GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 12, NO. 4, PAGES 715–727, DECEMBER 1998

A stochastic appraisal of the annual carbon budget of a large circumboreal peatland, Rapid River Watershed, northern Minnesota

J. S. Rivers,[1] D. I. Siegel,[1] L. S. Chasar,[2] J. P. Chanton,[2] P. H. Glaser,[3] N. T. Roulet,[4] and J. M. McKenzie[1]

Abstract. The probable limits of the carbon budget of the Rapid River Watershed, within the greater Glacial Lake Agassiz Peatland in northern Minnesota, were evaluated using a Monte Carlo simulation approach. Carbon enters the peatlands in groundwater, precipitation, and primary productivity. Carbon leaves the peatlands by groundwater and surface water outflow and by the outgassing of methane. Results of the simulations of the carbon budget show that the peatland is now probably a sink for carbon, supported by field data showing peat is, in fact, accumulating at the rate of about 1 mm yr^{-1} [*Glaser et al.*, 1997]. Excluding extreme values, Monte Carlo simulation results indicate that the Rapid River Peatland stores between –28.98 g C m^{-2} yr^{-1} (release) and 50.38 g C m^{-2} yr^{-1} (storage) with a mean accumulation of 12.74 g C m^{-2} yr^{-1} over the 1,506,200 m^2 watershed. The peatland appears to be delicately poised with respect to net gain or loss of carbon.

1. Introduction

There is an imbalance in the global carbon budget of about 20% [*Schimel*, 1995, 1998]. Despite extensive research on global sources, sinks, and residence times of carbon in the environment [*Charman et al.*, 1994; *Joos*, 1994; *Carol and Crill*, 1997; *Clymo et al.*, 1998], global mathematical carbon balances have failed largely because of uncertainties in how carbon dioxide partitions temporally and spatially among terrestrial, ocean, and atmospheric systems [*Gillis*, 1991]. For example, the modern oceans are now a net CO_2 sink, whereas the oceans were previously a gradual source for carbon to the atmosphere during the last deglaciation [*Sundquist*, 1993]. The deglacial CO_2 budget is a complex interaction of long-term dynamic behavior which is not adequately addressed by current mathematical models used to forecast future atmospheric CO_2 levels.

Atmospheric and ocean modeling [*Tans et al.*, 1990; *Sarmiento and Siegenthaler*, 1992], isotopic tracer studies [*Ciais et al.*, 1995; *Clymo et al.*, 1998; *Francois and Walker*, 1992], and the annual cycle of the ratios of atmospheric CO_2 and O_2 to N [*Keeling et al.*, 1996] all indicate that there is a carbon sink in the boreal and temperate forest regions. Boreal peatlands were past sinks for CO_2 of the order of 0.1 to 0.3 Gt C yr^{-1} [*Gorham*, 1991; *Gorham et al.*, 1995], an amount equivalent to between 10 and 30% of the current imbalance. It is difficult, however, to determine whether peatlands are contemporary sinks for CO_2. Measurements of carbon inputs and outputs from peatlands suggest [*Shurpali et al.*, 1993, 1995; *Whiting*, 1994; *Neumann et al.*, 1994; *Waddington and Roulet*, 1996] that they can be both sources and sinks, depending on the year and where in a peatland the measurements are made.

Given how difficult it is to quantify the role of peatlands in global carbon cycling, several global models omit peatlands entirely from their analyses [*Melillo et al.*, 1994], even though they probably represent a significant component of the terrestrial productivity. A contemporary multiyear, spatially integrated, continuous measurement of all input and output variables is required to clearly assess carbon cycling in large peatlands, but no such integrated measurements exist.

In this paper, we use a stochastic approach to modeling the carbon balance of a large peatland to assess probability for this type of ecosystem to be a source or sink given the data constraints that currently exist. We present calculations of an annual carbon budget for part of the large circumboreal Glacial Lake Agassiz Peatland, the ecology, hydrology, and geochemistry of which has been studied for over 20 years [e.g., *Heinselman*, 1963, 1970; *Eng*, 1980; *Glaser et al.*, 1981; *Siegel*, 1981; *Glaser*, 1987b; *Siegel*, 1982, 1983; *Almendinger et al.*, 1986; *Chason and Siegel*, 1986; *Siegel and Glaser*, 1987; *Siegel et al.*, 1990, 1991; *Romanowicz et al.*, 1993, 1995]. Although carbon budgets have been calculated for small wetlands in local depressions in the landscape [*Carroll and Crill*, 1997; *Waddington and Roulet*, 1997], this paper is an attempt to quantify the probable range in the parts of a carbon budget in a peatland type and at a scale commensurate to address issues related to climate change.

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[1] Department of Earth Sciences, Syracuse University, Syracuse, NY.

[2] Department of Oceanography, Florida State University, Talahasee.

[3] Limnological Research Center, University of Minnesota, Minneapolis.

[4] Department of Geography, McGill University, Montreal, Canada.

Paper number 98GB02636.
0886-6236/98/98GB-02636$12.00

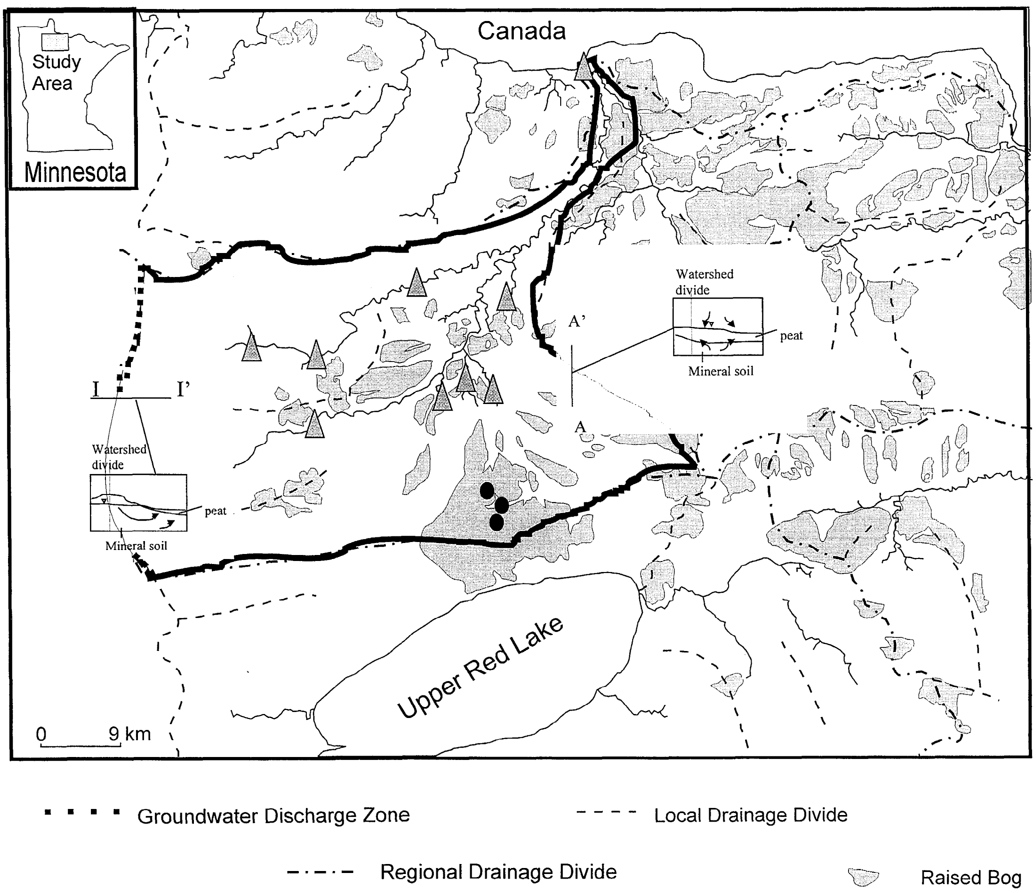

Figure 1. Map of the Glacial Lake Agassiz Peatland. The Rapid River Watershed is designated by bold lines. Three circles represent the sampling sites for net ecosystem exchange (NEE) measurements. Triangles represent areas where the Rapid River was sampled for dissolved inorganic carbon and dissolved organic carbon.

