Carbon Sequestration in Peatlands: Using Environmental Proxies to Understand the Impact of a Changing Climate on Global Carbon Storage

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Abstract

Peatlands are a type of terrestrial wetland ecosystem in which consistently waterlogged conditions prevent the decomposition of organic matter. These conditions allow for sequestered carbon in plant matter to remain stored in the soil to such a great degree that peatlands store more carbon than all other vegetation types in the world combined. By inhibiting decomposition, the composition of water-rich peat soil remains representative of the environmental conditions during the period in which the peat was formed. The collected peat samples can then be utilized as environmental proxies to determine historical temperature, moisture, and carbon content and extrapolated to predict the future capacity of carbon sequestration in the context of a changing climate.

The peat samples in this research were collected during the fall of 2020 in the Echo Lake Fen of Grand Mesa, Colorado, and analyzed using humification analysis to determine changes in organic content over time. This research examines over 200 cm of peat from the Echo Lake Fen, dating back over 8,000 years. Each sample was divided into smaller sections to represent shorter periods of time and tested to determine organic matter content. Results suggest that warmer climates lower the water table of a peatland and expose plant matter to oxygen, allowing plants to decay and release carbon into the atmosphere. This raises concerns about the amount of carbon that could be released into the atmosphere in the future as the climate is predicted to get hotter and drier.

Understanding that carbon, as a greenhouse gas, exacerbates already rising global temperatures and increases the rate of plant decomposition is important in predicting how the loss of peatlands would impact future climate conditions. Peat soils contain more than 600 gigatons of carbon worldwide, which represents up to 44% of all soil carbon. Thus, it is essential that efforts to preserve and restore peatlands are prioritized to minimize the amount of carbon in the atmosphere. This research serves as strong evidence for investing in peatland conservation and restoration.

Keywords: *Peat, proxy, carbon sequestration, humification, greenhouse gas, climate change*

1 INTRODUCTION

Wetland ecosystems are among the most productive ecosystems in the world. They serve as important buffers that filter water, control erosion, and protect against flooding, but their value also lies in their unique ability to preserve historical climate information. The nearly constant state of saturation in peatlands creates an anaerobic environment, meaning that the accumulated organic matter will not decompose and can be analyzed to determine the presence or absence of nutrients over time. Peatlands are a specific type of wetland that is comprised of partially decomposed organic matter and a large percentage of water. The lower layers of peat lack sufficient dissolved oxygen to fully decompose, meaning that dead plants continue to store carbon in their roots. For this reason, peatlands can be used as environmental proxies to understand the relationship between climate and carbon storage during different historical periods. Radiocarbon dating determines the age of the peat samples, and readily available research into historical temperatures aids in depicting the climate during which peat accumulated. This research adds to that depiction by determining moisture/levels or precipitation, as well as carbon content. Determining how much carbon was stored in the soil during intervals of peat accumulation serves as a prediction for how changing climate conditions may result in net carbon storage or loss in peatlands.

The peatlands of Grand Mesa, Colorado, are especially effective proxies because of their unique isolation from outside inputs, lacking direct access to navigable bodies of water. These peatlands can then be studied using loss of ignition tests and humification analysis to determine exactly how much carbon was stored during different climate conditions. Loss of ignition (LOI) testing is a process used to measure the weight of a soil sample before and after burning away its organic matter, which determines the carbon content. Humification analysis is a technique that measures the relative degree of decomposition (or humification) of the peat, representing the degree of moisture in a sample. Oxidation accelerates humification of organic matter, so humification analysis provides a method to determine when a section of peat experienced dry/aerobic conditions. Comparing the humification of several sections of the same core, we can measure the fluctuations in the water table of a fen over time. LOI tests and humification analysis can be used to create a timeline of carbon storage as it compares to temperature and precipitation. These results can then be extrapolated to make predictions about the impact of a changing climate on the rate/amount of carbon released into the atmosphere.

The samples in this research were taken from what is considered a "high elevation fen," a type of peatland at an elevation higher than 3,000 m. Previous research has shown that fens in Colorado situated above 3,000 m preserve a record of Holocene climate fluctuations and responded to changes in past summer temperatures with changes in the rates of peat accumulation. During warmer summers, these fens accumulated peat faster than during cooler intervals, suggesting that these peatlands stored more carbon during these warmer periods. However, humification data in this research indicates that, while the rate of peat accumulation was greater, the peat was also more humified or decomposed. This research expands on current knowledge of peatlands by closely examining carbon sequestration in high elevation peatlands and presents an alternate relationship between peat accumulation and carbon storage.

