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DISSERTATION

Carbon Dynamics of Southern Rocky Mountain Fens

Submitted by
Rodney Allen Chimner
Graduate Degree Program in Ecology

In partial fulfillment of the requirements
for the degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Fall 2000

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AUGUST 25, 2000

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY RODNEY ALLEN CHIMNER ENTITLED CARBON DYNAMICS OF SOUTHERN ROCKY MOUNTAIN FENS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Advisor

Department Head/Director

ABSTRACT OF DISSERTATION

CARBON DYNAMICS OF SOUTHERN ROCKY MOUNTAINS FENS

The objectives of my dissertation were to determine: (1) the current carbon accumulation rates in Rocky Mountain National Park pristine fens, (2) whether the Grand Ditch water diversion in Rocky Mountain National Park decreased carbon accumulation in fens, (3) how much the water table must be lowered in fens before significant changes in gas efflux occurs and (4) how well the CENTURY ecosystem model can be used to simulate long-term carbon accumulation.

Carbon balances were calculated during 1997 and 1998 to quantify carbon accumulation rates in three pristine fens and two fens beneath the Grand Ditch. Site hydrologic regime was found to directly control carbon accumulation in the five study fens. All fens accumulated carbon when the water table remained at or above the soil surface. However, both pristine fens and fens beneath the Grand Ditch lost carbon during years when the water table dropped beneath the soil surface for more than three weeks during the summer.

Microcosms were installed in a Colorado fen to manipulate water levels and measure the response in CO_2 and CH_4 efflux. The experiment showed that CO_2 efflux was lowest when the water table was above the soil surface, but efflux rates doubled when the water table dropped beneath the soil surface. However, further lowering of the water table beneath the soil surface had little additional effect on CO_2 efflux. The highest CH_4 efflux occurred when the water table was just above the soil surface and decreased when the water table was either deeper or more ponded.

CENTURY was able to simulate carbon cycling in peatlands by altering three anaerobic variables. However, CENTURY was unable to properly simulate carbon accumulation in an uncalibrated peatland because of limitations in how anaerobic conditions are created in CENTURY. Nevertheless, once calibrated, the usefulness using an ecosystem model for peatland carbon budget analyses became apparent as it allowed predictions to be made of peat composition and the consequences of exposing peat bodies to aerobic conditions. CENTURY predicted that most of the fen peat stored came from root material, which was easily decomposed when exposed to aerobic conditions.

Key words: peatlands, fens, CO_2, CH_4, water table drawdown, carbon balance, carbon budget, hydrology, water table levels, CENTURY, carbon accumulation, climate change, Colorado, Rocky Mountains

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Dedicated to Sigrid, my loving wife.

Whose belief in me

kept me going through all the hard times

And also to my parents,

who were always supportive and encouraged me to chase my dreams

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SOUTHERN ROCKY MOUNTAIN FENS

INTRODUCTION

Peatland or mire, the equivalent European word, is a general term used to classify wetlands that accumulate profiles of peat. There are numerous ways to classify peatlands based on topography, edaphic conditions, hydrologic regime, water chemistry, or vegetation communities. One of the most common distinctions of peatlands is the bog-fen dichotomy. Bogs are considered ombrogenous because they are raised above the groundwater table by an accumulation of peat, with precipitation their only source of water or nutrients (Crum 1992, Mitch and Gosselink 2000). Although in some bogs, groundwater has been found to periodically recharge the lower peat horizons (Glaser *et al.* 1997). Because bogs are dependent on precipitation, they develop in regions where precipitation is higher than potential evapotranspiration and there are no extended seasonal droughts (Maltby and Proctor 1996 Mitch and Gosselink 2000).

Fens differ from bogs in several key ways. They are considered minerotrophic peatlands because they are supported by groundwater, with precipitation contributing a small proportion of the water budget (Drexler *et al.* 1999). Because fens are supported by groundwater, they can develop in any area that has perennially saturated soils and are not limited to regions of high precipitation. Fens are often found along river floodplains, on slopes with discharging groundwater, or in basins (Maltby and Proctor 1996).

However, because fens are supported by groundwater the peat surface cannot grow above the water table. In regions with high precipitation, bogs form from fens through the autogenic process of peat accumulation or through allogenic succession as climate changes (Winkler 1988, Nicholson and Vitt 1994).

Bogs and fens also differ in their water chemistry. Bogs are strongly acidic with pH's often below 4.0, because rainwater is the only source of base cations (Clymo 1987). Fens generally have higher pH levels than bogs due to groundwater influx of base cations, although fens vary widely in their water chemistry depending on the hydrologic, edaphic and geologic conditions of their watershed. Fens are often further subdivided into a number of different types, with an extremely rich to poor fen gradient caused by water chemistry parameters such as pH, specific conductivity and calcium levels (Vitt and Chee 1990, Glaser *et al.* 1990). The hydrologic and water chemistry differences between bogs, poor fens, moderately rich, rich and extremely rich fens give rise to different plant community composition, with *Sphagnum* spp. dominating bogs and many poor fens, while moderately rich, rich and extreme rich fens are dominated by herbaceous graminoids such as *Carex* species (Vitt and Chee 1990, Glasier *et al.* 1990).

The Southern Rocky Mountains have a continental climate with cool dry summers and cold snowy winters. Up to 80% of the annual precipitation falls as snow (Windell *et al.* 1986, Cooper 1990a, Hauer *et al.* 1997). During the summers precipitation is less than potential evapotranspiration, and this limits peatland development to areas that receive snowmelt-derived groundwater through most of the summer (Cooper 1990a, Cooper and Andrus 1994). Thus, all peatlands in the Southern Rocky Mountains are fens, although they are sometimes referred to as bogs in the literature.

EXTENT AND PHYSICAL CHARACTERISTICS OF SOUTHERN ROCKY MOUNTAIN PEATLANDS

Peatlands are one of the most widespread wetland types in the world, occurring from the tropics to polar regions and covering an estimated area of 4 million km^2 or 3% of the earth's land surface (Maltby and Proctor 1996). Although peatlands are widespread, over 90% of the area occupied by peatlands is in the boreal regions of the Northern Hemisphere (Maltby and Proctor 1996). In the United States the majority of peatlands occur in Alaska, the upper Midwest, the Northeast, and the low-lying Gulf and Atlantic-Coast regions (Malterer 1996)(Fig. 1-1). There are few peatlands in the western United States (Fig. 1). Colorado has the second largest area of peatlands in the western United States, estimated at 330 km^2 (Malterer 1996).

Little information exists for fens in the Southern Rocky Mountains with most studies being paleobotanical rather than focusing on the ecological properties of the fens themselves. Therefore a literature review was carried out to acquire information about the physical properties of Southern Rocky Mountain fens (Table 1-1). Most Southern Rocky Mountain peatlands are located at higher elevations, ranging from about 2640 m to 3750 m (Table 1-1). Although Table 1-1 is not an exhaustive account of the elevation distribution of all peatlands in the region, it does indicate the elevations where they are commonly located.

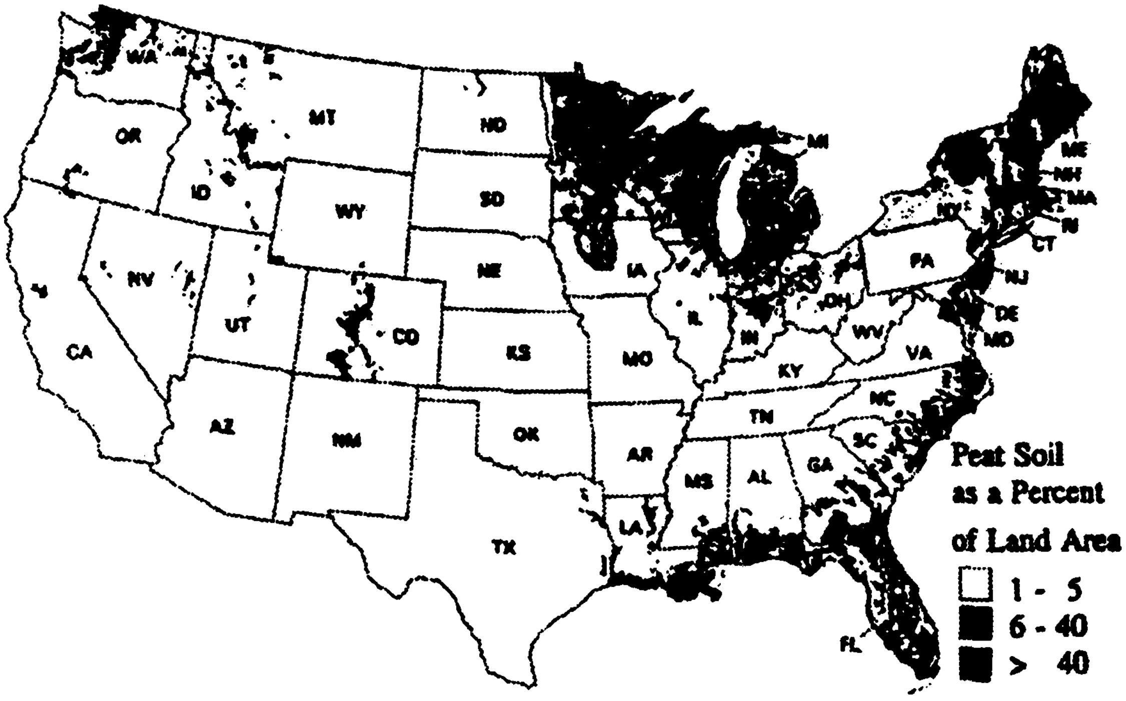

Figure 1-1. Peatland resources in the contiguous United States (Figure taken from Malterer, T.J. 1996).

Climate reconstruction studies indicate that a climate cooler than at present occurred in the Southern Rocky Mountain region from the end of the Pinedale glaciation (~14,000 years before present; YBP) to about 8,000-10,000 YBP (Pennak 1963, Maher 1972, Baker 1976, Madole 1980, Legg and Baker 1980, Markgraf and Scott 1981, Short 1985, Elias 1985). Basal ^{14}C dates for 25 Colorado peatlands listed in Table 1-1 indicate that 9 fens started to accumulate peat between 9,000 and 12,000 YBP, while 15 peatlands were established between 8,000 and 12,000 YBP. This range of establishment dates is older than peatlands from many boreal regions of the world where establishment is largely since 8,000 YBP (Ovenden 1990, Botch *et al.* 1995). Between 8,000 and 6,000 YBP the climate was similar to today and peatlands continued to form during this period.

Most paleoecological studies suggest a warmer and drier Altithermal period from 6,000-4,000 YBP, followed by cooler conditions that persist to the present day. It would be expected that few if any peatlands would have established during the Altithermal period, but several peatlands have established since the end of the Altithermal period. There are two possibilities for the young basal ^{14}C age of peatlands that formed since the end of the Altithermal. The first possibility is that these peatlands first developed after the Altithermal period in basins that never supported peatlands. These basins could have been ponds with an extended aquatic stage or because the modern climate conditions were more favorable than previous climate periods. The second possibility is that peatlands were formed prior to the Altithermal period, the peat was oxidized during the Altithermal and reformed when cooler and moister conditions developed after the Altithermal period.

The average thickness of peat bodies in Southern Rocky Mountain fens is about 2 meters and ranges from 0.85 m to 3.6 m (Table 1-1). These are relatively thin peat bodies compared to peatlands in other regions of the world (Ovenden 1990, Botch *et al.* 1995). The relatively thin peats accumulated over long time spans resulting in Southern Rocky Mountain fens having a mean peat accumulation rate of 0.25 mm per year (Table 1.1). Comparable long-term accumulation rates for peatlands in other regions are: N. Europe = 0.60 mm/yr (Aaby 1986), boreal Russia = 0.6-0.8 mm/yr (Botch and Masing 1983), Canada = 0.48 mm/yr (Gorham 1991) and Eurasia = 0.52 mm/yr (Zurek 1976).

Table 1-1. Elevation, basal dates (years BP ± error in years), peat thickness, and long-term average accumulation rates (basal date/peat thickness) for selected peatlands in the Southern Rocky Mountain region. N/A indicates data not available.

Location	Elevation (m)	Basal Date YBP	Peat Depth (m)	Accumulation Rate (mm/yr)
South Park, CO				
Sacramento Creek (Cooper 1990b)	3,100	9,820±150	2.13	0.22
Carpenter's Fen (Cooper 1990b)	3,150	9,280±180	3.20	0.34
McMaster's Fen (Cooper 1990b)	3,175	9,220±110	3.33	0.36
East Lost Park Fen (Cooper 1990b)	3,100	10,080±150	2.64	0.26
High Creek Windmill Fen (Cooper 1990b)	3,010	8,270±140	0.90	0.11
Lost Park Fen (Vierling 1992)	3,079	11,820±100	3.30	0.28
Gore Range, CO				
Dome Creek Meadow (Feiler and Anderson 1997)		7,800±100	3.62	0.46
Buffalo Pass (Madole 1980)	3,146	7,730±250	1.93	0.25
Front Range, CO				
Green Mt. Pond (Cooper 1990)	2,865	11,820±170	1.50	0.13
Big Meadows (Cooper 1990)	2,865	11,230±170	1.50	0.13
Winding River Kettle (Madole 1976)	2,640	10,320±200		
Silver Lake Bog (Pennak 1963)	2,979	6,190±300	1.75	0.28
Albion Bog (Pennak 1963)	3,247	2,470±200	1.25	0.51
Caribou Fen (Benedict and Maher, unpublished data)	3,400	10,500±70	1.90	0.18
Zapf's Fen (Benedict and Maher, unpublished data)	2,725	5,000±140	1.32	0.26
La Poudre Pass (Madole 1980)	3,103	9,800±400	N/A	N/A
San Juan Mountains, CO				
Eureka Gulch Bog (Carrara *et al.* 1991)	3,665	6,180±160	2.40	0.29
California Gulch Bog (Carrara *et al.* 1991)	3,165	7,860± 40	1.55	0.20
Placer Gulch Bog (Carrara *et al.* 1991)	3,600	8,790±260	0.85	0.10
Picayne Gulch Bog (Carrara *et al.* 1991)	3,750	8,350±250	1.30	0.16
Hurricane Basin Bog (Carrara *et al.* 1991)	3,660	8,420±750	2.05	0.24
Gunnison County, CO				
Red Lady Fen (Fall 1997)	3,350	4,675±155	0.95	0.20
Red Well (Fall 1997)	3,290	2,805±160	1.00	0.36
Iron Bog (Fall 1997)	2,290	8,260±220	2.20	0.27
Splains Gulch Meadow (Fall 1997)	3,150	8,560±600	2.00	0.23
Average	3,146	8,190	1.99	0.25

Using the average depth and area of peatlands, it is possible to estimate the amount of carbon stored in Southern Rocky Mountain peatlands. The area of peatlands in Colorado is estimated to be 330 km^2 (Malterer 1996) with a mean peat thickness of 2 m (Table 1-1). Assuming a carbon content of 50 % (Moore 1989, Ovenden 1990, Gorham 1991, Belyea and Warner 1996, Robinson and Moore 1999) and a mean bulk density of 0.2 g cm^{-3} (average of Caribou and Zapfs Fen from Chapter 4), then the total carbon content of peatlands in Colorado = 0.066 Gt of carbon. This indicates that Colorado peatlands store a small fraction, 0.015 %, of global carbon stored in peatlands (Gorham 1991).

CARBON CYCLING IN FENS

Carbon cycling in fens is important for several reasons. First, to understand and manage peatlands it is imperative to understand the processes that regulate carbon budgets, which affects the growth or decay of peat soils, and support the peatland. The peat soil can modify the hydrologic conditions by affecting water table levels, soil hydraulic conductivity and water holding capacity (Boelter and Verry 1977), which in turn can influence the vascular and non-vascular plant composition (Mitch and Gosselink 2000). The second major reason to study the carbon cycle of peatlands is their importance in the global carbon cycle. Recent concerns over global climate change due to greenhouse gas emissions have focused on peatlands due to their large carbon pools. It is hypothesized that global warming could convert some peatlands into net sources of gaseous carbon creating a significant positive feedback to global warming. In addition, wetlands are the single greatest natural source of CH_4 (Schlesinger 1997), which has a global warming potential 56 times greater than CO_2 over a 20-year period (IPCC 1995).

Peat accumulates in ecosystems where and when annual primary production is greater than annual organic matter decomposition (Frolking *et al.* 1998). Peat accumulation in northern and mountainous regions is a function of low decomposition rates rather than high net annual primary production (Malmer 1986, Francez and Vasander 1995). Almost all carbon entering a peatland is from *in situ* plant growth, although carbon can also enter peatlands as dissolved organic carbon or dissolved inorganic carbon from precipitation, groundwater, streams and adjacent hillslopes (Rivers *et al.* 1998). However, these secondary sources of carbon are a minor addition (Carroll and Crill 1997, Rivers *et al.* 1998, Waddington and Roulet 2000) and are often ignored in peatland carbon budgets (Francez and Vasander 1995, Alm *et al.* 1997, Minkkinen *et al.* 1999).

Organic matter decomposition by microbes produces CO_2 or CH_4, with CO_2 often being emitted in concentrations an order of magnitude greater than CH_4 (Hamilton *et al.* 1994, Francez and Vasander 1995). Dissolved organic carbon (DOC) is exported from certain peatlands (Moore *et al.* 1998), but typically is a minor source of carbon export (Carroll and Crill 1997). Herbivory is also a minor output but it is rarely measured because of the difficulty in quantifying this loss and the small amounts of carbon usually involved. Oxidation of carbon by fire can be an important carbon output in the long-term, but is not important on an annual time scale due to the relatively long fire return interval (Hogg *et al.* 1994).

Decomposition is the breaking down of carbon bonds by microbes to release energy and carbon for their growth, and is influenced by many interactive factors in fens. The reduction-oxidation (redox) status of the soil reflects the species of microbes dominating the decomposition process as well as the rate of decomposition with efficiency decreasing at lower redox potentials (Schlesinger 1997). Aerobic decomposition is the most efficient form of decomposition with microbes using oxygen as the terminal electron acceptor and releasing CO_2 as the byproduct (Schlesinger 1997). Oxygen diffuses 10,000 times slower in water than in air, thus replacement of oxygen in saturated soils is so slow that it results in oxygen deficiencies in peatland soils. Although oxygen is the most efficient terminal electron accepter, it is not the only element or compound that can be used as an electron acceptor. When soil oxygen is depleted, other elements and compounds are used in the order of their thermal dynamic energy gain, commonly called sequential reduction. Nitrate is the next compound to be used as a terminal electron acceptor, and respiration using nitrate releases almost as much energy as respiration utilizing oxygen (Schlesinger 1997). After nitrate is depleted, oxidized forms of manganese, iron and sulfur are sequentially used as terminal electron acceptors. Methanogenesis occurs after sulfate is depleted. Methane is produced by obligate anaerobes (archaebacterial) by reducing CO_2 or simple carbon substrates, which are predominantly supplied from by-products of fermentation (Valentine *et al.* 1994).

Water table levels influence the rate of CO_2 and CH_4 emissions by creating a barrier to oxygen diffusion into saturated soil horizons that allow low redox potentials to develop. High water tables result in lower CO_2 emissions and higher CH_4 emissions (Hogg *et al.* 1994, Bubier 1995, Silvola *et al.* 1996, Libliket *et al.* 1997). Lower water tables increase the volume of aerobic soils increasing CO_2 emissions while simultaneously decreasing CH_4 emissions. Increasing soil temperature has been shown to increase both CO_2 and CH_4

fluxes (Crill *et al.* 1988, Froliking and Crill 1994). Methane emissions were also found to respond to nutrient concentrations of the peat, with higher nutrient levels increasing emissions (Yavitt *et al.* 1988, Valentine *et al.* 1994).

Vegetation composition also plays a role in gas emissions. Most wetland plants have large amounts of aerenchyma tissue that allows oxygen diffusion from the atmosphere through leaves and stems down to roots. Aerenchyma also provides a pathway for CH_4 and CO_2 emissions to move to the atmosphere from waterlogged soils (Thomas *et al.* 1996, Shannon *et al.* 1996, Mitch and Gosselink 2000).

Peatland water tables can be lowered by human removal of water from the watershed or aquifers supplying the peatland, unusually dry weather patterns, or climate change. On a local scale ditching has been used all over the world to lower water tables in peatlands (Gorham 1991). In Rocky Mountain National Park, the Grand Ditch (Woods 2000) and the ditch in Big Meadows (Cooper *et al.* 1998) are two examples of human effects on local water supplies and water tables. Lower water tables associated with ditching have been found to greatly increase CO_2 emissions (Francez and Vasander 1995, Silvola *et al.* 1996) while decreasing CH_4 emissions (Silvola *et al.* 1996, Nykänen *et. al* 1998). The overall effect of lowered water tables due to ditching is usually an increase in organic matter decomposition that results in peatlands becoming carbon sources instead of sinks (Armentano and Menges 1986, Silvola *et al.* 1996). Drained peatlands worldwide annually release between 11 and 55% of the annual total carbon fixed by undrained peatlands (Gorham 1991). However, in certain forested peatlands, ditching has been found to increase carbon storage by increasing tree biomass more than decomposition (Laine *et al.* 1996).

RESEARCH OBJECTIVES

My dissertation research has several objectives. The first objective was to determine the annual carbon accumulation rates in pristine Southern Rocky Mountain peatlands. It is not known if Southern Rocky Mountain peatlands are still accumulating carbon, have reached a steady state, or are losing carbon under the current climate regime. I quantify this in Chapter 2 by calculating detailed carbon budgets for three pristine peatlands that have a range of seasonal water table depths and vegetation types.

My second objective was to determine if the Grand Ditch water diversion decreases carbon storage in two peatlands located below the ditch. The Grand Ditch is a large transmountain water diversion project that removes water from the Colorado River watershed and transfers it to the Cache le Poudre River watershed. There have been no analyses of how this project, or similar water depletions, influences the long-term persistence of peatlands in the Southern Rocky Mountains. I quantify this objective in Chapter 2 by calculating carbon budgets for two fens that are below the Grand Ditch and comparing them to the three pristine peatlands studied in the same area.

While it is known that lowering water levels may change a peatland's carbon balance, it is unknown how much the water table must be lowered before significant changes in decomposition rates occur. If fens are sensitive to water level changes then a small hydrologic change due to water diversion, groundwater pumping or climate change might be sufficient to alter them from sinks to sources of carbon. But if fens are less sensitive to water levels, than they may be less impacted by small changes in their water levels. I quantify this objective in Chapter 3 by experimentally manipulating water tables within independent microcosms to develop a water table relationship for CO_2, CH_4 and total gaseous carbon ($CO_2 + CH_4$) efflux.

The fourth objective, which I address in Chapter 4, was to determine how well the CENTURY ecosystem model can be used to simulate long-term carbon accumulation in a fen. Despite the importance of peatlands to the global carbon cycle, peatlands continue to be neglected in modeling. No model exists that can be used to predict carbon accumulation rates in a peatland in response to environmental changes, such as temperature or hydrologic regime. Predictive, process-based models are necessary to understand the complex effects of climate change, physical disturbances and drainage on carbon cycling in peatlands. If CENTURY can be calibrated for a fen, then it will be used to predict short-term changes in carbon storage in response to hydrologic changes.

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Chapter 2

CARBON BALANCES OF PRISTINE AND HYDROLOGICALLY MODIFIED SUBALPINE FENS, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

ABSTRACT

Carbon balances were calculated during 1997 and 1998 for five fens in Rocky Mountain National Park, Colorado. Carbon balances were calculated as the difference between plant production and gaseous carbon efflux (CO_2 and CH_4). Two fens were located beneath a large water diversion, and three pristine fens were located away from any water diversions. Two pristine fens maintained a water table at or above the soil surface during both years. The other pristine fen had a water table that dropped 10 cm below the soil surface during 1997, but stayed above the surface in 1998. One fen beneath the water diversion project maintained a constant water table 3 cm above the soil surface for both years. The other fen beneath the water diversion had a minimum water table 60 cm below the soil surface during 1998, but the water table remained above the soil surface during 1997. Plant productivity averaged 217 g C m^{-2} yr^{-1} for all sites and years, with belowground productivity averaging 60% of total plant production. All the fens accumulated a calculated mean of 84 g C m^{-2} yr^{-1} when the water table remained at or above the soil surface. However, sites lost an average of 96 g C m^{-2} yr^{-1} when the water table dropped beneath the soil surface. When the water table was beneath the soil surface CO_2 efflux increased and CH_4 efflux decreased, but the increase in CO_2 was larger than the reduction in CH_4 resulting in a net efflux of carbon to the atmosphere.

Key words: peatlands, fens, CO_2, CH_4, water table drawdown, carbon balance, carbon budgets, water table levels, climate change, Colorado, plant production

INTRODUCTION

Peatlands cover an estimated 4 million km^2, or 3% of the earth's land surface, with over 90% occurring in the cool, boreal northern latitudes (Maltby and Proctor 1996). Most peatlands have developed on flat or gently sloping landscapes with poor drainage (Chadde *et al.* 1998), however, peatlands also occur in mountainous regions. Colorado, located in the Rocky Mountains of the western United States, is reported to have 330 km^2 of peatlands, more than any other Rocky Mountain state (Malterer 1996). Most of Colorado's peatlands occur in glaciated valleys or inter-mountain basins where abundant snowmelt and low soil temperatures provide suitable conditions for peat to accumulate (Cooper 1990, Cooper and Andrus 1994). Colorado peatlands are important because of their habitat value, especially to large populations of Elk (*Cervus elaphus*) and Moose (*Alces alces*) in Rocky Mountain National Park. Colorado peatlands are also areas of high regional biodiversity and rare species (Cooper 1996).

Peat accumulation in northern and mountainous regions is a function of low decomposition rates due to water logged soils rather than high net annual primary production (Frolking *et al.* 1998). Estimates of peat stored globally range from 224 to 455 Pg (1 Pg=10^{15}g), which is 12-30% of the global soil carbon pool (Gorham 1991, Botch *et al.* 1995, Lappalainen 1996, Clymo *et al.* 1998). Peatlands also release large amounts of carbon to the atmosphere as carbon dioxide (CO_2) and methane (CH_4), which are byproducts of decomposition. Since the amount of carbon stored annually is a fraction of the total plant production, small changes in the rate of decomposition can shift a peatland from a sink to a source of atmospheric carbon (Gorham 1991, Francez and Vasander 1995, Silvola *et al.* 1996a).

Peatland decomposition rates are strongly controlled by water table levels. The water table is a physical barrier to oxygen diffusion from the atmosphere into the peat, limiting microbial activity and slowing decomposition rates (Maltby and Proctor 1996, Oechel *et al.* 1998). A declining water table increases the volume of aerobic soil and increases CO_2 production, while decreasing anaerobically produced CH_4 (Moore and Knowles 1989, Bubier 1995, Silvola *et al.* 1996a, Liblik *et al.* 1997, Nykänen *et al.* 1998). Lower water tables can increase CO_2 efflux far more than CH_4 efflux decreases, increasing the rate of carbon loss from the system (Armentano and Menges 1986, Silvola *et al.* 1996a, Nykänen *et al.* 1998).

Peatland water tables can decline during drought periods or due to human activities, such as ditching or intercepting water before it reaches a peatland. Ditching has been used extensively for forestry and agriculture practices (Gorham 1991, Vasander *et al.* 1997) and has been shown to increase the rate of organic matter decomposition (Armentano and Menges 1986, Francez and Vasander 1995, Silvola *et al.* 1996a). Gorham (1991) estimated that worldwide drained peatlands annually release between 11-55% of the total carbon fixed by undrained peatlands. Ditched peatlands have often been used as analogs for peatlands with lower water tables that could occur in a drier or warmer climate (Roulet *et al.* 1993, Silvola *et al.* 1996a, Nykänen *et al.* 1998). However, the soils and vegetation of ditched peatlands are physically altered by ditch construction, and forestry and agricultural practices may not be a suitable analog for a drier or warmer climate period. In addition, the water table depths in ditched peatlands are spatially heterogeneous due to ditch spacing and the depth of ditches. The analysis of peat carbon balances during drought periods or when the water supply to a peatland is intercepted may provide a more suitable proxy for determining the effects of a climatically-driven reduction in water delivered to a peatland.

I calculated the annual carbon balance of five peatlands, three of which are pristine and two are beneath a large water diversion. This diversion reduces the amount of water delivered while not physically disturbing the peatlands. The objectives were to: (1) quantify the carbon accumulation rates in the pristine peatlands and, (2) quantify differences in carbon accumulation rates in the two peatlands potentially affected by the water diversion.

STUDY AREA

This study was conducted in the headwaters of the Colorado River on the west side of Rocky Mountain National Park in the Southern Rocky Mountains of Colorado (Fig. 1). The study area has a continental climate with cool summers, frequent thunderstorms, and cold snowy winters. Up to 80% of the annual precipitation falls as snow (Windell *et al.* 1986, Cooper 1990, Hauer *et al.* 1997). Mean annual precipitation at the Phantom Canyon SNOTEL station, located 5 km from the study sites, is 65 cm with a mean annual temperature of 0.8 °C. Snowmelt usually begins in May, which recharges wetlands in the valley bottoms, and diminishes by midsummer. The dry summers limit peatland development to areas supplied with groundwater through most of the summer (Cooper 1990).

In Colorado, most of the precipitation falls in the mountainous western half of the state, while most of the human population and agriculture occurs in the semi-arid, flat, eastern half of the state. To counter this imbalance of available water and demand for water, large-scale water diversion projects have been built to transport water from western to eastern Colorado. The Arapaho-Roosevelt National Forest, which surrounds Rocky Mountain National Park, has approximately 40 major water storage reservoirs (Stohlgren 1998). National Parks are not immune to water development; Rocky Mountain National Park has many ditches that were constructed before the park was established in 1915 (Graf 1997, Cooper *et al.* 1998). The largest diversion is the Grand Ditch, which was begin in the late 1800's and finished in the 1930's.