2. Study Area

The Glacial Lake Agassiz Peatland complex, located in northern Minnesota, may be the most studied large peatland in circumboreal regions. It extends intermittently over 950,000 km^2 into Manitoba [*Clayton*, 1983] and occupies the former lake bed of Glacial Lake Agassiz of late Wisconsin time. Our 1,506,200 m^2 study area, the Rapid River Watershed of the Peatland complex (Figure 1), is covered by approximately 50% peatlands [Glaser, 1992] consisting of large, patterned, raised bogs and fens, with the remaining 50% consisting of mineral soil. The region is dominated by a nearly flat lake plain, which has a gradient of less than 20 cm km^{-1} [*Wright*, 1972].

Bog vegetation consists of an overstory of stunted *Picea mariana* and *Larix laricinia* radiating from bog centers; an understory of *Ledum groenlandicum*, *Andromeda glaucophylla*, and *Chamaedaphne calyculata*; and ground cover consisting of *Sphagnum* mosses including *Drosera* spp. and *Sarracinia* spp. [*Glaser et al.*, 1990]. Fen vegetation is dominated by *Carex oligosperma*, *Scirpus cespitosus*, and *Rhyncospora alba*, with ombrotrophic pools containing *Nuphar variegatum* and *Menyanthes trifoliata*.

The peatlands are underlain by 60 to 100 m thick deposits of calcareous silt and clay lake sediments [*Heinselman*, 1963; *Glaser*, 1987a] and glacial drift [*Siegel*, 1981]. The surficial deposits are, in turn, underlain by Proterozoic granites, metasedimentary rocks, and isolated Cretaceous shales [*Siegel*, 1981]. Sand and gravel beach ridges 4 to 5 m high and about 150 m wide mark the positions of retreating proglacial lake shores, trending east to west across the peatland [*Eng*, 1980]. Regional groundwater flow to the peatland discharges to the Red Lakes and to rivers that flow to the Rainy River to the north [*Bidwell et al.*, 1970; *Lindholm et al.*, 1976].

The climate of this region is unusually dry to maintain extensive peat cover with true raised bogs [*Baker et al.*, 1967; *Siegel et al.*, 1996]. Evapotranspiration increases from east to west from 38 to 51 cm yr^{-1} [*Baker et al.*, 1979]. Extreme multiyear droughts have occurred in the peatland [*Romanowicz et al.*, 1993], several within the past century.

The distinctive vegetation patterns in the peatlands are a product of sensitive feedback systems that involve vegetation processes, carbon flux, and hydrology [*Glaser*, 1987b, 1992]. Vegetation landforms are closely related to groundwater flow systems, so much so that vegetation may be used to detect the location and distribution of groundwater discharge zones [*Siegel and Glaser*, 1987; *Glaser*, 1987a] and changes in surface water chemistry. Prominent beach ridges may be connected to raised bogs downslope by buried sand lenses, which are confined by thick layers of silt and clay [*Boldt*, 1986]. Dramatic changes in water table elevation and groundwater flow system dynamics may be caused by even short seasonal fluctuations in climate [*Romanowicz et al.*, 1993, 1995; *Siegel et al.*, 1996]. Despite the dry climate, carbon is accumulating in bogs and fens in the peatland at approximately 1 mm yr^{-1} [*Glaser et al.*, 1997] although they also emit anomalously high amounts of CO_2 and CH_4 compared to other large peatlands [*Harriss et al.*, 1985; *Crill*, 1991; *Crill et al.*, 1988; *Whiting and Chanton*, 1993; *Chanton et al.*, 1993].

Computer simulations of groundwater flow suggest that bogs in the peatlands replenish local groundwater flow systems, whereas fens are the discharge zones for both local and regional flow systems [*Siegel*, 1983]. However, detailed field studies of hydraulic head and peat pore water chemistry show that hydrogeological settings of bogs in the peatland can reverse seasonally from recharge to discharge [*Siegel and Glaser*, 1987; *Siegel et al.*, 1990; *Romanowicz et al.*, 1993; *Siegel et al.*, 1996]. Reversals in the vertical hydraulic gradient in bogs may be common throughout Glacial Lake Agassiz Peatlands. For example, during a drought in 1990, groundwater flowed upward under all major raised bogs; conversely, when the drought broke in 1991, groundwater flowed downward [*Siegel et al.*, 1990, 1991; *Romanowicz et al.*, 1993]. The dynamic state of groundwater flow within these peatlands makes it difficult to quantify.

The Rapid River Watershed study area within the Glacial Lake Agassiz Peatlands is located approximately 5 km north of Upper Red Lake and extends for 1,506,200 m^2. Roughly 50% of this watershed is covered with peat (12.5% bog and 37.5% fen), and 50% is mineral soil. It is bounded to the south, west, and east by regional drainage divides and bounded to the north by the Rainy River.

3. Conceptual Peatland Carbon Budget

Carbon enters the Glacial Lake Agassiz Peatlands as dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) in groundwater, as DIC in precipitation, consumption of atmospheric CH_4 (methane), and primary productivity (CO_2 fixation from the atmosphere). It leaves as DIC and DOC in groundwater and surface water and as CO_2 and CH_4 flux as gases. Finally, carbon can be stored in peatlands as biomass accumulates [*Gorham*, 1991; *Gorham and Janssens*, 1993; *Grigal et al.*, 1989; *Wieder et al.*, 1994; *Wieder and Lang*, 1982], and the purpose of our study is to constrain the extent of this storage term.

The annual carbon budget equation for the peatland may be written as

$$(C_{\mathrm{ppt}}V_{\mathrm{ppt}}) + (C_{\mathrm{gwi}}V_{\mathrm{gwi}}) + M_{\mathrm{CNEE}} - (C_{\mathrm{gwo}}V_{\mathrm{gwo}}) - (C_{\mathrm{swo}}V_{\mathrm{swo}}) - M_{\mathrm{CH_4}} = M_{\mathrm{peat}} + M_{\mathrm{pore\ water}}$$

where

C_{ppt}	concentration of dissolved inorganic carbon (DIC) contained in precipitation (mg L^{-1});
V_{ppt}	volume of precipitation falling on the Rapid River Watershed (m yr^{-1});C_{gw} total carbon concentration (Σ DIC and DOC) of groundwater (mg L^{-1}) entering the peatland as recharge through mineral soils along the watershed divide (*i* if positive) or leaving (*o* if negative) the peatland (L yr^{-1});
V_{gw}	volume of precipitation recharging mineral soils to form minerotrophic groundwater (*i* if positive) or discharging as mineral-rich groundwater (*o* if negative) (L yr^{-1});
C_{sw}	total carbon concentration (Σ DIC and DOC) leaving the peatland in surface waters (mg L^{-1});
V_{sw}	volume of surface leaving (*o* is out) the peatland (L yr^{-1});
$M_{\mathrm{CH_4}}$	mass of total carbon in the form of methane emitted from (*i* if positive) or taken up from the atmosphere by the peatland (*o* if negative)(g C yr^{-1});
M_{CNEE}	net ecosystem exchange of CO_2 fixed by the system because of photosynthesis (if positive), and leaving the system because of respiration and decomposition (if negative) (g C m^{-2} yr^{-1});
$M_{\mathrm{peat}} + M_{\mathrm{pore\ water}}$	total amount of carbon accumulating in the peatland (g C m^{-2} yr^{-1}) as organic carbon in peat or as DIC or DOC in the pore water (if positive, the peatland is a sink; if negative, the peatland is a source).

