Carbon Storage in Northern Peatlands

Clarence Lehman
Eville Gorham
Richard Clymo
Art Dyke
Jan Janssens

November 26, 2013

Outline

1. Background
2. Peatland examples
3. Ice retreat
4. Peatland initiation
5. Carbon accumulation
6. Relaxation ocillator
7. A great prehistoric flood

Core, Gander Bay, Nfld 1982

Mining peat in Ireland

Northern peatlands

Ten percent of Minnesota is peatland. That is 8,000 square miles, our largest wilderness type.

Mining peat in Ireland

Northern peatlands

Ten percent of Minnesota is peatland. That is 8,000 square miles, our largest wilderness type.

Twelve percent of Canada is peatland.

Mining peat in Ireland

Northern peatlands

Ten percent of Minnesota is peatland. That is 8,000 square miles, our largest wilderness type.

Twelve percent of Canada is peatland.

More carbon is stored in the earth's soils than in the atmosphere, and a large share of that is in peatlands.

Mining peat in Ireland

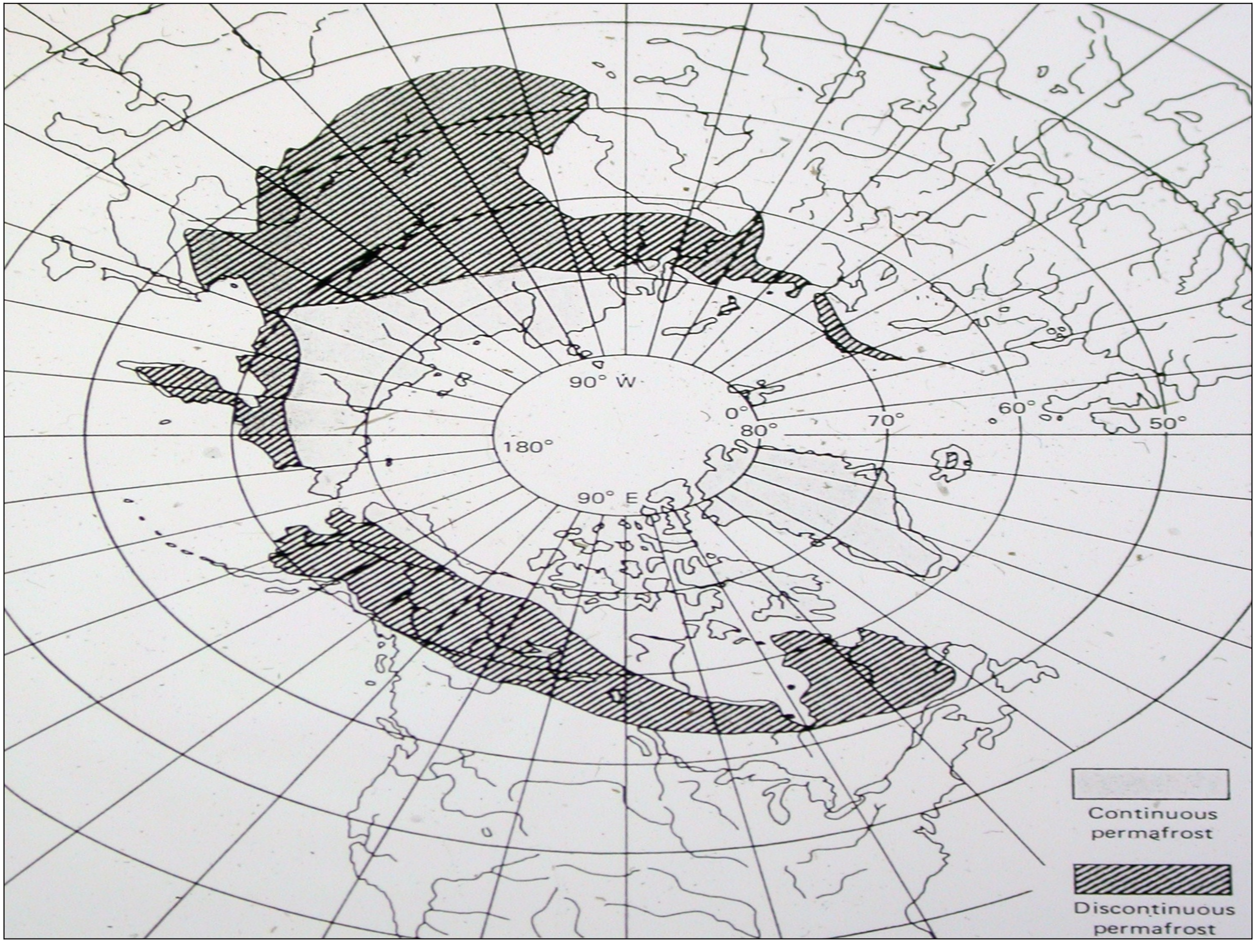
Northern peatlands

Ten percent of Minnesota is peatland. That is 8,000 square miles, our largest wilderness type.

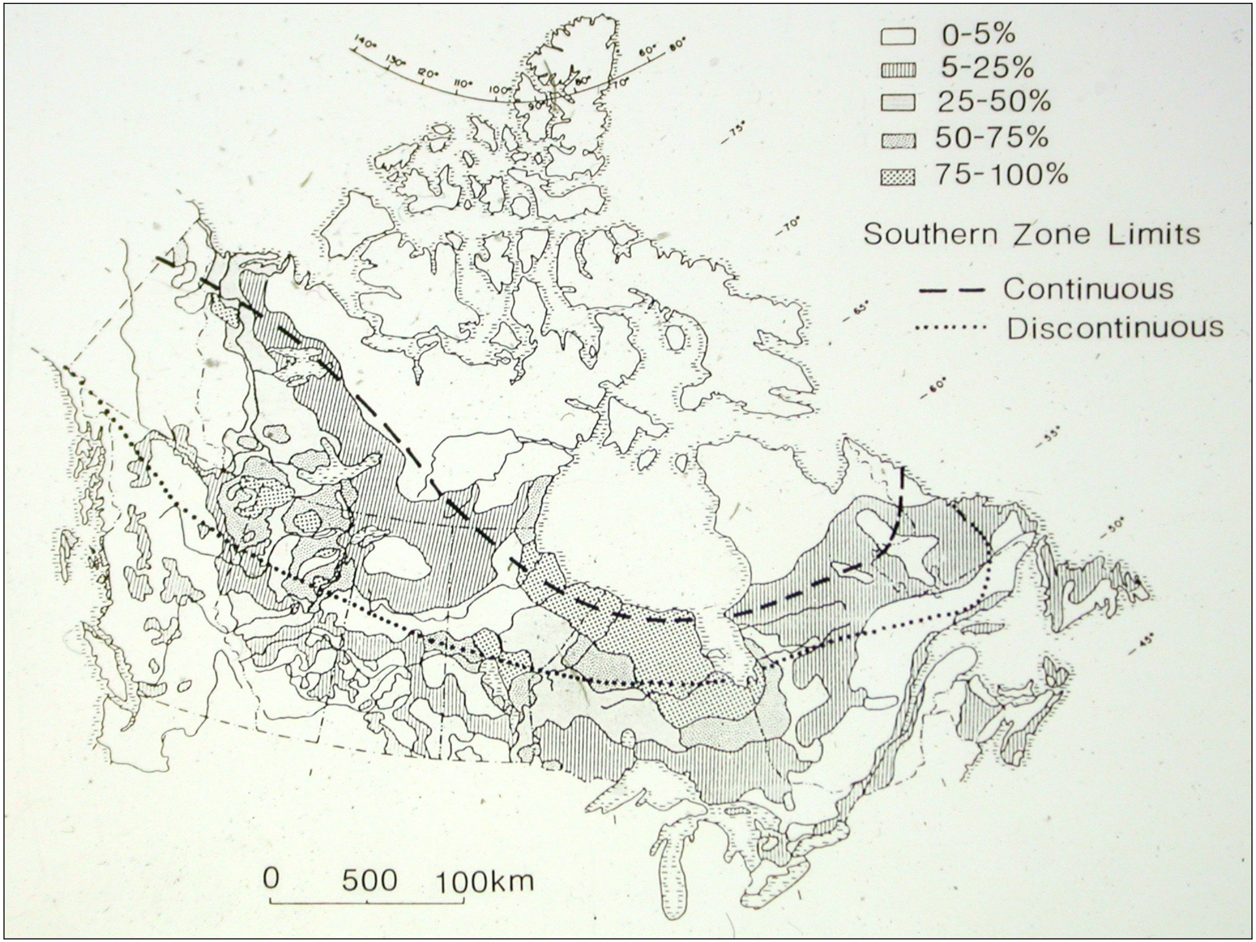
Twelve percent of Canada is peatland.

More carbon is stored in the earth's soils than in the atmosphere, and a large share of that is in peatlands.

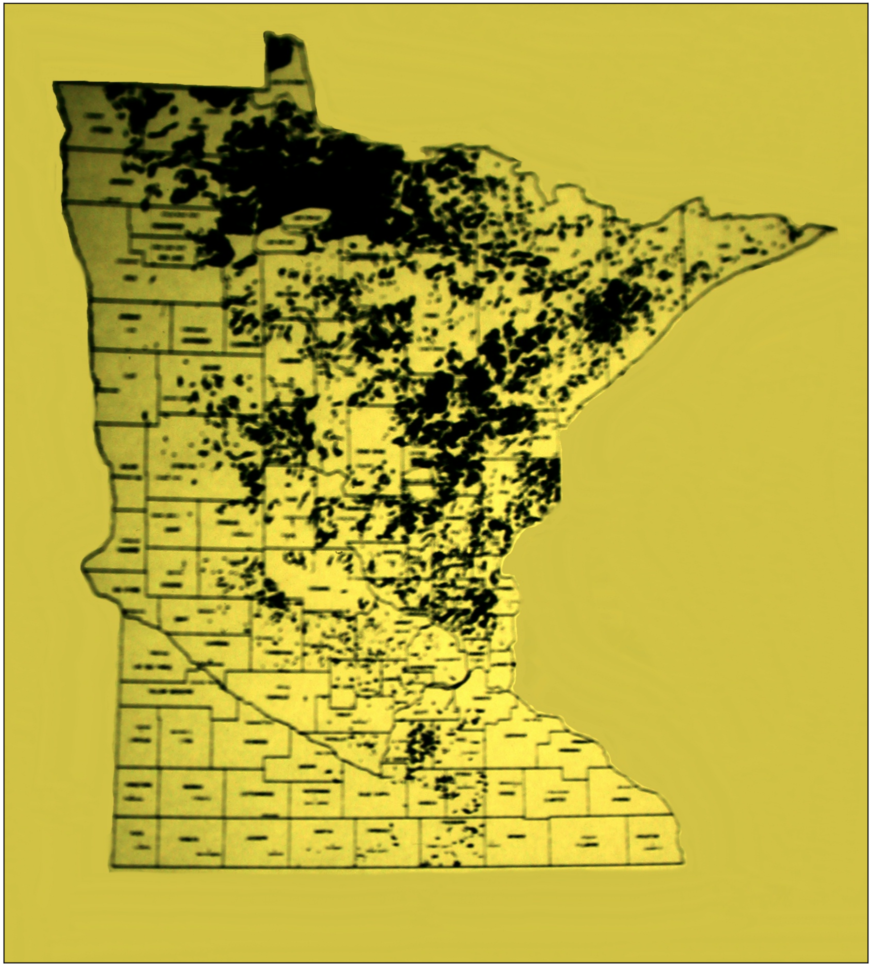
As the northern hemisphere warms, we do not know whether peatlands will sequester more carbon or release their carbon to the atmosphere.



Polar region with peatlands.



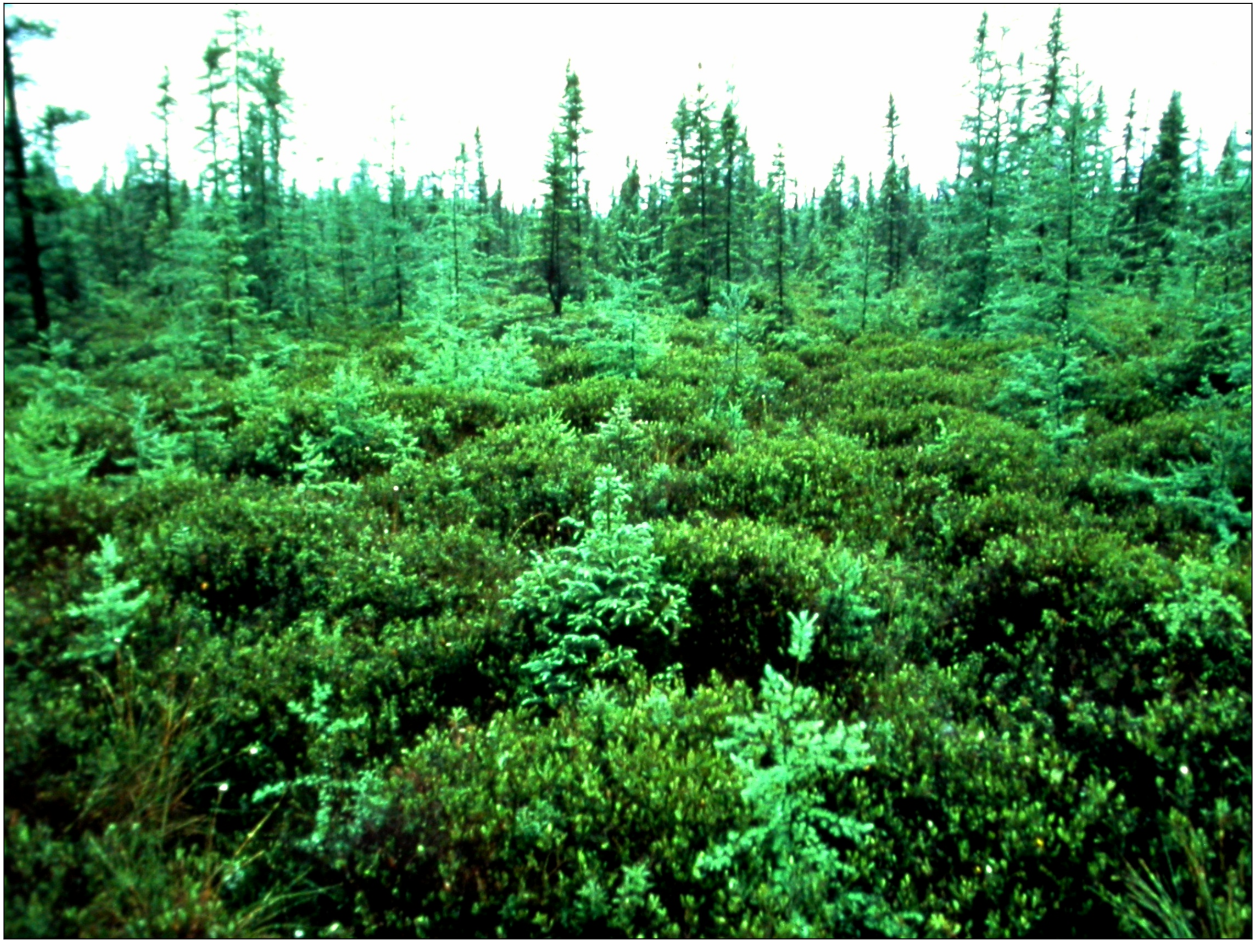
Peatlands of Canada.



Peatlands of Minnesota.