The Grand Ditch diverts water during June through September from the west flowing Colorado River to the east flowing Cache la Poudre River (Fig. 1). The ditch is 26-kilometers long and intercepts surface flow from eleven streams flowing from the Never Summer Range to the Colorado River. On average about 20 million cubic meters per year is diverted from the Colorado River watershed into the Cache la Poudre River watershed (Woods 2000). During dry years the ditch may intercept as much as 40% of the runoff, nearly drying up the tributaries that it diverts and depleting streamflow in the Colorado River (Woods 2000). I selected two study fens on the western side of the valley floor that were potentially hydrologically affected by the Grand Ditch, and three pristine fens in the nearby Tonahutu Creek watershed that were not affected by any water diversions (Fig. 2-1).

Circle Fen is a soligenous fen (Fig. 2-1, Table 2-1) supported by groundwater flowing through the Red Creek alluvial fan and discharging at the fans toe. Red Creek is intercepted by the Grand Ditch 400 m above the valley floor, which depletes its flow by as much as 60% during the summer reducing recharge to the alluvial fan (Woods 2000). The vegetation of Circle Fen is dominated by the willows *Salix planifolia* and *S. wolfii* with an understory of *Carex aquatilis* that grades into a nearly homogenous stand of *Carex aquatilis*, *C. utriculata*, and *Eriophorum angustifolium*. Plant nomenclature follows Weber and Whittman (1996). Carbon budgets were developed in the herbaceous portion of the fen.

Hell's Fen is located at the base of the Never Summer Mountains and is supplied with water from a small unnamed stream flowing into the central portion of the fen creating a water track as well as abundant groundwater discharging from a large lateral moraine. The study site is located in the water track dominated by *Eleocharis quinqueflora*. Other common species include *Swertia perennis*, *Clementsia rhodantha*, *Pedicularis groenlandica*, *Carex aquatilis* and the moss *Drepanocladus aduncus*.

Tonahutu Creek Area

Three peatlands were studied in the Tonahutu Creek watershed, which is tributary to the Colorado River and located 2 km east and 200 m higher in elevation than the Colorado River Valley (Fig. 2-1).

Big Meadows is a soligenous peatland complex occupying the bottom of a glacial valley upstream of a terminal moraine (Fig. 2-1, Table 2-1) (Cooper *et al.* 1998). It is fed by groundwater discharging from the toeslope of the adjacent western hillslopes and from an unnamed stream discharging from Spring Fen (Cooper *et al.* 1998). Tonahutu Creek flows along the eastern side of the valley, and is not a major source of water to the peatland (Cooper 1990). The study site is located in the pristine northern portion of Big Meadows, up gradient from the central peatland where an agricultural drainage ditch was restored in 1990 (Cooper *et al.* 1998). The vegetation is dominated by *Carex aquatilis* with *Carex utriculata* and *Psychrophila leptosepala* also occurring.

Green Mountain Pond is a kettle basin located just west of Big Meadows in which a topogenous fen has formed. Green Mt. Pond has a small shallow pond in the center of the fen. The fen vegetation is dominated by a near monoculture of *Carex utriculata* that surrounds the pond. No surface water inlet or outlet occurs, and groundwater draining from the adjacent hillslopes is the main input of water. This site has the lowest pH, calcium and NH_4^+ content (Table 2-1), probably due to the limited amount of surface and ground water flowing through the site.

Spring Fen is a soligenous fen occurring at the toe of a large talus and moraine slope about 0.5 km NE of Big Meadows. Water enters from a small stream to the north and from springs discharging from adjacent southwest-facing slopes (Johnson 1996). The surface water at this site has the highest pH of the study fens (Table 2-1). The vegetation of Spring Fen is diverse including stands dominated by *Carex aquatilis*, *Eleocharis quinqueflora* and *Picea engelmannii* (Johnson 1996). The study site is located in an *Eleocharis quinqueflora* stand.

METHODS

Hydrology

Ground water levels were measured in monitoring wells constructed from 3.8 cm slotted PVC pipes in each peatland. Wells were installed by hand auguring with a standard bucket auger of the same diameter as the well casing. Well casings were inserted into the hole and tops sealed with native clay to prevent surface water from running into the casing. Water table depth was measured in wells every 1-2 weeks from May to October.

Development of Carbon Balances

A simple fen carbon balance can be stated as:

$$\textit{carbon input} - \textit{carbon output} = \Delta\ \textit{carbon storage}$$

The largest carbon input is from *in situ* plant growth. Carbon can also enter peatlands as dissolved organic carbon or dissolved inorganic carbon from precipitation, groundwater, streams and adjacent hillslopes (Rivers *et al.* 1998). However, this secondary source of carbon is often a minor addition (Carroll and Crill 1997, Rivers *et al.* 1998, Waddington and Roulet 2000) and is often not measured in peatland carbon budgets (Francez and Vasander 1995, Alm *et al.* 1997, Minkkinen *et al.* 1999). Microbial decomposition of organic matter is the main carbon output, producing either CO_2 or CH_4 gas, with CH_4 efflux typically being an order of magnitude less than CO_2 efflux (Hamilton *et al.* 1994, Francez and Vasander 1995, Aerts and Calune 1999). DOC can be exported from peatlands (Johnson *et al.* 1996), but is typically a minor source of carbon export (Carroll and Crill 1997). Herbivory is also an output, but is rarely measured because of the difficulty in quantifying this loss, and the small amounts of carbon presumably involved. Oxidation of carbon by fire is an episodic output that is important to the long-term carbon balance, but unimportant on an annual scale (Hogg *et al.* 1992).

I calculated a carbon budget for each site by measuring carbon inputs and outputs. Measured carbon inputs to each fen were above and belowground net primary production. Carbon output was measured as the gaseous carbon efflux (CO_2 + CH_4). Other forms of carbon exports and imports (e.g., DOC and herbivory) were not measured. CO_2 effluxes measured are a combination of microbial and root respiration. Root respiration has been found to range between 35% - 60% of the total CO_2 efflux in both peat and mineral soils (Moore 1989, Haynes and Gower 1995, Nakane *et al.* 1996, Silvola *et al.* 1996b); the mean of these published studies, 45%, was used for this study.

Annual Plant Production

Aboveground net primary production (ANPP) was measured using the harvest method (Bartsch and Moore 1985, Francez and Vasander 1995). Herbaceous vegetation was clipped three times from August through September at the ground surface in 0.25m x 0.25m quadrats. Three quadrats in 1997, and six quadrats in 1998, were randomly placed (but never in a spot previously cut) in the study stand in each peatland. The clipped biomass was stored frozen in plastic bags prior to being analyzed. In the laboratory, the biomass was oven-dried at 70 °C for up to 72 hours, weighed and analyzed for carbon content using a LECO CHN-100 Analyzer (St. Joseph, MI).

Belowground net primary production (BNPP) was calculated using in-growth root bags (Neill 1992). Mesh bags 60 cm long and 6 cm in diameter made of fiberglass window screen (1.5 mm mesh) were filled with *Sphagnum* peat moss and inserted in an augured hole to a depth of 50 cm. Three replicates were installed in 1997 and 6 replicates in 1998. The bags were installed just after snow melt in the spring and collected in October. Bags were collected by first cutting the roots around the outside of the bag with a fine toothed saw blade, then pulling the bag out of the soil. Root biomass was the dry weight of roots that grew into the mesh bag. Roots were collected from the mesh bags, washed free of sediment, oven dried, weighed and analyzed for carbon content using a LECO CHN-100 Analyzer (St. Joseph, MI). Total net primary production (NPP) was calculated by summing ANPP and BNPP.

Gaseous Carbon Efflux

Methane efflux rates were measured using the static chamber technique (Hutchinson and Mosier 1981, Waddington and Roulet 1996, Melloh and Crill 1996). Static chambers were constructed of 20 cm diameter x 20 cm length PVC pipe. Three static chamber collars per site were inserted 2 cm into the peat soil in each study site, and left in place for the duration of the study. Gas samples were collected during the snow free season approximately monthly in 1997 and weekly in 1998. Gas samples were collected using a nylon syringe inserted through a septum on top of the static chambers. An initial gas sample was collected at time zero when the chamber was sealed with subsequent samples collected at 5 and 10 minutes. The collected gas was stored in evacuated flasks with tops sealed with silicone for transport and storage. The collected gas sample was analyzed for within three days for CH_4 using a Shidmazdu GC-14A gas chromatograph.

Carbon dioxide efflux was measured using a Li-Cor 6200 Portable Photosynthesis Infrared Gas Analyzer (IRGA) (Li-cor Inc., Lincoln, NE). A dynamic chamber top attached to the IRGA was placed on the same permanent static chamber collars used to measure CH_4. Efflux rates were calculated as the mean of four 15-second readings.

Wintertime CO_2 and CH_4 effluxes were not measured and the efflux rates from a nearby subalpine fen in Rocky Mountain National Park are used in annual carbon budget calculations (Mast *et al.* 1998). The vegetation of this site is dominated by *Carex utriculata* and *C. aquatilis*, has a similar peat thickness of 175 cm, and a similar hydrologic regime with the water table normally remaining 5-10 cm above the soil surface during the growing season. However, this site has no *Eleocharis quinqueflora* to compare with Hell's Fen and Spring Fen, and is at a higher elevation of 3200 m. Nevertheless, differences in elevation or vegetation should have minimal wintertime differences as all high elevation sites are under deep snow and gaseous efflux rates are minimal (Mast *et al.* 1998). All values were reported in weight of carbon for CO_2 (mg C-CO_2 m^{-2} hr^{-1}), CH_4 (ug C m^{-2} hr^{-1}), NPP (g C m^{-2} yr^{-1}) and carbon budgets (g C m^{-2} yr^{-1}).

I calculated daily CH_4 and CO_2 efflux rates for each site by developing a site-specific temperature-gas efflux relationship in a spreadsheet model:

$$\text{efflux} = ae^{(bT)} \qquad \text{(Equation 2-1)}$$

where efflux is either CH_4 (ug C m^{-2} hr^{-1}) or CO_2 (mg C m^{-2} hr^{-1}), T is soil temperature (C) at 20 cm depth for CH_4 and air temperature (C) for CO_2 and a and b are dimensionless coefficients (Table 2-2). The nonlinear equations were optimized for the lowest root mean square error. The temperature relationships were than used to calculate seasonal CH_4 and CO_2 efflux rates by using mean daily temperature values from a nearby SNOTEL station

(Phantom Canyon, 2752 m). Daily soil temperatures were not available for CH_4 efflux modeling; therefore the running 14-day mean air temperature from the SNOTEL station was used as a proxy for soil temperature at 20 cm ($R^2 = 0.67$, $P < 0.001$, $n = 90$).

CO_2 and CH_4 efflux was modeled differently for Circle Fen in 1998 and Green Mt. Pond in 1997 because the water table dropped beneath the soil surface at these sites on these years, which altered the gas efflux rates. A nonlinear regression was developed using the exponential temperature function described above and a water table arctangent function:

$$efflux = b + \frac{c * \arctan(\pi * d(-a + wt))}{\pi} \qquad \text{(Equation 2-2)}$$

where efflux = CO_2 (g C m^{-2} hr^{-1}) or CH_4 (g C m^{-2} hr^{-1}), a-d are dimensionless coefficients and wt = water table depth. The coefficients were optimized for the lowest root mean square error of the combined temperature and water table functions. The final coefficients for the water table arctangent function for CO_2 are: a = -17.4, b = -0.6, c = 999.7 and d = 0.007. The final temperature coefficients are a = 84.54 and b = 0.07. The optimal combined regressions had a final root mean square error of 31.9 and a final predicted vs. observed R^2 of 0.81 with a sample size of 47. The final coefficients for the water table arctangent function for CH_4 are: a = -5.50, b = 1.27, c = 2476.03 and d = 75.15. The final temperature coefficients are a = 1151.8 and b = 0.065. The optimal combined regressions had a final root mean square error of 81.9 and a final predicted vs. observed R^2 of 0.36 with a sample size of 47.

Ancillary Measurements

Soil temperatures were measured coincidentally with gas efflux measurements at 5 cm, 10 cm and 20 cm beneath the soil surface using a thermometer. pH of the surface water was measured with an Orion pH-Mv meter and combination electrode. Redox potential was measured with the same pH meter using bright platinum electrodes inserted into the soil at 5, 10 and 20 cm and corrected with a Calomel electrode (Mars *et al.* 1996). Redox measurements were not made when the water table was more than 20 cm beneath the soil surface (the mean pe and pH measurements are given in Table 2-1).

The availability of nitrogen was compared with *in-situ* ion exchange resin bags. Resin bags were constructed with an anion resin (14 mL of Sybron IONAC ASB-IPOH, Sybron International, Milwaukee, WI) and a separate compartment of cation resin (14 mL of Sybron IONAC c-251 H+). Five resin bags were placed roughly 1 m apart at 5-cm depth in each study site. Resin bags were installed on 6/9/98 and removed 7/24/98. In the laboratory, the cation and anion pouches were combined and extracted with 100 mL of 2 M KCL. Ammonium and nitrate concentrations were analyzed colorimetrically on an Alpkem continuous autoanalyzer (the mean NH_4^+ and NO_3^- measurements are given in Table 2-1). Two surface water samples per site were analyzed for calcium at Colorado School of Mines using atomic emission spectrometry (the mean Ca^{+2} values are given in Table 2-1).

RESULTS

Hydrology

Total precipitation at the Phantom Canyon SNOTEL station was higher in 1997 (80 cm or 122% of the 62 year mean) than in 1998 (58 cm or 89% of mean). 1997 snowpack was one of the largest in the 62-year record and summer precipitation was 150% of the mean. In both years a mid-summer dry spell extending from late June to mid-July was followed by a period of monsoon rains that lasted until the middle of August (Fig. 2-2).

Water tables in Big Meadows, Spring Fen, and Hell's Fen remained above the ground surface during the summer in both study years (Fig. 2-2), with approximately 8 cm of water flowing across Big Meadows in early summer and 4 cm at Spring Fen and Hell's Fen all summer. Green Mountain Pond had 12 and 13 cm of standing water on June 8th and May 19th, 1997 and 1998 respectively. Green Mt. Pond water levels dropped in mid-summer in both years but increased in August in response to monsoon rains (Fig. 2-2). The water table in Green Mt. Pond dropped to 10 cm below the soil surface in 1997 but remained at or above the soil surface in 1998.

In 1997, the water table in Circle Fen remained at or above the ground surface throughout the growing season (Fig. 2-2), while in 1998 it dropped to 60 cm below the soil surface in July and remained below the surface for the remainder of the summer. Research by Woods (2000) suggests that the low 1998 water table was due to the Grand Ditch diverting Red Creek and reducing groundwater flow through the Red Creek alluvial fan.

Plant Production

Above ground net primary production for all sites and years ranged from 47 to 142 g C m^{-2} yr^{-1} with a mean of 88 g C m^{-2} yr^{-1} (Table 2-3). Big Meadows and Green Mt. Pond had the highest ANPP, and Hell's Fen the lowest.

BNPP ranged from 75 to 181 g C m^{-2} yr^{-1} and averaged 129 g C m^{-2} yr^{-1} for all sites and years (Table 2-3). Root production in ingrowth cores was highest in the upper soil profile (Fig. 2-3). Approximately half of the root production occurred in the upper 10 cm of soil and 75% in the top 20 cm. Below ground net primary production (BNPP) was not determined for Big Meadows in 1997 due to ingrowth root bags being pulled out by elk, and one bag coming apart at the seams when it was removed. 1997 BNPP for Big Meadows was estimated using 1997 ANPP and applying the ANPP/NPP ratio calculated from 1998. Elk also created problems at Circle Fen where one bag was pulled out in both 1997 and 1998.

Total NPP for all sites ranged from 130 to 316 g C m^{-2} yr^{-1} and averaged 217 g C m^{-2} yr^{-1} for the two years (Table 2-3). The mean NPP in 1998 was not significantly higher (243 g C m^{-2} yr^{-1}) than 1997 (190 g C m^{-2} yr^{-1}) (t-test, $P = 0.28$). ANPP comprised 30% to 50% of the total NPP (Table 2-3). The ANPP/NPP ratio was similar between years for all sites except Circle Fen despite annual NPP differences. For example, 1998 NPP at Green Mt. Pond was 143% of 1997 NPP, yet the ANPP/NPP ratio was similar. 1998 Spring Fen NPP was 53% of 1997 NPP, but the ANPP/NPP ratio changed only from 0.44 to 0.48. Circle Fen had similar ANPP in both years, but lower BNPP in 1998.

CO_2 and CH_4 Effluxes

Strong seasonal trends in both CO_2 and CH_4 efflux exist at all sites (Fig. 2-4). Modeled CO_2 and CH_4 efflux were similar across all sites from October to May when the soil temperature was low. Gas efflux rates increased throughout the summer, with maxima occurring for most sites in July and August. Maximum CO_2 efflux was approximately 2 g C m^{-2} day^{-1} for all sites except for Green Mt. Pond in 1997 and Circle Fen in 1998, which had CO_2 efflux up to 7 and 5 g C m^{-2} day^{-1}, respectively, when the water table dropped below the soil surface (Fig. 2-4).

Methane efflux rates for the five sites fell into three regimes (Fig 2-4). Big Meadows had the highest CH_4 effluxes with a maximum of 0.9 and 1.3 g C m^{-2} day^{-1} for 1997 and 1998, respectively. Hell's and Spring Fen CH_4 efflux rates were nearly identical, peaking at 0.19 g C m^{-2} day^{-1}. Circle Fen and Green Mt. Pond, which had the highest CO_2 efflux, had the lowest CH_4 efflux with peak rates at 0.07 and 0.04 g C m^{-2} day^{-1} respectively.

CO_2 and CH_4 efflux rates varied with water table depth as seen at Circle Fen in 1998 (Fig. 2-5). As the water table dropped from near the soil surface to 30 cm depth from 6/24/98 to 7/2/98 the CO_2 efflux rate increased 125% and CH_4 efflux decreased by 61% (Fig. 2-5). In late July the water table increased 61.5 cm in one week as monsoon rains recharged local ground water flow systems and CO_2 efflux decreased 53% while CH_4 efflux increased 69%.

Chemistry

The average pe measurements (Table 2-1) reveal that all sites were anaerobic with Green Mt. Pond the least reduced and Big Meadows the most reduced site. There were no significant differences with redox measurements with soil depth or with time.

The nitrogen at all sites was predominantly ammonium (NH_4^+) with nitrate (NO_3^-) found in only minute amounts (Table 2-1). The resin bag nitrogen levels showed no significant correlation with plant production, gas efflux or carbon budgets. There was a trend of decreased NO_3^- with decreasing pe ($R^2 = 0.64$, $p = 0.1$, $n = 5$). There was also a trend of increasing NH_4^+ ($R^2 = 0.67$, $p = 0.09$, $n = 5$) and decreasing NO_3^- ($R^2 = 0.65$, $p = 0.10$, $n = 5$) with an increase in pH.

Carbon Balances

CO_2 efflux accounted for approximately 90% of the carbon output ranging between 204 to 515 g C m^{-2} yr^{-1} (not counting root respiration) for Hell's Fen and Spring Fen (Table 2-4). CO_2 accounted for only 65% of the carbon output in Big Meadows because of the large CH_4 efflux. CO_2 accounted for roughly 90% of the carbon output in Circle Fen in 1997 and Green Mt. Pond in 1998 when the water table stayed above the soil surface, but over 95% of the carbon output at Circle Fen in 1998 and Green Mt. Pond in 1997, when the water table dropped below the surface.

Big Meadows, Hell's Fen and Spring Fen had positive carbon balances in both 1997 and 1998 (Table 2-4). Green Mt. Pond fen lost 85 g C m^{-2} yr^{-1} in 1997 when the water table dropped below the ground surface, but gained 179 g C m^{-2} yr^{-1} in 1998 when the water table remained above the soil surface for the entire year. The two peatlands beneath the Grand Ditch (Hell's Fen and Circle Fen) had distinctly different carbon balances. Hell's Fen had high water tables and a net carbon gain in both years, while Circle Fen gained carbon in 1997 (134 g C m^{-2} yr^{-1}) but lost 107 g C m^{-2} yr^{-1} in 1998 when the water table dropped 60 cm beneath the surface.

DISCUSSION

Hydrology

The Grand Ditch water diversion reduced the flow of Red Creek in 1997 and 1998 and this probably diminished groundwater flow to Circle Fen (Woods 2000). The decrease in groundwater inflow resulted in a lower water table in Circle Fen during the summer of 1998, an average precipitation year. The water table also dropped 100 cm below the soil surface in 1996 during another average precipitation year, but gas efflux and plant production were not measured that year. The water table in 1997 probably remained high due to the combination of larger than average snowpack and abundant summer precipitation (Woods 2000). Large snowpacks increase the water available to Circle Fen in two ways. First, more snowmelt occurs on mountain slopes below the Grand Ditch that can reach hillslope aquifers. Second, the Grand Ditch removes approximately the same amount of water each year due to a finite transport capacity (Woods 2000). Therefore, on large snow years more water flows through the Grand Ditch into Red Creek, which recharges the hillslope and alluvial fan aquifers that supply groundwater to Circle Fen (Woods 2000). The Grand Ditch did not affect water levels in both peatlands on the floor of the Colorado River Valley as water levels in Hell's Fen fluctuated by less than 1 cm over the three years of monitoring (1996-1998). This most likely is due to the majority of Hell's Fen's watershed being below the Grand Ditch (Woods 2000).

Three different types of hydrological regimes support fens in the study area. Hell's Fen and Spring Fen, both dominated by *Eleocharis quinqueflora*, had stable water tables with sheet flow across the soil surface throughout the summer. Big Meadows is dominated by *Carex aquatilis* and had high water tables and sheet flow in early summer but the water table dropped during the summer, although it remained above the soil surface. Circle Fen had a similar hydroperiod to Big Meadows in 1997, but the water table dropped 60 cm beneath the surface in 1998. Green Mt. Pond Fen is dominated by *Carex utriculata* and has a more variable water table with more deeply ponded conditions in early summer and deep water tables in late summer.

Groundwater levels have been monitored in Big Meadows and Green Mt. Pond since 1987 and these data add a longer-term perspective to the hydrologic conditions encountered during 1997 and 1998 (Cooper 1990, Cooper *et al.* 1998, Cooper unpublished data). Although mean water table levels in Big Meadows from June to October were slightly higher in 1997 and 1998 (mean of 6.6 and 5.4 cm respectively) than the 12-year mean of 3.7 cm (Figure 6), water levels were above the soil surface in the early summer in all years (mean water table in early June is 5.1 cm above the soil surface) and slowly declined during the summer. In 1987 through 1990 the water table dropped below the soil surface but generally not until mid-August.

Long-term groundwater monitoring in Green Mt. Pond (since 1988, excluding 1995 and 1996 when no data was collected) reveals a different hydrologic pattern than Big Meadows (Fig. 2-7) (Cooper 1990, unpublished data). Water ponds 10-20 cm deep in the

Green Mt. Pond fen in early summer but due to the small watershed the water table may drop sharply in August. In 8 of the 10 years with data the water table dropped to an average of 23.8 cm below the surface by the end of July. In 1992 and 1998 the water table remained above the soil surface for the entire growing season. The importance of summer rain for maintaining a high water table in Green Mountain Pond was clearly illustrated in 1997 and 1998. 1997 was one of the highest snowpack years, yet the water table dropped below the surface in late June through late July. The water table remained above the surface in 1998, despite an average snowpack, due to abundant rain in July.

Plant Production

Above ground net primary production in the study fens ranged from 47 – 142 g C m^{-2} yr^{-1}. This is similar to values reported for herbaceous fens in Canada (Bartsch and Moore 1985, Szumigalski and Bayley 1997, Thorman and Bayley 1997a, Thorman and Bayley 1997b, Thorman *et al.* 1998). ANPP in Big Meadows during 1997 and 1998 had a mean of 119 g C m^{-2} yr^{-1} and is not significantly different than average ANPP for Big Meadows in 1988, 1990 and 1991 that was 139 g C m^{-2} yr^{-1} (t-test, $P = 0.45$) (Cooper unpublished data). However average ANPP for Green Mt. Pond for 1997 and 1998 of 99 g C m^{-2} yr^{-1} is lower than average ANPP for Green Mt. Pond in 1988, 1990 and 1991 that was 177 g C m^{-2} yr^{-1} (t-test, $P = 0.11$)(Cooper unpublished data), due to the low ANPP measured in 1997 of 55 g C m^{-2} yr^{-1}. Total NPP ranged from 149 to 316 g C m^{-2} with a mean of 217 g/m^2 for the two study years (Table 2-3). The ANPP/NPP ratio was relatively similar at all sites for the two years even though production varied. This suggests that carbon is allocated in the same proportion to above and below ground tissue despite yearly differences in total carbon gain. Belowground net primary production ranged from 75 to 177 g C m^{-2} yr^{-1} and is similar to values reported by Francez and Vasander (1995) for fens in France and Finland. However, Saarinen (1996) using ^{14}C to calculate BNPP measured values 5 times higher in a Finnish fen.

Both Green Mt. Pond and Circle Fen had lower NPP in the years when the water table dropped beneath the ground surface, suggesting that sedge production is modified by water levels. NPP at Green Mt. Pond was 59% greater in 1998 than in 1997 when the late summer water table was 15 cm lower. Circle Fen NPP was 29% lower in 1998 than in 1997, corresponding with a water table maximum 60 cm lower. Similar patterns of lower plant production with drier conditions have also been reported in Finnish and western Canadian fens (Francez and Vasander 1995, Szumigalski and Bayley 1997, Thorman and Bayley 1997b, Thorman *et al.* 1998).

CO_2 and CH_4 Effluxes

The calculated annual CO_2 effluxes ranged from 204 to 386 g C m^{-2} yr^{-1} for the four pristine fens and are comparable to rates for Finnish fens (Martikainen *et al.* 1995, Silvola *et al.* 1996a, Nykänen *et al.* 1998) and one in Minnesota (Kim and Verma 1992). However, the calculated CO_2 efflux rate of 515 g C m^{-2} yr^{-1} measured in Circle Fen in 1998 was higher than the CO_2 rates measured in drained Finnish fens (Martikainen *et al.* 1995, Silvola *et al.* 1996a, Nykänen *et al.* 1998).

The calculated annual CH_4 efflux for the five study fends ranged from 3 to 75 g C m^{-2} yr^{-1}, and are similar to rates measured in boreal fens of Canada and Finland (Bubier *et al.* 1993, Martikainen *et al.* 1995, Silvola *et al.* 1996a, Nykänen *et al.* 1998, Bellisirio *et al.*

1999), New Hampshire (Frolking and Crill 1994), Minnesota (Shurpali 1998), and a subalpine fen located elsewhere in Rocky Mountain National Park (Wickland *et al.* 1999). CH_4 efflux from in Circle Fen was higher than reported for drained fens (Martikainen *et al.* 1995, Silvola *et al.* 1996a, Nykänen *et al.* 1998). The higher CO_2 and CH_4 efflux measured in Circle Fen during 1998 could be explained by the high NPP during the wet year of 1997, which could have created a large labile carbon pool that was decomposed in 1998.

CO_2 and CH_4 efflux rates were strongly influenced by temperature and water level. CO_2 and CH_4 fluxes both increased throughout the summer as the air and soil warmed (Crill *et al.* 1988, Frolking and Crill 1994, Moore *et al.* 1994, Silvola *et al.* 1996a, Granberg *et al.* 1997). Water levels differentially affected CO_2 and CH_4 efflux; lower water levels increased CO_2, and simultaneously decreased CH_4 production. Others have also demonstrated that as CO_2 effluxes increase CH_4 efflux decreases to near zero as soils dry (Nykänen *et al.* 1994, Moore *et al.* 1994, Francez and Vasander 1995, Bubier 1995, Waddington and Roulet 1996, Silvola *et al.* 1996a, Moosavi *et al.* 1996).

CH_4 rates in Big Meadows were up to 350% higher than the other sites (Table 2-4). The difference in water levels probably explain the differences in CH_4 efflux between Big Meadows, which has the highest values, and Circle Fen and Green Mt. Pond, which have the lowest values. Low CH_4 efflux is often found in drained peatlands (Roulet *et al.* 1993, Nykänen *et al.* 1998), which could explain the low levels of CH_4 in Circle Fen and Green Mt. Pond that experience frequent drying. The difference in CH_4 production between Big Meadows and Hell's Fen and Spring Fen is probably a combination of several factors. Big Meadows has 50% higher BNPP and NPP than Hell's and Spring Fens, which would provide more substrate for methanogenesis (Whiting and Chanton 1993, Bellisario *et al.*

1999). There may also be inherent differences in either vegetation quality or gas transport ability between *Eleocharis quinqueflora*, which dominates Hell's and Spring Fens, and the *Carex aquatilis* that dominates Big Meadows.

Chemistry

Redox levels are an important measurement of the reduction-oxidation status of wetlands (Mitch and Gosselink 2000). However, in this study redox measurements did not significantly explain any measured values. There are a couple of possible reasons why the redox measurements were not significant. The redox measurements fluctuated widely during measurements and between measurement periods. This could be due to cracked probes or loose connections with the probes and the Orion pH-Mv meter. There was also only one redox probe per depth per site. This lack of repetition decreased the reliability of the measurements. Another factor is the limited sample size. I had only five sites with varying vegetation and hydroperiods. The small sample size made it difficult to find statistical significance.

The resin bags provide an integration of nutrient concentration and flow moving through a wetland, instead of a point concentration sample. The majority of nitrogen in the fens was NH_4^+, with NO_3^- only in trace amounts. In a laboratory experiment, Patrick and Jugsujinda (1992) found decreasing amounts of NO_3^- in reducing conditions because it was being used as an electron acceptor. They also found an increase in NH_4^+ in reducing conditions and attributed this to anaerobic mineralization of organic N, not from reduction of NO_3^-. This pattern was also seen in this study as NO_3^- levels decreased and NH_4^+ levels increased with decreasing pe.