The inputs in the equation are positive terms, and the negative terms are outputs. Representative annual values are needed for each term to prepare an annual carbon budget for a peatland. Although carbon fluxes and water fluxes vary substantively at daily scales, the scale of the peatland and the quality of the data available in this remote area are such that only annual data can be evaluated at this time.

4. Approach and Methods

Calculating a carbon budget for a peatland of the size of the Rapid River Watershed is a formidable task. Many assumptions have to be made because temporal data on carbon concentrations and water flux in most compartments of the budget are scant. Therefore, rather than using simple mean values to calculate carbon flux, we used summary statistical characterizations to bracket probable values and then used the Monte Carlo simulation to determine a final range of values representing the amount of carbon accumulating (if positive) or leaving (if negative) the Rapid River Watershed.

There are two types of methods to evaluate the carbon budget, deterministic and probabilistic. Deterministic calculations are made with discrete values, whereas probabilistic methods use input distributions to formulate a final probability distribution of a storage term (positive if the peatland is a sink and negative if it is a source). The probabilistic technique called the Monte Carlo method evaluates problems that involve uncertainty and is used extensively by, among others, the oil industry to pinpoint reserves [*Murtha and Janusz*, 1995; *Santos and Ehrl*, 1995]. The Monte Carlo method approximately solves mathematical and physical problems by simulating random quantities [*Sobol*, 1974] with distributions similar to those of actual data. It is a statistical algorithm including a process for producing a random event. This process is repeated n times, each trial being independent of the rest, and the results of all the trials are averaged together. The variable n is selected based on a desired confidence interval and is chosen by the following equation:

$$F(\bullet) = P\,[x \leq \bullet]$$

(the function of a given number is equal to the probability that x is less than or equal to that number) where

$$+2\sqrt{\frac{P(1-p)}{n}} < +2\sqrt{\frac{0.5x0.5}{n}} = \frac{1}{\sqrt{n}} = \varepsilon$$

and ε is the confidence interval. Therefore an n of 10,000 yields a confidence interval of 0.01.

The simulation starts with this equation and a set of assumptions for each variable. The variables used in the equation are classified as inputs or outputs as a range and are treated as probability distributions rather than numbers. Using both published and unpublished data for each source and sink, we generated a set of 10,000 random numbers for each term. The distribution of random numbers mirrors the distribution of reported values. Chi^2 tests of uniformity and normality are done, and in the case of rejection of either distribution, a generalized lambda distribution is constructed using the first four moments of the distribution: mean, variance, skewness, and kurtosis [*Ramberg et al.*, 1979]. A simulation consists of summing the 10,000 repeated trials for each input and subtracting the 20,000 trials for carbon output.

The result is a distribution of 10,000 values representing the distribution of a storage term (the numbers will be negative if the peatland is a source of carbon to the environment and will be positive if the peatland is a sink for carbon). The storage output variables, shown as a histogram, assign the probability that the peatland has a particular storage term. Monte Carlo simulation is thus a powerful alternative to primary data collection and subsequent estimation of the carbon budget of the Rapid River Watershed of the Glacial Lake Agassiz Peatlands. The equation above augments the extensive existing database of carbon values to effectively constrain how much carbon is entering or leaving the system.

The end result of this Monte Carlo simulation is a cumulative probability versus carbon input/output curve (such as a 20% probability that the Rapid River Watershed of the Glacial Lake Agassiz Peatlands releases 10 g C m^{-2} yr^{-1} reported with a confidence interval of 0.01). Each input parameter, such as groundwater flux and carbon from precipitation, has a range of values. The distribution function of each of these values influences the shape of the cumulative probability versus input/output of carbon curve.

Probability distributions used in this simulation followed those for reported data for each parameter. Random numbers were generated using Microsoft Excel for each input and output (we first tested the generator running a Chi^2 test on the values using the software package MINITAB) [*Ryan and Joiner*, 1994]. Where normal or uniform distributions were appropriate, they were used. Generalized lambda distributions may also be specified by a mean, standard deviation, kurtosis, and skewness of the actual values for factors contributing to inputs and outputs [*Ramberg et al.*, 1979].

5. Data Sources

5.1. Inputs

The amount of average annual precipitation falling on the Rapid River Watershed area was obtained from *Baker et al.* [1967], *Peters and Bonelli* [1982], *Shen* [1993], and *Gorham* [1991]. Between 37.6 and 116.6 cm yr^{-1} (14.8 and 45.9 inches yr^{-1}) falls on the watershed, and annual totals are approximately normally distributed over a 20 year database [*Baker et al.*, 1967]. Precipitation in this area has about 0.4 mg L^{-1} of DIC [*Peters and Bonelli*, 1982]. Integrating concentration by volume over the 1,506,200 m^2 watershed study area yields a minimum total value of 0.02 g C m^{-2} yr^{-1} and a maximum of 3.95 g C m^{-2} yr^{-1} input from precipitation, with a distribution shown in Figure 2.

By definition, the source for all the groundwater in the watershed is precipitation. Some of the precipitation recharges the shallow groundwater flow system at raised bog water table mounds. Precipitation also recharges local and deeper flow systems at sand and gravel beach ridges transecting the peatland and through beach and glacial morainal deposits around it [*Glaser*, 1997; *Siegel*, 1983]. The acidic groundwater recharging through the peat at bogs has a low dissolved inorganic carbon content (less than 25 mg L^{-1} C [*So*, 1996]) because it does not contact carbonate minerals. In contrast, precipitation recharging through mineral soils at the beaches and moraines dissolves carbonate minerals, and the resultant groundwater has alkalinities usually exceeding 150 mg L^{-1} C. Groundwater also discharges upward throughout much of the peatland toward the base of the mineral soil [*Romanowicz et al.*, 1993; *Siegel et al.*, 1996; *Glaser*, 1997]. It is unknown whether this discharge mostly reflects internal hydrodynamics related to the beach ridges and moraines on the watershed boundaries or discharge from regional flow systems at a larger scale. We assume for this study that most of the upward head gradients are caused by internal hydrodynamics.

How much carbon from dissolving carbonate minerals enters the watershed can be estimated from Darcy's law for groundwater entering from the margins of the watershed, where it is defined by mineral soil divides:

$$C_t = K\,I\,A\,C_{\mathrm{gw}}$$

where

C_t annual flux of carbon (g m^{-2} yr^{-1}) due to groundwater flow;
K horizontal hydraulic conductivity (m yr^{-1});
I horizontal gradient;
A cross-sectional area (m^2);
C_{gw} concentration of carbon (g m^{-2} yr^{-1}) in groundwater;

