DePaul Discoveries

Volume 3 | Issue 1 Article 8

2014

Quantifying the Effects of Vegetation on the Carbon Storage of Northern Great Lakes Coastal Wetlands

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Acknowledgements

I would like to acknowledge and thank both Dr. Beth A. Lawrence and Shane C. Lishawa for their advisement, dedication, and continuous support. I would like to thank the National Science Foundation and the University of Michigan Biological Station's Research Experience for Undergraduates program for funding this project. Additionally, I would like to thank DePaul University for providing the lab space and tools necessary to complete this project.

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Abstract

Given the rising concentration of carbon dioxide (CO_2) in the Earth's atmosphere, it is important to assess the natural reservoirs in which carbon can be stored. Great Lakes coastal wetlands are a potentially significant pool of carbon that have yet to be thoroughly investigated. Our study measured soil C (carbon) and depth of organic matter in swamp, transitional, and wet meadow vegetation zones of three wetlands located in the Eastern half of Michigan's Upper Peninsula, in the Les Chenaux Islands. It was hypothesized that soil C would decrease moving lakeward (swamp>transitional>wet meadow); however, this hypothesis was only supported in one of our three sites. Vegetation zones were found to influence soil C and organic depth, though the direction and strength of this influence differed depending on the site. Our data suggest that Great Lakes coastal wetlands as a whole may store a disproportionally large amount of soil C (53.2 kg/m^3) compared to average estimates of North American wetland soils (16.2 kg/m^3), warranting further investigation of the relationship between vegetation, hydrology, and soil carbon in these dynamic ecosystems.

Introduction

The combination of deforestation, biomass burning, conversion of natural habitats to agricultural uses, and CO_2 emissions from fossil fuel combustion is quickly outpacing nature's natural carbon cycle and its ability to sequester carbon through photosynthesis (SOCCR, 2007). As a result, CO_2 has been accumulating rapidly in the atmosphere (>30% increase in concentration since 1750; Lal, 2004), aiding the greenhouse effect and causing negative environmental impacts around the world (IPCC, 2005). Carbon sequestration via photosynthesis is one way in which CO_2 is removed from the atmosphere and can be subsequently stored in plants and soil. Examining and indentifying the carbon sequestration potential of natural carbon sinks is critical to prioritize CO_2 mitigation efforts. Sequestration of carbon in soils has potential to mitigate CO_2 as it is a significant pool, the third largest behind oceanic and geologic pools (Lal, 2004), and can be enhanced through ecosystem management.

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Project Completed: Winter 2014
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Wetlands, including peatlands, occupy approximately 5.3-7.8 million km^2 (only ~5% of terrestrial surface) of the earth's surface, yet store a disproportionately large (~30%) amount of soil carbon (Zelder and Kercher, 2005).

Wetland soils are the largest terrestrial pool of carbon, storing approximately 500-700 Gt globally (Kusler, 2005; Whiting and Chanton, 2001). This is due to their often semi-flooded state and steady influx of organic material (Bridgham et al., 2006). When soil is flooded, the decomposition rates of biomass are restricted due to anaerobic soil conditions, allowing more carbon to accumulate than is released through decomposition, creating a sink of carbon (Whiting and Chanton, 2001). Environmental variables, such as the type of vegetation present and water level, may strongly influence the balance between carbon accumulation and decomposition, and thus the carbon storage potential of a wetland. Wetlands in North America cover 2.42 million km^2 of land and are capable of sequestering approximately 0.049 Gt of carbon each year, demonstrating the potential of wetlands to serve as carbon sinks (Bridgham et al., 2006; Zelder and Kercher, 2005). However, there are gaps in our understanding of carbon storage and sequestration among different wetland types, even within North America.

The Laurentian Great Lakes, which consist of five large freshwater lakes located in North America, are fringed by coastal wetlands that provide an array of ecosystem services, such as delivering wildlife habitat and water purification services, but there is limited knowledge about their ability to regulate climate change through carbon storage and sequestration (Sierszen et al., 2012). These diverse ecosystems are classified into various groups based on their vegetation, hydrology, formation, location, and size, which may help characterize their carbon storage potential (Albert et al., 2005). This study quantifies the effects of vegetation on the carbon storage potential of protected embayment coastal wetlands in the Great Lakes of Northern Michigan.