2 BACKGROUND INFORMATION

2.1 Peatland Formation and Classification

Peat forms through the accumulation of organic matter and is preserved in the anaerobic environment of a consistently high water table, preventing decomposition. In its natural state, peat is 88-97% water, 2-10% dry matter, and 1-7% gas, with 65% of all partially decomposed material being organic matter[1]. The botanical composition and state of decomposition are the most important characteristics for categorizing a peatland; particularly, the plant communities dictate the source of decaying matter in the peat.

There are four broad categories of plants used in peat classification: moss, herbaceous plants, wood, and detrital or humified peat, in which the bulk of the plant is no longer identifiable. Classifying peatlands is important because the rate of growth or decay will be dependent on the plant genera, which can include trees, mosses, heathers, and grasses. Vegetation like *Sphagnum* mosses are more resistant to decomposition than vascular plants are.

Sphagnum mosses are the keystone species in peatland ecosystems and can be credited for many of this ecosystem's unique characteristics[2]. These mosses are made of ordinary cells that photosynthesize and cells whose pores absorb water and can release stored water during times of drought to keep the bog or fen moist. The high water retention capacity of *Sphagnum* mosses allows for the persistence of wet surface conditions, which, among other benefits, prevent deep burning during forest fires and consequently limit the amount of carbon transferred from plant roots to the atmosphere[3]. *Sphagnum* moss grows at a rate of 2–12 cm each year, and once it dies, it will accumulate at the bottom of a fen or bog, gradually forming peat. As long as the underground dead zone of *sphagnum* remains below the water table, it will continue to hold carbon dioxide (CO_2) and methane (CH_4). Under the general anaerobic conditions of a peatland, peat accumulates through two slightly different processes known as *terrestrialization* or *paludification*. Terrestrialization occurs when peat accumulates over open water systems either at the bottom of the lake from dead biomass or in floating mats on the lake's surface[4]. Paludification is different in that the peat accumulates directly over previously dry mineral soil that has become waterlogged due to changing environmental conditions. Through the process of paludification, the fens of the southern Rocky Mountains accumulate organic matter at a rate of 8-30 cm every 1000 years[5].

Peatlands are divided into two layers based on the presence or absence of oxygen, but the boundary between the two is more continuous than distinctive. The upper layer is known as the *acrotelm* and is the layer near the surface of the peat in which oxygen is rich, water is absent, and decomposition occurs. Below the *acrotelm* is the *catotelm* which encompasses the deeper, oxygen-poor, and waterlogged layers of peat in which decomposition is halted. Low oxygen content and waterlogging are key factors required for peatlands to form, but the source of that water determines whether the peatland is a fen or a bog.

Bogs are *ombrotrophic*, meaning they receive all their water and nutrients from the atmosphere, creating conditions that are more acidic and lower in plant nutrients. Fens are *minerotrophic*, meaning they receive outside inputs from groundwater or surface runoff. Because of this, fens are more alkaline and nutrient-rich than bogs and are influenced by the surrounding rocks and soils through which the water flows. A higher pH value corresponds with a greater abundance of plant species that will one day contribute to further peat formation.

Peat soils, also called organic soils, have a number of distinguishing properties that make them different from mineral soils. Organic soils have large organic matter content, low bulk density, large pore density, and large water storage capacity[4]. By definition, such soils contain more than 15% carbon (C), but that number often exceeds 50%. Having such a large organic content means that these soils will have a low bulk density, ranging from 0.01 to 0.2 g/cm^{-3}, increasing naturally and in direct correlation with mineral content. Less decomposed organic matter can hold more water because of the larger pore space and greater presence of Sphagnum mosses compared to strongly decomposed organic matter. In peat soils, the water content at saturated conditions can range from 86% to 94%, and undecomposed peat can hold up to 20-30 times its own weight in water[4]. This high water content makes peat soils softer and more susceptible to instability but aids in their ability to store climate data. The presence of water necessarily leads to a loss of oxygen and therefore limits decomposition.

2.2 Where Peatlands are Found

Peatlands are found in every climate zone on the planet and cover about 3% of the Earth's surface[6]. The majority of peatlands are located in Asia and North America, although they are formed under different conditions. In the boreal temperature regions of the northern hemisphere, peatlands are formed under high precipitation and low-temperature conditions, whereas the humid tropics necessitated formation under high precipitation and high-temperature conditions[6]. Regardless of the climate, peatlands serve as major carbon reservoirs and are an important component of the global carbon cycle.

