Carbon Cycling in Northern Peatlands

Andrew J. Baird, Lisa R. Belyea, Xavier Comas, A. S. Reeve, and Lee D. Slater
Editors

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Cover Photo: Open pools in the central unit of Caribou Bog, Orono, Maine. Modified from R. B. Davis original (taken June 2006).

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PREFACE

Even though they cover only between 2 and 3% of its land mass, peatlands are a major component of the Earth's carbon cycle, containing about one third of the carbon in the pedosphere. These large carbon stores remove carbon from, and release it to, adjacent systems (most significantly the atmosphere) in a complex cycle. Although large peatlands are found in the tropics, this monograph focuses on recent developments in our understanding of carbon dynamics in northern peatlands, that is, those peatlands that occur at latitudes higher than 45°N. We focus exclusively on northern peatlands because of their significance in terms of surface areal extent and their importance as carbon stores. Northern peatlands are also most likely to be affected by climate change and warming.

Peatlands science cuts across disciplines, and it can be difficult for peatland researchers in one discipline to find advances made by peatland scientists in other disciplines. Recognition of this problem was partly behind our decision to propose the monograph; in other words, we wanted to produce a collection of papers that brought together the state of knowledge on peatland science. Obviously, a monograph that considered all areas of peatland science would have been a huge, if not impossible, undertaking. We chose to focus on carbon cycling and climate, and we did so for two reasons. We felt that much previous work has looked at peatlands primarily as archives of climate change, with less emphasis on the processes that control how a peatland responds to variations in climate and how it may itself influence climate. We were also aware of the need to include peatlands in climate models and the need to communicate current understanding of the role of peatlands in the global carbon cycle to a larger audience, especially, but not exclusively, climate modelers.

Many individuals helped with the production of this monograph. Each chapter was independently reviewed, and we are indebted to those academics who undertook reviews, and in some cases rereviews, on very tight deadlines. Finally, this effort was inspired by a National Science Foundation funded "Peatlands Geophysics Workshop" held at the University of Maine in June 2007. The purpose of the workshop was to bring together peatland scientists from a range of disciplines to consider novel ways of mapping the subsurface structure of peatlands. We hope some of that ambition and novelty is reflected in the current collection.

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Understanding Carbon Cycling in Northern Peatlands: Recent Developments and Future Prospects

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Although one of the earliest recorded investigations of peatlands is attributed to *King* [1685] more than 3 centuries ago [*Gorham,* 1953], *Weber's* [1902] treatise on the Aukštumala Raised Bog in Lithuania is still considered the first comprehensive ecohydrological study of peatlands and the foundation for modern peatland science. Weber's monograph was pioneering for different reasons: (1) it integrated disciplines such as stratigraphy, hydrology, chemistry, and ecology to describe, classify, and model peatlands forms and their development (e.g., internal processes), and (2) it investigated potential interactions between peatland (mostly hydrology) and changes in climate and sea level (e.g., external forcing). Since then, most peatlands science has focused on the peatland archive (e.g., pollen and macrofossils) for environmental and climate reconstruction over the Holocene, whereas processes controlling the response of peatlands to climate change have tended to be overlooked.

The effect of peatlands on global climate is currently unclear. Peatlands influence climate by sequestering CO_2 from the atmosphere and storing it in living and dead biomass. They return some of this CO_2 via the decay of plant litter and peat and are the largest natural terrestrial source of atmospheric methane (CH_4), which is produced during anaerobic decomposition. Through the Holocene, peatlands have been a persistent sink for atmospheric CO_2 and a persistent source of atmospheric CH_4. Although CH_4 is a much more potent greenhouse gas than CO_2, modeling work by *Frolking et al.* [2006] suggests that peatlands have had a negative radiative forcing (cooling) effect on climate through the Holocene. However, that may change in the coming decades as peatlands respond to climate change. For example, existing peatlands may become net emitters of CO_2 as peat warms and rates of decomposition increase, while in areas of permafrost the formation of thaw lakes may lead to higher rates of CH_4 loss. On the other hand, new peatlands may develop in areas that are currently tundra and become large sinks of atmospheric CO_2 in the next 100–200 years, thus offsetting, at least in part, greater losses of CO_2 and CH_4 from northern peatlands at lower latitudes. To understand how peatlands affect global climate, we need to represent them as land surface schemes coupled to global climate models (GCMs). Before we can do so, there is a need to understand better how peatlands function as ecohydrological entities. Part of this understanding can come from the paleorecord, but part must come from process and modeling studies at a range of scales. Where possible, peatland models should be process-based and applicable to a range of climatic, geomorphological, and geological settings; that is, they should be transportable.

