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Long-term carbon sequestration in North American peatlands

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Abstract

Peatland ecosystems store about 500-600 Pg of organic carbon, largely accumulated since the last glaciation. Whether they continue to sequester carbon or release it as greenhouse gases, perhaps in large amounts, is important in Earth's temperature dynamics. Given both ages and depths of numerous dated sample peatlands, their rate of carbon sequestration can be estimated throughout the Holocene. Here we use average values for carbon content per unit volume, the geographical extent of peatlands, and ecological models of peatland establishment and growth, to reconstruct the time-trajectory of peatland carbon sequestration in North America and project it into the future. Peatlands there contain ~163 Pg of carbon. Ignoring effects of climate change and other major anthropogenic disturbances, the rate of carbon accumulation is projected to decline slowly over millennia as reduced net carbon accumulation in existing peatlands is largely balanced by new peatland establishment. Peatlands are one of few long-term terrestrial carbon sinks, probably important for global carbon regulation in future generations. This study contributes to a better understanding of these ecosystems that will assist their inclusion in earth-system models, and therefore their management to maintain carbon storage during climate change.

1. Introduction

Following retreat of the Laurentide ice sheet, mainly between 20,000 and 5,000 years ago, fens and bogs developed on terrain of low relief in North America (Gorham et al., 2007). Large amounts of carbon were extracted from the atmosphere and deposited in layers of peat, chiefly in boreal and subarctic regions. Peat is an important sink in the carbon cycle, and empirical and theoretical studies have examined the size and dynamics of peatland reservoirs (Clymo, 1992; Zoltai and Martikainen, 1996; Clymo et al., 1998; Dean, 1999; Hilbert et al., 2000; MacDonald et al., 2006; Bhatti et al, 2009; Wang et al., 2009; Beilman et al., 2010; Yu, 2011). The location and pace of peat accumulation, since deglaciation and into the future, is therefore of great interest.

Climate change is already significant in peatlands. It has been suggested that satellite monitoring of the expanse of open waters in peatlands of the Hudson Bay Lowland and the West Siberian Plain might show whether it is lessening (Gorham, 1991). A recent study in Siberia revealed “the disappearance of lakes greater than ~300 m” (no further information given) between 1973 and 1998 (Smith et al., 2000), suggesting a drying likely to increase CO_2 emissions and decrease CH_4 emissions. Melting in permafrost peatlands must also affect such emissions, and increase the release of dissolved organic carbon to streams draining them (Frey and Smith, 2005) so that colored humic acids exported to such streams (Gorham et al., 1986, 1998) will increase. Although not a major emission source presently, massive peat fires smoldering in remote boreal and subarctic regions for years are not impossible should frequency and severity of drought increase sufficiently (Gorham, 1995; Davidson and Janssens, 2006).˙ Unfortunately, peatland carbon -- although a major sink in the carbon cycle and animportant uncertainty affecting the nature of climate change (Moore et al., 1998) – is not included explicitly at present in models of earth or climate systems (Limpens et al., 2008) because peatland dynamics are not sufficiently understood. Progress is, however, being made toward this end (Frolking et al., 2009, Wania et al., 2009, Kleinen et al., 2012).

2. Methods

Carbon accumulation in peatlands depends upon past and future rates of peatland initiation and the rate of carbon accumulation after initiation. Both vary, but can be estimated by fitting ecological models to data from sample peatlands. Past rates (Table 1, equation 1) we estimated earlier (Gorham et al., 2007). Here we combine that result with average carbon accumulation rates in established peatlands to estimate past and future carbon accumulation.

Methane concentration generally increases with depth in peat (Clymo and Pearce, 1995; Romanowicz et al., 1995; Kravchenko and Sirin, 2007; Clymo and Bryant, 2008) indicating that decay does continue, albeit very slowly, at all depths. To fit carbon accumulation data for existing peatlands we use the simplest model that includes both addition at the surface and decay in anoxic conditions. We make two assumptions (Clymo, 1984): carbon accumulates by net photosynthesis at a constant average rate per unit area (parameter *a*, Table 1, equation 2), and carbon is lost at a constant average rate per unit volume (parameter *b*, Table 1, equation 2). These assumptions cause an exponential rise to an equilibrial depth in any peatland, carbon added by photosynthesis eventually being balanced by carbon lost by decomposition (Table 1, equation 3). These assumptions are simplistic, for instance fire may cause substantial losses of peat from time to time (Kuhry, 1994), but they fit as well to real data as do more realistic models and are much better, and more realistic, than a straight line (Clymo, 1992). The underlying assumption is that each peatland has followed the same growth trajectory though starting at different times. Over the large area of North America this cannot be true, so the scatter is much greater than it would be for a single peatland age/depth profile: Individual depth/age relationships range widely from curvilinear to linear (Gorham et al., 2003). All we are interested in here, however, is getting the most plausible simple summary for the whole data set. Yu (2011) also uses this model. Fitting the resulting equation (Table 1, equation 3) to depths and ages of sample peatlands gives depth of an average peatland as a function of time (Fig. 1).

