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NUTRIENT CYCLING AT MARCELL BOG, MINNESOTA

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Fourteen kg ha^{-1}yr^{-1} of N enter the mire acrotelm, and 12 are sequestered in the catotelm peat. However, 66 kg ha^{-1}yr^{-1} cycle between plant growth and decay in the acrotelm each year, primarily as ammonium and organic N. Fifty eight percent of the sulfate inputs to the mire are retained, but the export of organic sulfur (1.5 kg ha^{-1}yr^{-1}) yields a total sulfur retention of 37%. As with N, recycling within the acrotelm and vegetation layer is large (12.5 kg ha^{-1}yr^{-1}). The proton cycle in the mire is dominated by nutrient uptake and plant decay (about 80% of the 1 044 meq m^{-2} yr^{-1}). Organic acid production is the major source of free acidity (263 meq m^{-2}yr^{-1}) and buffers the water near pH 4. About half of the metals entering the mire are retained, and about 60% of the P is retained. Retention of P is particularly high (about 80%) during the spring snowmelt season. The carbon cycle at the Marcell mire consists of about 655 g C m^{-2}yr^{-1} entering and leaving the acrotelm and vegetation. Eighteen to 28 g C m^{-2}yr^{-1} are sequestered each year in the catotelm (true and apparent rate of accumulation). Net primary production in the moss, tree, and herbaceous layers accounts for about 385 g C m^{-2}yr^{-1}, while CO_2 losses in soil and plant respiration account for about 589 g C m^{-2}yr^{-1}. Root net primary productivity (unmeasured) is estimated at 152 g C m^{-2}yr^{-1}. Water export of C is 37 and methane losses are about 6 g C m^{-2}yr^{-1}.

Keywords: Carbon cycling, global change, Minnesota, nutrient budgets, peatlands

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INTRODUCTION

Marcell Bog is located in north central Minnesota, USA (47°32´N, 93°28´W) in a glaciated region of ground moraines and outwash. Its topographic position and water table isolation give it a mixed classification in the Secondary/Tertiary terminology defined by Moore and Bellamy (1974). Clay loam till (3–4 m thick) collapsed into a vacated ice-block depression in deep outwash sands, and, because of the low hydraulic conductivity of the till (10^{-5} cm sec^{-1}), this depression subsequently filled with peat (about 80% of the basin is 4 m deep, while a deep part in 20% of the basin extends to nearly 8 m). At a low spot in the surrounding clay loam slopes, the peat and its water table have risen to find an outlet to a surface stream. Thus the mire deposit is secondary in nature.

The surrounding mineral soils drain to the mire edge and then to the stream outlet. The mire has developed a rudimentary central dome which rises about 15 cm above the mire edge where a 5–7-m wide lagg exists (Verry 1984). The regional water table (in the underlying sands) is about 8 m below the mire water table. A slow seepage from the mire occurs beneath the lagg through the saturated clay loam till; it then travels as unsaturated flow through the sands to the regional water table several meters below. The mire water table is thus perched above the regional aquifer system, and in this respect the mire can also be considered tertiary. Development of the rudimentary dome is a recent feature, beginning in the last 150 years.

The forested bog is dominated by *Picea mariana* (Black Spruce) averaging 123 years old (nutrient cycling studies were done at ages 103 through 110). The mire surface consists of *Sphagnum magellanicum*-dominated hummocks (up to 55 cm above the hollows), and *Sphagnum angustifolium*-dominated hollows. Ericaceae shrubs (*Ledum groenlandicum, Chamaedaphne calyculata, Gaultheria hispidula*) form the low understory. Water pH typically ranges from 3.6 to 4.2, ash content in the peat is low (1–7%), as are exchangeable bases (<20 meq/100 g).

Marcell Bog is actually the mire portion of experimental basin number 2 of the Marcell Experimental Forest (S-2). Since 1960, it has been instrumented for the measurement of streamflow, precipitation, air and soil temperature, near-surface and subsurface flow from the mineral soil portion, canopy throughfall and stemflow, water tables in the mire and regional setting, and soil water in the mineral soil (some records began later, and some are for short periods). The entire Number 2 basin is 9.7 ha. The uplands encompass 6.5 ha and the mire 3.2 ha. The mire has been further divided into a lagg portion (0.4 ha) and a bog portion (2.8 ha).