Protected embayment wetlands typically have 50-100 cm of organic accumulation in their surface sediment and are exposed to the lake, but experience reduced wave action due to protection by a till or bedrock enclosed bay or other landforms (Albert et al., 2005). Four generalized wetland vegetation zones, differing in hydrology and vegetation along a lake to landward gradient, can be defined in this ecosystem, including emergent marsh, wet meadow, transitional, and swamp. Emergent marshes are characterized by non-woody vegetation and are continuously flooded with water (Maynard and Wilcox, 1997). Emergent marshes receive the most wave action from the lake, stripping away most of the organic material formed. Wet meadows, located upland of the emergent marsh, are occupied by shallower water, and are dominated by sedges and grasses (Maynard and Wilcox, 1997). Wet meadow communities are protected from wave action, allowing organic material and carbon to accumulate in their soils. Transitional zones are the areas between wet meadows and swamps, usually dominated by small trees, grasses, and shrubs. Swamp zones are defined by woody vegetation, such as trees and shrubs, and are upland of the wet meadow community, containing standing water during various times of the year (Maynard and Wilcox, 1997).

Water levels in the Great Lakes have been experiencing a low water period (USACE, 2009). Further decreases in water levels are projected in the future due to climate change, as temperature and evaporation rates increase, but precipitation decreases (Hayhoe et, al, 2010). Moderate estimates report water declines in the Great Lakes ranging from 0.25 to 0.41 meters (Angel and Kunkel, 2010), which can expose a wide band of exposed sediment along shallowly sloped lake edges. As water levels decrease, vegetation zones of wetlands are expected to move lakeward (Maynard and Wilcox, 1997). During low water phases, swamp zones are expected to expand and move lakeward, as woody vegetation tends to outcompete wet meadow grasses under drier conditions. Likewise, wet meadows are expected to shift lakeward as their vegetation is more tolerant of lower water levels than the emergent marsh (Maynard and Wilcox, 1997). Given projected future water level decline, analyzing shifts in vegetation and how carbon pools may change is important to understand how lowered water levels can affect carbon storage in this changing wetland complex.

Soil carbon storage by Great Lakes coastal wetlands has yet to be thoroughly quantified (Sierszen et al., 2012). This study investigates soil carbon storage in three northern Michigan Great Lakes protected embayment wetlands among three vegetation zones: swamp, transitional, and wet meadow. We hypothesize that due to the high biomass production of trees and protection from wave energy, swamp zones will contain more soil C than transitional zones, which will contain more soil C than wet meadow zones; therefore, soil C will decrease moving lakeward (swamp > transitional > wet meadow). Additionally, we hypothesize that organic depth will positively correlate with soil C, and will decrease towards the lake (swamp > transitional > wet meadow).

Methods

Site Selection

Three study sites were chosen based on several criteria: 1) they were protected embayment wetlands as defined by Albert et al. (2005); 2) vegetation zonation was distinct with wet meadow, transitional, and swamp zones characteristic of the northern Great Lakes; and 3) native wet meadow vegetation was dominated by *Carex stricta* and *Calamogrostis canadensis*, the most common native wet meadow graminoids (Albert et al., 1987). The three study sites chosen were Duck Bay (DB), Mackinac Bay (MB), Cedarville Bay (CB), which were all located in the Les Chenaux Islands in the eastern half of Michigan's Upper Peninsula.

Data Collection

During the summer of 2013 (July-August), two 100-meter transects were established in each wetland site perpendicular to the lake, traversing the wet meadow, transitional and swamp zones, along a hydrologic gradient from high to low water levels. Soil cores (5cm diameter, to 30cm depth) were taken every 10 meters along each transect, resulting in approximately 6-8 samples per zone per site. Soil cores typically contained both a surface horizon and underlying mineral clay or sand layers. At each point of sampling, dominant vegetative species, water level (cm), organic depth (cm) using a peat probe, and geographic coordinates using a GPS were collected and recorded (see Table 1). Within the treed transitional and swamp zones along transects at Cedarville and Duck Bay, (Mackinac Bay's swamp was inaccessible), ten tree cores were collected. Tree cores were used to estimate the age of trees by sanding down each core in the laboratory and counting the tree rings under a microscope (Speer, 2010). The diameter at breast height (DBH) and tree type were also recorded for every tree within a 10x10 meter area encompassing the sample point. Tree basal area (# trees/m^2) was then calculated for every site in which a tree core was retrieved (Table 1).