Using observations on 2,061 sample peatlands of known ages (Fig. 2), we identified an ecological model that best represented peatland initiation over time. We employed algorithms for inverse modeling established earlier (Gorham et al., 2007) to fit equation 1, Table 1, to cumulative data on peatland initiation. Each sample peatland has a probability distribution associated with its initiation date, determined when the ^{14}C date for that sample was assigned (see gray horizontal bars in Fig. 3). The median date in each distribution orders the peatlands by age. That ordering is not definitive, however, because probable dates from the distribution other than the median will induce different orderings and in turn produce alternative sets of cumulative data. To assess potential differences we generated 1,000 sets, randomly selecting probable dates from each individual ^{14}C probability distribution and reassembling them into the order induced by those random selections. The continuous curve beneath the dots in Fig. 3 shows the central 95% of those cumulative curves. Varying selection of dates reorders individual peatlands but has little effect on the shape of the cumulative curve.

The peatland-initiation model (Table 1, equation 1) uses three parameters (Gorham et al.,

2007) to fit chronological data: (1) average lag following glacial retreat, as sites become suitable for peat deposition, (2) average fraction of land area that becomes suitable for peatland initiation, and (3) average rate of peatland initiation per unit of suitable land area. Fitting equation 1, Table 1, gives the resulting cumulative function, shown as a dotted curve in Fig. 3, with best-fit parameters $\lambda = 249.5$, $\tau = 1330$, and $r = 0.000198$. This step was accomplished with customized computer programs (Gorham et al., 2007) using simulated annealing. The results describe the data well ($R^2 > 0.99$), allowing initiation to be projected as a dotted line into the future (Fig. 3, incorporating 381 ^{14}C ages additional to those in Gorham et al. (2007). Using a subset of observations on 1,686 sample peatlands for which both age and depth are known, we continued by finding a curve representing average depth of peat as a function of age. Employing functional parameter fitting (Clymo et al., 1998) to accommodate uncertainties in both age and depth, we determined parameters for equations 2 and 3, Table 1. The curve in Fig. 1 (solid) and its 95% confidence intervals (dashed) are the result, with parameters given in Table 1, again fitted by a customized computer program using simulated annealing. Combining the results of the prior two steps with equation 4, Table 1, gives total peatland carbon accumulation and rate of accumulation in both the past and future. The curve in Fig. 4, with its 95% confidence intervals, is the result, with parameters $s = 0.0602$ and $H^*=434.5$. This step employed a standard computational package (Mathematica).

3. Results

Peatland initiation lagged behind deglaciation (Fig. 3), probably as a result of several causes: slow migration of peatland plant propagules, time to drain large postglacial lakes, filling lakes by sediment prior to peat deposition, impedance of upland drainage by leaching and formation of relatively impermeable iron "pans" in sandy soils, regional rises of sea level, regional isostatic rebound, and slow migration of beaver into deglaciated landscapes (Gorham et al., 2007).

At 9,000 BP most peatlands were newly formed. Today the most common age is about 7,000 years. Peaks of age distribution shift right with time (Fig. 5), so that 5,000 years from now the average peatland will be 12,000 years old and only about 1% will be initiating**.** The present pattern of rise and decline in peatland age is explained in Fig. 3. Rate of initiation first increased because deglaciation released suitable sites almost linearly. By 7,000 BP deglaciation was almost complete, new suitable sites became increasingly scarce, and the rate of initiation slowed.

Rates of peat accumulation in North American biomes (Dyke, 2005) vary widely and average 0.43 mm yr^{-1} (Table 2). The overall range is from 0.28 mm yr^{-1} to 0.65 mm yr^{-1}. The range for northerly subalpine forest and tundra is 0.28-0.38 mm yr^{-1}, for non-tundra forests 0.34-0.51 mm yr^{-1}, and for dry steppe, savanna, and prairie grassland (only 37 sites) 0.43-0.65 mm yr^{-1}. Gorham et al. (2003) observed that long-term mass accumulation rates in 21 North American peatlands were inversely related to present-day mean annual precipitation.

