THESIS

THE EFFECTS OF LONG TERM DRAINAGE AND RESTORATION ON SOIL PROPERTIES OF SOUTHERN ROCKY MOUNTAIN SEDGE FENS

Submitted by

David W. Schimelpfenig

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Master's Committee:

Advisor: David J. Cooper

John S. Sanderson
Gregory Butters

ABSTRACT

THE EFFECTS OF LONG TERM DRAINAGE AND RESTORATION ON SOIL PROPERTIES OF SOUTHERN ROCKY MOUNTAIN SEDGE FENS

Mountain sedge fens are unique ecosystems which require thousands of years to form, provide refuge for rare plant species, and are easily disturbed by human activity. Peatland soils are significant players in the global carbon cycle, storing 1/3 of the terrestrial carbon stock. Drained peat is a persistent source of atmospheric CO_2, restoring the carbon storage function to disturbed peatlands is an increasingly important justification for peatland restoration. I measured water table dynamics and CO_2 flux at three small fens (< 10 ha) in SW Colorado for one year before and one year after restoration. The fens were hydrologically restored with the installation of small check dams in ditches that had drained the sites for a century. Water tables in restored areas increased during the driest periods of the summer from -45 cm below the surface to -15 cm. We measured CO_2 flux (net ecosystem exchange (NEE), ecosystem respiration (ER), and gross ecosystem photosynthesis (GEP)) bi-weekly during the two growing seasons using an infrared gas analyzer attached to a 60 x 60 x 60 cm closed chamber. Mean NEE over the two year study was lowest in the disturbed areas (-1.28 g CO_2 m^{-2} hr^{-1}). Mean NEE in the reference area was -1.74 g CO_2 m^{-2} $hr^{-1}$and in the restored areas was -2.19. Mean ER was similar across treatments, ranging from 0.77 and 0.92 g CO_2 m^{-2} hr^{-}

[1]. Soil samples were extracted from three fens restored during this study and 1 restored in 1990 to test the effects of long term drainage and restoration on the physical properties of peat soil including; bulk density, porosity, % organic matter (OM), residual water content, and saturated hydraulic conductivity. Disturbance has caused significant changes in the peat soil including; 25% reduction in soil OM, increased bulk density, decreased porosity, and reduced saturated hydraulic conductivity. These effects persist in peat soil 20 years after restoration. Calculated OM losses of 1.4 to 3.6 kg m^{-2} have resulted in an estimated loss of 14.7 to 91 tons OM from each of these fens. The hydrologic regime and CO_2 storage has been successfully restored in these fens, while the peat soil bears a legacy of disturbance two decades after restoration.

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1. INTRODUCTION

Peatlands have a strong influence on the global carbon cycle, storing approximately one third of the terrestrial soil carbon stock (Gorham 1991). The accumulation of organic matter (OM), which forms peat soil, is a slow process occurring where the production of plant matter outpaces decomposition on a time scale of centuries to millennia (Ivanov 1981). Carbon dating of Rocky Mountain peat suggests that basal soil layers are up to 12,000 years old (Cooper 1990). The slow buildup of peat over millennia reflects the long term stability of these ecosystems. In addition to carbon storage, other valuable peatland functions include; 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 Rockies are fed by groundwater sources in addition to direct precipitation and are classified as fens (Cooper & Adrus 1994; Bedford & Godwin 2003). Approximately 2,000 fens occur in the San Juan Mountains covering less than one percent of the land area (Chimner et al. 2010). These fens enhance regional biodiversity by providing important habitat for species that are disjunct from their dominant range by thousands of kilometers (Cooper 1996).

In-situ plant growth is the primary carbon input to peatland ecosystems, with more than half of annual net primary productivity being root growth (Chimner & Cooper 2003a). Near surface water tables create anoxic soil conditions that inhibit microbial activity, reducing decomposition of plant material and soil CO_2 emissions. Lowering the natural water table can cause a peatland to switch from a net sink to a net source of atmospheric carbon (Waddington et al. 2002; Chimner & Cooper 2003b), increasing microbial activity, decomposition rates (Cooper et al. 1998; Ellis et al. 2009), soil respiration (Laiho 2006), and causing changes in the vegetation composition (Coulson et al. 1990). Peatland drainage causes subsidence and consolidation resulting from increased OM decomposition, both of which lead to increases in soil bulk denisty (Minkkinen & Laine 1998). A peat soil with increased density will have reduced saturated hydraulic conductivity and water storage capacity (Schlotzhauer & Price 1999).

Fens rely on local and regional groundwater sources to maintain saturated soil conditions. Because of the narrow range of environmental conditions in which peat soils develop and the connection to larger scale hydrology, fens are good indicators of long term stability and present health of their surrounding watersheds. Mountain fen function is sensitive to variations in climate (Ise et al. 2008) and disturbance that alters their hydrologic regime. Nearly 1/4 of San Juan fens have been affected by some form of disturbance with the most significant impacts being from roads, housing, mining, and drainage ditches (Chimner et al. 2010). Road cuts and ditches intercept ground water flowing through fens, cutting off the water supply to the soil and increasing the depth of aerobic soil.

Previous efforts to restore drained peatlands have reestablished hydrologic regimes and natural vegetation (Cooper et al. 1998; Wilcox et al. 2006; Patterson & Cooper 2007). Blocking or filling ditches has commonly been used to restore peatland hydrologic regimes (Armstrong et al. 2009; Malson et al. 2010). Rewetting the soil is a primary goal in fen restoration, because the native vegetation can reestablish only after hydrologic conditions are restored (Heikkila & Lindholm 1995). Although hydrologic regimes and vegetation can be restored on relatively short time scales of years to decades, the effects of drainage on peat soil may persist for longer periods of time.

A key topic in peatland restoration is determining how to measure success. A growing body of information suggests that some processes and characteristics of natural peatlands can be restored in a relatively short time frame. Appropriate vegetation cover has been returned to bogs in eastern Canada in 3-5 years (Rochefort et al. 2003), while carbon dynamics and the carbon sink function of a northern peatland was predicted to return 6 – 10 years following restoration (Waddington et al. 2010). Water table level of a Rocky Mountain fen was restored rapidly with ditch blocking techniques (Cooper et al. 1998). However, in a comparative study of hydrologic regimes of blanket peatlands in northern England, restoration was not successful 6 -7 years following the implementation of a restoration program (Holden et al. 2011). Luccese et al. (2010) set the goal for successful restoration to be achieved when the accumulation of OM in the acrotelm is thick enough to contain seasonal water table fluctuations. In these restored Canadian bogs, where new soil accumulates in peatlands at nearly 1 cm per year, this goal could be achieved in 20-30 years. However, soil accumulates at the rate of 20 cm per 1000 years in Rocky Mountain peatlands (Cooper 1990) despite similar net primary production of Rocky Mountain fens and boreal peatlands (Chimner and Cooper 2003a). The slower soil accumulation is attributed to increased density of soil in sedge fens compared to peatlands with *Sphagnum* mosses.

Understanding the rate of OM loss caused by increased decomposition in drained peatlands is necessary to estimate the effects of disturbance and accurately assess the benefits of restoration. Without active restoration efforts these ecosystems will continue to be sources of atmospheric C rather than sinks (Waddington et al. 2002). Chamber measurements can be a responsive and non-invasive method for measuring gas fluxes from fens (Vourlitis et al. 1993). However, caculating entire system carbon budgets from chamber measurements of gas flux was found to underestimate the total loss from peatlands when compared to methods based on quantifying soil carbon pools (Gronlund et al. 2008). Estimates of OM losses from northern peatlands vary by method, and the most accurate measurements of OM losses would require knowledge of peat thickness, bulk density, and OM content before the disturbance occurred, which rarely exists. A method which calculates OM losses from differences in ash content of drained, harvested, and afforested peat from ombotrophic bogs in Switzerland with background levels found in older, deeper peat, estimated OM losses of 15 to 50% from peat sampled at depths up to 1 m and was applicable in both disturbed and relatively natural sites (Leifeld et al. 2011).

While many studies have addressed the effects of disturbance on peatlands and the results of restoration, most studies have been on *Sphagnum* dominated peatlands (Price 1996, Gorham & Rochefort 2003, Shantz & Price 2006, Luccese et al. 2010, Holden et al. 2011). Investigations of sedge fen restoration have focused primarily on vegetation community changes (Cooper & Macdonald 2000; Patterson & Cooper 2007), the maintenance of high water tables (Cooper et al. 1998), and carbon dynamics (Chimner & Cooper 2003a).

I worked in four Colorado fens, each of which had experienced hydrologic disturbances created by ditches (Figure 1). One site was restored prior to and the other three during the study period. The objectives of this study were to analyze the effects of long-term drainage and recent ditch blocking on hydrologic conditions, soil properties, and CO_2 fluxes at four Rocky Mountain sedge fens. I hypothesized that long term drainage led to increased ecosystem respiration and OM decomposition, decreased carbon uptake, and persistent losses of soil OM. The altered soil environment conditions developed peat soil with increased bulk density, reduced porosity and residual water content, and slower saturated hydraulic conductivity. Further, following restoration, I hypothesized that fen water table fluctuations and CO_2 flux would reflect reference conditions while the soil profile would not change in response to hydrologic restoration on the time scale of this study. Drained peat soils would retain the legacy of disturbance in altered physical soil properties for at least 20 years. Finally, total losses in OM are calculated for each fen based on differences in bulk density and OM content between reference fens and restored peat.

2. SITE DESCRIPTION

The San Juan Mountains, in southwestern Colorado, are the highest elevation Rocky Mountain range, with 14 peaks exceeding 4,270 m (14,000 ft) elevation, and hundreds of peaks above 3,660 m (12,000 ft). The range is geologically complex, having a core of Precambrian crystalline rocks with areas of localized volcanism and intrusive igneous rock. The climate is typically cool, with a bimodal precipitation pattern including significant winter snowfall and late summer monsoon rain. The mean annual temperature (1909-2009) for Silverton, CO is 1.9 °C (NOAA 1909-2009). A deep winter snowpack provides early season surface water flow and recharges aquifers, which deliver groundwater to fens through natural springs and high water tables discharging from toeslopes. Monsoon rains provide the region with a precipitation pulse in late summer when ground water levels begin to recede following the typically dry early summer (Table 1). Two of the study fens are located outside of the San Juan Mountains. NE Eggleston fen is located on Grand Mesa, a 3,000 m elevation basalt capped mesa in the Grand Mesa, Uncompahgre, Gunnison National Forest in western Colorado. Big Meadows fen is located within Rocky Mountain National Park (RMNP) in north central Colorado. Both Grand Mesa and RMNP experience similar precipitation and temperature regimes as the San Juan Mountains.

Lateral Moraine fen (LM) covers approximately 1.5 hectares at an elevation of 3100 m in the Trout Lake watershed. The vegetation was dominated by *Carex aquatilis* and *C. utriculata*. This fen had 8 ditches or channels of unknown origin flowing south through the fen, joining to form one outlet in the southwest corner. Restoration began in 2008 with the partial blocking of one major channel with peat bag dams. In 2009 five ditches on the west side of the fen were blocked using a combination of peat bag and plywood dams. The eastern half of the fen was left in the disturbed condition. A suitable reference fen for LM was located approximately 100 m upslope. I analyzed the reference, restored, and disturbed areas in or associated with LM.

Pirate ship fen (PS) is located in the upper Uncompahgre River watershed. It is a sloping fen approximately 10 hectares in size with vegetation dominated by *Carex aquatilis, Eleocharis quinqueflora,* and *Salix planifolia.* Several ponds were present as was a ~0.3 km long straight diversion ditch running south to north through the east side of the fen, and a natural stream channel running northwest through the southwest side of the fen. The ditch was likely built to divert water from Simpson's Creek for use in mining activities occurring north of the fen. The stream diversion was upslope from the fen on its southeast corner. Seven check dams were installed in September 2009 to eliminate flow through ditches and redistribute water across the fen surface as sheet flow. Four additional dams were installed to promote water redistribution in areas not affected by the initial dam placements. PS had reference, restored, and disturbed areas with soil samples extracted from reference and restored areas.

NE Eggleston fen (NE) is a sloping fen dominated by *Carex aquatilis* and *C. utriculata*. Near its northern end groundwater discharges from the surrounding hills and the vegetation has a high cover of *Eleocharis quinqueflora*. A ditch running north to south through the center of the fen captured surface and groundwater inputs from the western half of the fen drying up portions of the fen's eastern half. *Salix planifolia* was present along the length of the ditch, especially on the east bank. Restoration took place in midsummer 2009 with the installation of five plywood and eight peat dams. NE had reference, restored, and disturbed areas.

Big Meadows fen (BM) was studied to compare peat from a site restored 21 years ago with peat from LM, PS, and NE fens that were restored during this study. BM was ditched in the early 1900's for agricultural use. The ditch was not maintained after the establishment of the Rocky Mountain National Park in 1915, but continued to intercept surface and groundwater flow. In 1990 sheet metal dams were installed along the length of the ditch, effectively restoring hydrologic conditions to much of the fen (Cooper et al. 1998). The vegetation composition of this fen is similar to the San Juan and Grand Mesa fens, and is dominated by *Carex aquatilis* and *C. utriculata,* with *Salix planifolia* around the margins. BM had reference and restored areas.

3. MATERIALS AND METHODS

3.1 FIELD AND LABORATORY METHODS

3.1.1 Depth to Water Table

Groundwater monitoring wells were constructed with 5.1 cm inside diameter schedule 40 PVC pipe slotted over their entire length and installed into hand augered holes that were backfilled with native soil in LM, PS, and NE (Table 2). Depth to the water table was monitored bi-weekly during the snow free period from late May to September in 2008, 2009, and 2010. Water levels were also recorded hourly in selected wells in LM disturbed and restored treatments, and PS disturbed and reference using submersible pressure transducers (WL 15, Global Water Instrumentation, Inc). Negative values indicate depth of water table below the ground surface.

3.1.2 CO_2 flux

Mid-day CO_2 flux was measured using the chamber method (Vourlitis et al. 1993) during the growing seasons of 2009 and 2010. was measured with Measurements were taken in 5 – 6 replicate marked plots placed along the circumference of a 3 m radius circle centered around groundwater monitoring wells in reference, disturbed, and restored treatments at LM (4 wells, 20 plots), PS (3 wells, 18 plots), and NE (3 wells, 18 plots). CO_2 flux measurements were made every 10 – 14 days during June – August using a 60 x 60 x 60 cm chamber constructed of plexiglass and fitted with circulating fans to ensure adequate mixing of air within the chamber. CO_2 concentration within the chamber was analyzed using an Infrared Gas Analyzer (EGM-4, PP Systems) for 1 – 2 minutes until a linear rate of change was established. Net ecosystem exchange (NEE), which is the net CO_2 exchange between the ecosystem and the atmosphere, was measured with a 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 lid was opened between measurements to ventilate air within the chamber. Gross ecosystem photosynthesis (GEP) is 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 to the peatland, positive values indicate a loss of CO_2 to the atmosphere.

3.1.3 Soil Properties

Undisturbed peat cores were extracted from near selected disturbed, reference, and restored wells with a fine toothed saw and PVC cylinders using methods similar to Schlotzhauer and Price (1999). The cylindrical sampling tube was carefully pressed into the peat while cutting around the outer edge of the core to minimize soil compression and ensure a tight seal between the peat and the container wall. Three samples were taken from each of three depths, 0-15, 15-30, and 30-45 cm. Two samples were extracted for measuring horizontal and vertical saturated hydraulic conductivity (d = 6.4 cm, L = 10.0 cm). The third undisturbed peat sample was collected in PVC sampling rings (d = 5.3 cm, L= ~2.5cm) to measure soil water retention, bulk density, porosity, and percent OM. All soil samples were collected in late summer and kept sealed and refrigerated until measurements were made.

