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RESEARCH ARTICLE

Effectiveness of Ditch Blockage for Restoring Hydrologic and Soil Processes in Mountain Peatlands

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Abstract

Drained peatlands are a global concern due to alterations of the water and carbon cycle, loss of habitat, and increased fire frequency. However, methods for restoring drained sloping peatlands are limited and poorly tested. Therefore, we measured water table dynamics, CO_2 fluxes, and soil properties at four sloping fens that were restored (1–20 years post-restoration) with the installation of small check dams in ditches that had drained the sites for a century. Restoration had a positive effect on water tables, increasing from approximately 45 cm below the surface to approximately 15 cm below the surface during the summers. Restoration also benefited CO_2 fluxes, as the mean net ecosystem exchange was greatest in the restored areas ($-2.19\,g\,CO_2\,m^{-2}\,hour^{-1}$) compared to the unrestored drained areas ($-1.28\,g\,CO_2\,m^{-2}\,hour^{-1}$), while in reference areas it was $-1.74\,g\,CO_2\,m^{-2}\,hour^{-1}$. Drainage also caused significant changes to the peat soil including: 25% reduction in soil organic matter (lost between 1.4 to 3.6 kg/m^2), increased bulk density, decreased porosity, and reduced saturated hydraulic conductivity. Restoration did not affect these parameters, even 20 years after restoration. This study suggests that although natural water table levels have been reestablished and the process of carbon sequestration improved, the physical properties of the most disturbed, near surface peat soils do not mimic reference conditions 20 years post-restoration.

Key words: **carbon balance, disturbances, ditches, fens, mountains, peat soil.**

Introduction

Peatlands influence the global carbon cycle, storing approximately one third of the total soil carbon stock (Gorham 1991). The accumulation of organic matter (OM) occurs where the production of plant matter outpaces decomposition and other losses on a time scale of centuries to millennia and forms peat soil. Peatlands began to form approximately 12,000 years BP in the Rocky Mountains and other mountain regions in western North America (Cooper et al. 2012). The slow buildup of peat reflects the long-term stability of these ecosystems. In addition to carbon storage some peatlands perform other valuable functions including water storage and flood mitigation, habitat and species diversity, tourism and recreation opportunities, and improvements in water quality through reduction in sediment load and nutrients.

All peatlands in the southern Rocky Mountains are supported largely by groundwater flow and are classified as fens (Cooper & Andrus 1994). Approximately 2,000 fens occur in the San Juan Mountains of southern Colorado, and cover less than 1% of the land area (Chimner et al. 2010). Fens enhance regional biodiversity by providing habitat for species that are disjunct from their main range in the boreal region thousands of kilometers to the north (Cooper 1996; Cooper et al. 2012).

In-situ plant growth is the primary carbon input to fens, with more than half of annual net primary productivity being root growth (Chimner & Cooper 2003*a*). The water table persists near the soil surface creating anoxic soils that inhibit microbial activity, and reduce decomposition and soil CO_2 emissions. Lowering the water table via ditching can increase microbial activity, decomposition (Ellis et al. 2009), soil respiration (Laiho 2006), alter vegetation composition (Coulson et al. 1990; Cooper & MacDonald 2000; Hedberg et al. 2012) and switch a peatland from a net sink to source of atmospheric carbon (Waddington et al. 2002; Chimner & Cooper 2003*b*). Drainage may cause peat subsidence and consolidation leading to increased soil bulk density (Leifeld et al. 2011), and reduced saturated hydraulic conductivity and water storage capacity (Schlotzhauer & Price 1999).

Mountain fens are supported by local groundwater sources making them excellent indicators of long-term watershed stability and condition. Roads, building construction, mining, or drainage ditches have impacted nearly one fourth of the fens in the San Juan Mountains (Chimner et al. 2010). Ditches intercept ground water reducing water supplies to fens and increase the aerobic soil layer thickness. Previous efforts to restore drained peatlands have reestablished hydrologic

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regimes by blocking or filling ditches (Cooper et al. 1998; Patterson & Cooper 2007; Armstrong et al. 2009). Although the hydrologic regime and vegetation of fens can be restored on relatively short time scales of years to decades, the effects of drainage on peat soil may persist for a much longer time.

Most work on peatland disturbance and restoration has been on *Sphagnum* dominated boreal peatlands (Price 1996; Gorham & Rochefort 2003; Shantz & Price 2006; Lucchese et al. 2010; Holden et al. 2011). Our objectives were to test the effect of ditch blocking in four mountain fens on: (1) the rate of water table response, (2) patterns of carbon sequestration, and (3) whether hydrologic restoration influences the physical properties of degraded peat soil. We were particularly interested in understanding the relative rates of hydrologic, carbon storage, and soil structure responses to restoration efforts.

Methods

Site Description

We worked in four fens, Lateral Moraine (LM) and Pirate Ship (PS), in the San Juan Mountains (Chimner et al. 2010), northeast Eggleston (NE) on Grand Mesa (Austin 2008), and Big Meadows (BM) in the Front Range (Cooper et al. 1998). All are sloping (1.5–2.0%), intermediate fens (pH 5.7–6.3) in the southern Rocky Mountains of Colorado, U.S.A. The 20-year (1987–2006) mean daily temperature at the Park Reservoir (# 682) SNOTEL station on Grand Mesa was −0.7°C, mean April 1 snow water equivalent was 1,880 mm, and mean yearly precipitation total was 2,870 mm (NRCS 2011). These values are typical for the region at the elevation of these fens. Deep winter snowpack recharges hillslope moraine, talus, and colluvial aquifers that deliver summer groundwater to fens and monsoon rains recharge aquifers in late summer. In each fen were narrow (>2 m), shallow (>1 m), low gradient (>2%) ditches capturing surface and groundwater flow from portions of the fens.

LM (37°48.5′N, 107°51.9′W) is a 1.5 ha oval-shaped fen at 3,100 m elevation with *Carex aquatilis* and *C. utriculata* dominated vegetation. It has eight ditches or channels separated by less than 40 m and running generally with the slope with lengths ranging from 30 to 50 m. Restoration began in 2008 blocking one channel with peat bags. In 2009, the five western channels were blocked using plywood dams and peat bags. The eastern three ditches were used as disturbed reference areas. A reference fen occurred 100 m away.

