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Soil carbon sequestration in freshwater wetlands varies across a gradient of ecological condition and by ecoregion

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ABSTRACT

We evaluated the ability of freshwater riparian wetlands along a gradient of ecological condition to act as sinks for carbon and sediment. We compared rates of carbon accretion and soil accretion across 20 wetlands in the Lake Erie Drift Plain and the Ridge and Valley ecoregions. Soil cores were collected and analyzed using ^{137}Cs dating to quantify long-term (~50 year) rates of sediment and carbon accumulation. Data on hydrology and floristic quality were used to help explain variability in rates. Sites were classified as being in low, moderate, or high ecological condition based on a rapid assessment method, which was verified by their floristic quality. Wetlands of low ecological condition (more human disturbance) had higher mean soil accretion and carbon accretion rates. Soil accretion averaged 0.24 ± 0.17 cm yr^{-1} and 0.14 ± 0.04 cm yr^{-1} in low condition sites and high condition sites, respectively. Carbon accretion averaged 88 ± 50 gC m^{-2} yr^{-1} in low condition and 65 ± 27 gC m^{-2} yr^{-1} in high condition sites. Low condition sites had lower mean soil carbon concentrations in the upper 10 cm of the soil profile, suggesting that the higher carbon burial in these sites was related to allochthonous carbon inputs in incoming sediment, rather than autochthonous carbon inputs. There were also striking rate differences between ecoregions. Erie Drift Plain wetlands had significantly higher mean soil accretion rates, compared to Ridge and Valley wetlands. These data indicate that freshwater wetlands play a role in regulating climate by acting as carbon sinks and that anthropogenic disturbance can impact rates of carbon burial.

1. Introduction

Wetlands are increasingly recognized for their ability to sequester and store large amounts of carbon, particularly in their soils. Globally, wetlands hold an estimated 530 PgC, equivalent to nearly 75% of the total atmospheric carbon (Mitsch and Gosselink, 2015). Carbon pools can make up 30–40% of soil mass in wetlands (Bridgham et al., 2006), in comparison to agricultural soils, which typically contain 0.5–2% (Lal et al., 1995). Wetland scientists have focused much of their attention on measuring carbon sequestration rates in peatlands (e.g., Gorham, 1991) and tidal salt marshes (i.e., "blue carbon", Chmura et al., 2003). In a synthesis of carbon sequestration rates from 154 tidal saline sites, Chmura et al. (2003) estimated that the average annual rate for these systems was 210 gC m^{-2} yr^{-1}. Currently, it is unclear whether freshwater riparian wetlands also act as significant carbon sinks (but, see Bernal and Mitsch, 2013). Overall, freshwater wetlands comprise a significant portion of total wetland extent, for example 95% of the total wetland area in the United States (Dahl, 1990), and so have the potential to act as globally significant carbon sinks (Nahlik and Fennessy, 2016).

Wetland loss has reduced the rate of carbon sequestration by as much as 15 million tons of carbon per year in North America (Bridgham et al., 2006). Anthropogenic disturbance and the resulting change to a wetland's ecological condition is also expected to play a role in its ability to store carbon (Bridgham et al., 2006; Nahlik and Fennessy, 2016). The 2011 National Wetland Condition Assessment (NWCA) was the first probabilistic, spatially representative national survey designed to provide estimates of human disturbance and identify the ecological condition of wetlands across the conterminous US (USEPA, 2016). Nahlik and Fennessy (2016) used this survey to estimate total carbon storage at 11.52 PgC across all wetlands in the conterminous US. There was large regional variability, and substantially lower (by more than

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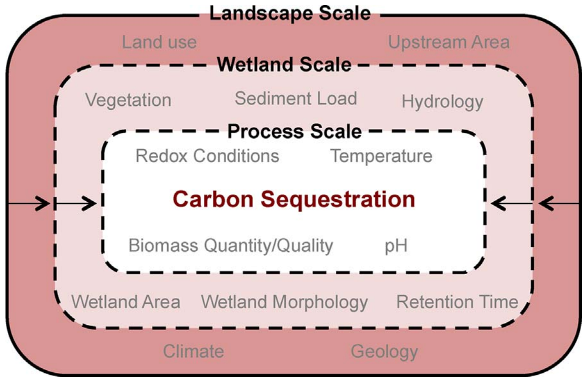

Fig. 1. Carbon sequestration is affected by proximal and distal drivers across scales of influence (i.e., process level, site level, landscape level). In this study we focus on land use (described through measures of wetland condition), sediment load, hydrologic metrics (e.g., wetness and flashiness), and floristic quality of the vegetation (modified from Trepel and Palmeri, 2002).

40%) storage in wetlands affected by anthropogenic activities (Nahlik and Fennessy, 2016). Similar reductions in soil carbon with disturbance have been shown in salt marshes (Macreadie et al., 2013). However, the mechanisms that control differences in carbon stocks across an ecological condition gradient are not well understood.