Peat is formed when the rate of biomass accumulation is greater than that of decay, a process that is most conducive to climates that are cold and/or saturated with water[4]. Peatlands are most common in the subarctic and boreal regions of the Great Lakes and Rocky Mountains of North America. In mountain regions, cold temperatures and orographic precipitation lead to increased water availability, subsequently encouraging the formation of organic soils on mountain slopes.

2.3 Benefits of Peatlands

2.3.1 Carbon Storage

Peatlands are uniquely equipped to store carbon in the soil because of their slow rate of decomposition. Peatlands capture CO_2 from the atmosphere through photosynthesis and store it in the soil, but because of the wet conditions, plants do not decompose and release that carbon in the same way that plants in aerobic environments would. By storing carbon, peatlands provide a net-cooling effect and help to mitigate rising global temperatures. While peatlands comprise only about 3% of global land cover, they store one-third of all soil carbon. It is estimated that, in the Northern Hemisphere, peatlands store between 733 and 1650 billion metric tons of CO_2 and in North America, carbon accumulates in peat at a rate of 7 to 300 g/m^2 per year[7].

The capacity for carbon storage in peat deposits has historically been overlooked. When carbon content is measured in forested peatlands, research methods typically focus on understanding aboveground forest components. However, in a study of forested peatlands in the boreal biome of Canada, researchers found that peat carbon stocks were significantly higher than those of aboveground and belowground tree biomass. Even when measured during the short-term historical timeframe of the last ~200 years, peat deposits were shown to contain 4 to 25 times more carbon than the tree components[3]. These findings are significant because they reframe the potential of an ecosystem that was previously thought to be unproductive. Due to their open canopy structure and low stem density, boreal forests (including forested peatlands) were believed to store low amounts of carbon, impacting their degree of conservation priority. While reforestation is an important practice for restoring habitat and increasing the rate of carbon sequestration, such practices can be expensive, and the impact of rising atmospheric CO_2 concentration has been shown not to affect tree growth[3]. For this reason, focusing on restoring and protecting existing peatlands will be essential to reaching climate mitigation goals.

2.3.2 Ecosystem Services

In their natural wet state, peatlands are able to provide a number of invaluable services to humans and the surrounding ecosystems. Vegetation filters pollutants and particulate matter, improving water quality and serving as an effective water catchment/retention system. These characteristics make peatlands excellent buffer zones capable of regulating water flows and lowering the risk of early snowmelt flooding or drought. The upper layer of peat, or the "peat blanket" on the surface, protects underlying soils from wind and water erosion and supports soil formation.

Wet peatlands lower ambient temperatures in surrounding areas, making them less likely to burn during wildfires. By offering a refuge from extreme heat, these wetlands provide habitat for unique plants and animals. The biodiversity of a peatland is essential for maintaining a balanced ecosystem and supports all the other services a peatland provides. This includes the cultural services associated with the recreational and aesthetic use of peatlands and the educational opportunities they provide. Preserved peatlands serve as accurate environmental proxies to learn and teach about historical climate conditions.

2.4 Peatland Destruction

2.4.1 Conversion to Agricultural Land

The use of organic soils varies greatly with their properties, but fens and bogs are most often used for agriculture and forestry. Worldwide, about 25% of all peatlands have been destroyed or degraded anthropogenically, with a rate of further degradation of about 1% annually[4]. Agriculture is responsible for 50% of degradation and use, while 30% of peatlands have been anthropogenically afforested. To be utilized for grazing or crop production, fens must be drained and often fertilized, destroying their ability to capture and store carbon. Instead, they release that carbon into the atmosphere. Drained peat will dry and shrink, promoting oxidative decay of organic material as well as wind and water erosion. Consequently, several meters of peat soil can be lost within a few decades of sustained drainage[4]. Strongly decomposed peat under agricultural use has low available water content, meaning that plant-available water is lower and crops are more susceptible to drought than in less decomposed peat.

2.5 Drainage

Artificial drainage creates an aerobic environment that enhances decomposition and, through a process known as *earthification*, will eventually transform a peatland into a disintegrated, crumbly powder that easily erodes in the wind. This process only occurs through heavy, anthropogenic use with deep drainage[4]. Managed peatlands often have an underdeveloped or missing upper layer due to human alteration, impacting the environmental services offered by healthy peatlands. In a study focusing on fens in Grand Mesa, Colorado, in 2015, 294 ha of the 374 ha studied (79%) had been impacted by human activities that left them with very little restoration potential[5].