Scale is an important factor to consider in studies of carbon cycling in northern peatlands for at least two reasons. First, when considering processes operating across the whole peatland or at the regional scale, it is uncertain whether small-scale processes (those at plan scales of about 1 m) can be ignored or simplified adequately. Second, it is becoming clear that little is known about the off-site components of the carbon budget of peatlands; carbon exchanges are not just between peatlands and the atmosphere; dissolved carbon can also be exported from peatlands, where its fate remains uncertain. As part of this second reason, other off-site factors such as topographic setting are also important controls on carbon cycling in individual peatlands. Although this monograph focuses on peatlands occurring across a limited latitudinal range, study sites are included across geographical longitudes spanning three different continents and a total of seven countries.

The chapters consider some of these scale and geographical issues and also how we can improve our understanding of key ecohydrological processes in peatlands and how they affect carbon cycling. The monograph is divided into four sections, and the content of each is discussed briefly below.

Section 1 considers the role of peatlands in the global carbon cycle. It does so from a variety of perspectives. The first chapter considers how peatlands respond to climate change. Many workers still consider peatlands to respond in simple linear ways to climate. However, it is becoming clear that peatlands are complex adaptive systems that do not show simple responses to climate. Sometimes peatlands undergo large ecohydrological changes in the absence of a climate driver, and sometimes they show extreme sensitivity to apparently small climatic changes. If we are to model peatlands adequately, then we need to know the reasons behind such nonlinear behavior. Climate modelers are only now starting to recognize the importance of the peatland carbon store and the need to include peatlands in GCMs. How peatlands should be represented in climate models is the focus of the second and third chapters. The second looks at how peatlands differ from other land surface types and the challenges these differences present when trying to incorporate peatlands into land surface schemes. The third looks at the problem of what it means to ignore small-scale variability when modeling CH_4 losses from peatlands and the importance of such small-scale variability when trying to represent peatlands in GCMs. The fourth chapter provides a broad temporal and spatial perspective and uses meta-analyses of data from previous studies to investigate the factors that influenced peatland initiation and carbon accumulation during the Holocene. Finally, there is a chapter on direct human impacts on the peatland carbon store. Much of the current concern is with the indirect human impacts (climate change) on peatlands; therefore, it is useful also to consider how direct impacts such as changes in land use to forestry and agriculture affect carbon cycling.

Section 2 focuses on processes operating at and near the peatland surface, where climate change is likely to have the greatest impact through disturbance (e.g., fire and permafrost thaw) and changes in water table and temperature regimes. One of the unique characteristics of peatland land surfaces is the prevalence of mosses, which have distinct biophysical and biochemical properties compared with vascular plants. The relative abundance of these plant types has a profound effect on carbon cycling because the biochemistry of plant-derived substrates is a key control on rates and pathways of decomposition. The other major control on carbon cycling relates to vertical and horizontal heterogeneity in water table regime, which, in turn, controls oxygenation, the distribution of plants and microbes, and microbial metabolic pathways. The first chapter in this section reviews remote sensing approaches to obtaining land surface data relevant to the carbon cycle, both for generating land surface classifications and for retrieving biophysical properties that can be used to parameterize process-based models. The second chapter considers mass loss and nutrient release from fresh plant litter, noting that changes that affect the relative production of *Sphagnum* versus vascular plant litter are likely to have feedbacks on carbon and nutrient cycling. The third chapter examines carbon flow from a microbial perspective, identifying the main microbial players, metabolic pathways, and factors controlling substrate use in the oxic, periodically oxic/anoxic, and permanently anoxic zones. The final chapter considers the relative amounts of CO_2 and CH_4 produced during terminal mineralization of carbon under anoxic conditions, noting the importance of both substrate characteristics and physical factors and making a plea for further studies using consistent methodologies.