Outline

1. Background
2. <u>Peatland examples</u>
3. Ice retreat
4. Peatland initiation
5. Carbon accumulation
6. Relaxation ocillator
7. A great prehistoric flood

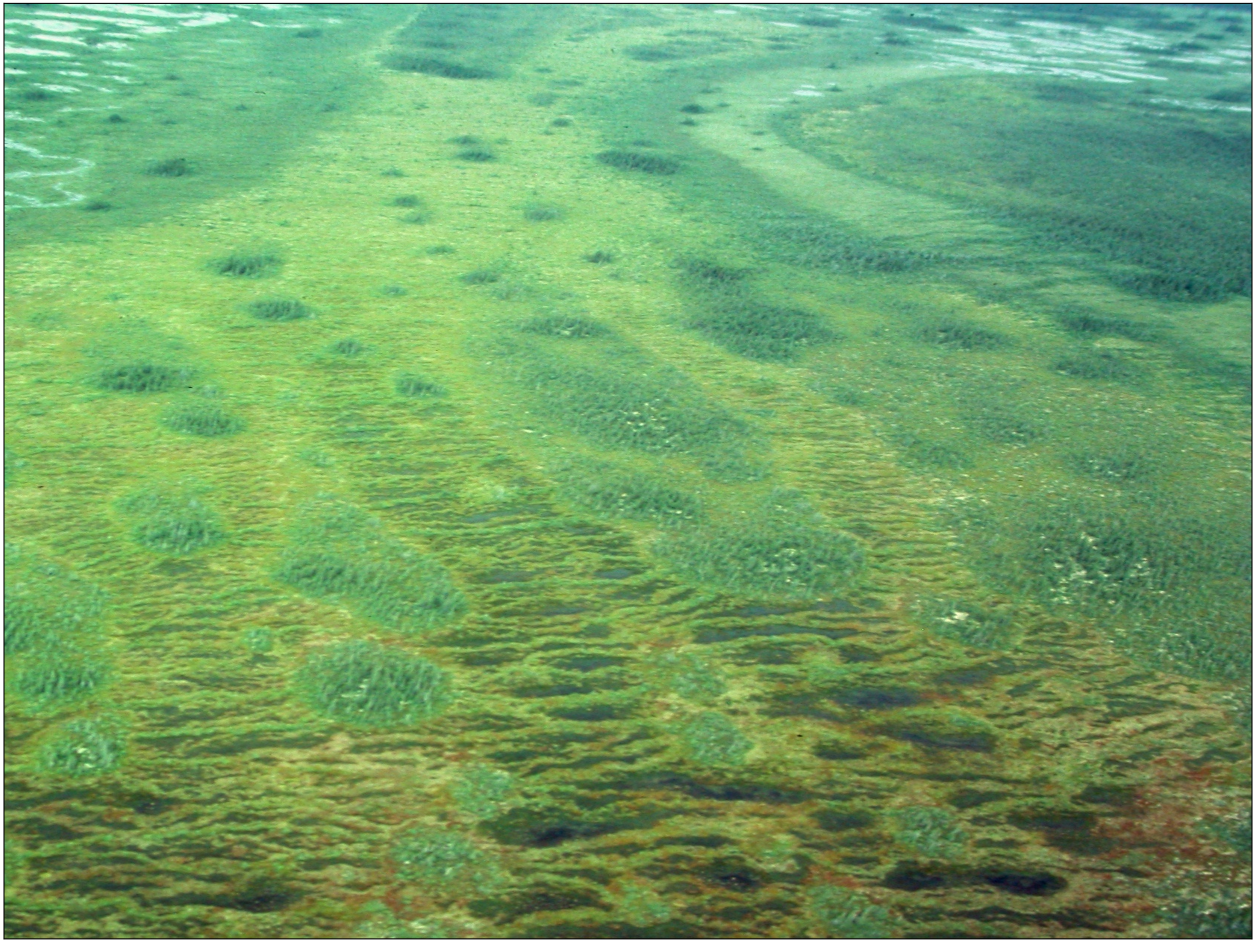


Raised bog

Red Lake Peatland with water track, Minn., EG

Red Lake Ridge and Trough, 8/1979, CLA

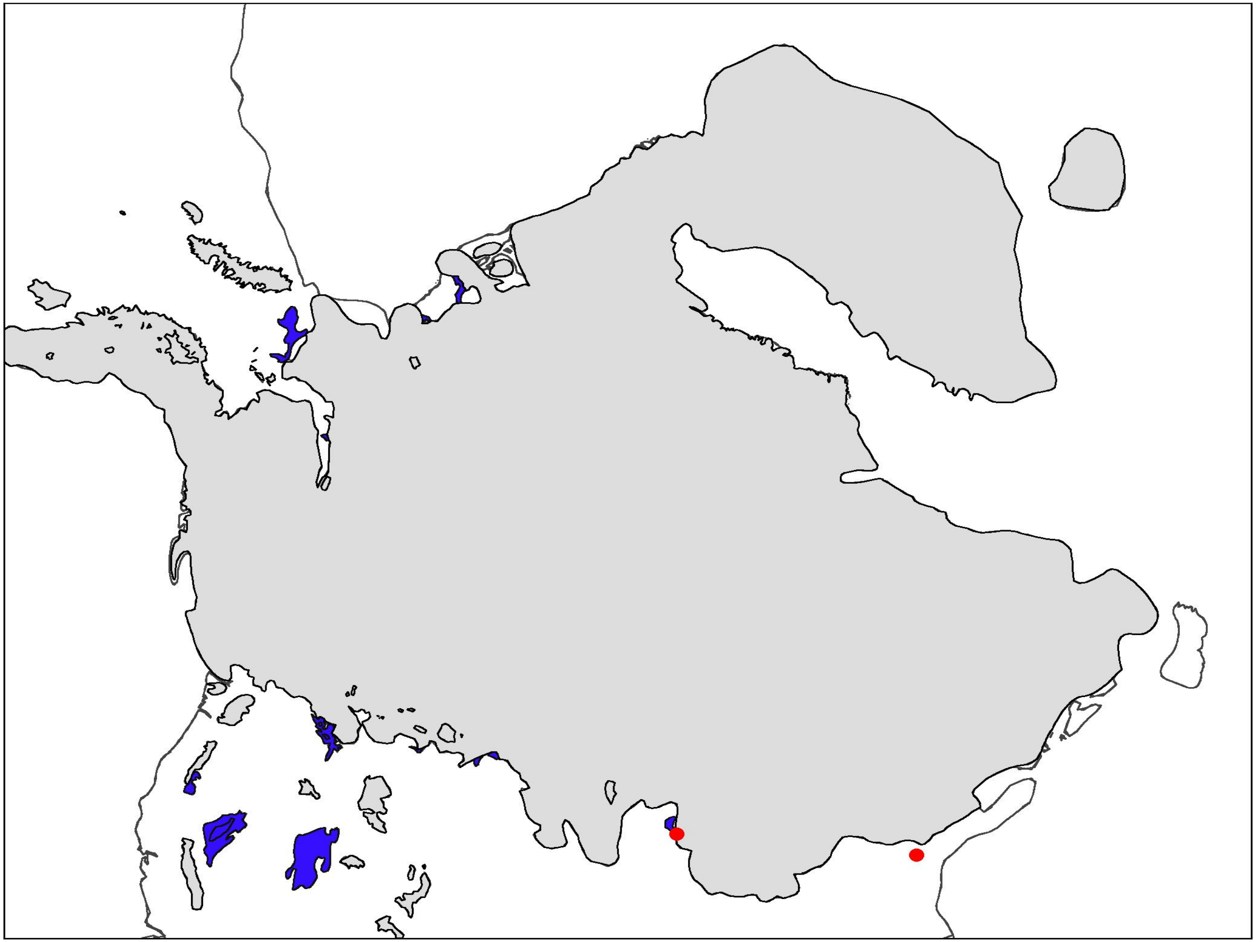
Bog "islands" in sedge fen, Upper Red Lake Peatland, perfect "teardrops", 10-24-1961



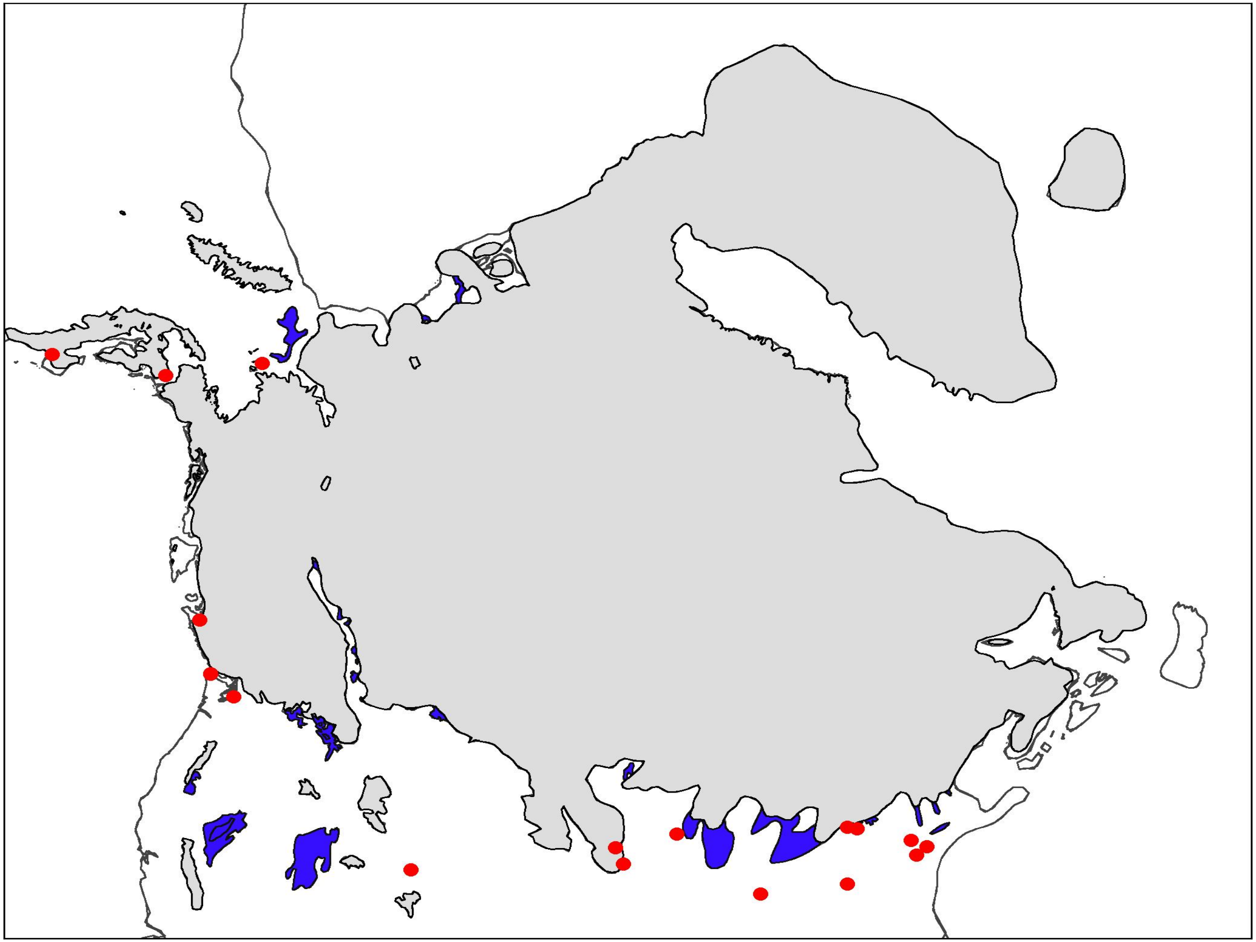
Hudson Bay Lowlands

Outline

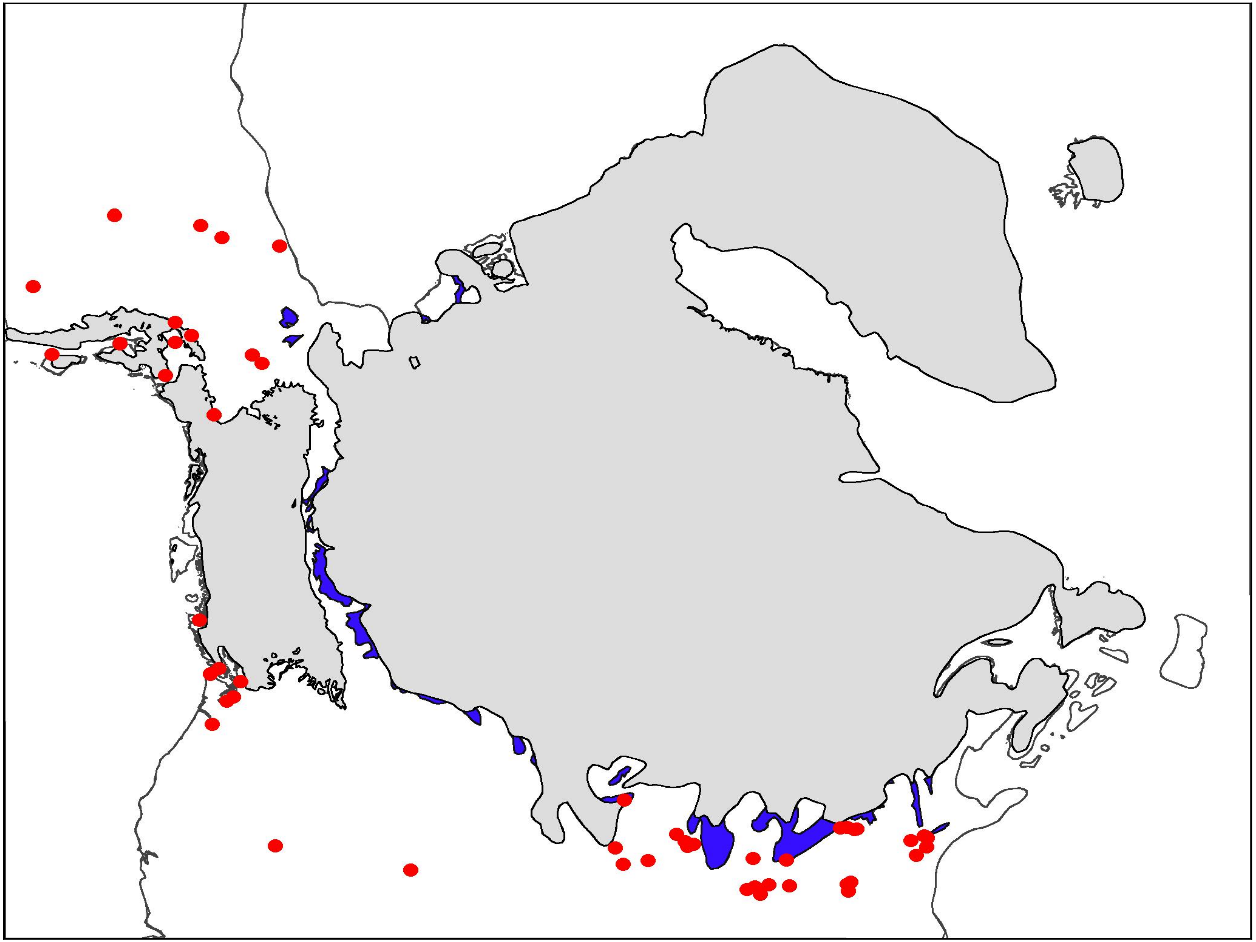
1. Background
2. Peatland examples
3. <u>Ice retreat</u>
4. Peatland initiation
5. Carbon accumulation
6. Relaxation ocillator
7. A great prehistoric flood