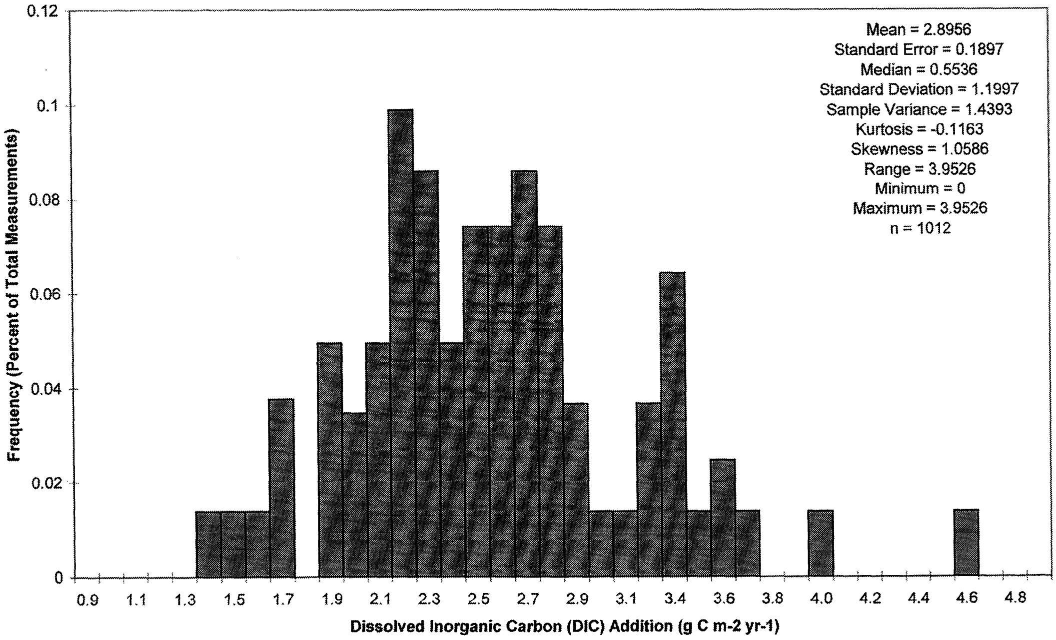

Figure 2. Amount of carbon (g m^{-2} yr^{-1}) entering the Rapid River Watershed by precipitation.

Where the watershed receives carbon input from the watershed divides is apparent, as a first approximation, from the patterns of fen vegetation observed on Landsat images [e.g., *Glaser*, 1987b]. At these places, we assume that the thickness through which groundwater mostly moves laterally into the peatland at fens is 1 m, the thickness of the most permeable part of the peat. Groundwater flowing from local water table mounds toward the flat peatland margins is focused toward the upper meter of the peat, similar conceptually to the discharge at lake-groundwater boundaries [e.g., *Winter*, 1976; *Winter and Pfannkuch*, 1984; *Pfannkuch and Winter*, 1984]. Approximately 22% of the length of the western boundary consists of offshore sand outcrops [*Eng*, 1980], and it is through this that we hypothesize much of the dissolved inorganic carbon enters as infiltration and then discharge. This groundwater mixes with surface water and flows through the upper peat column, gaining DOC from peat decomposition. The length of the discharge zone near the peatland margin (35 km) is shown in Figure 1. The hydraulic gradient along the margins was assumed to be 0.05 [*Siegel*, 1983; *Hegelsen et al.*, 1975], and the hydraulic conductivity was assumed to be 10^{-3} m s^{-1} [*Chason and Siegel*, 1986]. We used a distribution of DIC and DOC values for groundwater measured in peat pore water at 1 m depth, reflecting that which most likely is moving horizontally at rates meaningful on a mass balance basis (Figure 3). We recognize that groundwater also moves horizontally deeper in the profile [e.g., *Siegel et al.*, 1996] but at a velocity at least 10 times smaller than found in the upper fibric zone of the peat. This deeper groundwater may be very important geochemically on a transient basis, but because of the small volumes, it can be neglected for a steady state simulation like this.

The flora of peatlands sequester large volumes of atmospheric inorganic carbon by the highly generalized equation:

$$12\ H_2O + 6\ CO_2 \xrightarrow{\text{sunlight}} 6\ O_2 + C_6H_{12}O_6 + 6\ H_2O$$

Peat, partially decomposed vegetation, fixes and accumulates atmospheric carbon within peatlands. Peatlands also emit CO_2 by plant respiration. How vegetation affects carbon dynamics is thus best approached by calculating net ecosystem exchange (NEE). To obtain this parameter, we used enclosed chamber measurements on a forested bog, an unforested bog, and a fen in the peatland (Figure 1) once a month during the 1997 growing season (June – September). Light curves were extrapolated from photosynthetically active radiation, which were conducted at both ambient and manipulated light levels. Seasonal CO_2 exchange values were obtained from simple rectangular and nonrectangular hyperbolic models (see *Whiting and Chanton* [1992, 1993] for a discussion on these models). Curves were generated for both midseason (peak) production and late season when the plants are approaching the end of the growing season and winter senescence.

These curves were generated for an open (unforested) bog, a closed (forested) bog, and a fen location. The percent cover of bogs in the Rapid River Watershed is 25%, that of fens is 25%, and the remaining 50% is covered by mineral soils. NEE was computed in terms of g CO_2 m^{-2} d^{-1} and converted to g C m^{-2} yr^{-1} to obtain the weight of carbon, multiplied by the growing season, which has been found to be 150 days [*Matthews and Fung*, 1987].

Carroll and Crill [1997] found, for Sallie's fen, in Barrington, New Hampshire, NEE (n = 414) values between –192 and 492 mg C m^{-2} hr^{-1}. *Frolking* [1997] found net ecosystem productivity values of 126 g C m^{-2} in 1994 and 2.5 g C m^{-2} in a spruce/moss boreal ecosystem near Thompson, Manitoba, in 1995. *Shurpali et al.* [1993, 1995] found in a Minnesota peatland that NEE ranged from –35 g C m^{-2} yr^{-1} in a wetter, cooler year to 70 g C m^{-2} yr^{-1} during a drier, warmer

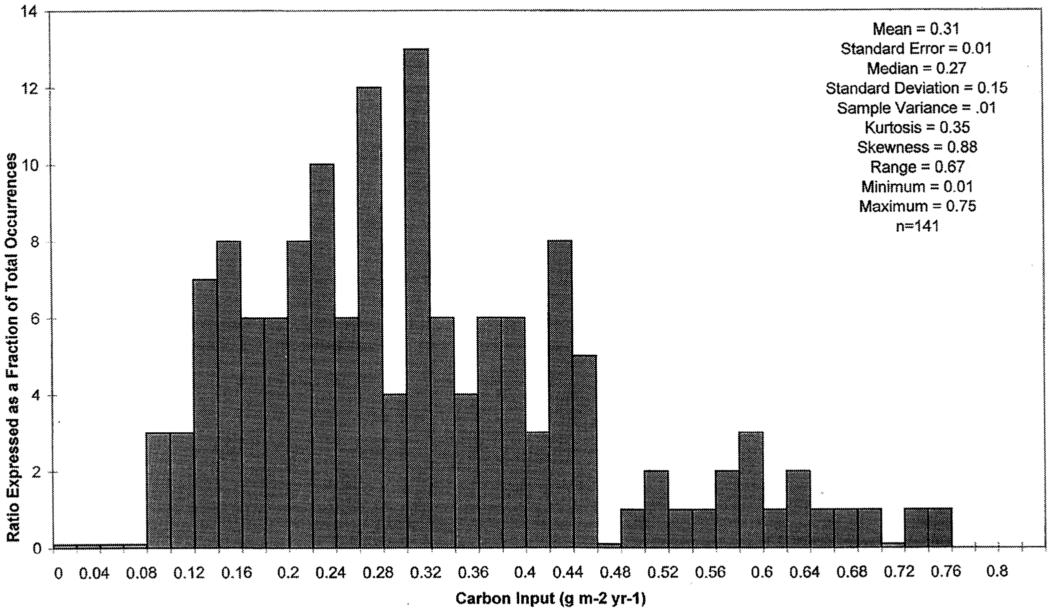

Figure 3. Amount of carbon (g m^{-2} yr^{-1}) entering the Rapid River Watershed by groundwater recharge at watershed divides.

year. All of these values for NEE from circumboreal peatlands have been incorporated as supplemental data into our own primary data to yield the distribution shown in Figure 4.

5.2. Outputs

Groundwater leaves the watershed through the flood plain of the Rapid River near its mouth. The cross-sectional area across the floodplain is only 4500 m^2, less than 0.3% of the cross-sectional area through which carbon is input into the peatland by internal groundwater discharge from the watershed margins. On the basis of extensive values for dissolved organic and carbon concentrations [*So*, 1996; D. I. Siegel, unpublished data, 1995], groundwater has approximately 300 mg DIC L^{-1} and 78 mg DOC L^{-1}. As developed in the inputs section, we computed that the volume of groundwater flow possibly leaving the watershed as underflow at the mouth of the Rapid River (Figure 5) is only 0.08 g C m^{-2} yr^{-1}.

