Science of the Total Environment 550 (2016) 880–892

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Comparisons of soil nitrogen mass balances for an ombrotrophic bog and a minerotrophic fen in northern Minnesota

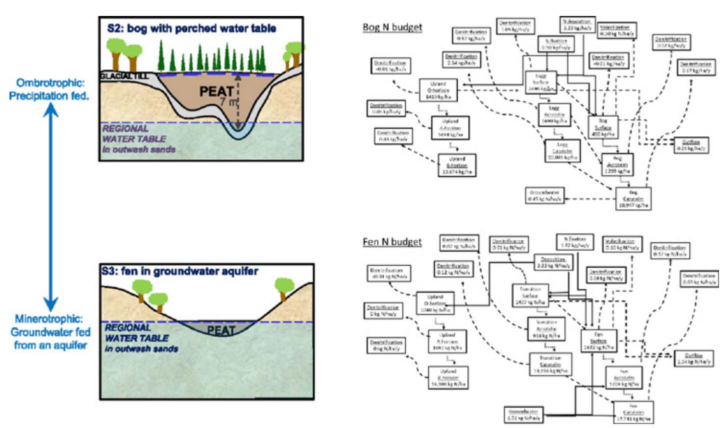
Brian H. Hill [a,*], Terri M. Jicha [a], LaRae L.P. Lehto [a,1], Colleen M. Elonen [a], Stephen D. Sebestyen [b], Randall K. Kolka [b]

[a] US Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Laboratory, Mid-Continent Ecology Division, Duluth, MN 55804, USA
[b] US Forest Service, Northern Research Station, Center for Research on Ecosystem Change, Grand Rapids, MN 55744, USA

HIGHLIGHTS

- We compared N budgets for soils from an ombrotrophic bog and a minerotrophic fen.
- Soil N content depended on location within the bog or fen, and on soil depth.
- We highlight the importance of biogeochemical hotspots within the peatlands.
- We show the importance of organic N storage, as a source of N for denitrification.
- We propose a link between N storage, denitrification and N export from peatlands.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form 26 January 2016
Accepted 26 January 2016
Available online 4 February 2016

Editor: D. Barcelo

Keywords:
Bog
Denitrification
Fen
Peat
Soils
Watershed N budget

ABSTRACT

We compared nitrogen (N) storage and flux in soils from an ombrotrophic bog with that of a minerotrophic fen to quantify the differences in N cycling between these two peatlands types in northern Minnesota (USA). Precipitation, atmospheric deposition, and bog and fen outflows were analyzed for nitrogen species. Upland and peatland soil samples were analyzed for N content, and for ambient (DN) and potential (DEA) denitrification rates. Annual atmospheric deposition was: 0.88–3.07 kg NH_4^+ ha^{-1} y^{-1}; 1.37–1.42 kg NO_3^- ha^{-1} y^{-1}; 2.79–4.69 kg TN ha^{-1} y^{-1}. Annual N outflows were: bog—0.01–0.04 kg NH_4^+ ha^{-1} y^{-1}, NO_3^- 0.01–0.06 kg ha^{-1} y^{-1}, and TN 0.11–0.69 kg ha^{-1} y^{-1}; fen—NH_4^+ 0.01–0.16 kg ha^{-1} y^{-1}, NO_3^- 0.29–0.48 kg ha^{-1} y^{-1}, and TN 1.14–1.61 kg ha^{-1} y^{-1}. Soil N content depended on location within the bog or fen, and on soil depth. DN and DEA rates were low throughout the uplands and peatlands, and were correlated with atmospheric N deposition, soil N storage, and N outflow. DEA was significantly greater than DN indicating C or N limitation of the denitrification process. We highlight differences between the bog and fen, between the upland mineral soils and peat, and the importance of biogeochemical hotspots within the peatlands. We point out the importance of organic N storage, as a source of N for denitrification, and propose a plausible link between organic N storage,

* Corresponding author at: USEPA/NHEERL/MED, 6201 Congdon Blvd., Duluth, MN 55804, USA.
E-mail address: hill.brian@epa.gov (B.H. Hill).
[1] Current address: AMI Consulting Engineers, Superior, WI 55792, USA.

http://dx.doi.org/10.1016/j.scitotenv.2016.01.178
0048-9697/Published by Elsevier B.V.

denitrification and N export from peatlands. Finally, we considered the interactions of microbial metabolism with nutrient availability and stoichiometry, and how N dynamics might be affected by climate change in peatland ecosystems.

