

# Peatlands, carbon, and climate: the role of drought, fire, and changing permafrost in northern feedbacks in climate change

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## Abstract

Peatlands store ~30% of the world's soil carbon and are located primarily at northern latitudes, where they are experiencing rapid climate warming. As climate change alters peatland hydrology and soil temperatures, changes in ecology and biogeochemistry may alter rates of carbon storage as peat. Moreover, warmer and drier conditions may enhance the decomposition of old carbon in peatlands, accelerating greenhouse gas emissions with positive feedbacks to climate change. Here, I present findings from experiments, regional surveys, and modeling studies that examine the consequences of warming, drought, and disturbance on the ecology and carbon cycling of boreal peatlands. While fast ecosystem responses to drought include reduced ecosystem carbon storage, a long-term experiment showed that drainage increased woody inputs to soils and soil carbon storage. However, increased forest cover made these drained ecosystems more susceptible to burning during wildfires, leading to large carbon losses through fuel combustion and ecosystem succession. In addition to changes in ecosystem carbon storage and exchange, additional research on other aspects of radiative forcing, such as surface albedo change, is required for a more complete understanding of the role of peatlands in climate warming.

## Key Words

Soil carbon mineralization, greenhouse gases, disturbance, vegetation productivity, plant-soil feedbacks.

## Introduction

Over the past several decades, high latitude ecosystems have experienced rapid climate change that has resulted in soil warming, permafrost degradation, increased snow pack thickness, and longer growing seasons (Hinzman *et al.* 2005). Remote sensing studies show that lakes and wetlands in many boreal regions are drying, often accompanied by the encroachment of drier terrestrial vegetation (Riordan *et al.* 2006). However, in other boreal regions, permafrost thaw and increased upwelling of melt water is leading to wetland saturation and the formation of thermokarst lakes (Jorgenson and Osterkamp 2005). Peatlands represent only 1-3% of the world's land surface, but play a major role in the global carbon cycle. Peatlands have served as a long-term sink of carbon dioxide (CO<sub>2</sub>), but also represent a natural source of atmospheric methane (CH<sub>4</sub>). The position of the water table within a peatland serves as a dominant control on peatland-atmosphere carbon exchange, as it influences plant structure and productivity, rates of decomposition, and dissolved carbon export. With climate models predicting enhanced evapotranspiration under a 2 x CO<sub>2</sub> scenario, and therefore a lower water table position in peatlands, many studies have predicted that peatland CH<sub>4</sub> emissions will decrease while CO<sub>2</sub> emissions will increase in the coming decades.

Wildland fire is one of the most common and important disturbances affecting boreal forests, and its role in regulating forest ecosystem structure and function long has been recognized (Viereck 1973). Until recently, fire was not considered to be an important control on peatland carbon cycling because high water table positions in peatlands were thought to limit fire frequency (Kuhry 1994) and fuel combustion severity (Zoltai *et al.* 1998). However, recent work has shown that fire influences North American peatlands more regularly than previously thought. As a result of recent climate change, the annual area burned in boreal North America has more than doubled since 1950, raising the question of whether the deep organic soils currently stored in peatlands are becoming more vulnerable to burning. Understanding peatland feedbacks to climate change requires information on rates of peat accumulation, CO<sub>2</sub> and CH<sub>4</sub> fluxes as well as surface energy balance (*i.e.*, albedo). Here I present findings from experiments and modeling studies examining ecological and biogeochemical responses in peatlands to warming, drought, permafrost thaw, and wildfires.