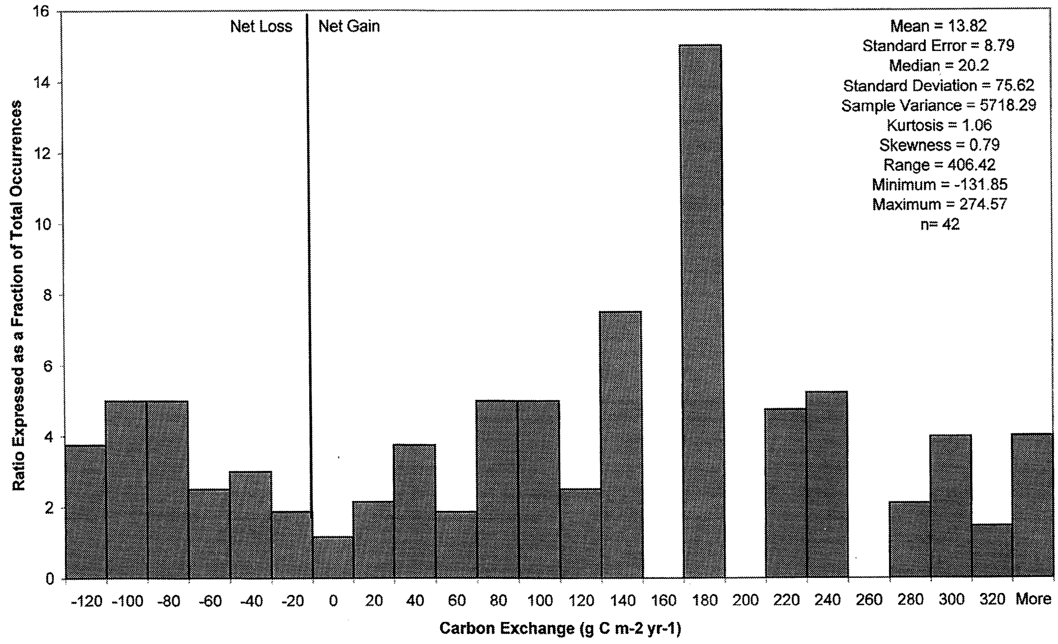

Figure 4. NEE of carbon with the atmosphere (g m^{-2} yr^{-1}). Negative numbers indicate a loss of carbon from the Rapid River Watershed, and positive values indicate a sink.

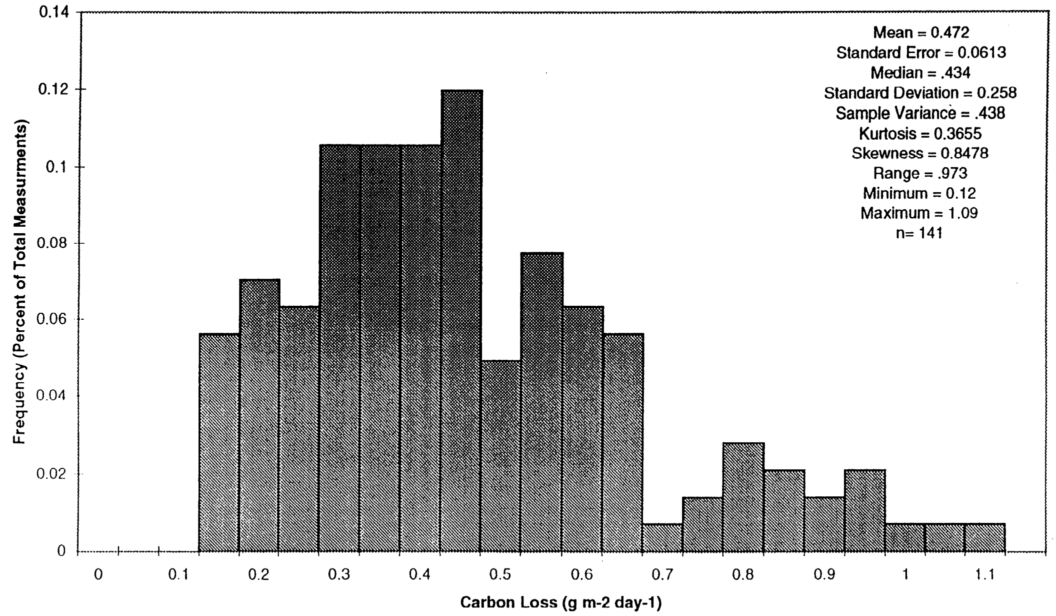

Figure 5. Amount of carbon (g m^{-2} yr^{-1}) leaving the Rapid River Watershed by groundwater flow underneath the mouth of the Rapid River.

Streamflow in this region varied throughout the year. The 30 day recurrence interval for high flow in the Rapid River near Baudette is 70 m^3 s^{-1}, and the 30 day recurrence interval for low flow is 0.1 m^3 s^{-1} [*Hegelsen et al.*, 1975]. Streams in this region draining areas less than 259 km^2 usually have no flow at times. Main streams of large rivers seldom go dry, but streamflow can be very low in late winter and during prolonged dry periods. Using DIC and DOC concentrations in surface water in the area (see input calculations) and from water collected at at several sites along the Rapid River (see Figure 1 for locations) during August and September 1997 (n = 6), we derived a mean value of 9.80 g C m^{-2} yr^{-1} (Figure 6). We assume in the calculation that mass flux is fairly uniform in streamflow throughout the year. The carbon in base flow is concentrated relative to storm flow, although the mass remains the same. The fluctuating flow rate is inversely proportional to carbon concentration; thus the net carbon loss remains similar per continuous time. We recognize that

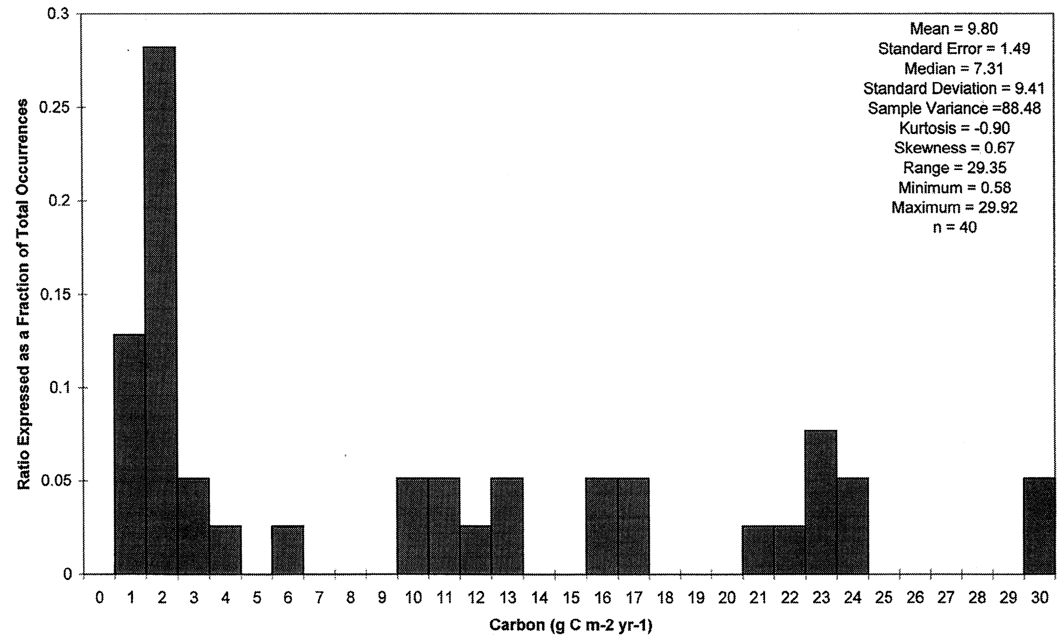

Figure 6. Amount of carbon (g m^{-2} yr^{-1}) leaving the Rapid River Watershed by surface water (including base flow).