1. Introduction

The role of wetlands, especially peatlands, in the global carbon budget has been widely discussed (Gorham, 1991; Bridgham et al., 2006; Kayranli et al., 2010), but less attention has been paid to the corresponding role of peatlands in nitrogen cycling (Drewer et al., 2010; Worrall et al., 2012; Loisel et al., 2014). Northern peatlands are particularly sensitive to N additions, owing to their unique hydrological and biogeochemical properties leading to carbon and nutrient limitation (Urban and Eisenreich, 1988; Bragazza et al., 2012; Sheppard et al., 2013; Toberman et al., 2015). Peatlands are divided into two broad classes on the basis of pH and hydrology (Gorham et al., 1985; Bridgham et al., 1996). Minerotrophic fens have ground and surface water inputs, are slightly acidic to neutral pH, while ombrotrophic bogs receive water and nutrients primarily from atmospheric deposition and are acidic. Both fens and bogs generally are dominated by *Sphagnum* mosses, with fens having a much more diverse understory plant community than bogs Gorham et al., 1985. Fens range from open to forested while bogs are generally forested (Bridgham et al., 1996). Both bogs and fens have distinct vertical zonation, with actively photosynthesizing vegetation lying above a transiently aerobic peat zone (the acrotelm), and this underlain by a layer of anaerobic peat (the catotelm; Limpens et al., 2008). Bogs have an added topographic feature called the lagg, which is the interface of the bog with the toe of the upland slope. The lagg has been identified as a biogeochemical "hot spot", a zone that has particularly high biogeochemical processing rates such as mercury methylation (Mitchell et al., 2008, 2009). A feature unique to some northern temperate peat bogs is the presence of speckled alder (*Alnus rugosa*) in the lagg. The nitrogen-fixing alder is suspected of pumping N into the lagg, further enhancing this biogeochemical hot spot (Compton et al., 2003; Eickenscheidt et al., 2013). Similarly, in both fens and bogs, hummocks (areas of peat raised above the mean peat surface) and hollows (at the mean peat surface) are biogeochemically distinct, with hollows having significantly greater respiration and mercury methylation than the hummocks (Waddington and Roulet, 1996; Branfireum, 2004).

There are four sources of N to peatlands, atmospheric deposition, mineralization, N-fixation, and upwelling from regional groundwater (Verry and Timmons, 1982; Bridgham et al., 1996). For bogs, all N inputs are via atmospheric deposition, watershed mineralization and N-fixation, but for fens some N inputs also occur as groundwater upwelling or surface water inflows (Verry and Timmons, 1982; Bridgham et al., 1998). Peatlands accumulate C as is evident from their global significance in soil C budgets, but they also store large quantities of N and P. Verry and Timmons (1982) reported that 56% of total N (80–90% of inorganic N) and 76% of total P inputs to a bog were retained rather than exported. Bridgham et al. (1998) reported that, while N and P stores in peatlands were large, the available fractions were much smaller and tightly cycled, leading to relative N and P limitations on productivity.

By the above accounting, nearly 50% of N inputs to peatlands are exported, mostly as organic forms (Urban et al., 1988; Seitzinger, 1994; Hayden and Ross, 2005; Keller and Bridgham, 2007; Worrall et al., 2012). Denitrification accounts for less than 5% of nitrate removal from bogs (Urban et al., 1988; Keller and Bridgham, 2007). These authors attribute low denitrification rates to low nitrate availability and low pH (Hayden and Ross, 2005; Keller and Bridgham, 2007).

