

RESEARCH LETTER

Carbon dioxide emissions in relation to water table in a restored fen

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Abstract

Many peatlands have been drained for anthropogenic purposes, and there is high interest in restoring them for their carbon storage ability and critical habitat. Peatlands hold a disproportionate amount of global soil carbon, making peatland restoration a promising approach for mitigating carbon emissions. In this study, site factors were investigated that affect peat carbon dioxide flux at Cold Spring fen in Minnesota, which is undergoing restoration. Peat carbon dioxide flux and water table depth were monitored throughout the growing season at two locations previously disturbed to different degrees by row-crop agriculture. Flux ranged from 0.55 to 12.71 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and was highest during peak growing season. Lower flux corresponded to elevated water table conditions. The more disturbed location often had lower flux, indicating success in hydrological restoration. The water table is an important factor in peatland restoration, and water table management should be considered to maximize carbon sequestration.

1 | INTRODUCTION

The draining of peatlands globally has been widespread over the past centuries, mainly driven by anthropogenic land uses such as row-crop agriculture, grazing, forestry, peat mining, and residential development (Chimner et al., 2017). Over the past several decades, global interest in restoring degraded peatlands has increased due to concern over their carbon dioxide (CO_2) emissions (Leng et al., 2019; Swindles et al., 2019) and potential to offer climate benefits if restored (Renou-Wilson et al., 2019). Organic soil peatlands have much greater carbon accumulation rates than mineral soils (Kolka et al., 2016; Leifeld & Manichetti, 2018); they currently store 30%

of Earth's soil carbon despite only taking up 3% of its land area (Page & Baird, 2016; Yu et al., 2010). While this sequestration ability makes peatland restoration a promising natural climate solution (Fargione et al., 2018), carbon benefits are difficult to quantify and affected by environmental conditions on a site-by-site basis.

The water table position in a peatland is a primary factor governing carbon cycling. Generally, higher water tables result in slower peat respiration, which can reduce CO_2 production but increase the emission of methane (Olson et al., 2013; Trettin et al., 2006; Zhong et al., 2020), and long-term water table drawdown can result in significant increases in respiration (Ballantyne et al., 2014). While dry conditions generate high CO_2 emissions in the short term, prolonged drought can result in leveling or reduction in respiration

Abbreviations: ANOVA, analysis of variance; CSA, Cold Spring A; CSC, Cold Spring C.

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(Bridgham et al., 2008; Carter et al., 2012; Trettin et al., 2006). Temperature increases due to climate change interact with hydrological variation to cause carbon loss in northern peatlands (Hanson et al., 2020; Lu et al., 2022). Fen peatlands in particular may experience higher carbon losses over time due to sharp decreases in primary production by sedges (Wu & Roulet, 2014) and could become carbon sources to the atmosphere (Bridgham et al., 2008).

Minnesota contains 1.40 million ha of peatlands, mainly distributed in the northern part of the state. Southern and western Minnesota also had large peatland areas that are now drained for agriculture (The Nature Conservancy-MN, ND, and SD Chapter, 2020). Historical drainage continues to drive carbon loss in Minnesota peatlands (Krause et al., 2021), though peatland restoration was identified as a potential natural climate solution for mitigating climate change through the uptake and soil sequestration of CO₂ (Lenhart et al., 2021). It is estimated that Minnesota peatlands have the potential to annually sequester 5.61 Mg CO₂-equivalent ha⁻¹ (Fargione et al., 2018), totaling 7.85 million Mg CO₂-equivalent each year, equivalent to offsetting 4% of Minnesota's emissions from energy consumption (Minnesota Commerce, 2022; US Energy Information Administration, 2020).

Given the potential for soil carbon sequestration following peatland restoration, this research aims to explore the effects of hydrological restoration on carbon dynamics at Cold Spring fen in south central Minnesota, a former agricultural site. We assessed how water table depth, soil temperature, and time in the growing season affect peatland soil CO₂ flux to assess restoration as an approach to enhance carbon sequestration. We hypothesized that water table depth would be the primary factor affecting CO₂ flux and flux would be lowest when the water table was high. We also hypothesized that the highest CO₂ flux would occur during the peak of the growing season due to higher temperatures, greater runoff, and lower water table depth.