The mineral soils are dominated by 64-year-old forests of aspen and paper birch (*Populus tremuloides, Betula papyrifera*). The mineral soil (Glossic Eutroboralf) yields near-surface flow through the organic horizon (forest floor) during snow melt, and subsurface flow laterally down slope (5–10% slopes), when snowmelt or large rains temporarily saturate the A horizon above the less permeable B horizon.

It is the Secondary/Tertiary nature of the Marcell Bog that has given rise to the analysis of nutrient and nutrient cycling processes in one of two formats. In one format, water and nutrient budgets have been developed for the upland, total mire, and total basin using their respective areas (6.5, 3.2 and 9.7 ha). In the other format, it is assumed that upland water is collected in the lagg and transmitted through the lagg to the mire exit stream. Additionally, water from the bog is collected in the lagg and then transmitted to the mire exit stream. Thus nutrient cycling and budget terms are assigned to the upland mineral soil, lagg, bog, and the entire basin (6.5, 0.4, 2.8, and 9.7 ha).

The site has a continental climate with wide extremes in temperature (–40 to +40°C), and an average annual temperature of 3.1°C (1961–1990). Snow persists from late November to mid-April, shielding the bog surface from low extremes, but the peat normally freezes to a depth of 10 cm unless December snowpacks exceed 45 cm and prevent soil freezing. Precipitation averages 76.4 cm annually, with 25% as snow. Average January and July temperatures are –15.7°C and 18.9°C respectively.

The depth to bog water table at this site has been measured for 30 years. The average water table resides 10 cm below the hollow elevation. For 90% of the time the water table fluctuates from 3 to 20 cm below the hollow surface. Intense storms can raise the water table as high as 15 cm above the hollow elevation. Droughts can lower the water table 60 cm below the hollows (Verry et al. 1988)

MAJOR WATERBORNE NUTRIENTS

A three-year water and nutrient budget for the Marcell Bog was reported by Verry and Timmons (1982). This reference contains photos and cross sections of the Marcell Bog as well as detailed seasonal and annual budgets for the mineral soil upland, entire mire, and the entire basin. The annual water budget (three years) is given for the mire portion (3.24 ha) in Table 1, and the nitrogen, metals and phosphorous budgets are given by season in Table 2. Spring is the period from the start of snowpack accumulation (in mid-November) until night temperatures exceed 0°C in the spring (usually mid-May). The summer period extends from mid-May until deciduous leaf fall (mid-September). The fall period is from mid-September until snowpacks begin to accumulate. Inputs to the mire include precipitation (chemistry measured as throughfall and stemflow), and near-surface and subsurface flow from the mineral soil uplands. Precipitation dominates nitrogen inputs, while phosphorous, K, Ca, and Mg inputs are dominated by near-surface flow through the organic, upland forest floor; Na inputs are dominated by subsurface flow from the upland.

On an annual basis, at least 36% of all nutrients are retained in the mire system. Inorganic N is retained at high rates (about 70%), while more of the organic N form leaves as dissolved or particulate organic matter (64%). Dissolved phosphorous, K, Mg, and Na show a strong seasonal change in nutrient retention, with higher retention occurring during the spring period in spite of high rates of snowmelt and streamflow. The active

Table 1. Water balance (cm) for Marcell Mire No. 2 (3.24 ha).

Year	1971	1972	1973	Average
Input				
Precipitation	85.0	80.3	74.8	80.0
Near-surface flow	25.2	13.9	10.1	16.4
Subsurface flow	17.9	17.3	17.3	17.5
Output				
Deep Seepage	13.7	11.9	4.6	10.1
Change in water table storage	+1.0	+3.8	−1.7	+1.0
Streamflow	53.1	57.4	46.5	52.4
Evapotranspiration (ET)				
ET by Balance	60.2	38.4	52.8	50.5
ET by Thornthwaite	52.7	51.1	53.6	52.5

Table 2. Mire nitrogen, phosphorous, and metal input, output, and retention (kg ha^{-1}yr^{-1}) at Marcell Bog No. 2; percent retention is given in parentheses. All values are 3-year averages (1971–1973).