Data Analysis

To quantify soil carbon storage, soil cores were divided into surface organic and mineral sections, dried at 60°C for 36 hours, sieved through a 2mm sieve, and separated from any large roots and rocks in order to determine bulk density (g/cm^3). The samples were then homogenized using a ball grinder and carbon content (%) was quantified using a CHN analyzer (Costech Elemental). Soil C (g/cm^3) contained in the organic layer of each core was determined by incorporating bulk density estimates for the organic layer, the depth of the organic layer, and the estimates of %C for the organic layer. The amount of soil C estimated in the organic horizon was multiplied by the depth of the organic layer and then scaled to kg of organic C/m^3.

Data Statistics

To test for differences between soil C (kg/m^3) and organic depth among vegetation zones at each site, we used Analysis of Variance (ANOVA). We were unable to conduct two-way ANOVAs simultaneously testing the effects of vegetation, site, and their interaction, as our data were not balanced (no swamp data from the inaccessible Mackinaw Bay site). For significant ANOVA models ($\alpha \leq 0.05$), post-hoc comparisons among the vegetation zones were conducted using Tukey-Kramer analyses. Additionally, we tested for a positive relationship between soil organic depth and soil C using a correlation analysis. Average values are presented (± 1 SD). All statistical analyses were conducted using Microsoft Office Excel.

Results

Averaged across sites, soil C in swamp, transitional and wet meadow zones averaged 3.6 ± 1.8 kgC/ m^3, 3.0 ± 0.6 kgC/ m^3, and 3.2 ± 1.0 kgC/ m^3, respectively. However, there were no significant differences among zones (P= 0.135 F= 2.07, df= 2, 66; Fig. 1). The average soil C within Mackinac Bay, Cedarville Bay, and Duck Bay was 3.0 ± 1.3 kgC/ m^3, 3.8 ± 1.3 kgC/ m^3, and 2.9 ± 0.6 kgC/ m^3 respectively, but these did not differ among sites (P= 0.440, F =0.977, df= 2, 66).

While there was no significant variation in total soil C between vegetation zones across sites, there was variation between zones within individual sites. Both Duck Bay (P= 0.025, F= 4.49, df=2, 21; Fig. 2) and Cedarville Bay (P= 0.007, F= 6.46, df=2, 21; Fig.1) had significant differences in soil carbon storage between swamp and wet meadow zones. While Duck Bay had greater soil C in the wet meadow than the swamp, we observed the opposite trend at Cedarville Bay. Mackinac Bay did not show any variation between transitional and wet meadow zones (P= 0.276, F =1.248, df= 1, 21; Fig. 1).

While there were no significant differences in organic depths across sites, there was a significant difference observed in organic depths between vegetation zones within Duck Bay. Duck Bay had significant differences in organic depth among zones, with the wet meadow having the greatest amount of organic depth (average of 31.0cm) and the swamp having the least (average of 22.1cm) (P=0 .003, F= 7.77, df=2, 21; Fig 2). Cedarville Bay did not show significant differences among vegetation zones (P=0.059, F=3.29, df=2, 21). The organic depths across all sites were also positively correlated to the amount of estimated soil C (r=0.66). The average age of trees within the transitional zones of Duck Bay and Cedarville Bay were 13.8 ± 2.3 years and 30.0 ± 6.0 years, respectively.

Table 1. Dominant vegetation, average water depth, and average tree basal area for every vegetation zone inthe three protected embayment wetland sites in northern Michigan. Dominant vegetation species are denoted as either trees (t), shrubs (s), or graminoids (g). Water depth values are relative to the soil surface.

Site	Zone	Dominant vegetation	Water depth ± SD (cm)	Tree basal area ± SD (m^2/m^2)
Mackinac Bay	Transitional	*Larix laricina* (t); *Salix* spp. (s); *Carex* spp. (g)	<-30.00	0.05 ±0.06
	Wet meadow	*Carex* spp. (g); *Phalaris arundinacea* (g)	-25 ± 2.32	N/A
Cedarville	Swamp	*Alnus rugosa* (t); *Larix laricina* (t); moss	-3.20 ± 0.83	0.20 ± 0.19
	Transitional	*Salix* spp. (s); *Calamogrostis canadensis* (g)	-7.40 ± 1.36	0.10 ±0 .12
	Wet meadow	*Carex* spp. (g); *Calamogrostis canadensis* (g)	-8.10 ± 2.45	N/A
Duck Bay	Swamp	*Larix laricina* (t);*Thuja occidentalis* (t); moss	-2.0 ± 0.49	0.43 ± .23
	Transitional	*Carex* spp. (g); *Calamogrostis canadensis* (g)	-2.4 ± 1.12	0.02 ± .02
	Wet meadow	*Carex* spp. (g); *Calamogrostis canadensis* (g)	-1.50 ± 0.15	N/A