PS (37°57.3′N, 107°35.8′W) is 10 ha in size and *C. aquatilis*, *Eleocharis quinqueflora*, and *Salix planifolia* dominate its vegetation. One 0.3 km long ditch running across the slope effectively drains more than 40% of the fen. Seven check dams were installed in September 2009 to block flow through the ditch and restore the sheet flow hydrologic regime. Within PS were undisturbed reference, restored, and unrestored disturbed areas.

NE (39°2.7′N, 107°55.6′W) is 1 ha in size and dominated by *C. aquatilis* and *C. utriculata*. A central ditch 180 m in length running with the slope for the upper approximately two third of its length and across the slope for the remainder drains approximately 30% of the fen. In 2009, we installed five plywood and eight peat dams. NE had undisturbed reference, restored, and unrestored disturbed areas.

BM (40°19.1′N, 105°48.5′W) was ditched in the early 1900s for agricultural use and the ditch was blocked in 1990 using sheet metal dams (Cooper et al. 1998). As a long-term restoration site it was compared with recently restored LM, PS, and NE. The vegetation is dominated by *C. aquatilis* and *C. utriculata*.

Water Table

Groundwater monitoring wells were constructed using fully slotted 5 cm inside diameter schedule 40 PVC pipe installed into hand augered boreholes that were backfilled with native soil. Wells were distributed in a regular grid across each fen to provide an understanding of water levels both near (>5 m) and distant (up to 100 m) from ditches. Water levels in sloping fens can be influenced at great distances beyond the ditch because sheet flowing water in early summer, and shallow ground water at all seasons are flowing largely laterally. Water table depth at LM (45 wells), PS (29 wells), and NE (15 wells) was monitored biweekly during the snow free period from late May to September in 2008, 2009, and 2010. Water levels in selected wells were recorded hourly using submersible and vented pressure transducers (WL-15, Global Water Instruments, White Plains, NY, U.S.A.) in LM disturbed and restored, and PS disturbed and reference sites.

CO_2 Flux

Mid-day growing season soil CO_2 flux was measured in 2009 and 2010 using the chamber method (Vourlitis et al. 1993). We measured 5–6 replicate plots along a 3-m radius circle around groundwater monitoring wells in reference, disturbed, and restored sites at LM (4 wells, 20 plots), PS (3 wells, 18 plots), and NE (3 wells, 18 plots), every 10–14 days during June–August using a 60 × 60 × 60 cm chamber constructed of clear Plexiglas and fitted with air circulating fans. CO_2 concentration within the chamber was analyzed using an Infrared Gas Analyzer (EGM-4, PP Systems, EGM-4, Amesbury, MA, U.S.A.) for 1–2 minutes until a linear rate of change was established. Net ecosystem exchange (NEE) was measured with the clear chamber. Ecosystem respiration (ER), the combined plant and microbial respiration, was measured by placing an opaque cover over the chamber to stop plant photosynthesis. The chamber was opened between measurements for ventilation. Gross primary production (GPP) was calculated by subtracting ER from NEE. Air temperature, relative humidity, and photosynthetically active radiation (PAR) were recorded with each measurement. Negative flux values indicate CO_2 uptake by the peatland, positive values indicate a loss of CO_2 to the atmosphere. Mean CO_2 flux by treatment was pooled from both study years and all study fens. Pre and post-restoration data are not pooled; rather, data for each treatment were pooled across years. "Restored" data from both study years and all restored sites are pooled. The "disturbed" data includes pre-restoration data for sites that would be restored, and data from sites that were disturbed and not restored during the study.

Soil Properties

Peat cores were extracted from disturbed, reference, and restored sites ($n = 4$, 17, 19, respectively) with a fine-toothed saw and PVC cylinders using methods similar to Schlotzhauer and Price (1999). Three samples were taken from each of three depths, 0–15, 15–30, and 30–45 cm. Cylindrical sampling tubes ($d = 6.4$ cm, $h = 10.0$ cm) were carefully pressed into the peat while cutting around the outer core edge to minimize soil compression and ensure a tight seal between the peat and container wall. Samples were extracted in both horizontal and vertical orientations to measure saturated hydraulic conductivity using the original sampling cylinder. During laboratory analyses if high flow rates or obvious gaps between peat and the PVC cylinder were observed, heated paraffin wax was poured around the edge to enhance the seal. A third sample was collected in PVC sampling rings ($d = 5.3$ cm, $h =$ approximately 2.5 cm) and used to measure porosity, soil water retention, bulk density, and percent OM. All soil samples were collected in late summer 2010 and kept sealed and refrigerated until analyzed.

Soil water retention characteristics were measured using a pressure plate apparatus by placing soil samples on a porous plate with tension applied using either a hanging water column or air pressure. Volumetric moisture content (θ (h)) measurements were made at incrementing intervals during desorption as tension on the system was increased from 0 (saturated) to −1.5 bars. Samples were allowed to equilibrate for 3–4 days at lower tensions (greater than −1 bar) and 7 days at higher tensions (less than −1 bar). $\theta(h)$ values were fit to the Van Genuchten Equation 1 using inverse modeling in HYDRUS 1D software, with variables for residual water content (θ_r), α, and n:

$$\theta\,(h) = \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\,|h|)^n\right]^m} + \theta_r \qquad (1)$$

where $m = (1 - 1/n)$. Porosity was assumed to be equal to the saturated water content (θ_s). Air entry pressure is related to the inverse of α and represents the extent of the capillary fringe above the water table.

Bulk density (ρ_b) was measured by weighing oven-dried samples at 105°C for 24 hours and using saturated soil volume. OM content was determined by heating 2 g of dry soil samples at 550°C for 4 hours. OM is presented as a percentage of the mass soil lost.