Carbon Balances

Annual carbon storage for pristine fens ranged from -107 to 179 g C m^{-2} yr^{-1} with a mean of 48 g C m^{-2} yr^{-1}. Recalculating the carbon budgets with the published range of root respiration values (35% - 60%) does not result in any sites switching from sinks to sources or sources to sinks. DOC output was not measured in this study, which could lower the stored carbon values 5 to 40 grams (Moore *et al.* 1998) for all fens except Green Mt. Pond which has no outlet. Using methods similar to this study, Moore (1989) estimated that a subarctic patterned string fen in northern Quebec accumulated 38 g m^{-2} yr^{-1}, while Francez and Vasander (1995) calculated that two fens in France and Finland accumulated 28 g C m^{-2} yr^{-1} and 20 g C m^{-2} yr^{-1} respectively. Using long-term accumulation rates (peat depth and basal date), Botch *et al.* (1995) estimated that fens in the former Soviet Union have accumulated a long-term mean of 72 to 80 g C m^{-2} yr^{-1}, while fens in Canada accumulated between 15 and 61 g C m^{-2} yr^{-1} (Ovenden 1990). Gorham (1991) estimated that mean long-term accumulation rates for northern peatlands was 28 g C m^{-2} yr^{-1}. However, it is hard to compare carbon accumulation values from yearly studies to long-term averages over thousands of years, including unfavorable climate periods and repeated fires.

Green Mt. Pond lost carbon as calculated in 1997 due to a combination of low NPP and a water table that dropped below the soil surface. It is difficult to assess the frequency of carbon storage in the pristine fens based on two years of record. However, by using the gas efflux regressions developed for 1997 and 1998 and applying them to the long-term water table data (Fig. 2-7), weather station temperature and measured ANPP (converted to NPP using the mean ANPP/NPP ratio measured in 1997 and 1998) for Green Mt. Pond, a longer-term picture of carbon storage can be calculated. Using the scenario described above, Green Mt. Pond stored a mean calculated value of 84 g C m^{-2} yr^{-1} for the nine years of record, accumulated carbon during 6 of the 9 years and losing carbon only in 1988, 1994 and 1997.

A water table gas efflux relationship could not be developed for Big Meadows because the water table never dropped beneath the surface in 1997 or 1998. Therefore the same carbon storage estimate could not be developed for Big Meadows as it was for Green Mt. Pond. But if the assumption is made that carbon storage occurred when the water table stayed above the soil surface for the majority of the growing season, than Big Meadows probably stored carbon 10 out of the last 12 years. Big Meadows may have lost carbon in 1987 when the water table dropped 24 cm below the soil surface during the summer, and 1988 when the water table dropped 19 cm in the late summer and fall

Lowering a fen's water table by diverting even a portion of its water supply can result in a net loss of carbon. In the study area, the Grand Ditch captures and diverts Red Creek's flow before it can recharge the hillslope and alluvial fan aquifers that directly support Circle Fen resulting in lower summer water tables (Woods 2000). These hydrologic changes did not result in the physical disturbance of soils or vegetation of Circle Fen. The Grand Ditch does not affect the May or early June water supply or water tables because water diversion begins in early June (Woods 2000). The effects of the Grand Ditch on Circle Fen are analogous to a water year with a small snowpack and light monsoon rains that allow hillslope aquifers to dry up. The 1998 water table decline in Circle Fen led to the calculated loss of 107 g C m^{-2} yr^{-1}. Circle Fen likely lost carbon in 1996 as well when the water table dropped 1 meter below the soil surface. However, Circle Fen accumulated carbon in 1997, most likely due to the large volume of snowmelt and abundant summer rain that allowed Circle Fen to maintain a water table at or above the soil surface for the entire summer (Woods 2000). Calculated carbon accumulation rates for 1997 indicate that Circle Fen can accumulate carbon at an annual rate similar to other pristine peatlands in Rocky Mountain National Park if water tables are maintained near the soil surface.

The length of time the water table needs to be beneath the soil surface to alter it from a sink to source of carbon can be calculated by applying the change in total carbon efflux that occurs when the water table drops beneath the water table, as quantified in Chapter 3, and apply it to the carbon budgets calculated in this chapter. The calculated number of weeks that the water table needs to be beneath the soil surface to convert the study fens to a negative carbon budget ranges from 1-week to up to 8-weeks with an average of 3-weeks. Therefore, to manage peatlands in Rocky Mountain National Park or perhaps anywhere in the Southern Rocky Mountains, a good rule of thumb for determining when a peatland carbon budget will be negative is the water table should not drop below the soil surface for more than 3-weeks during the summer.

Global climate change scenarios for the Southern Rocky Mountain region suggest increases in both summer temperatures and winter precipitation. Models predict that summer precipitation could either increase or decrease depending upon monsoonal flow patterns (IPCC 1995). Increased winter precipitation can increase water available to Southern Rocky Mountain fens in May, June and early July. But the hydrologic effect of large snowpacks diminishes by mid-summer because the coarse-textured aquifers drain rapidly (Windell *et al.* 1986), and a water table below the surface for a few weeks is enough to shift these fens from accumulating to losing carbon. Therefore maintaining a high late summer water table is important, which requires mid- and late-summer monsoon precipitation. Summer precipitation may have to increase to offset the increased evapotranspiration that will occur if summer temperatures increase. Increased summer temperatures will also increase decomposition rates and most likely NPP (Johnson *et al.* 1996, McKane *et al.* 1997, Shaver *et al.* 1998). However, recent studies have shown that if the water table remains high, increasing temperatures could increase carbon storage (Waddington *et al.* 1998, Oechel *et al.* 1998)

Globally, peatlands become a net source of carbon when the water table is lowered, and the mechanism of water table drawdown does not seem to be important. Lowered water tables produced by ditching (Armentano and Menges 1986, Gorham 1991, Francez and Vasander 1995, Silvola *et al.* 1996a, Nykänen *et al.* 1998), natural variation in precipitation (Carroll and Crill 1997, this study), water diversions (this study) and experiments (Waddington *et al.* 1998, Oechel *et al.* 1998) have all been found to convert peatlands from sinks of carbon to net carbon sources.

CONCLUSIONS

The carbon balance of Southern Rocky Mountain fens is modified by site hydrologic regime. The five fens that I studied accumulated carbon in years when the water table remained at or above the soil surface for most of the summer. However, both pristine and hydrologically modified fens lost carbon when the water table dropped beneath the surface for more than three weeks during the summer.

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Table 2-1. Physical and chemical characteristics of the study sites.

	Big Meadows	Circle Fen	Green Mt. Pond	Hell's Fen	Spring Fen
Elevation (m)	2,865	2,725	2,865	2,730	2,925
Size (ha)	63	0.8	0.5	1.5	9.0
Peat depth (m)	1.5	0.8	1.5	1.2	1.65
pH	6.2	5.8	5.6	6.3	6.5
pe	0.63	1.53	3.84	1.01	1.37
Ca (mg/l)	2.3	3.6	1.4	3.1	2.6[1]
NH_4^+ (mg/resin bag)	0.213 ±0.005	0.267 ±0.049	0.087 ±0.026	0.460 ±0.136	0.414 ±0.00
NO_3^- (mg/resin bag)	0.005 ±0.002	0.019 ±0.01	0.023 ±0.008	Not Detectable	0.003 ±0.007

Notes: pH and pe are mean values for the duration of the study. pH and Ca are surface water samples. NH_4^++ and NO_3^- are resin bag data.

[1] Data from Johnson 1996.

Table 2-2. **Regression coefficients and root mean square error when water table is above the soil surface for the relationship between temperature and CO_2 and CH_4 flux rates.**

	Big Meadows	**Circle Fen**	**Green Mt. Pond**	**Hell's Fen**	**Spring Fen**
CO_2					
a	15.00	10.27	19.13	17.87	15.00
b	0.113	0.156	0.078	0.08	0.11
RMSE	30.7	41. 9	33.9	20.6	28.7
R^2	0.61	0.75	0.33	0.22	0.45
Q_{10}	3.09	4.74	2.19	2.23	3.00
CH_4					
a	854.84	1151.84	818.21	984.44	642.71
b	0.29	0.07	0.04	0.14	0.17
RMSE	4012.8	1469.9	947.8	6043.6	3620.4
R^2	0.90	0.29	0.16	0.38	0.47
Q_{10}	18.17	2.01	1.49	4.08	5.47

Note: **See method section for regression coefficients of Circle Fen and Green Mt. Pond when water table drops beneath the soil surface.**

Table 2-3. Calculated aboveground net primary productivity (ANPP), belowground net primary productivity (BNPP), net primary productivity (NPP) and ANPP/NPP ratios for 1997 and 1998.

Site	1997				1998			
	ANPP (g Cm^{-2})	BNPP (g Cm^{-2})	NPP (g Cm^{-2})	ANPP/ NPP	ANPP (g Cm^{-2})	BNPP (g Cm^{-2})	NPP (g Cm^{-2})	ANPP/ NPP
Big Meadows	107	148[1]	254	N/A	131	181	312	0.42
Circle Fen	81	177	258	0.31	84	101	185	0.46
Green Mt Pond	55	75	130	0.42	142	174	316	0.45
Hell's Fen	47	102	149	0.31	51	117	169	0.30
Spring Fen	70	88	159	0.44	111	123	234	0.48

Note: Carbon content of above ground biomass is 44% and carbon content of belowground biomass is 46%.

[1] Estimated BNPP using 1998 ANPP/NPP plus 1997 ANPP.

Table 2-4. Calculated carbon balances for 1997 and 1998.

Site	Year	CO_2	CH_4	Carbon Efflux	NPP	Carbon Storage
Big Meadows	1997	211	58	174	254	80
	1998	241	75	208	312	104
Circle Fen	1997	204	12	124	258	134
	1998	515	9	292	185	-107
Green Mt. Pond	1997	386	3	215	130	-85
	1998	235	8	137	316	179
Hell's Fen	1997	204	17	129	149	20
	1998	225	20	144	169	25
Spring Fen	1997	207	10	124	159	35
	1998	235	12	141	234	93

Notes: All units are in g C $m^{-2}yr^{-1}$. Carbon Efflux = (CO_2 efflux * 0.55) + CH_4 efflux.

FIGURE CAPTIONS

Figure 2-1. Location of study sites, BM= Big Meadows, CF=Circle Fen, GM = Green Mt. Pond, HF = Hell's Fen and SF = Spring Fen, Grand Ditch (dotted line), Upper Colorado River valley and Tonahutu Creek.

Figure 2-2. Snow free water table levels (lines) and precipitation (bars) for 1997 and 1998. Mean water table depths (1997 and 1998): Big Meadows = 6.6 and 5.4 cm, Circle fen = -1.1 and -19 cm, Green Mt. Pond = 1.0 and 11.2 cm, Hell's Fen = 3.1 and 3.4 cm and Spring Fen = 3.3 and 1.2 cm.

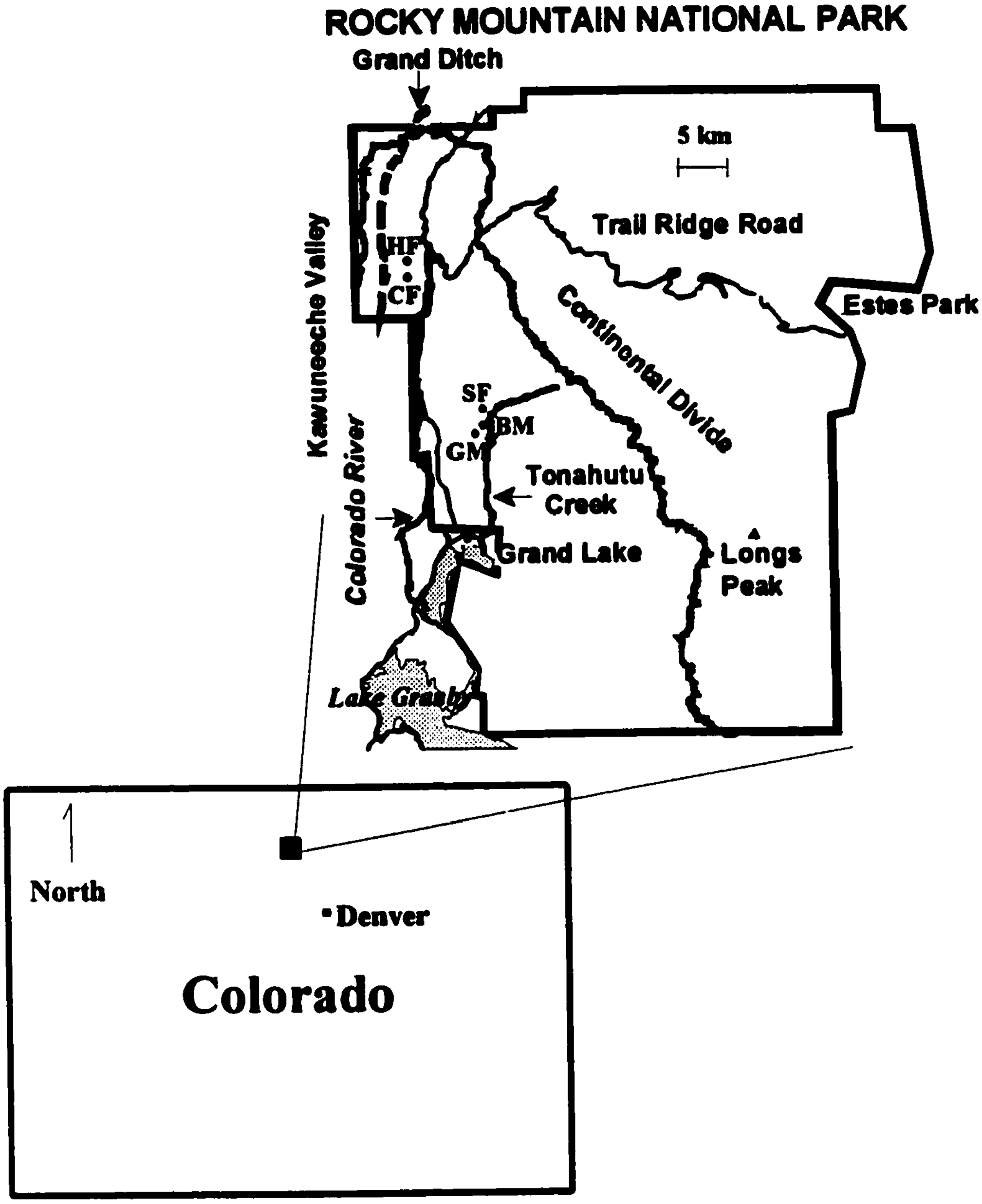
Figure 2-3. Depth profile of belowground net primary production for 1998.

Figure 2-4. Modeled daily CO_2 and CH_4 effluxes for 1997 and 1998 (see Table 2-1 for regression coefficients).

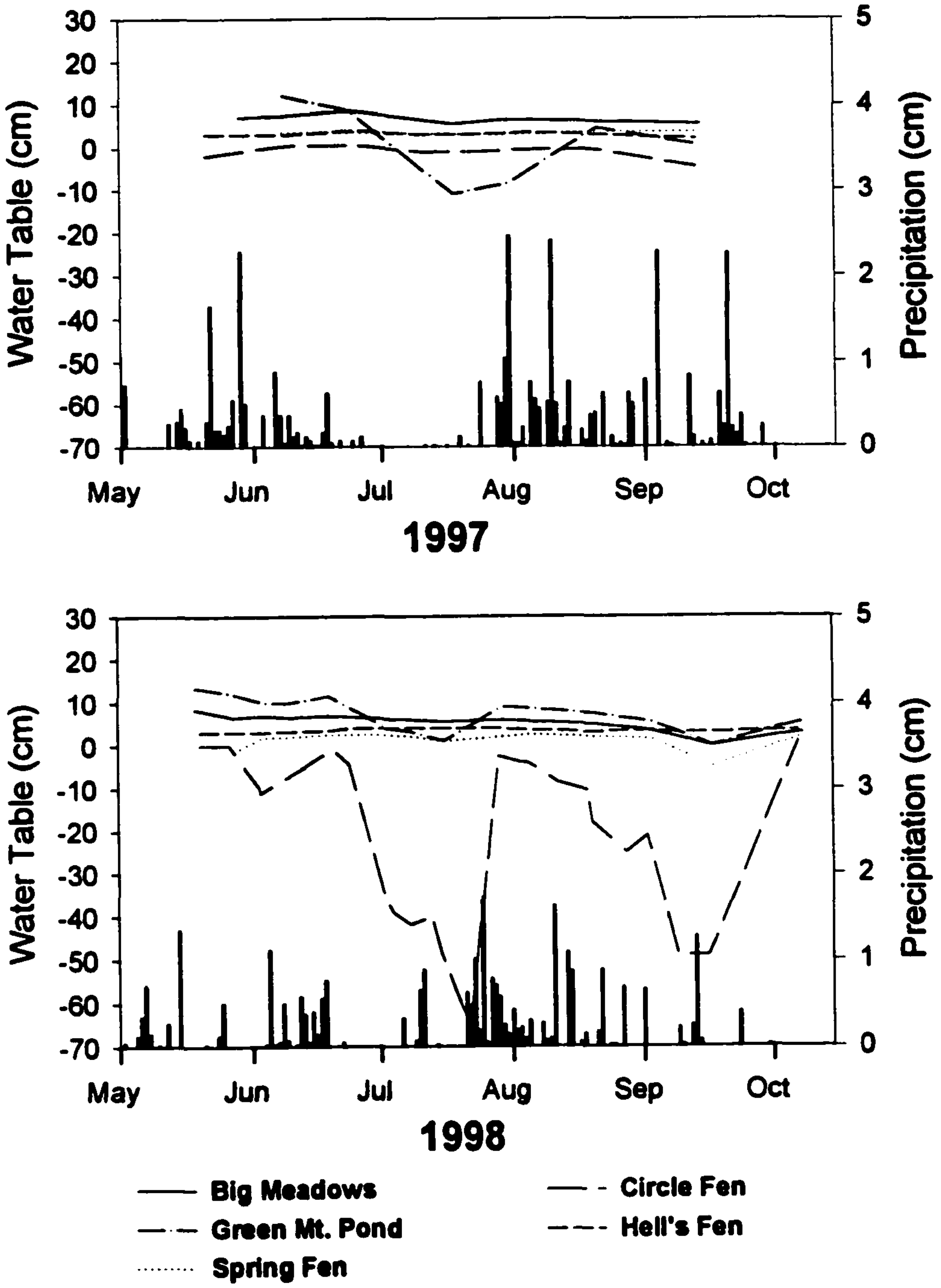
Figure 2-5. Circle Fen water table levels and CO_2 (mg C m^{-2} yr^{-1}) and CH_4 (10^{-5}g C m^{-2} yr^{-1}) efflux.

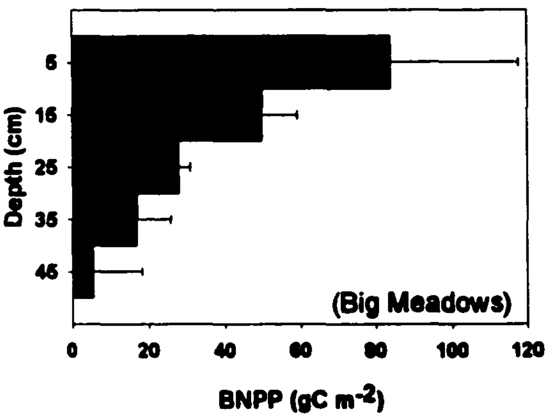
Figure 2-6. Hydrographs for Big Meadows from 1987 to 1998, excluding 1996.

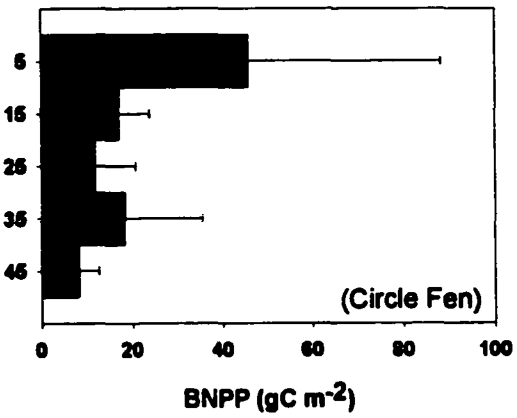
Figure 2-7. Hydrographs for Green Mt. Pond from 1988 to 1998, excluding 1995 and 1996.

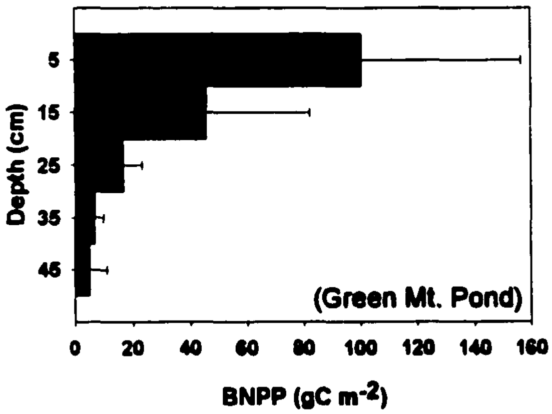


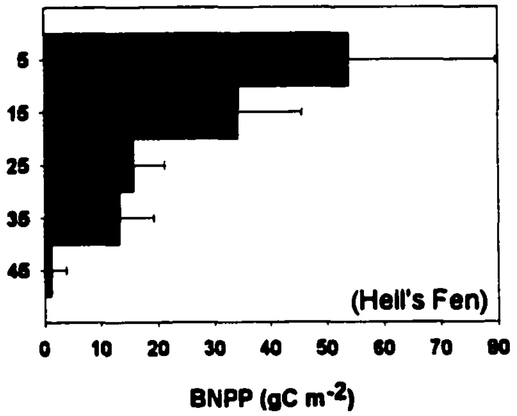
ROCKY MOUNTAIN NATIONAL PARK
Grand Ditch
5 km
Trail Ridge Road
Estes Park
Kawuneeche Valley
HF
CF
Continental Divide
SF
BM
GM
Colorado River
Tonahutu Creek
Grand Lake
Longs Peak
Lake Granby
North
Denver
Colorado

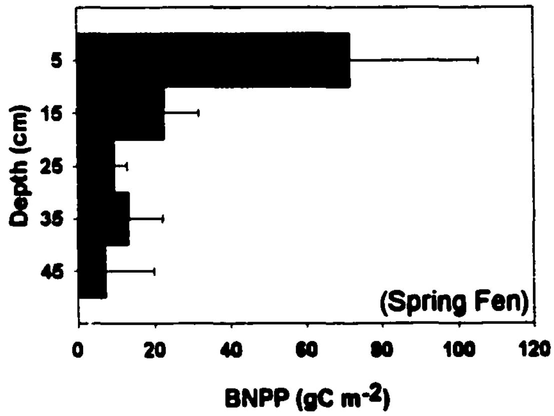
Water Table (cm)
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Precipitation (cm)
5
4
3
2
1
0
May
Jun
Jul
Aug
Sep
Oct
1997
1998
Big Meadows
Green Mt. Pond
Spring Fen
Circle Fen
Hell's Fen

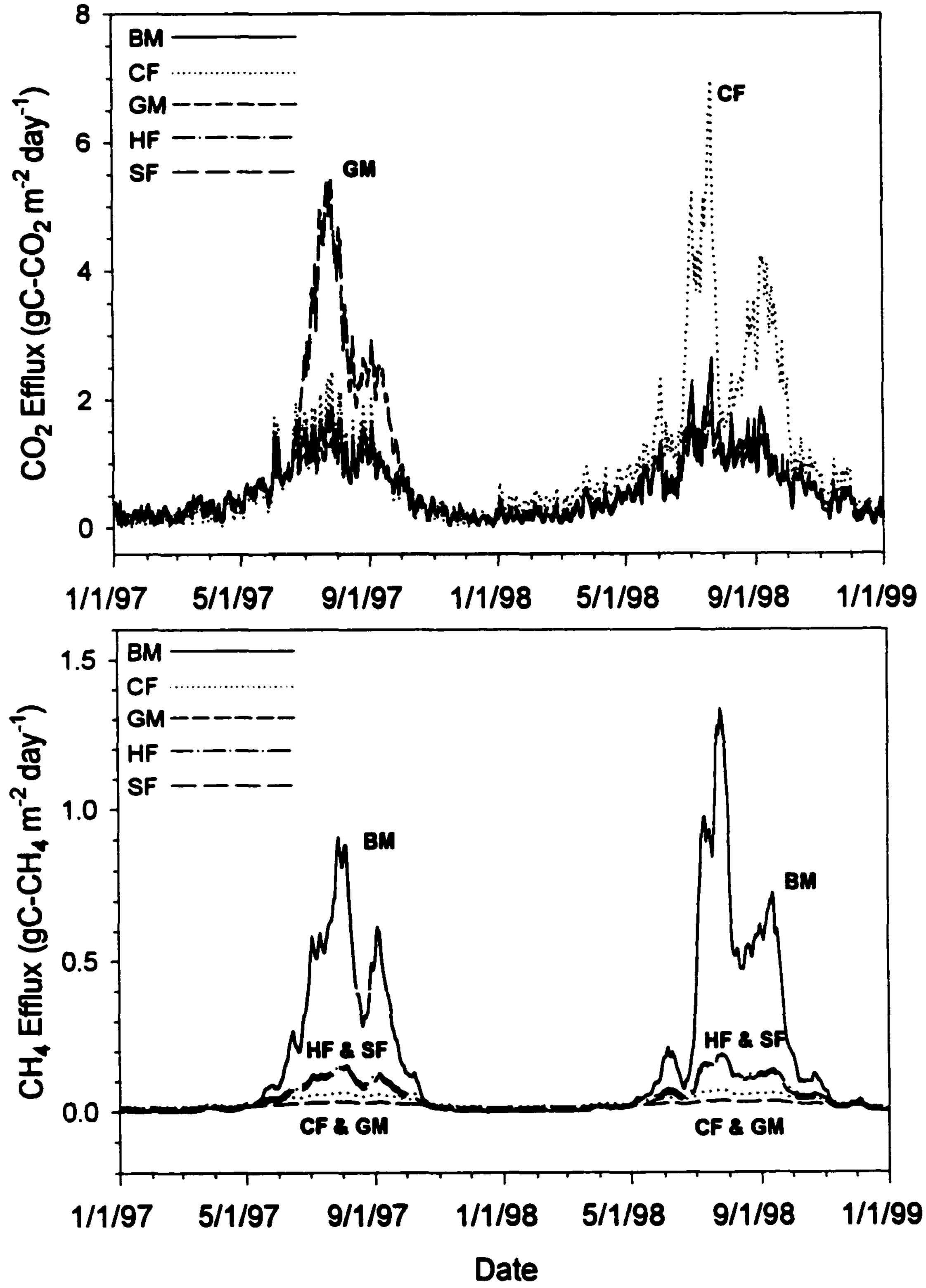

Depth (cm)
5
15
25
35
45
(Big Meadows)
0
20
40
60
80
100
120
BNPP (gC m-2)

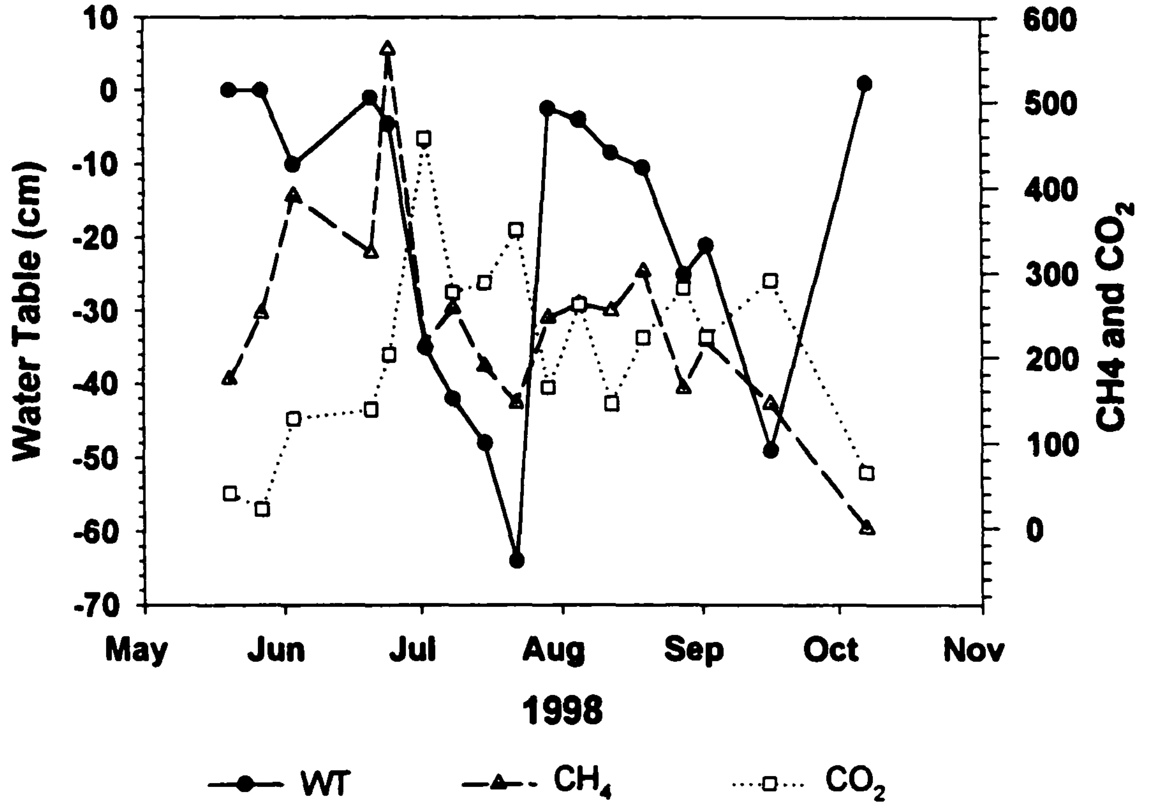

5
15
25
35
45
(Circle Fen)
0
20
40
60
80
100
BNPP (gC m-2)


Depth (cm)
5
15
25
35
45
(Green Mt. Pond)
0
20
40
60
80
100
120
140
160
BNPP (gC m-2)