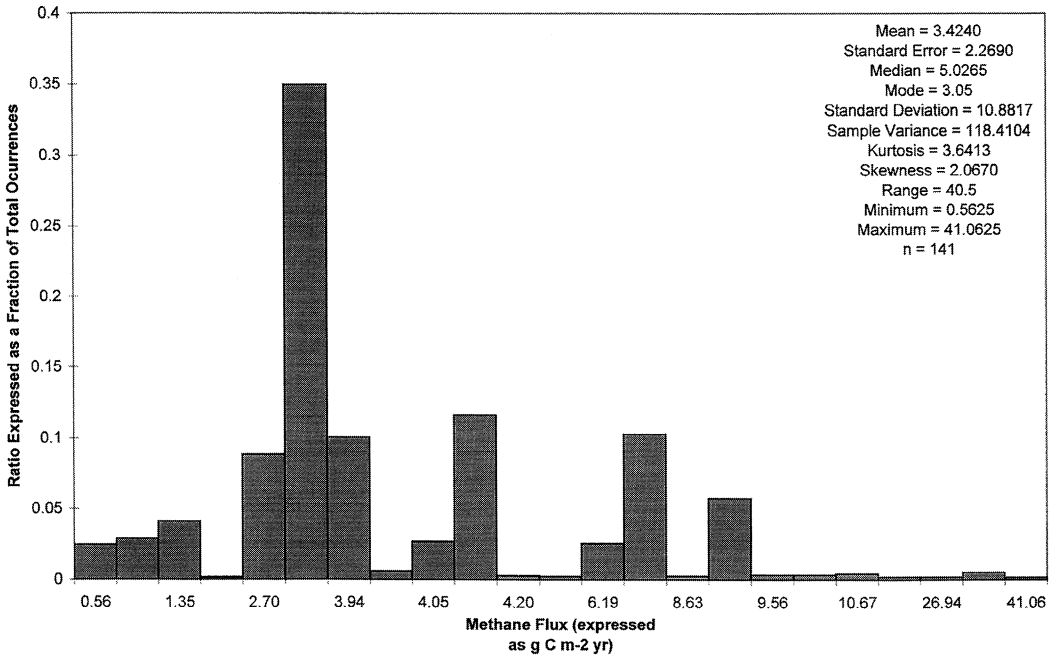

Figure 7. Amount of carbon (g m^{-2} yr^{-1}) emitted from the Rapid River as methane (CH_4).

additional DOC may flush out during storms, but we are unable to assess the loss at this time.

Methane flux from the Glacial Lake Agassiz Peatlands to the atmosphere results from complex and dynamic processes. The term in the carbon budget equation for methane ($C_{CH_4}V_{CH_4}$) can be partitioned into three variables [*Crill et al.*, 1992]:

$$C_{CH_4}V_{CH_4} = \text{wetland area} * \text{emission rate} * \text{emission period}$$

Emission rates for methane reported from Minnesota are generally significantly higher than those from Canada [*Crill et al.*, 1992] and have striking regional differences in the Rapid River Watershed [*Crill*, 1991]. The third term, emission period, has been addressed by *Matthews and Fung* [1987]. For latitudes between 30° and 60°, the productive season is approximately 150 days [*Matthews and Fung*, 1987], which is, crudely, the duration of the thaw. Indeed, for a fen in this site (D. I. Siegel, unpublished data, 1995), temperatures at 1 m in 1996 were below 3° from mid-March through mid-June. In a nearby bog, temperatures at 1 m drop below 2° in mid-January to below 1° in mid-March, and in mid-April they were at 0.6°. Thus the peat in the Rapid River Watershed is at least intermittently frozen for 6 months (January through June). *Moore and Knowles* [1989] report a minimum methane emission rate of 0.7 mg CH_4 m^{-1} d^{-1} and a maximum of 28 mg CH_4 m^{-1} d^{-1} in Minnesota peatlands. *Dise et al.* [1993] give a minimum of 3.5 mg CH_4 m^{-2} to a maximum of 67.5 mg CH_4 m^{-2} during the growing season in northern Minnesota peatlands. Crill [1991] measured fluxes in Minnesota peatlands from 11 to 866 mg CH_4 m^{-2} d^{-1}, averaging 207 mg CH_4 m^{-2} d^{-1} overall in bogs. In Rapid River Watershed circumneutral fens, Crill [1991] measured 325 ± 31 mg CH_4 m^{-2} d^{-1}. *Waddington and Roulet* [1996], *Fechner and Hemond* [1992], *Kelly et al.* [1992] have reported similar values for circumboreal peatlands. All of these numbers were input into our methane distribution (Figure 7), producing a mean of 3.42 g C m^{-2} yr^{-1}.

Evapotranspiration removes water with little DIC; thus carbon losses are disregarded from this parameter. Evapotranspiration does, however, account for a loss of 43.2 cm yr^{-1}, or 4.54 x 10^7 m^3 yr^{-1} of water loss over the area of the watershed, which is detailed in the hydrologic budget (Figure 8). Evapotranspiration is significant in that it may serve to concentrate carbon contained in the output.

6. Results

Results of the Monte Carlo simulation output are shown in Figure 9. This histogram has a mean of 12.74 g C m^{-2} yr^{-1}, standard deviation is 3.03 x 10^4, kurtosis is -0.40, and skewness is -0.10. Figure 10 shows a cumulative probability versus output curve. The most likely scenario (the mean of the final distribution) which evolves from this simulation is that the Rapid River Watershed of the Glacial Lake Agassiz stores 12.74 g C m^{-2} yr^{-1}; however, the lower quarter of the Monte Carlo simulation distribution indicates there could potentially be emission of carbon from this wetland system. Figure 11 is a box model showing average inputs and outputs for each parameter in the simulation.

7. Uncertainties

7.1. Modeling Approach

There are several limitations and uncertainties inherent in stochastic modeling. The biggest problem with this approach is that it cannot overcome data limitations. For example, as with a deterministic model, if a probability density function for an input variable is not a good representation of nature, this adverse effect propagates through the model. The

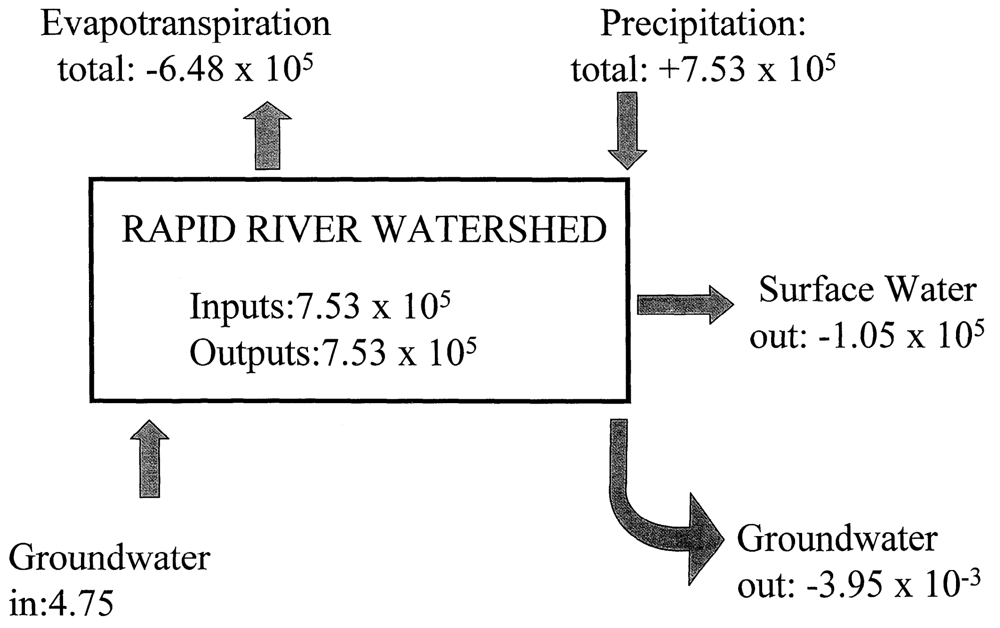

Figure 8. Hydrologic budget of the Rapid River Watershed, Glacial Lake Aggasiz Peatlands, northern Minnesota. All units are m^3 yr^{-1}.