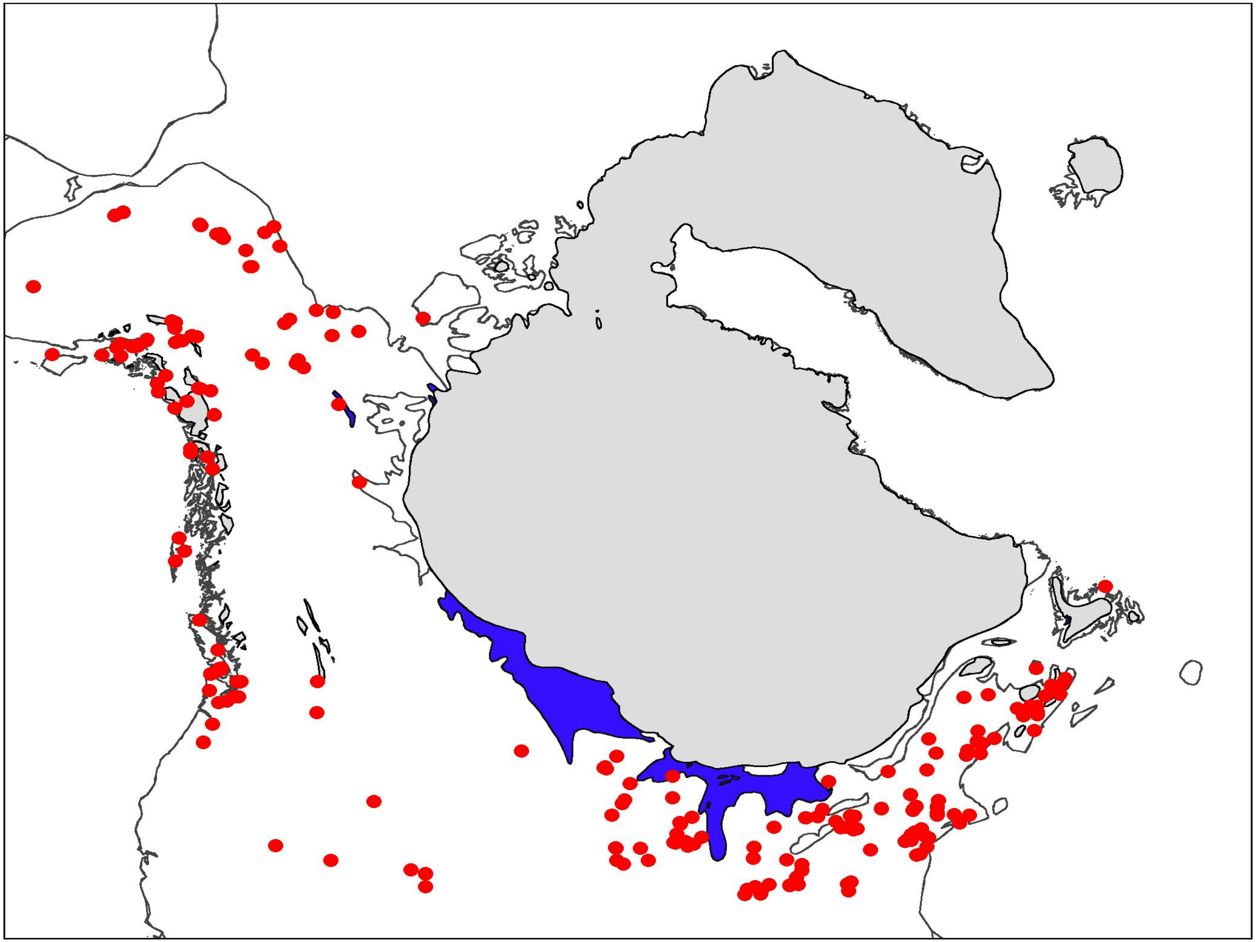
Sample peatlands initiated as of 19,650 BP



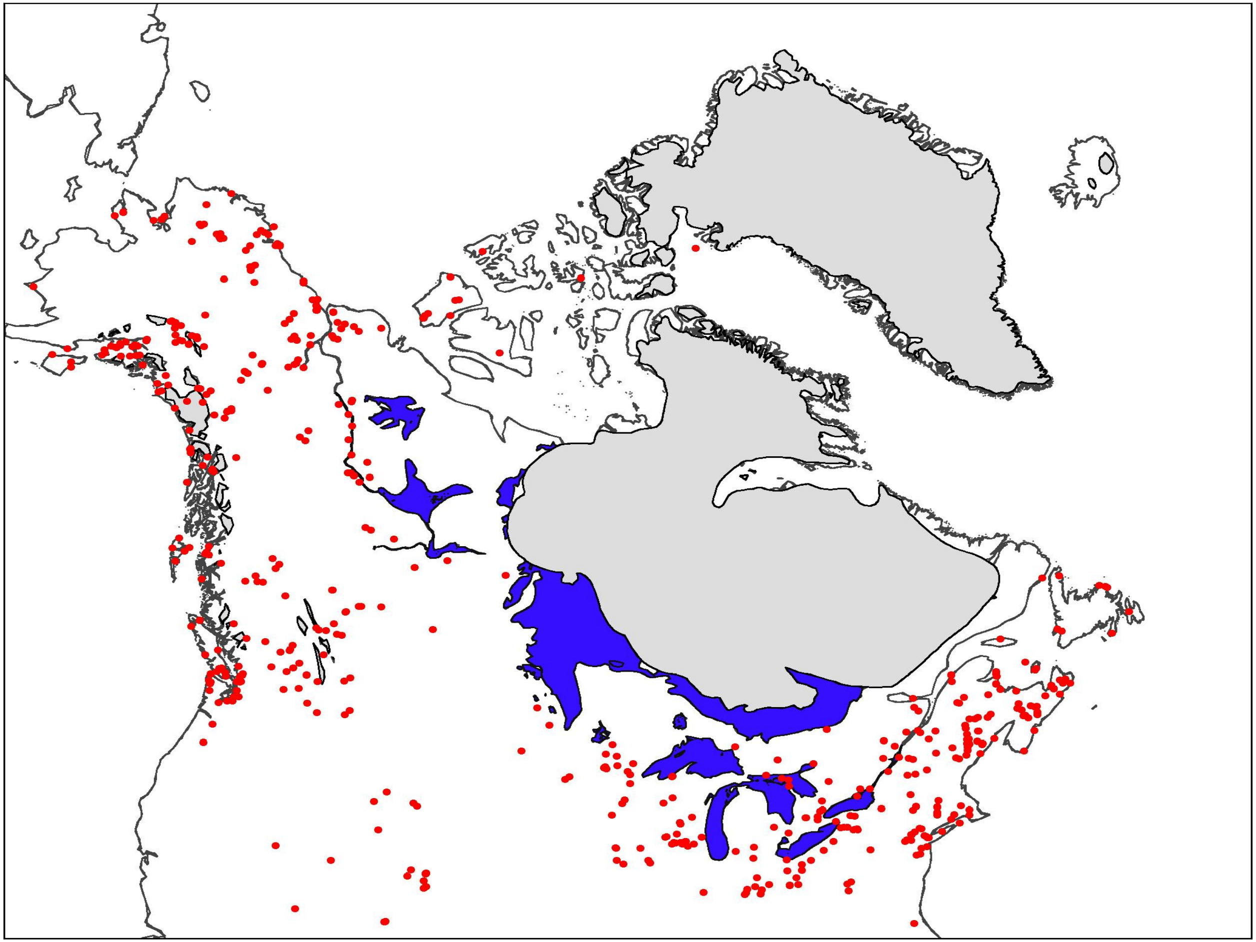
Sample peatlands initiated as of 16,200 BP



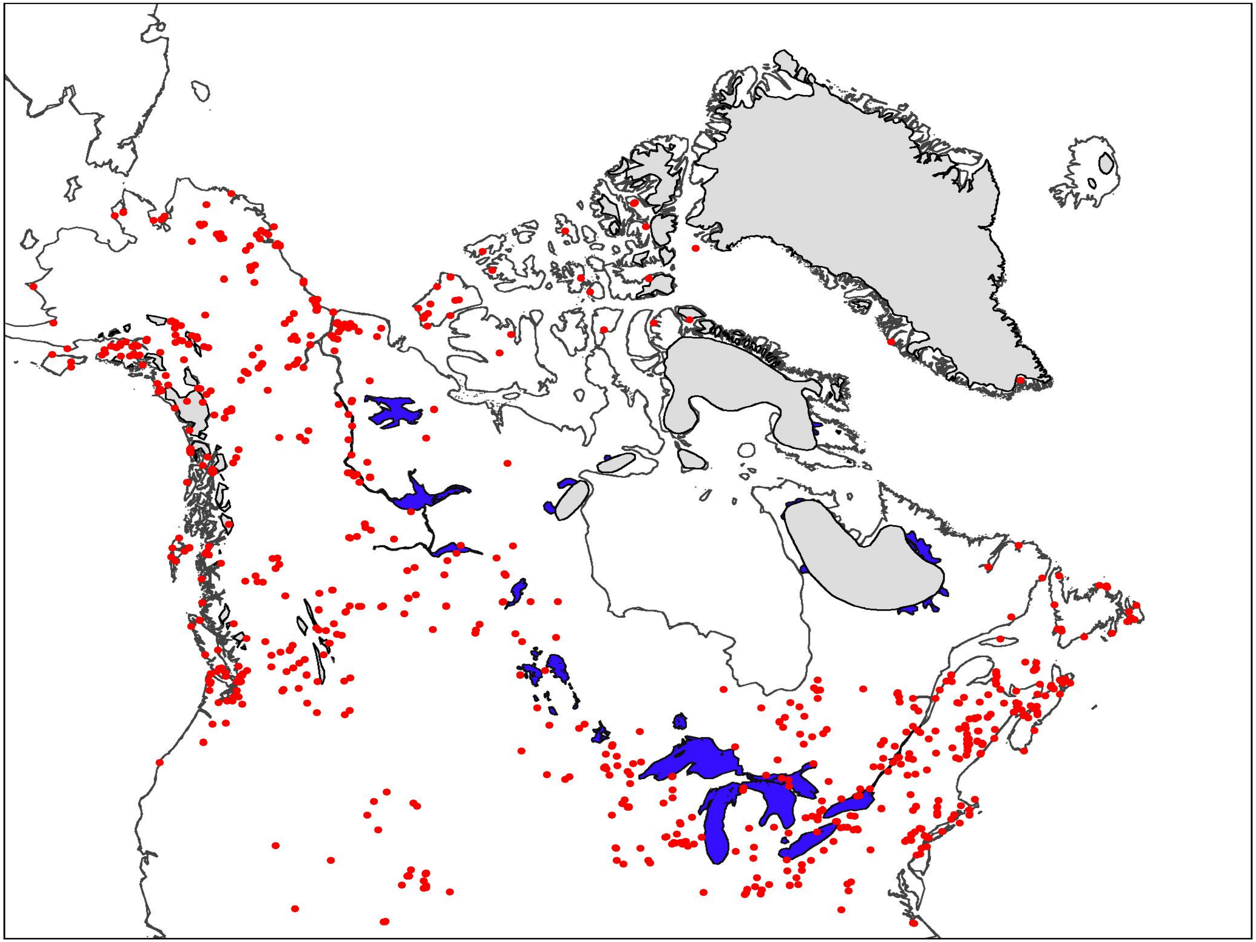
Sample peatlands initiated as of 14,700 BP



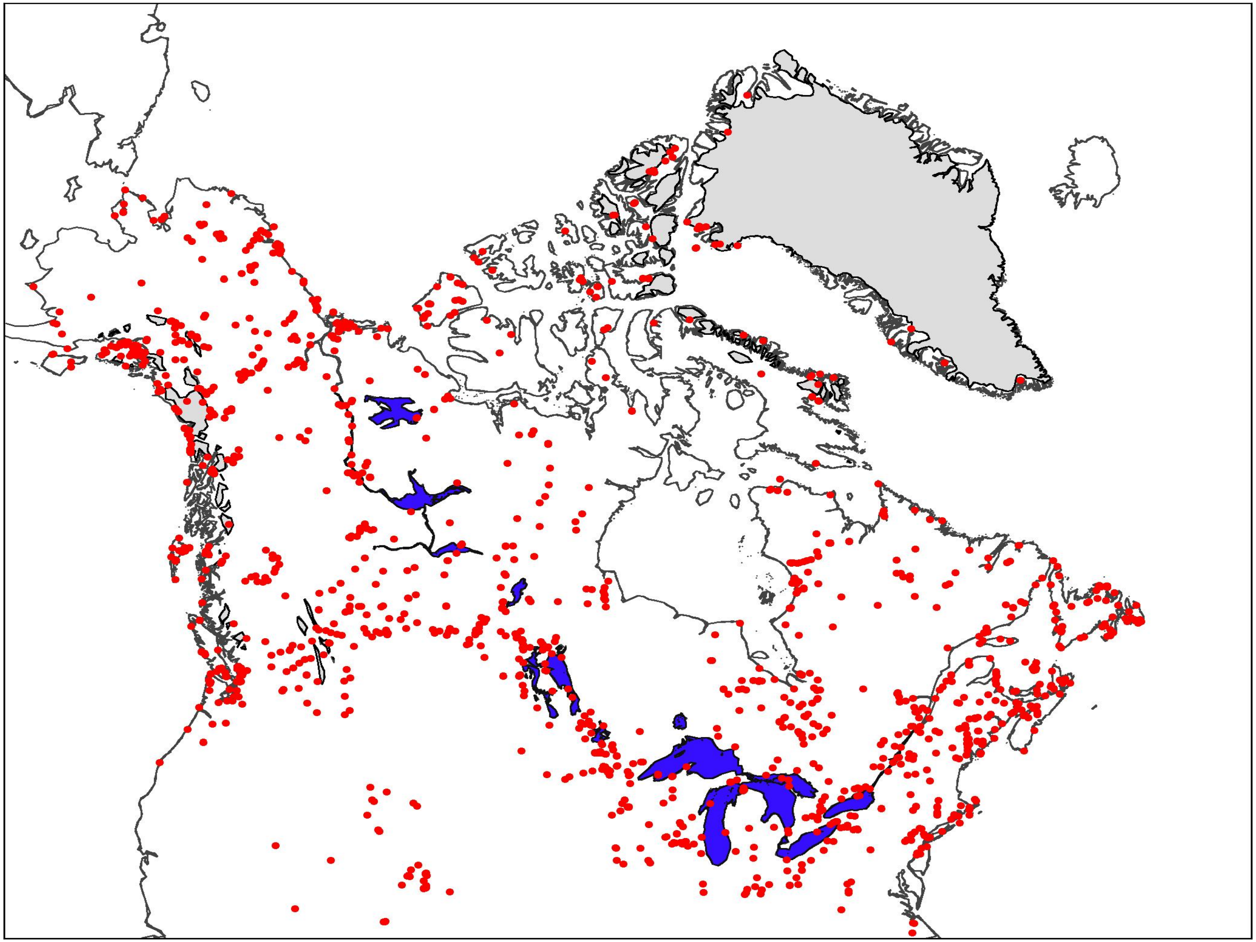
Sample peatlands initiated as of 12,000 BP



Sample peatlands initiated as of 8,900 BP



Sample peatlands initiated as of 7,400 BP



Sample peatlands initiated at present

Outline

1. Background
2. Peatland examples
3. Ice retreat
4. <u>Peatland initiation</u>
5. Carbon accumulation
6. Relaxation ocillator
7. A great prehistoric flood

Cedar Bog Lake, University of Minnesota, CCNHA

Peatland initiation

1. Start with a database of radiocarbon dates for the bottom levels of peatland sites in Canada and the USA (basal dates), and depths where available.