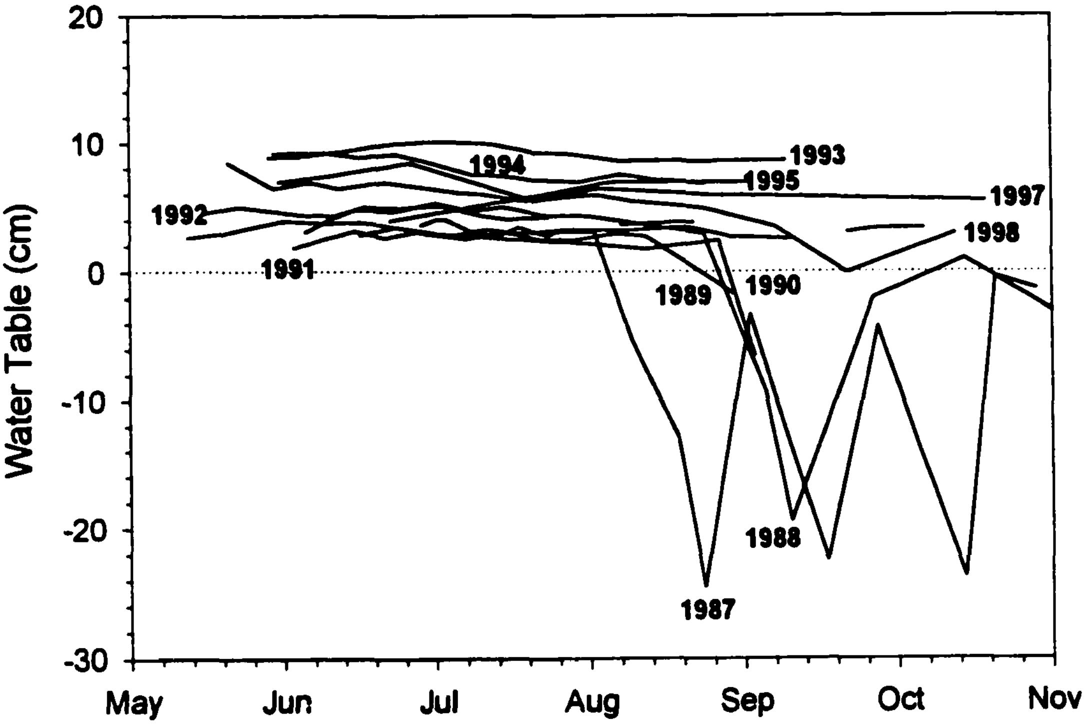

5
15
25
35
45
(Hell's Fen)
0
10
20
30
40
50
60
70
80
BNPP (gC m-2)


Depth (cm)
5
15
25
35
45
(Spring Fen)
0
20
40
60
80
100
120
BNPP (gC m-2)

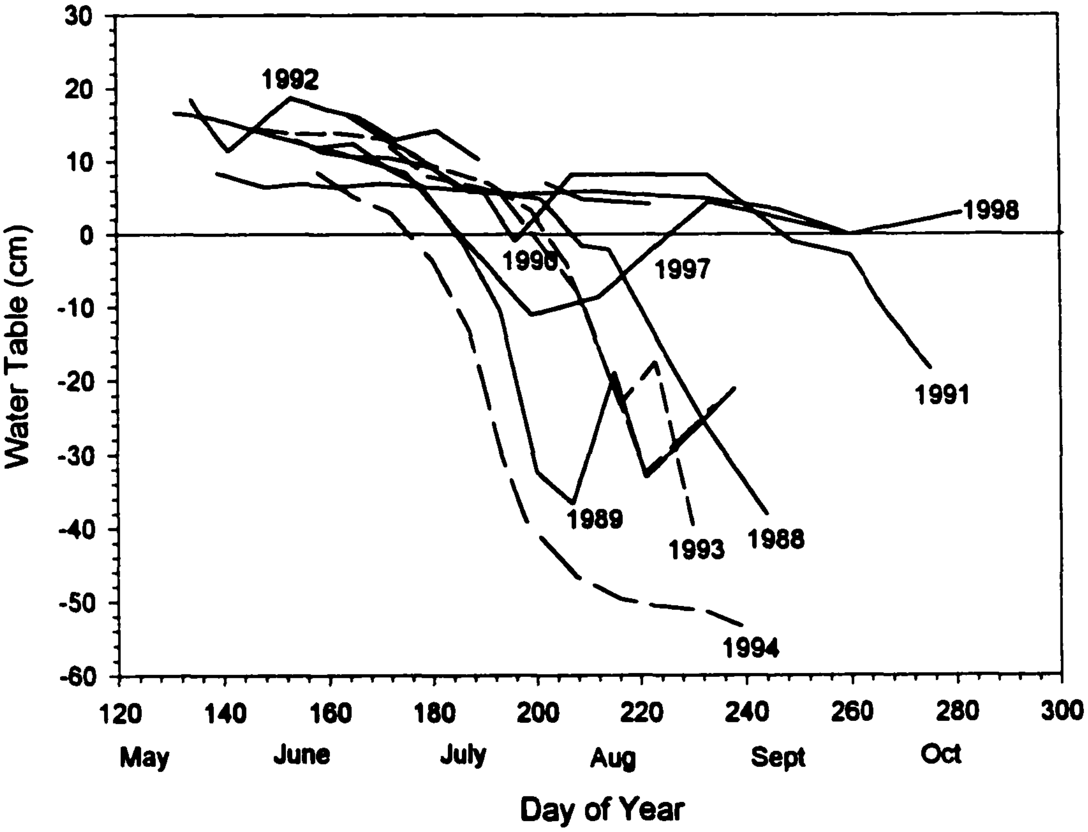

CO$_2$ Efflux (gC-CO$_2$ m^{-2} day^{-1})
0
2
4
6
8
BM
CF
GM
HF
SF
GM
CF
1/1/97
5/1/97
9/1/97
1/1/98
5/1/98
9/1/98
1/1/99
CH$_4$ Efflux (gC-CH$_4$ m^{-2} day^{-1})
0.0
0.5
1.0
1.5
BM
CF
GM
HF
SF
BM
BM
HF & SF
HF & SF
CF & GM
CF & GM
1/1/97
5/1/97
9/1/97
1/1/98
5/1/98
9/1/98
1/1/99
Date



10
0
-10
-20
-30
-40
-50
-60
-70
Water Table (cm)
600
500
400
300
200
100
0
CH4 and CO$_2$
May
Jun
Jul
Aug
Sep
Oct
Nov
1998
WT
CH$_4$
CO$_2$



Water Table (cm)
20
10
0
-10
-20
-30
May
Jun
Jul
Aug
Sep
Oct
Nov
1992
1991
1994
1993
1995
1997
1998
1989
1990
1988
1987



Water Table (cm)
30
20
10
0
-10
-20
-30
-40
-50
-60
120
140
160
180
200
220
240
260
280
300
May
June
July
Aug
Sept
Oct
Day of Year
1992
1998
1996
1997
1991
1989
1993
1988
1994

Chapter 3

A WATER TABLE THRESHOLD EFFECT ON CO_2 AND CH_4 EMISSIONS IN A SUBALPINE FEN, COLORADO

ABSTRACT

While it is known that lowering water levels may change a peatland's carbon balance, it is unclear how much the water table must be lowered before it significantly affects decomposition rates and gas efflux. The objective of this study was to quantify short-term changes in CO_2, CH_4 and total carbon efflux (CO_2 + CH_4) by manipulating water table levels in 6 microcosms installed in a Colorado fen. Installing the microcosms had no effect on CO_2 efflux, but increased CH_4 efflux by an average of 7 times. Higher soil temperatures increased CO_2 and CH_4 fluxes, but the increase was dependent upon the water table position. CO_2 and total gaseous carbon efflux was lowest when the water table was above the soil surface, but efflux rates doubled when the water table dropped beneath the soil surface threshold. However, further lowering of the water table beneath the soil surface had little additional effect on CO_2 and total gaseous carbon efflux. The highest CH_4 efflux occurred when the water table was just above the soil surface and decreased when the water table was either deeper or more ponded. The existence of a threshold effect for CO_2 and total gaseous carbon efflux when the water table dropped below the soil surface has important implications for possible climate change scenarios. In this study, a 3 °C increase in soil temperature at 5 cm soil depth, was calculated to increased total carbon gaseous efflux by 16 % when the water table was above the soil surface. However, when the water table dropped beneath the soil surface threshold, total gaseous carbon efflux increased by 134%.

Key words: peatland, fen, CO_2, CH_4, *water table drawdown, Colorado, Rocky Mountains.*

INTRODUCTION

Peatlands store approximately 224 to 455 Pg of carbon (1 Pg=10^{15}g), 12-30% of the current global soil carbon pool (Gorham 1991, Botch *et al.* 1995, Lappalainen 1996, Clymo *et al.* 1998), despite occupying only 3% of the land surface (Maltby and Proctor 1996). Peatlands store carbon because the amount of carbon fixed during photosynthesis is greater than the amount released during decomposition. The balance between carbon uptake and release is largely dependent upon decomposition rates, which is low in peatlands due to waterlogged soils (Maltby and Proctor 1996).

Research on possible global climate change effects in peatlands has focused much attention on the impact of increased air temperature on peat decomposition rates. Barring substrate limitations (Bergman *et al.* 1998), warmer air and soil temperatures have been shown to stimulate microbial activity resulting in greater CO_2 and CH_4 fluxes from peatlands (Crill *et al.* 1988, Frolking and Crill 1994, Silvola *et al.* 1996). However, the effect of increasing temperature on net carbon storage is surprisingly minimal with increased plant production in the warmer environment balancing greater decomposition rates.

Global or regional hydrologic changes may have more important effects than temperature changes on net peatland carbon storage (Hogg *et al.* 1992, Johnson *et al.* 1996, Silvola *et al.* 1996, McKane *et al.* 1997, Oechel *et al.* 1998, Chapter 2). A high water table limits the diffusion of atmospheric oxygen into peat, which limits microbial activity and maintains low anaerobic decomposition rates (Oechel *et al.* 1998). Conversely, lowering the water table increases the rate of oxygen diffusion into soils and this allows aerobic decomposition, increased CO_2 fluxes, and decreased CH_4 fluxes (Moore and Knowles 1989, Bubier 1995, Silvola *et al.* 1996, Nykänen *et. al* 1998). A lower water table usually increases CO_2 production far more than it decreases CH_4 production, resulting in a net increase in total gaseous carbon efflux and a net loss of carbon (Armentano and Menges 1986, Silvola *et al.* 1996, Nykänen *et al.* 1998, Chapter 2).

While it is known that lowering water levels may change a peatland's carbon balance, it is unclear how much the water table must be lowered before it significantly affects decomposition rates and gas efflux. I present the results of a two-year experiment conducted in Rocky Mountain National Park, Colorado quantifying the relationship between water table depth and CO_2, CH_4 and total gaseous carbon (CO_2 + CH_4) efflux. Microcosms were installed in a Colorado fen, and water table levels were manipulated independently within each microcosm to measure the response in CO_2, CH_4 and total gaseous carbon (CO_2 + CH_4) efflux.

STUDY SITE

This study was conducted in unnamed fen on the western side of Rocky Mountain National Park, Colorado (Fig. 3-1) at 2655 m elevation. This site will be referred to as Moose Fen in this paper. The peat body averages 2.25 m thick. Moose Fen is fed primarily by ground water discharging from the toe of the adjacent mountain slope. Surface water has a pH of 6.0, and the fen is classified as transitional rich (Cooper and Andrus 1994). The climate at Moose Fen is typical of the Rocky Mountain region, with cool summers, and frequent late summer thunderstorms. The winters are cold and snowy and up to 80% of the annual precipitation falls as snow (Windell *et al.* 1986, Cooper 1990). Average annual precipitation at Phantom Canyon SNOTEL station located 10 km N of the study site is 65 cm with a mean annual temperature of 0.8 °C. The vegetation is entirely of herbaceous plants with *Carex aquatilis* Wahlenberg and *C. utriculata* Boott as the dominants, *Calamagrostis canadensis* (Michaux) P. Beauvois occurs in low cover.

METHODS

Experimental Design

Nine microcosms were installed in early June 1998 in a 120 m^2 area of homogenous vegetation in the center of Moose Fen (Fig. 3-2). Each microcosm was constructed from a 30.5 cm diameter and 80 cm long PVC pipe. Plant roots and peat were cut with a circular corer of the same diameter as the PVC pipe. The microcosms were then inserted to a depth of 60 cm. A 1.25 cm slotted PVC pipe was inserted to a depth of 50 cm into all microcosms. Water was pumped from the well to draw the water table down, and for measuring water table depth.

Three microcosms were randomly selected as cut-controls (Fig. 3-2). The cut-control microcosms had slots cut so that the water levels in microcosm were the same as the surrounding fen. Three uncut controls were also selected, which did not have any microcosms inserted (Fig. 3-2).

A Campbell CR-7X datalogger (Logan, Utah) controlled a self-priming pump via a relay switch. The relay switch was programmed to turn on for 20 seconds every 15 minutes to remove water from each microcosm. Two automobile batteries powered the pump. Three microcosms were randomly selected for this pumping treatment in 1998, while six microcosms were pumped in 1999.

During 1998 three randomly selected microcosms had water added to them via a constant head watering system. An airtight 113.5 liter plastic container with a 1.27 cm PVC pipe extending through the top into the container created the constant head. Water was added to the microcosms through a 2.54 cm plastic tubing connected to the container and allowed stable water levels to be maintained in the microcosms. Figure 3-3 shows the effects of the treatments on water table levels in the manipulated microcosms.

CO_2 and CH_4 Measurements

Gas flux rates were measured in all microcosms every 3 to 14 days from 15 July to 2 September 1998, and from 2 June to 27 August 1999. All measurements were made mid-day between 1100 and 1500 hours. CH_4 effluxes were measured using the static chamber technique (Hutchinson and Mosier 1981, Lessard *et al.* 1994, Waddington and Roulet 1996, Melloh and Crill 1996, Shannon *et al.* 1996). Static chambers were constructed of 20 cm diameter x 20 cm long sections of PVC pipe. Static chamber collars were inserted 2 cm into the peat within the microcosms and left in place for the duration of the study. CH_4 samples were collected using a nylon syringe inserted through a septum on top of the static chambers. An initial CH_4 sample was collected at time zero when the chamber was sealed and subsequent samples collected at 5 and 10 minutes. The CH_4 was stored in evacuated flasks sealed with silicone for transport and storage. CH_4 samples were analyzed the following day using a Shimadzu GC-14A gas chromatograph.

Carbon dioxide fluxes were measured using a Li-Cor 6200 Portable Photosynthesis Infrared Gas Analyzer (IRGA) (Li-Cor Inc., Lincoln, NE). An opaque dynamic chamber top attached to the IRGA was placed on the static chamber collars. CO_2 flux rates were calculated as the mean of four 15-second readings.

Depth of the water table in each microcosm was measured during each gas sampling period. In 1998 the temperature in each microcosm was measured at 5 cm and 20 cm soil depth using a thermometer. In 1999 thermocouples were installed at the same soil depths to continuously measure temperature.

On 25 August, 1999 the pump used to lower microcosm water tables was shut off and water levels allowed to equilibrate to the surrounding fen water level, which was 8 cm above the soil surface. Seven days later the *Carex* shoots in all microcosms were cut at the ground surface and removed. Microcosm CH_4 efflux rates were measured immediately prior to and 2 hours after the vegetation was cut to determine the amount of CH_4 moving through the plants.

Temperature Corrections of Gas Fluxes

All instantaneous gas flux measurements (R) were corrected for soil temperature differences by transforming to the mean summer temperature (T^0) (Silvola *et al.* 1996). CO_2 fluxes had the highest correlation with soil temperatures at 5 cm depth ($R^2 = 0.74$), which had a summer mean of 12 °C. CH_4 efflux was most highly correlated with soil temperature at 20 cm depth ($R^2 = 0.38$), which had a summer mean of 10.5 °C. Transformation was accomplished by fitting an exponential regression model of gas efflux to measured soil temperatures (T_s);

$$R = a * \exp(b * T_s) \qquad (1)$$

R is the measured CO_2 or CH_4 flux rate, T_s is the soil temperature at either 5 or 20 cm depth, and a and b are regression coefficients. The adjusted gas flux rates (R^0) were calculated by subtracting the differences in gas flux at the measured soil temperature (T_s) and the gas flux at the mean soil temperature (T^0) and adding it to the measured gas flux (R) using equation (2):

$$R^0 = R + a * \exp[b * T^0 - T_s] \qquad (2)$$

R^0 is the temperature adjusted CO_2 or CH_4 efflux calculated using coefficients a and b previously calculated from equation 1. Q_{10} values (changes in gas flux with a 10 °C change) were calculated for CO_2 and CH_4 using equation (3):

$$Q_{10} = \exp[10*b] \qquad (3)$$

where b is from equation (1).

Statistical Analysis

All statistical analyses were performed using SYSTAT 7.0 (SYSTAT 1997). An ANOVA was performed to test for differences in control and cut-control CO_2 and CH_4 efflux, with water table depth and soil temperature at 5 and 20 cm depths used as covariates. I tested post hoc whether CO_2, CH_4 and total carbon increased or decreased significantly when the water table dropped beneath the soil surface. I tested for a threshold of carbon gas emissions when the water table was above vs. below the soil surface, by comparing a polynomial model of all data vs. a general linear model that incorporated a dummy variable identifying samples that had a water table above or below the soil surface.

Where the general linear model explained a higher percentage of variance than the polynomial regression, a threshold effect is inferred. Both models were developed by backward stepwise regressions. The variables used in the polynomial regression were water table depth, treatment vs. cut-control, water table depth squared, water table*treatment, and water table squared * treatment. Variables used for general linear model are: water table, threshold dummy variable (0 if the water table is below the soil surface and 1 if the water table is above the surface), treatment, water table*threshold dummy variable, and water table*treatment.

RESULTS

Microcosm Effects on CO_2 and CH_4

There was no significant difference in the 2-year mean uncut-control and cut-control CO_2 efflux (222.2 and 218.1 mg C m^{-2} hr^{-1}, respectively) ($P = 0.74$) (Fig. 3-4, Table 3-1). However, CH_4 efflux was significantly higher in the cut-controls than the uncut-controls ($P < 0.001$) and was not significantly affected by water table level or soil temperature (Fig 3-4, Table 3-1). The CH_4 efflux in the cut-control microcosms averaged seven times greater for the entire study period than the uncut-control plot efflux, 35.16 mg C m^{-2} hr^{-1} vs. 271.7 mg C m^{-2} hr^{-1}, respectively (Fig. 3-4). The effect of temperature and water table variation on CH_4 efflux are adjusted for the microcosm effect by dividing measured CH_4 efflux by the ratio of mean cut-control CH_4 efflux rates / mean uncut-control CH_4 efflux rates for each day of sampling.

Temperature Effects on CO_2 and CH_4

In order to distinguish the effects of water table depths on CO_2 and CH_4 efflux, it was necessary to standardize all flux rates for soil temperature. Higher soil temperatures increased CO_2 and CH_4 fluxes, but the increase was dependent upon the water table position (Figs 3-4 and 3-5). A single Q_{10} relationship could not be developed for CO_2 or CH_4 as soil temperature had relatively little effect (Q_{10} near 1.00) on CO_2 and CH_4 efflux when the water table was below the soil surface. The Q_{10} of CO_2 was 3.46 when the water table was above the soil surface compared to only 1.30 when the water table was beneath the soil surface (Fig. 3-5). CH_4 followed a similar pattern with a high Q_{10} value of 6.10 when the water table was above the soil surface and 0.70 with the water table below the soil surface (Fig. 3-6).

Water Level Effects on CO_2, CH_4 and Total Gaseous Carbon Efflux

Temperature standardized CO_2 efflux varied from 16 to 1029 mg C m^{-2} hr^{-1}. There were large differences between CO_2 effluxes when the water table was above vs. below the soil surface (Fig. 3-7). CO_2 efflux averaged 182.1 mg C m^{-2} hr^{-1} when the water table was above the soil surface and averaged 414.1 mg C m^{-2} hr^{-1} when the water table was below the soil surface (ANOVA, $P<0.001$, $n=163$). Further lowering of the water table beneath the soil surface did not significant change the CO_2 efflux (slope of regression, $P = 0.22$).

The largest increase in CO_2 efflux occurred when the water table dropped just below the soil surface, suggesting a threshold effect (Fig. 3-7). This is supported by comparing the general linear model, which explained 56% of the variance in this data set to the polynomial model, which explained 40%. In addition, the dummy variable for water table above or below the soil surface was the most significant variable in the GLM model (Table 3-2). Carbon dioxide efflux in the cut-controls was significantly higher than in the treatment microcosms when the water table was above the soil surface ($P = 0.004$, Table 3-2).

Adjusted rates of CH_4 efflux varied from –10 mg C m^{-2} hr^{-1} to over 100 mg C m^{-2} hr^{-1}, with most measurements between 1 and 45 mg C m^{-2} hr^{-1} (Fig. 3-8). Methane efflux was highly variable, with coefficients of variation ranging from 105% to 190%, a common range of variation for field trace gas measurements (Bubier *et al.* 1993). The highest CH_4 efflux occurred when the water table was just above the soil surface and decreased when the water table was deeper or shallower (Fig. 3-8). Mean CH_4 efflux dropped to near zero when the water table was more than 10 cm below the soil surface. No threshold effect was found for CH_4 efflux as the polynomial regression had a similar fit to the general linear model ($R^2 = 0.36$ vs. $R^2 = 0.35$, respectively)(Table 3-2). Cut-control CH_4 efflux was significantly higher (30.8 mg C m^{-2} hr-1) than treatment microcosms (10.5 mg C m^{-2} hr-1) ($P < 0.001$).

CH_4 efflux in Moose Fen averaged 75 mg C m^{-2} hr^{-1} prior to clipping vegetation, and dropped to a mean of 4 mg C m^{-2} hr^{-1} after the vegetation was cut (t-test, $P < 0.001$). This indicates that >90% of the CH_4 is moving through *Carex* shoots. This is consistent with the results of other studies (Shannon *et al.* 1996, Thomas *et al.* 1996) and emphasizes the importance of plant tissue as a pathway for CH_4 efflux.

Total gaseous carbon (CO_2 + CH_4) efflux rates were similar to CO_2 efflux rates because CO_2 comprised 87% - 94% of the total adjusted carbon efflux (Fig. 3-9). Mean total carbon efflux was 202.5 mg C m^{-2} hr^{-1} when the water table was above the soil surface and 463.9 mg C m^{-2} hr^{-1} when the water table was below the surface, a difference of 129% ($P < 0.001$) (Fig. 3-9). A threshold effect was also found when the water table dropped below the soil surface (Table 3-2).

DISCUSSION

Microcosm and Temperature Effect

The large increase in CH_4 efflux in the cut-control microcosms was most likely due to an increase in labile carbon availability in the anaerobic soils. *Carex* roots and rhizomes were cut to a depth of 60 cm during microcosm installation releasing labile root carbon into the anoxic peat. In anoxic soils, labile carbon availability is often a major factor limiting CH_4 production (Valentine *et al.* 1994, Bergman *et al.* 1998, Segers 1998). CH_4 efflux rates in the cut-controls were much higher than the CH_4 efflux in nearby undisturbed natural fens in the region (Chapter 2) and elsewhere (Mitsch and Wu 1995), although relatively similar rates are reported for laboratory incubations of peat monoliths (e.g., Aerts and Ludwig 1997). Yavitt *et al.* (1993) and Updegraff *et al.* (1995) measured high CH_4 efflux rates in laboratory incubations, which they attribute to labile carbon mineralization released during the cutting of peat. Their laboratory CH_4 efflux rates were highest during the first month but decreased over time (Updegraff *et al.* 1998). In this study, high CH_4 efflux lasted for the entire 2-year study period. This was most likely due to the large volume of soil and roots disturbed, which would provide large amounts of substrate for CH_4 production. CO_2 production was probably not affected by insertion of the microcosms because the majority of CO_2 is produced in oxic conditions that occur at the surface, where relatively few roots and little soil volume were disturbed.

Gaseous carbon efflux had higher Q_{10}'s when the water table was above the soil surface, and lower Q_{10}'s when the water table was below the soil surface. Silvola *et al.* (1996) similarly found higher Q_{10} values for CO_2 with high water tables (0 - 20 cm) compared to water tables deeper than 20 cm beneath the soil surface, 4.9 and 1.3 respectively. Nykänen *et al.* (1998) found that CH_4 fluxes were temperature responsive only when the water table was near the soil surface. However, Hogg *et al.* (1992) found the opposite pattern with lower Q_{10}'s for CO_2 in flooded soils. Kim and Verma (1992) also found that CO_2 flux in a Minnesota bog was less temperature dependent when the water table was in the range of 0 to 12 cm below the soil surface, compared with a deeper water table of 12 cm to 38 cm below the soil surface.

Threshold Effect

Several studies have found a linear increase in CO_2 efflux with decreasing water tables (Moore and Knowles 1989, Kim and Verma 1992, Hogg *et al.* 1992, Silvola *et al.* 1996, Verville *et al.* 1998) and there are several reasons why they may not have detected a threshold. In field studies, it is difficult to sample gas efflux with sufficient frequency to measure the threshold effect as the water table drops. Laboratory studies using water table treatments at static levels may not have used water levels at appropriate depths to test for this effect. A third possibility is the practice of presenting mean site CO_2 efflux vs. mean site water table depths for entire peatlands or features within peatlands. This approach can illustrate general patterns of increasing CO_2 efflux with decreasing water table depth, but cannot detect changes in gas flux as the water table in individual sites drops. A fourth possibility is that not all peatland types have a threshold effect. Bogs, for example, most likely will not have a threshold effect for CO_2 efflux because of the low decomposability of *Sphagnum* spp. that could limit rapid changes in decomposition rates as the water table changes position (Kim and Verma 1992). However, it is clear that gaseous carbon flux rates can be sensitive to water table changes of as little as a few centimeters.

This study corroborates findings that water table changes have more influence on peatland carbon emissions than temperature changes (Hogg *et al.* 1992, Moore and Knowles 1989, Gorham 1991, Johnson *et al.* 1996, Silvola *et al.* 1996). Using the temperature, water table level, and gaseous carbon relationships developed from this study, it is possible to calculate changes in gas efflux with changing temperature or water table levels. When the water table is above the soil surface, a 3 °C increase in soil temperature at 5 cm soil depth is estimated to increase total gaseous carbon efflux by 16 %. However, when the water table dropped below the soil surface, total carbon efflux increased by 134%. Similar rates of increase were found by Silvola *et al.* (1996), who estimated that a 2-4 °C increase in temperature would increase CO_2 by 30-60% in Swedish boreal peatlands, but a water table drop of 14-22 cm would increase CO_2 efflux by 50-100%. Updegraff *et al.* (1995) also found that aerated laboratory samples mineralized twice as much carbon as anaerobic laboratory samples, and suggested that drying alone was enough to double carbon turnover. The present study adds the critical concept that the water table need only decline below the soil surface to double carbon mineralization rates in the fen studied.

CONCLUSIONS

CO_2, CH_4 and total gaseous carbon efflux responded significantly to temperature and water table depth when the water table is above the soil surface. However, when the water table dropped beneath the soil surface, CO_2 and total carbon efflux doubled. In addition, temperature did not significantly influence efflux rates when the water table was below the soil surface. Lowering the water table to greater and greater depths beneath the soil surface had little additional effect on CO_2, CH_4, and total gaseous carbon efflux. The threshold effect indicates that fens release large amounts of gaseous carbon when water tables drop below the soil surface.

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Table 3-1. **Results of one-way ANOVA for CH_4 and CO_2 efflux from control and cut-control treatment plots. Control and cut-control are the dependent variables, and water level and soil temperature are covariates.**

Source of variation	CH_4 efflux		CO_2 efflux	
	F-ratio	P	F-ratio	P
Treatment	28.188	<0.000	0.115	0.736
Water level	0.173	0.680	0.169	0.684
Soil temperature at 5 cm	0.633	0.432	1.591	0.216
Soil temperature at 20 cm	0.329	0.570	0.221	0.642

Table 3-2. **Final backward stepwise threshold regressions statistics for temperature and microcosm adjusted CO_2, CH_4 and total carbon efflux (Trt = water manipulated or cut-control treatment, Tsh = dummy threshold variable, Wt = water table level).**

CO_2: General linear model (n=163, $P < 0.001$, $R^2 = 0.56$)

Variable	Coefficient	T	P
Constant	538.60	17.31	0.000
Wt	2.25	1.88	0.062
Tsh	-338.82	-10.60	0.000
Trt	-66.50	-2.90	0.004

CH_4: Polynomial model (n=166, $P < 0.001$, $R^2 = 0.36$)

Variable	Coefficient	T	P
Constant	37.28	12.64	0.000
Trt	-28.72	-8.29	0.000
WT squared	-0.22	-3.22	0.002
WT squared *Trt	0.21	3.12	0.002

Total Carbon efflux: General linear model (n=144, $P < 0.001$, $R^2 = 0.55$)

Variable	Coefficient	T	P
Constant	593.29	16.01	0.000
Tsh	-353.90	-10.17	0.000
Trt	-101.06	-3.90	0.000
Trt*Wt	2.47	1.86	0.065

FIGURE CAPTIONS

Figure 3-1. Location of study site (Moose Fen).

Figure 3-2. Experimental design showing control, cut-control and water table manipulated microcosms. Manipulated and cut-control microcosms have wells to allow pumping and for monitoring the water table levels.

Figure 3-3. Water table levels in microcosms for 1998 (A) and 1999 (B). Low batteries from 7/6/1999 to 7/9/1999 allowed water levels to rise in the 6 microcosms with artificially lowered water tables.

Figure 3-4. Control and cut-control CO_2, CH_4, and soil temperature. Soil temperature was measured at a depth of 5 cm for CO_2 and 20 cm for CH_4. Error bars are standard deviations.