We calculated the original concentration of soil OM and 20th century loss using differences in bulk density and OM content between reference, drained and restored sites (Leifeld et al. 2011). Using a mass balance approach, estimations of peat subsidence (Equation 2) were derived from measured differences in bulk density between reference ($\rho_{b_{ref}}$) and drained and restored areas ($\rho_{b_{dist}}$), with reference depth (L_{ref}) being fixed at the upper level sampling depth (15 cm).

$$\text{Subsidence} = L_{ref} * \left(1 - \frac{\rho_{b_{ref}}}{\rho_{b_{dist}}}\right). \qquad (2)$$

The quantity of soil OM lost from drained areas was calculated using Equation 3. In our study sites, significant changes in soil properties occurred only in the upper 15 cm of soil, therefore changes in OM are reported for this sampling depth.

$$\Delta\text{OM} = \left[\rho_{b_{ref}} * L_{ref} * \left(\%OM_{ref} - \%OM_{dist}\right)\right] \qquad (3)$$

Saturated hydraulic conductivity (K_s) of peat samples was measured using a constant head permeameter. Samples were saturated for at least 72 hours at room temperature in a 0.005 mol $CaCl_2$ solution, with three grains of Thymol to

Table 1. Water table mean, low, and variation for summer seasons (June to September) 2008–2010 averaged by treatment within each fen.

	Mean Water Table (cm)			*Water Table Minimum (cm)*			*Water Table Variation (cm)*		
	2008	*2009*	*2010*	*2008*	*2009*	*2010*	*2008*	*2009*	*2010*
Pirate Ship									
Reference		−6.1[a]	−6.2[a]		−26.6	−13.2		28.1	14.7
Restored*		−26.6[b]	−10.4[a]		−39.8	−11.7		39.0	12.0
Disturbed		−28.8[b]	−19.2[b]		−49.4	−40.9		43.3	41.1
Lateral Moraine									
Reference		−6.4[a]	−13.9[a]		−19.8	−26.7		18.5	21.5
Restored*	−35.0[a]	0.2[a]	−3.8[a]	−60.1	−6.5	−15.9	55.0	11.2	18.0
Disturbed*	−38.8[a]	−18.7[b]	−36.3[b]	−55.5	−43.8	−58.0	45.9	39.5	45.0
NE Eggleston									
Reference		−14.4[a]	−8.1[a]		−27.8	−19.3		24.5	19.3
Restored*		−19.2[a]	−1.9[a]		−40.0	−9.1		38.2	12.5
Disturbed		−32.0[a]	−22.3[a]		−41.8	−42.7		25.2	46.9

Mean water table values for each fen, within each year, with the same letter are not significantly different ($p > 0.05$). Water table response to restoration was tested using repeated measures ANOVA with 2008 data used for prerestoration at Lateral Moraine fen and 2009 used for pre-restoration at Pirate Ship and NE Eggleston fens.
*Pre to post-restoration mean water table difference is significant ($p < 0.0001$).

reduce microbial activity. Solution was ponded over saturated samples until water flux through the soil achieved a constant rate. K_s was calculated using Darcy's law,

$$q = K_s * \frac{dh}{dl} \tag{4}$$

where dh is the hydraulic head, dl is the sample length, and q is the volume of water per unit time discharging from bottom of sample (Equation 4).

Statistical Analysis

Repeated measures analysis of variance (ANOVA) was used to analyze biweekly measurements of water table levels at LM, PS, and NE from June to September 2009 and 2010 using the Proc Mixed procedure (SAS 9.2) with each well representing an experimental unit. Comparisons were made by year for each fen by treatment as well as pre- versus post-restoration comparisons within each fen and treatment. Water table means by treatment were also compared after pooling measurements from all fens and study years. Differences in treatment means were compared using Tukey's HSD post hoc adjustment with $p < 0.05$ considered significant.

CO_2 flux means (NEE, ER, and GPP) were analyzed with repeated measures ANOVA with each site representing an experimental unit. Comparisons were made for each year and fen. Additionally, comparisons within fen and well were made across years to test for responses to restoration at PS and NE sites. Means across all sites by treatment were compared by pooling data from 2009 and 2010. Differences in treatment