Bulk density (ρ_b) was measured by weighing samples oven dried at 105 °C for 24 hours ($m_{dry\ soil}$) and using saturated soil volume (V_{soil}).

$$\rho_b = \frac{m_{dry\ soil}}{V_{soil}} \qquad (1)$$

Organic matter content was determined by heating 2 g dry soil samples at 550°C for 4 hr. Percent ash and percent OM were calculated as:

$$\%Ash = \left(\frac{m_{ash}}{m_{dry\ soil}}\right) * 100 \qquad (2)$$

$$\%\ OM = 100 - \%Ash \qquad (3)$$

Determining the original quantity of soil carbon and estimating the loss from disturbance with surety requires knowledge of soil bulk density, percent OM, and depth both before and after disturbance. When quantifying losses in OM, changes in peat volume from subsidence need to be calculated before OM loss from increased decomposition can be accurately assessed. Using a mass balance approach, estimations of peat subsidence are derived from measured differences in bulk density between reference and restored areas, with reference depth (L_{ref}) being fixed at the upper level sampling depth (15 cm).

$$L_{dist} = \frac{\rho_{b-ref} * L_{ref}}{\rho_{b-dist}} \qquad (4)$$

Using the corrected peat depth (L_{dist}) the quantity of soil OM in reference and restored areas can be calculated, with the difference being an estimate for the amount of

OM lost from disturbed soils. Significant changes in soil properties occurred only in the upper 15 cm; therefore changes in OM are reported for this sampling depth.

$$OM = \rho_b * L * \%OM \quad (5)$$

$$\Delta OM = [\rho_{ref} * L_{ref} * \%OM_{ref}] - [\rho_{rest} * L_{rest} * \%OM_{rest}] \quad (6)$$

Soil water retention characteristics were measured in the laboratory on a pressure plate apparatus as described by Klute (1986) where an undisturbed peat sample was saturated for 24 hours, weighed, and placed on a porous plate with tension applied to the system with either a hanging water column or by applying air pressure. Volumetric moisture content (VMC) 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 (> -1 bar) and 7 days at higher tensions (< -1 bar). VMC values were fit to the Van Genuchten equation using HYDRUS 1D software, with variables for residual water content (θ_r), α, and n,

$$\theta(h) = \frac{(\theta_s - \theta_r)}{[1+(\alpha|h|)^n]^m} + \theta_r \quad (6)$$

where m = (1-1/n). Porosity was assumed to be equal to the saturated water content (θ_s). Schwarzel et al. (2002) found the standard error of pressure plate measurements of soil water retention to be within 5% of field measurements. Air entry tension is related to the inverse of α.

Saturated hydraulic conductivity (K_s) was measured in the laboratory by placing undisturbed peat samples in a constant head permeameter (ASTM:D4511-00 2006). Samples were saturated for greater than 72 hrs at room temperature in a 0.005 mol $CaCl_2$ solution, with 3 grains of Thymol to reduce microbial activity (Allison 1947). Solution was ponded over saturated samples until water flux through the soil achieved a constant rate. K_s is calculated using Darcy's law, where dh = hydraulic head, dl= column length, and q= volume of water per unit time discharging from bottom of sample.

$$q = K_s * \frac{dh}{dl} \tag{7}$$

Care was taken during extraction to ensure a good fit of the soil in the cylinder to eliminate the potential for sidewall flow. In cases where high flow rates or obvious gaps were observed between the soil and PVC cylinder, heated paraffin wax was poured around the edge of the sample to enhance the sidewall seal.

3.2 STATISTICAL ANALYSIS

Repeated measures analysis of variance (ANOVA) was used to analyze bi-weekly measurements of water table levels at LM, from June – September 2009 and 2010 using the Proc Mixed procedure (SAS 9.2) with each well representing an experimental unit. Comparisons were made for each year within each fen by treatment as well as pre – 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 GEP) were analyzed with Repeated measures ANOVA with each plot representing an experimental unit. Comparisons were made for each year and fen by well. Additionally, comparisons within fen and well were made across years to test for responses to restoration at PS and NE sites. Treatment means across all sites by treatment were compared by pooling from 2009 and 2010. NE well 2E and PS well 25P data were included in the disturbed treatment in 2009 and restored treatment in 2010. Differences in treatment means were compared using Tukey's HSD post hoc adjustment with $p < 0.05$ considered significant.

The measured soil property values were not normally distributed, therefore differences in means between treatments (restored and reference) were analyzed with the non parametric Wilcoxon Rank Sums test using Proc npar1way (SAS 9.2). Two-sided p values < 0.05 were considered significant for comparisons made between treatment means at each sample depth. Samples collected from disturbed wells (n = 4) at LM were pooled with restored samples from all fens for analysis.

4. RESULTS

4.1 PRECIPITATION AND TEMPERATURE

Twenty year mean annual temperature at nearby snow telemetry stations (NRCS 1987 - 2010) from 1987 – 2006 were between -0.7 °C and 0.1°C (Table 3). During the study period, mean annual temperatures were 0.7 to 2.4°C warmer than the 20 year mean. A study of temperature trends in the San Juan Mountains (Rangwala and Miller 2010) indicated that temperatures had risen ~1°C from 1990 – 2005 above the long term average, thus temperatures during this study were approximately 1.7 – 3.4 °C warmer than the previous century.

Precipitation patterns during 2009 and 2010 were distinctly different. Winter snowpack was similar for both study years, near the 20-yr (1980 – 2000) average. Early summer (April – June) 2009 was cool and wet, with precipitation well above the 20-yr average. The 2009 monsoon season did not begin until late August resulting in below average late summer rainfall. Summer precipitation in 2010 was similar to the average, with slightly below average early summer precipitation, and an average monsoon that started in late July (Figure 2). Total precipitation in both study years was slightly below the 20-yr average for all study sites. (Table 1).

4.2 DEPTH TO WATER TABLE

Prior to restoration, mean water tables in disturbed and pre-restored treatment wells were not statistically different ($p > 0.99$) in any fen. The mean reference water table in 2009 at PS (-6.1 cm) was significantly higher than in pre-restored (-26.6 cm, $p = 0.001$) and disturbed (-28.8 cm, $p = 0.002$) area wells. Mean reference water table in 2009 at NE (-14.4 cm) was higher than in pre-restored (-19.2 cm) and disturbed (-32.0 cm) wells although the differences were not significant ($p > 0.75$). Mean pre- restored water table in 2008 at LM (-35.0 cm) was similar to disturbed (-35.8 cm, $p = 1.00$). LM reference wells were not installed until after restoration and pre-restoration water table comparisons could not be made.

Ditch blocking significantly increased seasonal mean water tables by 35, 15 and 17 cm in the restoration treatment areas at LM, PS, and NE fens. The 2009 to 2010 mean water table changes in restored sections are all highly significant ($p < 0.0001$) (Table 4). Mean water tables in restored sections of BM were significantly higher in all but the driest water years following restoration, with water tables in the restored water track falling below -20 cm for only 1 week in normal precipitation years (Cooper et al. 1998). Following restoration, mean water tables in restored and reference areas were statistically similar ($p > 0.40$) at LM, PS, and NE (Table 4) while disturbed site mean water tables remained significantly deeper than in reference and restored treatments in LM (2009 and 2010) and PS (2010). Mean water table in 2010 at NE was lower in the disturbed treatment (-22.3 cm), but was not significantly lower than either reference (-8.1 cm, $p =$

0.82) or restored (-1.9 cm, $p = 0.27$). Ditch blocking also resulted in increased stability in seasonal water table levels in restored treatments (Figure 2).

4.3 CO_2 FLUX

4.3.1 Net Ecosystem Exchange

In 2009, before restoration began at PS fen, NEE in the reference area was greater than both the disturbed and restoration areas on each measurement date. The mean reference area NEE (-2.14 g CO_2 m^{-2} hr^{-1}) was significantly greater ($p < 0.05$) than both disturbed and restoration areas. In 2010, following restoration, NEE was greatest in the restoration area increasing from a 2009 mean of -1.23 g CO_2 m^{-2} hr^{-1} to -1.68 g CO_2 m^{-2} hr^{-1} ($p = 0.29$), while the disturbed area NEE remained unchanged at -0.66 g CO_2 m^{-2} hr^{-1} and the reference area NEE decreased significantly to -1.36 g CO_2 m^{-2} hr^{-1} ($p = 0.008$). This decrease could have been caused by consistent rainfall and near surface water table throughout the 2010 growing season (Figure 2). Mean air temperatures within the chamber for all NEE measurements within all fens during both study years was 25.1 °C (± 4.7, 1 standard deviation).

At NE fen in 2009, pre-restoration NEE in the reference areas were greater than the restoration area (Figure 3). The mean NEE for reference well 1E increased in 2010 from a 2009 mean of -1.15 g CO_2 m^{-2} hr^{-1} to -2.01 g CO_2 m^{-2} hr^{-1}. Meanwhile NEE at reference well 9E decreased from -2.14 g CO_2 m^{-2} hr^{-1} in 2009 to -1.36 g CO_2 m^{-2} hr^{-1} in 2010. Following restoration, NEE was not significantly different between reference and restored areas but the restored NEE increased significantly ($p = 0.013$) from a 2009 mean of -0.94 g CO_2 m^{-2} hr^{-1} to -2.12 g CO_2 m^{-2} hr^{-1} in 2010.

At LM fen in 2009 all CO_2 flux measurements were made after restoration was implemented. There were no significant differences in mean NEE between disturbed, restored, or reference areas. In 2010, mean NEE for reference and disturbed areas was slightly lower than 2009 means, while NEE at both restored areas increased (Figure 3).

4.3.2 Gross Ecosystem Photosynthesis

During both study years, GEP at PS fen was lower in the disturbed area on each measurement date than either reference or restored areas. Mean 2010 GEP for the reference area decreased significantly ($p < 0.001$) from -2.91 g CO_2 m^{-2} hr^{-1} in 2009 to -1.84 g CO_2 m^{-2} hr^{-1}. GEP in the disturbed area decreased slightly from a mean of -1.30 g CO_2 m^{-2} hr^{-1} in 2009 to -1.22 g CO_2 m^{-2} hr^{-1} in 2010. In contrast, the restored area GEP increased from -2.01 g CO_2 m^{-2} hr^{-1} in 2009 to -2.42 g CO_2 m^{-2} hr^{-1}.

In 2009, the first year following restoration at LM fen, mean GEP in the restored areas was less than the reference and disturbed areas. In the reference area, GEP decreased slightly from a 2009 mean of -2.96 g CO_2 m^{-2} hr^{-1} to -2.72 g CO_2 m^{-2} hr^{-1}. The disturbed area mean GEP also decreased in 2010 to -3.50 g CO_2 m^{-2} hr^{-1} from a 2009 mean of -3.64 g CO_2 m^{-2} hr^{-1}. As with PS fen, both restored areas at LM fen had greater GEP in 2010 than in 2009 with a significant increase ($p < 0.001$) at well 5L (Figure 3).

Pre-restoration GEP at NE fen was not significantly different between the reference areas and the disturbed area. While mean GEP decreased at reference well 9E from -2.8 g CO_2 m^{-2} hr^{-1} in 2009 to -2.27 g CO_2 m^{-2} hr^{-1} in 2010, it increased at reference well 1E mean GEP from -2.45 g CO_2 m^{-2} hr^{-1} in 2009 to -3.30 g CO_2 m^{-2} hr^{-1} in 2010. Following restoration, mean GEP in the restored area increased significantly ($p < 0.01$) from -1.93 g CO_2 m^{-2} hr^{-1} in 2009 to -3.25 g CO_2 m^{-2} hr^{-1} in 2010.

4.3.3 Ecosystem Respiration

In 2009, ER at PS fen was similar in all areas with both restored and disturbed areas decreasing slightly in 2010 following restoration and the reference area significantly decreasing ($p = 0.005$) from .77 g CO_2 m^{-2} $hr^{-1}$to .48 g CO_2 m^{-2} hr^{-1}.

At LM fen, ER was significantly lower ($p < 0.0001$) at restored well 5L in both 2009 and 2010 than either the control or disturbed areas (Figure 3). At each well, mean ER was slightly greater in 2010 than in 2009 with the greatest increase occurring at reference well 5L. Though mean ER at this well significantly increased from 0.22 g CO_2 m^{-2} hr^{-1} in 2009 to 0.54 g CO_2 m^{-2} hr^{-1} in 2010 ($p = 0.01$), the 2010 value is significantly lower ($p < 0.001$) than both the reference (1.16 g CO_2 m^{-2} hr^{-1}) or disturbed (1.36 g CO_2 m^{-2} hr^{1}) means.

Pre restoration mean ER at NE fen in 2009 was greatest in the restoration area, though differences between means at the restored well (0.98 g CO_2 m^{-2} hr^{-1}), and reference wells were not significant. Mean ER in all areas increased in 2010, with the greatest increase at reference well 1E which had a mean ER of 0.90 g CO_2 m^{-2} hr^{-1} in 2009 and 1.28 g CO_2 m^{-2} hr^{-1} in 2010 ($p < 0.001$).

Over the two year study period, mean NEE for all restored areas was significantly greater ($p < 0.014$) than reference and disturbed areas, while mean GEP for all disturbed areas was significantly lower ($p < 0.041$) than either reference or restored areas. (Figure 4). There was not a significant difference in ER between disturbed, reference, or restored areas which had mean values ranging from 0.77 g CO_2 m^{-2} hr^{-1} in the restored areas to 0.92 g CO_2 m^{-2} hr^{-1} in the disturbed areas. Though ER was lowest in areas with standing water, small fluctuations in water table below the ground surface in the dense peats of the study fens had minimal effect on ER (Figure 5).

4.4 SOIL PROPERTIES

Bulk density of the upper 15 cm of peat was significantly less in reference (0.148 g cm^{-3}) than restored samples (0.300 g cm^{-3}) ($p < 0.0001$). Bulk density of samples from below 15 cm depth were not significantly different between plots ($p > 0.50$) with averages of 0.25 - 0.27 g cm^{-3} for both reference and restored samples (Figure 6).

Disturbed peat samples from the upper 15 cm were significantly ($p = 0.019$) less porous (86%) than reference samples (90%). Average porosities from soils below 15 cm depth for reference and restored samples were not significantly different ($p > 0.73$) (Figure 6). Average residual water content in reference samples from the upper 15 cm was 35%, which was lower than the disturbed mean residual water content of 40%, though this difference was not significant ($p = 0.090$). Residual water content below 15 cm depth was similar for each depth and treatment at 42% ($p > 0.86$).

Mean air entry tension was greater in restored samples than reference samples at all sample depths. At depths of 0 – 15 cm, air entry tensions of -34.7 were measured in reference samples and -41.9 cm in restored samples. At 15 - 45 cm depths, values increased with sample depth, with means from -45.5 cm to -52.9 cm.

Steady state water flow rates through saturated peat were significantly slower in the upper 15 cm of restored peat (Figure 6). The vertical saturated hydraulic conductivity was 0.43 cm min^{-1} in reference site samples which was significantly higher ($p = 0.002$) than in disturbed site samples where it was 0.12 cm min^{-1}. Horizontal Ks was 0.53 cm min^{-1} in the reference peat (0-15 cm depth) and 0.28 cm min^{-1} ($p = 0.081$) in disturbed samples. Below 15 cm, both horizontal and vertical Ks was very low (< 0.15 cm min^{-1}) in both disturbed and reference samples with means that were not significantly different ($p > 0.06$) (Figure 6).

Mean OM content in the upper 15 cm of reference samples was 56%, which was significantly higher than that of restored samples, which was 45% ($p = 0.004$). Below 15 cm, OM content ranged from 50 – 55% but differences among reference, restored, and disturbed samples were not significant ($p > 0.41$). Calculations using Eq 4 reveal that disturbed soil has experienced subsidence of 5 – 7 cm from the original 15 cm (Table 5). Incorporating this change in volume with changes in OM content estimates losses from the disturbed areas of fens ranging from 1.4 kg m^{-2} at BM to 3.7 kg m^{-2} at LM (Table 5). Extrapolating these estimates over the entire disturbed areas in each fen reveals total OM losses from the upper 15 cm of peat from 14.7 tons at NE to 91 tons at PS (Table 6).

The difference between restored and reference soil properties at BM was greater than the difference between restored and reference properties at the other study fens for soil bulk density, residual water content, and saturated hydraulic conductivity (Figure 7). However, at BM, there was only a 12% difference between OM content in the restored plot versus the reference plot, which was approximately half the difference between these plots at LM, NE, and PS (within 25%). Below a depth of 15 cm, reference and restored soil properties did not vary by more than 30%, except in saturated hydraulic conductivity, which was highly variable within each treatment.

5. DISCUSSION

Higher summer mean and deepest seasonal water table levels along with decreased seasonal variation in all study fens are strong indicators that hydrologic restoration has been successful (Holden et al. 2011). The use of check dams constructed from plywood and bags filled with peat appear to be appropriate restoration techniques for the disturbances encountered in the San Juan fens. The ditches were generally narrow

(<1 m), shallow (< 0.75 m), low gradient (~1%), and had relatively low flow rates. These factors limited the erosion potential and allowed small, simple structures to block flow in the ditches. Dams must be securely anchored to the ditch walls and channel bottom (> 15 cm deep) to avoid failure by scour under the bottom or sides. The locations where excess water is directed as it flows out of the ditch is important to consider. At low flows it may be possible to redirect water across the fen as sheet flow, an effective method to create stable hydrologic conditions. However, during spring runoff or periods of high intensity precipitation, there is a potential for erosion and the creation of additional channels in poorly vegetated wetlands. Installing v-notch weirs to direct excess water during high flow events through the pre existing ditch is one way to address this concern (Figure 8).

Small check dams and the creation of ponds within the ditch channel can aid hydrologic restoration by storing water which can seep through the soil adjacent to the ditch, as well as reduce seepage into the ditch. This restoration technique is less secure than a more intensive and costly method of infilling the entire ditch with suitable material. Without filling the ditch, successful long-term restoration relies on the continued function of the dam structures. However, similar sheet metal structures placed into Big Meadow in 1990 are still intact after 21 years. Short sections (~1m) of the ditch at each dam structure were filled using peat from offsite that supported the dam structure, and allowed the establishment of a natural plug of vegetation and peat. This treatment may extend the long-term effectiveness of the dam structures. To increase the rate of vegetation colonization, sedge plugs were hand planted in each of the infill sections (9 plugs m^{-2}).