Season	Input	Output	Retention	
NO_3-N				
Spring	0.82	0.11	0.71	(87)
Summer	0.92	0.11	0.82	(89)
Fall	0.39	0.07	0.23	(78)
Annual	2.04	0.28	1.76	(86)
NH_4-N				
Spring	0.76	0.24	0.52	(68)
Summer	1.12	0.28	0.84	(75)
Fall	0.38	0.19	0.19	(50)
Annual	2.25	0.71	1.54	(69)
Organic-N				
Spring	3.80	2.05	1.75	(46)
Summer	2.97	2.23	0.73	(25)
Fall	1.64	1.10	0.54	(33)
Annual	8.41	5.39	3.02	(36)
Total-N				
Spring	5.38	2.40	2.97	(55)
Summer	5.00	2.61	2.39	(48)
Fall	2.32	1.36	0.96	(41)
Annual	12.70	6.37	6.32	(50)
Ortho-P				
Spring	0.264	0.047	0.21	(87)
Summer	0.085	0.078	0.00	(8)
Fall	0.034	0.029	0.00	(15)
Annual	0.383	0.154	0.22	(60)
Organic-P				
Spring	0.358	0.116	0.242	(68)
Summer	0.309	0.134	0.175	(57)
Fall	0.116	0.058	0.058	(50)
Annual	0.783	0.308	0.475	(61)
Total-P				
Spring	0.622	0.163	0.459	(74)
Summer	0.395	0.212	0.183	(46)
Fall	0.150	0.085	0.065	(43)
Annual	1.167	0.460	0.707	(61)

Season	Input	Output	Retention	
K				
Spring	6.55	2.96	3.59	(55)
Summer	3.22	1.87	1.35	(42)
Fall	1.29	1.29	0.00	(0)
Annual	11.06	6.10	4.94	(45)
Na				
Spring	2.01	0.97	1.03	(51)
Summer	1.30	0.96	0.34	(26)
Fall	0.92	0.46	0.46	(50)
Annual	4.23	2.39	1.83	(43)
Ca				
Spring	12.66	3.33	9.34	(74)
Summer	5.03	3.79	1.24	(25)
Fall	3.21	2.01	1.19	(37)
Annual	20.89	9.14	11.76	(56)
Mg				
Spring	3.58	1.38	2.20	(61)
Summer	1.42	1.53	−0.11	(−8)
Fall	0.99	0.91	0.08	(8)
Annual	5.98	3.83	2.16	(36)

growth of *Sphagnum* and Ericaceae species in this cold, wet period is apparently responsible for the high rates of nutrient uptake. *Sphagnum* typically grows 10 cm at this time. Phosphorous, Mg, and K have very low retention rates or even negative rates in the summer and fall periods when plants have senesced and died. Natural bogs are nutrient traps, but input/output budgets do not specifically identify the processes responsible for nutrient retention.

NITROGEN CYCLING

Nitrogen cycling studies have built on the water budget and gross chemical balances of Marcell Mire (S-2), but concentrate on processes happening within the bog dome and treat the lagg as a flow-through path for both upland and bog runoff. This work by Urban and Eisenreich (1988) can be summarized with a diagram of pool sizes and fluxes (Fig. 1). The large intra bog turnover of N relative to all inputs is apparent. The large internal cycle consists primarily of uptake by *Sphagnum*, mineralization in the acrotelm, and re-uptake by moss. Nitrification has not been observed in any low-pH, ombrotrophic peatland (Given 1975, Given & Dickinson 1975, Collins et al. 1978, Rosswall & Granhall 1980, Dierberg & Brezonik 1982, Hemond 1983) and was assumed to be negligible.

Ammonium in precipitation and ammonium uptake in moss dominate the input, mineralization, and plant uptake cycles. Twelve kg ha^{-1} of organic N are sequestered each year by burial of dead organic material in the catotelm. This accounts for much of the total N input of 14.6 kg ha^{-1} (weighted average input for entire mire). Thus N cycling rate is dependent on the atmospheric deposition rate and may increase as atmospheric deposition of N increases (Urban & Eisenreich 1988). The sequestration of organic N in the catotelm differs from upland systems because it represents a net loss to the actively growing biologic community. This results in a peatland ecosystem more dependent on the rate of nitrogen deposition than upland forests and a higher rate of nitrogen cycling in the acrotelm than in upland forests. The nitrogen turnover time within the acrotelm is 30–40 years, while nitrogen turnover times in mineral soil forests typically exceed 150 years (Nihlgård 1972, Turner & Singer 1975, Bormann et al. 1981, Rosswall & Granhall 1980, Van Cleve & Alexander 1981).