Cedar Bog Lake, University of Minnesota, CCNHA

Peatland initiation

1. Start with a database of radiocarbon dates for the bottom levels of peatland sites in Canada and the USA (basal dates), and depths where available.
2. Construct and fit ecological models of peatland initiation.

Cedar Bog Lake, University of Minnesota, CCNHA

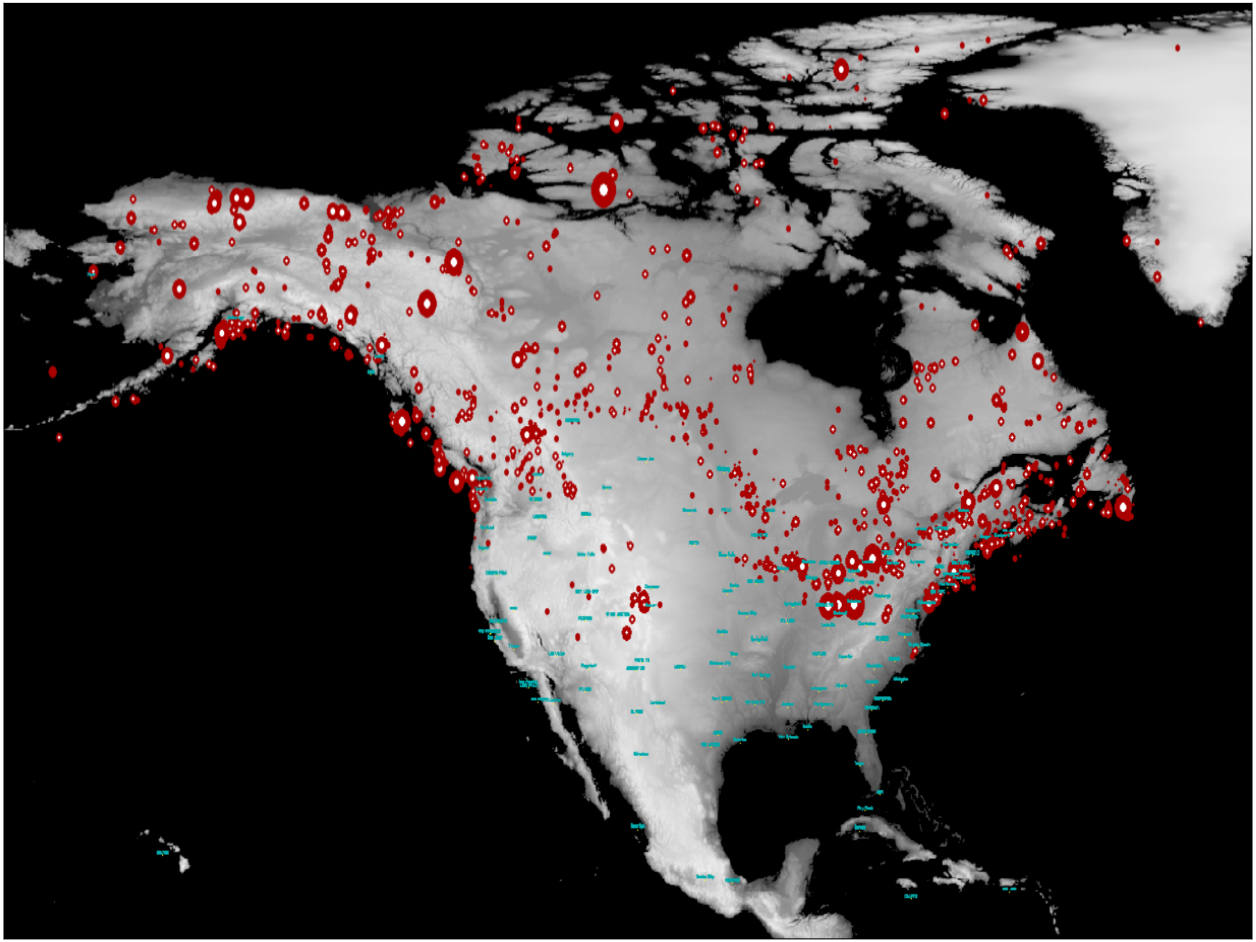
Peatland initiation

1. Start with a database of radiocarbon dates for the bottom levels of peatland sites in Canada and the USA (basal dates), and depths where available.
2. Construct and fit ecological models of peatland initiation.
3. Incorporate models of peatland depth growth and carbon accumulation.

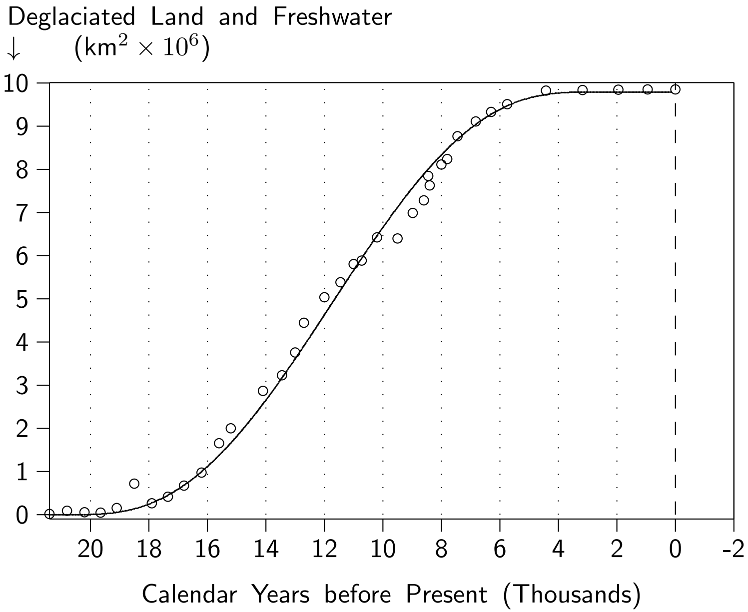
Cedar Bog Lake, University of Minnesota, CCNHA

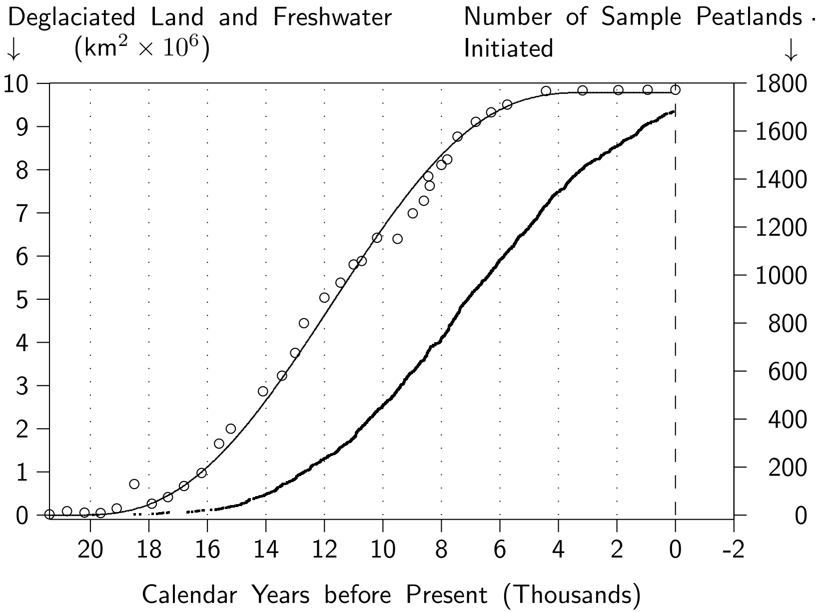
Peatland initiation

1. Start with a database of radiocarbon dates for the bottom levels of peatland sites in Canada and the USA (basal dates), and depths where available.
2. Construct and fit ecological models of peatland initiation.
3. Incorporate models of peatland depth growth and carbon accumulation.
4. Project to future.



NAmap.png


Deglaciated Land and Freshwater
↓ (km$^2 \times 10^6$)
10
9
8
7
6
5
4
3
2
1
0
20
18
16
14
12
10
8
6
4
2
0
-2
Calendar Years before Present (Thousands)


Deglaciated Land and Freshwater
↓ (km^2 × 10^6)
Number of Sample Peatlands
Initiated ↓
10
9
8
7
6
5
4
3
2
1
0
1800
1600
1400
1200
1000
800
600
400
200
0
20
18
16
14
12
10
8
6
4
2
0
-2
Calendar Years before Present (Thousands)

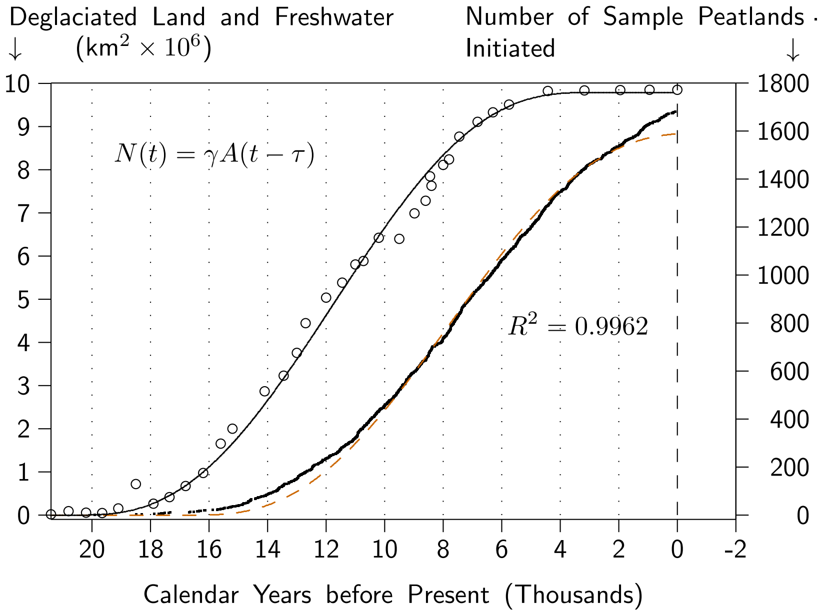
Four possible models of peatland initiation

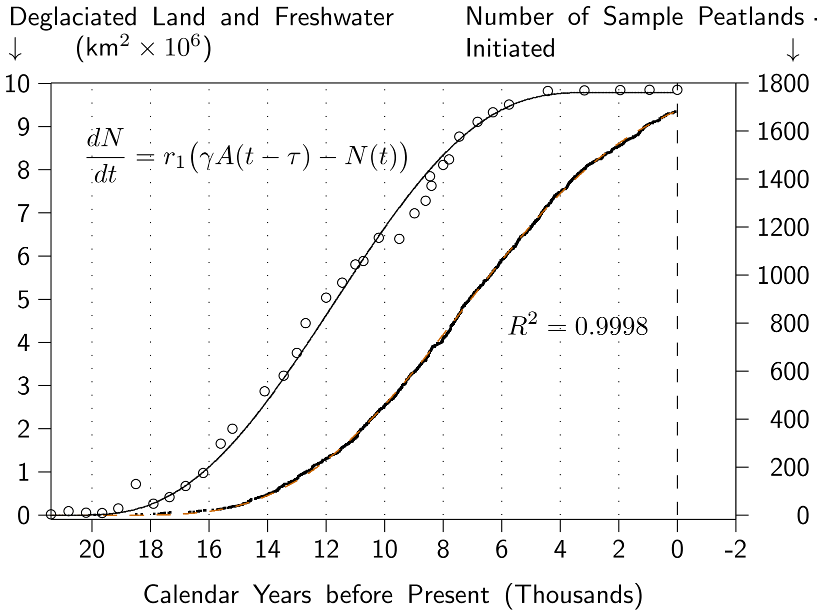
$$N(t) = \gamma A(t) \qquad \mathbf{(1)}$$

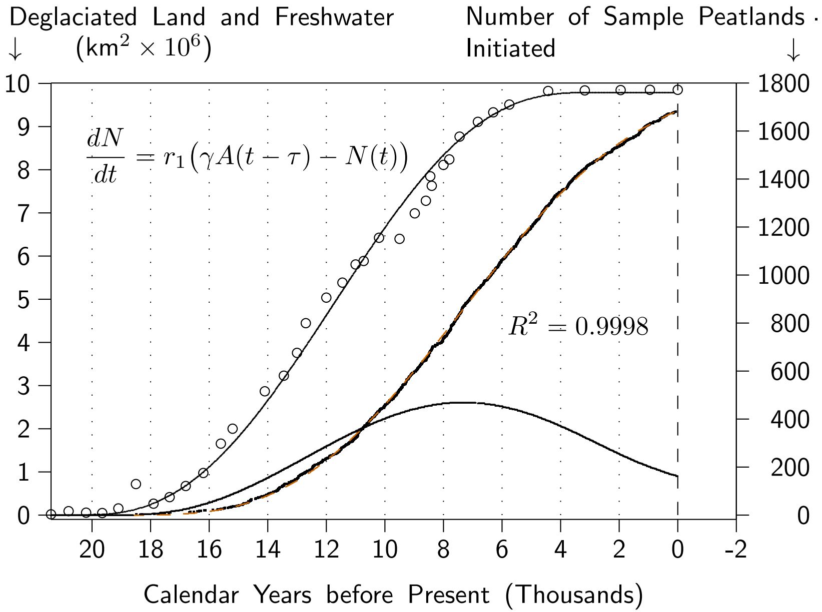
$$N(t) = \gamma A(t - \tau) \qquad \mathbf{(2)}$$

$$\frac{dN}{dt} = r_1(\gamma A(t - \tau) - N(t)) \qquad \mathbf{(3)}$$

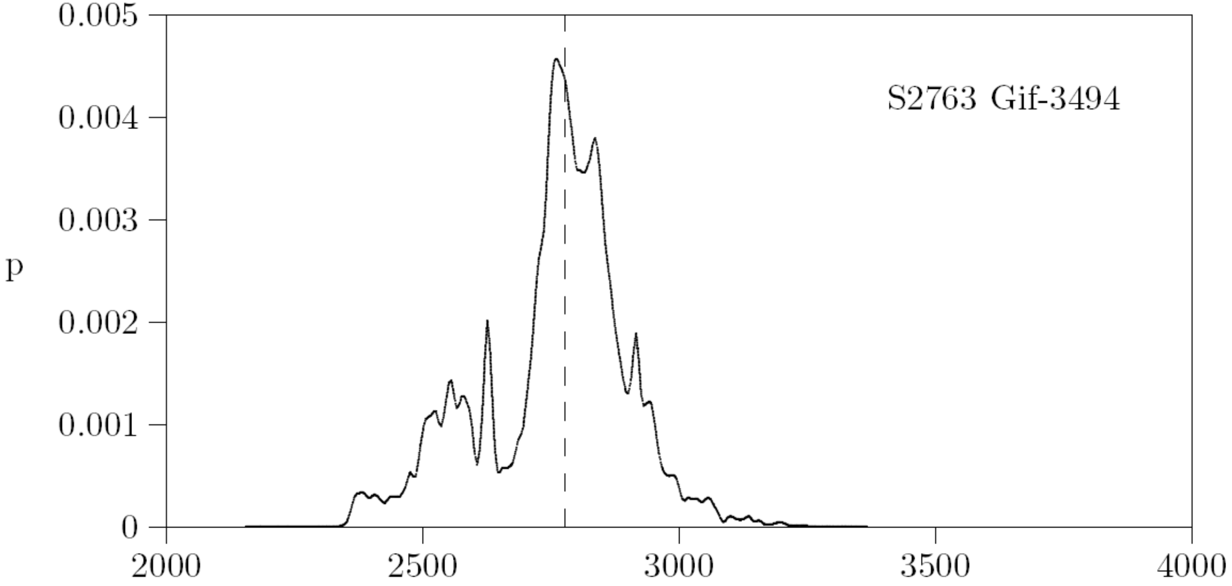
$$\frac{dN}{dt} = (r_1 + r_2 N(t))\,(\gamma A(t - \tau) - N(t)) \qquad \mathbf{(4)}$$


