ecosystem productivity (NEP) measured (dashed lines) and modelled (solid lines) during 2001 and 2003, the first and third years of a three-year drought at an aspen site in Saskatchewan. Drier soils lowered NEP by 2 t C/ha during the drought. NEP at day 365 indicates the total amount of carbon sequestered (positive value) or emitted (negative value) for the year.

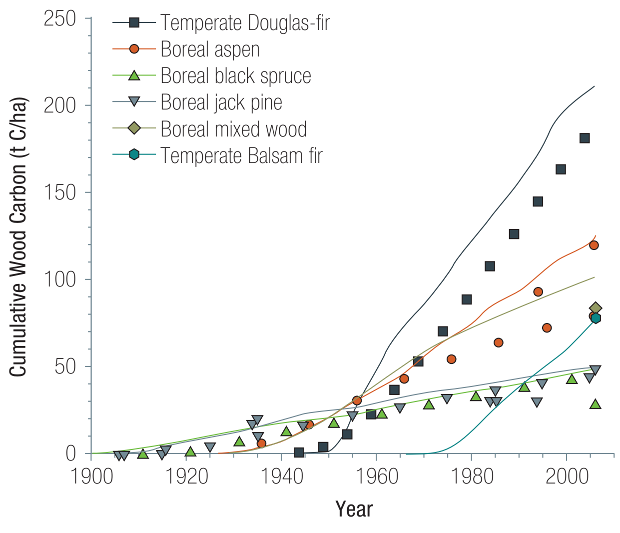


Figure 4. Total wood carbon modelled (lines) and measured, or derived from measurements in various studies, at or near Canadian Carbon Program flux tower sites. The effects of weather on NEP such as those in Figures 1 to 3 determine the effects of climate on forest growth.

How might the carbon cycle of Canada's forests and peatlands respond to future climate change?

Forests respond dynamically to changes in temperature and precipitation. Results from flux tower measurements have shown that, over a few days or weeks, decreased soil temperature or water content can reduce soil carbon loss from ecosystems because the respiration associated with decomposition decreases. Tree-level processes such as photosynthesis and transpiration are also reduced under colder conditions, but take longer to drop during droughts, resulting in a short-term increase in net carbon sequestration by forests during dry spells. However, over the long term, both carbon uptake by trees and respiration losses from decomposition adjust to new climatic conditions, leading to long-term changes in forest carbon stocks.

Measurements of tree growth and soil carbon content, across ten mature forest sites spanning a climate gradient within Canada, were used to predict the response of forests to climate change. Although mean annual tree growth, as represented by the mean annual increment in biomass carbon, was strongly correlated to mean annual temperature across the gradient, soil carbon content was not (Figure 1). This suggests that the extra carbon gained from the faster growing trees is generally offset by increased decomposition and carbon release from the soil under warmer growing conditions.

Based on this study, we do not see evidence that warming by itself would cause a long-term loss of carbon from well drained forest soils so long as tree growth is also stimulated, but a drying trend may cause such a release.

On the other hand, forest soil carbon content was strongly related to mean annual available moisture (the difference between precipitation, and potential evapotranspiration,) in that drier sites had less soil carbon than did wetter ones. Our analysis revealed differences between the short-term forest ecosystem responses to weather events and their response to long-term climate signals. Based on this study, we do not see evidence that warming by itself would cause a long-term loss of carbon from well drained forest soils so long as tree growth is also stimulated, but a drying trend may cause such a release.