Artificially drained peat soils experienced significant changes in physical properties that remained two decades following restoration. Disturbed peat soil had greater density and lower percent organic matter, lower porosity and greater residual water content, reducing overall soil water storage capacity. With reduced saturated flow rates and less water storage, these disturbed fens are less effective at buffering and reducing sediment from flood water than pristine fens. Significant measured changes in peat properties occurred primarily within the upper 15 cm, where aerobic soil conditions existed. This zone of increased aeration also corresponds with the majority of OM additions from root growth, of which 75% occurs in the upper 20 cm of peat in Rocky Mountain sedge fens (Chimner & Cooper 2003a). Below this depth, saturated soil conditions persisted despite a dramatic annual water table drawdown in disturbed areas due to the abundance of small pores and the capillary fringe extending 35 to 50 cm above the water table. The capillary rise is greater in peat soils that have undergone increased decomposition and consolidation after long term drainage. Degraded peat soil retains high volumetric water content further above the water table than pristine peat, thereby slowing the rate of decomposition. For fen restoration to be deemed successful, it may not be required to maintain a near surface water table throughout the growing season, it is most important to maximize soil saturation by avoiding larger water table reductions that allow aerobic conditions to develop at and below the peat surface.

The estimated OM losses reported here (Table 5) ranging from 1.4 – 3.6 kg m^{-2} are much lower than estimates from cultivated peat soils in Norway of 44 kg m^{-2} (Gronlund et al. 2008) and bogs in Switzerland of 24 – 120 kg m^{-2} (Liefeld et al. 2011). Both of these studies have incorporated losses from peat deposits with disturbance from peat extraction and cultivation and where the natural accumulation rates have produced peat soils which are several times thicker than is typical of Rocky Mountain fens (Cooper 1990; Chimner et al. 2010). The disturbances in these fens originated with mining and development activity around the turn of the 20th century, the reported OM losses are only 10 – 25% of the 70 g C m^{-2} y^{-1} losses predicted due to water table drawdown in a model of Rocky Mountain fen carbon budgets (Chimner & Cooper 2002). The lower OM loss estimates found in this study do not include losses of dissolved organic carbon, or potential losses from deeper in the soil profile.

Converting disturbed peatlands from net atmospheric carbon sources into net sinks is increasingly cited as a driver for peatland restoration and is an important issue given the significant role of peatlands in the global carbon cycle (Rochefort et al. 2003). Studies of disturbed northern peatlands have shown that carbon storage within cutover peatlands resumes after the hydrologic disturbance is restored and the site revegetated (Kivimaki et al. 2008; Waddington et al. 2010). Restored plots within each of this study's fens had greater NEE in 2010 than disturbed plots, indicating that restoration enhanced carbon storage. The ER rates in areas with standing water were similar to those reported in a water table drawdown experiment in another Rocky Mountain sedge fen (Chimner & Cooper 2003b), though in measurements when water tables were below the surface, rates were up to three times greater than the investigators reported. Additionally, restored plots at both PS and NE increased carbon uptake rates in the year following restoration, though this was only statistically significant at NE. Seasonal and inter annual variations in GEP were greater than changes in ER, suggesting that productivity was contributing more to total CO_2 flux than respiration, as was noted by Griffis et al. (2000)

(Figure 3). The minimal change in ER with increasing depth of water table below the surface has been observed in fens in the Rocky Mountains (Chimner & Cooper 2003b) and southern Finalnd (Ruitta et al. 2007). This is likely due to the high water holding capacity, low $K_{s,}$ and abundance of smaller pores that maintain high soil water content as the water table fluctuates below the surface (Deppe et al. 2010).

A necessary pursuit in ecological restoration research is determining how long the effects of disturbance persist following restoration. Restored soil properties in the fens restored during this study (LM, PS, NE) are more similar to their reference conditions than those in BM fen that was hydrologically restored 21 years ago (Figure 7). This is likely due to the increased drainage severity at BM where summer water tables fell to more than 100 cm below the soil surface (Cooper et al. 1998), while the San Juan and Grand Mesa fens had the deepest summer water table depths of only 40 to 60 cm during the study period (Table 4), which limited excessive air entry into the soil and peat oxidation to the most shallow depths (Deppe et al. 2010).

It is not possible to predict a timeline for complete recuperation of peat soil properties with the design of this study, although the smaller difference between reference and restored OM content in BM compared to the recently restored fens as well as lower estimated OM losses may indicate the effects of OM accumulation in the 21 years following restoration. The increase in OM accumulation in recently restored *Sphagnum* dominated Canadian peatlands has also been reported by Lucchese et al. (2010) who regarded this as an indication of successful restoration efforts 8 years after implementation, but which would require 17 years before a new peat layer of sufficient depth to moderate seasonal water table fluctuations was recreated.

6. CONCLUSION

The success of peatland restoration must be evaluated using a predetermined set of goals. A primary goal is often to create hydrologic conditions and vegetation communities which mimic natural peatlands. These conditions are the foundation for reestablishing other natural peatland processes, particularly peat accumulation. With natural seasonal deepest water tables in reference areas of the study fens 10 to 27 cm below the ground surface it may not be necessary to raise the water table to the surface throughout the year in restored fens as the abundance of small pores and low hydraulic conductivity may initially serve as a self preservation mechanism by maintaining high soil moisture content during dry periods and thus slowing the rate of OM loss. High soil moisture content and low soil temperatures, both of which limit soil respiration, may persist well above the measure water table. Therefore, in cases where near surface water tables are not maintained throughout the year, water table position alone, without knowing the distribution of moisture content below the surface, may not be a reliable indicator of peatland health, function, or restoration success.

How long effects of disturbance persist after hydrologic regimes and vegetation communities are restored is a critical topic for investigation. The results of this study suggest that although natural water table levels have been established and the process of carbon sequestration improved, the physical properties of the most disturbed, near surface peat soils do not mimic reference conditions for at least 20 years after restoration was implemented. It is possible that while restoration efforts have created appropriate conditions for peat accumulation, the return of some peatland functions, particularly water storage and filtration, will be impaired until new peat accumulates above the disturbed layers, a process which could take hundreds or thousands of years. Though soil structure of disturbed peatlands remains impaired following hydrologic restoration, environmental conditions which support desired vegetation, peat development, and ecosystem functions including the accumulation of atmospheric carbon have been reestablished.

The ability to restore many natural functions to drained peatlands using cost effective methods is a positive outcome that should encourage land managers to improve the condition of the many disturbed peatlands found in the Rocky Mountains. Without restoration, drained peat will continue to lose stored organic matter and undergo further consolidation. The quantity of OM already lost from these relatively small fens (Table 6) is considerable and makes understanding world peatland response to disturbance and changing climates imperative as well as demonstrating the need to reduce the loss of peatlands through conservation and restoration. Additional research aimed at understanding how restored peatlands function in regards to annual carbon budgets, water retention characteristics, flood buffering, and water quality will be important steps helping to guide future restoration efforts and set realistic expectations for how a restored peatland will function.

Table 1. Seasonal precipitation and April 1st snow water equivalent (SWE) at Pirate Ship fen (PS), Lateral Moraine fen (LM), and NE Eggleston fen (NE).

Fen - SNOTEL Station	April 1 SWE			April - June			July - Sept			Water Year Total		
units: cm	2009	2010	**20 yr avg**	2009	2010	**20 yr avg**	2009	2010	**20 yr avg**	2009	2010	**20 yr avg**
PS - Red Mountain Pass	58.9	57.7	**59.6**	28.2	13.2	**18.0**	14.7	23.1	**22.9**	108.5	101.1	**113.2**
LM - Lizard Head Pass	45.2	41.1	**40.2**	20.1	9.4	**12.8**	9.7	16.3	**18.6**	70.1	59.2	**83.5**
NE - Park Reservoir	61.7	60.5	**73.6**	25.9	19.8	**16.2**	7.1	19.6	**19.4**	104.9	108	**112.8**

Table 2. Number of groundwater monitoring wells in fens restored during this study period. Wells were constructed of 5.1 cm I.D. PVC pipe slotted along entire pipe length.

Fen / Area	Reference	Restored	Disturbed
Pirate Ship Fen	8	13	5
Lateral Moraine Fen	9	17	19
NE Eggleston Fen	7	6	2

Table 3. Mean daily temperatures (°C) from SNOTEL stations. The 20 yr average is from oldest 20 years which data is available from all 3 SNOTEL stations.

Year	**LM**	**PS**	**NE**
2009	2.3	1.1	1.9
2010	1.9	0.5	1.4
20 yr Average (1987 - 2006)	0.1	-0.2	-0.7

Table 4. Water table mean, low, and variation for summer seasons (June to September) 2008 – 2010 averaged by treatment within each fen. 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 pre treatment at Lateral Moraine fen and 2009 used for pre treatment at Pirate Ship and NE Eggleston fens.

	Mean Water Table (cm)			Annual Water Table Minimum (cm)			Annual Water Table Amplitude (cm)		
Pirate Ship Fen	2008	2009	2010	2008	2009	2010	2008	2009	2010
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 Fen									
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 *	-35.8$_a$	-18.7$_b$	-36.3$_b$	-55.5	-43.8	-58.0	45.9	39.5	45.0
NE Eggleston Fen									
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

* indicates pre to post restoration mean water table difference is significant ($p < 0.0001$).

Table 5. Quantity of organic matter (OM) and OM loss for top 15 cm of reference soil and bulk density corrected depth (L_{dist}) for disturbed soil.

	Reference OM ($g\ cm^{-1}$)	L_{dist} (cm)	Disturbed OM ($g\ cm^{-1}$)	**OM Loss ($Kg\ m^{-2}$)**
Pirate Ship Fen	1.72	10.2	1.50	**2.13**
Lateral Moraine Fen	1.60	9.9	1.23	**3.66**
NE Eggleston Fen	1.61	11.8	1.44	**1.73**
Big Meadows Fen	1.23	8.3	1.08	**1.43**

Table 6. Study fens summary information. Disturbed and restored areas are estimates derived from GIS analysis of orthophotos and field surveys. Organic matter (OM) losses extrapolated areas from average OM difference between reference and restored treatments. Positive OM loss values reflect calculated losses from upper 15 cm of soil from the disturbed area in each fen.

	Pirate Ship Fen	Lateral Moraine Fen	NE Eggleston Fen	Big Meadows Fen
UTM	13s, 271994 E, 4203980 N	13s, 247767 E, 4188593 N	13s, 256663 E, 4325882 N	13t, 431280 E, 4463413 N
Elevation	3570 m	3100 m	3100 m	2865 m
Condition[a]	Fair	Poor		
HGM type[a]	Sloping	Sloping	Sloping	Sloping
Vegetation class[a]	Sedge	Sedge	Sedge	Sedge
Restoration Priority[a]	Very High	High		
Area (m^2)	101152	14922	28708	63000
Disturbed Area (%)	42680 (42%)	14922 (100%)	8549 (30%)	
Restored Area (%)	36351 (36%)	5551 (37%)	5627 (20%)	
OM Loss - (kg OM)	91034	37637	14784	

[a] (Chimner et al. 2010b)

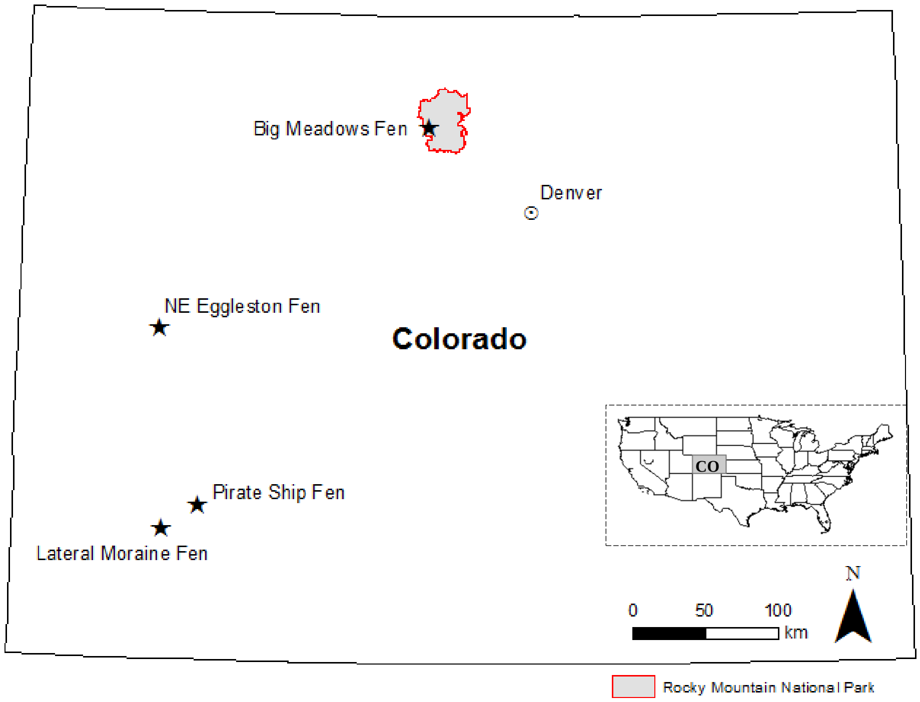

Figure 1.Location of study fens in Colorado, USA.

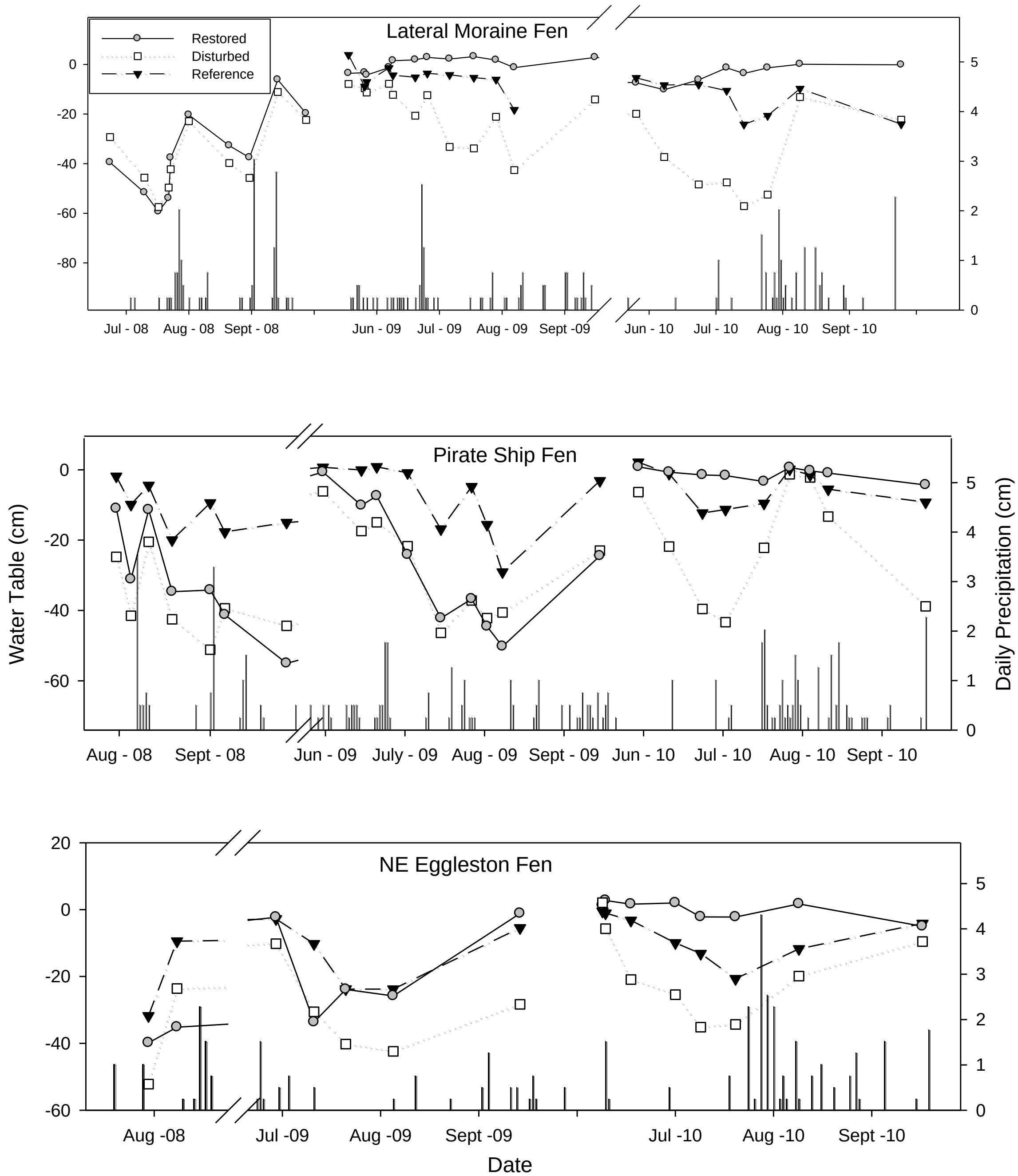

Figure 2. Depth to water table and daily precipitation for Lateral Moraine, Pirate Ship, and NE Eggleston fens for the study period. Water table values are averaged by treatment within each fen for each measurement day. Daily precipitation amounts were obtained from NRCS SNOTEL stations at similar elevation and within 7 miles of each fen.