## Methods

The Alaska Peatland Experiment (APEX) is an ecosystem-scale experiment using soil temperature and hydrology manipulations to study the consequences of climate change on peatland carbon cycling. Since 2005, growing season CO<sub>2</sub> and CH<sub>4</sub> fluxes have been monitored across a factorial design of *in situ* water

table (control, drought, and flooded plots) and soil warming (control vs. warming via open top chambers) treatments in a groundwater-fed fen that lacks surface permafrost. In 2007, the APEX study was expanded to include climate manipulations in a collapse scar that experienced recent permafrost thaw as well as in a forested bog with intact permafrost. While the APEX study examines fast ecosystem responses to altered soil climate, on a decadal scale changes in succession is likely to govern ecosystem responses to disturbances such as drought. In the mid-1980's, several peatlands in western Canada were drained in a government experiment intended to explore the potential for enhanced forest harvesting in peatlands. Today, this experiment provides a novel opportunity for exploring the effects of several decades of lowered water table position on peatland ecology and biogeochemistry. The Canadian Large Fire Database and peatland distribution maps have been used to explore patterns of burn area in peatlands across western Canada, representing about 40% of the Canadian land-base. Measurements of organic matter consumption have been made in a variety of natural and experimental fire events in both western Canada and Alaska to better understand vegetation and fire weather controls on carbon losses during burning. These data have been used in fire emissions models to estimate continental-scale emissions of carbon and mercury due to peat fires.

## Results

Results from the APEX study show that the drought (lowered water table position) treatment increased net ecosystem exchange, making the drought plot more of an atmospheric C source relative to the control, by lowering gross primary production and light-saturated photosynthesis rather than by increasing ecosystem respiration (Chivers *et al.* in press). Soil flooding caused the site to become a greater C sink due largely to increased vegetation production. Soil warming increased both ecosystem respiration and gross primary production of CO<sub>2</sub>, with no net effect on net ecosystem exchange. Both water table and soil temperature served as significant controls on CH<sub>4</sub> emissions, with the highest CH<sub>4</sub> emissions occurring in the flooded and warmed treatments (Turetsky *et al.* 2008).

While fast responses to drought (lowered water table position) in the APEX study included increased CO<sub>2</sub> fluxes to the atmosphere, 30+ years of experimental drainage in an Alberta peatland resulted in increased soil bulk density, faster rates of peat accumulation, and overall larger soil carbon pools compared to undrained sites. Increases in carbon pools post-drainage are due primarily to increased forestation, with greater tree density and growth rates that likely altered both the amount and quality of litter inputs to soils.

Analysis of annual peatland area burned in western Canada show that large areas of peatlands in continental Canada can burn, with interannual variability similar to annual area burned in forests. The total burn area of large fire events between 1980 and 1999 is positively correlated to the abundance of peatlands in western Canada, suggesting that these peatlands are particularly susceptible to burning during large fire years and/or extreme fire weather conditions (Turetsky *et al.* 2004; Benscoter *et al.* in press). Published estimates of fuel consumption rates in Canadian peatlands range from 0.9-3.7 kg C/m<sup>2</sup> per fire event, which is similar to forest combustion rates (Benscoter and Wieder 2003; Turetsky and Wieder 2001). However, fuel combustion in permafrost forests with thick peat deposits in Alaska are much higher than previously anticipated. Patterns of fuel combustion in the long-term drainage sites in Alberta were 4-fold higher than in undrained peatlands, suggesting that deep soil carbon may become more vulnerable to burning with increasing thaw depth and/or under sustained drought conditions.

## Conclusion

Fast ecosystem responses to drought in our Alaskan experiment included increased CO<sub>2</sub> emissions to the atmosphere, primarily because of reduced CO<sub>2</sub> fixation by plants, and reduced CH<sub>4</sub> emissions. However, longer-term ecosystem responses to drought in Canada included changing plant community composition and substrate quality that favored peat accumulation, yielding larger soil carbon pools relative to pristine peatlands. In the forested peatlands of western Canada, about 30% of soil carbon is situated above the regional water table in aerobic peat layers and is vulnerable to burning under current climate conditions. However, deeper peat layers will become increasingly exposed to fire as these ecosystems are subjected to regional changes in both fire weather and drought. Both empirical and modeling results demonstrate that drought conditions that lower regional water tables and/or increase fire severity in peatlands greatly exacerbate regional emissions of carbon and mercury to the atmosphere (Turetsky *et al.* 2006). While peatlands in North America have served as a long-term carbon sink, drier climatic scenarios that lead to altered carbon mineralization rates or fire regimes could accelerate greenhouse gas emissions and cause much of the stored soil organic matter to be released back to the atmosphere.

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