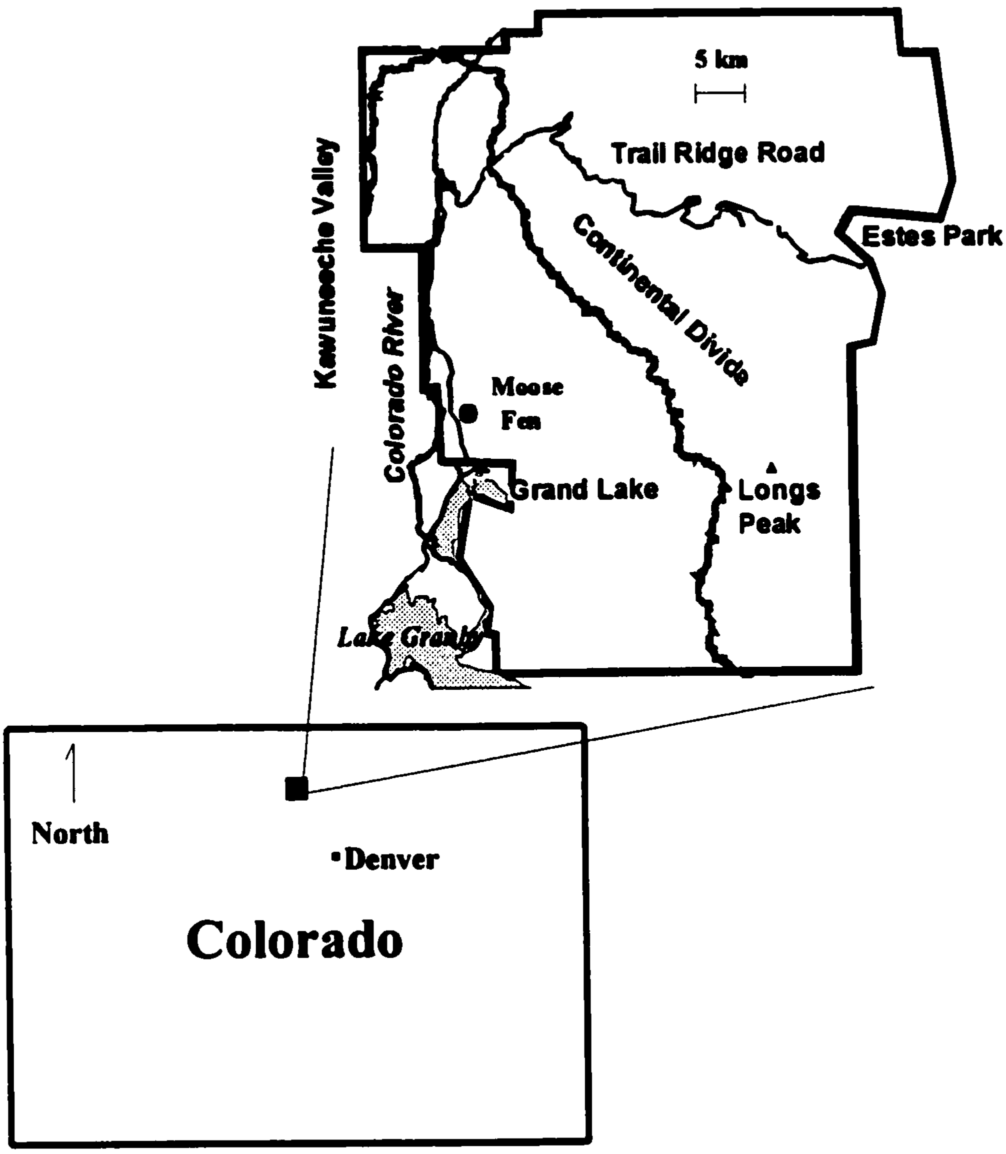
Figure 3-5. Relationship between CO_2 efflux and soil temperature at 5 cm when the water table was above and below the soil surface. Regression statistics for when water table is above surface: CO_2 efflux = 41.4 * exp(0.124*soil temperature @ 5 cm) ($Q_{10} = 3.46$, $R^2 = 0.34$, $n = 97$). Regression statistics for when water table is below surface ($WT \leq 0$): CO_2 efflux = 331.2 * exp(0.026*soil temperature @ 5 cm) ($Q_{10} = 1.3$, $R^2 = 0.28$, $n = 65$).

Figure 3-6. Relationship between CH_4 efflux and soil temperature at 20 cm when the water table was above and below the soil surface. Regression statistics for when water table is above surface: CH_4 efflux = 3.44 * exp(0.18*soil temperature @ 20 cm) ($Q_{10} = 6.1$, $R^2 = 0.16$, $n = 96$). Regression statistics for when water table is below surface: CH_4 efflux = 10.7 * exp(-0.032*soil temperature @ 20 cm) ($Q_{10} = 0.7$, $R^2 = 0.01$, $n = 65$).

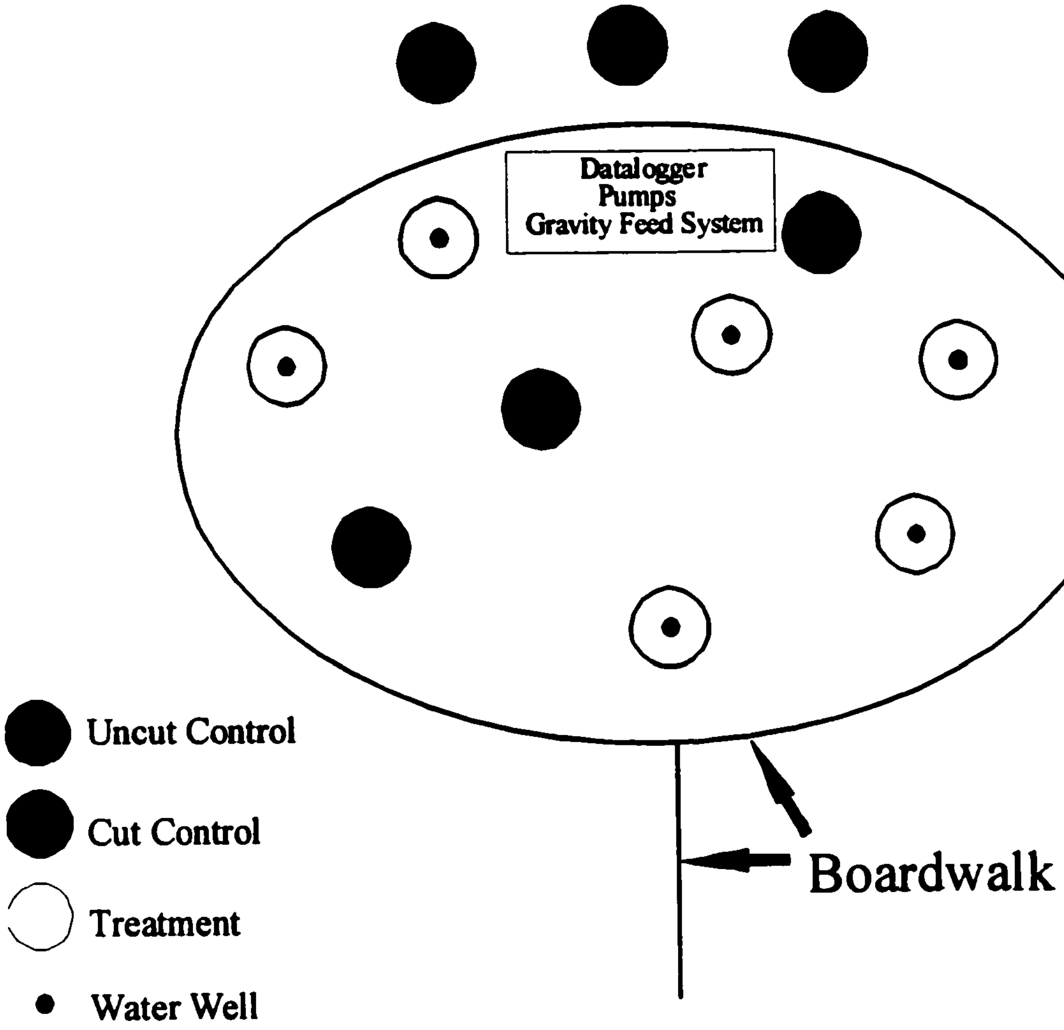
Figure 3-7. **The relationship between CO_2 efflux and water table depth (see Table 3.2 for regression coefficients).**

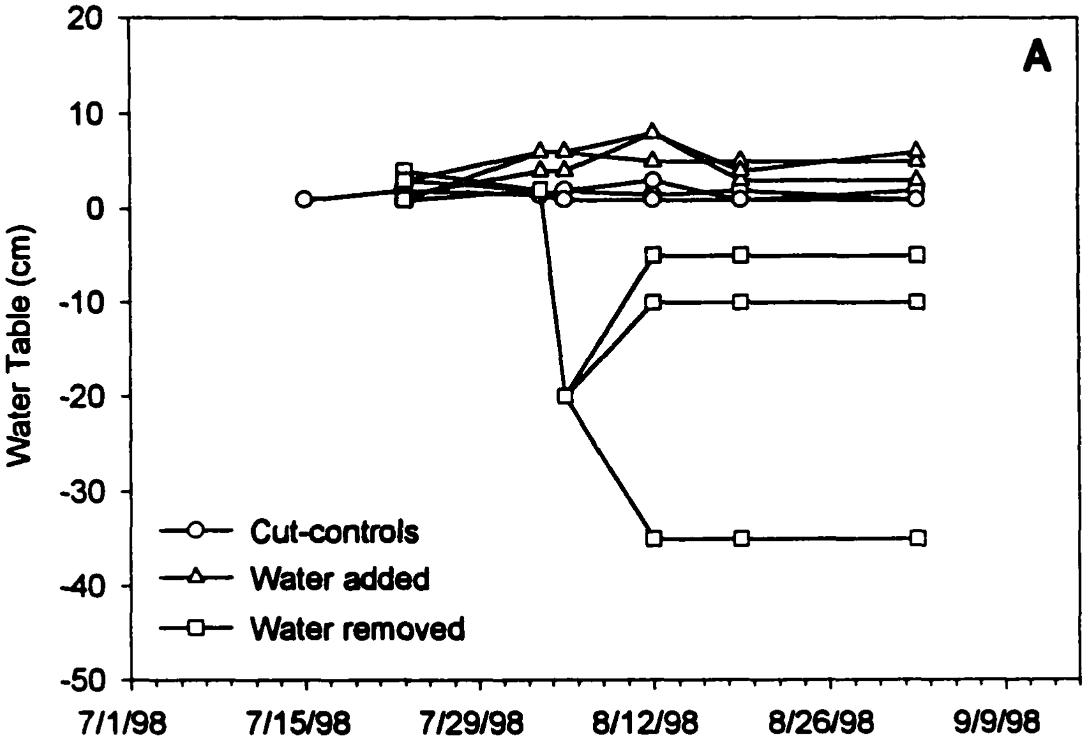
Figure 3-8. **The relationship between CH_4 efflux and water table depth (see Table 3.2 for regression coefficients).**

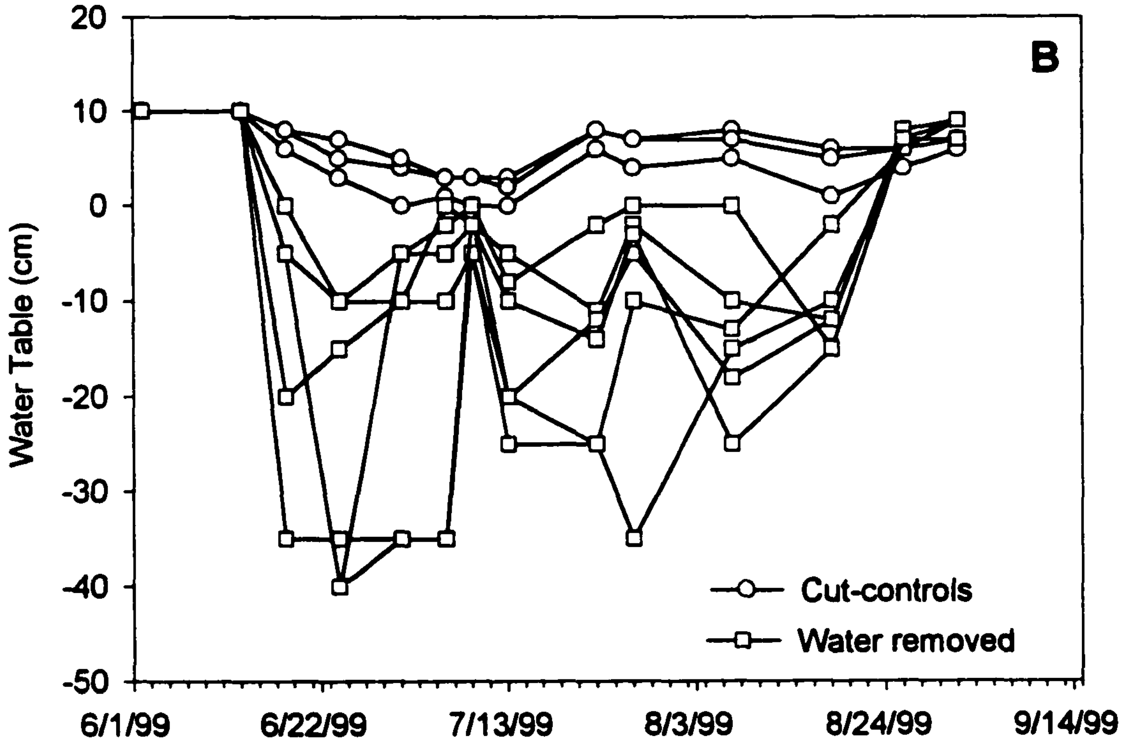
Figure 3-9. **The relationship between total carbon (CO_2 + CH_4) and water table depth (see Table 3.2 for regression coefficients).**

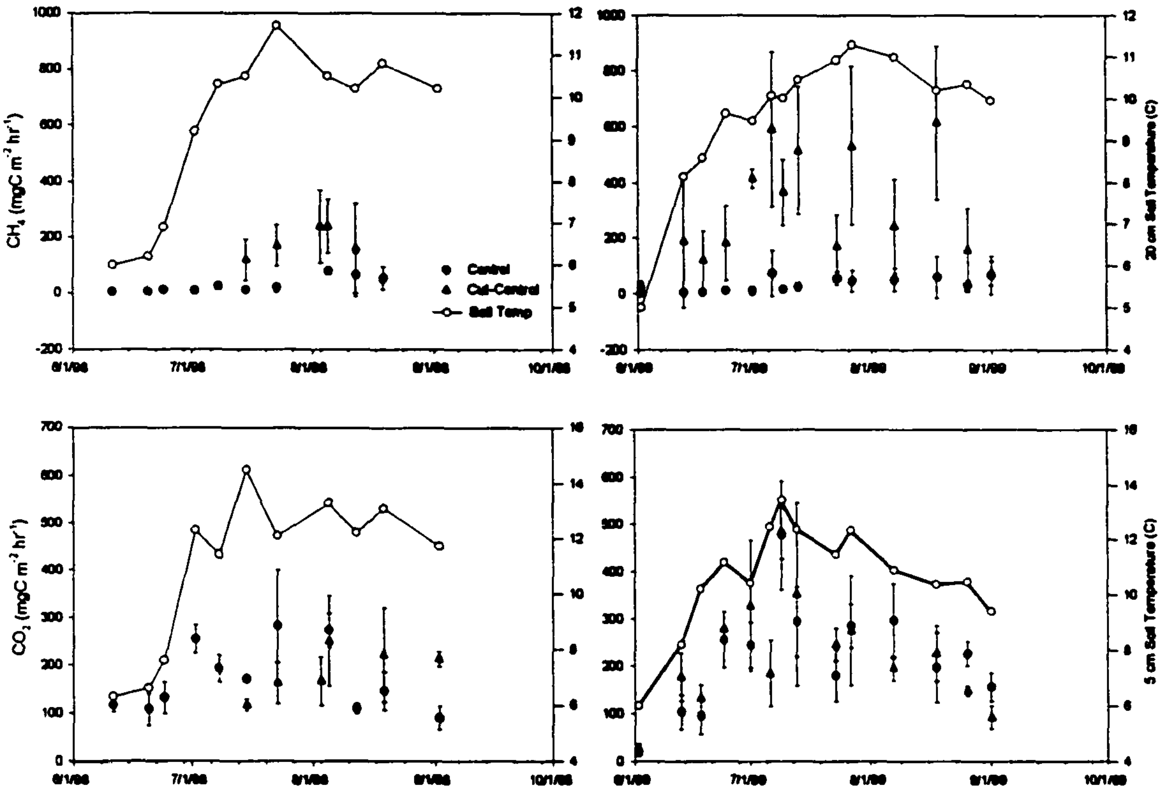


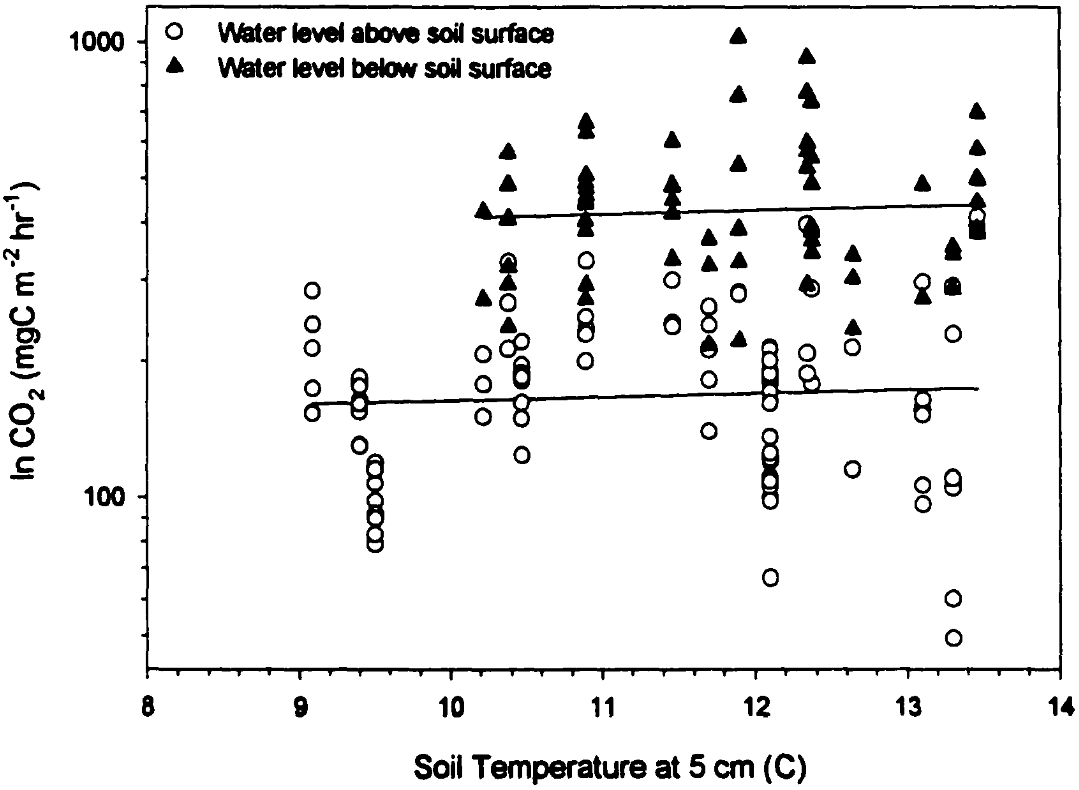
ROCKY MOUNTAIN NATIONAL PARK

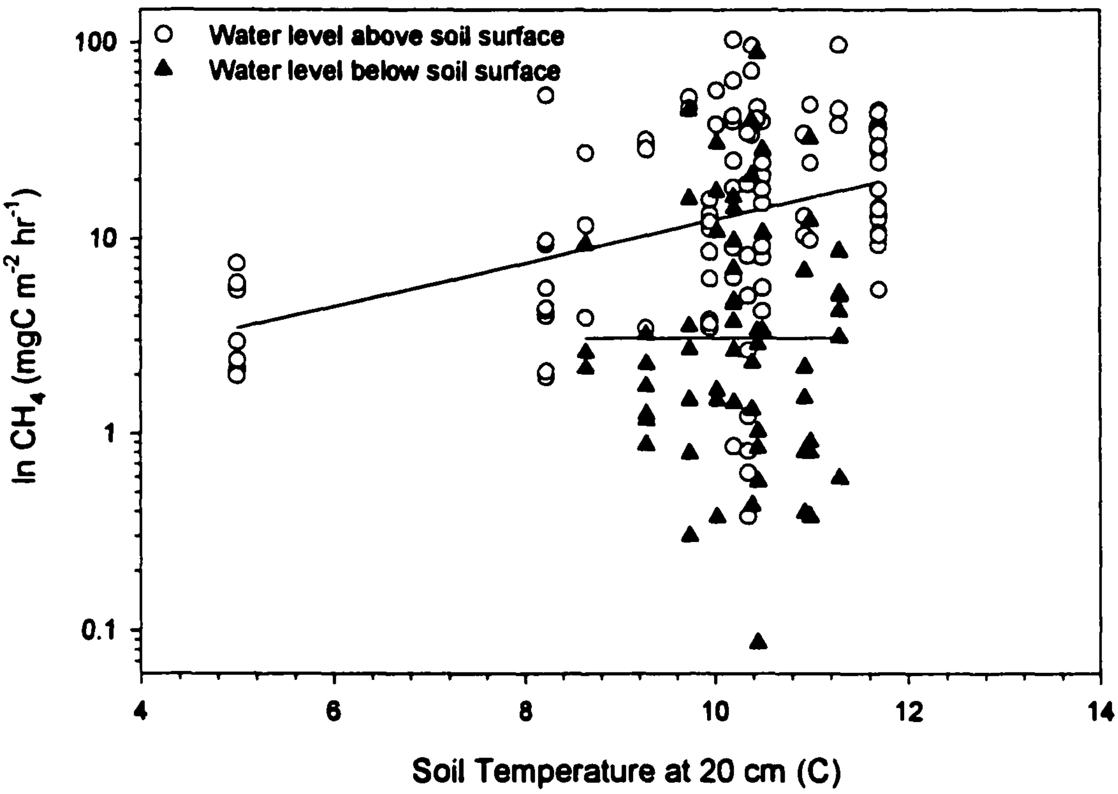

Datalogger
Pumps
Gravity Feed System
Uncut Control
Cut Control
Treatment
Water Well
Boardwalk


A
Water Table (cm)
20
10
0
-10
-20
-30
-40
-50
7/1/98
7/15/98
7/29/98
8/12/98
8/26/98
9/9/98
Cut-controls
Water added
Water removed

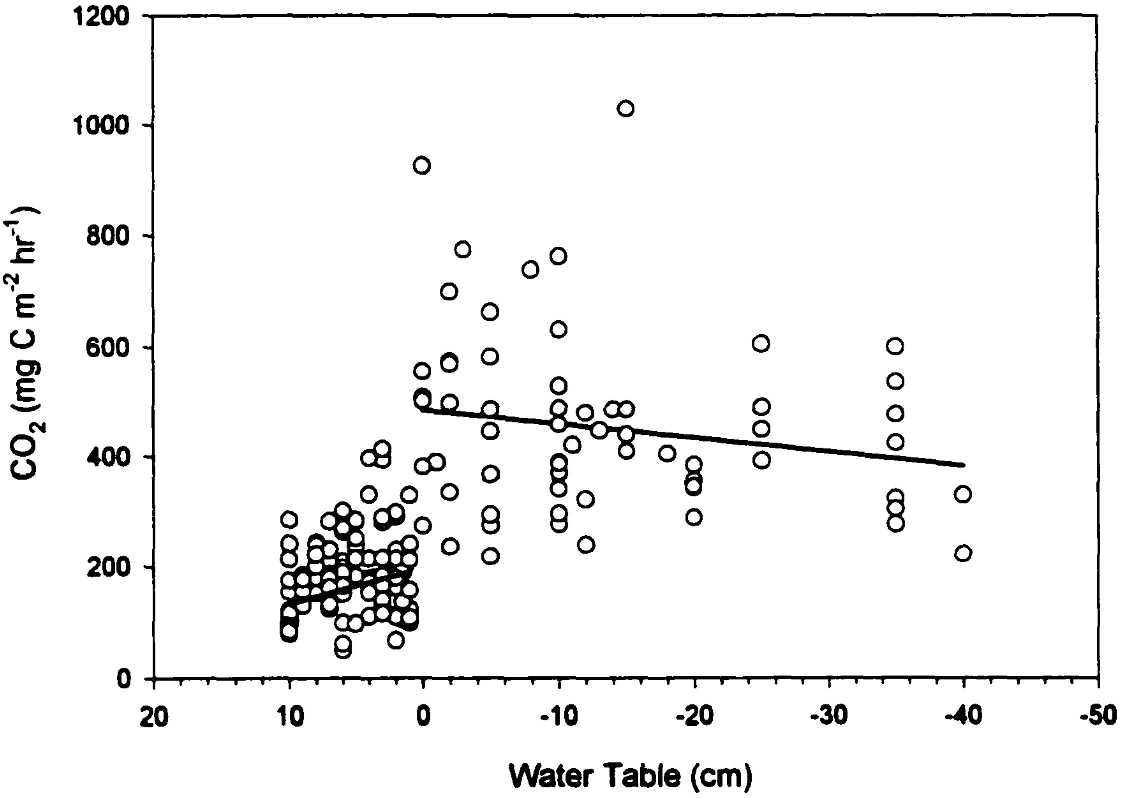

B
Water Table (cm)
20
10
0
-10
-20
-30
-40
-50
6/1/99
6/22/99
7/13/99
8/3/99
8/24/99
9/14/99
Cut-controls
Water removed

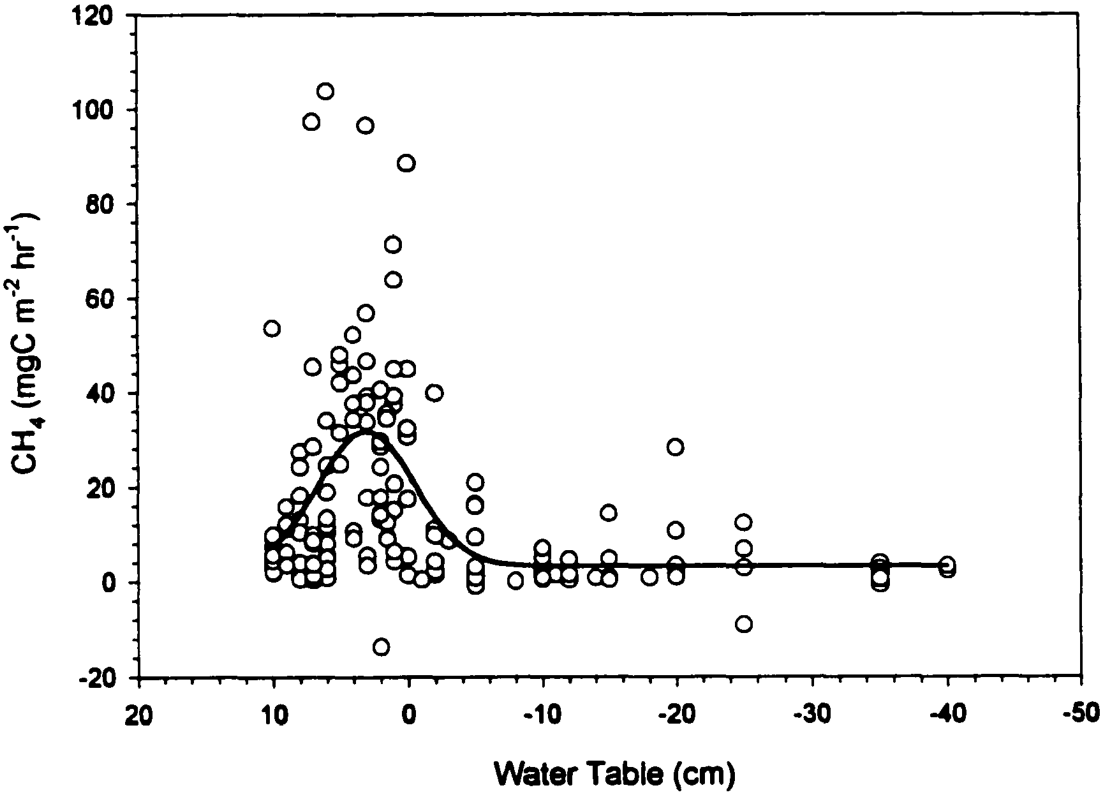

CH$_4$ (mgC m^{-2} hr^{-1})
1000
800
600
400
200
0
-200
12
11
10
9
8
7
6
5
4
● Control
▲ Cut-Control
—○— Soil Temp
6/1/98
7/1/98
8/1/98
9/1/98
10/1/98
6/1/99
7/1/99
8/1/99
9/1/99
10/1/99
20 cm Soil Temperature (C)
CO$_2$ (mgC m^{-2} hr^{-1})
700
600
500
400
300
200
100
0
16
14
12
10
8
6
4
5 cm Soil Temperature (C)

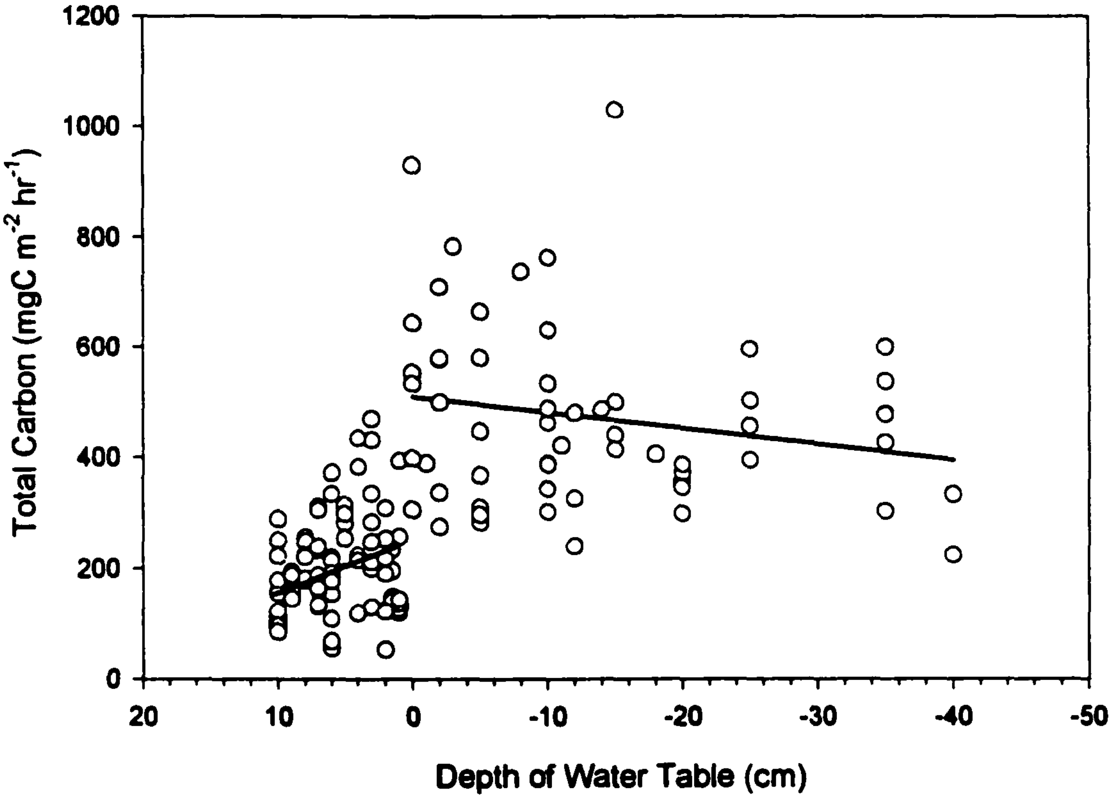

Water level above soil surface
Water level below soil surface
1000
100
ln CO$_2$ (mgC m^{-2} hr^{-1})
8
9
10
11
12
13
14
Soil Temperature at 5 cm (C)



○ Water level above soil surface
▲ Water level below soil surface
100
10
1
0.1
ln CH$_4$ (mgC m^{-2} hr^{-1})
4
6
8
10
12
14
Soil Temperature at 20 cm (C)


1200
1000
800
600
400
200
0
CO$_2$ (mg C m^{-2} hr^{-1})
20
10
0
-10
-20
-30
-40
-50
Water Table (cm)


120
100
80
60
40
20
0
-20
CH$_4$ (mgC m^{-2} hr^{-1})
20
10
0
-10
-20
-30
-40
-50
Water Table (cm)



Total Carbon (mgC m^{-2} hr^{-1})
0
200
400
600
800
1000
1200
20
10
0
-10
-20
-30
-40
-50
Depth of Water Table (cm)

Chapter 4

MODELING CARBON ACCUMULATION IN SOUTHERN ROCKY MOUNTAIN FENS USING THE CENTURY ECOSYSTEM MODEL

ABSTRACT

Despite the importance of peatlands in the global carbon cycle, no widely applicable ecosystem model exists for peatlands. The objectives of this paper were to determine how well the CENTURY ecosystem model could be used to simulate: 1) long-term carbon accumulation; and 2) short-term changes in carbon storage due to hydrologic changes in peatlands. The CENTURY model was able to simulate long-term carbon accumulation in fens for 10,000 years by adjusting three variables that represent anaerobic soil conditions. CENTURY predicted that most of the fen peat stored came from root material, which was easily decomposed when exposed to aerobic conditions. However, after calibrating with two peatlands, CENTURY was unable to simulate long-term carbon accumulation in a third peatland, most likely due to limitations in how anaerobic conditions are created in CENTURY. To model peatlands at different sites than calibrated for, CENTURY should be modified to allow anaerobic conditions to be created by high ground water levels instead of the ratio of rain to PET as currently used.