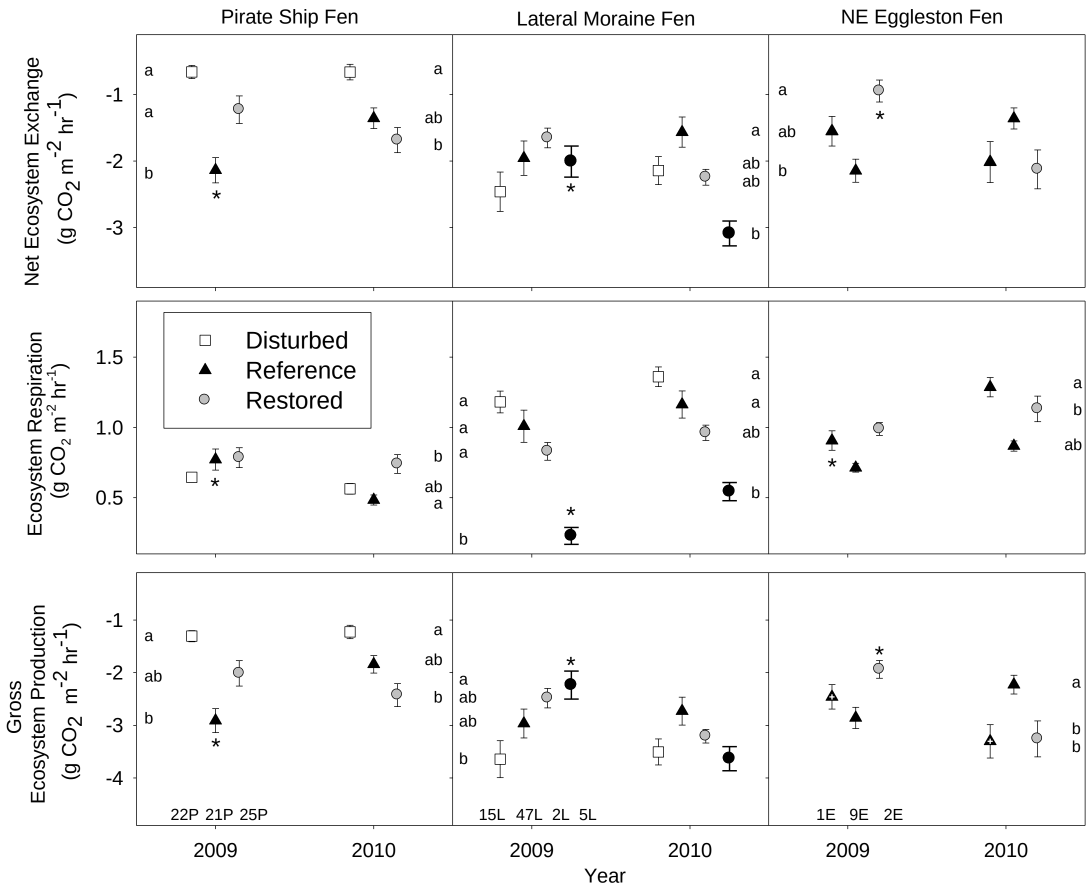

Figure 3. Mean CO_2 flux by well and year at each study fen. Error bars show 1 standard error from the mean. Negative values indicate CO_2 uptake into fen soil, positive values indicate loss to atmosphere. (*) indicates 2009 mean significantly different from 2010 mean within each treatment ($p < 0.05$). Letters indicated statistical significance of fluxes compared across treatments within each fen and year. Flux means within each year with same letter are not significantly different ($p > 0.05$). Well numbers are included along x-axis for reference.

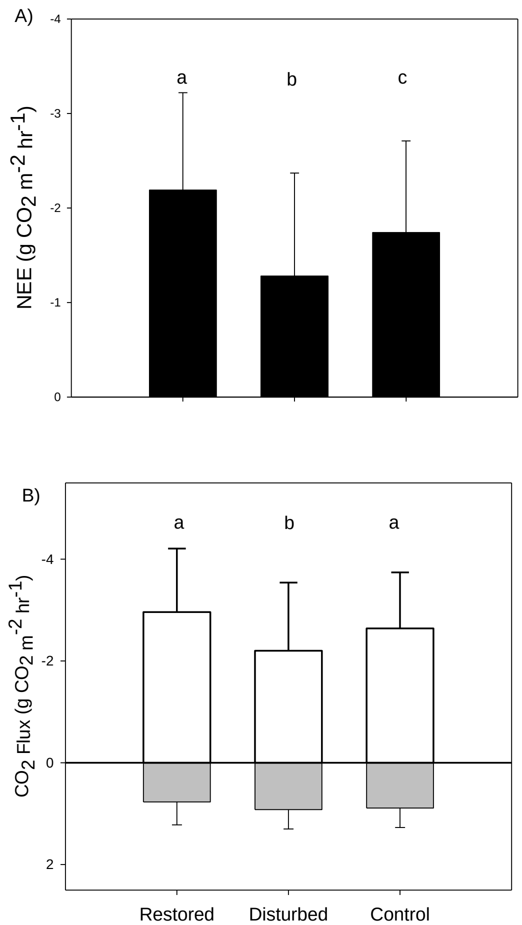

Figure 4. Mean CO_2 flux by treatment with data pooled from both study years and all study fens. A) Net Ecosystem Exchange (NEE). B) *white bars* - Ecosystem Respiration (ER) and *grey bars* - Gross Ecosystem Photosynthesis (GEP). Error bars indicate 1 standard deviation from the mean. Treatment means with the same letter are not significantly different ($p > 0.05$).

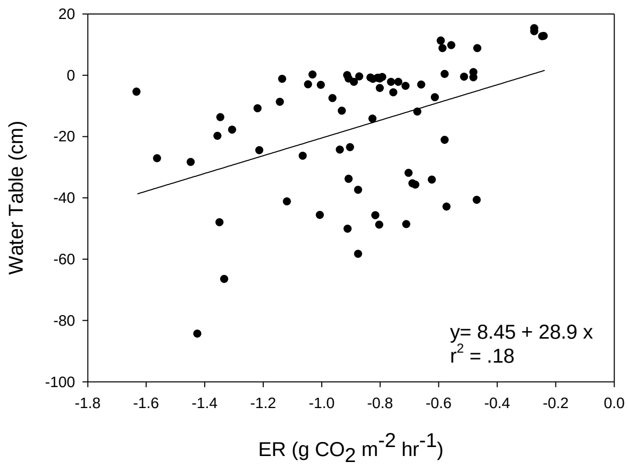

Figure 5. Ecosystem respiration (ER) from all fens and both study years plotted against depth to water table. Negative ER indicates loss of CO_2 from fen to atmosphere.

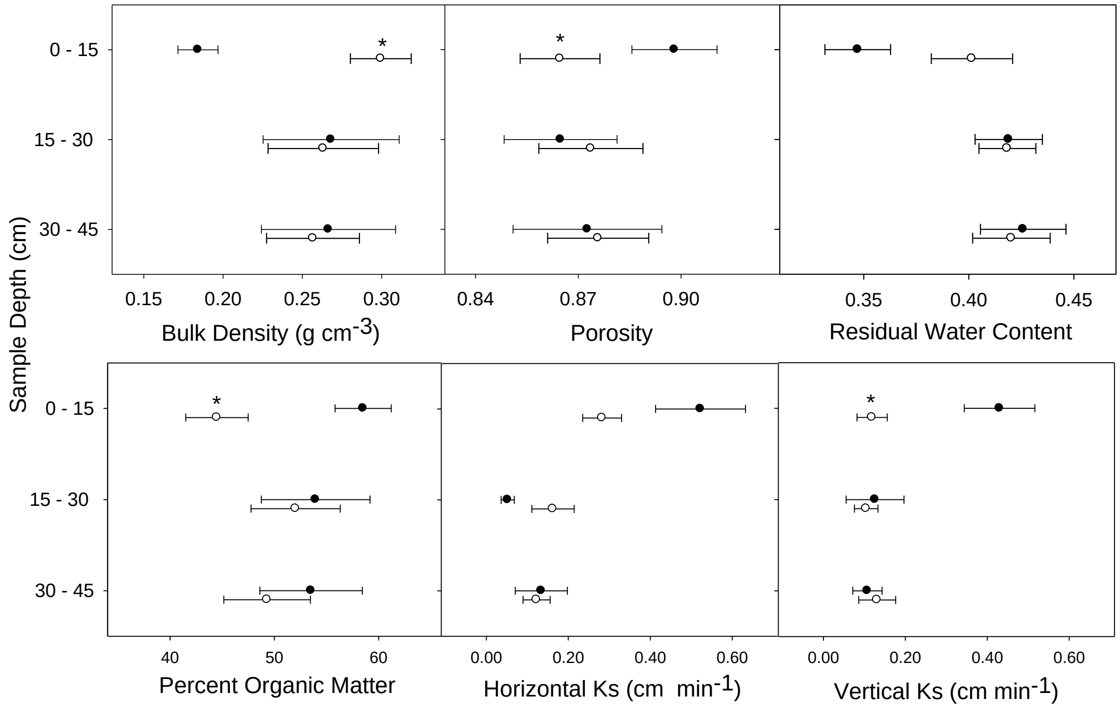

Figure 6. Soil property means (standard error) with samples from all fens pooled by treatment (open = disturbed/restored, closed = reference). Differences in means were analyzed at each sample depth using the Wilcoxon rank sum test. (*) indicates means are significantly different ($p < 0.05$).

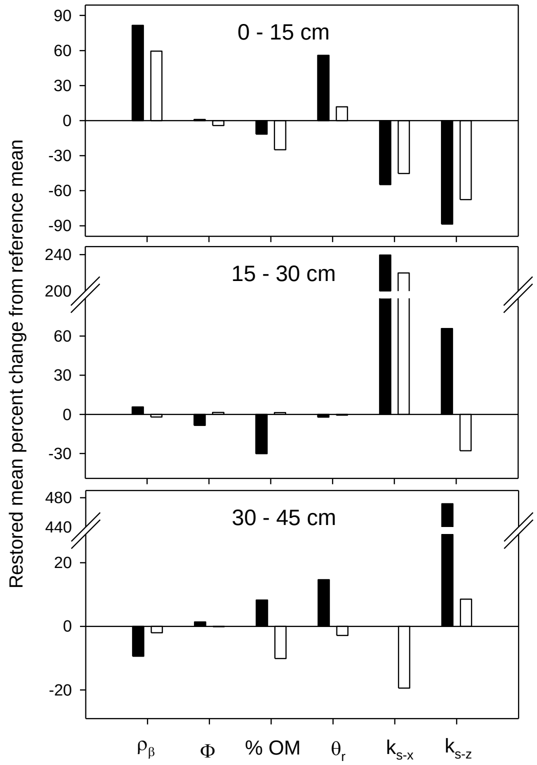

Figure 7: Normalized magnitude of change in restored soil property means from reference condition at each sample depth. *Closed bars* represent Big Meadows fen (BM), restored 1990, *open bars* represent pooled samples from Lateral Moraine (LM), Pirate Ship (PS), and NE Eggleston fens (NE), restored during this study. BM restored soil samples were compared only to BM reference samples, likewise, 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 ($k_{s\text{-}x}$) and vertical ($k_{s\text{-}z}$) orientations.

Figure 8. Pre restoration (left) and post restoration (right) view of plywood dam in Lateral Moraine Fen. Dam has v-notched weir, rock armoring on spillway, and has been filled with peat blocks planted with sedge plugs.

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8.APPENDIX

8.1 PIRATE SHIP FEN

8.1.1 Restoration Report

Water table and carbon flux was monitored biweekly in Pirate Ship fen throughout the summers of 2009 and 2010 following the installation of 25 ground water monitoring wells in 2008. A vegetation survey recording percent cover by species in a 2 m radius circle around groundwater monitoring wells was conducted in august of both 2009 and 2010.

In late July, 2009 a US Forest Service archeologist visited the fen to assess potential impacts that could result from restoration efforts on nearby historical sites. We received the necessary permits from the US Forest Service and US Army Corps of Engineers in September 2009 and installed five Oriented Strand Board (OSB) dams backfilled with peat collected from off site. An additional 5 dams were installed in July 2010. The dams effectively stopped water flow throughout the ditch system, blocked the diversion of water from the natural stream into the ditch, and dispersed inflowing surface water across the center of the fen. Dams were constructed of plywood, Oriented Strand Board (OSB), local rocks, and peat collected from a source on Grand Mesa, Colorado was used to fill short (~1m) sections of ditch to support the dam structures and promote revegetation across the ditch.

Early signs of success were observed the day of and next morning after construction. Some dams were visibly filling with water and diverting it out across the dried section of the fen. This standing water front had occurred over a 10 m wide swath extending 50 m from the ditch in the center of the fen. The installation of dams has eliminated drainage from the ditch and reestablished hydrologic connectivity of inflowing water from the Eastern watershed to the western portion of the fen. The flat surface of the central fen has allowed for a wide distribution of surface water and sheet flow across much of the restored area. The long term success of this restoration project hinges on the effectiveness and durability of the wooden dams, with the dam at the stream / ditch junction in the middle of the ditch having the greatest importance, as this stream contributes most of the water which maintains saturated soil conditions in the restored area. All dams in the fen should be inspected annually to ensure proper function and evaluate the long term durability of this restoration technique. The most likely causes of dam failure will be from water undercutting the sides or bottom of the dam. If this has led to dam failure, the hole either needs to be plugged or the entire structure replaced in a nearby location.

In addition to dam inspection, the conditions of gullies at the south end of the ditch (near well 15 location) and on the SW side of the fen (caused by vehicle use) need to be monitored annually. If the diversion dam retains function, there will be minimal water flow in the gully at the south end of the ditch, and it may revegetate itself without the need for additional restoration activities. Several of the gullies in the SW section of the fen have formed in the tracks of off road vehicle use and will continue to degrade if active restoration methods are not enacted. As of fall 2010, the shallow gullies could be easily repaired with small, porous check dams (peat bags or straw wattles similar to those installed by Dr. Rod Chimner, Michigan Technical University, on the adjacent gully), which would sufficiently retard water flow, reduce erosion, and allow the gullies to revegetate naturally.

Long term hydrologic monitoring of this fen can be used to evaluate the continued effectiveness of the restoration. In addition to the presence of surface water or saturated soil throughout parts of the fen, selected ground water monitoring wells remain in the central section of the fen and should be gauged at least once per summer, preferably in mid – late July when the water table level is at the annual minimum.

Pirate Ship Study Design

- Study treatments: Reference – East side of ditch, some wells on South end. Restored – West side of ditch. Disturbed - wells 14P, 15P, and 22P were not significantly affected by ditch blocking in 2010.
- GW monitoring – 29 Ground water monitoring wells –GL loggers at wells 13 and 14. 11 monitoring wells remain in the fen to assist long term monitoring. Most of these are located in the center section of ditch.
- Soil temperature (-5, -21, -38 cm) - 2 I-button Nests Wells 13 and 14.
- PZ nests – 8 – 4 reference, 4 restored
- CO2 flux – 3 wells with 6 sites per well – 2x disturbed (restored (25P) , disturbed (22P), reference (21P)

Supporting documentation

Figures:

PS-1 : Study design and maximum instrumentation.

PS–2: Final instrumentation and dam locations (as of September 2010)

PS-3: Daily CO_2 flux averages by treatment (NEE, ER, GEP).

PS-4: Annual CO_2 flux averages by treatment (NEE, ER, GEP).

PS-5: Water table charts for a) CO_2 flux wells and b, c) long term monitoring wells.

Tables:

In supplemental spreadsheets:

- Pirate Ship well – contains well locations, instrumentation records, water table data
- Pirate Ship pz – contains piezometer data, recorded as depth of water in piezometer below ground surface.
- Dam locations – contains locations of all dam structures as of September 2009.
- Lm and PS I buttons – All soil temperature data recorded during study period
- Pirate Ship IRGA – All CO_2 gas flux measurements recorded during study.

8.1.2 Site Maps and Additional Figures

Figure PS-1: Study design of Pirate Ship Fen with location of groundwater monitoring wells, piezometer nest, CO_2 flux wells, dams, and soil sample extraction locations. Treatment classification is also shown.

