Geoderma 213 (2014) 371–378

Contents lists available at ScienceDirect

Geoderma

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

Beaver pond effects on carbon storage in soils

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ARTICLE INFO

Article history:
Received 11 April 2013
Received in revised form 11 August 2013
Accepted 17 August 2013
Available online 17 September 2013

Keywords:
Soil type
Soil organic matter
Wetland
Lowland wet grassland
Carbon density

ABSTRACT

Beaver ponds have been shown to be hot spots of carbon trace gas flux, which begs the question, "What is the source of the carbon?" The density and stratigraphy of carbon storage was studied in soils of boreal beaver meadows, graminoid wetlands that develop after a beaver pond is abandoned and drained, at Voyageurs National Park on the U.S.–Canada border, where beaver re-colonized the landscape during the latter half of the 20th century. Carbon density was measured to a depth of 60 cm by collecting volumetric samples in mineral soils from the side walls of hand-dug trenches and in a Histosol using a box corer. Interpretation of pre-beaver (1940) aerial imagery showed the presence of cedar swamps in locations that currently have Haplosaprists and Argiaquolls, with deep carbon storage that cannot be attributed to recent beaver activity. Excluding these sites, carbon density to a depth of 60 cm was still significantly greater in beaver meadow pedons (15.1 ± 6.8 kg m^{-2}) than in adjacent forest soils that had not been impounded (8.2 ± 2.9 kg m^{-2}). The difference was attributed to the accumulation of graminoid plant debris in thick surface O horizons. Volumetric carbon concentrations were greatest in O horizons, and a linear regression between O horizon thickness and carbon density was significant. Parent material origin (i.e., glacio-fluvial vs. glacio-lacustrine) did not significantly affect carbon density. This research confirms the presence of soil carbon adequate to supply trace gas fluxes, but suggests that considerable carbon is sequestered by beaver impoundments in the meadow stage, which may offset carbon release that occurs during the pond stage.

1. Introduction

Numerous studies have reported that beaver ponds are "hot spots" of carbon dioxide and methane emissions, based on laboratory incubations of beaver pond soils (Scanlon and Moore, 2000; Updegraff et al., 1995; Vecherskiy et al., 2011), gas fluxes into field chambers (Bubier et al., 2003; Naiman et al., 1991; Weyhenmeyer, 1999), and eddy covariance towers (Dove et al., 1999; Roulet et al., 1997). The 1994 Boreal Ecosystem-Atmosphere Study (BOREAS) estimated a total gaseous carbon flux of 210 g C m^{-2} yr^{-1} from a beaver pond in northern Alberta, in contrast to the carbon sink provided by forests (-5 g C m^{-2} yr^{-1}) (Roulet et al., 1997). The high rate of carbon gas flux from beaver ponds begs the question, "What is the source of the carbon?"

Soils beneath the beaver ponds are a possible source of carbon, but this is counterintuitive when beaver ponds are perceived as small lakes, because lake sediments in temperate climates typically have low sediment carbon concentrations (<60 kg Mg^{-1}) (Avnimelech et al., 2001). However, beaver ponds are not permanent bodies of water. Beaver "ponds" alternate between being flooded and drained as they are colonized and abandoned by beaver colonies. Drained beaver ponds often become beaver meadows, vegetated by wetland grasses and sedges that can sequester carbon via photosynthesis. Thus, the carbon dynamics of beaver meadow soils cannot be generalized from lake ecosystems.

Beaver ponds inundate diverse geomorphic settings, which may affect their soil physical and chemical properties (Johnston, 2012). In the U.S. Mountain west, riparian beaver ponds experience high sedimentation rates due to alluvial deposition (Butler and Malanson, 1995; Polvi and Wohl, 2012; Westbrook et al., 2011). In boreal regions, beaver may flood peatlands (Rebertus, 1986; Scanlon and Moore, 2000). Some of these settings may contain antecedent carbon stocks that are a legacy of their pre-beaver condition, so it is important to understand the geomorphology of the pre-beaver landscape before assessing beaver pond effects on landscape carbon storage.