2 | METHODS

2.1 | Study site

Cold Spring fen is a calcareous peatland previously degraded by row-crop agriculture and ditching in the 1960s. Restoration of the fen began in summer 2018 and is ongoing, with collaboration across multiple organizations and agencies. Located at 45.46° N, 94.40° W, the 28.3-ha restored area consists of organic peatland soils and contains a hillside hanging fen, terrace, and floodplain. To correct negative hydrological effects from a drainage ditch at the summit, a diversion was created in 2020 to redirect groundwater to a flat terrace below the hill, thereby restoring the fen. The diversion caused flooding of the site and adjacent fields during stormflow in 2020. To prevent

Core Ideas

- Water table can be managed in restored wetlands to minimize CO₂ emissions.
- Large range of peat CO₂ effluxes throughout the growing season.
- A water table closer to the soil surface corresponds to lower peat CO₂ flux.

flooding and distribute water more evenly across the terrace, a second diversion was constructed in May 2021, simulating a shallow meandering swale that existed prior to ditching (Figure 1). As indicated by paired wells and piezometers, the fen receives water from both precipitation and groundwater. pH across the site is near neutral, ranging from 6.0 to 7.5. The Histosols are classified as Markey muck (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2021), with organic horizon depths exceeding 40 cm. Due to drainage effects, soils are highly friable and have little structure, limiting water retention and capillary action (Ethier, 2019). The climate is temperate, with the growing season peak occurring during high temperatures and precipitation in July and August (Table 1).

Sampling locations Cold Spring A (CSA) and Cold Spring C (CSC) were selected near two existing wells. CSA was on a small terrace on the backslope, and CSC was on the terrace past the shallow diversion (Figure 1). The locations represent two distinct restored areas. CSA corresponds to the hanging fen, which was less hydrologically disturbed near the surface prior to restoration. CSC, which contains poorly drained soils, was greatly disturbed by row-crop agriculture and experienced a significant rise in water table depth as a result of restored groundwater flow from the hillslope.

2.2 | Field monitoring

At each of the two field sites, we conducted CO₂ flux monitoring monthly from June through October 2021 using a LICOR LI-8100A with triplicate collars around each well, providing three replicates per site. Vegetation growing within collars was removed before taking flux readings. Wells were equipped with Solinst Barologgers and Leveloggers to continuously measure water table elevation, soil temperature, and atmospheric pressure. Leveloggers in well CSA and well CSC were placed at 96.52 cm and 111.76 cm depth, respectively.

TABLE 1 Monthly normal climate data (1991–2020) during growing season for Cold Spring, Minnesota (Minnesota Department of Natural Resources, 2022a). Warm season data refers to May through September.

Month	Normal minimum temperature (°C)	Normal maximum temperature (°C)	Normal mean temperature (°C)	Normal precipitation (cm)
May	8.3	20.5	14.4	9.6
June	13.9	25.6	19.7	11.3
July	16.6	28.1	22.3	10.1
August	15.5	26.6	21.0	10.0
September	11.0	22.2	16.6	7.7
October	3.8	14.0	8.9	6.7
Warm season	13.0	24.6	18.9	48.8

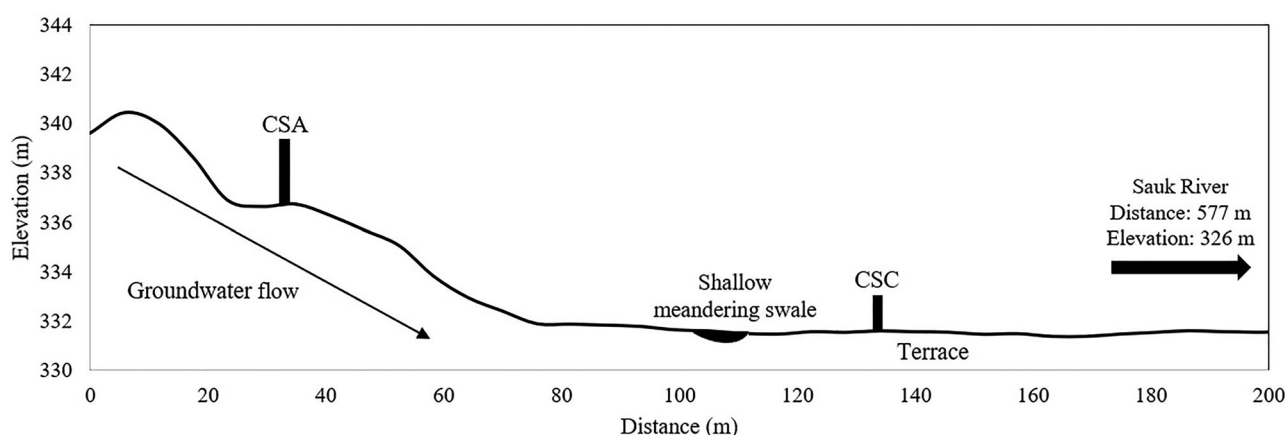


FIGURE 1 Cold Spring fen topography, hydrological features, and monitoring locations. Features enlarged from true scale. Elevation data was collected by the Minnesota Department of Natural Resources (2022b) using light detection and ranging (LiDAR). CSA, Cold Spring A; CSC, Cold Spring C.