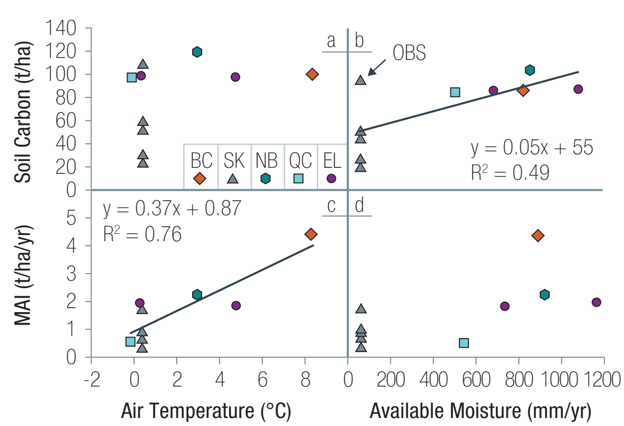


Figure 1. Soil carbon (a, b) and mean annual increment in biomass carbon (c, d) expressed as a function of mean annual temperature (a, c) and mean annual available moisture (b, d). Data are presented for closed-canopy sites at Fluxnet-Canada stations in New Brunswick (NB), Québec (QC), Saskatchewan (SK) and British Columbia (BC). Also included are two ECOLEAP balsam fir sites (EL) located in Québec and New Brunswick. The value of $R^2 = 0.79$ in (b) when the poorly drained Old Black Spruce (OBS) site is excluded from the analysis.

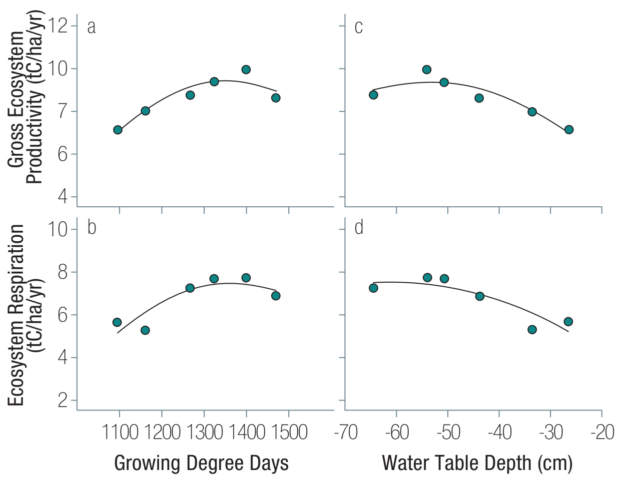


Figure 2. Response of annual (a) gross ecosystem productivity and (b) ecosystem respiration to variations in temperature (expressed as cumulative growing degree days, March to October). Also shown are the responses of: (c) gross ecosystem productivity and (d) ecosystem respiration to variations in water table depth (May to October; average value) at the Western Peatland site.

Most peatland ecosystems have been consistent carbon sinks for millennia. However, it has been predicted that exposure to warmer temperatures and drier conditions associated with climate change will shift the balance between ecosystem photosynthesis and respiration, thereby potentially releasing CO_2 from peatlands. One research objective at the Western Peatland Flux Station in northern Alberta was to determine the sensitivity of gross ecosystem productivity, ecosystem respiration and net ecosystem productivity to variations in temperature and water table depth. Our study was conducted in a moderately-rich treed fen, the most abundant peatland type in western Canada, in a region where peatland ecosystems are a significant landscape component. Measurements made from 2004 to 2009 showed that the average growing season (May-October) water table declined and temperature varied strongly (Figure 2c, d). Contrary to previous predictions, both gross ecosystem productivity and ecosystem respiration showed similar increases in response to warmer and drier conditions (Figure 2). The ecosystem remained a strong net sink for carbon with an average annual sequestration of 1.9 t/ha. A detailed statistical analysis indicated that inter-annual variation in water table depth was the major cause of the observed variation in gross ecosystem productivity and respiration. Lower water tables can increase soil temperature, enhance oxygen supply to roots and improve nutrient availability, all factors that should stimulate both productivity and respiration.

In the absence of fire or other major disturbance, significant net carbon sequestration could continue for decades at the Western Peatland site. However, climate change-induced warmer and drier conditions could also increase the risk of fire disturbance, which would release significant amounts of stored carbon and reset the ecosystem to an earlier, less productive successional stage.

In the absence of fire or other major disturbance, significant net carbon sequestration could continue for decades at the Western Peatland site.

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Glossary

Albedo: The proportion of solar radiation reflected, rather than absorbed, by a surface that it strikes. The darker the surface, the lower the albedo (fresh snow: 0.9, asphalt: 0.04).

Autotrophic Respiration: Emission of CO2 by living vegetation through metabolic processes.

Carbon balance: The inputs and outputs of carbon pertaining to a given system.

Carbon cycle: The process by which carbon in its various forms moves through and among the Earth's systems.