The draining of peatlands using ditches is one of the most common human disturbances to peatlands in the world and has been occurring in the Rocky Mountains for more than a century. Research in the upper 15 cm of peat of four drained Colorado fens indicated losses of 14.7–91.0 tons of organic matter within the last 20 years. The extent of hydrologic impacts on Grand Mesa is considered highly unusual for a high elevation region and has become one of the most impacted high mountain regions in the U.S.[5].

2.5.1 Greenhouse Gas Emissions/Climate Change

The anthropogenic use of peatlands has a great impact on greenhouse gas (GHG) emissions; once the drained peat is no longer able to store carbon, it must release it into the atmosphere. Degraded peatlands are responsible for 25% of global CO_2 emissions from the land use sector and for 75% of the GHG emissions from agricultural land in the European Union[8]. The rate of GHG emissions depends on the trophic conditions and what the peatland is being used for, including the degree of water saturation, climate, and nutrient status. Croplands, for example, emit 29.0 t CO_2 ha^{-1} a^{-1} on average, while afforested peatlands emit between 0.9 and 9.5 t CO_2/ha. And because temperature so strongly influences decomposition, tropical peatlands generally have a higher rate of CO_2 emissions than peatlands in boreal or temperate regions[4].

There are two general pathways of carbon loss: on-site and off-site emissions. On-site emissions include gaseous fluxes that occur when the water table is lowered, when organic matter is exposed to oxygen, and when CO_2 is released as a byproduct of soil respiration. Off-site emissions involve waterborne fluxes and/or biomass removals that can be converted to gaseous fluxes at a later state[8]. This primarily consists of dissolved organic carbon (DOC) from drainage waters and erosional losses of particulate organic carbon (POC). Healthy peatlands serve as a long-term carbon sink and have had a net cooling effect on the climate for the last 10,000 years[9]. While rewetting peatlands may cause a short-term increase in CH_4 emissions, this does not offset the benefits of reducing oxidative carbon losses and enhanced long-term CO_2 storage. This is especially true if peatland rewetting/restoration encourages the re-establishment of *Sphagnum* moss species, which can reduce CH_4 emissions from waterlogged peat[8].

The correlation between atmospheric CO_2 concentrations and global temperature is well established, and rising temperatures come with a myriad of effects. Increased atmospheric temperatures lead to increased ocean and freshwater temperatures, fewer frost-free days, sea level rise, shrinking glaciers, and more variable weather patterns[7]. These changing conditions consequently have an impact on human health and safety, water supply, agriculture, energy needs, infrastructure, and recreation.

3 MATERIALS AND METHODS

3.1 Sample Area

Peat cores were collected from the Echo Lake Fen (ELF) located on the east slope of the Colorado Front Range in the fall of 2020. The Colorado Front Range is the easternmost range of mountains within the Southern Rocky Mountains and is marked by steeply dipping sedimentary layers that mark contact with the Great Plains[10]. The Front Range is about 300 km long, extending from the Arkansas River to the south to the Colorado-Wyoming border to the north. Throughout this region, the topography is rugged and steep, with broad glaciated valleys that are most prominent over 2800 feet[11].

The Front Range is a faulted anticline that was uplifted during the Laramide Orogeny nearly 70 million years ago. The core is primarily made of metamorphic and granite rocks, with permanent snowfields supplying water to the Colorado, North Platte, South Platte, and Arkansas River systems. The climate on the Front Range is classified as highland continental, meaning there are short, cool summers, long, cold winters, and relatively dry conditions year-round[12]. Changes in the average temperature and precipitation occur with increased elevation, in which higher elevations generally correspond with decreased temperatures and increased precipitation. The overall climate is controlled by latitude, elevation, air mass trajectories, and continentality[10].

Echo Lake is located about 15 km south of Idaho Springs, Colorado, at an elevation of 3230 m. The lake itself is within an unglaciated basin about 300 m below the treeline and surrounded by coniferous forest to the north, south, west, and the fen occupying the land east of the lake[10]. Echo Lake was formed during the late Pleistocene after a lateral moraine dammed a small side-valley tributary. Radiocarbon dating of the lake sediments indicates that the lake was formed at least 18,500 years ago. This makes Echo Lake the oldest known lake in the Front Range.

The lake level is believed to be maintained by groundwater flow from the meadow east of the lake and by direct inflow of surface runoff and precipitation. The age of the lake and its relative geographic isolation make the ELF an excellent location to reconstruct a paleoenvironmental timeline. As opposed to younger lakes on the Front Range that occupy glacial basins after the ice retreated, Echo Lake offers a continuous climate record that extends back to the Pleistocene.