2.3 | Statistical analysis

We performed Tukey's test to determine pairwise significant differences between mean fluxes for each site and time point. Three-way repeated measures analysis of variance (ANOVA) was used to relate CO₂ flux measurements to water table depth and temperature over time at each site. Water table depth, soil temperature, and time were fixed effects, with time as the repeated measure, and site was a random factor.

3 | RESULTS AND DISCUSSION

3.1 | Hydrologic trends

Minnesota experienced a drought in 2021, which is responsible for large water table drawdowns at the sampling locations. Well CSA recorded water table depths between 70 and 96.5 cm from mid-June through mid-August, with several spans of readings below the maximum logger depth of 96.5 cm (Figure 2). The water table began to rise begin-

ning in mid-August, reaching a peak at approximately 18 cm below the surface in early October. The water table at well CSC reached a local maximum of 18 cm below the surface in late June before steadily decreasing through much of August. After reaching a low of approximately 109 cm, the water table rose until a peak of approximately 4 cm below the soil surface in early October due to increased precipitation and reduced evapotranspiration.

3.2 | Carbon dioxide flux

Flux varied between the CSA and CSC throughout the growing season, with no clear relationship between the two sites (Figure 2). The highest CO₂ flux of 12.71 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was observed in August at CSA, while the lowest of 0.55 $\mu\text{mol m}^{-2} \text{s}^{-1}$ was recorded at CSC in October. Flux remained above 8 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at CSA from June through August, while CSC only exceeded this flux in July despite a falling water table. The diversions were completely dry during these months, indicating the severity of the drought. The