Carbon neutrality: Balancing a measured amount of carbon emission with an equivalent amount of carbon sequestration.

Carbon sequestration: The process of removing carbon from the atmosphere and depositing it in a reservoir such as trees or soil.

Carbon Sink: Absorption of carbon from the atmosphere by an ecosystem. A carbon sink is a reservoir of carbon that accumulates and stores carbon for an indefinite period of time.

Carbon Source: Emission of carbon from an ecosystem to the atmosphere. A carbon source is a reservoir of carbon that emits carbon to the atmosphere.

Carbon Stock: The quantity of carbon contained in a "pool", meaning a reservoir or system which has the capacity to accumulate or release carbon. In the context of forests it refers to the amount of carbon stored in the world's forest ecosystem, mainly in living biomass and soil, but to a lesser extent also in dead wood and litter.

Chronosequence: A set of forested sites that share similar attributes but are of different ages.

Climate: The typical average weather conditions—predominantly temperature, humidity, precipitation, wind, and sunshine—of a particular area.

Climate change: A long-term change in the statistical distribution of climate patterns over periods of time that range from decades to millions of years

Decomposition: The process by which plant material is broken down sequentially through leaching by water, physical fragmentation by fauna and fungi and chemical alteration by microbes.

Disturbance: A pronounced change in environmental conditions leading to a change in an ecosystem, e.g. fire, harvest, insect infestation, disease, and windthrow.

Ecosystem: All of the living and non-living parts of a natural system that functions as a unit of interdependent relationships.

Ecosystem Respiration (ER): All CO_2 emitted by an ecosystem through autotrophic and heterotrophic respiration.

Eddy covariance: Also called eddy correlation. A technique used in micrometeorology to measure vertical fluxes (e.g. of CO2, water vapour, heat) within the atmospheric boundary layer.

Emission: The release of a substance, such as a greenhouse gas, into the atmosphere.

Evaporation: The process by which a liquid is transformed into a gas.

Evapotranspiration: The sum of evaporation and transpiration, two processes by which ecosystems return water to the atmosphere

Fossil fuel: Fuel formed over millions of years from remains of dead plants and animals (natural gas (methane), petroleum and coal).

Flux: The measure of the flow of some quantity—heat, CO2, water vapour--per unit area per unit time.

Global warming potential (GWP): A measure of how much a given mass of greenhouse gas is estimated to contribute to global warming in comparison to that of the same mass of carbon dioxide (GWP = 1). For a GWP to have meaning, the time interval over which it is calculated must be specified.

Greenhouse gas: An atmospheric trace gas that allows shortwave radiation to pass through it but absorbs and re-emits longwave (infrared) radiation coming from Earth's surface. The primary greenhouse gases in the Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide, and ozone.

Gross ecosystem productivity (GEP): The absorption of CO_2 via photosynthesis over a given period of time.

Hectare (ha): a surface area of 10,000 m^2. i.e. 100 m x100 m.

Heterotrophic respiration: Emission of CO_2 by soil microbes (e.g., bacteria, fungi) and animals via metabolic processes, including the decomposition of soil organic matter.

Latent heat flux: The portion of net radiation that is used to evaporate water from the land surface to the atmosphere.

Net ecosystem productivity (NEP): The net absorption or emission of CO_2 by an ecosystem over a given period of time. A positive number denotes net absorption of CO_2 by an ecosystem (a carbon sink), a negative number denotes a net release of CO_2 to the atmosphere (a carbon source).

Net primary productivity (NPP): Biomass produced per unit of time.

Petagram (Pg): a unit of mass equal to 10^{15} g, 10^9 tonnes (t) or 1 gigatonne (Gt).

Photosynthesis: a process by which plants and algae convert carbon dioxide into organic compounds, especially sugars, using the energy from sunlight.

Potential evapotranspiration: The amount of evaporation that would occur if a sufficient water source were available to satisfy the atmospheric demand for moisture from a surface.

Sensible heat flux: The amount of net radiation that is dissipated in the form of sensible heat.

Teragram (Tg): a unit of mass equal to 10^{12} g, 10^6 tonnes (t) or 1 megatonne (Mt).

Transpiration: The process by which water vapour in plants is transferred to the atmosphere.