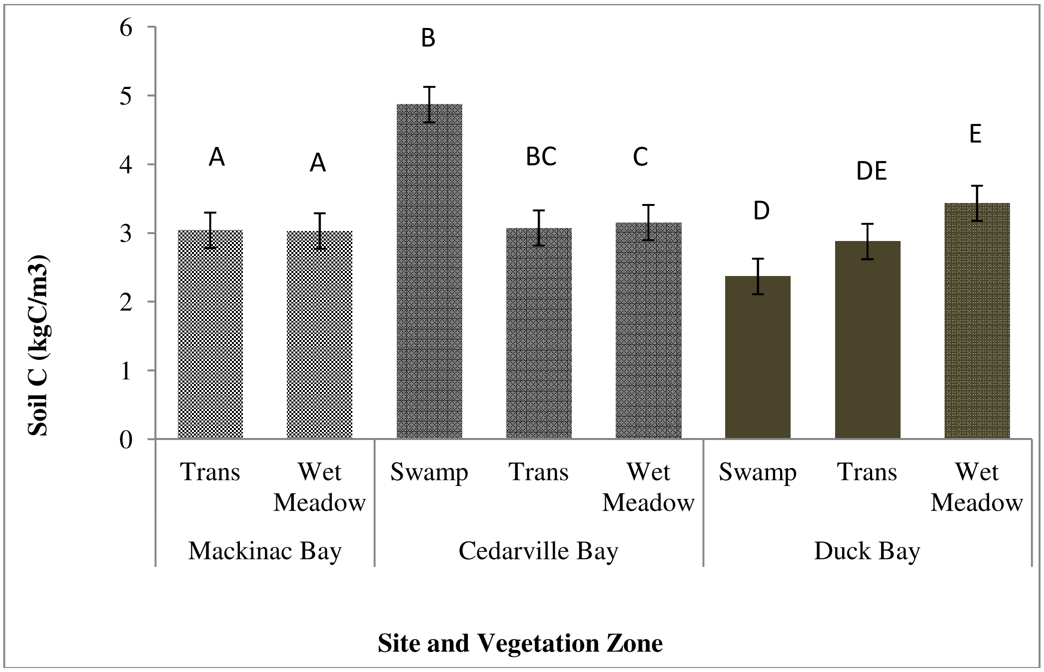

Figure 1: Average soil carbon (±1 SD) for each vegetation zone within Mackinac, Cedarville, and Duck Bay sites. There was no significant difference in soil C between the vegetation zones of Mackinac Bay, while both Cedarville and Duck Bay had significant differences in soil C. Within each site, vegetation zones that do not share a common letter differed significantly after Tukey-Kramer multiple comparisons.