Key words: peatlands, fens, Colorado, Rocky Mountains, CENTURY, carbon accumulation, modeling

INTRODUCTION

In a time of changing climate and with significant increases in concentrations of atmospheric greenhouse gases, understanding peatland carbon cycling processes is crucial (Gorham 1991). Peatlands function as long-term sinks of atmospheric CO_2 because plant production is greater than decomposition. Peatlands store between 224 to 455 Pg (1 Pg=10^{15}g) of carbon, about 12-30% of the current global soil carbon pool (Gorham 1991, Botch *et al.* 1995, Lappalainen 1996, Clymo *et al.* 1998), despite occupying only 3% of the land surface (Maltby and Proctor 1996). Peatlands slowly accumulate carbon over thousands to tens of thousands of years. However, if hydrologically modified by ditching, draining or climate change, decomposition rates can increase. If decomposition rates are than higher than production rates, peatlands can release large amounts of carbon as CO_2 (Armentano and Menges 1986, Gorham 1991, Silvola *et al.* 1996, Nykänen *et al.* 1998, Chapters 2 and 3). This sensitivity to disturbance is especially important because the greatest concentration of peatlands occur in high latitude regions where global climate change scenarios predict the greatest temperature increases and hydrologic changes (IPCC 1995).

Despite the global importance of peatlands as a major sink or potential source of carbon, they continue to be neglected in global carbon modeling (Maltby and Procter 1996). Concerted efforts have been made to develop models to simulate carbon dynamics in many other ecosystems, including grasslands, croplands and forests, but few ecosystem models exist for peatlands. The most widely used method of modeling peat accumulation is Clymo's (1984) theoretical mathematical decay model. Clymo's model back-calculates plant production and decay with dated peat cores and cumulative carbon increases in the profile. It has been used to model long-term peat accumulation in several peatlands (Warner *et al.* 1993, Charman *et al.* 1994, Belyea and Warner 1996, Clymo *et al.* 1998). However, there are inherent drawbacks in using this model. First, it can only be used to explain peat growth after it has happened. Second, it cannot be used to make predictions based on environmental changes, such as in soil or air temperature or hydrologic regime. Predictive, process-based models are necessary to understand the potential effects of climate change, physical disturbances, drainage or pathways for increased carbon sequestration.

The objectives of this paper are to test the capabilities of the CENTURY ecosystem model to simulate; 1) long-term carbon accumulation, and 2) short-term changes in carbon storage in response to hydrologic changes. The CENTURY ecosystem model was developed to simulate soil carbon dynamics and has been successfully applied in many ecosystems. However, CENTURY has not previously been adapted for peatlands.

MODEL DESCRIPTION

A detailed description of the most recent version of CENTURY model is presented in Parton *et al.* (1993) and only a brief summary is provided here. CENTURY is an ecosystem model that simulates soil organic matter (SOM) dynamics on a monthly time step with the major input variables being monthly precipitation, monthly average maximum and minimum air temperatures, soil texture, atmospheric and soil nitrogen inputs, and lignin and nitrogen content of plant material. CENTURY uses a plant submodel to simulate plant production that cycles into the SOM submodel that simulates carbon and nitrogen cycling in the soil (P and S cycling modules are also available). Plant production and carbon cycling are modified by soil temperature and soil wetness, which are simulated in the hydrology and soil temperature submodels.

The plant production submodel can simulate grass, tree, agricultural crop and savanna production. CENTURY simulates grass growth by defining a potential growth (genetic maximum) and decreasing that maximum growth rate by scaling factors. Some of the important scaling factors are soil temperature, moisture status and nutrient availability. Grass is subdivided into readily decomposable material (metabolic) and more resistant material (structural) for live shoots, standing dead shoots and roots.

The SOM submodel uses a series of functional pools to categorize various stages of plant litter and soil organic matter decomposition (Fig. 4-1). Above and below ground plant litter are partitioned into either the structural or metabolic pools based on the lignin to nitrogen ratio. The greater the lignin concentration, the greater the partitioning into the structural pool, and the slower the turnover rate compared with the metabolic pool. The surface microbial pool consists of dead microbes and microbial residues that result from decomposing the plant litter and has a very fast turnover time.

Soil organic carbon decomposition is simulated via three-pools, active, slow and passive organic carbon pools (Fig. 4-1). The active pool (SOM1C) consists of microbes and microbial byproducts associated with SOM decomposition and have a turnover time of less than one year. The slow (SOM2C) pool includes plant and microbial products that are biologically resistant to decomposition and has a turnover time in the tens of years. The passive pool (SOM3C) is very resistant to decomposition and includes stabilized biological products that are chemically recalcitrant or physically protected with a turnover time of hundreds to thousands of years. The modeled turnover time of these pools is a function of the abiotic decomposition factor (DEFAC), which is controlled by soil temperature, nutrient and water availability, and anoxic conditions.

CENTURY uses a soil temperature and hydrologic submodel to simulate the soil temperature and moisture status, both of which affect plant growth, decomposition and nutrient cycling. Soil temperature is calculated as a monthly average of the near soil surface using monthly minimum and maximum air temperatures. Either monthly weather data or mean monthly weather data can be used in CENTURY. CENTURY also can run in a stochastic mode that varies monthly precipitation around the mean.

CENTURY uses a simple hydrologic model to calculate soil moisture by using precipitation in the weather file as the sole water input and calculating monthly evaporation, transpiration, leaching and stream flow as outputs. Soil water is routed via a bucket method between soil layers by adding water at the top soil layer, with any water above field capacity being passed on to the next soil layer and so on. Water draining below the bottom layer of soil can be lost as fast storm flow, leached into the subsoil and accumulate, or released more slowly as streamflow.

Anaerobic conditions in CENTURY are determined by a ratio of rainfall to potential evapotranspiration (PET). Two parameters, ANEREF1 and ANEREF2 are used to set the occurrence of anaerobic conditions in relation to the rain:PET ratio. When rain:PET is larger than ANEREF2 than anaerobic conditions occur. When rain:PET is smaller than ANEREF1 than aerobic conditions occur. If the rain:PET ratio is between

ANEREF1 and ANEREF2 then intermediate anaerobic conditions occur. The anaerobic decay modifier ANEREF3 reduces the amount of anaerobic decomposition by multiplying ANEREF3 by the maximum decomposition rate (DEFAC).

METHODS

Data from Caribou and Zapfs Fens were used for the calibration phase of the modeling (Table 4-1). Caribou Fen is located on Arapaho Pass, in Colorado's Front Range on the west side of the Continental Divide at 3,400 m elevation. The peat is 190 cm thick and has a basal date of 10,525 years. The vegetation is dominated by *Carex aquatilis, C. nigricans* and *Eleocharis quinqueflora*. Zapfs Fen is at a lower elevation, 2725 m on the east side of the continental divide. It has a peat thickness of 130 cm and a basal carbon date of 5,000 years. It is dominated *Carex utriculata*. Little moss cover occurs at either site.

Both peatlands were cored and dated by Jim Benedict in the mid-1980's (Benedict and Maher, unpublished data). Caribou Fen was AMS ^{14}C dated every 20 cm through the core for a total of 10 dates, while Zapfs Fen was bulk carbon ^{14}C dating every 20 cm for a total of 7 dates. In the fall of 1996, I returned to the sites and collected two peat cores from each site at the same locations as the cores collected for carbon dating.

Each peat core was cut into 5 cm sections, oven-dried for two days at 105 °C and ashed to determine mineral-free bulk densities (Belyea and Warner 1996). Carbon storage was calculated by multiplying the mineral-free bulk densities by depth and assuming a carbon content of 50%. The carbon content of peat varies, but has been found to average approximately 50% (Moore 1989, Ovenden 1990, Gorham 1991, Belyea and Warner 1996, Robinson and Moore 1999). Caribou Fen had a 10-cm thick clay lens between 10-20 cm depth that was not included in the analysis.

After CENTURY was calibrated using Caribou and Zapfs fen, a fen located in the West Elk Mountains near Crested Butte, in western Colorado was used to test whether CENTURY could predict peat accumulation in an uncalibrated fen. The fen is called "Keystone Ironbog" and was previously used for pollen analysis of paleoclimate and timberline fluctuations during the Holocene (Fall 1997a and 1997b). Keystone Ironbog is located at 2,920 m elevation, intermediate between Zapfs and Caribou Fens (Table 4-1). The dominant plant species at Keystone are *Carex aquatilis*, *C. utriculata* and *Eriophorum angustifolium* (Fall 1997a) and in contrast to the other sites, *Sphagnum* mosses are abundant.

The Keystone Ironbog peat body has one meter of sedge peat on top of one meter of woody and humified peat (Fall 1997b). The basal peat from near the center of the peatland was originally bulk-dated to 7,100 yr B.P. (Fall 1997a), but this sample appeared to be contaminated with younger carbon. Fall (1997b) calculated that the basal date was closer to 9,000 yr B.P. by AMS dating of wood fragments in the peat body, developing an age-depth relationship, and dating the insoluble fraction of the bulk sample. No bulk density data wee available for Keystone Ironbog fen, so I used the average bulk density value of Caribou and Zapfs Fen, which was 0.25 g/cm^3, and carbon content of 50%.

MODEL PARAMETERIZATION AND CALIBRATION

The CENTURY agroecosystem version 4.0 (Parton *et al.* 1993) was used in the grassland mode for all simulations with several adjustments and assumptions to configure it for a peatland. Most importantly, I changed several site parameters to induce saturated soil conditions. The DRAIN variable, which controls how much water drains out of the soil, was set to 0 (1 = maximum drainage and 0 = no drainage) to maximize water storage and anaerobic conditions. The baseflow and stormflow variables were also set to 0 to limit the amount of water leaving the sites.

CENTURY has no soil texture parameter that can be used to define an organic soil. Raich *et al.* (in press) parameterized CENTURY for Hawaii's organic soils as being 98% sand, 1% silt and 1% clay with a bulk density of 0.15 g cm^{-3}. By setting the soils mostly to sand, it turned off any texturally mediated carbon transformations in CENTURY. Raich *et al.* (in press) also predicted that there should be little physical stabilization of soil C, and little passive soil organic C formation. I used this primarily sand texture but used bulk density values to reflect average values 0.20 g cm^{-3}, 0.30 g cm^{-3} and 0.25 g cm^{-3} for Caribou, Zapfs Fen and Keystone Ironbog, respectively.

All simulations were run in the mean weather mode. The Saddle Ridge weather station on Niwot Ridge, an alpine tundra location, was used for Caribou Fen simulations, although it is 125 m higher in elevation than Caribou Fen (Table 4-1). The Nederland (USWS station # 55878) weather station was used for Zapfs Fen simulations, which is 210 m lower in elevation than Zapfs Fen and 16 km to the south. Crested Butte (station # 51959) weather was used for Keystone Ironbog simulations and is 216 m lower in elevation than Keystone Ironbog and 7 km away. Since all three weather stations were at different elevations than the study sites, elevation corrections were made to both temperature and precipitation by using lapse rates calculated by Fall (1997a). Fall calculated that for every 1000 meters in elevation gain, mean annual temperature decreased by 6.0 °C and mean annual precipitation increased by 22.5 cm.

CENTURY simulates plant production, but is often adjusted for site differences. Niwot Ridge vegetation type was used for all simulations. Plant production values are not needed for CENTURY because it is simulated, but since CENTURY has not previously been used for peatlands, I wanted to be certain that simulated plant production values were close to measured values. Unfortunately, measured plant production values were only available for Caribou Fen in 1997 (R.A. Chimner unpublished data) (Table 4-1). No plant production data were available for either Zapfs Fen or Keystone Ironbog. To estimate plant production for Zapfs Fen and Keystone Ironbog, I used plant production from other Colorado fens at similar elevations and with similar vegetation. I used NPP values from Green Mt. Pond in 1997 (Chapter 2) for Zapfs Fen and the average 1997 and 1998 NPP from Big Meadows for Keystone Ironbog (Chapter 2). CENTURY simulated plant production close to estimated values and only minor adjustments were made by setting the amount of symbiotic nitrogen fixation (SNFXMF) to 0.002 to reflect NPP values of Caribou Fen and Zapfs Fen.

I calibrated long-term carbon accumulation rates in CENTURY by altering the three anaerobic variables ANEREF1 though 3 and compared the predicted long-term carbon accumulation rates to measured values. The first step was to determine the value of

ANEREF3, which determines the influence of soil anaerobic conditions on decomposition. This was done by creating completely anaerobic conditions for Caribou and Zapfs Fen by setting ANEREF1 and ANEREF2 to 0.1 and 0.2 respectively, thereby creating maximum anaerobic conditions year round. After complete anaerobic conditions were created, I adjusted the anaerobic decomposition variable ANEREF3 for both Caribou and Zapfs Fen until CENTURY simulated total carbon (SOMTC) similar to that measured for each site. To accumulate sufficient carbon, ANEREF3 was lowered to 0.008 and 0.04 for Caribou and Zapfs Fen, respectively. The large difference in ANEREF3 between Caribou and Zapfs Fen indicates that either anaerobic decay differs or frequencies of aerobic conditions differ between these peatlands. Because one objective was to determine if CENTURY could be calibrated for several fens using the same variables, I assumed that anaerobic decay processes are similar between peatlands but real differences occur in the frequency and duration of aerobic conditions. Caribou Fen is 700 m higher in elevation, with an assumed higher snowpack, precipitation, lower temperatures and evapotranspiration. Zapfs Fen is at the low elevation end of peatland distribution in Colorado with presumed higher temperatures, evapotranspiration rates, and lower precipitation than Caribou Fen. Therefore, the assumption was made that Zapfs Fen would have greater water table fluctuations and greater frequency and duration of aerobic conditions than Caribou Fen.

The second step was to determine the values for ANERF 1 and 2, which account for periods of anaerobic conditions. Using the hydrologic information presented above, I set the anaerobic decay variable ANEREF3 of Zapfs Fen to that of Caribou Fen, 0.008, and altered the duration of anaerobic conditions at Zapfs Fen by altering the ANEREF1 and 2 variables. This allowed Zapfs Fen to have the same anaerobic decay rate as Caribou with a seasonal water table decline. By altering ANEREF1 and ANEREF2 for Zapfs Fen, the best fit for total carbon was found by changing ANEREF1 from 1.5 to 0.35 and ANEREF2 from 3.0 to 1.1.

The final values for ANEREF1-3 for Caribou and Zapfs Fens are given in Table 4-2. The final simulation for Caribou and Zapfs Fens are shown in Figures 4-2 and 4-3, respectively. CENTURY under-predicted carbon accumulation rates for the time period 3,000 and 8,000 years BP for Caribou Fen, but better predicted the first 1000 years and the ending value (Fig. 4-2). CENTURY slightly over-predicted carbon accumulation rates in Zapfs Fen for the time period 3,000 and 4,500 year BP, but also better predicted the first 1,500 years and end value (Fig. 4-3). Long-term peat accumulation rates were simulated using current mean weather, which does not allow for climate variability over time. By incorporating paleoclimatic conditions, it might be possible to better model long-term carbon accumulation, but it should not alter the basic findings of this paper.

APPLICATION OF THE MODEL

To test how well CENTURY predicted total carbon storage in Keystone Ironbog (Fall 1997a and Fall 1997b), the model was run using the calibrations from Caribou and Zapfs Fen. Measurements of soil carbon showed that Keystone Ironbog accumulated around 200 kg C m^{-2} over 9,000 years. However, CENTURY predicted 56 kg C m^{-2}, while it over-predicted the amount of plant production at 394 g C m^{-2} yr^{-1} (data not shown). The ANEREF1 and 2 variables calibrated using Caribou Fen and Zapfs Fen did not produce a successful model for Keystone Ironbog, as CENTURY predicted that the soils were more aerobic then occur. However, CENTURY correctly simulated the amount of carbon storage by changing ANEREF1 from 0.35 to 0.3 and ANEREF2 from 1.1 to 0.95 (Table 4-2). This adjustment of ANEREF variables1 and 2 to simulate carbon accumulation for Keystone Ironbog (Fig 4-4) reveals that CENTURY is highly sensitive to anaerobic soil conditions.

A sensitivity analysis was performed for Keystone Ironbog to determine how sensitive total soil carbon and plant production are to the anaerobic model variables ANEREF1 and ANEREF2. Total soil carbon (Fig. 4-5A) and plant production (Fig. 4-5B) are sensitive to anaerobic variables, especially to ANEREF2. Total soil carbon was approximately 400 g C m^{-2} when the ANEREF2 was below 0.8, but dropped 25% when ANEREF2 was 0.9 and dropped an additional 77%, to near 70 g C m^{-2}, when ANEREF2 was 1.0. Plant production had the opposite trend maintaining a level of 270 g C m^{-2} yr^{-1}at an ANEREF2 of ≤ 0.8 but increased when ANEREF2 was higher than 0.8. Changing ANEREF1 had very little affect on total soil carbon or plant production.

I ran two simulations using the final calibrations (Table 4-2) for Caribou Fen, Zapfs Fen and Keystone Ironbog to investigate, 1) the physical composition of fen peat and 2) the effect of altering precipitation on carbon accumulation rates. Figure 4-6(a-c) shows the amount of carbon stored in different carbon pools as simulated by CENTURY. For all three sites, the STRUCC2 pool comprised ~55% of soil organic carbon (SOMTC) for the three sites. The STRUCC2 pool is the belowground structural pool composed of recalcitrant structural root material. The second most abundant form of carbon is the slow pool (SOM2C), and the third is the passive SOM pool (SOM3C). The slow SOM pool is intermediate in decomposability and the passive SOM pool is the most resistant form of soil carbon composed of physically and chemically resistant material (Fig. 4-1). The slow and passive pools are derived from the most resistant portions of the litter and active SOM pools. The sum of the remaining carbon pools (aboveground structural, aboveground metabolic, surface microbial, belowground metabolic, and active organic carbon) (Fig. 4-1) make up on average less than 2 % of the carbon stored.

To explore the usefulness of an ecosystem model for carbon accumulation in peatlands, I altered precipitation levels in CENTURY for Zapfs Fen to determine if CENTURY could predict the change in carbon accumulation rates. This scenario accumulated carbon for 5,000 years using the mean weather mode, where all years are wet, and the variables in Table 4-2. Then for the next 100 years, the weather mode was changed to stochastic, which varied the amount of monthly rain based on monthly standard deviations, which altered the rain:PET ratio allowing for random dry years. Zapfs Fen accumulated 109 kg C m^{-2} over the first 5,000 years, an average of 19.5 g C m^{-2} yr^{-1}, but then lost 7 kg C m^{-2} over the next 100 years. In this model run 38 out of the 100 years had lower than average annual precipitation than the 5000 year average (Fig. 4-7A). The loss of carbon occurred despite the plant production increasing from an average of 249 g C m^{-2} yr^{-1} for the proceeding 5,000 years to 391 g C m^{-2} yr^{-1} for the 100 years. The plant production increased due to decomposing peat releasing mineral nitrogen, stimulating plant growth (Fig 4-7B). Slightly over 90% of the carbon loss was from the belowground structural (STRUCC2) and slow pools (SOM2C), while there was no carbon loss or a slight net carbon gain in the passive pools and aboveground structural and metabolic pools.

DISCUSSION

The CENTURY model successfully simulated long-term carbon accumulation in fens for a period of 10,000 years by adjusting three variables that represent anaerobic soil conditions. Total soil carbon, and to a lesser extent plant production were very sensitive to ANEREF2 but only slightly sensitive to ANEREF1 (Fig. 4-5). This occurred because ANEREF2 sets the upper limit of anaerobic conditions in the soil profile, therefore a site is completely anaerobic when the rain:PET ratio is greater than ANEREF2. However, decomposition rates increase quickly as soon as the rain:PET ratio drops below ANEREF2. Total carbon storage and plant production showed opposite patterns because year-round anaerobic conditions increased soil carbon accumulation rates by decreasing decomposition rates. However, decreasing decomposition decreased plant production because nutrients were bound up in the peat. Aerobic conditions increased decomposition and decreased total soil carbon while increasing the availability of nutrients, especially nitrogen, which then increased plant production.

The calibration of CENTURY for two Colorado fens did not allow a successful simulation of a third fen with different weather variables. This was because the method for calculating the timing, duration and depth of anaerobic soil conditions is not easily manipulated in CENTURY. CENTURY was developed for non-wetland ecosystems that rarely, if ever, have high groundwater tables. The model allows anaerobic conditions to occur only when an excess of precipitation over PET occurs. However, fens are driven by groundwater inflow (Drexler *et al.* 1999) that cannot be currently accounted for in CENTURY. Groundwater inflow to a fen is a complex process controlled by many factors such as the amount and timing of precipitation amounts, hydraulic conductivities of rocks, soils and peat, and the size and topography of the watershed. The variability of these factors makes each fen hydrologically distinct and indicates that it may be impossible to use one general rain:PET ratio to simulate complex hydrologic processes.

CENTURY predicted that the majority of fen peat is belowground structural material. This suggests that aboveground material is less important for peat accumulation than belowground material. Aboveground decomposition rates are high enough to decompose most of the aboveground structural and metabolic material. The frequency and duration of aerobic conditions belowground is considerably lower than aboveground yet the decomposition rates are still high enough to decompose all belowground metabolic material (METABC2), which can be released as anaerobically produced CH_4 (Thomas *et al.* 1996).

If fen peat accumulates primarily from belowground production as CENTURY predicts, then peat formation is another important distinction between herbaceous fens and *Sphagnum* bogs. Herbaceous fens have a large proportion of their biomass and net primary production belowground (Reader and Stewart 1972, Francez and Vasander 1995, Saarinen 1996, Chapter 2), whereas *Sphagnum*-dominated bogs have most of their biomass and net primary production aboveground (Reader and Stewart 1972). Bogs are often cited as being created from top down for this reason (Clymo 1984, Clymo *et al.* 1998). Clymo (1984) suggested that carbon is added to the upper peat profile (acrotelm) through net primary production, where it undergoes relatively rapid decomposition, and less than 20% is incorporated into the lower peat profile (catotelm). This framework of peat formation is probably correct for *Sphagnum* dominated bogs, but should not be applied to fens. Fens are built from within as high root production occurs in the lower acrotelm and in the catotelm where carbon is less subject to rapid decomposition rates.

Because fen peat is accumulated from belowground structural material and the slow SOM pool, it is vulnerable to drying soil conditions. The passive pool is resistant to decay in both anaerobic and aerobic soil conditions because it is chemically recalcitrant and possibly physically protected by complexing with clays or other soil particles (Parton *et al.* 1987). However, the belowground structural pool is not physically or chemically protected and has accumulated due to persistent anaerobic conditions that limit decomposition. If the fen dries, the large below ground soil carbon pool is exposed to aerobic conditions and relatively high decomposition rates can develop. The simulated drying of Zapf's Fen predicted an average C loss of 70 g m^{-2} yr^{-1}. This is similar to the calculated rates for two fens in Rocky Mountain National Park when water tables dropped below the soil surface during a drought year or were affected by drainage (Chapter 2). These two fens lost a calculated value of 107 and 85 g C m^{-2} yr^{-1} when the water table dropped beneath the soil surface. CENTURY also predicted that annual soil respiration (RESP1) increased an average 2.1 times in the drying scenario. This also compares very closely with gas flux data from a water table experiment in another Rocky Mountain National Park fen (Chapter 3), which reported that soil respiration increased 2.3 times when the water table dropped beneath the soil surface.

CONCLUSION

CENTURY is an ecosystem model developed to simulate soil carbon dynamics in grasslands. This paper has shown that CENTURY successfully simulated long-term carbon accumulation in Colorado peatlands by altering three anaerobic variables. However, after calibration for two peatlands CENTURY was unable to simulate carbon accumulation in a third peatland, likely due to limitations in how anaerobic conditions are created. To model peatlands at different sites than calibrated for, CENTURY should be modified to allow anaerobic conditions to be created by high ground water levels instead of the ratio of rain to PET as currently used.

Once calibrated, the usefulness of using an ecosystem model for peatlands became apparent by allowing predictions to be made of peat composition and changes in carbon accumulation when exposed to drying conditions. CENTURY predicted that most of the fen peat stored came from root material, which was easily decomposed when exposed to drying conditions.

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Table 4-1. Site characteristics of sites used for modeling, NPP = plant net primary production, MAT = estimated mean annual temperature and MAP = estimated mean annual precipitation.

Site	Elevation (m)	Peat Depth (m)	Age (years)	NPP ($g\ C\ m^{-2}yr^{-1}$)	MAT[a] (°C)	MAP[a] (cm)
Caribou	3400	1.9	10,525	110[b]	-0.8	61.5
Keystone	2920	2.0	9,000	283[c]	0.5	73
Zapfs	2725	1.3	5,000	316[c]	2.7	50

[a] Adjusted for difference in elevation between site and weather station.
[b] Chimner unpublished data.
[c] Average values from similar sites.

Table 4-2. **Default and final values of anaerobic variables used for simulations.**

Variable	Default	Caribou	Zapfs	Keystone
ANEREF1	1.5	0.35	0.35	0.30
ANEREF2	3.0	1.1	1.1	0.95
ANEREF3	0.30	0.008	0.008	0.008

FIGURE CAPTIONS

Figure 4-1. Carbon pools and flows in the CENTURY model (Metherell *et al.* 1993).

Figure 4-2. Modeled versus measured total carbon for Caribou Fen, $R^2 = 0.95$.

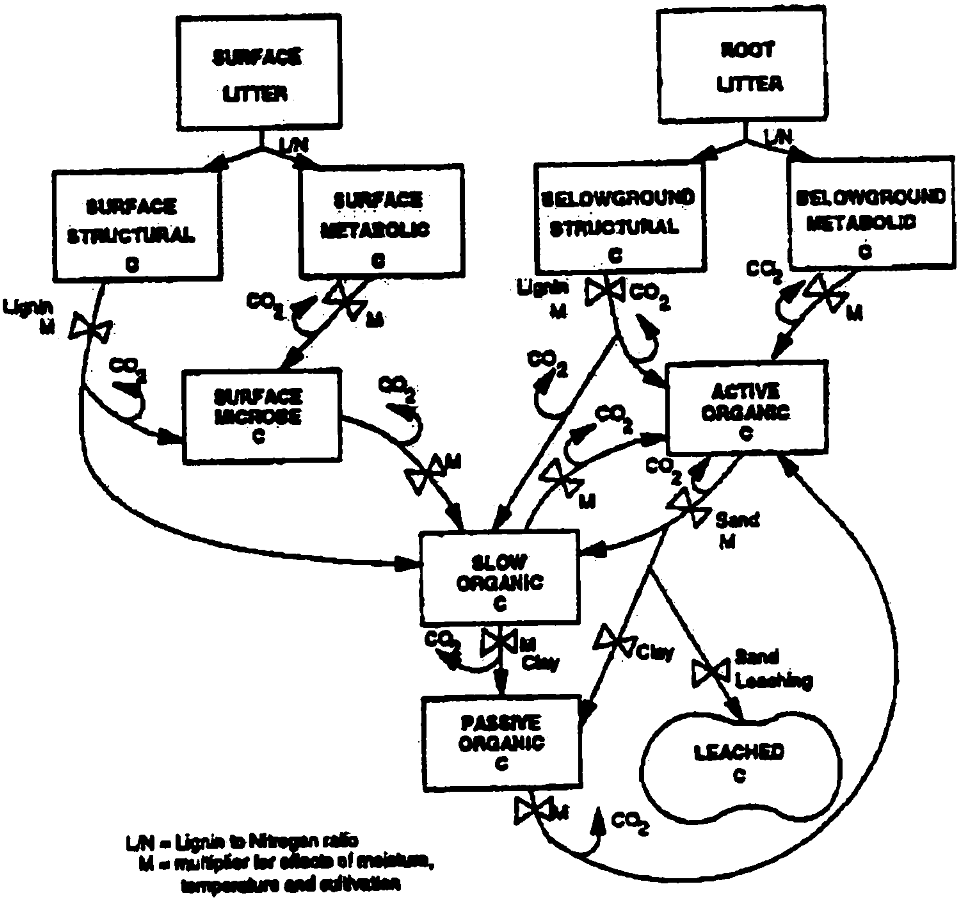
Figure 4-3. Modeled versus measured total carbon for Zapfs Fen, $R^2 = 0.94$.