The bog is a large sink for N with approximately 65% of inputs retained. Annual turnover of N (66 kg ha^{-1}) is much larger than the total input (14.6 kg ha^{-1}). This large turnover is achieved by rapidly cycling a relatively small pool of N in the aerobic layers of peat. Plant uptake is closely coupled to mineralization such that losses from the system in runoff are small.

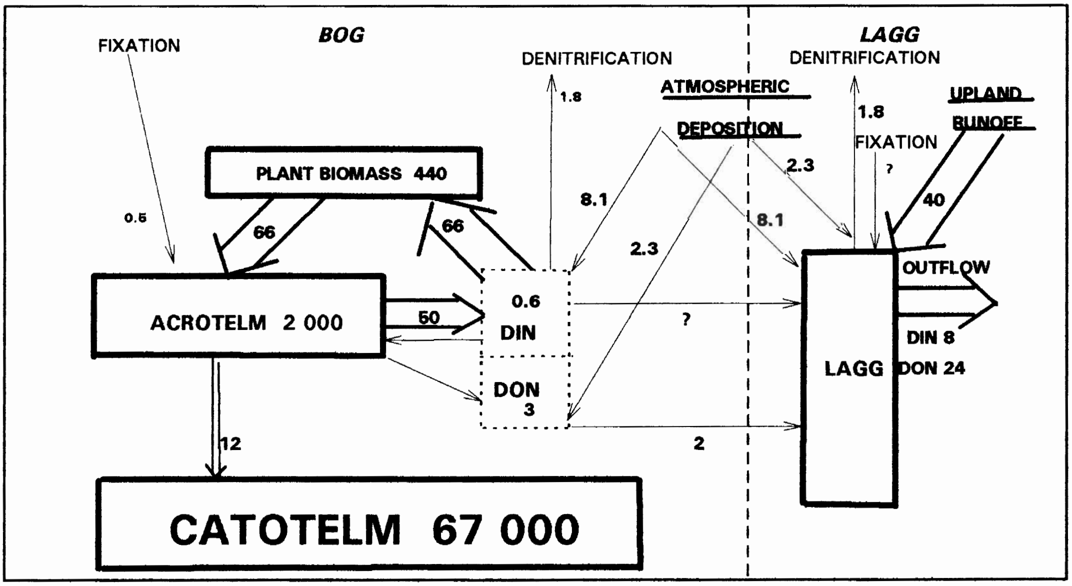

Fig. 1. The nitrogen cycle in the Marcell Bog (S-2). Pool sizes are in kg ha^{-1} (boxes), fluxes are in kg ha^{-1}yr^{-1} (arrows) per unit area of the bog (2.8 ha) and lagg (0.4 ha). Acrotelm pool is the N content of peat to a depth of 30 cm. Catotelm pool is based on an average depth of 4 m, average bulk density (0.1 g cm^{-3}), and N contents measured in two deep cores. Dissolved inorganic N (DIN), and dissolved organic N (DON) are from Urban (1983) based on seasonal pore water profiles (to a depth of 30 cm), and three cores extracted with 2 N KCL. DON export from the bog (2 kg ha^{-1}yr^{-1}) is based on the average concentration of DON in bog water times the excess of precipitation over evapotranspiration in the bog (Verry & Timmons 1982). (Fig. adapted from Urban & Eisenreich 1988).

Denitrification rates measured at this site and a bog in western Ontario were similarly low (<0.20–2.28 µg $m^{-2}hr^{-1}$ as N). In contrast, NO_3^- uptake by *Sphagnum* was much faster (100–24 000 µg $m^{-2}hr^{-1}$ as N) and is thus the dominant sink for NO_3^- (Urban & Eisenreich 1988).