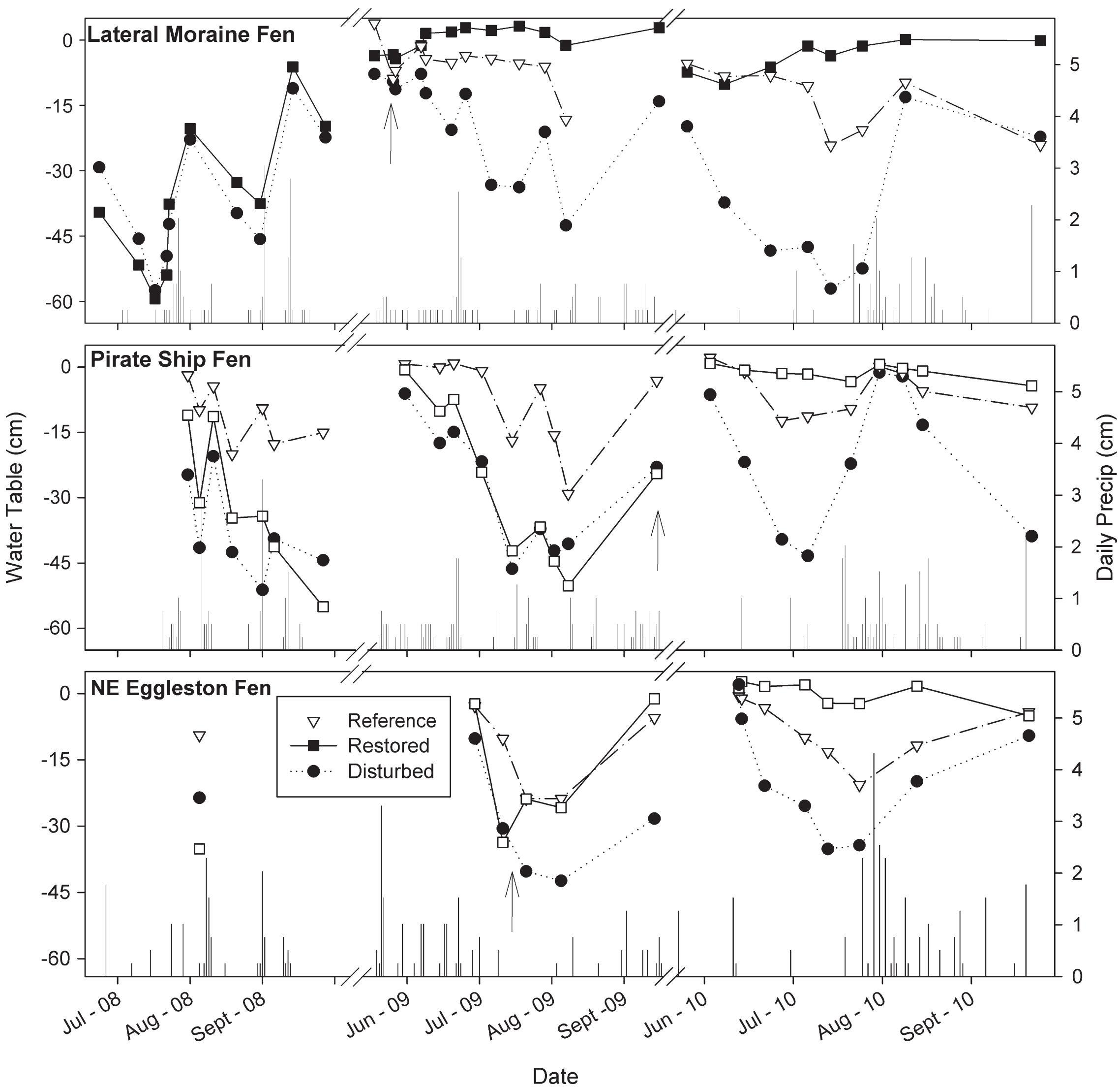

Figure 1. Depth to water table and daily precipitation for Lateral Moraine (LM), Pirate Ship (PS), and NE Eggleston (NE) fens for the study period. Water table values are averaged by treatment within each fen for each measurement day. Daily precipitation amounts were obtained from NRCS SNOTEL stations #586 (LM), #713 (PS), #682 (NE). Each station is located at a similar elevation and within 7 miles of the associated fen. Arrows indicate date of restoration.

means were compared using Tukey's HSD post hoc adjustment with $p < 0.05$ considered significant.

The measured soil properties were not normally distributed and differences between treatments were analyzed using the nonparametric Wilcoxon rank sums test using Proc npar1way (SAS 9.2). Two-sided p values <0.05 were considered significant for comparisons between sample depths. Samples from disturbed sites ($n = 4$) at LM were pooled with restored samples for analysis.

Results

Depth to Water Table

The mean water table depth in ditched sites that would and would not be restored was similar prior to restoration ($p > 0.99$). For example, mean water table was −35.0 and −38.8 cm for sites that would and would not be restored at LM ($p = 1.00$). Reference site mean water table depths were significantly higher ($p < 0.01$) than pre-restoration disturbed sites, for example −6.1 cm in reference sites, compared with −26.6 cm and −28.8 cm in disturbed sites that would and would not be restored at PS fen (Table 1).

Ditch blocking significantly ($p < 0.0001$) increased the mean growing season water table depth by 35, 15, and 17 cm at LM, PS, and NE. The restored mean water table depths in 2010 at LM, PS, and NE were statistically similar to their reference areas ($p > 0.40$) (Table 1) while disturbed site mean water tables were deeper at LM ($p > 0.001$), PS ($p = 0.01$), but not NE ($p = 0.82$). Ditch blocking also reduced the variance in seasonal water tables in all restored areas (Fig. 1) by reducing maximum water table drawdown by as much as −40 cm (Table 1). The mean water table in BM was significantly higher in all but the driest water years following restoration (Cooper et al. 1998).

CO_2 Flux

There were no significant differences in NEE, GPP, or ER at drained sites in PS (PS was the only site that had appropriate before and after CO_2 flux data for this analysis) that would and would not be restored (Fig. 2). After restoration, mean NEE

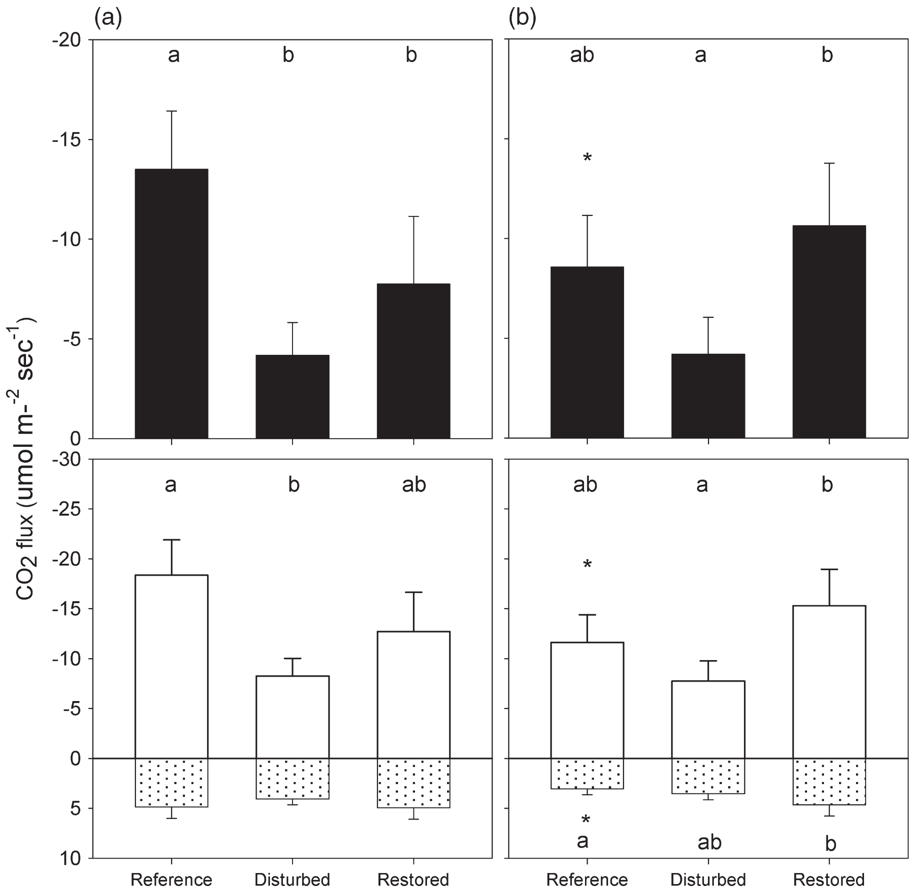

Figure 2. Net ecosystem exchange (black bars), gross ecosystem production (gray bars), and ecosystem respiration (dotted bars) for Pirate Ship Fen CO_2 flux sites before (a) and after (b) restoration. Pre-restoration data were collected from July to August 2009 and post-restoration data from June to August 2010 following implementation of hydrologic restoration in the fall of 2009. Error bars indicate 1 standard error from the mean. Means with the same letter are not significantly different ($p > 0.05$) for comparisons made within each year. Asterisk indicates 2009 mean significantly different ($p > 0.05$) from 2010 mean.