3.2 Sediment Coring

The cores were taken from the ELF during the fall of 2020. Using a piston-equipped corer, several cores of about 30-40 cm were retrieved from the fen and stored for later analysis. Each core was wrapped in plastic wrap and aluminum foil and placed in a PVC pipe for protection. The cores were briefly described in the field by observing changes in color or the presence of large pieces of organic matter. The cores were labeled to mark the fen they were retrieved from, the year, sample number, and depth of the core. All collected samples were transported back to the University of Denver for later analysis in a laboratory setting.

3.3 Humification Analysis

3.3.1 Bulk Density

Each core was divided into 1 cm increments by length, and 3 cm^3 of each division were collected and placed into a separate crucible to determine bulk density. Bulk density was measured by drying the sample in the oven at 100°C for a minimum of three hours to evaporate water from the samples. The resulting weight was then subtracted from the initial weight of the crucible. This gives the dry weight of the sample. The dry weight (DW) is then divided by the sample volume (V), which gives the bulk density (D_b) of the sample in g/cm^3.

$$D_b = \frac{DW}{V} \tag{1}$$

Bulk density is the dry weight of soil per unit volume of soil and is used to determine the amount of mineral material in the peat sample. It is likely that much of the mineral matter in a peat sample was delivered to the fen by eolian processes or large flooding events because of the very slow rate at which water flows through peat[13]. The bulk density is influenced by several factors including temperature/length of the growing season, moisture, nutrients, and rates of decomposition in the soil. This metric can be used to determine the infiltration, water availability, soil porosity, and rooting/depth restriction. A higher bulk density is reflective of a decrease in the ability of soil to shrink and conduct water and indicates that the soil is more rocky or sandy rather than fine-like clay and silt. There is also evidence that decreased organic carbon in the soil increased the bulk density[14].

3.3.2 Organic Content

After finding the dry weight, 0.2 g of dry peat was measured out of each sample and ground into a fine powder using an agate pestle and mortar. Each sample was done separately, using clean and dry equipment to prevent cross-contamination of samples. The new samples were then put into a 200 ml beaker used in later steps to determine humification. The remaining peat samples in each crucible were then placed in the drying oven at 100°C for 1 hour, cooled to room temperature in a desiccator, and weighed to provide "organic content 1" (OC1). This step is necessary because the samples may have absorbed moisture during the previous step and must be re-dried.

After being re-dried and weighed, the samples were placed in a furnace at 550°C for at least 4 hours to combust all organic matter. After at least 4 hours, the crucibles were removed from the furnace and placed in the desiccator to cool to room temperature. Each sample was then weighed again, and the weight is recorded as "organic content 2" (OC2). The following equations utilize the previous data to determine organic matter content.

$$\frac{OC1\ weight - OC2\ weight}{OC1\ weight} = \\ Organic\ matter\ content(\%)$$

$$Bulk\ density \times Organic\ matter\ content = \\ Ash\text{-}free\ bulk\ density\ (g/cm^3)$$

These steps are used to determine loss of ignition (LOI), which is the weight change of a sample after it has been heated to a high temperature, causing some of its content to burn or to volatilize. This process is used in inorganic analytical chemistry and soil science, particularly in the analysis of minerals and the chemical makeup of soil. LOI tests consist of heating a sample of the material (peat soil) at a specified temperature, allowing volatile substances to escape until its mass ceases to change. LOI can be used as a relative paleotemperature proxy and depending on the temperature at which the sample is heated, this process can measure water, organics, or inorganic degradation.

3.3.3 Humification

Using the 0.2 g of each sample from the previous steps, 100 ml of 8% NaOH solution was added to each labeled sample beaker using a 100 ml graduated cylinder. The beakers were then placed on a hotplate at 100°C and left to simmer for one hour, occasionally topped to 100 ml with deionized water to prevent drying out and to ensure the solutions do not become too concentrated. After one hour, the contents of each beaker were poured into separate 200 ml volumetric flasks, topped to the 200 ml mark with deionized water, and shaken. Each sample was filtered into a 50 ml volumetric flask using a funnel and Whatman No. 1 grade paper. The filtrate from each 50 ml volumetric flasks were then decanted into a 100 ml volumetric flask, topped to the 100 ml mark with deionized water, and shaken. The samples were measured using a spectrophotometer to determine the percentage of transmissivity. Transmissivity measures the amount of light that passes through a sample, with high transmissivity indicating that little to no light was absorbed as it passed through the sample. When the water table in a peatland is high, conditions are wet, and the peat is less humified/better preserved. These conditions support a high percent transmissivity, while a more humified section of peat would have a lower percentage of transmissivity. The spectrophotometer was set to 540 nm and zeroed using a 10 ml cuvette of deionized water before measuring each sample. Using a pipette, 10 ml of each sample is measured into a separate cuvette and placed into the spectrophotometer. The spectrophotometer reading will fluctuate slightly so three readings from each sample are taken, and two cuvettes are tested for each 200 ml sample of solution. The final data sheet should have six transmissivity readings for each sample. The corrected percent transmissivity is calculated by dividing the average transmissivity by the percent of organic matter for each sample.