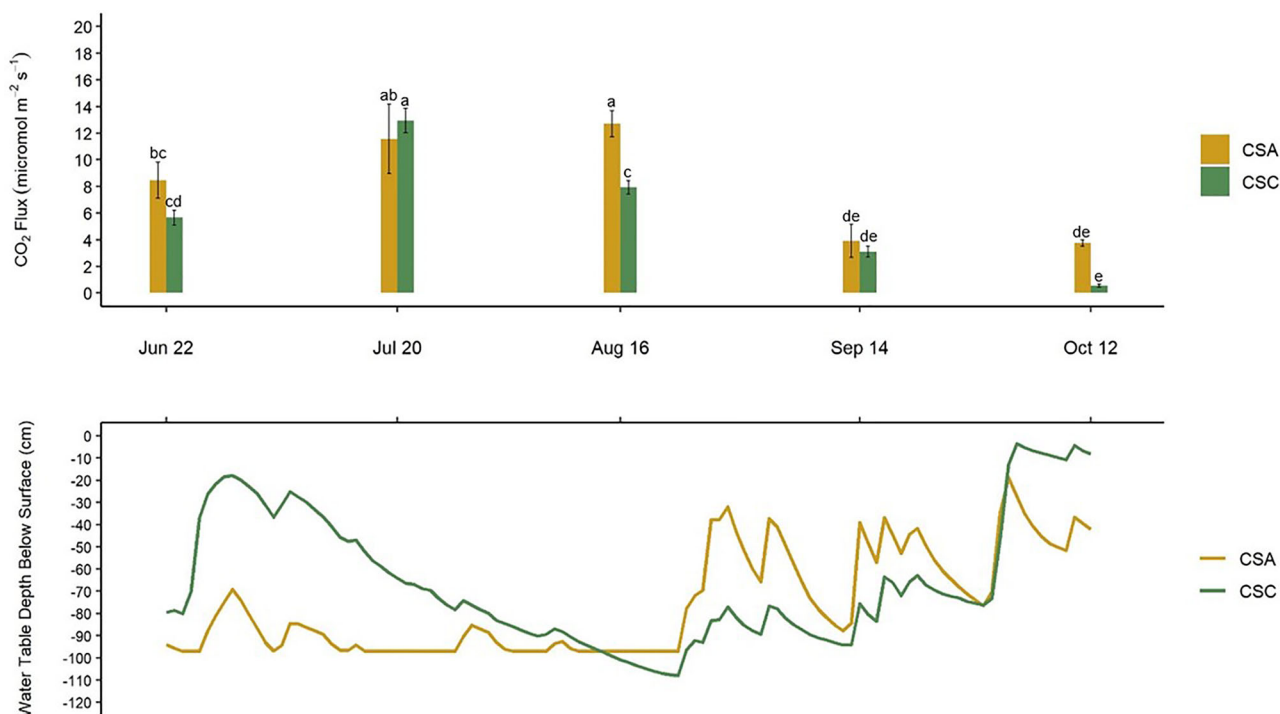


FIGURE 2 Mean instantaneous peat CO₂ flux and continuous water table depth at Cold Spring A (CSA) and Cold Spring C (CSC). Letters represent significance ($p < 0.05$). Error bars represent standard deviation.

diversions contained standing water in September and October, and rising water tables were observed during that time period, corresponding to the lowest flux readings for both sites.

With the exception of August 16, there is no significant difference in CO₂ flux between sites for a given sample date (Figure 2). Based on three-way repeated measures ANOVA, there is a significant within-subjects relationship between CO₂ flux and water table elevation ($F[1,12] = 47.07$, $p < 0.001$; Table S1), with a water table nearer the soil surface corresponding to lower CO₂ flux. Additionally, there is a significant interaction of water table elevation and time ($F[1,12] = 68.193$, $p < 0.001$; Table S1). There is no significant relationship between CO₂ flux and soil temperature ($F[1,12] = 2.43$, $p = 0.145$; Table S1); however, there is a significant two-way interaction of soil temperature and time ($F[1,12] = 110.267$, $p < 0.001$; Table S1). Given the significant three-way interaction of water table elevation, soil temperature and time ($F[1,12] = 4.922$, $p < 0.05$; Table S1), there appears to be a seasonal relationship with CO₂ flux, with the highest CO₂ fluxes occurring during the growing season peak in July and August when the water table is low and temperatures are highest.

As expected, CO₂ emissions generally increase through the growing season until peak in July and August, and then decrease significantly at both sites until the end of the growing season with plants senescing, greater precipitation, and cooler temperatures. These findings support our hypothesis

that CO₂ flux would be lowest at the highest water table elevations and highest at growing season peak. An exception to this relationship occurs between July and August at CSC, where CO₂ flux decreases despite a lowering of the water table. Peat CO₂ respiration may decrease during drought due to excessive dryness (Carter et al., 2012; Kechavarzi et al., 2010), highlighting the need for further investigation of the site's drought response. Similar to our findings, soil temperature has previously been observed to have a limited relationship to peat CO₂ flux (Marwanto & Agus, 2014), though the interaction of soil temperature with other seasonal characteristics warrants further exploration.

To minimize peat CO₂ fluxes to the atmosphere, maintaining high water tables appears to be effective across sites. The diversions placed in May 2021 were opened to different levels throughout the sampling period based on storm events, which affected the amount of surface water reaching the terrace and ultimately percolating to the water table. The terrace was highly disturbed by agriculture, and these hydrological restoration measures successfully elevated the water table so that low CO₂ fluxes could be maintained for much of the growing season. Though the initial purpose of site restoration was to improve water quality and replenish groundwater, low peat CO₂ emissions are an additional benefit.

The restored fen's influence on the site carbon balance needs to be studied further and include measures of plant production and methane emissions. Plants sequester carbon to different extents throughout the growing season, and peat

methane emissions often increase when water table increases (Olson et al., 2013), so all three fluxes must be monitored to fully characterize the carbon balance. As site restoration progresses, it would be useful to continue to monitor how fluxes change in response to restoration and landscape position over time. In particular, measurements during non-drought years would better elucidate the relationship between water table and CO₂ flux for a typical growing season. It is anticipated that the restored fen will become more efficient at sequestering carbon. Further implementation of water level control structures during restoration would enable managers to adaptively manage greenhouse gas fluxes in the face of changing precipitation and drought patterns due to climate change (Koebsch et al., 2020; Peacock et al., 2019).

AUTHOR CONTRIBUTIONS

E. Anu Wille: Conceptualization; investigation; formal analysis; writing—original draft; writing—review and editing.

Christian F. Lenhart: Conceptualization; funding acquisition; methodology; supervision; writing—review and editing.

Randall K. Kolka: Methodology; resources; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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