Section 3 describes the state of knowledge on CH_4 accumulation in, and release from, peatlands by considering both deep and shallow sources of the gas at a wide range of scales. Methane is lost to the atmosphere through three main mechanisms: diffusion through the peat matrix, transport through vascular plants, and ebullition (as bubbles). Until recently, most studies considered the first two mechanisms almost exclusively. However, there is burgeoning interest in the significance and causes of ebullition. Nonsteady or episodic ebullition events have generated particular interest because of the potentially large amounts of CH_4 involved. Ebullition fluxes in northern peatlands typically exceed average diffusive fluxes on a per-event basis and often on a seasonal basis as well. Current ebullition estimates are unclear for several reasons: (1) our poor understanding of gas spatial variability related to the heterogeneous nature of the peat matrix; (2) uncertainties related to contrasting models of gas accumulation (e.g., shallow entrapment in poorly decomposed peat versus deep entrapment below confining layers of woody peat); and (3) factors affecting ebullition dynamics, often related to environmental parameters such as soil chemistry, substrate quality, or plant community structure. To further complicate estimates, biogenic gas emissions from wetlands are often related to changes in temperature, atmospheric pressure, and/or water table elevation. The first and second chapters in this section emphasize the importance of CH_4 accumulation in deep peats (i.e., >2 m) and describe the use of minimally invasive techniques such as global positioning systems (GPS) and ground-penetrating radar to investigate deep free-phase gas accumulations in peatlands. The third and fourth chapters examine the role of shallow peat soils (i.e., <1 m) as both zones of CH_4 production and zones from which CH_4 is lost to the atmosphere. The third chapter proposes a new conceptual model for bubble buildup and release in shallow peat soils, while the fourth identifies key zones of enhanced methanogenesis at shallow depths based on carbon isotope composition. The fifth chapter presents an overview of an experimental design that can be used for investigating the accumulation and release of CH_4 from shallow peats under controlled laboratory conditions. Finally, the last chapter looks at some of the controls that may induce losses of CH_4 gas from peatlands such as atmospheric pressure, peat temperature, and water table position for both deep and shallow peats.

All of the topics presented in this monograph reveal the importance of the physical and chemical processes related to water supply to and movement within peatlands. Section 4 focuses on peatland hydrology and its role in carbon dynamics. Efforts to understand peatland hydrological processes typically focus on (1) saturation state and water table position and (2) rates and directions of water movement. Water in peatlands isolates organic matter from the atmosphere, altering the redox state and slowing the oxidation of organic matter while creating an environment favorable for methane production. This mixture of organic matter and water indirectly results in high concentrations of dissolved organic carbon (DOC) in peat pore waters. The production of DOC within and export from peatlands is discussed in the first two chapters of section 4. The rate and direction of surface and groundwater flow within a peatland regulate the export of DOC from the peatland and influence the supply of nutrients to it. The third chapter describes the hydrological and hydrochemical importance of natural soil pipes in the peatlands in which they occur. Chapter five focuses on the hydrodynamics of the unsaturated zone in harvested peatlands. Chapter six discusses the role of subsurface heterogeneity on groundwater flow patterns. There are a variety of feedback mechanisms between the hydrology of a peatland and associated carbon dynamics that complicate this relationship. The relationship between hydrology and biogenic gas dynamics is one of these feedback systems and is discussed in chapter four. While there are many similarities among the peatland systems discussed in this section, it is important to note the differences between individual systems and to use caution when generalizing processes observed in one peatland to another.

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Section I: Large-Scale Peatland Dynamics and Carbon Cycling

Nonlinear Dynamics of Peatlands and Potential Feedbacks on the Climate System

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Peatlands have potential for strong feedback on the global climate system, but their response to future climate change is highly uncertain. In this chapter, I review a range of evidence demonstrating that peatland dynamics are nonlinear. Rather than gradual change that converges on a single dominant pathway and matches the frequency of external forcing, peatlands show (1) sensitivity to initial conditions and divergence onto multiple pathways of development, (2) long periods of little change, punctuated by abrupt transitions of state even under weak or steady environmental forcing, and (3) responses to external forcing at unexpected frequencies. Nonlinear systems exhibit persistence when stabilizing forces (i.e., negative feedback mechanisms) dominate and undergo rapid transformation when destabilizing forces (i.e., positive feedback mechanisms) dominate. In peatlands, stabilizing and destabilizing forces result from interactions among hydrological processes, organic matter dynamics, and energy exchanges. The depth dependence of peat hydraulic conductivity tends to stabilize hydrological conditions, whereas local flow networks may amplify water losses