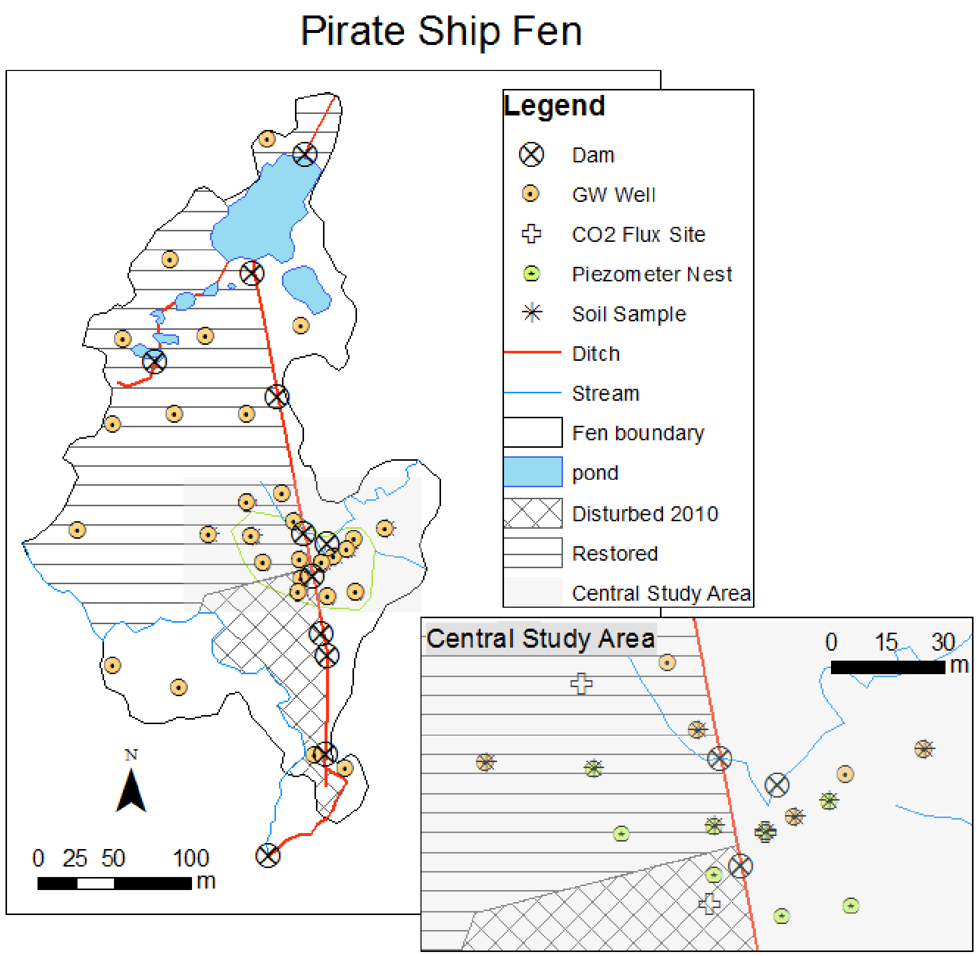


Figure PS-2: Long term monitoring wells and dam locations for Pirate Ship Fen.

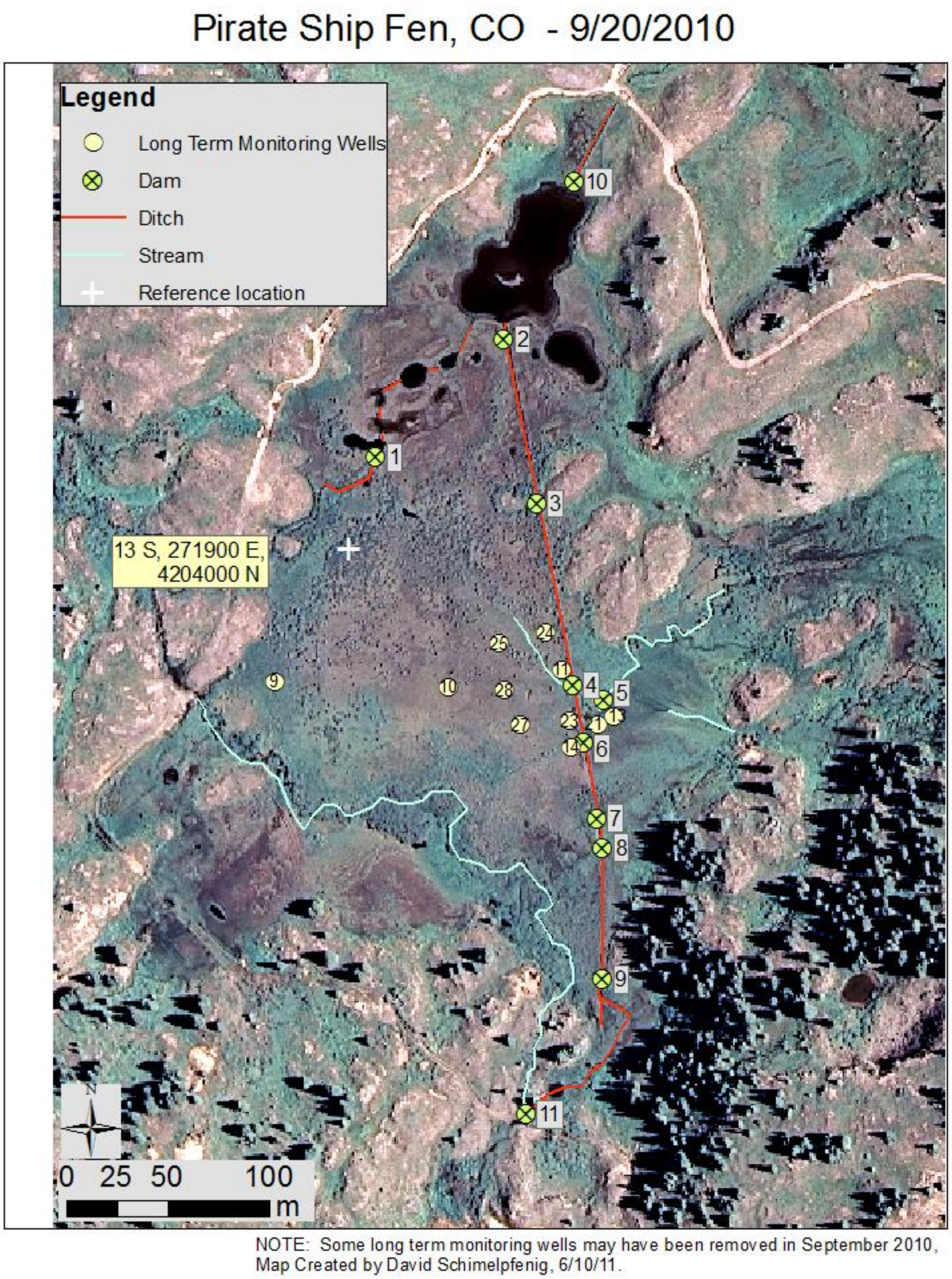


Figure PS-3: Mid day CO_2 flux averaged by well from Pirate Ship fen, *Open symbols* are Gross Ecosystem Production (GEP), *Closed symbols* are ecosystem respiration (ER). Net ecosystem exchange (NEE) error bars represent 1 standard deviation from the mean.

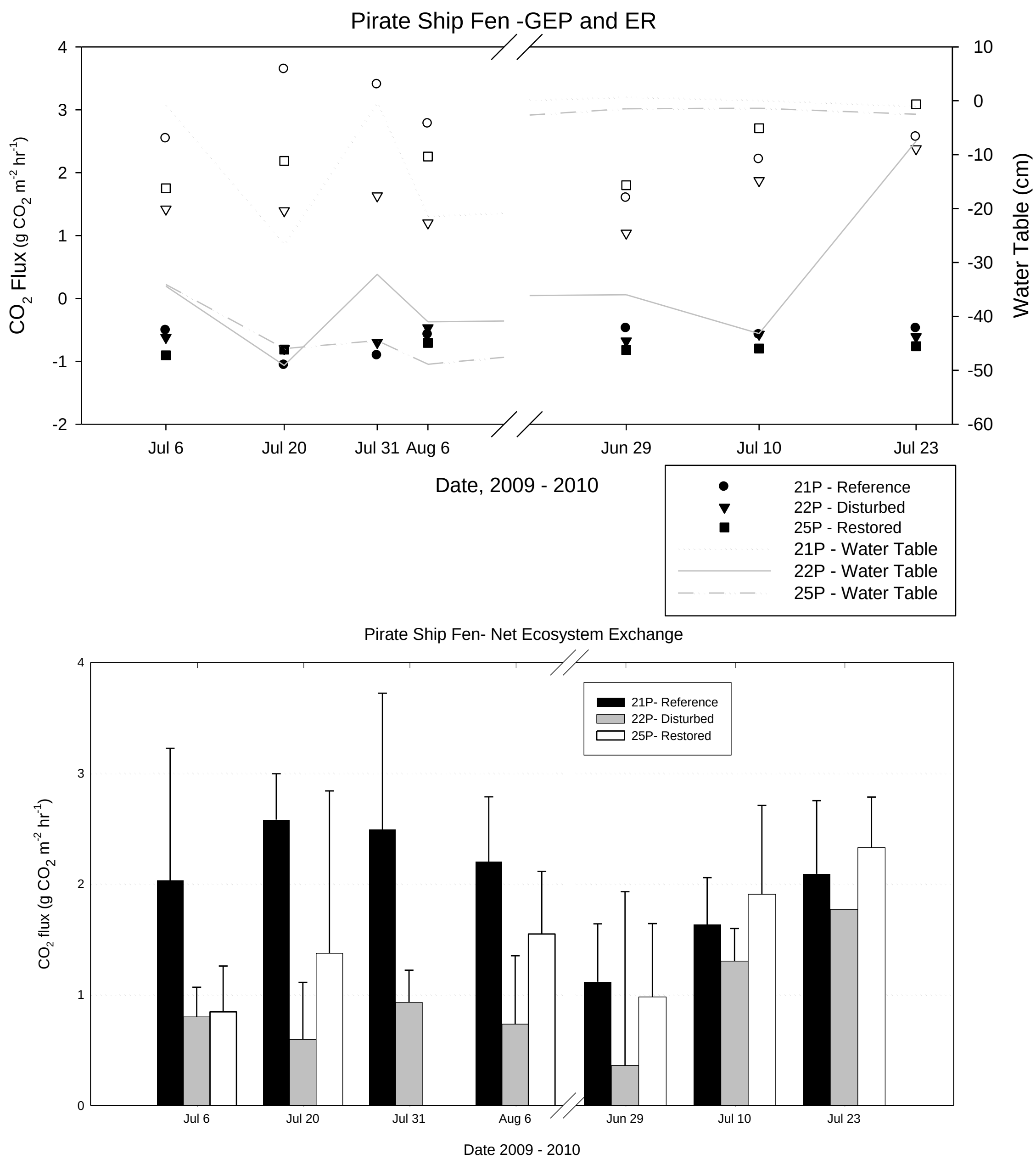


Figure PS-4: Treatment means of net ecosystem exchange (NEE), ecosystem respiration (ER), and gross ecosystem production (GEP) for Pirate Ship fen, Tukey's HSD pairwise comparisons of treatment means were made separately for each study year and pooling both years within each fen. Means with the same letter are not significantly different ($p > 0.05$). (*) indicates 2009 treatment mean is significantly different ($p < 0.05$) from 2010 mean. Note different y-axis scales.

Pirate Ship fen

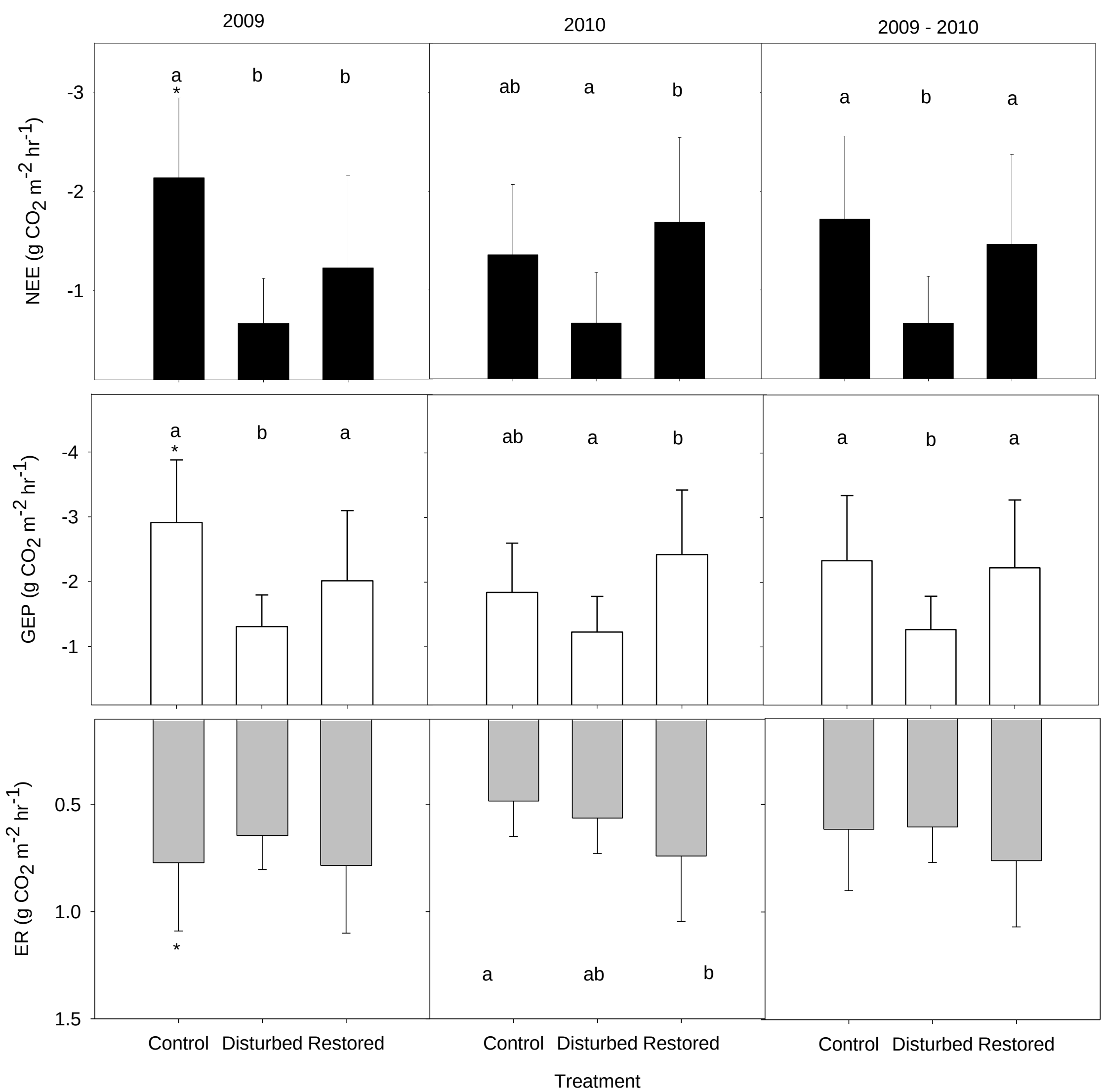
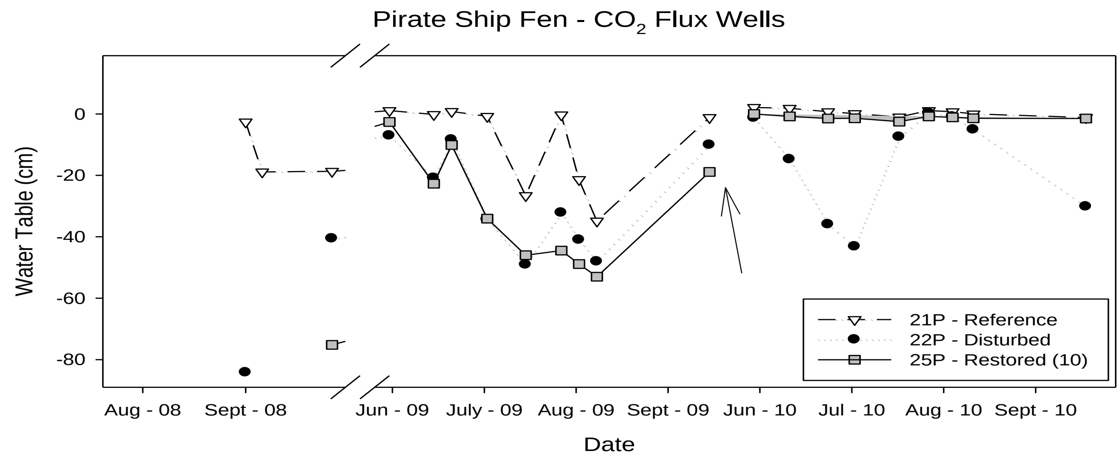
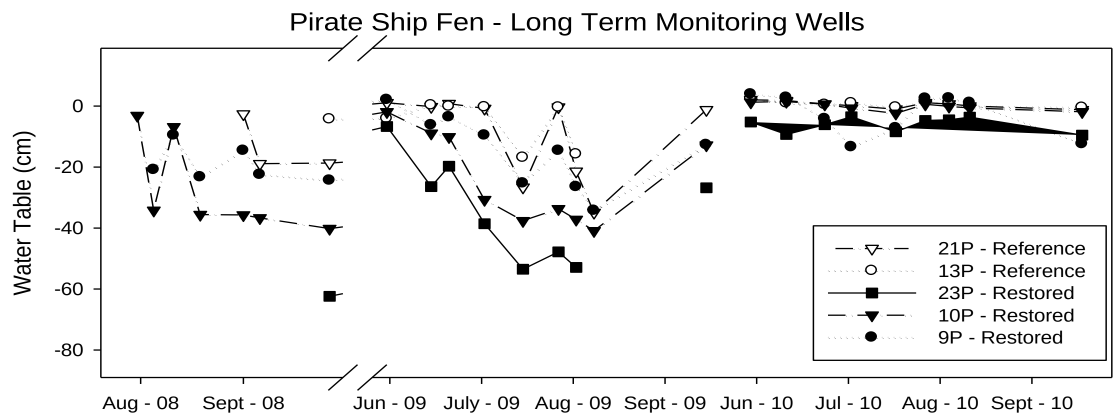


Figure PS-5: Water Table position for Pirate Ship wells with a) CO_2 flux sites. b, c) Long term monitoring wells remaining in the fen. Arrow indicates approximate date of restoration for restored wells.