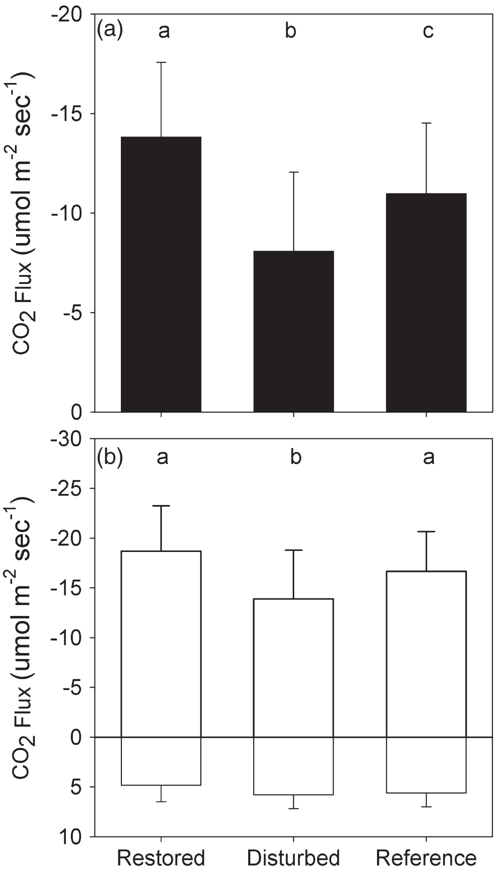

Figure 3. Mean CO_2 flux by treatment with data pooled from both study years and all study fens. (a) Net Ecosystem Exchange (NEE). (b) Positive values—Ecosystem Respiration (ER) and negative values—Gross Primary Production (GPP). Error bars indicate 1 standard error from the mean. Treatment means with the same letter are not significantly different ($p > 0.05$). Pre and post-restoration data are not pooled; rather, data for each treatment were pooled across years. "Restored" data from both study years and all restored sites are pooled. The "disturbed" data includes pre-restoration data for sites that would be restored, and data from sites that were disturbed and not restored during the study.

for all the restored sites ($-13.84\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$) was significantly greater ($p < 0.014$) post-restoration, than reference ($-10.98\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$) and disturbed sites ($-8.08\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$) (Fig. 3). The increase in NEE was mostly due to an increase in GPP. The mean GPP for disturbed sites ($-13.89\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$) was significantly lower ($p < 0.041$) than reference ($-16.41\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$) or restored sites ($-18.94\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$). However, there was no significant difference in ER between disturbed, reference, or restored sites, which had mean values of 5.81, 5.62, and $4.86\,\mu\text{mol}\,CO_2\,m^{-2}\,\text{second}^{-1}$, respectively.

Soil Properties

Soil at 0–15 cm depth in the drained portion of fens had higher bulk density ($p < 0.0001$), lower porosity ($p = 0.019$), lower percent OM ($p = 0.004$), and lower saturated hydraulic conductivity in both vertical ($p = 0.002$) and horizontal ($p = 0.081$) orientations than soil samples from reference areas (Fig. 4). Air entry pressure was greater in the disturbed samples, -37.0 cm H_2O, than in reference samples where it was -31.3 cm H_2O ($p = 0.12$). Reference and disturbed site samples for 15–30 and 30–45 cm sample depths were not significantly different in any measured soil properties.

The original upper 15 cm of peat in disturbed areas appears to have subsided 3–7 cm, or up to 40%. OM losses ranged from 1.4 kg/m^2 at BM to 3.7 kg/m^2 at LM (Table 2). Total OM losses from the upper 15 cm of peat from fens ranged from 14.7 tons at NE to 91.0 tons at PS. At depths below 15 cm restored soil properties differed by <30% from restored samples except saturated hydraulic conductivity, which was highly variable (Fig. 5).

At BM, 20 years after restoration, the greatest differences between restored and reference soil properties were for bulk density and saturated hydraulic conductivity (Fig. 5). However, there was only a 12% difference in OM content between restored and reference plots, which was approximately half the difference between restored and reference plots at LM, NE, and PS.

Discussion

Restored fen areas had mean and maximum summer water table depths closer to the soil surface than occurred prior to restoration, as well as reduced seasonal water table variation. These two characteristics are strong indicators that hydrologic restoration has been successful (Holden et al. 2011) and indicates that the use of dams constructed from plywood and peat filled bags are appropriate short-term restoration techniques for drained mountain fens. The water table in study fens began to rise within one week of ditch blockage and up to 85% of drained fen areas had water level increases during the study period (Fig. 1). The rapid water table rise is driven by the availability of groundwater inflow at all sites.

Restoring the natural hydrologic regime is a fundamental change in environmental conditions that affects most aspects of fen ecosystem function including vegetation composition and structure, carbon dynamics, and soil-forming processes. Restoration that relies on blocking ditches with metal or wooden dams and/or bags filled with peat relies on the continued functioning, and periodic maintenance, of the dam structures. Sheet metal structures placed into Big Meadows in 1990 are still in excellent condition in 2012 after 23 years, and will last half century or more. The goal of ditch plugging is to improve hydrologic conditions to allow increased plant growth and organic carbon storage. Few plants can colonize the deep water of ditches before or after blocking, and little mineral or organic sediment flux occurs in fens to fill the ditch. Little natural filling has occurred in the Big Meadows ditch, and ditches more than 50 cm deep may be permanent landscape features unless they are filled. It is unknown how long other material used for ditch plugs will last and the type of maintenance that will be required.