Carbon stored in North American peatlands was computed by multiplying the cumulative area of 1,372,000 km^2 (Bridgham et al., 2006), by the mean depth, 2.49 m, for 1,686 sites (Fig. 2) and carbon content (average bulk density and carbon percentage from Table 3, which also includes mean depths from other North American peatland studies). The resulting mass is 163 Pg.

4. Discussion

Gajewski et al. (2001) used *Sphagnum* spores in North American and Eurasian peat cores to derive a curve (their Fig. 7) similar to our Fig. 4, with total accumulation based on an estimate by Gorham (1991) of 455 Pg for all northern peatlands. Yu (2011) showed a peatland-initiation curve, based on 1,516 basal-peat dates for all northern peatlands, that is similar to our Fig. 3 and to Fig. 12 in Gorham et al. (2007). Owing to inclusion of Eurasian peatlands, however, his initiation dates peak about 2,500 years earlier than ours.

Total carbon accumulated over time, scaled to our calculated value of 163 Pg, reflects the number of peatlands initiated. Because the initiation model (Table 1, equation 1) fits the data so precisely, it can be used with the carbon sequestration model (Table 1, equations 2 and 3) to estimate total carbon accumulation (Fig. 4) and to estimate what future accumulation would be without effects of anthropogenic climate change. Postglacial climate change appears to have had little long-term effect upon reservoir size. The single prominent anomaly was suppression of peatland initiation during the 8,200 BP Cold Event (Gorham et al., 2007). The Holocene Thermal Maximum, 1.8 +/- 0.8 ^{o}C above 20th-century summer temperatures and timetransgressive from northwest North America across to northeast North America between ~12,000 and 5,000 BP (Kaufman et al., 2004), does not appear to have disrupted carbon sequestration.

Mathematically the model (Table 1, equation 4) involves a convolution (Kecs 1982), applying the depth/age relationship in reverse to cumulative dates since 20,000 BP. Fig. 4 (solid line with 95% confidence intervals) shows calculated carbon accumulation to have been negligible 15,000 years ago, increasing rapidly after 10,000 BP. The rate of accumulation peaked at 17.3 Tg yr $^{-1}$ about 2,600 BP and is now 16.1 Tg yr $^{-1}$. After 5,000 years the number of peatlands initiated will have increased by 12% and the amount of carbon accumulated by 42%, though the rate of accumulation will have decreased by 31%. These projections provide baselines to assess effects of climate change upon future carbon accumulation in peatlands. They suggest a gradually declining rate in the absence of human interference. Such interference is, however, likely to have profound effects upon both CO_2 and CH_4 dynamics in peatlands (Gorham, 1991, 1995; Bridgham et al., 1995; Davidson and Janssens, 2006; Ise et al., 2009).

Table 4 provides a range of constraints for carbon mass, calculating them with minimum, mean, and maximum estimates of depth and dry bulk density (Table 3) along with peatland area (Bridgham et al., 2006) and our mean value for carbon content (Table 3). Calculated minimum and maximum masses are 74 and 212 Pg. Using mean values for depth and dry bulk density yields 152 Pg, 93% of the estimate (above) based on our data set. Our estimates compare to independent estimates of 178 Pg in North America (Bridgham et al. (2006), and147 Pg in Canada (Bhatti et al., 2009). Other large regional estimates are 70 Pg in the West Siberian Plain (Smith et al., 2004), 214 Pg in the former Soviet Union (Kolchugina et al., 1998), and 547 Pg in all northern peatlands (Yu, 2011).

For North American peatlands, dividing total mass (163 Pg) by average age (6,950 yrs) yields an accumulation rate of 23.5 Tg yr^{-1}, and dividing further by total area yields a rate of 17.2 g m^{-2} yr^{-1}. Our annual accumulation rate is a little less than one-third of Yu's (2011) estimate of 74.8 Pg for all northern peatlands. His estimate of 18.6 g m^{-2} yr^{-1} is a little greater than ours. As observed by Gorham (1991), direct measurement (as above) yields accumulation rates distinctly greater than those using models such as that of Clymo (1984) and the model we present.

Conclusions

Estimates of carbon sequestration by North American peatlands indicate that they are an important sink, approximately one-quarter of the 615 Pg estimated by Yu (2011) for global peatlands. The chief uncertainty, which needs to be researched, concerns the importance of the Hudson Bay Lowland, one-quarter the size of Ontario and covered largely by fens and bogs developed over the past 7,000 years (Riley, 2003). Possible underestimation of carbon in thin peats also needs to be studied.