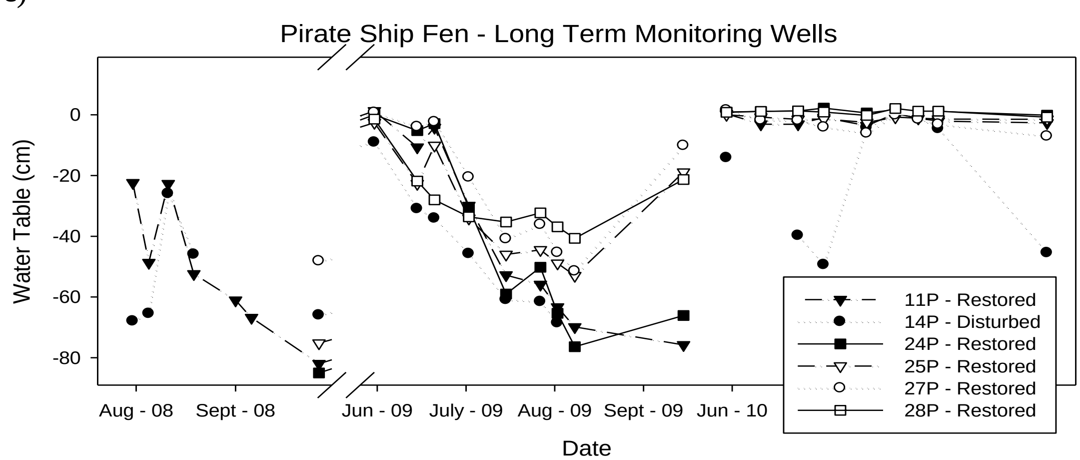
a)



b)



c)



8.2 LATERAL MORAINE FEN

8.2.1 Restoration Report

Lateral Moraine fen (LM) covers approximately 1.5 hectares at an elevation of 3100 m in the Trout Lake watershed (UTM 13s, 24767, 4188593). The fen is bounded on its lower end by a lateral moraine, giving it its name. A regional assessment of San Juan fens (Chimner, et al. 2010) rated this site in poor condition with a high restoration priority. The plant community was dominated by *Carex aquatilis* and *C. utriculata*. This fen had 8 ditches or channels of unknown origin flowing south through the fen, joining to form one outlet in the southwest corner. In the summer of 2008, over 40 ground water wells were installed. Wells were constructed with 5.1 cm diameter schedule 40 PVC tubes slotted over their entire length. Three wells were also installed in a reference fen 100 m upslope from Lateral Moraine fen. In 2009 an additional six wells were installed in the reference section. Restoration of this fen began in 2008 when one of the major ditches in the center of the fen was partially blocked with peat bag dams. In 2009 five ditches on the west side of the fen were blocked using a combination of peat bag and plywood dams. The eastern half of the fen was left in the disturbed condition. The reference area of LM was an undisturbed fen 100 m upslope from the disturbed section of the fen. For the purpose of this study, LM had three treatments; reference, restored, and disturbed.

A total of 21 dams were installed in 4 ditches in Lateral Moraine Fen. Our goal was to restore the hydrologic regime to levels found naturally in fens. We used three methods to construct the dams; sand bags, plywood dams, and weed free straw bales. Plywood dams were strengthened by backfilling with ~ 1m of peat collected ofsite and stake braces on the downstream side. V-notch wiers were cut into the top of the structures to direct excess water flow through the existing stream channel during rain and snowmelt flood events. In addition to general restoration of the fen, we are interested in the long term effectiveness of the three different dam materials. Dams should be inspected a minimum of once per year to check stability and effectiveness, monitor erosion in the stream channel and from undercutting of flow around the structure. If a breach has occurred, attempts to plug the hole or replace the dam in a nearby location is recommended.

Hydrological results have shown significantly higher water levels in the half of the fen where we installed the dams, while water levels in half of the fen we did not restore fell after spring runoff ceased. Six groundwater wells were left in place for long term monitoring of water table conditions. Wells should be gauged at least once per year, preferably in late July or early August when water levels in the fen are near their lowest annual levels.

Study design:

- Treatments: Reference (section in separate fen across access road), Restored (West side of fen), Disturbed (East side of fen).
- GW monitoring – 45 groundwater monitoring wells –GL loggers at wells 6 and 14.
    - Six monitoring wells remain in the fen to assist long term monitoring, these are located in a transect running through the center section of the fen.
- Soil temperature (-5, -21, -38 cm) - 2 I-button Nests Wells 6 and 14.
- Piezometer nests – 8 : 2 ref, 4 restored, 2 disturbed
- CO2 flux – 4 wells with 5 sites per well : 2 restored (wells 2L, 5L), 1 disturbed (15L), 1 reference (47LR)

Supporting documentation

Figures:

LM-1 : Study design and maximum instrumentation.

LM-2: Final instrumentation and dam locations (as of September 2010).

LM-3: Daily CO_2 flux averages by treatment (NEE, ER, GEP)

LM-4: Annual CO_2 flux means by treatment (NEE, ER, GEP)

LM-5: Water table charts for a)CO_2 flux wells, b) Long term monitoring wells

LM-6: Soil temperatures at well 6L and 14L

Tables:

In supplemental spreadsheets:

- Lateral Moraine well – well locations, instrumentation records, water table data
- Lateral Moraine pz –piezometer data, recorded as depth of water in piezometer below ground surface.
- Dam locations – locations of all dam structures as of September 2009.
- Lm and PS I buttons – All soil temperature data recorded during study period
- Lateral Moraine IRGA – All CO_2 gas flux measurements recorded during study.

8.2.2 Site Maps and Additional Figures

Figure LM–1: Lateral Moraine Fen site map. Monitoring wells, piezometer nests, soil sample wells, ditch and dam locations, and treatment classifications are shown.

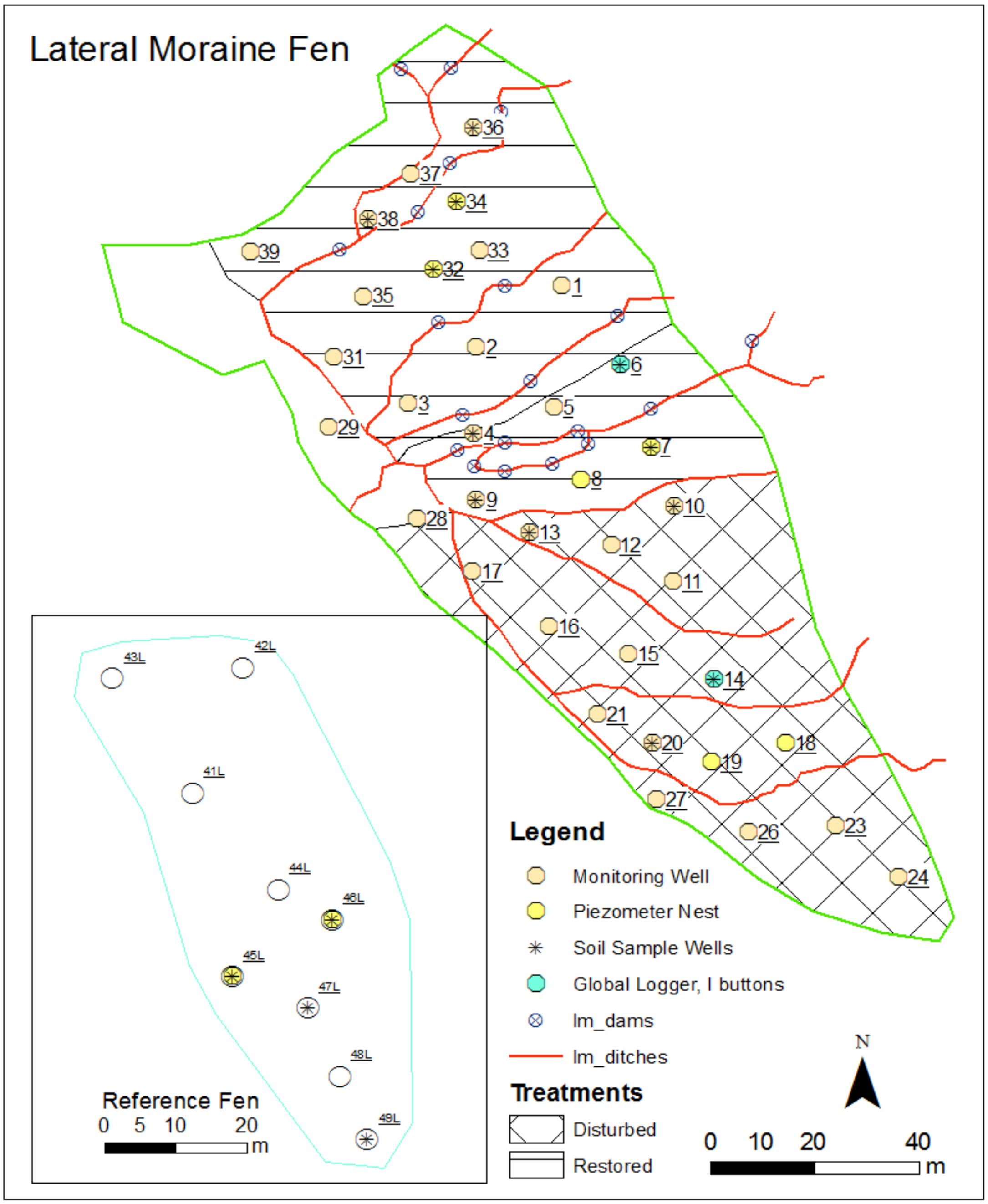


Figure LM-2: Long term monitoring map of Lateral Moraine fen. Locations of ditches, dams, and long term wells left in the fen are shown.

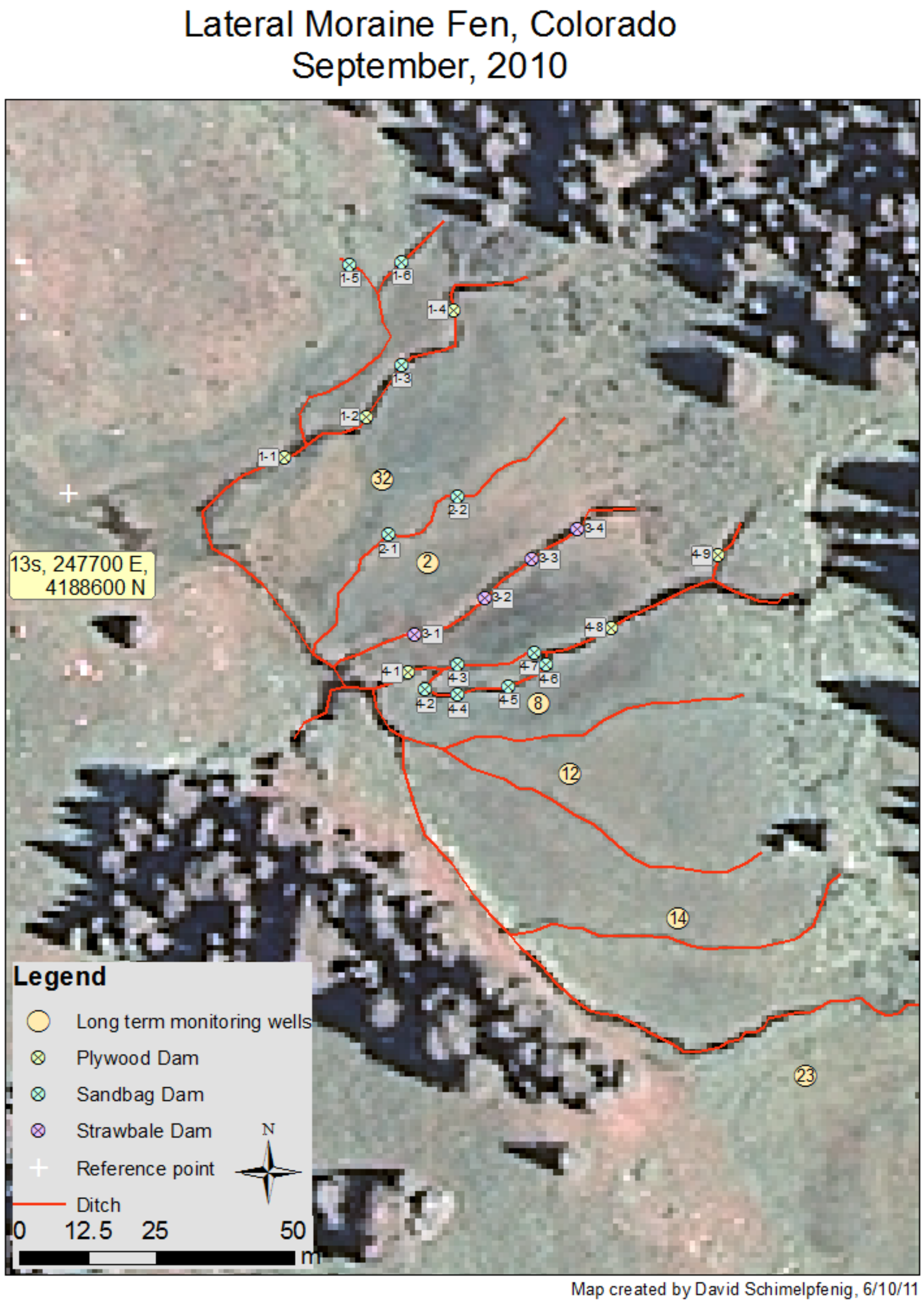


Figure LM-3: Mid day CO_2 flux averaged by well from Lateral Moraine fen. *Open symbols* are Gross Ecosystem Photosynthesis (GEP), *Closed symbols* are ecosystem respiration (ER). Net ecosystem exchange (NEE) error bars represent 1 standard deviation from the mean.