Our goals for this research were to compare the soil N inputs, storage and outflows of two peatlands, an ombrotrophic bog and a minerotrophic fen, and to compare the relative importance of N gains and losses to the overall soil N budget of peatlands and their watersheds. We also compare N storage and outflows of the upland watersheds to those of the bog/fen and quantify the contribution to the different soil strata to the overall bog and fen N budget.

2. Methods

2.1. Study sites

We studied two peatland watersheds within the US Department of Agriculture's Forest Service Marcell Experimental Forest (MEF; N 47° 30.17′, W 93° 28.97′), located approximately 40 km north of Grand Rapids, Minnesota, USA (Fig. 1). The MEF is within the Laurentian Mixed Forest Province, which is a transitional zone between boreal forests to the north and broadleaf deciduous forests to the south (Verry et al., 2011). The landscape is a typical low-relief, moraine landscape of the Upper Great Lakes Region, and includes uplands, peatlands, and lakes. Peatlands at the MEF range in size from several hectares to several hundreds of hectares and may have forest, shrub, or sedge cover. The MEF has an extensive historical database of hydrology, chemistry, and meteorology that documents ecosystem processes since the early 1960s (Sebestyen et al., 2011). The climate is sub-humid continental, with wide and rapid diurnal and seasonal temperature fluctuations. Over the period of record (1961–2009), the average annual air temperature was 3 °C, with daily mean extremes of −45 °C and 38 °C, and the average annual precipitation was 780 mm, most of which fell as rain from mid-April to early November. Mean annual air temperatures have increased about 0.4 °C per decade over the last 50 y (Sebestyen et al., 2011).

Our two study peatlands include an ombrotrophic bog and a minerotrophic fen. The two peatlands are within 2 km of one another and have similar dominant aspects, watersheds with <20 m of topographic relief, and mixed conifer-deciduous forest covers. The bog watershed, designated as S2, contains a 3.2 ha bog (black spruce, *Picea mariana* on the bog; some areas of dense speckled alder, *Alnus incana*; *Sphagnum* sp. in the lagg) and a 6.5 ha upland (quaking aspen, *Populus tremuloides*; paper birch, *Betula papyrifera*). Mean annual stream pH at the watershed outlet averages 4.1 (Urban et al., 2011). The bog watershed was instrumented for measurement of precipitation volume, surface and sub-surface runoff, bog (perched) water level, and depth to the regional water table starting in the 1960s, and has served as the undisturbed reference watershed for the southern MEF study unit (Sebestyen et al., 2011). Streamflow has been measured at a 120 degree V-notch weir (Sebestyen et al., 2011).

The fen watershed, designated as S3, has an 18.6 ha fen (willow, *Salix* sp.; *A. incana*, *P. mariana*, white cedar, *Thuja occidentalis*) surrounded by a 53.4 ha upland (*P. tremuloides*; *B. papyrifera*; balsam fir, *Abies balsamea*; jack pine, *Pinus banksiana*; red pine, *Pinus resinosa*). Mean annual stream pH at the outlet averages 6.9 (Urban et al., 2011). The fen was instrumented for measurement of precipitation volume, fen water level, and depth to the regional water table starting in the 1960s. Although instantaneous streamflow has occasionally been measured, monthly, annual, and yearly streamflow amount is estimated from a fen water level-discharge relationship (Sebestyen et al., 2011). The entire fen (but not the uplands) was clear-cut and the slash was burned in 1972–1973 (Sebestyen et al., 2011). Water yields did not change after harvesting and nutrient concentrations had returned to pre-harvest levels by 1976 (Sebestyen and Verry, 2011).

The bog peatland is composed of Loxley soils (Dysic, Frigid Typic Haplosaprist) with an Oi horizon from 0 to 20 cm, Oe horizon from