SULFUR CYCLING

Marcell Bog is a large sink for sulfate with 58% of sulfate inputs retained within the bog. Because of the proportionately large export of organic S (1.5 kg $ha^{-1}yr^{-1}$), retention efficiency for total-S (organic-S plus sulfate-S) within the system is only 37%. Nevertheless, 2.7 kg $ha^{-1}yr^{-1}$ of S accumulate within the peat. Dynamic recycling of S occurs within the bog. Inputs account for 47% of annual plant S uptake; the remainder is recycled from the peat. Mineralization of S occurs primarily in aerobic strata of peat and decreases exponentially below the surface (Fig. 2). Because of this recycling, S profiles cannot be interpreted as precise records of atmospheric deposition. At this site, inorganic S species, predominantly pyrite, are unimportant reservoirs of S (Urban et al. 1989b).

PROTON CYCLING

In contrast to the detailed N and S cycles developed within the bog portion (2.8 ha) of the mire at basin S-2, a proton budget was developed for the entire mire including both lagg and bog (3.2 ha). Proton budgets provide a holistic view of ecosystems by identifying sources and sinks of acidity, and thus integrating the many processes involving acid-base and oxidation-reduction reactions. Feedback loops are controlled by the concentration of H as it influences the capacity of the system to generate or consume acidity by such processes as nutrient uptake, decomposition, weathering, ion exchange, and others. Table 3 illustrates the acidity balance for Marcell Mire S-2 (Urban et al. 1987).

The production of organic acids is the dominant source of acidity (263 meq $m^{-2}yr^{-1}$) and serves to buffer the bog water at pH 4. Sequestering of elements in the peat (nutrient uptake — 827 meq $m^{-2}yr^{-1}$ minus plant decomposition — 784 meq $m^{-2}yr^{-1}$) is also a significant source of acidity (43 meq $m^{-2}yr^{-1}$). This difference has been called Net Biological Uptake (NBU). NBU includes the process of ion exchange on *Sphagnum*. Because most exchange sites are ultimately decomposed, ion exchange is <u>not</u> a significant net source of acidity. The Marcell site is within 120 km of agricultural areas in the North American, Great Plains, thus the weathering of dust fall is a significant source of alkalinity (76 meq $m^{-2}yr^{-1}$). Nitrate and sulfate reduction contribute little to this site because inputs (NO_3 and SO_4) are low.

Analysis of peat and water from bogs across North America (Manitoba to Newfoundland) reveals: (1) the production of organic acids varies between 104 and 263 meq $m^{-2}yr^{-1}$; (2) acidity generation associated with NBU varies between 20–117 meq $m^{-2}yr^{-1}$, and varies with the rate of peat accumulation; (3) NBU exhibits high values in maritime bogs and lower values in mid-continental bogs; and (4) bogs have a large capa-

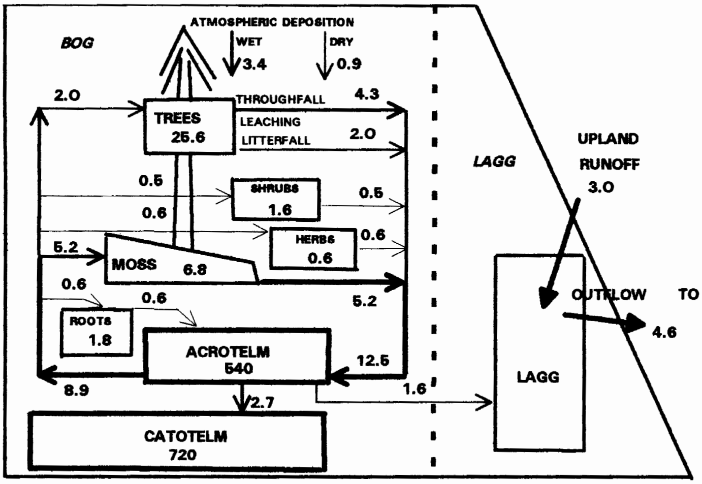

Fig. 2. Sulfur cycle for Marcell Bog S-2. Pool sizes are in kg ha^{-1} (boxes), fluxes are in kg $ha^{-1}yr^{-1}$ (arrows) per unit area of the bog (2.8 ha) and lagg (0.4 ha). Acrotelm and catotelm as defined in Fig. 1. Upland runoff is confined to the lagg. Net uptake of 0.3 kg $ha^{-1}yr^{-1}$ by trees is not included in this figure. (After Urban et al. 1989a).

Table 3. Acidity balance for Marcell Mire S-2 (3.2 ha). All values are in meq m^{-2}yr^{-1} with standard deviations in parentheses (after Urban et al. 1987).