Soil carbon storage is of international concern due to potential feedbacks to atmospheric trace gases and global climate change (Bridgham et al., 1995; Lal, 2004). Although global soil carbon stocks are fairly well characterized for upland soils (Batjes, 1996), considerable uncertainty exists about carbon storage in wetland soils, particularly mineral wetland soils (Bridgham et al., 2006). Factors contributing to this uncertainty include poorly characterized bulk density and depth of carbon storage in wetland soils, both of which are essential for extrapolating the carbon concentrations of soil samples to carbon stocks of whole landscapes and the globe (Bridgham et al., 2006; Johnston et al., 2004). Documentation of the carbon density of beaver wetlands

Abbreviations: ANOVA, analysis of variance; C_{mass}, carbon per unit soil mass; C_{vol}, carbon per unit soil volume; TC_{60}, total soil carbon density per unit area to 60 cm depth; NP, National Park; ρ_b, bulk density.

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http://dx.doi.org/10.1016/j.geoderma.2013.08.025

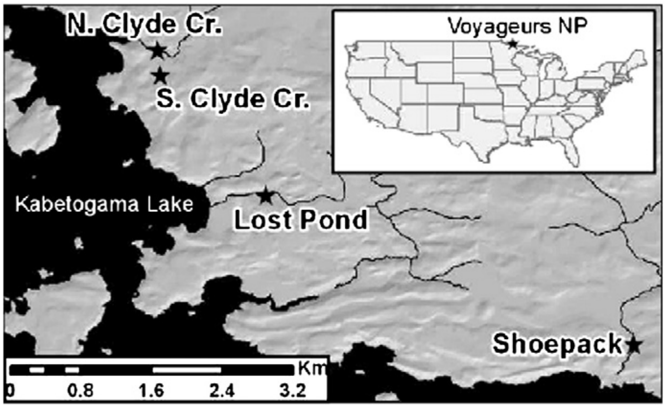

Fig. 1. Study sites and location of Voyageurs National Park.

(i.e., the mass of carbon per unit area of landscape) can contribute to our general knowledge about wetland soil carbon stores.

Mineral particle size distribution can also influence soil carbon stability. Fine mineral particles (i.e., silt and clay) adsorb organic carbon, thus protecting it from decomposition (Lützow et al., 2006; Six et al., 2002; Swift, 2001; Torn et al., 1997). Silt and clay content is also correlated with the ability of mire subsoil samples to sorb dissolved organic carbon added from solution (Turunen and Moore, 2003). Beaver meadow soils represent a wide range of particle sizes (Johnston et al., 1995; Polvi and Wohl, 2012; Westbrook et al., 2011) that could affect their carbon retention.

Voyageurs National Park (NP) on the U.S.–Canadian border is a site of international significance for research on beaver–landscape interactions due to long-term studies of its dense beaver population (Naiman et al., 1988). My colleagues and I previously described the morphology, taxonomy, and biogeochemistry of beaver-impounded soils at Voyageurs NP, but we focused on plant nutrients and other inorganic elements rather than carbon (Johnston, 2000; Johnston et al., 1995). We showed that the area of beaver ponds and meadows increased from 1% of the landscape in 1940 to 15.1% by 1986 as the beaver population recovered from historic overtrapping. The antecedent land types flooded by beaver were mainly upland mixed forests, lowland deciduous forests, and coniferous peatlands.

The aim of this paper is to quantify the pool of soil carbon associated with beaver meadow soils, and to determine how beaver dam-building activity alters that pool. Specific objectives are to evaluate soil carbon relative to soil physical properties (bulk density, particle size) and the thickness and arrangement of master soil horizons. Potential implications to the carbon cycle of boreal landscapes are discussed.

2. Materials and methods

2.1. Site description

Soils were sampled in four beaver meadows on the Kabetogama Peninsula of Voyageurs NP, a wilderness area accessible only by boat from Kabetogama Lake (Fig. 1). The watersheds draining to the beaver meadows were 31 km^2 or less (Table 1). Three of the meadows had low-gradient inlet streams; South Clyde Creek was an impounded wetland without an inlet stream.