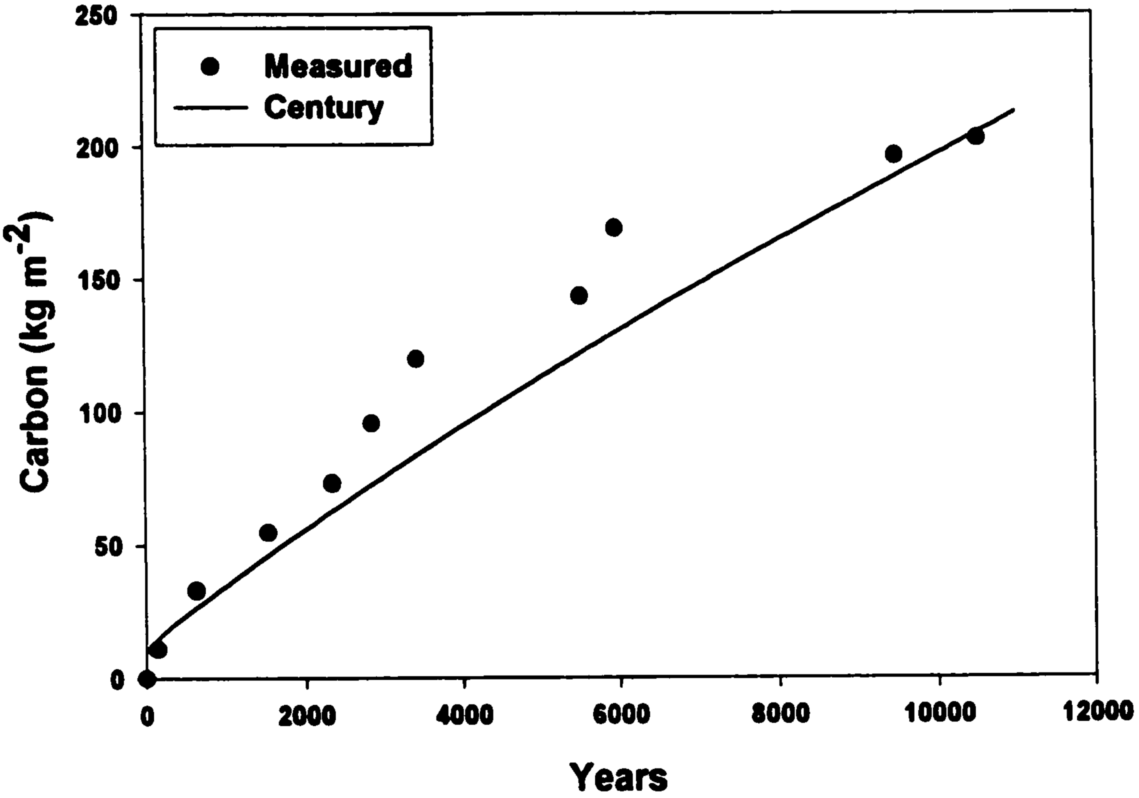
Figure 4-4. Modeled versus measured total carbon for Keystone Ironbog, $R^2 = 0.99$.

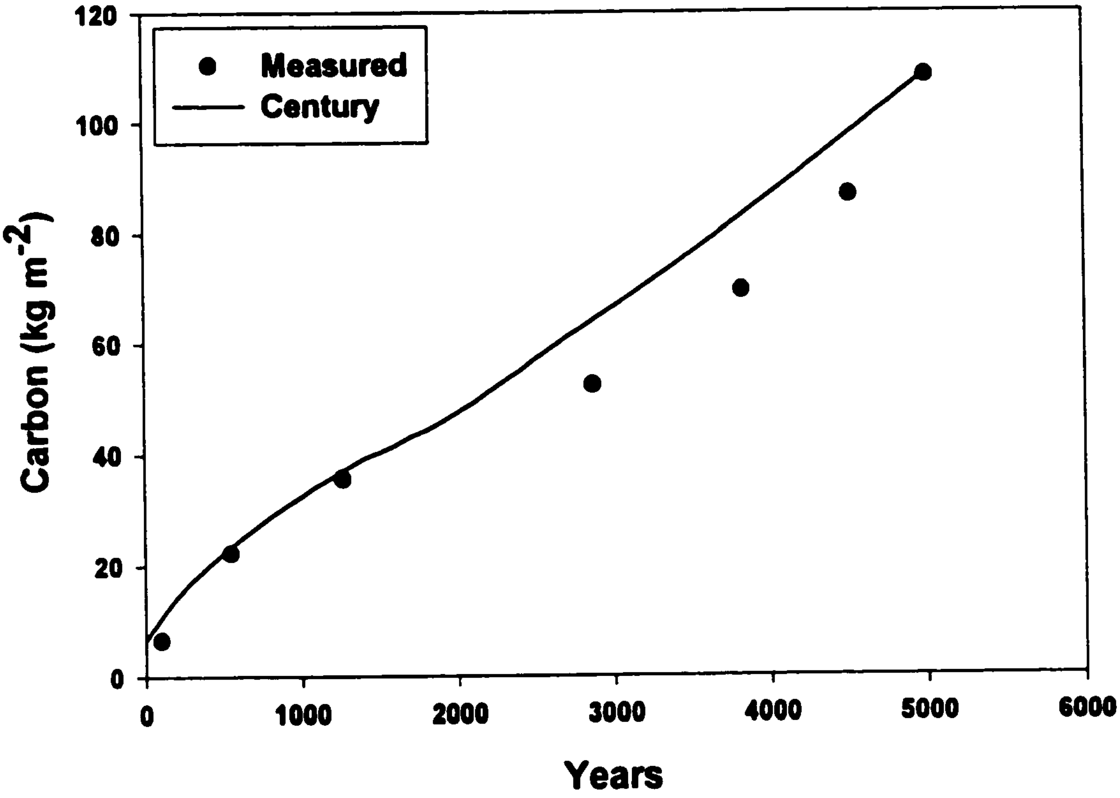
Figure 4-5. Sensitivity analysis for Keystone Ironbog, A) total soil carbon pool and B) plant production.

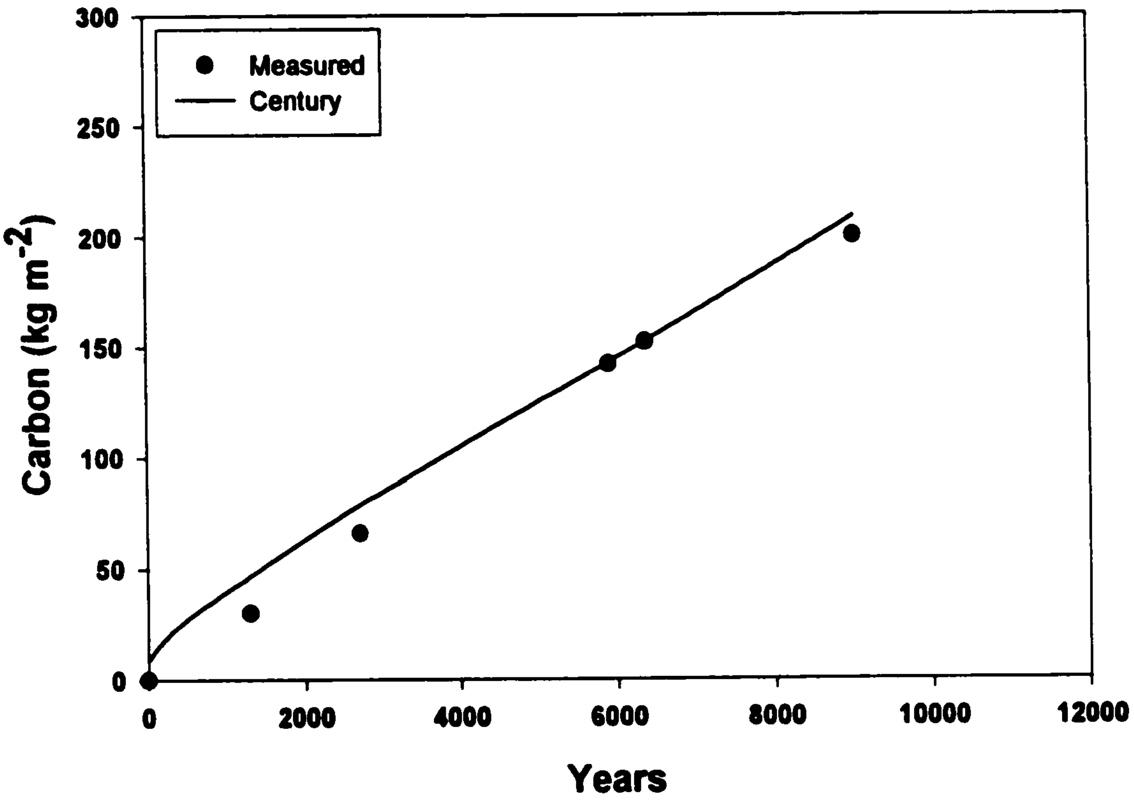
Figure 4-6. Different soil carbon pools for (A) Caribou Fen, (B) Keystone Ironbog and (C) Zapfs Fen using values from Table 2. Strucc(2) = structural belowground material, Som2c = slow soil organic pool, and Som3c = passive soil organic pool.

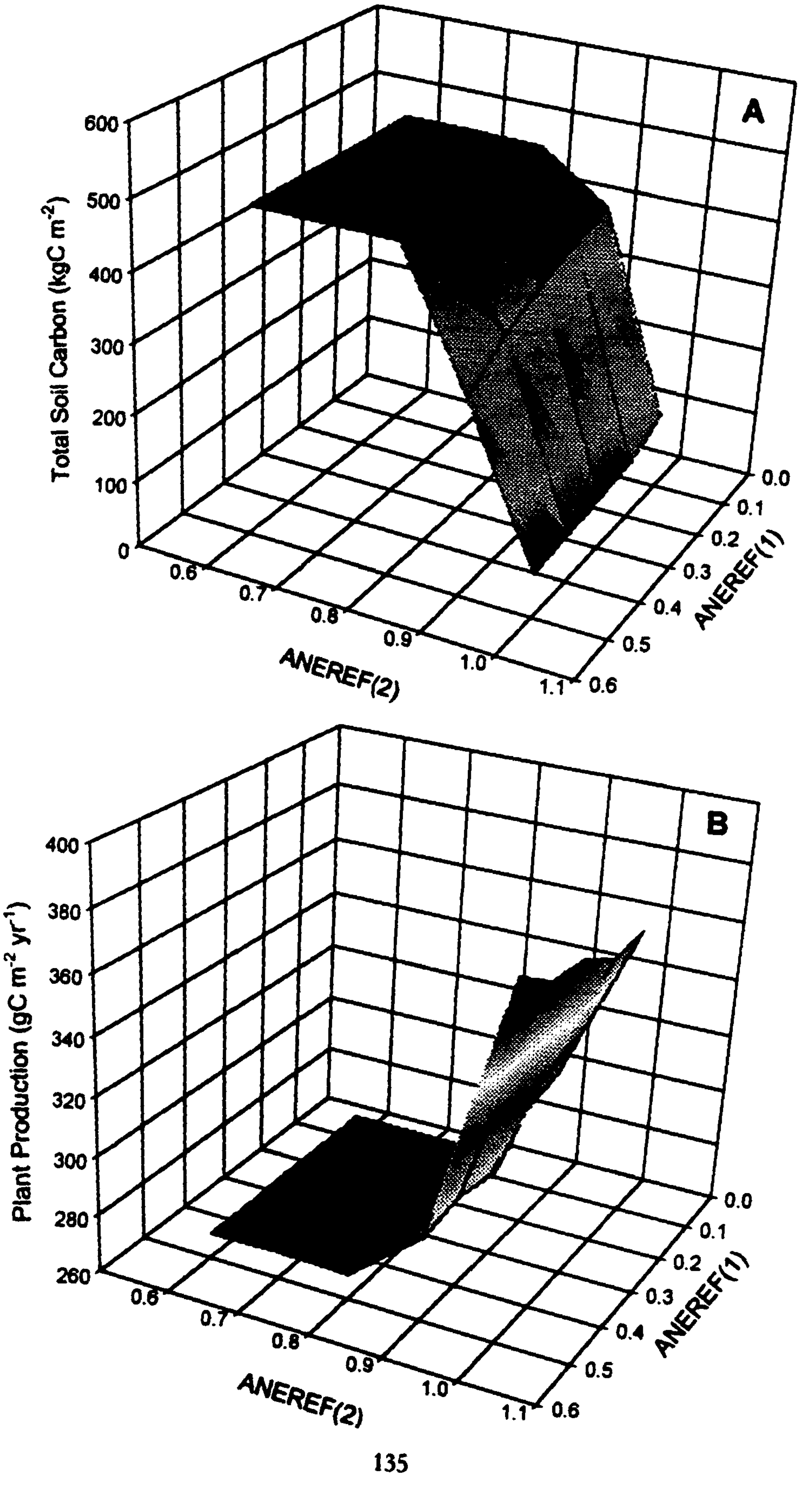
Figure 4-7. Total soil carbon of Zapfs Fen for 100 years of simulated drier conditions.

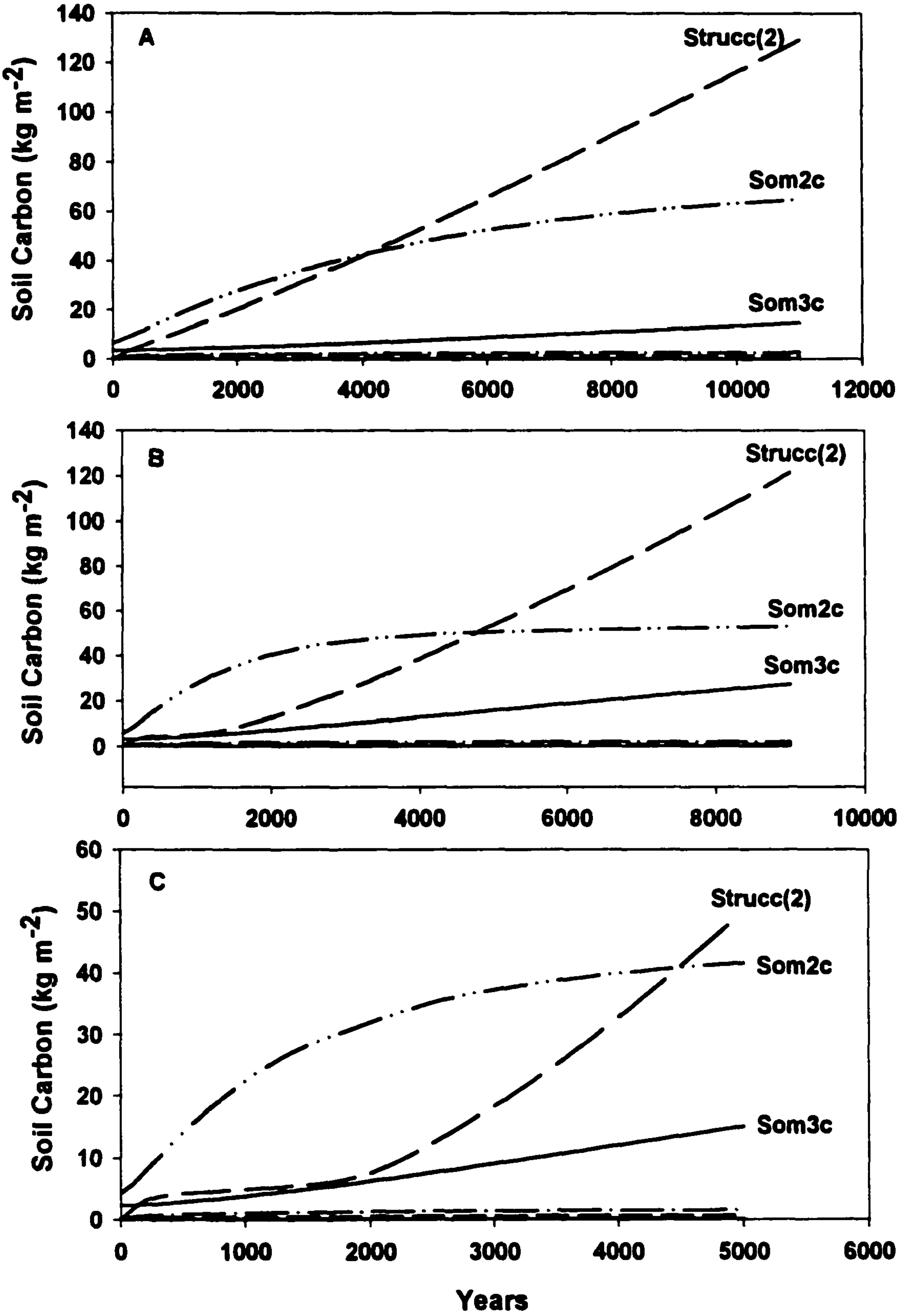

SURFACE LITTER
ROOT LITTER
L/N
L/N
SURFACE STRUCTURAL C
SURFACE METABOLIC C
BELOWGROUND STRUCTURAL C
BELOWGROUND METABOLIC C
Lignin M
CO_2
M
Lignin M
CO_2
CO_2
M
CO_2
CO_2
SURFACE MICROBE C
CO_2
M
CO_2
CO_2
ACTIVE ORGANIC C
M
CO_2
Sand M
SLOW ORGANIC C
CO_2
M Clay
Clay
Sand Leaching
PASSIVE ORGANIC C
LEACHED C
M
CO_2
L/N = Lignin to Nitrogen ratio
M = multiplier for effects of moisture, temperature and cultivation

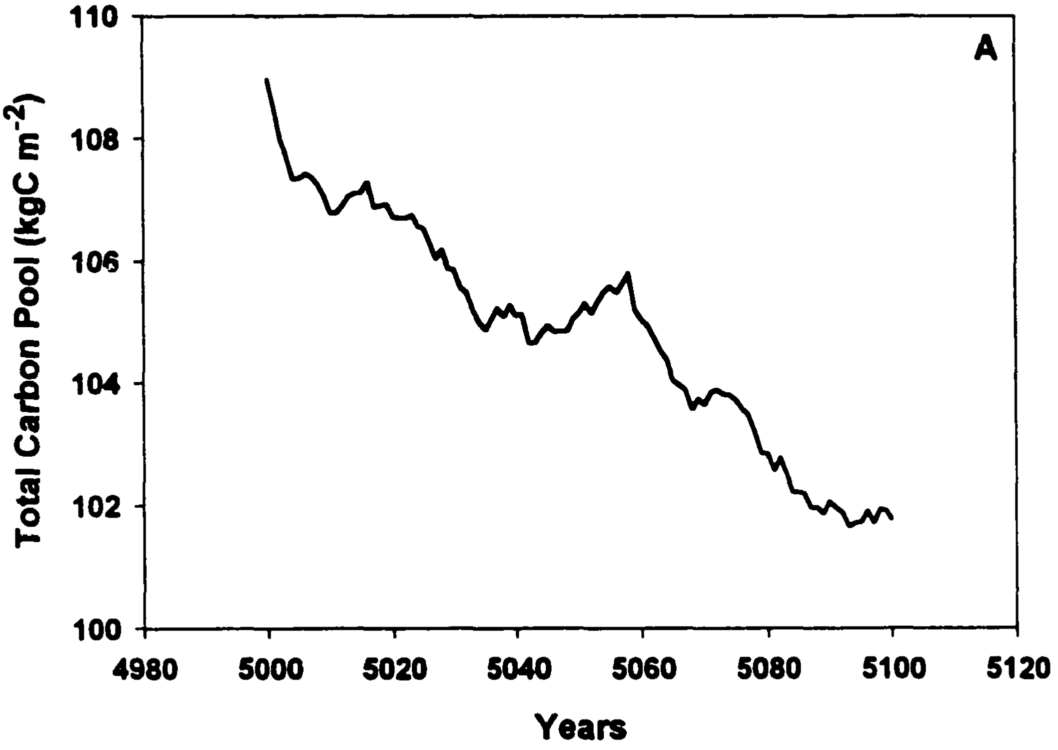

250
200
150
100
50
0
Carbon (kg m^{-2})
0
2000
4000
6000
8000
10000
12000
Years
● Measured
Century

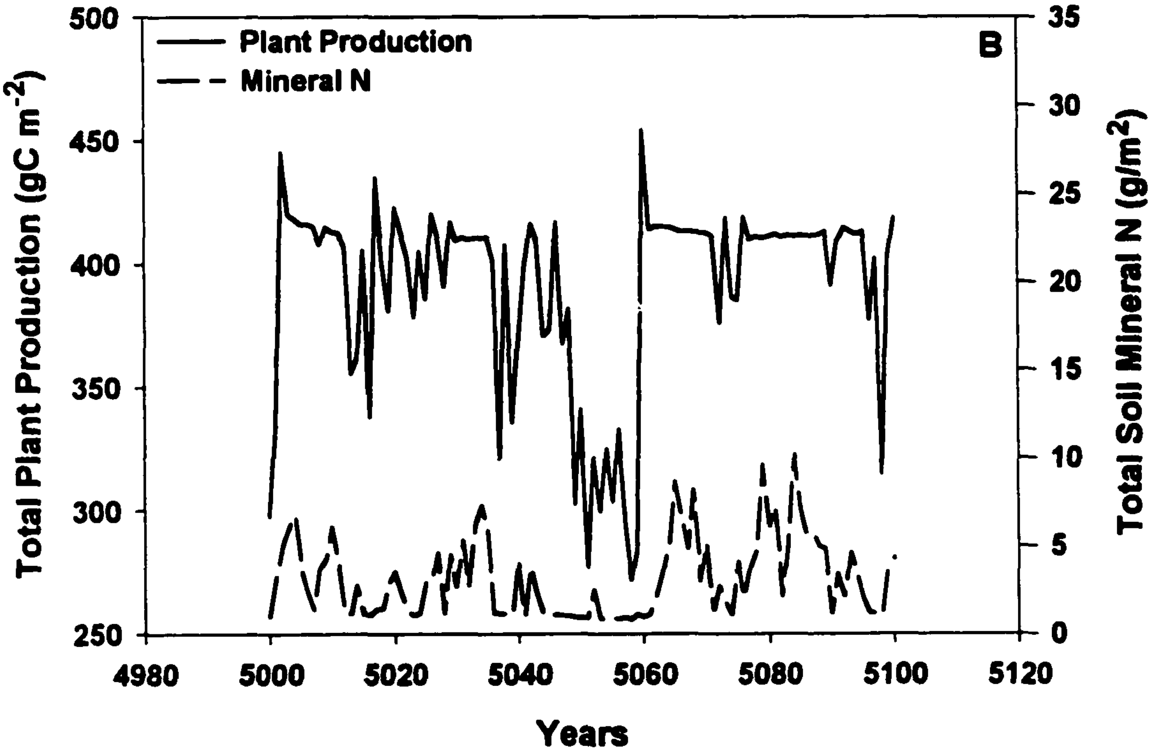

120
100
80
60
40
20
0
Carbon (kg m^{-2})
0
1000
2000
3000
4000
5000
6000
Years
● Measured
—— Century


Measured
Century
Carbon (kg m-2)
300
250
200
150
100
50
0
0
2000
4000
6000
8000
10000
12000
Years


A
Total Soil Carbon (kgC m^{-2})
0
100
200
300
400
500
600
ANEREF(2)
0.6
0.7
0.8
0.9
1.0
1.1
ANEREF(1)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
B
Plant Production (gC m^{-2} yr^{-1})
260
280
300
320
340
360
380
400
ANEREF(2)
0.6
0.7
0.8
0.9
1.0
1.1
ANEREF(1)
0.0
0.1
0.2
0.3
0.4
0.5
0.6


A
Soil Carbon (kg m-2)
140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
12000
Strucc(2)
Som2c
Som3c
B
Soil Carbon (kg m-2)
140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
10000
Strucc(2)
Som2c
Som3c
C
Soil Carbon (kg m-2)
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
Strucc(2)
Som2c
Som3c
Years


A
Total Carbon Pool (kgC m^{-2})
110
108
106
104
102
100
4980
5000
5020
5040
5060
5080
5100
5120
Years


B
Plant Production
Mineral N
Total Plant Production (gC m^{-2})
500
450
400
350
300
250
Total Soil Mineral N (g/m^2)
35
30
25
20
15
10
5
0
4980
5000
5020
5040
5060
5080
5100
5120
Years

Chapter 5

CONCLUSIONS

The quantification of current carbon accumulation rates in pristine peatlands was the first objective in this dissertation. I answered this question in Chapter 2 by calculating carbon budgets for pristine peatlands that have a range of seasonal water table depths and vegetation types. The pristine fens accumulated carbon in years when the water table remained at or above the soil surface for most of the summer. One pristine fen, Green Mountain Pond fen, lost carbon when the water table dropped beneath the surface during the summer. Using hydrologic and plant production data collected since 1986 for Big Meadows and Green Mt. Pond indicates that pristine peatlands are storing carbon on most years, with Green Mt. Pond accumulating carbon during 6 of the 9 years, and Big Meadows on 10 out of the last 12 years. My conclusion is that pristine peatlands in Rocky Mountain National Park, and most likely elsewhere in Colorado, are storing carbon under the current climate regime.

My second objective was to determine whether water diversions by the Grand Ditch decreased carbon storage on peatlands. I answered this question in Chapter 2 by calculating carbon budgets for two fens located below the Grand Ditch and compared them to pristine peatlands in the same area. As with the pristine fens, the peatlands beneath the Grand Ditch accumulated carbon when their water table remained above the soil surface, but became net sources of carbon when the water table dropped beneath the surface during the summer. This analysis indicates that peatlands can be negatively impacted by hydrologic diversions located within, adjacent to, or far from the site of peat accumulation.

The third objective was to document how much the water table must be lowered before significant changes in decomposition rates occur? I quantified this objective in Chapter 3 by experimentally manipulating water tables within independent microcosms to develop statistical relationships between the water table and CO_2, CH_4 and total gaseous carbon ($CO_2 + CH_4$) efflux. I found that CO_2, CH_4 and total gaseous carbon efflux respond significantly to temperature and water table depth when the water table is above the soil surface. However, with the water table beneath the soil surface CO_2 and total carbon efflux nearly doubled, while CH_4 efflux decreased more slowly. In addition, temperature was not a significant factor on efflux rates when the water table was below the soil surface. Lowering the water table to greater depths beneath the soil surface had little additional effect on CO_2, CH_4, and total gaseous carbon efflux. The threshold effect indicates that fens can be highly sensitive to relatively small changes in water table levels.

My fourth objective was to determine how well the CENTURY ecosystem model could be used to simulate long-term carbon accumulation in a fen. Despite the importance of peatlands to the global carbon cycle, they are neglected in modeling, as no peatland model yet exists for use in making predictions of carbon accumulation rates based on environmental changes, such as temperature or hydrology. My analysis indicated that CENTURY could be calibrated for long-term carbon accumulation by altering only three anaerobic variables. However, after calibrating carbon accumulation rates with two fens, CENTURY was unable to properly simulate the carbon accumulation rates in a third uncalibrated peatland. This was likely due to how anaerobic conditions are modeled in

CENTURY. To model peatlands at different sites than calibrated for, CENTURY should be modified to allow anaerobic conditions to be created by high ground water levels instead of the current ratio of rain to PET method. Once calibrated, CENTURY predicted that most of the fen peat stored came from root material, which was easily decomposed when exposed to drying conditions. This analysis demonstrates that an ecosystem model can simulate peatland carbon cycling and is beneficial to understanding the complex interactions that occur in peatlands due to climate change or physical disturbances.

"Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes" (Mitch and Gosselink 2000). Nowhere is the statement more true than in peatland carbon cycling. The hydrologic regime of fens is the key driving force binding the three research chapters in this dissertation together. The results of my dissertation suggest that any variation in water supplied to a peatland, whether by climate variability, human induced ditching, drainage, or reductions in water supply due to diversions, or indirectly by increasing site evapotranspiration rates will significantly alter peatland carbon balances and carbon storage. It also indicates that Southern Rocky Mountain fens are sensitive to small changes in water table levels, which if dropped below the soil surface during the summer can change fens from sinks to sources of atmospheric carbon.

APPENDICES

APPENDIX A

Gas efflux, standard deviations (std) and environmental variables for carbon balance sites from Chapter 2. Site (BM=Big Meadows, CF = Circle Fen, GM=Green Mt. Pond, HF=Hell's Fen and SF=Spring Fen), CO_2 and CH_4 are in mg Cm^{-2} hr^{-1}, air (Air Temp) and soil temperature (Soil) are in Celsius, water table (WT) in cm and reduction-oxidation potential (redox) in millivolts. The number along soil temperature and redox is the soil depth in cm that measurements were taken at.