	Acidity	
Sources		
Wet Deposition	–0.05	(9)
Dry Deposition	–1.5	(1.7)
Upland Run-Off	–44.3	(18.6)
Nutrient Uptake	827	(248)
Organic Acid Production	263	(50)
Total	1044	(254)
Sinks		
Denitrification	12.2	
Decomposition	784	
Weathering	76	
Outflow	142	(50)
Total	1014	

Table 4. Estimated carbon budget for Marcell Mire S-2 (3.24 ha). Standard errors for these terms are ± 30 to 60% of the mean.

	g C m^{-2}yr^{-1}
Inputs to the acrotelm	
Living moss respiration (passed through)	118
Sphagnum moss net primary productivity	190
Tree and shrub net primary productivity	175
Herbaceous net primary productivity	20
Total	503
Outputs from the acrotelm	
Peat accumulation in the catotelm	18–28
Dissolved organic carbon in streamflow	21
Particulate organic carbon in streamflow	10
Total organic carbon lost in deep seepage	6
Methane evolution	6
CO$_2$ soil surface efflux	471
CO$_2$ moss respiration	118
Total	650–660

city for sulphate reduction, and sulphate reduction becomes an increasingly important source of alkalinity as rates of sulphate deposition increase. From 60 to 93% of annual sulphate loadings are retained as reduced sulphur in bogs across eastern North America (Urban et al. 1987).

CARBON CYCLING

Various components of the carbon cycle have been measured at Marcell Mire S-2 or within 2 km in a poor-fen peatland and permit, at least, a preliminary estimate of the carbon budget (Table 4). Net primary productivity (NPP) for the tree, shrub, and herbaceous components are taken from Grigal et al. 1985, and Grigal 1985. The respective NPP values are 3.8, 3.5 and 0.4 metric tons ha^{-1} year^{-1} and converted to carbon assuming a ratio of 0.5 g C per gram of oven dry mass.

Moss respiration is estimated as 20% of the total surface CO$_2$ flux from the Bog Lake peatland (a poor fen with *Sphagnum/Rhynchospora/Scheuchzeria*) about 2 km from S-2 (Kim & Verma, in press). Annual surface CO$_2$ flux is 1 350 g CO$_2$ m^{-2}yr^{-1} (x 0.2727 for C only). However, the S-2 water table is about 10 cm lower, on average, than the poor fen site. Measurement sites at the poor fen were on hummocks and hollows about 10 cm apart vertically. Monthly hummock/hollow ratios of total CO$_2$ soil flux for June, July, August, and September were: 2, 2, 1.2, and 1.1, or an average of 1.6 in the growing season. Thus the average total CO$_2$ flux at the drier S-2 site was estimated at 1.6 times the 368 g C m^{-2}year^{-1}, or 589. Twenty percent of this was assigned to root respiration (118).

Peat accumulation in the catotelm is estimated from a ^{14}C-dated core from 0–100 and 100–205 cm deep. Both cores give apparent accumulation rates of 27.7 and 27.9 g C m^{-2}yr^{-1}, and thus show a linear accumulation rate with depth (data from Jan Janssens, Univ. of Minnesota; core M8307). However, more dates might indicate a curvilinear accumulation rate with depth. The general 2/3 correction factor for a true accumulation rate (Tolonen et al. 1992) can be applied, but about 80% of the dated peat cores in North America appear linear.

DOC is taken from Urban et al. 1989a, where DOC averaged 44 mg L^{-1}. TOC in streamflow (and deep seepage) was estimated from 1992 measures of TOC that averaged 60 mg C L^{-1}. Particulate organic carbon is TOC–DOC. Methane (CH$_4$) loss is measured at S-2 over 2 years (from Dise 1992).

The difference between outputs (660) and inputs (503) is as much as 157 g C m^{-2}year^{-1}. Root net primary productivity is a missing component of the input side of the budget, and can be as large as the above ground net primary productivity. In this case, the above-ground net primary productivity for trees, shrubs, and herbaceous materials is 195 g C m^{-2}year^{-1}.

There are many assumptions in this preliminary carbon budget for the S-2 peatland that can be improved by direct measurements of soil CO_2 flux, and root net primary productivity.

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