3.4 Calculating the Accumulation of Organic Carbon

The rate of peat accumulation has been extrapolated from the radiocarbon chronology of a peat core from the Echo Lake Fen. Ten radiocarbon dates were obtained on the core. These were used to calculate the average accumulation rate through time intervals identified as the Little Ice Age (LIA), 8200-year event (8.2 ka), Holocene Climatic Optimum (HCO), and Medieval Climate Anomaly (MCA). The LIA and 8.2 ka events were periods of cooler temperatures, while the MCA and HCO were periods of warmer temperatures. Multiplying the mean density by the mean % organics for each interval gives the average organic mass per cubic centimeter sample, as shown in Table 1. The average organic mass per cubic centimeter sample is then multiplied by the average peat accumulation rate during that climate event to yield the grams of carbon/cm^2/yr for each interval, as shown in Table 2. Organic matter accumulation is representative of temperature conditions, with higher organic matter content correlating to warmer conditions because the growing period is longer and there is more opportunity for organic matter to accumulate.

4 RESULTS

By the end of the study, ~75 cm of peat had been sampled and analyzed to determine the average percent transmissivity and the percent organic matter in the samples. The high elevation Echo Lake Fen shows increased organic content during warm periods. Average percent transmissivity represents the relative degree of precipitation. High transmissivity indicates wet conditions in which the water table is high, and the peat is less humified/better preserved. Used in tandem, transmissivity and organic matter can be used to track changes in climate and carbon sequestration through history.

5 DISCUSSION

Studying peat from the Echo Lake Fen allows us to build a timeline of climate conditions as far back as ~8,000 years. Echo Lake is the oldest known lake in the Rocky Mountains, and the surrounding fen is dominated by wet, anoxic conditions that preserve environmental proxies like pollen and plant matter. These characteristics make the ELF uniquely equipped to store

Depth	Interval	Mean Density	Mean Percent Organics	Organic Mass
14–21 cm	Little Ice Age	0.45 g/cm^3	50%	0.225 g/cm^3
186–187 cm	8.2 ka event	0.95 g/cm^3	35%	0.33 g/cm^3
33–39 cm	MCA	0.32 g/cm^3	62%	0.20 g/cm^3
196–212 cm	HCO	0.57 g/cm^3	49%	0.28 g/cm^3

Table 1 Four sections of peat coinciding with four major historical climate events and their mean density, mean percent organics, and organic mass.

Interval	Organic Mass	Average Accumulation Rate	$gG/cm^2/yr$
Little Ice Age	0.225 g/cm^3	0.033 cm/yr	0.0074$gC/cm^2/yr$
8.2 ka event	0.33 g/cm^3	0.02 cm/yr	0.0066 $gC/cm^2/yr$
MCA	0.22 g/cm^3	0.025 cm/yr	0.0055 $gC/cm^2/yr$
HCO	0.28 g/cm^3	0.02 cm/yr	0.0056 $gC/cm^2/yr$

Table 2 The average accumulation rates in cm/yr for each interval were multiplied by the organic mass (g/cm^3) to yield the grams of carbon/cm^2/yr for each interval.