Deglaciated Land and Freshwater
↓ (km^2 × 10^6)
Number of Sample Peatlands Initiated ↓
$N(t) = \gamma A(t - \tau)$
$R^2 = 0.9962$
0
1
2
3
4
5
6
7
8
9
10
0
200
400
600
800
1000
1200
1400
1600
1800
20
18
16
14
12
10
8
6
4
2
0
-2
Calendar Years before Present (Thousands)

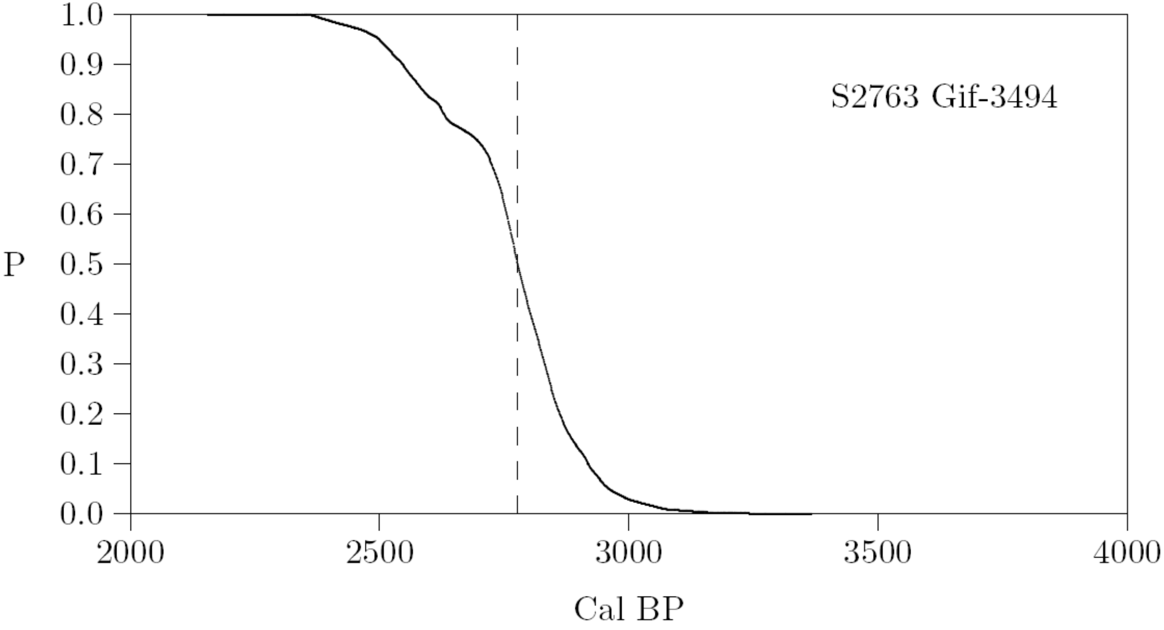

Deglaciated Land and Freshwater
↓ (km^2 × 10^6)
Number of Sample Peatlands Initiated
↓
$\frac{dN}{dt} = r_1\big(\gamma A(t-\tau) - N(t)\big)$
$R^2 = 0.9998$
10
9
8
7
6
5
4
3
2
1
0
1800
1600
1400
1200
1000
800
600
400
200
0
20
18
16
14
12
10
8
6
4
2
0
-2
Calendar Years before Present (Thousands)


Deglaciated Land and Freshwater
↓ (km^2 × 10^6)
Number of Sample Peatlands Initiated ↓
$\frac{dN}{dt} = r_1\big(\gamma A(t-\tau) - N(t)\big)$
$R^2 = 0.9998$
10
9
8
7
6
5
4
3
2
1
0
1800
1600
1400
1200
1000
800
600
400
200
0
20
18
16
14
12
10
8
6
4
2
0
-2
Calendar Years before Present (Thousands)

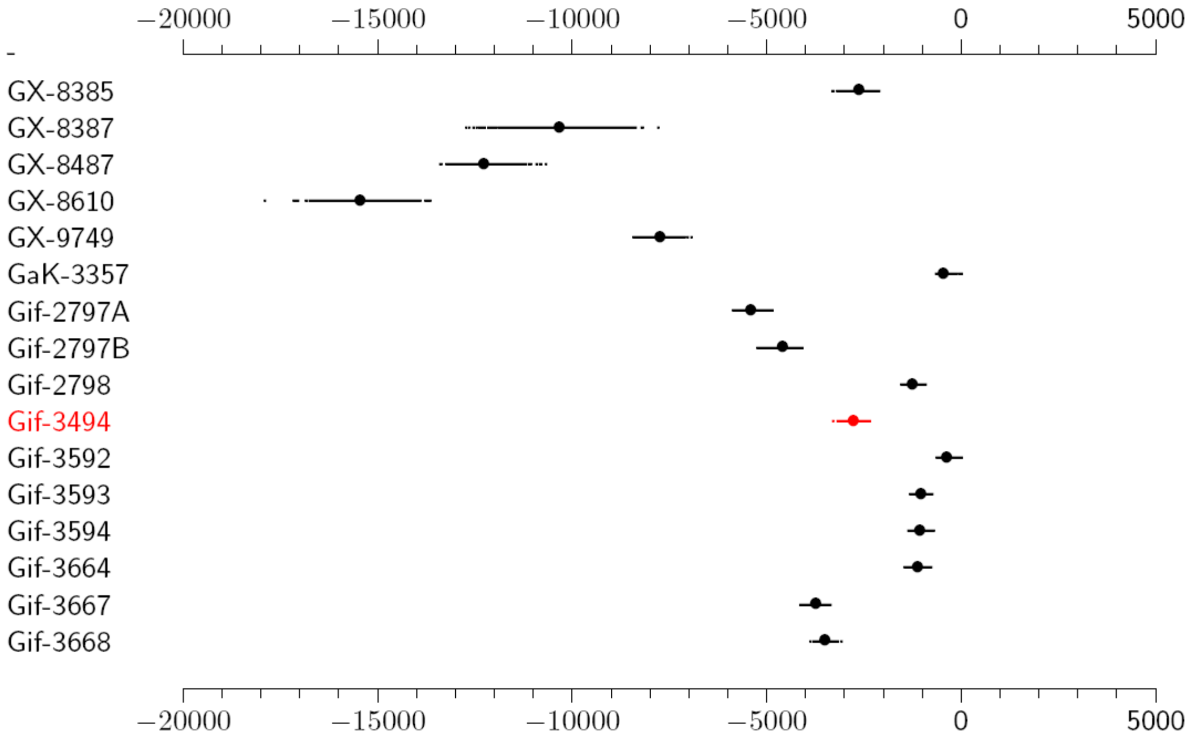
Eqn.	R^2	*Fraction* γ	*Delay* τ	*Rate* r_1	*Rate* r_2
1	0.7135	116.8	0	–	–
2	0.9962	162.6	3969	–	–
3	0.9998	196.1	1342	0.000229	–
4	0.9998	196.1	1342	0.000229	0.000000


0.005
0.004
0.003
0.002
0.001
0
p
2000
2500
3000
3500
4000
S2763 Gif-3494

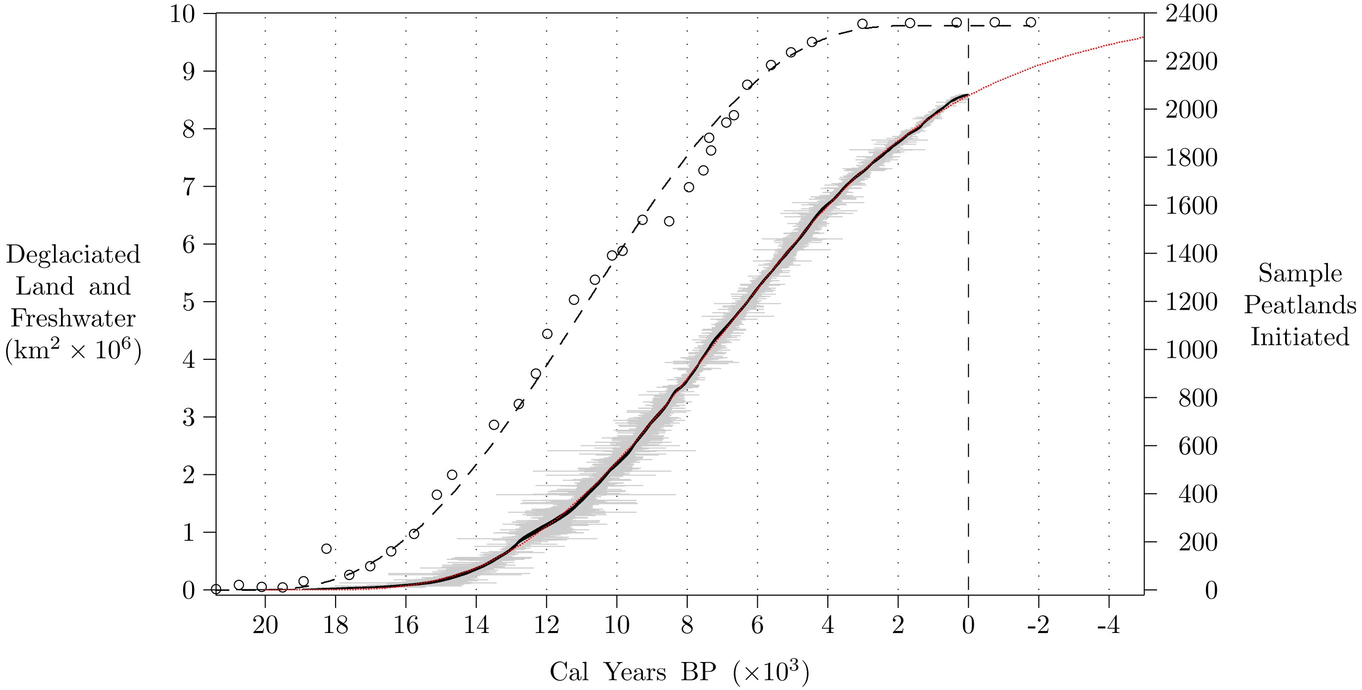
RCdist1.png


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
P
S2763 Gif-3494
2000
2500
3000
3500
4000
Cal BP

RCdistC.png


−20000
−15000
−10000
−5000
0
5000
GX-8385
GX-8387
GX-8487
GX-8610
GX-9749
GaK-3357
Gif-2797A
Gif-2797B
Gif-2798
Gif-3494
Gif-3592
Gif-3593
Gif-3594
Gif-3664
Gif-3667
Gif-3668
−20000
−15000
−10000
−5000
0
5000

RCvar.png


Deglaciated Land and Freshwater (km^2 × 10^6)
Sample Peatlands Initiated
Cal Years 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

Outline

1. Background
2. Peatland examples
3. Ice retreat
4. Peatland initiation
5. <u>Carbon accumulation</u>
6. Relaxation ocillator
7. A great prehistoric flood

Carbon Accumulation

Simplest view of the carbon accumulation in peatlands:

(1) new carbon is added to the surface through photosynthetic processes at a rate proportional to the surface area, independent of the volume of material already accumulated.

Carbon Accumulation

Simplest view of the carbon accumulation in peatlands:

(1) new carbon is added to the surface through photosynthetic processes at a rate proportional to the surface area, independent of the volume of material already accumulated.

(2) existing carbon is lost through decomposition at a rate that is proportional to the volume already accumulated.

Carbon Accumulation

Simplest view of the carbon accumulation in peatlands:

(1) new carbon is added to the surface through photosynthetic processes at a rate proportional to the surface area, independent of the volume of material already accumulated.

(2) existing carbon is lost through decomposition at a rate that is proportional to the volume already accumulated.

Then the dynamics are

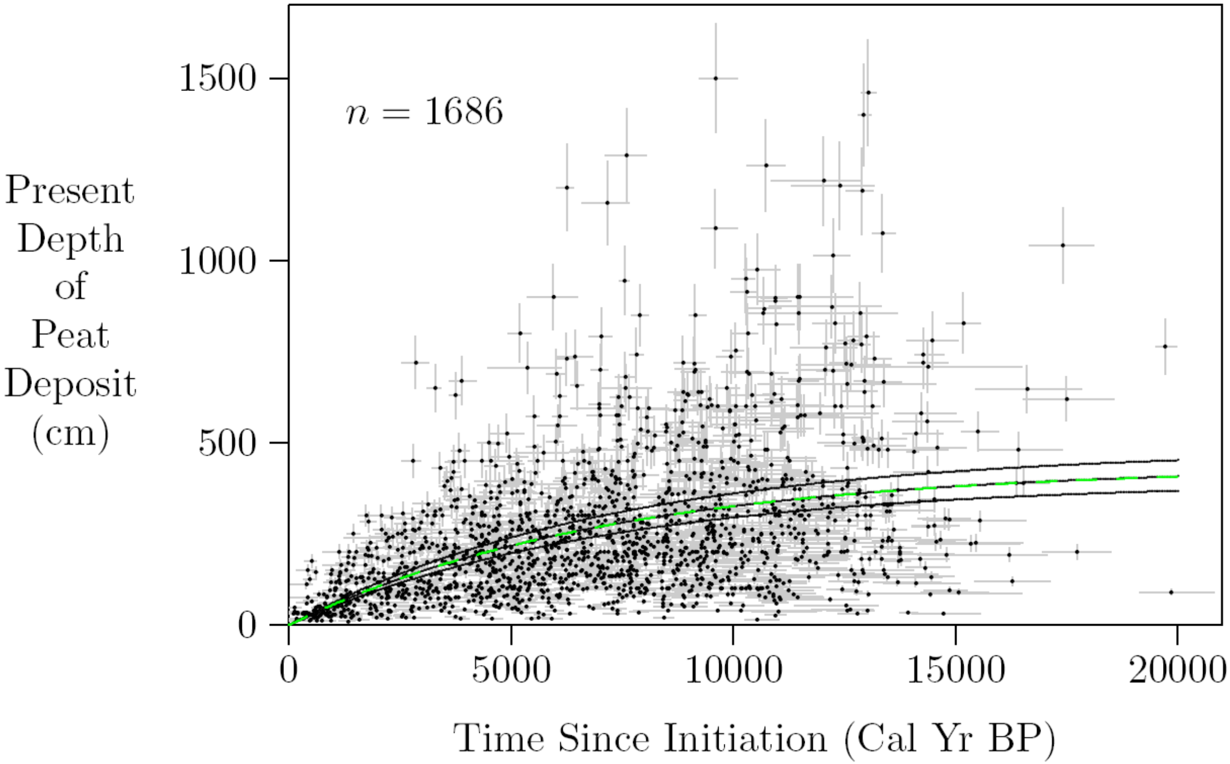
$$\frac{dH}{dt} = a - bH$$

$$\frac{dH}{dt} = r_0 \left(1 - \frac{H}{H_0}\right)$$

$$H(t) = H_0 \left(1 - e^{-r_0 t/H_0}\right)$$

r_0 is the rate of increase in depth when the peatland is young (just initiated).

H_0 is the maximum depth, where decomposition exactly balances production.