Site	Date	CO_2	std	CH_4	std	Air Temp	WT	Soil5	Soil10	Soil20	Redox5	Redox10	Redox20
BM	06/08/97	20.4	10.0			11.0	-7.5	9.5	7.0	7.0			
BM	09/14/97	31.1	7.4			14.0	-5.5	11.0	11.0	11.0	-410.0	10.0	-300.0
BM	05/19/98	32.1	50.6	4.3	1.4	17.0	8.5	5.0	4.0	4.0	164.0	194.0	214.0
BM	05/28/98	8.2	1.6	5.5	3.2	16.0	6.5	6.0	6.0	6.0	-6.0	-6.0	-6.0
BM	06/04/98	46.0	24.3	9.8	10.9	4.0	7.0	7.0	6.3	6.3	-56.0	-81.0	-81.0
BM	06/10/98	43.4	9.4	5.5	1.4	11.2	6.5	8.1	6.3	6.1	-81.0	-36.0	-36.0
BM	06/19/98	54.4	55.7	4.1	3.1	17.8	7.0	6.0	3.9	3.5	-116.0	-81.0	-116.0
BM	07/03/98	111.3	47.8	28.3	10.2	23.0	6.2	12.7	12.1	11.8	-156.0	-306.0	-106.0
BM	07/09/98	120.5	56.0	27.4	12.2	12.8	6.0	13.4	11.7	10.7	194.0	19.0	229.0
BM	07/16/98	183.6	42.3	19.6	3.4	21.3	5.5	11.0	10.5	10.5	-116.0	-66.0	14.0
BM	07/30/98	162.9	15.3	24.8	6.1	16.1	6.0	11.4	10.9	11.1	281.0	291.0	293.0
BM	08/06/98	209.9	31.5	18.8	3.7	21.0	5.5	11.5	10.1	10.7	-36.0	-106.0	-6.0
BM	08/20/98	274.0	28.4	20.9	3.7	19.0	5.0	12.4	11.3	11.1	4.0	-26.0	54.0
BM	09/03/98	176.6	42.3	21.9	12.9	22.0	3.5	9.5	9.8	10.3			
BM	09/17/98	219.4	37.6	22.8	6.0	19.3	0.0	9.5	9.0	9.8			
BM	10/08/98	3.5	6.1	1.5	1.4	12.3	3.0	2.2	2.6	3.3			
CF	06/09/97	20.9	0.5			10.0	-0.5	8.0	9.0	9.0			
CF	07/24/97	56.1	47.6			16.0	1.0	14.5	13.5	13.0			
CF	09/13/97	56.7	16.0			17.0	4.5	12.0	10.0	10.0	-345.0	-345.0	-330.0
CF	05/20/98	41.2	16.5	1.7	0.6	17.0	0.0	8.0	6.0	6.0	-156.0	-156.0	-156.0
CF	05/27/98	22.5	4.5	2.5	1.2	16.0	0.0	12.0	9.5	9.5	-66.0	-116.0	-116.0
CF	06/03/98	128.3	46.0	3.9	1.7	18.0	-10.0	14.4	9.9	9.4	-106.0	-181.0	-156.0
CF	06/20/98	138.8	47.1	3.2	1.6	17.5	-1.0	9.1	7.7	7.7	-131.0	-106.0	-106.0
CF	06/24/98	203.2	44.8	5.6	2.2	16.4	-4.5	10.4	9.6	9.0	194.0	194.0	194.0
CF	07/02/98	457.8	6.2	2.2	0.2	23.0	-35.0	17.9	13.0	11.2			
CF	07/08/98	277.2	40.8	2.6	0.4	23.0	-42.0	14.5	13.1	11.6			
CF	07/15/98	288.5	30.7	1.9	0.5	20.8	-48.0	13.6	12.1	12.0			
CF	07/22/98	350.2	29.6	1.5	0.2	18.2	-64.0	14.3	13.0	12.8			

CF	07/29/98	164.5	36.8	2.5	0.4	11.2	-2.5	12.4	12.8	13.1	377.0	328.0	410.0
CF	08/05/98	262.7	37.4	2.6	0.2	17.7	-4.0	14.0	12.1	11.9	144.0	94.0	114.0
CF	08/12/98	145.4	33.4	2.6	0.3	19.6	-8.5	11.8	11.1	12.0			
CF	08/19/98	223.4	16.5	3.0	0.1	18.0	-10.5	13.3	11.6	11.4			
CF	08/28/98	281.8	28.2	1.6	0.3	20.4	-25.0	11.0	10.5	11.3			
CF	09/02/98	224.4	27.3	2.2	0.2	21.3	-21.0	13.3	10.5	10.7			
CF	09/16/98	290.9	25.9	1.5	0.2	19.7	-49.0	12.1	9.8	10.5			
CF	10/07/98	65.1	20.2	0.0	0.0	5.4	1.0	2.8	3.7	4.8			
GM	06/08/97	39.6	20.6			10.5	-12.0	8.5	8.5	8.5			
GM	07/18/97	79.6	32.4			18.0	11.0	11.0	11.0	11.0	400.0	-30.0	-250.0
GM	09/14/97	316.8	122.8			14.0	-0.5	15.0	12.0	11.0	-250.0	-100.0	-330.0
GM	05/19/98	6.6	2.5	0.8	0.2	15.0	13.5	12.0	8.0	8.0	384.0	266.0	344.0
GM	05/28/98	5.4	13.5	0.4	0.2	20.0	12.0	15.0	10.0	10.0	44.0	174.0	-6.0
GM	06/04/98	53.4	46.2	0.8	0.4	2.1	10.0	12.4	11.6	11.4	244.0	384.0	269.0
GM	06/10/98	44.5	45.1	0.5	0.1	7.8	10.0	9.0	9.8	9.9			
GM	06/19/98	62.5	26.9	0.4	0.1	16.6	11.5	9.5	7.0	7.0	269.0	269.0	304.0
GM	07/03/98	88.0	50.2	0.9	0.1	19.8	4.0	18.3	15.3	13.0	-31.0	-56.0	-156.0
GM	07/09/98	66.8	29.1	1.1	0.3	13.2	3.0	15.0	13.0	12.1	6.0	114.0	184.0
GM	07/16/98	173.2	44.1	1.4	0.3	26.5	1.0	19.4	14.7	13.0	584.0	514.0	314.0
GM	07/30/98	59.8	20.1	1.2	0.5	11.8	9.0	14.2	13.0	12.7	444.0	395.0	336.0
GM	08/06/98	119.2	34.7	1.6	0.7	22.5	8.5	15.7	13.3	13.3	-136.0	-56.0	-106.0
GM	08/20/98	91.0	49.3	2.3	0.5	18.1	7.5	15.4	13.9	13.1	4.0	69.0	184.0
GM	09/03/98	91.9	27.7	2.3	1.6	22.6	5.5	13.0	11.8	12.1			
GM	09/17/98	91.9	33.0	2.3	0.9	20.6	0.0	13.1	10.6	10.6			
GM	10/08/98	2.5	3.1	0.4	0.0	14.3	5.5	3.0	2.3	3.3			
HF	06/09/97	19.1	0.1			10.0	-3.0	8.5	7.0	6.0			
HF	07/24/97	46.2	8.2			18.0	-3.0	15.0	15.0	13.5			
HF	09/13/97	133.9	17.0			19.0	-2.0	20.0	14.0	13.0	-320.0	-260.0	-285.0
HF	05/20/98	12.9	10.5	3.5	1.0	15.0	3.0	12.0	7.0	7.0	-6.0	-6.0	-6.0
HF	05/27/98	43.3	3.6	2.6	1.2	19.0	3.0	15.0	9.0	9.0	-31.0	-56.0	-81.0
HF	06/03/98	99.1	8.7	4.3	2.8	20.1	3.0	18.5	13.1	10.5	-106.0	-56.0	94.0
HF	06/20/98	53.0	14.5	0.7	0.2	13.0	3.5	9.4	8.3	8.9	-36.0	-26.0	-56.0
HF	06/24/98	82.0	25.1	1.7	0.4	18.2	4.0	11.9	10.3	10.3	-56.0	94.0	-56.0
HF	07/02/98	68.5	34.9	3.8	2.1	23.0	4.0	16.3	14.3	13.7	44.0	94.0	-6.0
HF	07/08/98	60.7	35.4	7.7	4.4	18.3	4.0	17.7	15.7	13.2	-6.0	64.0	219.0
HF	07/15/98	76.0	16.9	7.5	2.3	22.6	4.0	16.4	14.4	13.9	-76.0	77.0	-31.0
HF	07/22/98	92.0	30.1	15.5	5.3	17.0	4.0	15.2	14.6	15.2	154.0	94.0	-31.0
HF	07/29/98	91.8	20.8	13.1	3.7	13.4	4.0	13.5	13.4	13.7			
HF	08/05/98	170.3	46.7	6.5	0.8	15.7	3.5	13.4	12.6	13.1	144.0	-26.0	-16.0
HF	08/12/98	122.4	22.6	8.5	2.6	20.2	3.5	15.7	13.0	13.3	-6.0	64.0	-136.0
HF	08/19/98	154.6	31.0	17.8	11.8	22.0	3.0	13.9	12.1	13.3	160.0	64.0	-118.0
HF	08/28/98	120.9	20.0	5.1	1.2	24.5	3.5	12.4	12.3	13.4			
HF	09/02/98	96.8	11.6	8.9	0.8	18.2	3.5	12.4	12.3	13.4			
HF	09/09/98	75.5	7.0	3.1	1.7	20.5	3.0	17.4	15.1	13.5			
HF	09/16/98	76.2	18.0	0.8	0.2	19.3	3.0	16.4	12.7	12.1			
HF	10/07/98	13.6	4.2	1.1	0.4	8.1	3.5	5.0	2.9	4.0			
SF	06/24/97	112.0	101.2			13.0	-3.5	19.5	15.0	13.5	-70.0	130.0	90.0
SF	07/18/97	77.7	8.6			24.0	-3.0	19.0	16.0	14.0	120.0	-15.0	-270.0
SF	09/14/97	46.2	12.7			14.0	-3.5	10.0	10.0	10.0	-270.0	-10.0	-320.0
SF	05/28/98	74.3	4.8	5.5	0.9	17.0	-1.5	8.0	7.0	6.5	14.0	194.0	19.0
SF	06/04/98	67.4	8.8	4.0	0.5	8.8	2.0	8.3	8.0	8.2	-56.0	144.0	-36.0

SF	06/10/98	54.8	19.9	2.0	0.3	11.7	2.0	9.0	7.5	7.6	-281.0	-106.0	-281.0
SF	06/19/98	83.8	19.8	1.4	0.3	10.9	2.5	5.2	3.9	4.7	194.0	219.0	-56.0
SF	07/03/98	118.4	27.9	3.0	0.9	20.6	2.4	14.2	14.3	14.2	-31.0	109.0	-106.0
SF	07/09/98	96.6	3.9	7.1	3.0	18.5	2.0	15.0	13.3	13.0	6.0	179.0	-86.0
SF	07/16/98	146.6	17.4	10.1	1.7	19.1	1.0	15.2	13.0	13.4	319.0	474.0	274.0
SF	07/30/98	110.9	11.9	14.3	3.4	13.2	2.0	13.0	13.1	13.1	300.0	299.0	295.0
SF	08/06/98	175.1	8.5	7.5	0.4	13.1	2.5	12.0	12.1	13.2	-6.0	199.0	-56.0
SF	08/20/98	238.0	26.5	7.9	1.6	19.0	2.0	13.3	13.0	13.0	-36.0	-86.0	-186.0
SF	09/03/98	129.4	42.4	5.2	0.5	14.5	1.5	9.3	9.8	11.2			
SF	09/17/98	116.3	11.1	3.2	0.2	12.0	-5.0	7.7	8.6	9.7			
SF	10/08/98	29.9	11.1	1.7	0.7	9.8	2.0	2.0	2.4	3.2			

APPENDIX B

Gas efflux, standard deviations (std) and environmental variables for control microcosms in Moose fen from Chapter 3. Uncut = Uncut-control and Cut=Cut-control, CO_2 and CH_4 are in mg Cm^{-2} hr^{-1}, air (Air Temp) and soil temperature (Soil) are in Celsius and water table (WT) in cm. The number along soil temperature is the soil depth in cm that the measurements were taken at.

Controls	date	CO_2	std	CH_4	std	Air Temp	WT	Soil5	Soil20
Uncut	6/11/98	115.9	13.2	4.5	2.0	11.5	-10.1	6.3	6.0
Uncut	6/20/98	108.0	33.1	4.0	2.0	17.5	-11.1	6.6	6.2
Uncut	6/24/98	132.2	33.0	11.0	3.6	21.0	-10.0	7.6	6.9
Uncut	7/2/98	255.6	29.5	8.3	2.3	26.0	7.1	12.3	9.2
Uncut	7/8/98	193.5	28.8	24.4	12.1	23.0	-6.4	11.4	10.3
Uncut	7/15/98	171.3	4.8	11.8	2.3	22.4	-1.0	14.5	10.5
Uncut	7/23/98	283.2	116.7	19.1	14.4	13.4	-0.5	12.1	11.7
Uncut	8/5/98	273.8	34.8	78.8	9.6	20.3	-2.5	13.3	10.5
Uncut	8/12/98	109.9	9.9	65.7	77.1	18.7	-2.0	12.2	10.2
Uncut	8/19/98	146.8	39.5	52.5	40.5	23.0	-2.0	13.1	10.8
Uncut	9/2/98	90.2	24.6			23.0	-1.0	11.7	10.2
Uncut	6/2/99	18.5	6.5	2.6	0.8	21.0	-10.0	6.0	5.0
Uncut	6/13/99	103.1	36.0	5.0	2.0	25.0	-10.0	8.2	8.2
Uncut	6/18/99	95.1	37.8	5.8	2.3	20.5	-8.0	10.2	8.6
Uncut	6/24/99	255.3	59.1	11.4	3.5	20.0	-5.0	11.2	9.7
Uncut	7/1/99	244.2	48.0	13.0	14.2	22.0	-1.0	10.4	9.5
Uncut	7/6/99			72.9	82.3	24.0	-2.0	12.5	10.1
Uncut	7/9/99	476.7	115.8	15.7	6.9	20.0	0.0	13.5	10.0
Uncut	7/13/99	293.8	73.0	25.6	14.9	23.0	0.0	12.4	10.5
Uncut	7/23/99	180.0	54.3	54.9	23.8	23.0	-8.0	11.5	10.9
Uncut	7/27/99	285.0	45.6	45.6	38.6	22.0	-5.0	12.3	11.3
Uncut	8/7/99	296.4	78.4	49.7	40.9	15.0	-4.0	10.9	11.0
Uncut	8/18/99	196.7	73.9	59.3	74.5	20.0	-2.0	10.4	10.2
Uncut	8/26/99	226.0	25.7	29.5	19.5	20.0	-3.0	10.5	10.4
Uncut	9/1/99	155.8	29.4	66.6	69.2	15.0	-5.0	9.4	10.0
Cut	7/15/98	116.6	12.0	118.4	73.7	22.4	-1.0	14.5	10.5
Cut	7/23/98	162.8	43.0	169.8	74.5	18.7	-2.0	12.1	11.7
Cut	8/3/98	167.2	51.3	238.1	130.9	15.1	-1.5	12.1	11.7
Cut	8/5/98	251.0	94.6	238.7	96.7	20.3	-2.0	13.3	10.5
Cut	8/12/98			159.3	160.5	16.5	-1.5	10.1	10.2

Cut	8/19/98	222.5	99.0			23.0	-2.0	13.1	10.8
Cut	9/2/98	212.7	15.7			23.0	-1.0	11.7	10.2
Cut	6/2/99	26.8	9.8	28.8	14.5	20.5	-10.0	6.0	5.0
Cut	6/13/99	177.6	50.6	189.5	239.7	25.0	-10.0	8.2	8.2
Cut	6/18/99	131.6	28.3	120.1	104.9	20.5	-8.0	10.2	8.6
Cut	6/24/99	278.4	1.2	181.9	135.3	20.0	-5.0	11.2	9.7
Cut	7/1/99	327.6	138.1	417.0	35.3	22.0	-4.0	10.4	9.5
Cut	7/6/99	184.7	70.0	591.6	278.1	24.0	-3.0	12.5	10.1
Cut	7/9/99	484.6	58.2	366.4	119.4	20.0	-3.0	13.5	10.0
Cut	7/13/99	351.8	194.2	515.6	229.4	23.0	-3.0	12.4	10.5
Cut	7/23/99	244.8	34.6	170.6	113.5	23.0	-8.0	11.5	10.9
Cut	7/27/99	274.3	115.3	532.8	284.9	22.0	-7.0	12.3	11.3
Cut	8/7/99	195.4	25.4	242.9	169.8	15.0	-8.0	10.9	11.0
Cut	8/18/99	226.8	58.3	614.3	275.5	20.0	-6.0	10.4	10.2
Cut	8/26/99	147.6	10.2	158.4	147.9	20.0	-6.0	10.5	10.4
Cut	9/1/99	92.5	24.5	73.7	42.2	15.0	-7.0	9.4	10.0

APPENDIX C

Gas efflux and environmental variables for treatment microcosms in Moose Fen from Chapter 3. CO_2 and CH_4 are in mg Cm^{-2} hr^{-1}, air (Air Temp) and soil temperature (Soil) are in Celsius and water table (WT) in cm. The number along soil temperature is the soil depth in cm that the measurements were taken at.

Date	CO_2	CH_4	Air Temp	WT	Soil5	Soil20
7/15/98	122.7	135.9	22.4	1.0	12.1	10.5
7/15/98	102.8	181.9	22.4	1.0	12.1	10.5
7/15/98	124.4	37.5	22.4	1.0	12.1	10.5
7/23/98	192.7	255.5	18.7	2.0	12.1	11.7
7/23/98	182.3	132.5	18.7	2.0	12.1	11.7
7/23/98	113.6	121.3	18.7	2.0	12.1	11.7
7/23/98	101.5	333.8	18.7	1.0	12.1	11.7
7/23/98	185.7	162.4	18.7	3.0	12.1	11.7
7/23/98	138.7	116.1	18.7	1.5	12.1	11.7
7/23/98	216.4	99.9	18.7	4.0	12.1	11.7
7/23/98	214.7	401.1	18.7	1.0	12.1	11.7
7/23/98	127.9	53.8	18.7	3.0	12.1	11.7
8/3/98	190.1	87.1	15.1	1.5	12.1	11.7
8/3/98	108.4	318.3	15.1	1.5	12.1	11.7
8/3/98	203.0	308.8	15.1	1.5	12.1	11.7
8/3/98	165.4	220.7	15.1	6.0	12.1	11.7
8/3/98	101.1	97.6	15.1	6.0	12.1	11.7
8/3/98	174.1	390.3	15.1	4.0	12.1	11.7
8/3/98	69.5	-115.5	15.1	2.0	12.1	11.7
8/3/98	164.1	265.3	15.1	2.0	12.1	11.7
8/3/98	111.4	130.6	15.1	2.0	12.1	11.7
8/5/98	271.7	213.2	20.3	2.0	13.3	10.5
8/5/98	333.5	157.2	20.3	2.0	13.3	10.5
8/5/98	147.7	345.6	20.3	1.0	13.3	10.5
8/5/98	92.0	49.5	20.3	6.0	13.3	10.5
8/5/98	102.8	71.0	20.3	6.0	13.3	10.5
8/5/98	152.9	81.0	20.3	4.0	13.3	10.5
8/5/98	362.0	29.7	20.3	-20.0	13.3	10.5
8/5/98	350.3	248.4	20.3	-20.0	13.3	10.5
8/5/98	295.0	94.6	20.3	-20.0	13.3	10.5
8/12/98		78.7	16.5	1.5	10.1	10.2
8/12/98		344.1	16.5	3.0	10.1	10.2
8/12/98		55.1	16.5	1.0	10.1	10.2

8/12/98		6.4	16.5	8.0	10.1	10.2
8/12/98		218.1	16.5	5.0	10.1	10.2
8/12/98		159.8	16.5	8.0	10.1	10.2
8/12/98		33.0	16.5	-35.0	10.1	10.2
8/12/98		144.0	16.5	-5.0	10.1	10.2
8/12/98		23.5	16.5	-10.0	10.1	10.2
8/19/98	333.0		23.0	2.0	13.1	10.8
8/19/98	192.2		23.0	1.0	13.1	10.8
8/19/98	142.1		23.0	1.0	13.1	10.8
8/19/98	200.0		23.0	3.0	13.1	10.8
8/19/98	132.2		23.0	5.0	13.1	10.8
8/19/98	187.9		23.0	4.0	13.1	10.8
8/19/98	281.6		23.0	-35.0	13.1	10.8
8/19/98	491.1		23.0	-5.0	13.1	10.8
8/19/98	281.6		23.0	-10.0	13.1	10.8
9/2/98	230.8		23.0	1.0	11.7	10.2
9/2/98	204.7		23.0	2.0	11.7	10.2
9/2/98	202.6		23.0	1.0	11.7	10.2
9/2/98	130.7		23.0	3.0	11.7	10.2
9/2/98	172.6		23.0	5.0	11.7	10.2
9/2/98	253.5		23.0	6.0	11.7	10.2
9/2/98	321.4		23.0	-35.0	11.7	10.2
9/2/98	215.2		23.0	-5.0	11.7	10.2
9/2/98	367.3		23.0	-10.0	11.7	10.2
6/2/99	35.5	36.3	20.5	10.0	9.5	5.0
6/2/99	16.2	37.9	20.5	10.0	9.5	5.0
6/2/99	28.8	12.0	20.5	10.0	9.5	5.0
6/2/99	44.6	34.0	20.5	10.0	9.5	5.0
6/2/99	56.2	4.6	20.5	10.0	9.5	5.0
6/2/99	52.4	52.0	20.5	10.0	9.5	5.0
6/2/99	29.0	7.0	20.5	10.0	9.5	5.0
6/2/99	27.1	38.2	20.5	10.0	9.5	5.0
6/2/99	20.2	3.4	20.5	10.0	9.5	5.0
6/13/99	213.4	28.0	25.0	10.0	9.1	8.2
6/13/99	141.8	75.5	25.0	10.0	9.1	8.2
6/13/99		464.9	25.0	10.0	9.1	8.2
6/13/99	82.1	30.4	25.0	10.0	9.1	8.2
6/13/99		9.8	25.0	10.0	9.1	8.2
6/13/99	169.2	78.9	25.0	10.0	9.1	8.2
6/13/99	81.7	10.9	25.0	10.0	9.1	8.2
6/13/99	102.5	31.5	25.0	10.0	9.1	8.2
6/13/99		41.9	25.0	10.0	9.1	8.2
6/18/99	103.7	234.5	20.5	8.0	10.2	8.6
6/18/99	130.9	28.5	20.5	8.0	10.2	8.6
6/18/99	160.3	97.2	20.5	6.0	10.2	8.6
6/18/99	413.4	22.4	20.5	-35.0	10.2	8.6
6/18/99	354.2	18.5	20.5	-20.0	10.2	8.6
6/18/99			20.5	0.0	10.2	8.6
6/18/99			20.5	-5.0	10.2	8.6
6/18/99	263.5	82.3	20.5	-5.0	10.2	8.6
6/18/99			20.5	-5.0	10.2	8.6

6/24/99	279.5	272.9	20.0	5.0	11.9	9.3
6/24/99	278.6	246.4	20.0	7.0	11.9	9.3
6/24/99	277.1	26.4	20.0	3.0	11.9	9.3
6/24/99	535.2	10.0	20.0	-35.0	11.9	9.3
6/24/99	387.1	10.7	20.0	-10.0	11.9	9.3
6/24/99	1028.6	7.3	20.0	-15.0	11.9	9.3
6/24/99	221.2	19.7	20.0	-40.0	11.9	9.3
6/24/99	761.6	14.9	20.0	-10.0	11.9	9.3
6/24/99	329.2	28.1	20.0	-40.0	11.9	9.3
7/1/99	300.2	457.6	22.0	4.0	10.9	9.7
7/1/99	205.2	401.0	22.0	5.0	10.9	9.7
7/1/99	477.4	392.6	22.0	0.0	10.9	9.7
7/1/99	470.0	12.8	22.0	-35.0	10.9	9.7
7/1/99	624.2	6.7	22.0	-10.0	10.9	9.7
7/1/99	451.9	31.1	22.0	-10.0	10.9	9.7
7/1/99	470.0	2.4	22.0	-35.0	10.9	9.7
7/1/99	287.3	141.0	22.0	-5.0	10.9	9.7
7/1/99	655.8	23.5	22.0	-5.0	10.9	9.7
7/6/99	234.1	297.1	24.0	3.0	12.6	10.4
7/6/99	135.2	849.6	24.0	3.0	12.6	10.4
7/6/99		628.1	24.0	1.0	12.6	10.4
7/6/99	307.2	-5.3	24.0	-35.0	12.6	10.4
7/6/99		11.3	24.0	0.0	12.6	10.4
7/6/99	344.3	20.3	24.0	-10.0	12.6	10.4
7/6/99		3.7	24.0	-35.0	12.6	10.4
7/6/99	238.9	350.7	24.0	-2.0	12.6	10.4
7/6/99		184.5	24.0	-5.0	12.6	10.4
7/9/99	441.5	332.5	20.0	3.0	13.5	10.0
7/9/99	461.4	499.0	20.0	3.0	13.5	10.0
7/9/99	550.8	267.6	20.0	0.0	13.5	10.0
7/9/99	453.2	12.9	20.0	-5.0	13.5	10.0
7/9/99	505.9	14.5	20.0	-2.0	13.5	10.0
7/9/99	589.7	-7.7	20.0	-5.0	13.5	10.0
7/9/99	397.4	3.1	20.0	-1.0	13.5	10.0
7/9/99	429.0	152.7	20.0	0.0	13.5	10.0
7/9/99	707.6	96.5	20.0	-2.0	13.5	10.0
7/13/99	299.4	410.8	23.0	3.0	12.4	10.5
7/13/99	189.2	357.4	23.0	2.0	12.4	10.5
7/13/99	566.8	778.7	23.0	0.0	12.4	10.5
7/13/99	393.6	25.3	23.0	-25.0	12.4	10.5
7/13/99	368.5	7.4	23.0	-5.0	12.4	10.5
7/13/99	385.3	29.8	23.0	-20.0	12.4	10.5
7/13/99	347.3	9.0	23.0	-20.0	12.4	10.5
7/13/99	740.4	0.7	23.0	-8.0	12.4	10.5
7/13/99	489.0	5.0	23.0	-10.0	12.4	10.5
7/23/99	226.8	117.0	23.0	8.0	11.5	10.9
7/23/99	222.9	93.9	23.0	8.0	11.5	10.9
7/23/99	284.7	301.0	23.0	6.0	11.5	10.9
7/23/99	601.8	-80.0	23.0	-25.0	11.5	10.9
7/23/99	416.9	13.5	23.0	-11.0	11.5	10.9
7/23/99	445.4	60.7	23.0	-25.0	11.5	10.9

7/23/99	476.5	3.6	23.0	-12.0	11.5	10.9
7/23/99	331.3	19.4	23.0	-2.0	11.5	10.9
7/23/99	482.1	7.3	23.0	-14.0	11.5	10.9
7/27/99	197.9	403.0	22.0	7.0	12.3	11.3
7/27/99	218.2	859.4	22.0	7.0	12.3	11.3
7/27/99	406.9	335.9	22.0	4.0	12.3	11.3
7/27/99	600.9	5.5	22.0	-35.0	12.3	11.3
7/27/99	575.0	38.0	22.0	-2.0	12.3	11.3
7/27/99	530.1	45.6	22.0	-10.0	12.3	11.3
7/27/99	295.1	27.8	22.0	-5.0	12.3	11.3
7/27/99	935.3	49.8	22.0	0.0	12.3	11.3
7/27/99	776.7	76.5	22.0	-3.0	12.3	11.3
8/7/99	168.8	215.1	15.0	8.0	10.9	11.0
8/7/99	198.3	88.8	15.0	7.0	10.9	11.0
8/7/99	219.2	425.0	15.0	5.0	10.9	11.0
8/7/99	432.8	3.5	15.0	-15.0	10.9	11.0
8/7/99	379.8	7.2	15.0	-10.0	10.9	11.0
8/7/99	440.6		15.0	-13.0	10.9	11.0
8/7/99	397.9	8.2	15.0	-18.0	10.9	11.0
8/7/99	242.5	286.9	15.0	0.0	10.9	11.0
8/7/99	483.2	109.4	15.0	-25.0	10.9	11.0
8/18/99	225.1	912.4	20.0	6.0	10.4	10.2
8/18/99	169.3	369.2	20.0	5.0	10.4	10.2
8/18/99	285.9	561.3	20.0	1.0	10.4	10.2
8/18/99	285.8	62.4	20.0	-10.0	10.4	10.2
8/18/99	312.2	41.1	20.0	-12.0	10.4	10.2
8/18/99	560.1	85.9	20.0	-2.0	10.4	10.2
8/18/99	229.2	12.6	20.0	-12.0	10.4	10.2
8/18/99	476.2	126.7	20.0	-15.0	10.4	10.2
8/18/99	399.6	42.4	20.0	-15.0	10.4	10.2
8/26/99	140.4	6.6	20.0	6.0	10.5	10.4
8/26/99	154.9	166.6	20.0	6.0	10.5	10.4
8/26/99		302.1	20.0	4.0	10.5	10.4
8/26/99	108.2	44.4	20.0	6.0	10.5	10.4
8/26/99	179.5	5.0	20.0	8.0	10.5	10.4
8/26/99	146.8	22.9	20.0	6.0	10.5	10.4
8/26/99	120.5	2.7	20.0	7.0	10.5	10.4
8/26/99	82.7	71.7	20.0	7.0	10.5	10.4
8/26/99	143.4	10.3	20.0	7.0	10.5	10.4
9/1/99	65.5	31.6	15.0	7.0	9.4	10.0
9/1/99	113.2	73.6	15.0	7.0	9.4	10.0
9/1/99	98.9	116.0	15.0	6.0	9.4	10.0
9/1/99	89.6	53.1	15.0	9.0	9.4	10.0
9/1/99	116.2	28.7	15.0	9.0	9.4	10.0
9/1/99	118.6	96.4	15.0	9.0	9.4	10.0
9/1/99	96.1	30.2	15.0	7.0	9.4	10.0
9/1/99	65.0	137.5	15.0	9.0	9.4	10.0
9/1/99	111.1	105.4	15.0	9.0	9.4	10.0