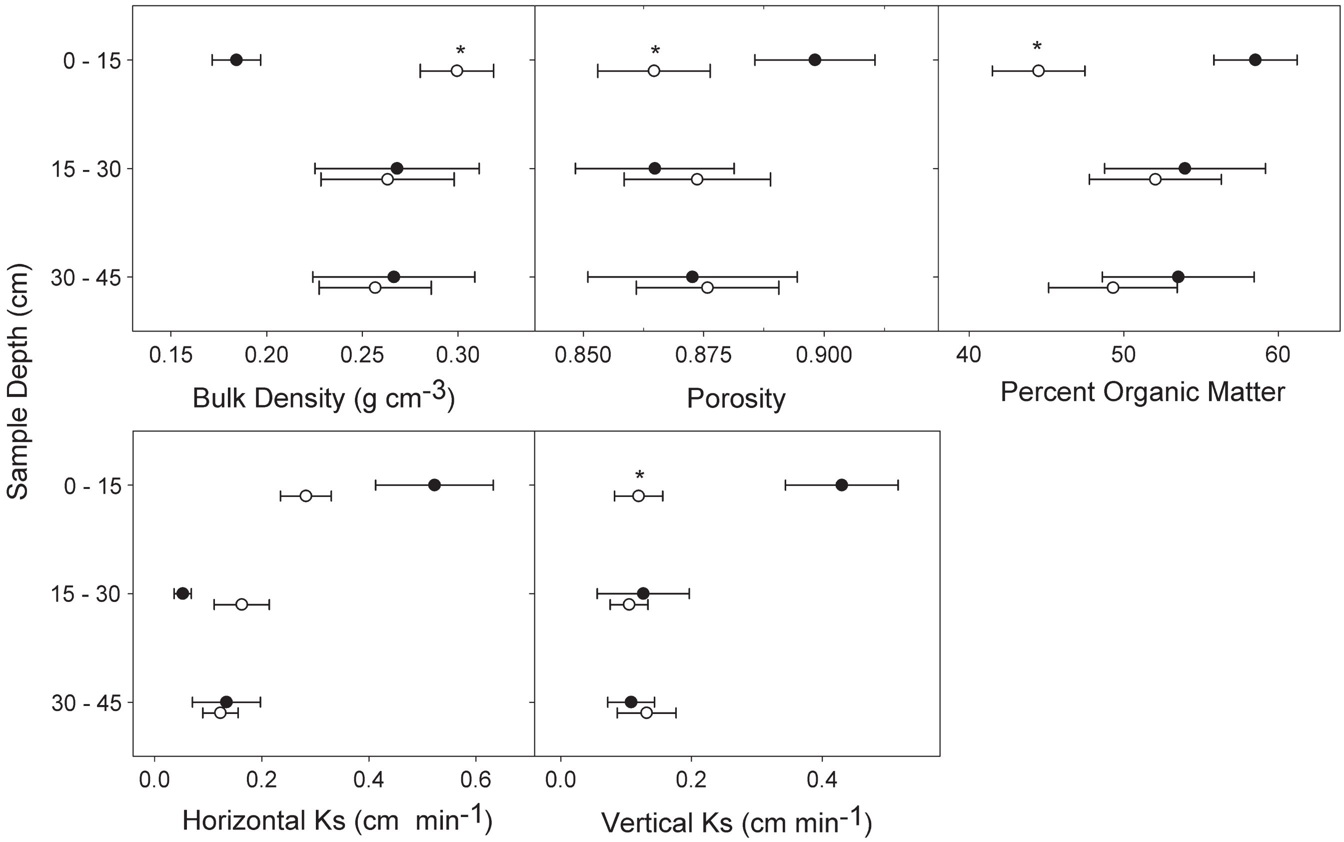

Figure 4. Soil property means (bars are ±1 standard error) with samples from all fens pooled by treatment (open = disturbed/restored, closed = reference). Differences in means were analyzed at each sample depth using the Wilcoxon rank sum test. Asterisk indicates means are significantly different ($p < 0.05$).

Table 2. Mass of organic matter (OM) per cm for sample depth 0–15 cm for reference and disturbed soils.

Study Site	*Reference OM (g/cm^2)*	*Disturbed OM (g/cm^2)*	*Subsidence (cm)*	*OM Loss (kg/m^2)*
Pirate Ship	1.72	1.50	4.8	2.13
Lateral Moraine	1.60	1.23	5.1	3.66
NE Eggleston	1.61	1.44	3.2	1.73
Big Meadows	1.23	1.08	6.7	1.43

Disturbed OM calculations made using corrected sample depth to account for subsidence, which were calculated from the ratio of reference to disturbed bulk densities over the sampling depth (15 cm). Total OM loss is the difference between reference OM and Disturbed OM (note unit change).

Converting disturbed peatlands from net atmospheric carbon sources into sinks is a goal for most peatland restoration programs (Rochefort et al. 2003). Carbon storage within cutover northern peatlands resumes after the hydrologic disturbance is restored and the site revegetated (Kivimaki et al. 2008; Waddington et al. 2010; Samaritani et al. 2011). NEE increased following restoration in our study fens, suggesting enhanced carbon storage. The increase in NEE was primarily from an increase in GPP, not a reduction in ER. For instance, GPP increased in PS and NE by an average of 40% after restoration. We expected that increasing the water table would decrease ER. The lack of significant change in ER after restoration was likely due to offsetting factors. The large increase in GPP after restoration would have increased ER by increasing plant respiration, while at the same time the higher water table could have lowered ER (Chimner & Cooper 2003*b*; Riutta et al. 2007).

A key topic in ecological research is determining how long the effects of disturbance persist following the implementation of restoration actions. Our results indicate that water table levels and carbon cycling can respond quickly after restoration actions are implemented, whereas the restoration of soil physical properties requires a much longer time. For example, the altered soil physical properties produced by long-term drainage have persisted for more than two decades after the Big Meadows restoration. Overall, disturbed peat soil at all sites were denser, had lower percent OM and porosity. Most significant differences in peat properties between disturbed and reference areas occurred in the upper 15 cm of soil. This soil zone sustained long duration aerobic soil conditions during the many decades of drainage and is also where most OM additions from root growth occur in mountain fens (Chimner & Cooper 2003*a*). In the disturbed fen areas soil layers below 15 cm deep maintained saturated conditions despite a dramatic annual water table drawdown. We attribute this to