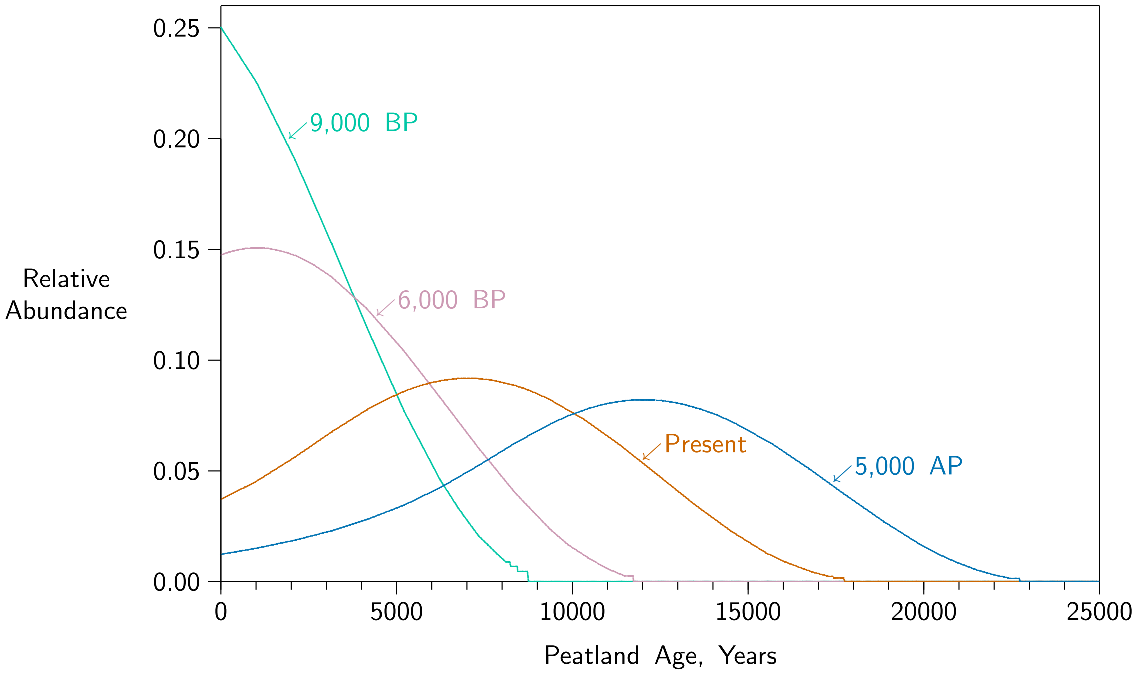
AgeDepth2.png

Peatland age distributions

The cumulative curve of peatland initiation encodes the entire age distribution of peatlands across all times. If $F(t)$ is the number of sample peatlands existing at time t, then the normalized age distribution at time t is

$$g(a,t) = F'(t-a)/F(t)\,,$$

where $F'(t)$ is the derivative of $F(t)$ with respect to t.



Nine thousand years ago the most common peatlands were newly formed. Today the most common peatlands are about 7,000 years old. The peak of the age distribution continues to shift right uniformly with time.

Cumulative depth

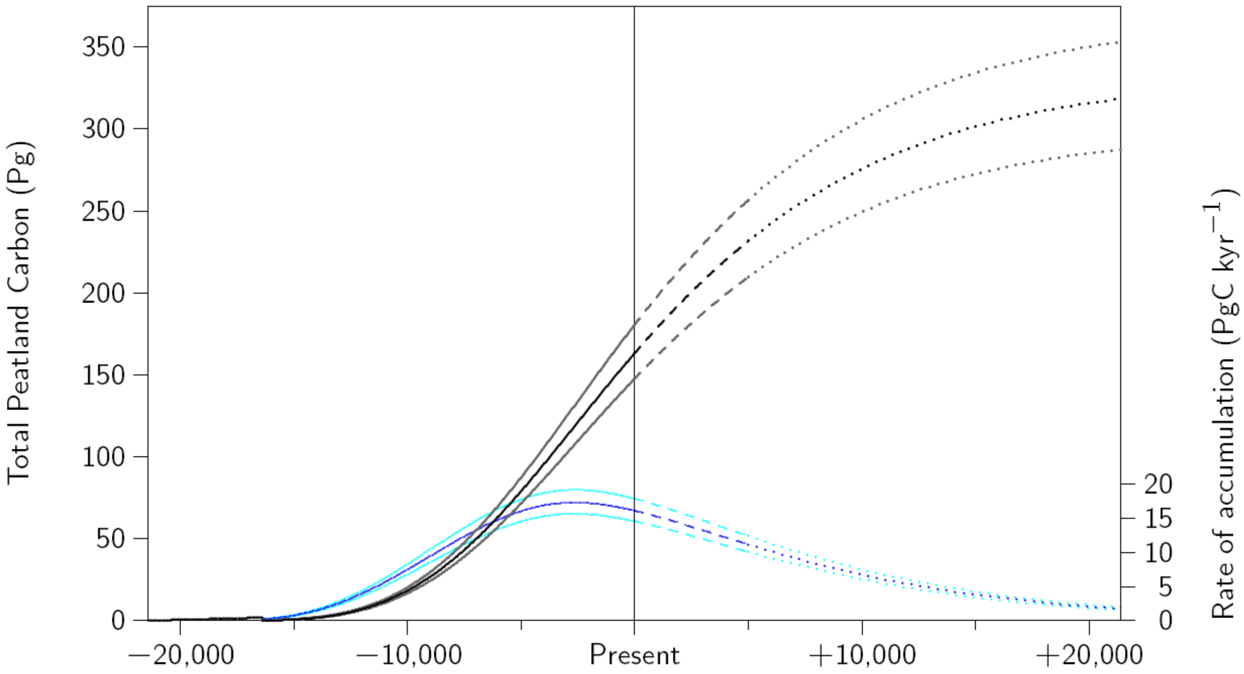
All age distribution functions can be combined with the peatland depth function to give the the cumulative depth of the sample peatlands at time t. This is the convolution

$$D(t) = \int_0^\infty h(a)\, F'(t-a)\, da \,,$$

where $h(a)$ is the expected depth of a peatland of age a. As before, this function is

$$h(a) = (1 - e^{-ra/H})H \,,$$

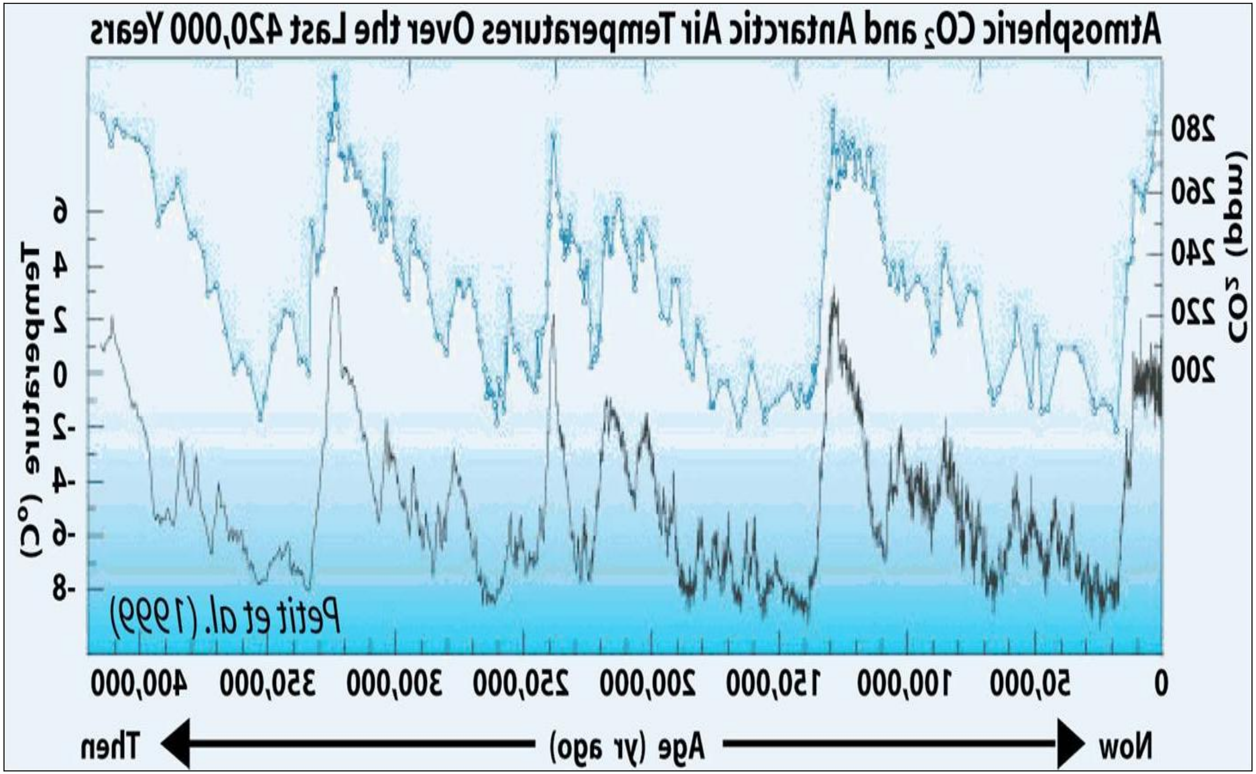
where r is an intrinsic rate of increase in depth, H is the equilibrial depth, a is the age of the peatland.

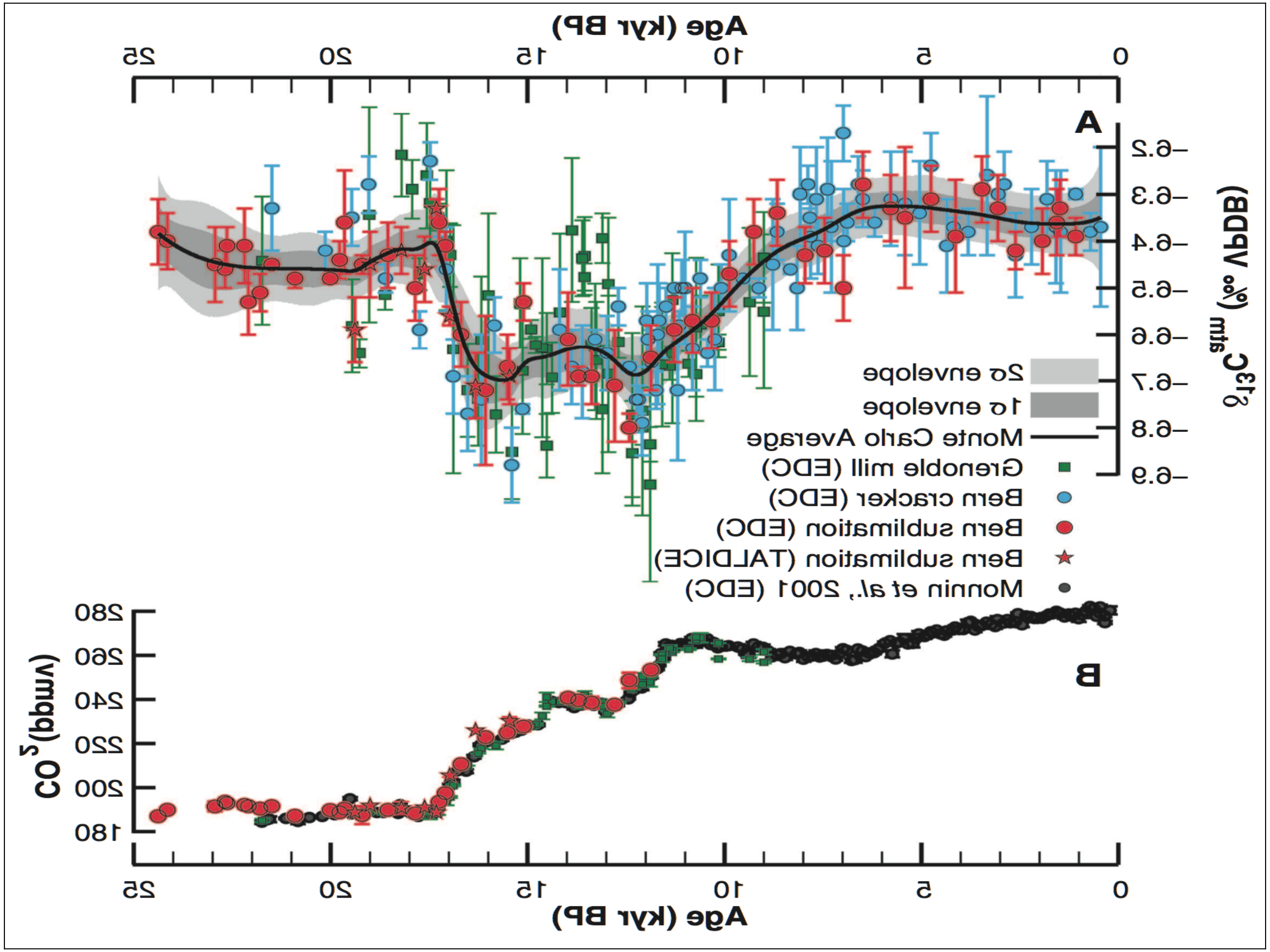

Total Peatland Carbon (Pg)
350
300
250
200
150
100
50
0
Rate of accumulation (PgC kyr^{-1})
20
15
10
5
0
−20,000
−10,000
Present
+10,000
+20,000

Carbon.png

Outline

1. Background
2. Peatland examples
3. Ice retreat
4. Peatland initiation
5. Carbon accumulation
6. <u>Relaxation ocillator</u>
7. A great prehistoric flood

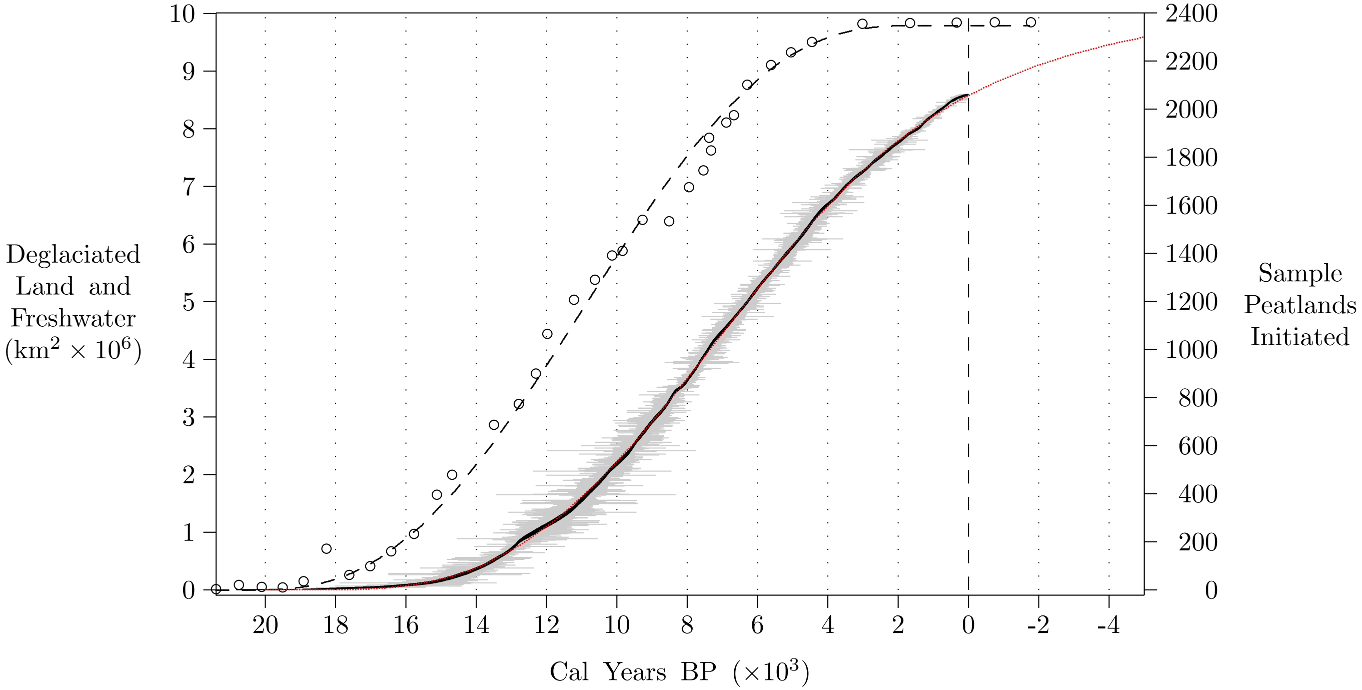

Atmospheric CO₂ and Antarctic Air Temperatures Over the Last 420,000 Years
Temperature (°C)
6
4
2
0
-2
-4
-6
-8
CO₂ (ppm)
280
260
240
220
200
Petit et al. (1999)
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Then
Age (yr ago)
Now