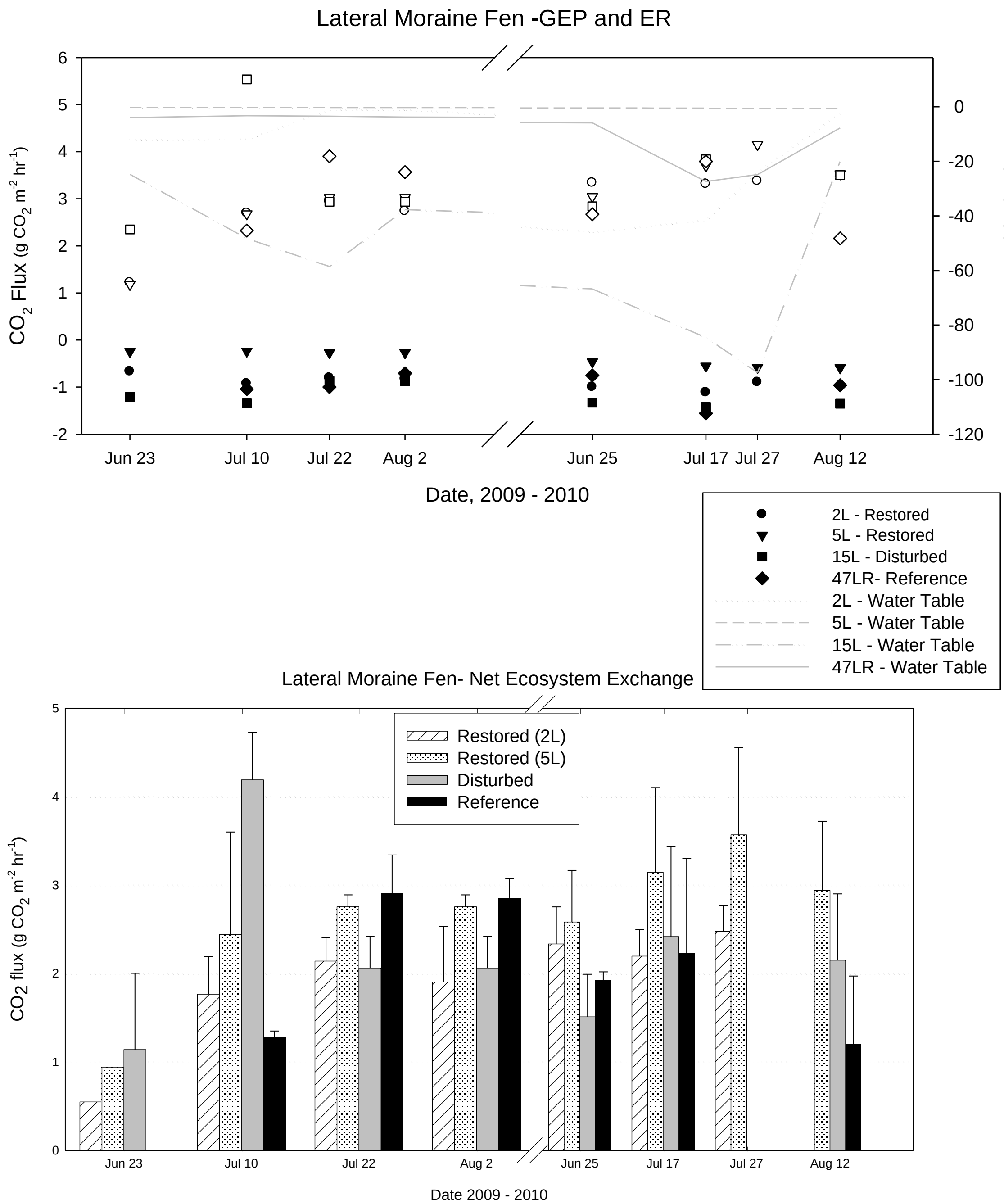


Figure LM-4: Treatment means of net ecosystem exchange (NEE), ecosystem respiration (ER), and gross ecosystem photosynthesis (GEP) for Lateral Moraine fen. Tukey's HSD pairwise comparisons of treatment means were made separately for each study year and pooling both years within each fen. Means with the same letter are not significantly different ($p > 0.05$). (*) indicates 2009 treatment mean is significantly different ($p < 0.05$) from 2010 mean. Note different y-axis scales.

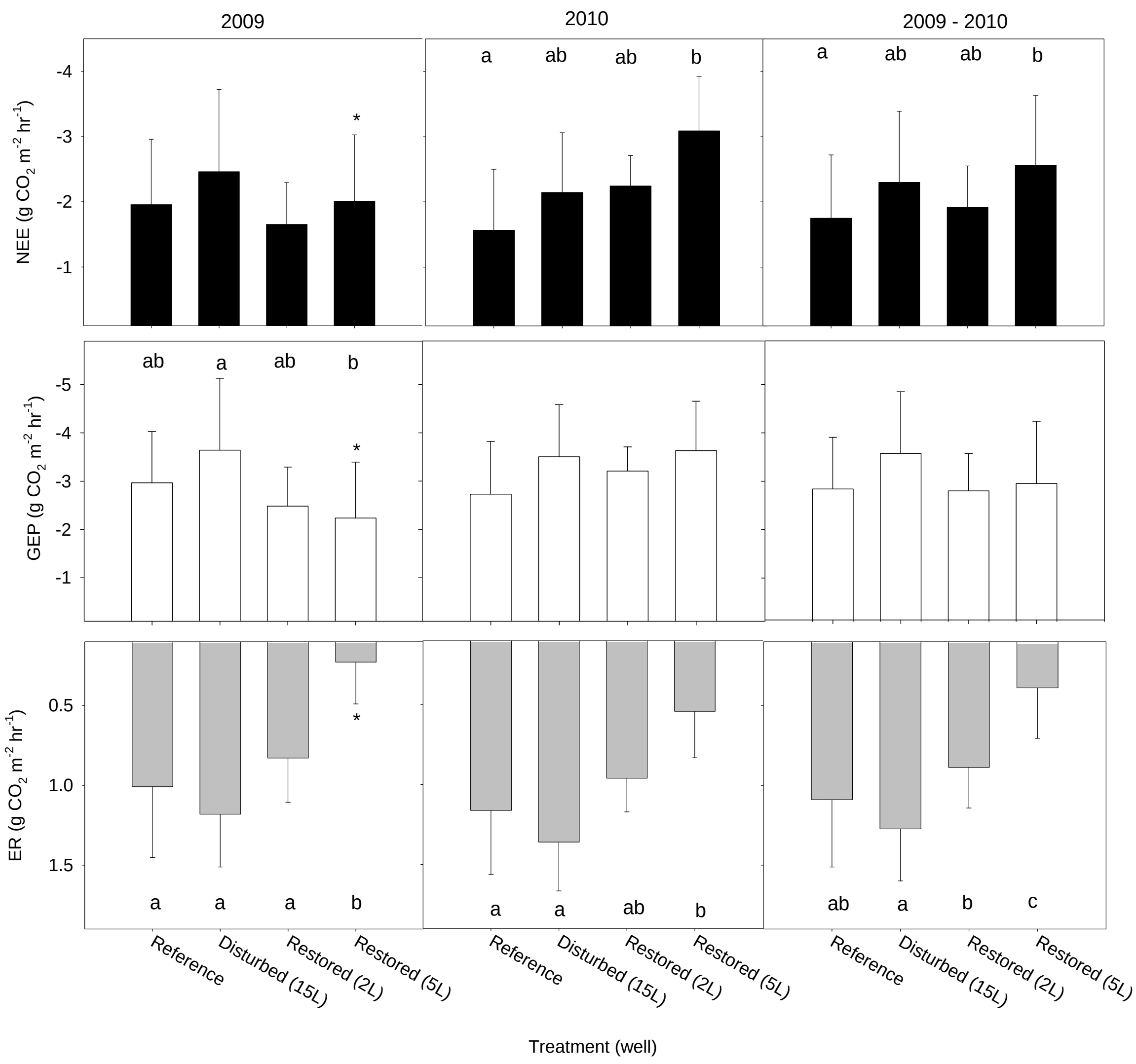


Figure LM-5: Water Table position for Lateral Moraine Fen wells with CO_2 flux sites and long term monitoring wells. Arrow indicates approximate date of restoration for restored wells.

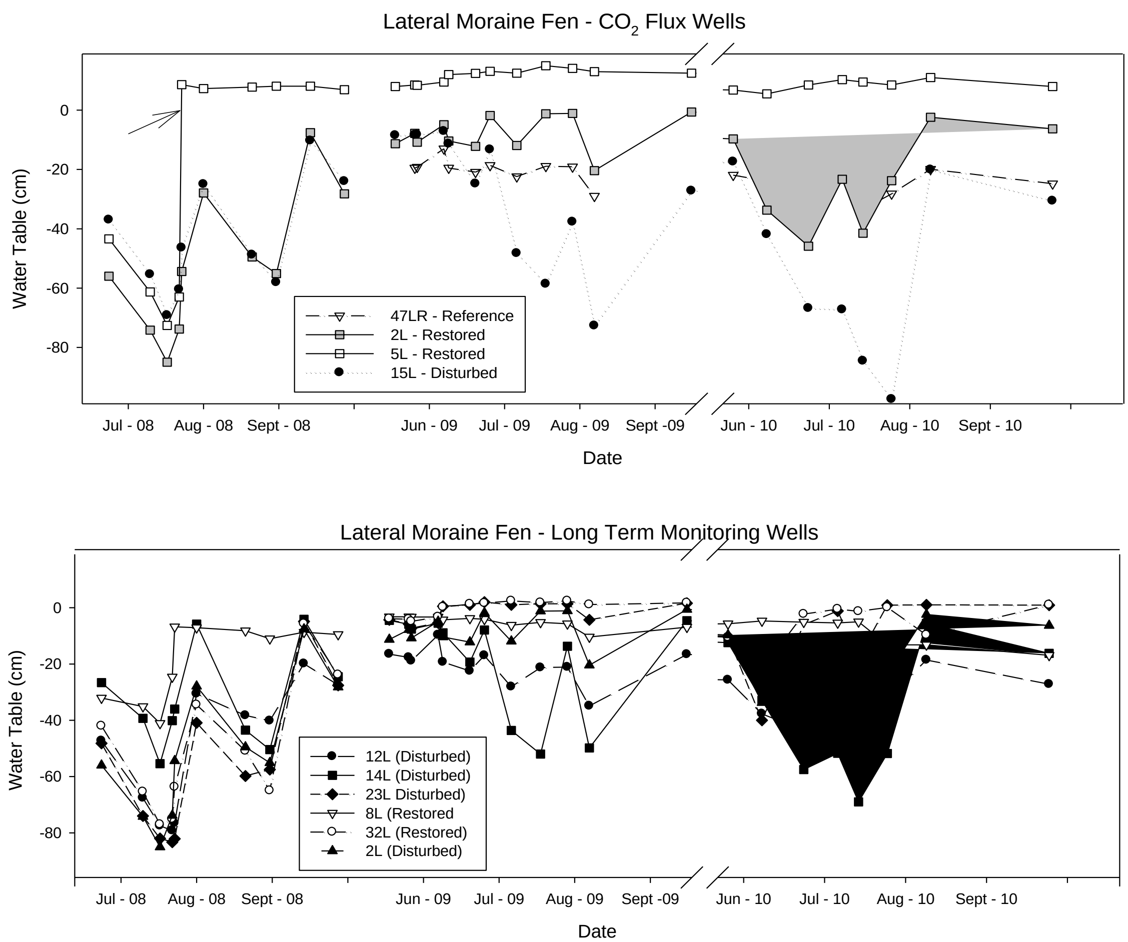
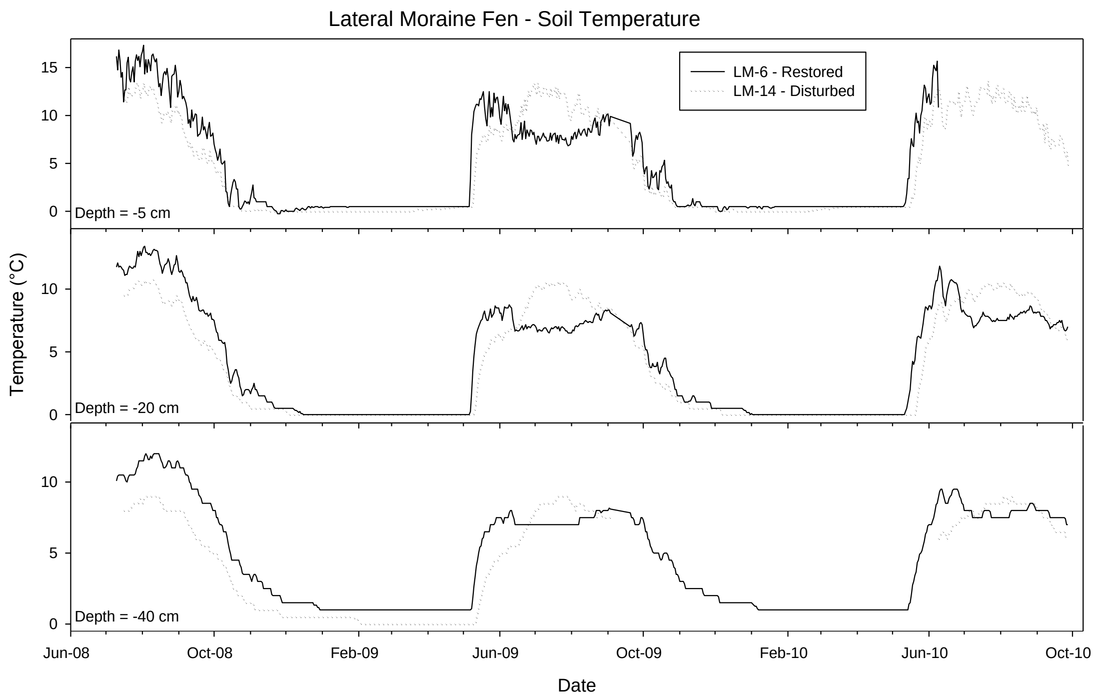


Figure LM-6: Soil temperature for Lateral Moraine fen disturbed well 14 (dashed line) and restored well 6 (solid line) at three depths. Temperatures were logged at 6 hour intervals from June 2008 to September 2010 using Thermocron® I- buttons. Note -40 cm depth disturbed I button was not functioning from September 2009 to June 2010.



8.3 NE EGGLESTON FEN

8.3.1 Restoration Report

NE Eggleston fen (NE) (UTM 13s, 246663, 4325882) is situated at an elevation of 3100m on Grand Mesa, a basalt capped mesa in west central Colorado. It is a sloping fen mostly dominated by *Carex aquatilis* and *C. utriculata* while near its northern end groundwater discharges from the surrounding hills and the vegetation has high cover of *Eleocharis quinqueflora*. A pipe was found running north to south through the middle of the fen transferring a portion of discharge out of the fen. A ditch that captured surface and groundwater inputs from the western half of the fen formed along the length of the pipe, creating drought conditions in the eastern half. *Salix planifolia* was present along the length of the ditch, especially on the east bank. Restoration took place in midsummer 2009 with the installation of five plywood and eight peat dams. NE had reference, restored, and disturbed treatment sections.

In the summer of 2008, eight monitoring wells and one piezometer nest were installed in this fen. During 2009, an additional five wells were installed along the length of the ditch, the pipe was severed, and 13 dams constructed of plywood (5) and bags filled with peat from onsite (7) the ditch. The peat bag dams were topped with transplanted surface peat sections to disguise the dams and increase the lifespan of the bags. Plywood dams were backfilled with ~1 m of peat collected from offsite to increase long term stability and promote natural revegetation across the ditch.

Five groundwater monitoring wells were left in place for long term monitoring of the fen. Water table should be checked at least once per year, preferably at the end of July or early August when water levels are near the annual minimum. All dams should be inspected at least once per year for signs of undercutting, erosion around the sides, and overall effectiveness. Attempts to plug holes or replace dams in nearby locations should be made to ensure long term restoration success. It should be noted that large cavities exist in the peat profile along the length of the ditch and need to be filled, or dams long enough to be firmly anchored into solid peat to avoid below ground water flow bypassing dams.

Study design:

- Treatments: Reference (west side of fen) , Restored (most of the east side of fen), Disturbed (a small section near wells 7E and 13E).
- GW monitoring – 15 groundwater monitoring wells.
    - Five monitoring wells remain in the fen to assist long term monitoring.
- Piezometer nests – 9 : 5 reference, 4 restored.
- CO2 flux – 4 wells: 2 reference (wells 9E, 1E) with 6 plots per well, 2 restored (Wells: 2E – six plots, 10E – 4 plots).

Supporting documentation

Figures:

NE-1 : Study design and maximum instrumentation.
NE-2: Final instrumentation and dam locations (as of September 2010).
NE-3: Daily CO_2 flux averages by treatment (NEE, ER, GEP)
NE-4: Annual CO_2 flux means by treatment (NEE, ER, GEP)
NE-5: Water table charts for a)CO_2 flux wells, b) Long term monitoring wells

Tables:

In supplemental spreadsheets:

- NE Eggleston well – well locations, instrumentation records, water table data
- NE Eggleston pz –piezometer data, recorded as depth of water in piezometer below ground surface.
- Dam locations – locations of all dam structures as of September 2009.
- NE Eggleston IRGA – All CO_2 gas flux measurements recorded during study.

8.3.2 Site Maps and Additional Figure

Figure NE-1: NE Eggleston fen site map. Groundwater monitoring wells, soil sample wells, dam locations, ditch location, and treatment zones are shown.