The model we present, illustrating sequestration of atmospheric carbon in peat over the past 20,000 years and into the future, provides information useful for the peatland component of models treating temporal dynamics of soil carbon following the Laurentide deglaciation shown in Fig. 3 (Harden et al., 1992). For all terrestrial ecosystems (including peatlands), glacial/interglacial change in carbon storage was estimated at 700-1,350 Pg by Sigman and Boyle (1992), of which the North American peatland carbon pool (especially if projected 20,000 years into the future without anthropogenic climate change) is by itself a substantial proportion. It is the persistence of the global peatland-carbon sink that makes it significant climatologically (Frolking and Roulet, 2007).

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E.G. conceived and drafted the manuscript, C.L. carried out and described the modeling, A.D. provided information on deglaciation, biome designation, and the majority of peat ages and depths, D.C. fitted the curve in Fig. 1, and J.J. provided many age and depth data, and assisted with early drafts.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online material.

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Table 1.

Equations used to model peatland initiation and carbon accumulation

$$1. \quad \frac{dN(t)}{dt} = r\Big(\gamma A(t-\tau) - N(t)\Big)$$

$$2. \quad \frac{dH(t)}{dt} = a - bH(t) = s\left(1 - \frac{H(t)}{H^*}\right)$$

$$3. \quad H(t) = H^*\left(1 - e^{-s\,t/H^*}\right)$$

$$4. \quad C(t) = B\int_0^{\infty} N'(t-z)\,H(z)\,dz$$

Parameters and variables: $N(t)$ is the number of peatlands established at time t; $A(t-\tau)$ is the area exposed by deglaciation τ years before time t ; r is the intrinsic peatland initiation rate; γ is the average number of sample peatlands supportable per unit area; $H(\alpha)$ is average peatland depth at age α; H^* is mean equilibrial peatland depth; a is average height added at the surface per unit time by photosynthesis; b is average height lost in the column per unit time and depth by decomposition; s is the maximal mean rate of increase in peatland height; B is the carbon content of peatlands per unit depth per sample peatland; $C(t)$ the total carbon content of peatlands at time t; and z is a variable of integration.

Table 2.

Rate of accumulation of North American peats, top to bottom

Biome	*Rate* (mm yr^{-1})	*N*	*Youngest* (years)	*Oldest* (years)	*Range* (years)
Subalpine Forest	0.28	53	555	14590	14036
Alpine Tundra	0.29	24	9265	16471	7207
Conifer Forest	0.34	21	9764	14720	4957
Shrub Tundra	0.34	200	375	17327	16953
Forest Tundra	0.35	99	197	15702	15506
Herb Tundra	0.38	111	165	19903	19739
Interior Forest	0.40	13	3515	11478	7964
Steppe	0.43	4	7762	11598	3837
Savannah	0.43	11	2120	9306	7187
Boreal Forest	0.46	702	73	17558	17486
Coast Forest	0.47	138	423	16349	15927
Mixed Forest	0.49	190	607	14121	13515
Deciduous Forest	0.51	82	653	10942	10290
Boreal Parkland	0.53	13	1992	11086	9095
Grassland	0.65	22	1140	9287	8148
Total	0.43	1683	73	19903	19831

Note: Top-to-bottom rates of peat accumulation vary a great deal over time (Fig.1) as does the variety of depositional patterns within individual peat deposits, as shown by numerous studies.

Table 3

Estimated characteristics of North American peats

A. Bulk density of dry peat (kg m^{-3})

Region	*Type*	*Bulk Density* (kg m^{-3})	*Reference*
Canada and Maine	Peatland	91	Gorham, Janssens & Glaser (2003)
Canada	Peatland	112	Tarnocai (1984)
Canada	Peatland	100	Ovenden (1990)
Canada	Peatland	112	Gorham (1988)
British Columbia	Bog	98	Turunen & Turunen (2003)
NW Canada	Bog	94	Robinson & Moore (1999)
NW Canada	Fen	88	Robinson & Moore (1999)
W Canada	Peatland	106	Vitt, Halsey, Bauer & Campbell (2000)
New Brunswick	Peatland	79	Keys & Henderson (1987)
Maine	Bog	71	Tolonen, Davis & Widoff (1988)
Mean (*n* = 10)		95.1 ± 13.5 s.d.	

B. Mean depth (m)

Region	*Mean Depth* (m)	*Reference*
North America	2.49	This study
Canada and USA	2.29	Gorham (1991)
Western Canada	2.59	Vitt, Halsey, Bauer & Campbell (2000)
Ontario	1.51	Riley (1987)
New Brunswick	2.76	Keys & Henderson (1987)
Mean (*n* = 5)	2.33 ± 0.49 s.d.	