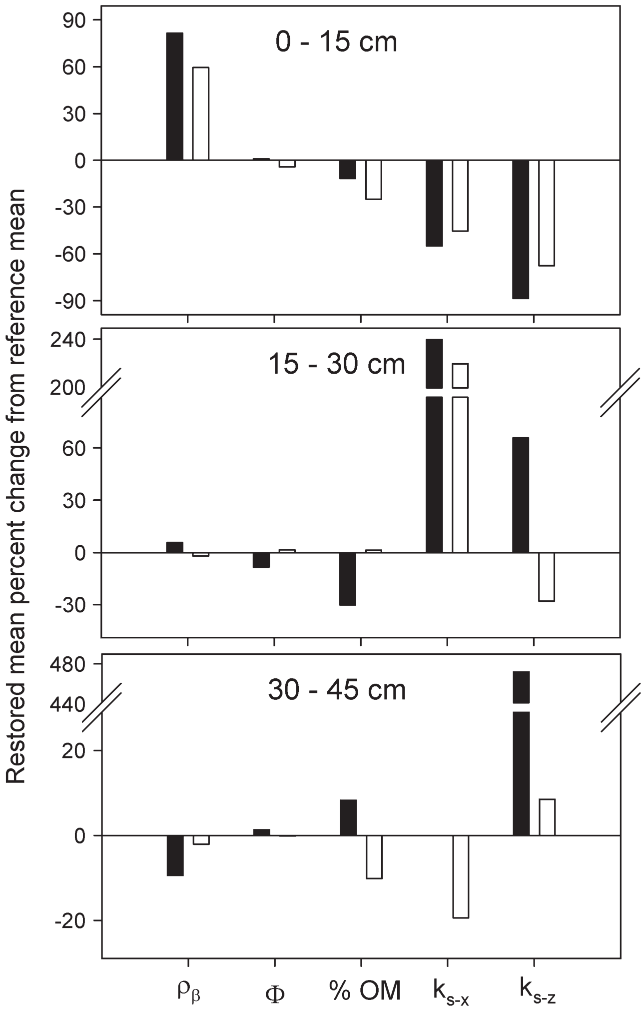

Figure 5. Normalized magnitude of change in restored soil property means from reference condition at each sample depth. *Closed bars* represent Big Meadows fen (BM), restored 1990, *open bars* represent pooled samples from Lateral Moraine (LM), Pirate Ship (PS), and NE Eggleston fens (NE), restored during this study. BM restored soil samples were compared only to BM reference samples. LM, PS, and NE pooled samples were compared to pooled reference samples from only these fens. Soil properties included in figure are bulk density (ρ_b), porosity (φ), % Organic Matter (%OM), residual Water Content (θ_r), and saturated hydraulic conductivities in both horizontal (k_{s-x}) and vertical (k_{s-z}) orientations.

the abundance of small soil pores in the highly decomposed peat and a capillary fringe that extended more than 35 cm above the water table. Degraded peat soil would have had increased capillary rise producing higher volumetric water content further above the water table than pristine peat, thereby reducing the effect of a lowered water table (Macrae et al. 2013). For successful fen restoration, raising the water table to the soil surface throughout the growing season may not be necessary or desired (Lamars et al. 2002), however it is important to maintain soil saturation by avoiding large water table declines that allow aerobic conditions to persist for extended periods of time (Deppe et al. 2010). For Rocky Mountain fens, this means stabilizing the water table within 20–30 cm of the surface.

One of the main reasons for restoring peatlands globally is to stop rapid carbon loss to the atmosphere and to reestablish carbon sequestration (Anshaari et al. 2010). We found that drainage resulted in long-term losses of 20–37 t C/ha at our study sites. Although we did not measure CH_4 and DOC to calculate total carbon budgets before and after restoration, we did measure NEE, which was found to account for 90–98% of gaseous C in similar Colorado fens (Chimner & Cooper 2003*a*). We consider the CO_2/CH_4 data from other drained and undrained Colorado fens to be representative of southern Rocky Mountain fens in general, therefore restoring ditched fens will likely decrease greenhouse gas emissions and improve carbon storage (Chimner & Cooper 2003*a*). Assuming that our restored fens are now accumulating carbon at similar rates of other southern Rocky Mountain fens (25 g C m^{-2} yr^{-1}: Chimner et al. 2002), it will take approximately 120 years to accumulate the amount of C lost due to ditching.

Many drained peatlands have lost much more carbon than our sites due to intensive land management practices. For example, peatlands drained for forestry or agriculture can release larger amounts of carbon. Leifeld et al. (2011) determined that 270–700 t C /ha was lost from a fen drained for agriculture in Switzerland, more than 10 times the loss we calculated, because its deeper and larger ditches have been maintained for a century and the soil was tilled and farmed.

Implications for Practice

- Ditches can alter hydrologic regimes in mountain fens for decades to centuries, creating significant impacts. Once created, the ditches do not naturally fill with peat or mineral sediment, and must be blocked or filled.
- The success of cost effective methods to restore many natural functions of drained peatlands can allow land managers to implement peatland ditch filling programs.
- Changes in depth to water table and CO_2 flux before and after restoration are useful criteria for quantifying restoration success, but must be quantified using monitoring wells and carbon flux measurement systems.
- More than 20 years after blocking the ditch in BM, soil properties were not restored. Soil properties may never be restored and instead a new peat layer must form over the degraded peat, a process that could take more than a century in Rocky Mountain fens.
- Ditch blockage could take decades to centuries to restore the hydrologic functioning of peat soils.

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LITERATURE CITED

Anshaari, G., M. Afifudin, M. Nuriman, E. Gusmayanti, L. Ariane, R. Susana, R. Nusantara, J. Sugardjito, and A. Rafiastanto. 2010. Drainage and land use impacts on changes in selected peat properties and peat degradation in western Kalimantan Province, Indonesia. Biogeosciences **7:** 3403–3419.

Armstrong, A., J. Holden, P. Kay, M. Foulger, S. Gledhill, A. T. McDonald, and A. Walker. 2009. Drain-blocking techniques on blanket peat: a framework for best practice. Journal of Environmental Management **90:** 3512–3519.

Austin, G. 2008. Fens of Grand Mesa, Colorado: characterization, impacts from human activities and restoration. Unpublished MS thesis, Prescott College, Prescott, Arizona.

Chimner, R., and D. Cooper. 2003*a*. Carbon dynamics of a pristine and hydrologically modified fens in the southern Rocky Mountains. Canadian Journal of Botany **81:**477–491.

Chimner, R., and D. Cooper. 2003*b*. Influence of water table levels on CO_2 emissions in a Colorado subalpine fen: an in situ microcosm study. Soil Biology & Biochemistry **35:**345–351.