distributions used as inputs and outputs could be skewed or biased. Further, there is no mathematical representation of the compartment sizes and associate rate constants and parameters that together determine flux rates. Rather, these rate constants have been incorporated directly into each parameter, and the flux rates were varied directly for this simulation. This could potentially have led to such difficulties as the loss of conservation of mass. Thus it is possible that inappropriate combinations of fluxes may result in possibilities such as more water inputs than outputs, though we calculated an independent water budget which was a reasonable estimate of annual water flow in this system (Figure 8). Finally, the model did calculate some extreme values of carbon loss or accumulation in the Rapid River Watershed.

7.2. Surface Water

Perhaps the most perplexing uncertainty in this model is figuring out a logical bracket on surface water values. While we have characterized the concentrations of DIC and DOC in

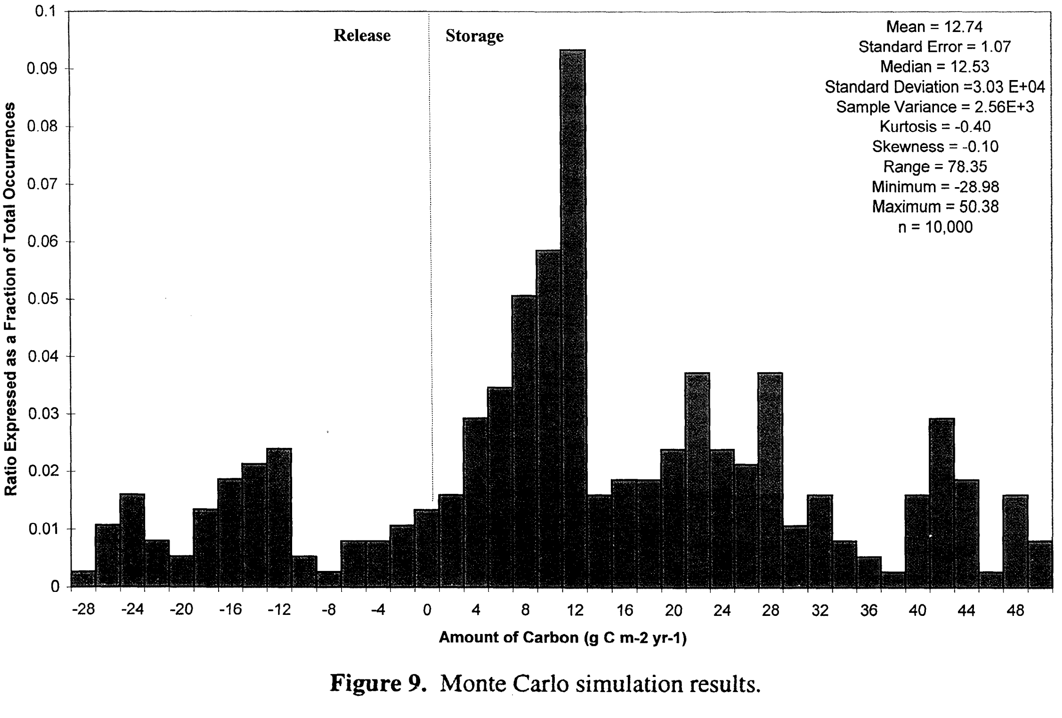

Figure 9. Monte Carlo simulation results.

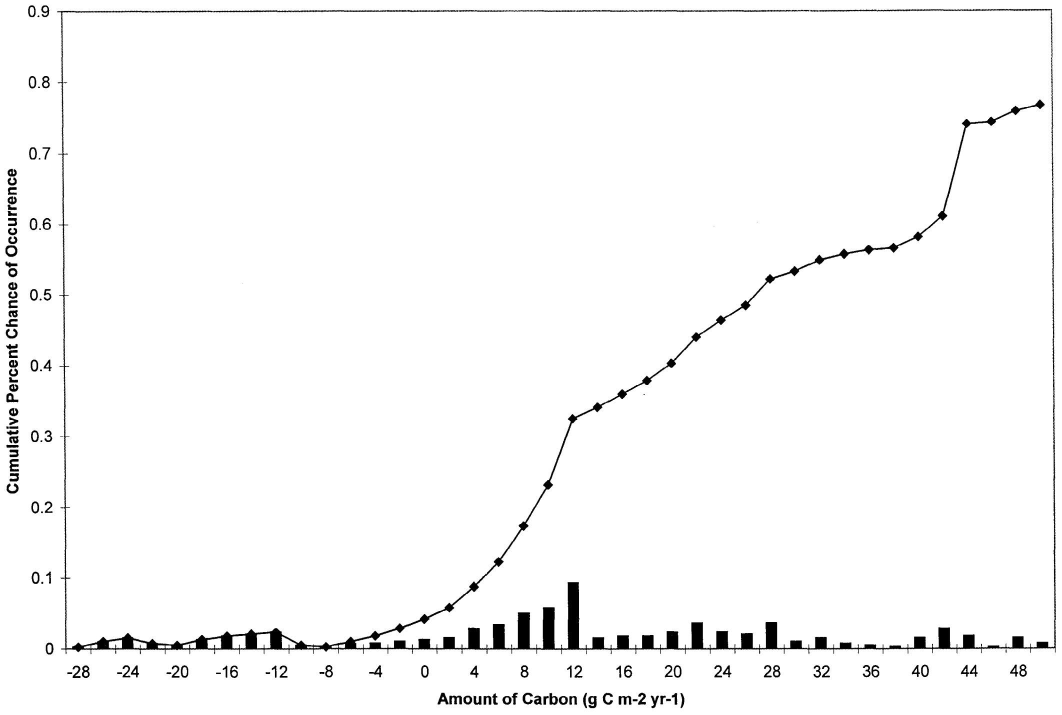

Figure 10. Monte Carlo results expressed as cumulative probability and normalized as percent of total trials.

surface, the volume of surface water is a constantly changing parameter, and given the relatively large volume of water which discharges out of the Rapid River Watershed and into the Rainy River, the surface water parameter in the equation is likely the largest source of possible error and uncertainty. It is difficult to derive an annual discharge rate given the variable climate in this region. For example, in times of heavy precipitation in the region, more water flows through the watershed, and the carbon concentration, as a result, is lower.