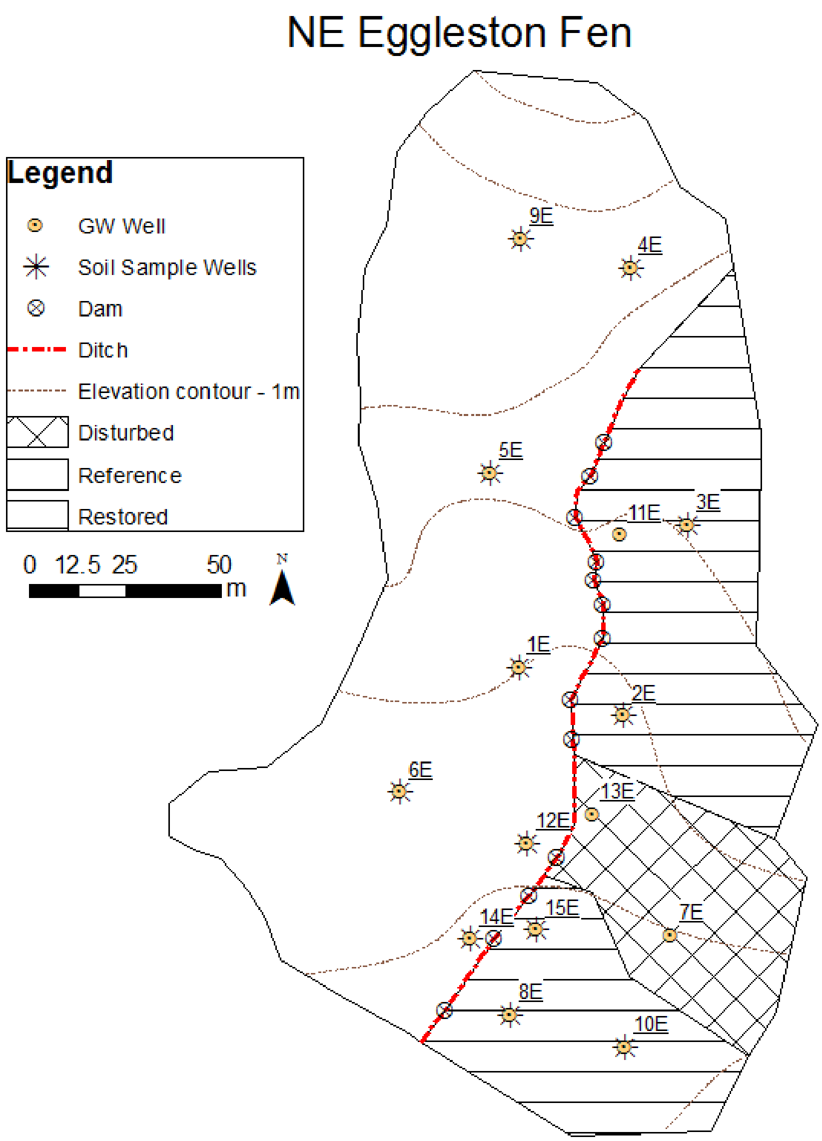


Figure NE-2: NE Eggleston fen map showing long term monitoring wells with dam and ditch locations.

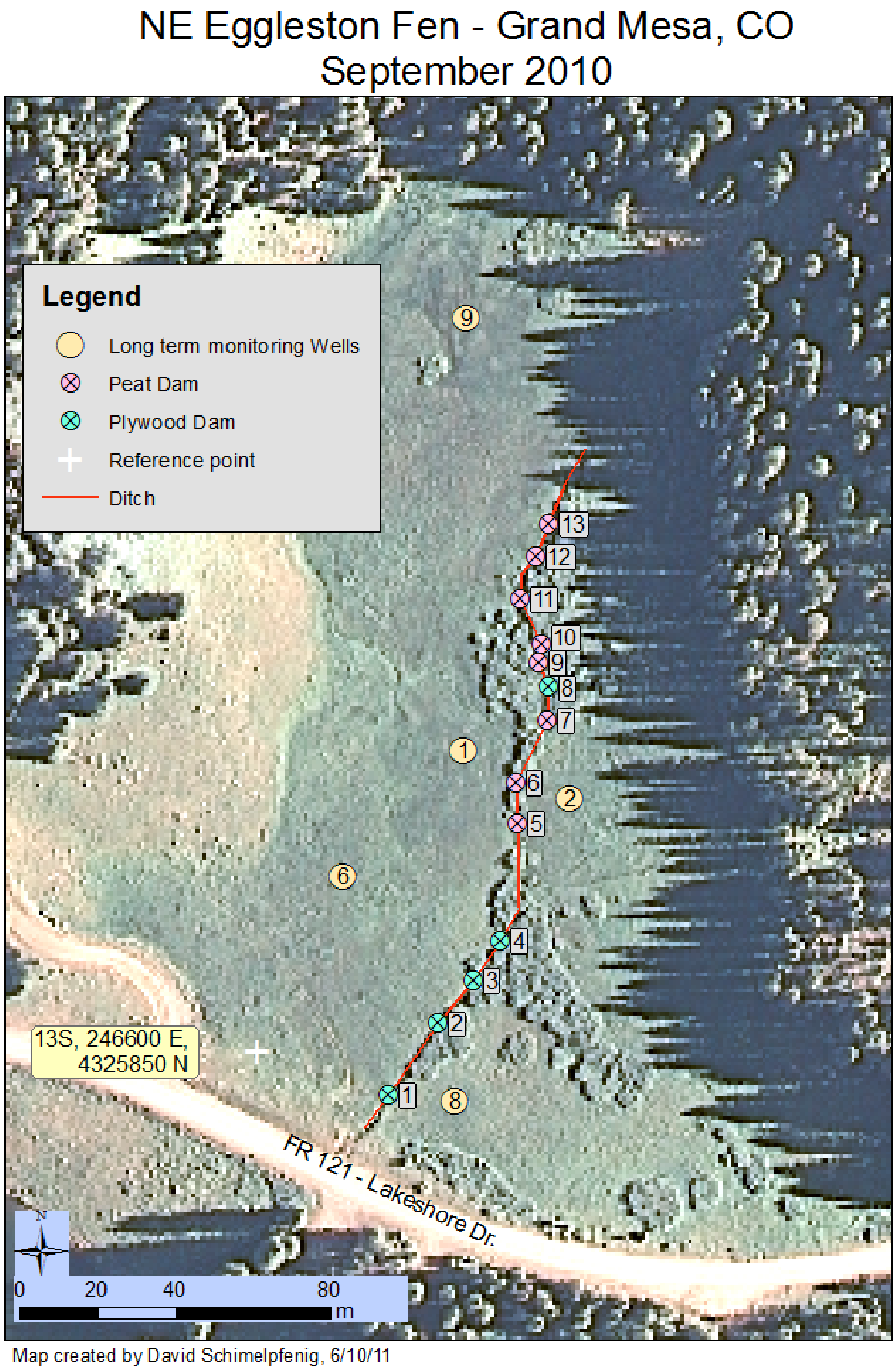
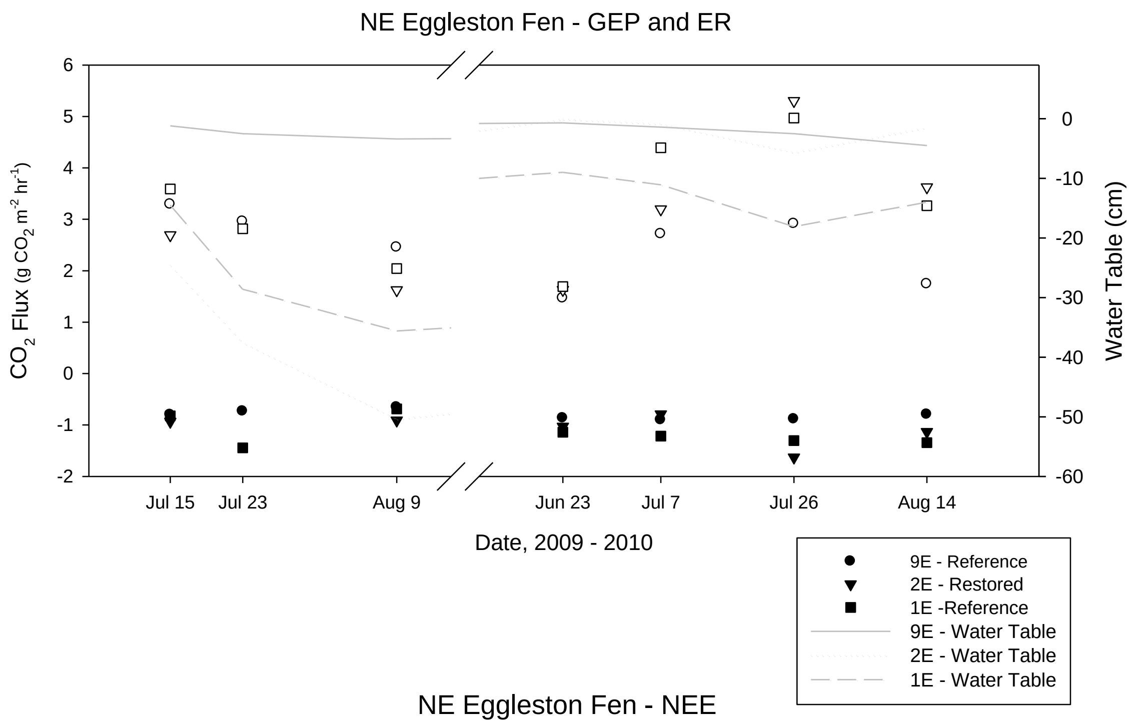


Figure NE-3: Mid day CO_2 flux averaged by well from, c) NE Eggleston fen. *Open symbols* are Gross Ecosystem Photosynthesis (GEP), *Closed symbols* are ecosystem respiration (ER). Net ecosystem exchange (NEE) error bars represent 1 standard deviation from the mean.



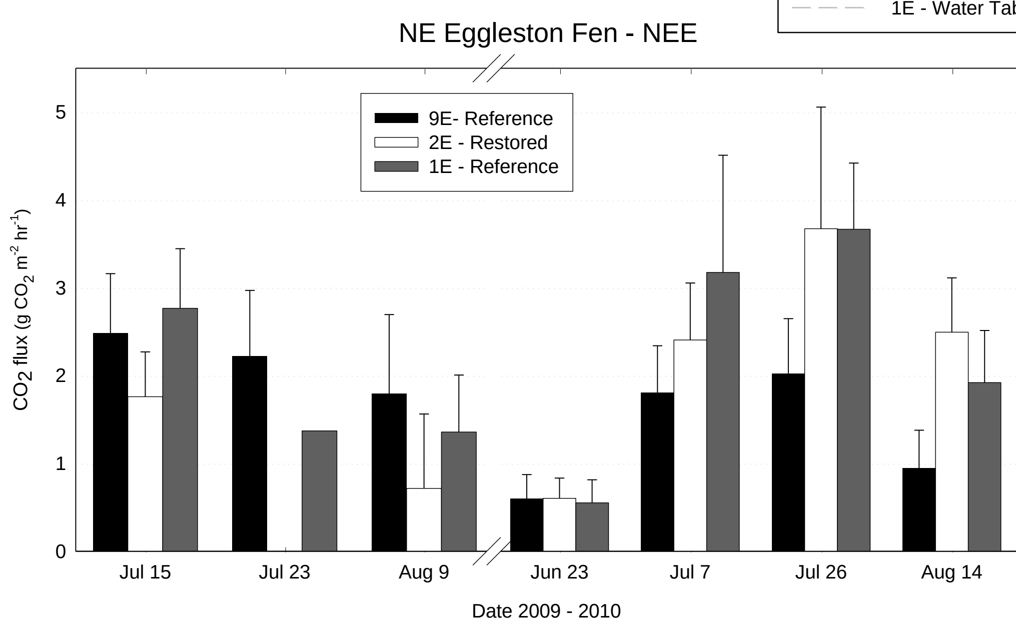


Figure NE-4: Treatment means of net ecosystem exchange (NEE), ecosystem respiration (ER), and gross ecosystem photosynthesis (GEP) for NE Eggleston fen. Tukey's HSD pairwise comparisons of treatment means were made separately for each study year and pooling both years within each fen. Means with the same letter are not significantly different ($p > 0.05$). (*) indicates 2009 treatment mean is significantly different ($p < 0.05$) from 2010 mean. Note different y-axis scales.

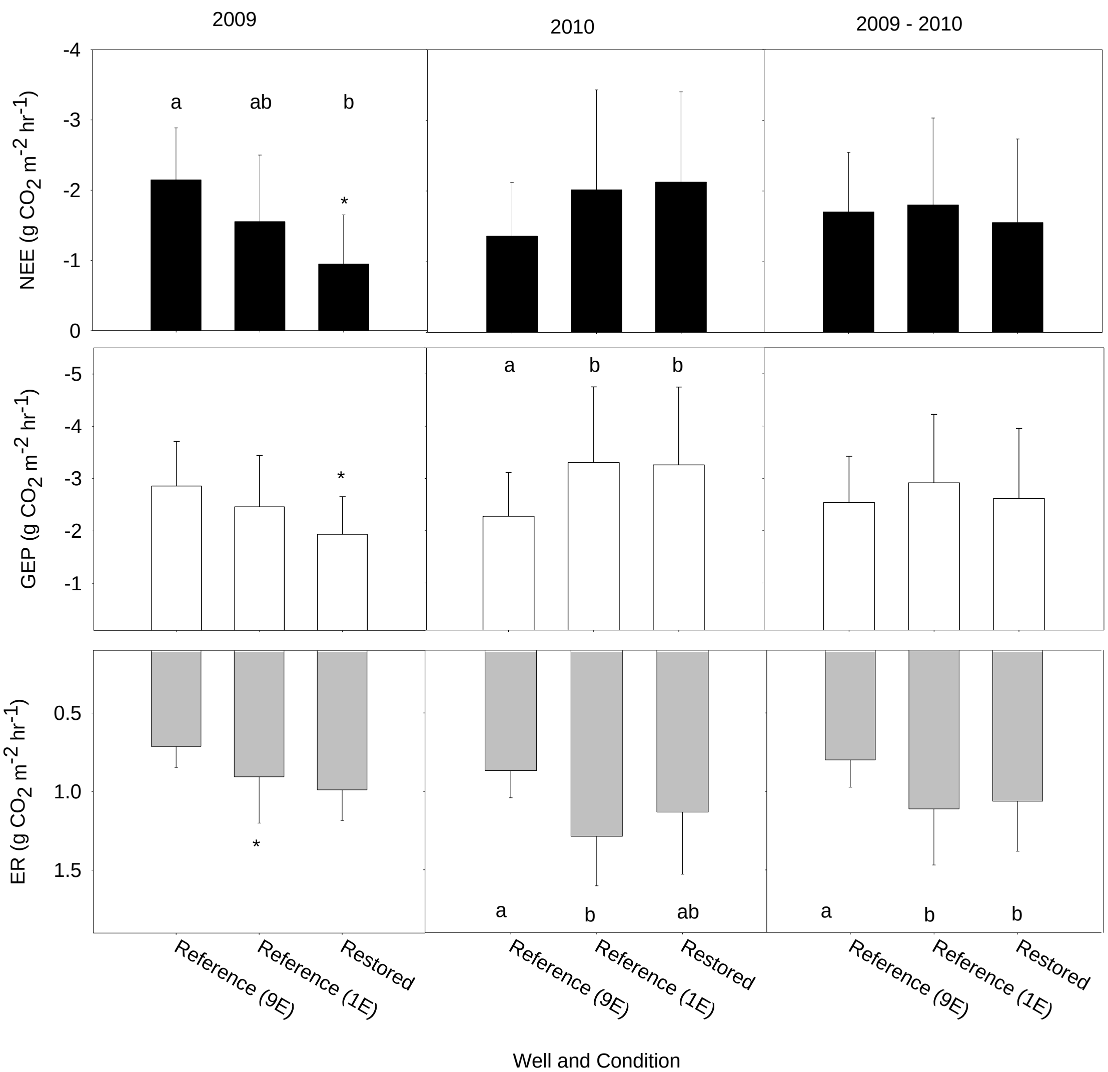
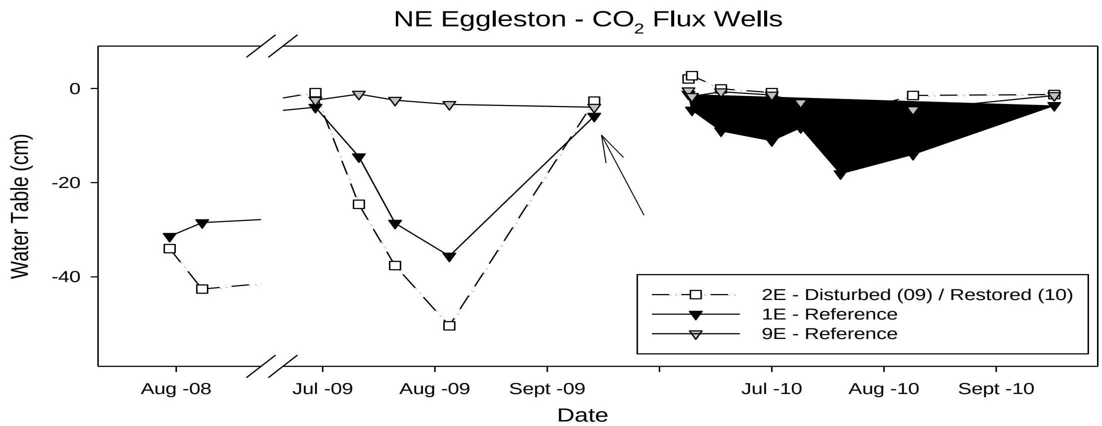


Figure NE-5**:** Water Table position for NE Eggleston wells with a) CO_2 flux sites and b) long term monitoring wells. Arrow indicates approximate date of restoration for restored wells.

a)



b)