Note: In Ontario and New Brunswick surveys were detailed and not restricted to the deepest points. In western Canada, maximum depths of 818 peatlands were adjusted for basin topography, but the peatlands were found to be relatively flat.

C. Carbon content of dry peat (%)

Region	*Type*	*Carbon* (*% dry weight*)	*Reference*
Canada	Peatland	51.7	Gorham (1991)
NW Canada	Bog	45.7	Robinson & Moore (1999)
NW Canada	Fen	46.2	Robinson & Moore (1999)
W Canada	Peatland	47.7	Vitt, Halsey, Bauer & Campbell (2000)
New Brunswick	Peatland	50.0	Keys & Henderson (1987)
W Siberia	Peatland	52.7	Turunen *et al.* (2001)
Finland	Pine mires	53.9	Minkkinen & Laine (1998)*
Sweden	Fens	52.0	Klarquist (2001)*
Ireland	Bogs	51.1	Tomlinson & Davidson (2000)*
Mean (*n* = 9)		50.1 ± 2.9 s.d.	*cited by Turunen (2003)

Table 4

A constraining range of estimates of carbon mass (Pg) in North American peatlands, using minimum, mean, and maximum estimates of dry bulk density and depth(Table 3A and B), and assuming an area[17] of 1,372 x 10^3 km^2 and a carbon content of 50.1 (Table 3C)

Dry Bulk Density (kg m^{-3})	*Depth of Basal Peat (m)*		
	Min.	*Mean*	*Max.*
	1.51	2.33	2.76
Min. 71	74	114	135
Max. 112	116	179	212
Mean 95	98	152	180

Captions to figures

Fig. 1**.** The relationship between peat accumulation and age in North American peatlands. Dots show individual depth/age measurements. Horizontal bars are the 95% confidence intervals of the corresponding ^{14}C probability distributions for age. Vertical bars are plus or minus 10% assumed possible errors in depth measurements. Because measurement errors occur on both axes, we used functional parameter fitting[3] to minimize orthogonal distances between points and fitted curves, giving equal weight to both standardized variables.. The depth/age relationship, with 95% confidence range, is that of equations 2 and 3, Table 1. It has an R^2 of only 0.19, owing to marked variation among sites resulting from differences in topography, substrate texture, climate, and fire history. Here we are only interested in average values encoded by the curve itself.

Fig. 2. The spatial distribution of sample peatlands in North America 27 sites spanning the Aleutian Islands are not shown.

Fig. 3. Peatland formation in North America through time. Horizontal gray bars are 95% confidence intervals on individual ^{14}C ages of sample peatlands. The continuous curve beneath the dots represents the central 95% of 1,000 permutations of peatland ages sampled from actual ^{14}C probability distributions. The resulting cumulative curve is thus insensitive to random variations in individual ^{14}C dates. The dotted curve is the best-fit model of equation 1, Table 1, which allows projection into the future, without possible effects of climate change. The circles and dashed curve show the pattern of deglaciation over time.

Fig. 4. Accumulation of carbon in North American peatlands over time and projected into the future (ignoring effects of climate change). The ascending curve is total accumulated carbon from equation 4, Table 1 in the past (solid), for 5,000 years (dashed), and to the

more distant future (dotted), with surrounding 95% confidence intervals. The other curve is the corresponding rate of accumulation.

Fig. 5. Relative abundance of North American peatlands at different times in the past and projected 5,000 years into the future.