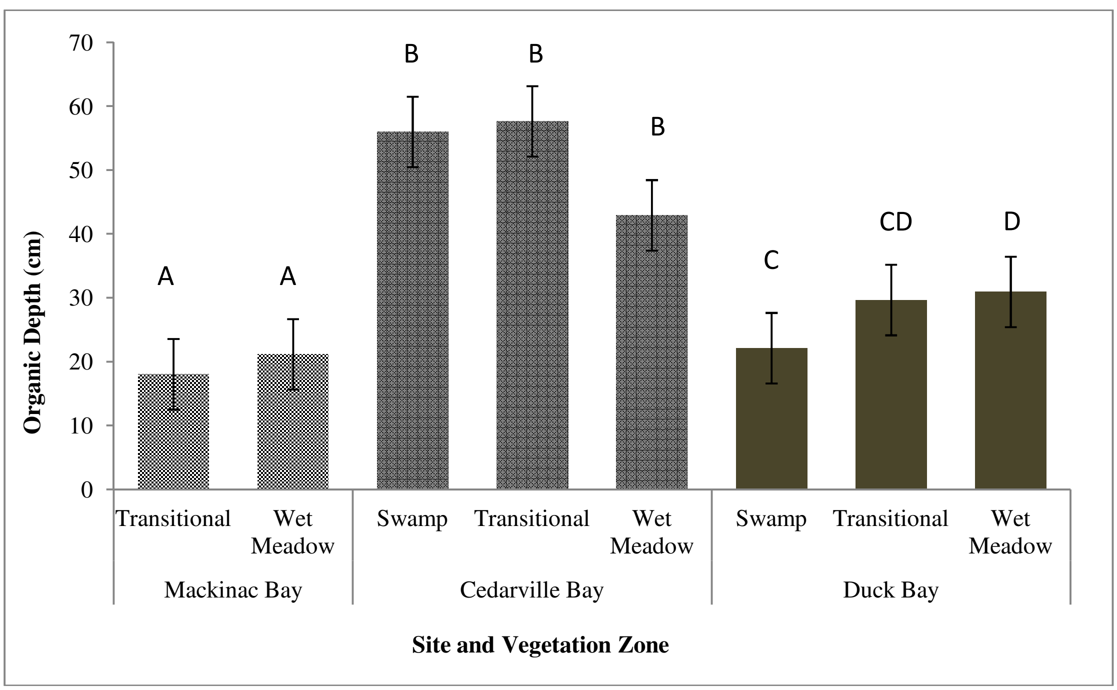

Figure 2: The average (± 1 SD) organic depth in each vegetation zone in each site. There was a significant difference in organic depth between vegetation zones in Duck Bay, while no significant differences were seen in Mackinac and Cedarville Bay. Within each site, vegetation zones that do not share a common letter differed significantly after Tukey-Kramer multiple comparisons.

Discussion

The goal of this study was to evaluate the differences in soil C storage and organic depth within wetland vegetation zones from three northern Great Lakes coastal wetlands to begin to understand the lakeward movement of Great Lakes wetlands as lake levels decrease. We initially hypothesized that both soil C and organic depth would decrease moving lakeward from the swamp to wet meadow zones. At two of the sites (Cedarville Bay and Duck Bay), we found significant differences between the swamp and wet meadow zones, suggesting that soil carbon storage is related to vegetation. However, these differences varied in their direction. At Duck Bay, soil C increased from swamp to wet meadow, along with organic depth, which contradicts our original hypothesis. This site was the most representative protected embayment wetland we sampled however, as it contained all three vegetation zones and the average age of trees in the transitional zone was approximately 14 years. The age of these trees suggest that they were established during the beginning of the most recent low water period in the Great Lakes and that vegetation zones are indeed moving lakeward as water levels decrease. In contrast, at Cedarville Bay, soil C decreased from swamp to wet meadow. This observation may be due to Cedarville being hydrologically disconnected from the surface water of the lake and having large ground water influence, particularly in the swamp. This would result in reduced decomposition rates and high organic matter accumulation in the swamp, possibly explaining the greater soil C we observed compared to the wet meadow. Trees in the transitional zone at Cedarville were relatively large (~30 years old), suggesting that they established during the high lake level period during the 1980's, which would have been unlikely given the necessity of low water levels for tree growth. This further indicates that this portion of the protected embayment is not hydrologically connected to Lake Huron, was not inundated during the period of high water levels, and therefore does not experience the same fluctuations in water levels as other hydrologically connected embayment wetlands.

While this study demonstrated that vegetation may have an effect on the carbon storage and organic depth of protected embayment wetlands, there are potentially confounding variables (eg: hydrology) across sites that mask the cause of these differences. Great Lakes coastal wetlands are dynamic ecosystems and further investigation of soil carbon relationships associated with shifting vegetation zones needs to account for surface and ground water influences. Duck Bay may be an appropriate site to further investigate the relationship between soil C and vegetation, as the vegetation zones appear to be responding strongly to shifts in recent lake level drawdowns. Future studies should also consider investigating the ecotone between wet meadow and emergent marsh habitats and the effect these shifts may have on Great Lakes coastal wetland soil C storage.

The average total soil C per cubic meter in both the organic and mineral layers in all sites was determined for comparison with current estimates of soil C for U.S wetlands. In the sites studied here, soil C averaged 53.2 kg/m^3 while the estimate for wetlands in the U.S were 16.2 kg/m^3 (Bridgham et al. 2006). This comparison suggests that Great Lake coastal wetlands may contain a disproportionally large amount of carbon compared to other wetlands, though, if true, the mechanism by which it does has yet to be clearly identified, thus requiring further study. Recent studies have suggested that freshwater wet meadows store more soil C than treed swamps, supporting the results found in Duck Bay, our most representative site (Neubauer, 2013;Wang & Dolda, 2013). Given that Great Lakes water levels are projected to continue decreasing, the effect this has on Great Lakes coastal wetlands is an important factor that should be studied (Hayhoe et, al, 2010; Sierszen et al., 2012). Based on tree establishment and the results found in Duck Bay, our most representative site, our study suggests that as water levels continue to decrease in response to climate change, vegetation zones may shift lakeward and affect soil carbon pools. Understanding how soil carbon may change based on vegetation zone movement can help to better predict the role of wetlands in carbon storage in the future.

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