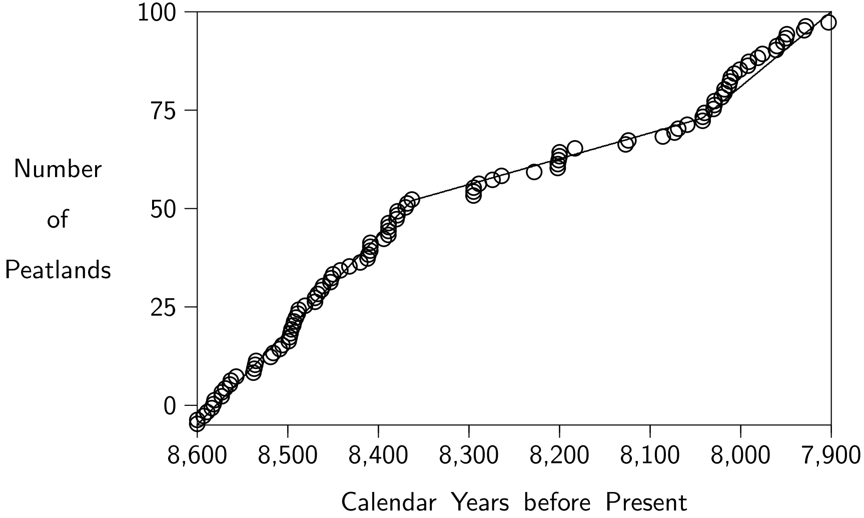


Schmitt et al. 2012

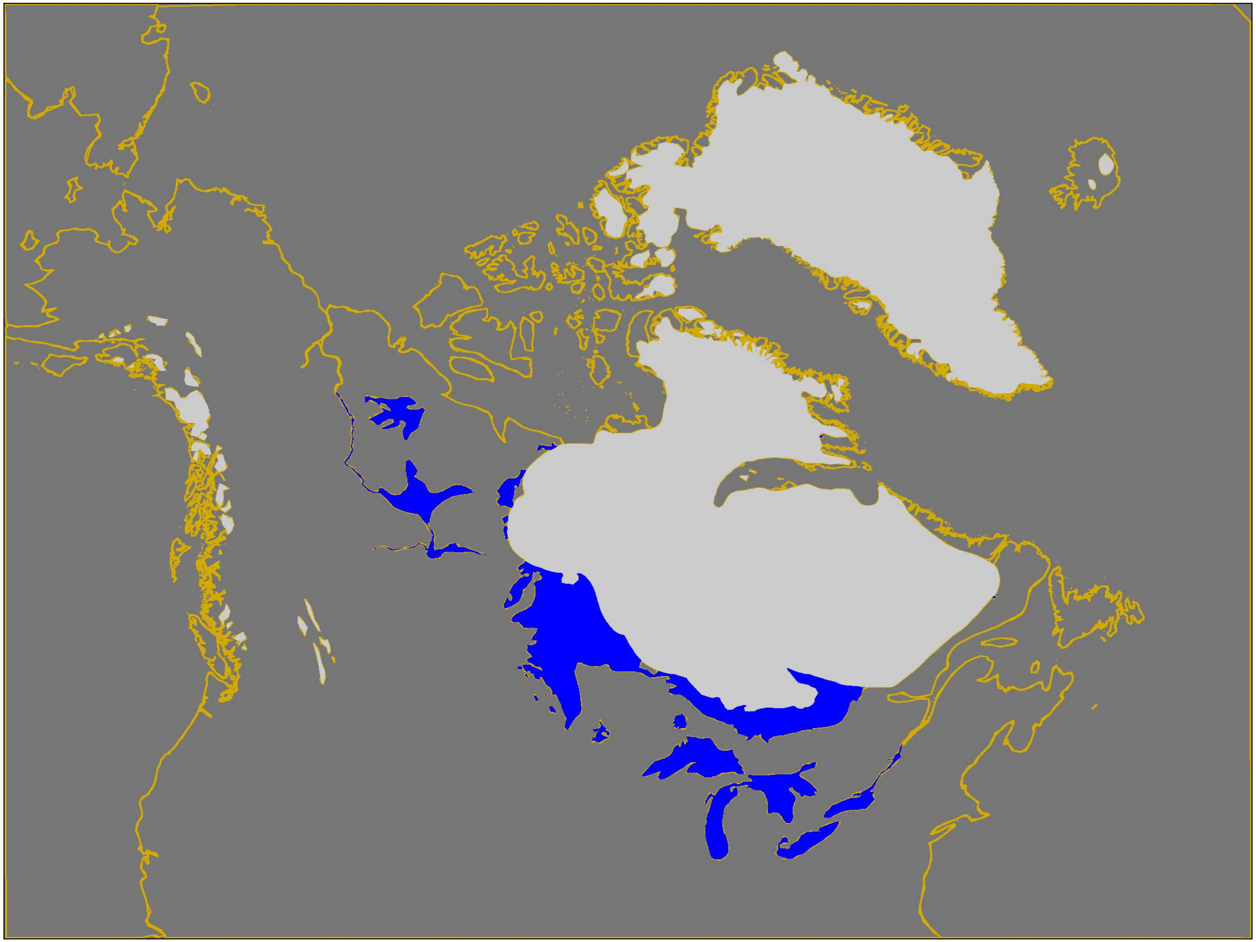
Outline

1. Background
2. Peatland examples
3. Ice retreat
4. Peatland initiation
5. Carbon accumulation
6. Relaxation ocillator
7. <u>A great prehistoric flood</u>

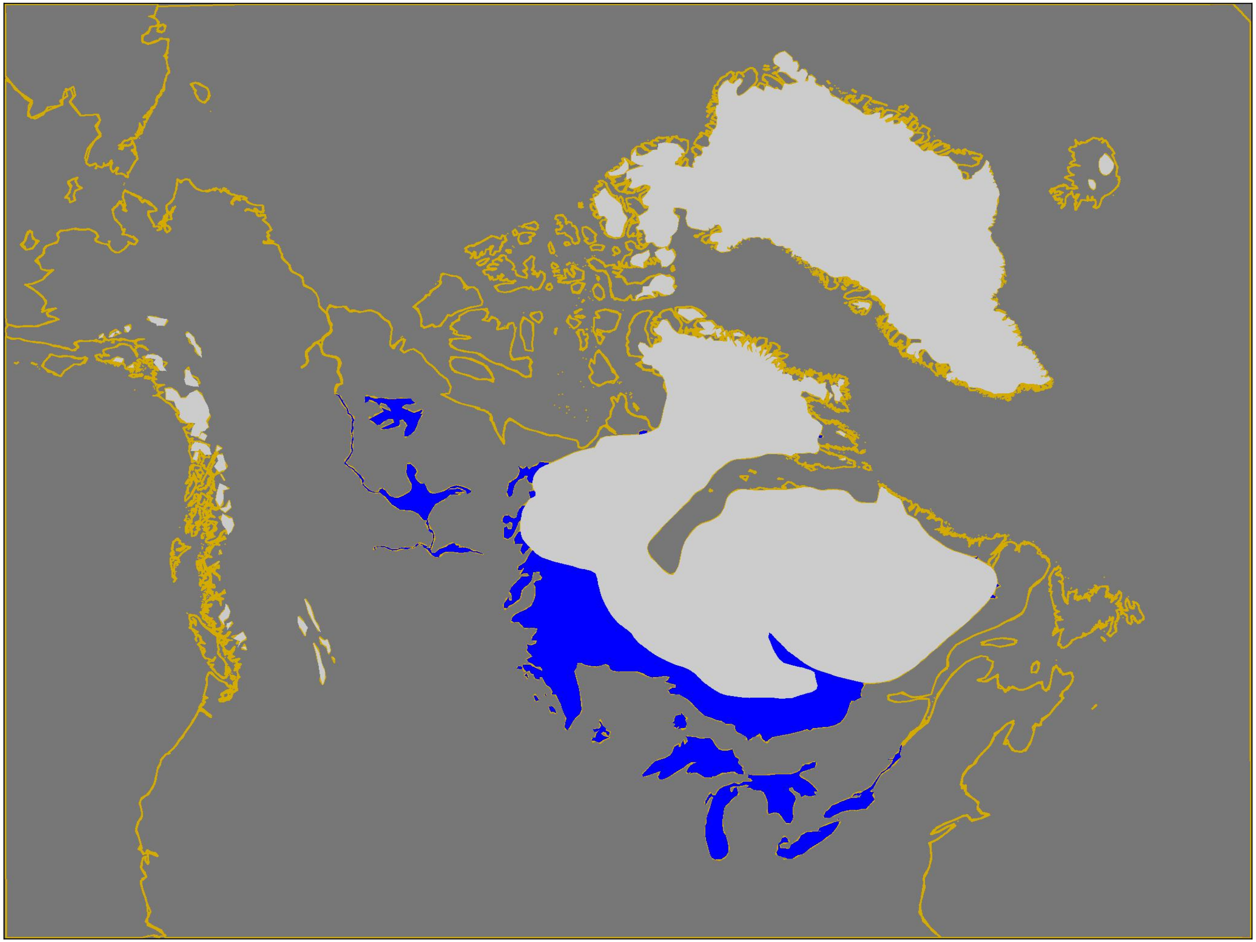

Deglaciated Land and Freshwater (km^2 × 10^6)
0
1
2
3
4
5
6
7
8
9
10
Sample Peatlands Initiated
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Cal Years BP (×10^3)
20
18
16
14
12
10
8
6
4
2
0
-2
-4


100
75
50
25
0
Number
of
Peatlands
8,600
8,500
8,400
8,300
8,200
8,100
8,000
7,900
Calendar Years before Present