Chimner, R. A., D. J. Cooper, and W. J. Parton. 2002. Modeling carbon accumulation in Rocky Mountain fens. Wetlands **22:**100–110.

Chimner, R., J. Lemly, and D. Cooper. 2010. Mountain fen distribution, types and restoration priorities, San Juan Mountains, Colorado, USA. Wetlands **30:**763–771.

Cooper, D. J. 1996. Water and soil chemistry, floristics, and phytosociology of the extreme rich High Creek fen, in South Park Colorado, USA. Canadian Journal of Botany **74:**1801–1811.

Cooper, D., and R. Andrus. 1994. Patterns of vegetation and water chemistry in peatlands of the west central Wind River Range, Wyoming, U.S.A. Canadian Journal of Botany **72:**1586–1597.

Cooper, D., and L. MacDonald. 2000. Restoring the vegetation of mined peatlands in the southern Rocky Mountains of Colorado, U.S.A. Restoration Ecology **8:**103–111.

Cooper, D., L. MacDonald, S. Wenger, and S. Woods. 1998. Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado, USA. Wetlands **18:**335–345.

Cooper, D. J., R. A. Chimner, and D. M. Merritt. 2012. Mountain wetlands of North America. In D. Batzer and A. Balswin, editors. Wetland habitats of North America: ecology and conservation concerns. University of California Press, Berkeley.

Coulson, J., J. Butterfield, and E. Henderson. 1990. The effect of open drainage ditches on the plant and invertebrate communities of moorland and on the decomposition of peat. Journal of Applied Ecology **27:**549–561.

Deppe, M., K. Knorr, D. McKnight, and C. Blodau. 2010. Effects of short-term drying and irrigation on CO_2 and CH_4 production and emission from mesocosms of a northern bog and an alpine fen. Biogeochemistry **100:**89–103.

Ellis, T., P. Hill, N. Fenner, G. Williams, D. Godbold, and C. Freeman. 2009. The interactive effects of elevated carbon dioxide and water table draw-down on carbon cycling in a Welsh ombrotrophic bog. Ecological Engineering **35:**978–986.

Gorham, E. 1991. Northern Peatlands: role in the carbon cycle and probably responses to climatic warming. Ecological Applications **1:**182–195.

Gorham, E., and L. Rochefort. 2003. Peatland restoration: a brief assessment with special reference to *Sphagnum* bogs. Wetlands Ecology and Management **11:**109–119.

Hedberg, P., W. Kotowski, P. Saetre, K. Mälson, H. Rydin, and S. Sundberg. 2012. Vegetation recovery after multiple-site experimental fen restoration. Biological Conservation **147:**60–67.

Holden, J., Z. Wallage, S. Lane, and A. McDonald. 2011. Water table dynamics in undisturbed, drained and restored blanket peat. Journal of Hydrology **402:**103–114.

Kivimaki, A., M. Yli-petays, and E. Tuittila. 2008. Carbon sink function of sedge and *Sphagnum* patches in a restored cut-away peatland: increased functional diversity leads to higher production. Journal of Applied Ecology **45:**921–929.

Laiho, R. 2006. Decomposition in peatlands: reconciling seemingly contrasting results on the impacts of lowered water levels. Soil Biology and Biochemistry **38:**2011–2024.

Lamars, L. P. M., A. Smolders, and J. Roelofs. 2002. The restoration of fens in the Netherlands. Hydrobiologia **478:**107–130.

Leifeld, J., M. Muller, and J. Fuhrer. 2011. Peatland subsidence and carbon loss from drained temperate fens. Soil Use and Management **27:**170–176.

Lucchese, M., J. Waddington, M. Poulin, R. Pouliot, L. Rochefort, and M. Strack. 2010. Organic matter accumulation in a restored peatland: evaluating restoration success. Ecological Engineering **36:**482–488.

Macrae, M. L., K. J. Devito, M. Strack, and J. M. Waddington. 2013. Effect of water table drawdown on peatland nutrient dynamics: implications for climate change. Biogeochemistry, **112:**661–676.

Natural Resources Conservation Service, National Water and Climate Center, 1987–2010. (available from http://www.wcc.nrcs.usda.gov/snotel/Colorado/colorado.html) [Accessed March 1, 2011].

Patterson, L., and D. Cooper. 2007. The use of hydrologic and ecological indicators for the restoration of drainage ditches and water diversions in a mountain fen, Cascade Range, California. Wetlands **27:**290–304.

Price, J. 1996. Hydrology and microclimate of a partly restored cutover bog, Quebec. Hydrological Processes **10:**1263–1272.

Riutta, T., J. Laine, and E. Tuittila. 2007. Sensitivity of CO_2 exchange of fen ecosystem components to water level variation. Ecosystems **10:**718–733.

Rochefort, L., F. Quinty, S. Campeau, K. Johnson, and T. Malterer. 2003. North American approach to the restoration of *Sphagnum* dominated peatlands. Wetlands Ecology and Management **11:**3–20.

Samaritani, E., A. Siegenthaler, M. Yli-Petays, A. Buttler, P. Christin, and E. A. D. Mitchell. 2011. Seasonal net ecosystem carbon exchange of a regenerating cutaway bog: How long does it take to restore the C-sequestration function? Restoration Ecology **19:**480–489.

Schlotzhauer, S., and J. Price. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: field and laboratory investigations. Water Resources Research **35:**3675–3683.

Shantz, M., and J. Price. 2006. Hydrological changes following restoration of the Bois-des-Bel peatlands, Quebec, 1999–2002. Journal of Hydrology **331:**543–553.

Vourlitis, G., W. Oechel, S. Hastings, and M. Jenkins. 1993. A system for measuring in situ CO_2 and CH_4 flux in unmanaged ecosystems: an arctic example. Functional Ecology **7:**369–379.

Waddington, J., K. Warner, and G. Kennedy. 2002. Cutover peatlands: a persistent source of atmospheric CO_2. Global Biogeochemical Cycles **16:**1002.

Waddington, J., M. Strack, and M. Greenwood. 2010. Toward restoring the net carbon sink function of degraded peatlands: short-term response in CO_2 exchange to ecosystem-scale restoration. Journal of Geophysical Research **115:**G01008.