Figure 1

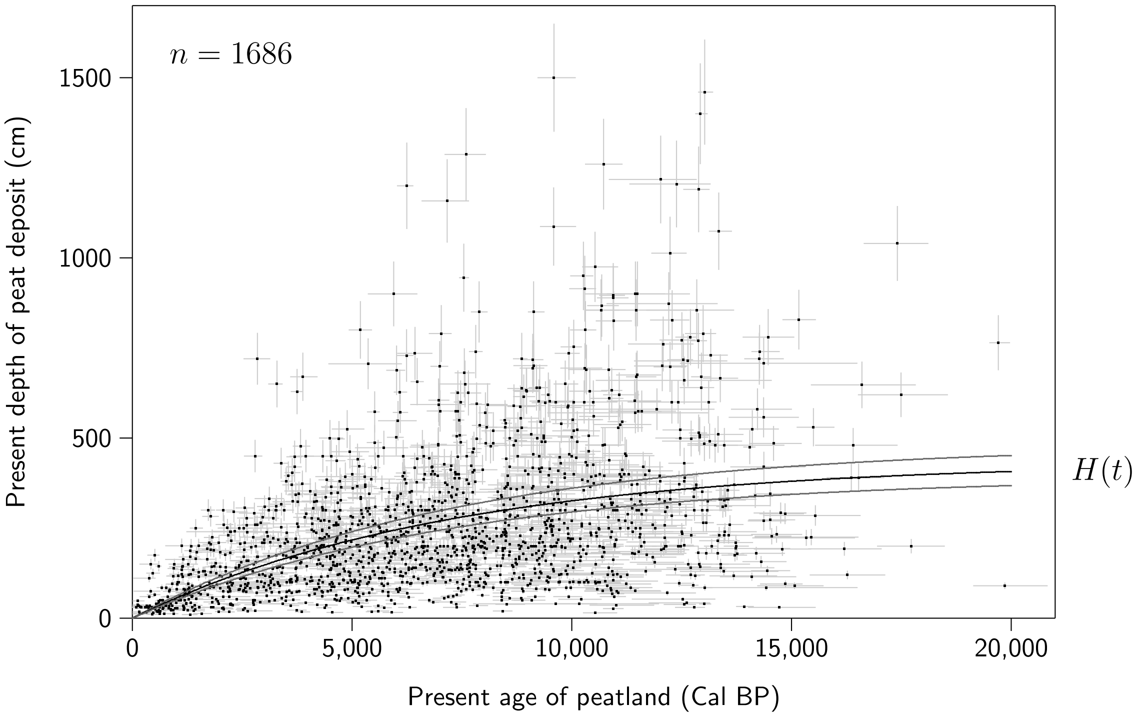

$n = 1686$
1500
1000
500
0
Present depth of peat deposit (cm)
0
5,000
10,000
15,000
20,000
Present age of peatland (Cal BP)
$H(t)$