Voyageurs NP lies 35 km east of International Falls, MN (48°34′N, 93°23′W). International Falls' mean annual temperature and precipitation are 3.0 °C and 608 mm yr^{-1}, respectively (NOAA, 2004). Upland soils of Voyageurs NP are shallow to bedrock, with many outcrops of Early Precambrian metasedimentary and granitic bedrock (Ojakangas and Matsch, 1982). Glacial deposits covering the bedrock include sandy loam till deposited by the Vermillion phase of the Rainy Lake lobe during the Wisconsinan glaciation (12,000 yr BP), clayey glacio-lacustrine sediments deposited by the southeastern arm of Glacial Lake Agassiz, and localized sand and gravel deposits of glacio-fluvial origin (Johnston, 2000; Johnston et al., 1995). The primary upland vegetation at Voyageurs NP is Aspen–Birch/Boreal Conifer Forest (*Populus tremuloides*, *Betula papyrifera*, and *Abies balsamea*); wetland vegetation includes black spruce, tamarack, and white cedar swamps (*Picea mariana*, *Larix laricina*, and *Thuja occidentalis*) (Faber-Langendoen et al., 2007). The beaver meadows studied were dominated by grasses and sedges: *Calamagrostis canadensis*, *Scirpus cyperinus*, and *Carex lacustris* (Erickson, 1994).

Beaver impounded sites were examined on aerial photographs (1:15,840 to l:24,000) taken in 1940, 1948, 1961, 1972, 1981, 1986, and 1991. Standard aerial photo interpretation techniques (Avery, 1969; National Wetlands Inventory, 1995) were used to determine when the study sites were first impounded, their vegetation cover prior to impoundment, and their vegetation cover after abandonment.

All of the beaver impoundment soils described were in the meadow stage at the time of sampling. In subsequent sections of this manuscript, the term "impounded" signifies a soil that had been impounded by beaver, and the term "unimpounded" indicates a forest soil adjacent to a beaver meadow that was never impounded.

2.2. Soil sampling and laboratory analysis

Soil sampling was done by hand from horizon or sub-horizon of thirteen trenches at the four beaver meadows (Table 1), following the procedure of Grüneberg et al. (2010). Samples ($n = 83$) were obtained by pushing cylinders of known volume into the trench sidewall at the midpoint of each horizon or sub-horizon.

An organic soil (Haplosaprist) was also sampled, but was too wet for trenching. This soil was volumetrically sampled from an intact vertical core taken to a depth of 75 cm with a 3 by 3 cm stainless steel box corer designed for sampling organic soils with minimal compaction (Cuttle and Malcolm, 1979). The core sample was then subdivided into increments at 0–5 cm, 5–10 cm, and every 10 cm thereafter ($n = 8$ samples).

Soil samples were dried at 105 °C to determine bulk density (ρ_b) and water content (Klute, 1986). Total carbon was determined from two replicates per sample using a Leco CHN-800 elemental analyzer (LECO Corporation, St. Joseph, MI). None of the horizons sampled tested positive for inorganic carbon using HCl effervescence. Particle size distribution of mineral soil samples was determined by the hydrometer method (Gee and Bauder, 1986).

Table 1
Description of study sites on the Kabetogama Peninsula of Voyageurs NP. Stream gradient calculated over the length of the stream from headwaters to the beaver dam.

Site name	Pedons sampled	Watershed area (km^2)	Stream gradient (%)	Parent materials	Pre-impoundment vegetation
N. Clyde Creek	6	30.9	0.52	Glacio-fluvial	Aspen–birch/boreal conifer
S. Clyde Creek	4	0.3	–	Glacio-lacustrine, histic	Aspen–birch/boreal conifer, cedar swamp
Lost Pond	2	0.4	0.68	Glacio-lacustrine, histic	Aspen–birch/boreal conifer, cedar swamp
Shoepack Pond	2	15.2	0.49	Glacio-lacustrine	Aspen–birch/boreal conifer