A wetland's capacity to sequester carbon is a function of factors that interact across multiple scales (Fig. 1). Landscape level controls (e.g., location, watershed size, and adjacent land use activities) affect wetland scale processes, such as water and sediment inflows, retention time, and hydroperiod. These wetland scale processes, in turn, affect plant community structure and redox conditions. Anthropogenic activities can alter controls at all scales and can elicit competing carbon sequestration responses. For example, nutrient enrichment from adjacent land use can increase primary production and lead to an increase in plant biomass and organic matter accretion (Craft and Richardson, 1993). However, hydrologic disturbances such as drainage and shortened hydroperiods tend to increase soil drying and organic carbon oxidation, resulting in the release of carbon dioxide to the atmosphere (Bridgham et al., 2006).

In this study we investigated whether or not carbon sequestration rates of freshwater riparian wetlands varied as a function of their ecological condition or location (i.e., ecoregion). We identified study sites along a gradient of ecological condition (i.e., changes in condition that result from human disturbance) in the Ridge and Valley (Pennsylvania) and Erie Drift Plain (Ohio) regions using a well-validated rapid assessment method (Mack, 2001). In addition to measures of soil carbon concentrations and carbon accretion rates, we measured wetland properties predicted to respond to human disturbance and affect soil carbon content and accretion rates. These included hydrologic metrics, sediment loading, and floristic quality. Hydrology is particularly important as a driver of ecosystem processes including sediment influx (Fennessy et al., 1994a; Wardrop and Brooks, 1998), biomass production (Fennessy et al., 1994b), and plant community structure (Ehrenfeld and Schneider, 1991). Previous studies in the region have shown that the hydrologic response of freshwater wetlands varies dramatically with the intensity and type of anthropogenic stress (for example, they may become wetter, or drier, and/or flashier; Ryan, 2005; Moon and Wardrop, 2012; Wardrop et al., 2016). We hypothesized that (1) soil carbon content (%) and carbon accretion rates would be most strongly linked to sediment loading and hydrologic metrics that measure the wetness and hydrologic flashiness of a site; (2) due to the expected high variability in hydrological regimes, lower condition wetlands would have a larger spread of carbon accretion rates compared to moderate or high condition wetlands. Further, we hypothesized that ecoregional differences, as expressed through hydrology or the pattern of land use, would lead to differences in soil and carbon accretion rates.

2. Materials and methods

2.1. Study sites

We selected 19 freshwater wetlands for assessment, including nine from the Erie Drift Plain region in northeastern Ohio, and 10 from the Ridge and Valley region in Pennsylvania (Fig. 2). The Ridge and Valley region is characterized by alternating sandstone ridges and shale or limestone valleys, which run in a northeasterly direction. Annual minimum temperatures are ~5.2 °C and maximum temperatures are ~15.0 °C, with mean annual precipitation of 100.6 cm (State College, PA, https://www.usclimatedata.com/as of 9/12/2017). Historically, the Ridge and Valley was predominately covered with temperate forests. Current land cover is still largely forested (second-growth), with relatively low agriculture land use, and little developed land (Myers et al., 2000). Anthropogenic activity is predominately located in the valleys.

The Erie Drift Plain is characterized by low lime drift and lacustrine deposits. Lakes, wetlands, and swampy streams occur where stream networks intersect or where the land is flat and clayey. Soils are often lower in carbonate and naturally less fertile than those of other glaciated ecoregions. Annual minimum temperatures are ~6.2 °C and maximum temperatures are ~15.3 °C, with mean precipitation of

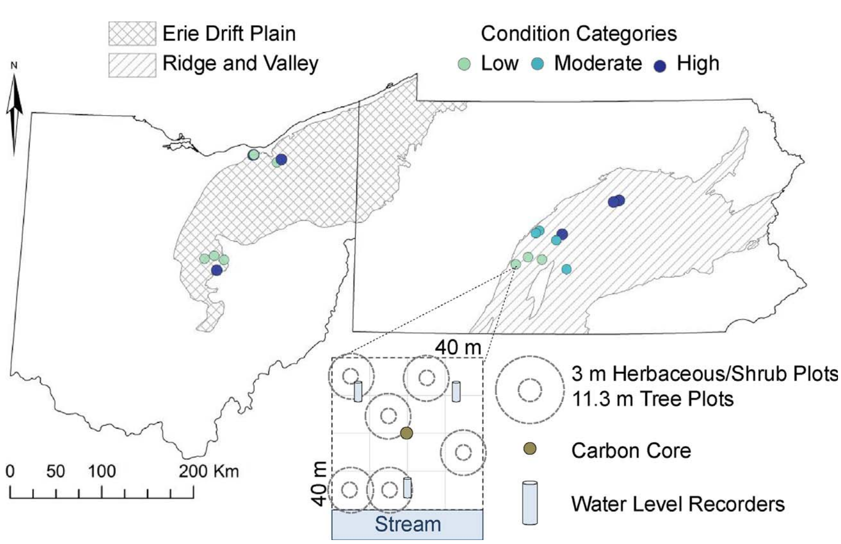

Fig. 2. Map and sampling design of wetland study sites in the Erie Drift Plain ecoregion of Ohio (n = 9) and the Ridge and Valley ecoregion of Pennsylvania (n = 10). Sites are colored by their condition category: low (light green), moderate (light blue) and high (dark blue). Condition categories were assigned based on condition categories established for use of the Ohio Rapid Assessment Method (i.e., Low = 0–45, Moderate = 45–65, and High = 65–100). At each site a carbon core was collected in the center a 1600 m^2-assessment area, and water level wells were installed in an equilateral triangle around this center. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)