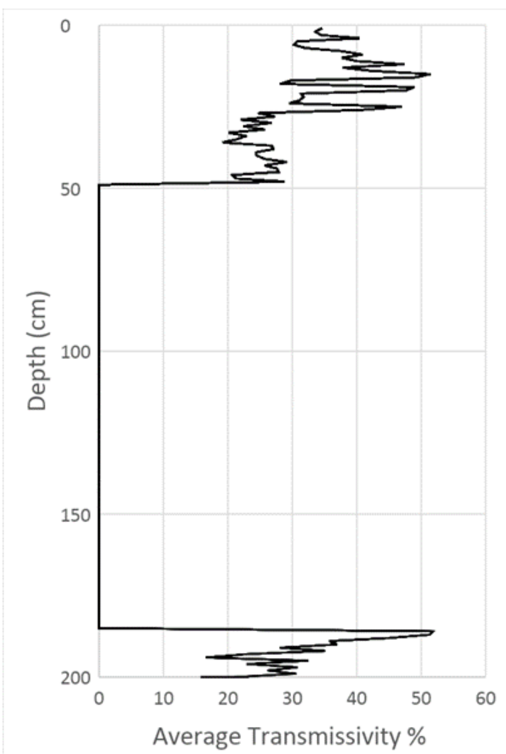

Figure 1. Average transmissivity percentage from 0-50 cm and 186-212 cm depth. The first major increase in transmissivity occurred during the Little Ice Age (1303-1850), followed by a decrease in transmissivity during the medieval climate anomaly (950-1250).

evidence of historical climates and warrant continued investigation. Using the loss of ignition (LOI) data as a proxy for temperature and the humification data as a proxy for paleo-moisture conditions, we can model the relationship between temperature, moisture, peat accumulation, and carbon storage capacity.

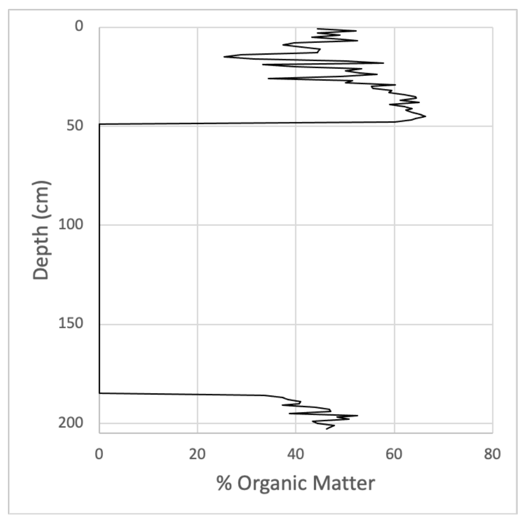

Figure 2. Percent organic matter from 0-50 cm and 186-212 cm depth. The first major decrease in organic matter occurred during the Little Ice Age (1303-1850), followed by an increase in organics during the medieval climate anomaly (950-1250). At 186 cm depth the % organics show a slight decrease, marking what is known as the 8200-year event.

Periods of high transmissivity in Figure 1 indicate wetter conditions or greater precipitation. While Figure 1 accounts for precipitation, Figure 2 serves as a proxy for temperature. When comparing the two graphs, periods of high transmissivity consistently coincide with periods of low organic content. Generally, the combination of high organic matter under wet conditions prevents the decomposition of plant matter and instead sequesters the carbon stored in plant roots into the peat. But to understand how the rate of peat accumulation compares to the amount of organic carbon stored in the soil, calculations relating to bulk density, percent organic content, and peat accumulation rates must be included.

Tables 1 and 2 show that the rate of peat accumulation was greater during periods of warm and dry conditions, but the peat was also more humified or decomposed. This is likely due to the greater amount of evaporation occurring during the warm intervals, which lowered the water table, increasing the exposure of peat in the *acrotelm* to oxidation.

These results suggest that more carbon is stored per cm^2/yr during cooler intervals than during warmer intervals, as much as 30% more. In other words, while rates of peat accumulation are greater during warmer summers, there is less carbon stored per cm^2 due to increased humification of the peat during these times.

When the climate is dry, peatland water tables are lowered and dead organic matter is exposed to oxygen, undergoing decomposition. Through this process, carbon previously sequestered in plant roots is released into the atmosphere as CO_2. The rate at which partially decomposed matter in the *acrotelm* is deposited into the *catotelm* is a large determining factor in how much carbon is stored at a given site[15]. While warmer conditions may encourage plant growth in some instances, these results suggest that high peat accumulation should not automatically be associated with greater organic carbon storage.

These results must be viewed as preliminary. While the data are compelling, more sampling and better chronological control are needed. However, if these results are supported by future work, the implications are great. With continued warming forecast by nearly all Global Climate Models for the western U.S., these results suggest that peatlands will become less efficient as carbon sinks in the future.

5.1 Peatland Degradation and Climate Change in the Future

These results have important consequences as the climate is predicted to become warmer and drier, and the increase of CO_2 in the atmosphere will compound the effects of climate change. For example, recent warming at high latitudes has accelerated permafrost thaw in northern peatlands. The presence of permafrost has been instrumental in the long-term accumulation of carbon in northern peatlands by slowing rates of microbial decomposition. In a study looking at peatland permafrost thawing in western Alaska, researchers found that, upon thaw, carbon loss in the peatlands was equivalent to ~30% of the initial forest carbon stock[16]. Their models indicate that permafrost thaw shifted these peatlands from a carbon sink to a carbon source for a decade after the thaw. At this point, carbon was again stored as more peat accumulated. Still, this process of regaining pre-thaw levels of carbon storage can take multiple centuries to reach (depending on the amount of carbon accumulated prior to the thaw). These researchers concluded that the loss of sporadic and discontinuous permafrost by 2100 could result in a loss of 24 Pg of carbon.