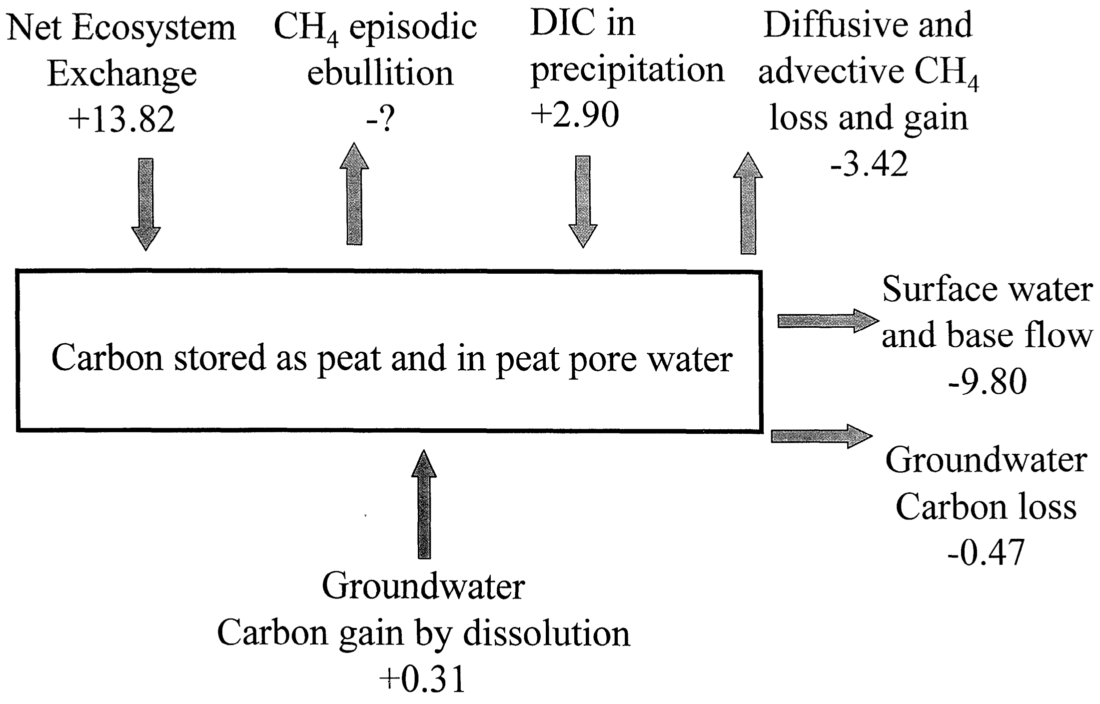

Figure 11. Schematic diagram of the carbon dynamics in the Rapid River Watershed, Glacial Lake Agassiz Peatlands, northern Minnesota (units are g m^{-2} yr^{-1}).

7.3. Net Ecosystem Exchange (NEE)

Productivity is a poorly investigated parameter of carbon cycling within Glacial Lake Agassiz. During the daytime, O_2 is released and CO_2 is consumed by the process of photosynthesis. At night, respiration releases CO_2 and consumes O_2. There is great seasonal variation in the amount of atmospheric CO_2 which is fixed by the peat vegetation. During winter months, the ground is frozen, which precludes active metabolic processes.

In the NEE measurements, we used dark respiration values for a proxy for nighttime respiration, and there may be some differences between dark values and true evening values. Further, both the light curve and the seasonal response are best guess approximations based on limited sampling opportunities.

7.4. Methane Flux

There are many factors which govern emission rate of CH_4 [*Crill et al.*, 1992] including precipitation (both total amounts and the timing of rainfall), temperature (such as changes in annual averages and seasonal distributions), frequency and severity of natural fires, changes in evapotranspiration; and human activity. In spite of numerous attempts [*Koyama*, 1963; *Svensson*, 1980; *Mayer*, 1982; *Matthews and Fung*, 1987], no quantitative relationships have been found to describe accurately the variations in methane fluxes resulting from the complex interactions among physical, chemical, and biological properties of the local environment. Methane accounts for a significant amount of carbon lost by the system; indeed, more than 25% of the current annual global flux of methane to the atmosphere may be from peatlands [*King*, 1990]. The estimated total CH4 flux from North American and Eurasian peatlands ranges from 0.3×10^{12} to 1.15×10^{12} g yr^{-1} [*Matthews and Fung*, 1987; *Shen*, 1993].

Ebullition, or sporadic CH_4 release under excess pore pressure (likely associated with drought cycles [see *Romanowicz et al.*, 1993; *Shen*, 1993], further complicates the assignment of a specific range of values to carbon loss due to methane emission. Preliminary calculations suggest that the combination of dissolved and free methane bubbles in the peatland could potentially contribute tens of percent to the annual flux rate. *Romanowicz et al.* [1995] hypothesized that as temperature increases and peatland water tables drop, the amount of CH_4 emitted from peatlands may increase, as well as the release of carbon dioxide to the atmosphere by higher rates of oxidation and decomposition [*Post et al.*, 1982].

7.5. Groundwater

Groundwater is also a parameter with great uncertainty, though this is less of a problem with respect to the entire model because groundwater moves so slowly and as such the net flux is small relative to the other parameters (an average of 0.31 g C m^{-2} yr^{-1} versus the 13.82 g C m^{-2} yr^{-1} average for NEE).

7.6. Environmental Fluctuations

We cannot directly address the important phenomena of diurnal, seasonal, and episodic changes in rates of carbon flux. Indirectly, we used carbon mass expressed per year. This study does not address changes through time or what proportion of carbon is being retained by the system and for how long. It is feasible that the watershed could transform from a sink to a source in the summer months when water table levels drop and CH_4 emissions increase.

Further, the role of fire is important in peatland carbon dynamics. Specifically, the oxidization of peat in fire is a source for atmospheric carbon. The net loss of carbon from peatlands from fire was not factored into this Monte Carlo simulation because of uncertainties as the frequency and duration of fires, and the duration of such fires.

Finally, given the dry climate [*Glaser et al.*, 1990] coupled with the high rates of CO_2 and CH_4 emission [*Chanton et al.*, 1993], there may be a seasonally very low rate of carbon accumulation or even a loss. Most peat accumulation models predict that the position of the water table regulates the carbon balance of a peatland because 90% of the carbon fixed by photosynthesis may be decomposed to CO_2 through aerobic decomposition [*Clymo*, 1984]. Decomposition may continue at a much slower rate in the anoxic saturated portion of the peat column by fermentation and methanogenesis [*Romanowicz et al.*, 1993]. Fluctuations of the water table were not addressed in the steady state stochastic carbon model.

8. Summary

Despite the uncertainties, we feel that our stochastic simulation captures the probable range in storage of carbon possible in the Rapid River portion of the Glacial Lake Agassiz Peatlands from –28.98 to 50.38 g C m^{-2} yr^{-1}. Extrapolated over the Rapid River Watershed, an average of 1.9×10^7 g C yr^{-1} may accumulate each year today. This simulation suggests that there is a 62% probability that the peatland is currently storing carbon, in agreement with observed rates of continual peat accumulation [*Glaser et al.*, 1997] of about 1 mm yr^{-1}. A carbon budget of this nature is an invaluable tool in visualizing carbon flux data and in visualizing how each component of the total carbon budget spans orders of magnitude. It also indicates the relative importance of each parameter (e.g., precipitation inputs less than 1 mg C m^{-2} yr^{-1}, whereas CH_4 is responsible for the output of thousands of mg C m^{-2} yr^{-1}).

Acknowledgments. We thank E. J. Dudewicz for thoughtful discussions and statistical suggestions.

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J.P. Chanton and L.S. Chasar, Department of Oceanography, Florida State University, Tallahassee, Fl 32306. (jchanton@mailer.fsu.edu; lstalder@mailer.fsu.edu)

P.H. Glaser, Limnological Research Center, University of Minnesota, Mineapolis, MN 55455. (glase001@maroon.tc.umn.edu)

J.M. McKenzie, J.S. Rivers, and D.I. Siegel, Department of Earth Sciences, Syracuse University, Syracuse, NY 13244. (jsrivers@syr.edu; jmmckenz@syr.edu; disiegel@syr.edu)

N.T. Roulet, Department of Geography, McGill University, Montreal, Canada H3A 2K6. (roulet@felix.geog.mcgill.ca)

(Received February 12, 1998; revised August 13, 1998; accepted August 13, 1998.)