Figure 2

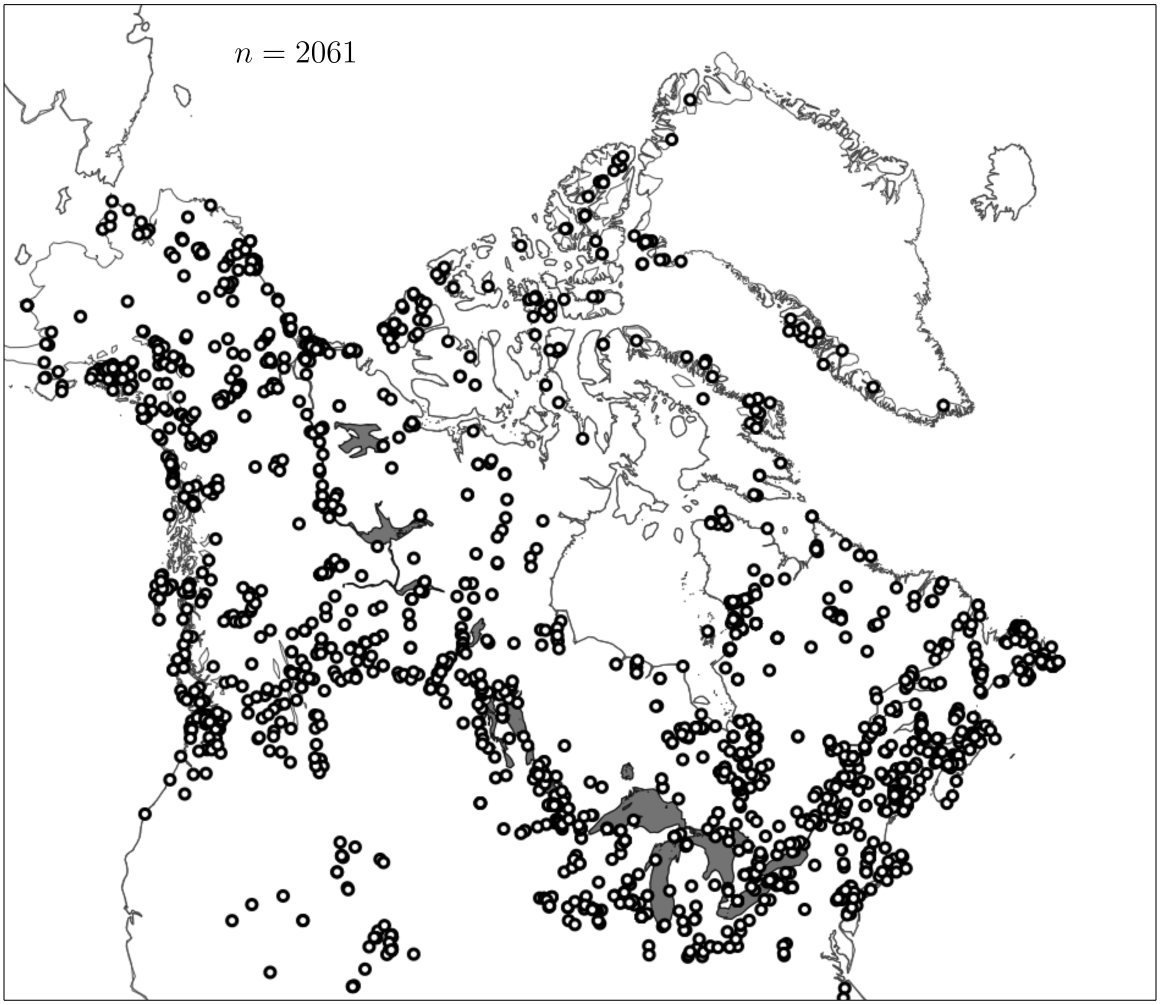


Figure 3

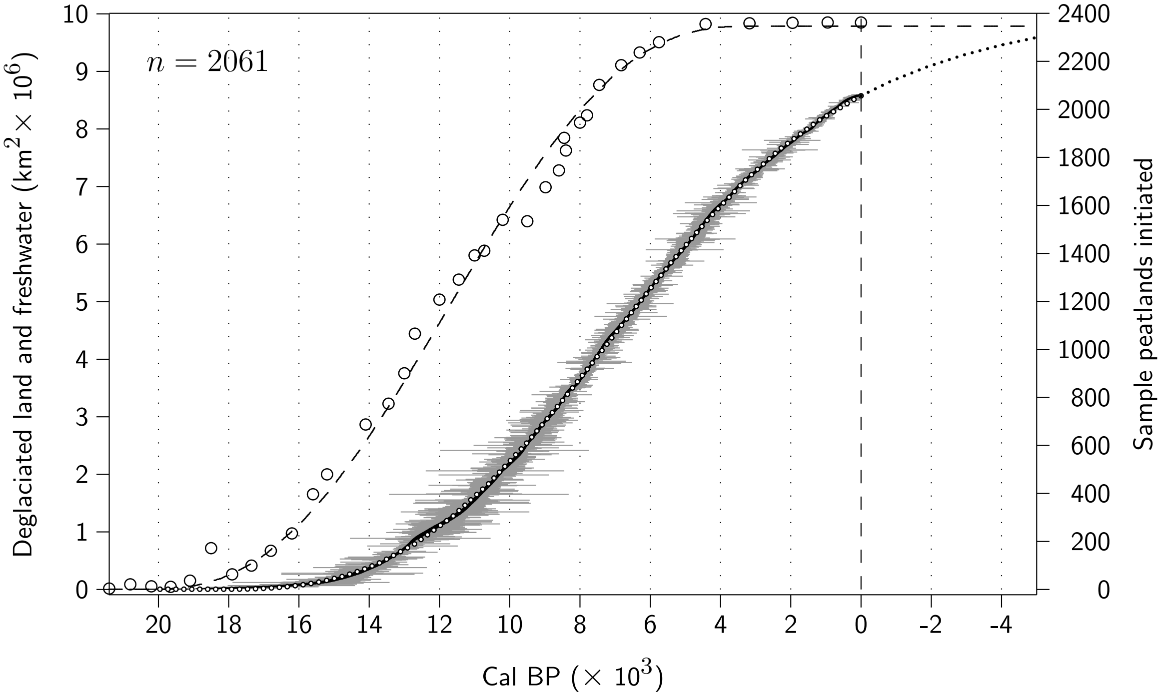
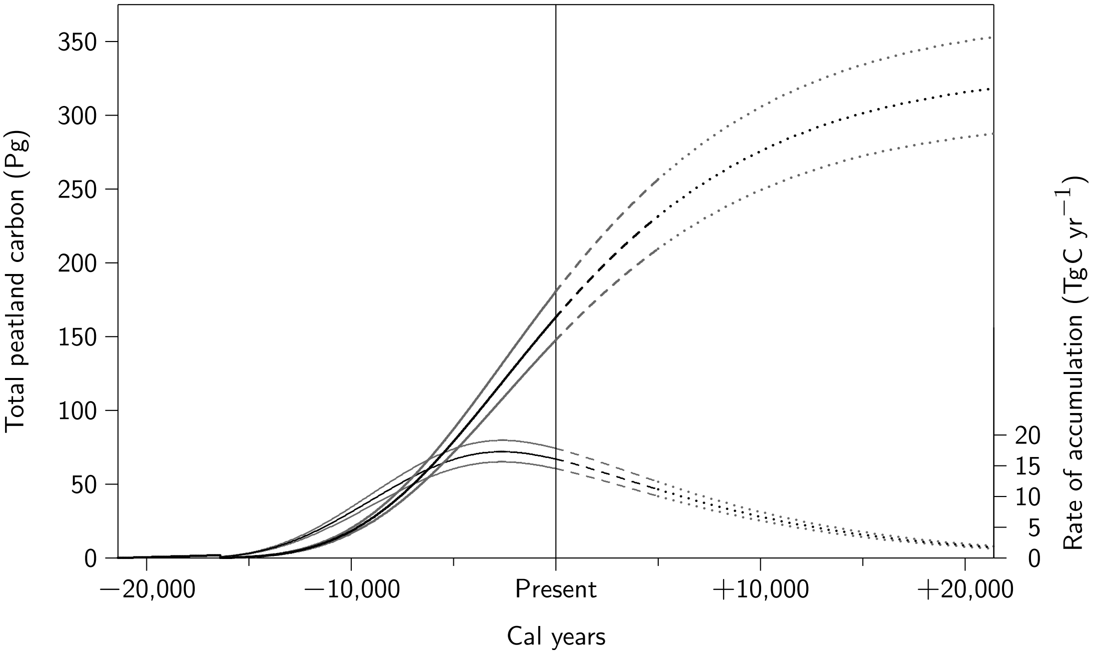
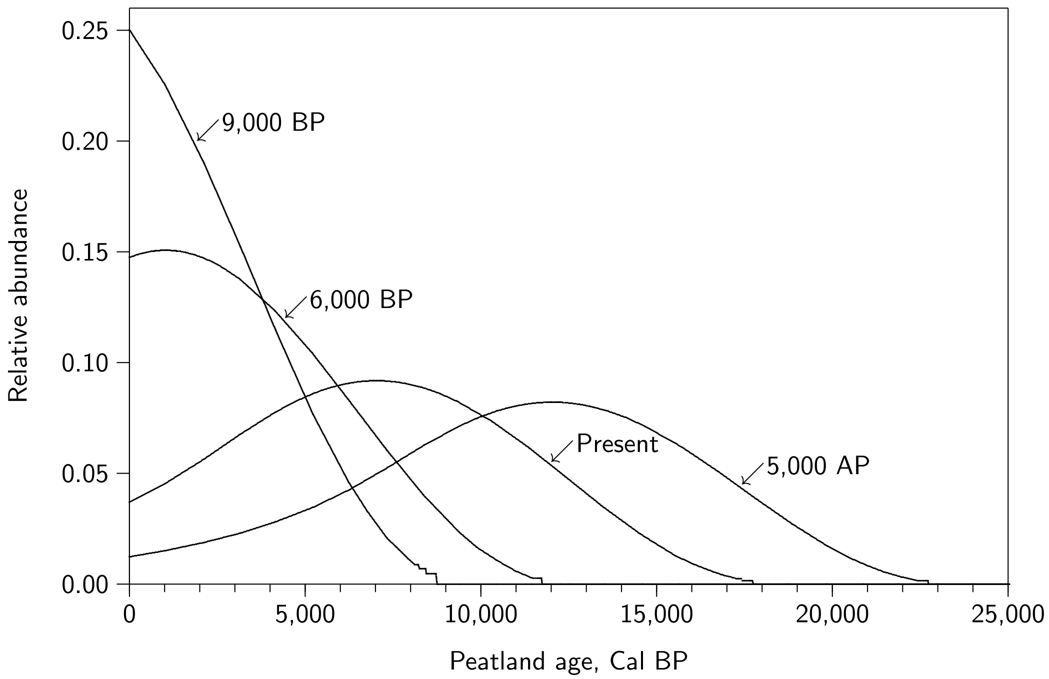

$n = 2061$
Deglaciated land and freshwater (km^2× 10^6)
Sample peatlands initiated
Cal BP (× 10^3)
0
1
2
3
4
5
6
7
8
9
10
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
20
18
16
14
12
10
8
6
4
2
0
-2
-4

Figure 4



Total peatland carbon (Pg)
0
50
100
150
200
250
300
350
Rate of accumulation (TgC yr^{-1})
0
5
10
15
20
−20,000
−10,000
Present
+10,000
+20,000
Cal years

Figure 5



9,000 BP
6,000 BP
Present
5,000 AP
Relative abundance
0.25
0.20
0.15
0.10
0.05
0.00
0
5,000
10,000
15,000
20,000
25,000
Peatland age, Cal BP