The positive feedback loop of released carbon, resulting in more warming, changes the wildfire regimes, and low precipitation/drought conditions make peatlands more susceptible to burning. In an undisturbed peatland, most of the stored carbon is protected by waterlogged, anoxic conditions, which cannot be burned by fire. However, drying as a result of climate change and human activity lowers the water table of peatlands, exposing partially decayed plant matter to oxygen and initiating decomposition[17]. Having greater quantities of dried peat in the *acrotelm* increases the presence of fuel for wildfires, which come with their own collection of ecosystem impacts. Specifically, fire in boreal peatlands initiates plant successional change, increases soil temperature, and increases nutrient availability.

Researchers have found that from an atmospheric point of view, low-intensity fires in an undisturbed peatland are likely to be CO_2-neutral because the released carbon will quickly be sequestered by recovering vegetation[17]. However, a longer, smoldering fire will transfer heat deep into the soil and increase the intensity of the burn. Fires like this increase damage to sensitive plant roots and microorganisms like ectomycorrhizal fungi or bacteria and release carbon that may have been stored in the soil for centuries. At this point, the peatland would no longer be CO_2-neutral but a source of atmospheric CO_2.

5.2 Rewetting and Restoration

Because drained peatlands are a significant source of greenhouse gas emissions, rewetting and restoring these soils is considered a critical climate change mitigation strategy. Researchers in Northeast Germany studied the long-term presence of greenhouse gasses in drained versus rewetted peatlands and found that rewetting reduced CO_2 emissions in unvegetated areas by 50%[18]. Rewetting is defined by the International Panel on Climate Change as "the deliberate action of raising the water table on drained soils to re-establish water saturated conditions[19]". This can include a wide variety of management strategies that are highly site-specific such as drain-blocking, bund construction, and peatland landscaping.

There is a large amount of variability in the impact of rewetting on peatlands that depends on factors like climate, peat type, nutrient availability, hydrology, vegetation, and human interaction. Variation in and exposure to weather inputs directly affect internal peatland functioning, and in some circumstances, drained peatlands have been so impaired that their original properties cannot be restored. Researchers suggest that restoration efforts should focus primarily on reestablishing hydrological conditions and vegetation similar to an intact system to have the best chance at rebuilding the carbon sink. While rewetting sites have been more sensitive to interannual changes in weather conditions than their undisturbed counterparts, rewetting is currently the most effective peatland restoration effort with regard to increasing carbon sequestration[18].

One way to encourage rewetting while still allowing for land use of peatlands is through paludiculture. Paludiculture is the practice of wet agriculture and forestry on peatlands, primarily crop production. Rather than draining wetlands as conventional farming would do, paludiculture focuses on preserving and/or restoring peatlands while simultaneously utilizing the produced biomass. The goal of paludiculture is minimal peat disturbance, meaning that the water table needs to remain near surface level to keep the peat saturated, and ploughing or harvesting below-ground biomass is prohibited[20].

6 CONCLUSION

Peatlands function as excellent environmental proxies and can be used to determine historical climate information. When compared to their known radiocarbon dates, the data collected from the Echo Lake Fen samples are able to track historical climate events as far back as ~8200 years ago. Aside from holding historical data that serves as an important educational resource, peatlands provide invaluable environmental services. Vegetation filters pollutants, improves water quality, and provides a buffer zone capable of regulating water flow and lowering the risk of snowmelt flooding or drought. Wet peatlands lower the ambient temperatures and provide habitat for many endangered plants and animals; also, they function as one of the most productive ecosystems in the world in terms of carbon sequestration.

Changing climate conditions at the Echo Lake Fen are predicted to have negative impacts on the ability to store carbon, especially with the newest findings in our data. The data suggests that warmer temperatures (despite accumulating more peat) lose more carbon than during cold conditions. Looking to the future, this means that predicted rising temperatures will result in a greater loss of stored carbon. Further research of high elevation fens and the changing carbon levels in peatlands will be necessary for understanding how rising temperatures will impact the global balance of CO_2 in the atmosphere.

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8 EDITOR'S NOTES

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