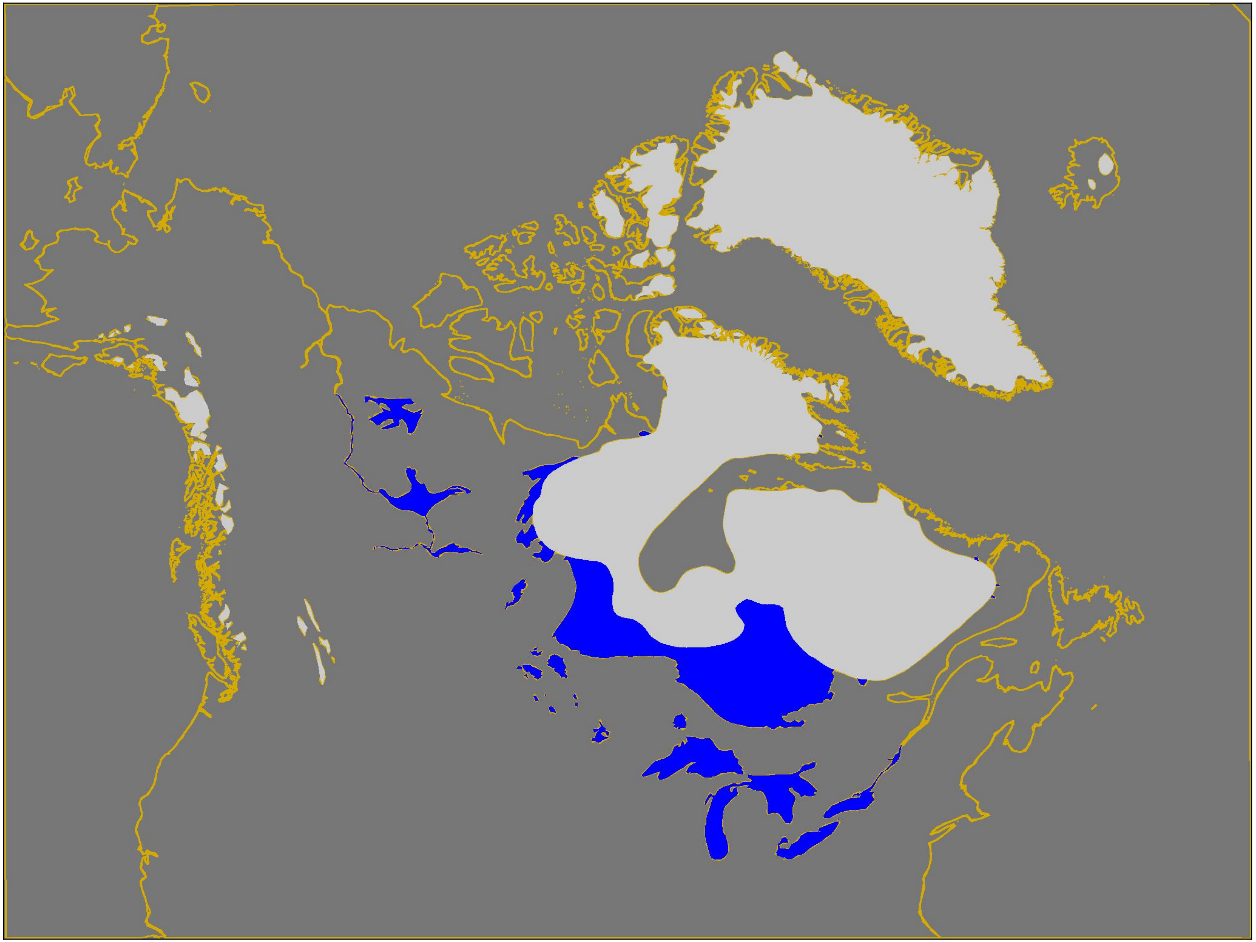
Glacial Lake Agassiz in Minnesota



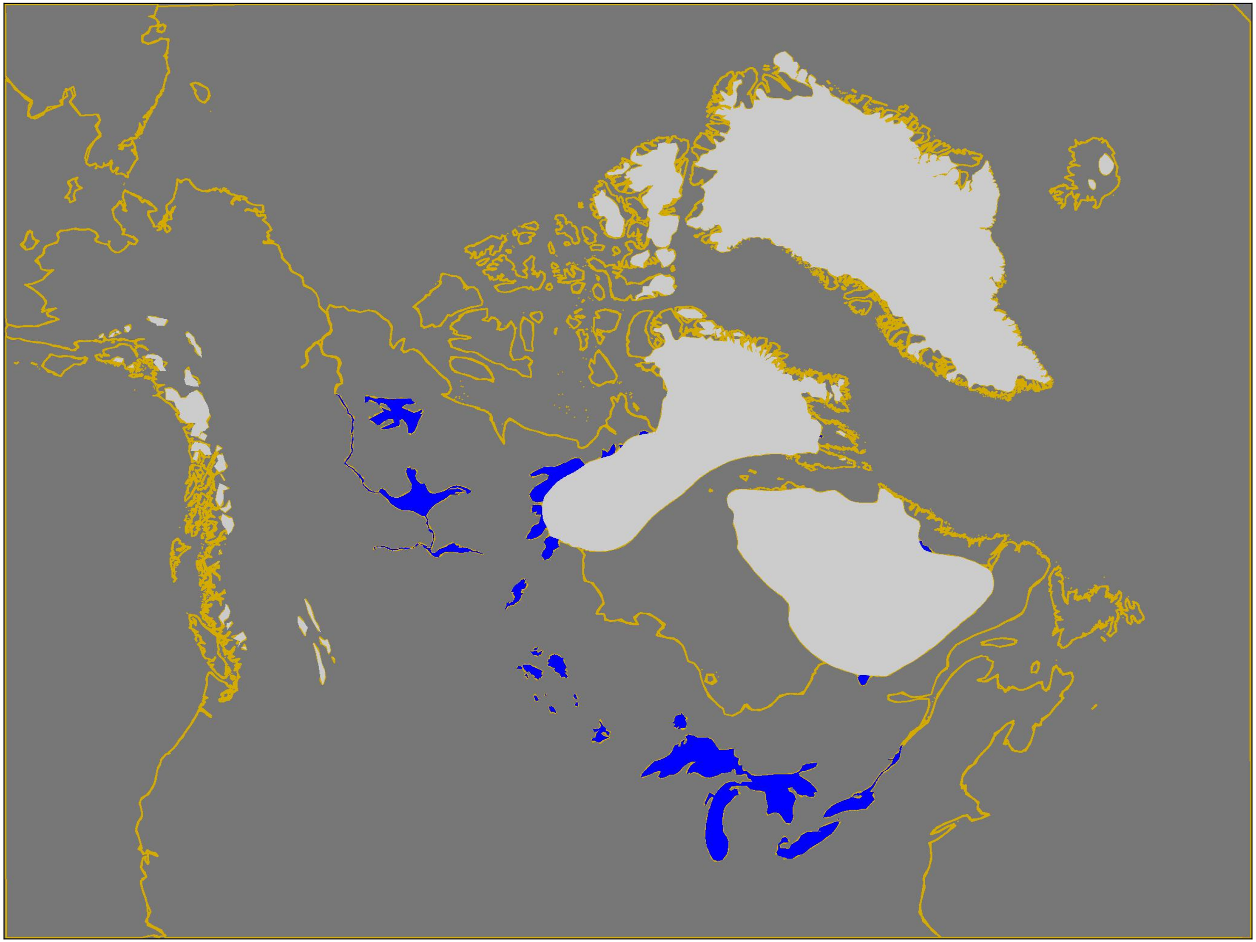
8900 BP. Glacial lakes dammed with ice to the north.



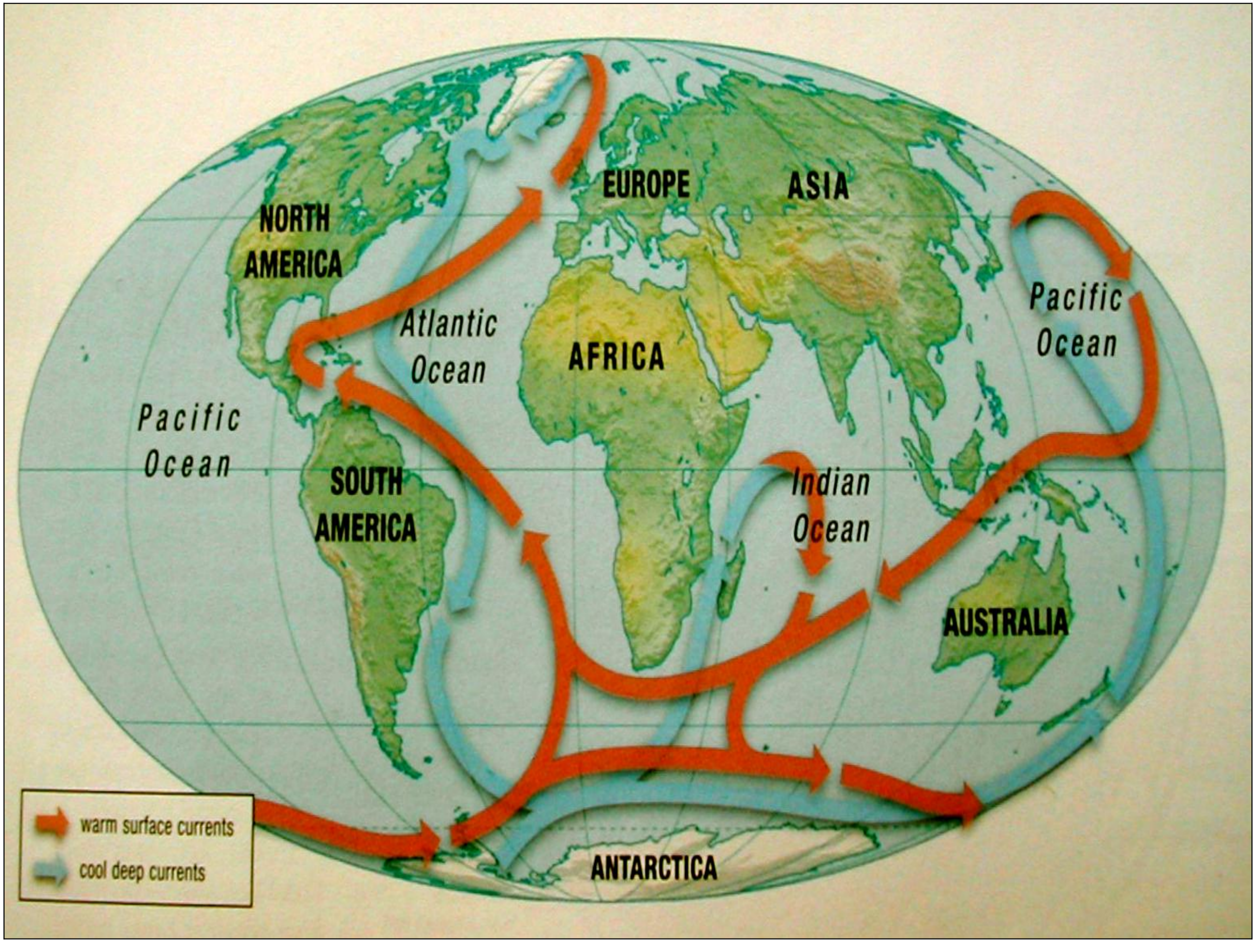
8600 BP. An open corridor pushing south through Hudson Bay.



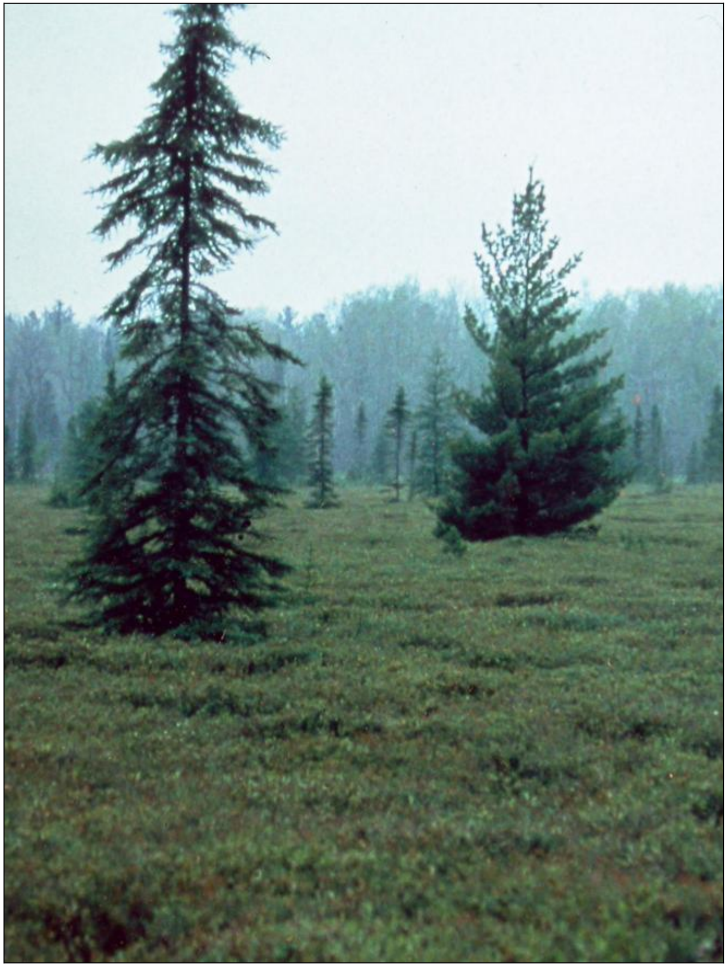
8500 BP. The ice dam progressively thinning.



8400 BP. 150,000 cubic kilometers of fresh water suddenly discharged (1/2 meter ocean rise worldwide).



World ocean currents



The End

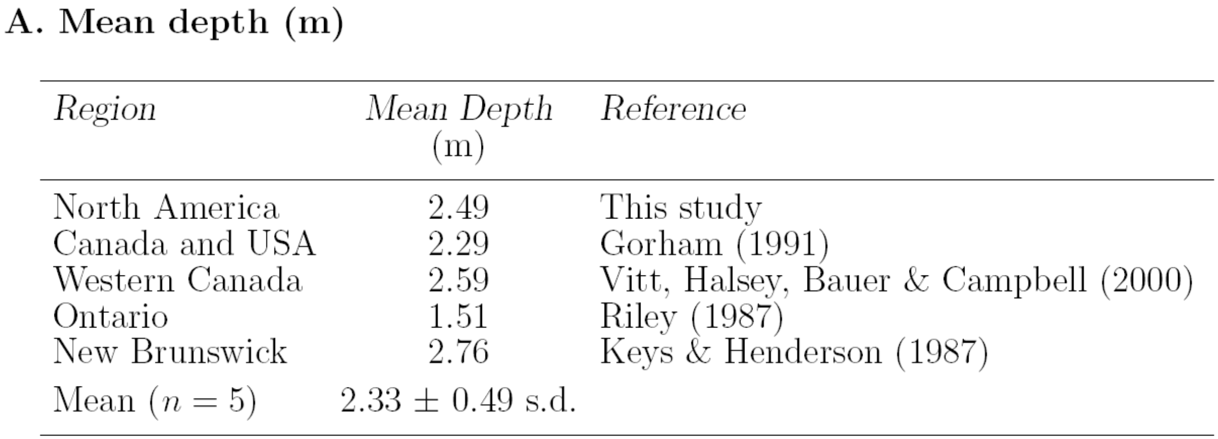
A. $$\frac{dN(t)}{dt} = r\Big(\gamma A(t-\tau) - N(t)\Big)$$

B. $$\frac{dH(t)}{dt} = a - bH(t) = s\left(1 - \frac{H(t)}{H_a}\right)$$

C. $$H(t) = H_a\left(1 - e^{-st/H_a}\right)$$

D. $$C(t) = B\int_0^\infty N'(t-z)\,H(z)\,dz$$

formulae.png

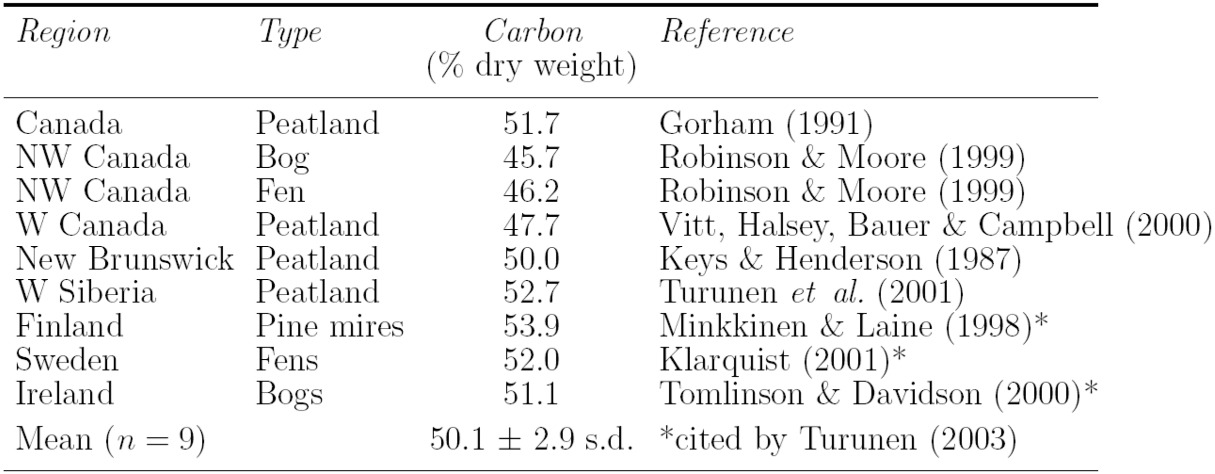


A. Mean depth (m)

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.	

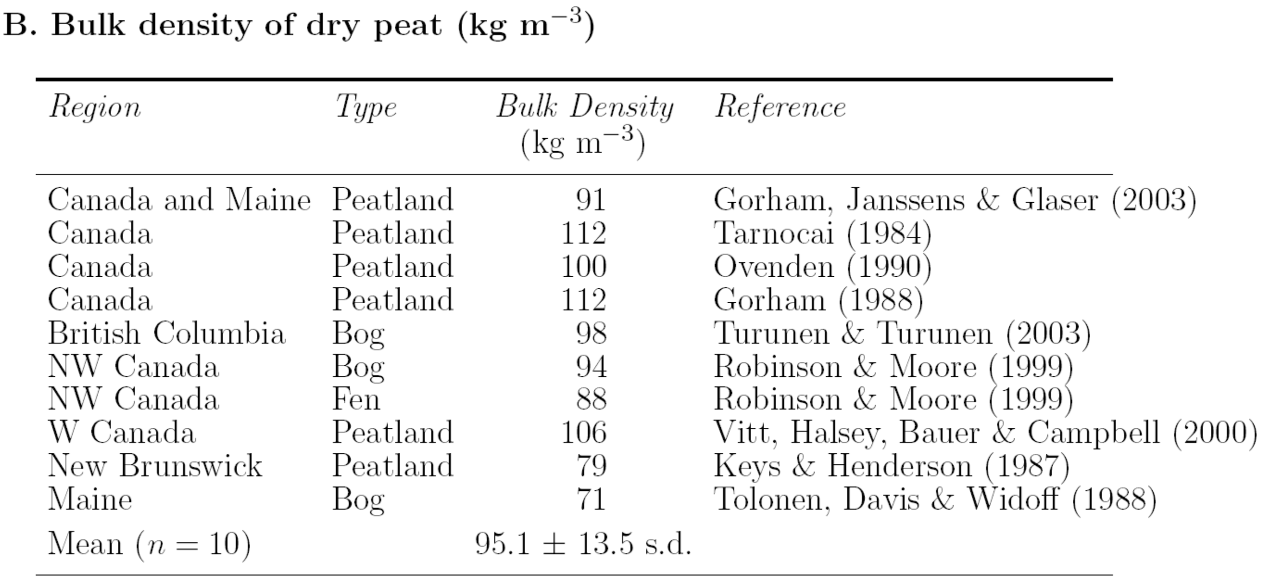
MeanDepth.png

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)

CarbonContent.png



B. 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.	

BulkDensity.png

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		1683	73	19903	19831

BiomeRate.png