Wetland carbon cycle responses to hydrological change:
Impacts on regional and global carbon budgets

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Outline

- What are wetlands?
- How are they important to the global carbon cycle?
- How do they respond to hydrological variations?
  - Inter-annual time scales
  - Century time scales
- Additional complications
- Conclusions

What are wetlands?

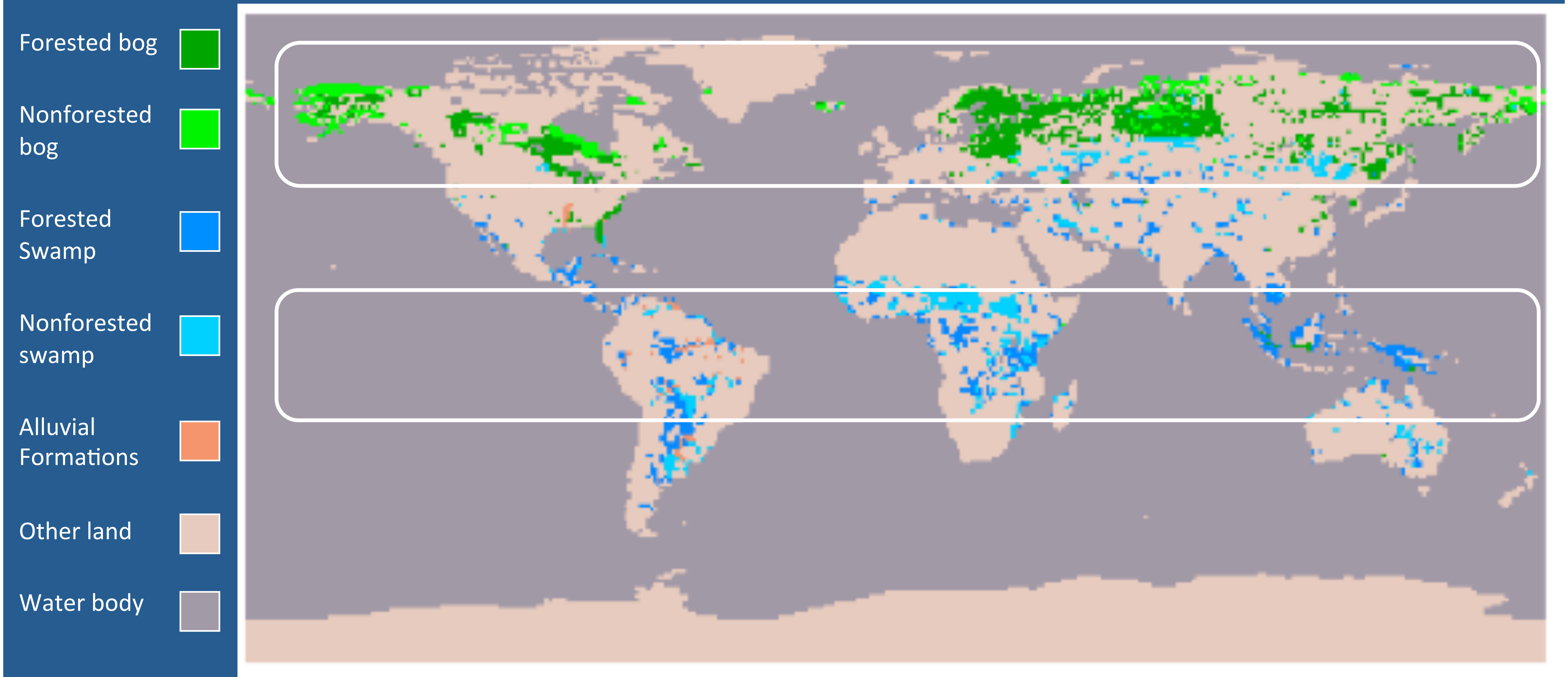
U.S. Clean Water Act definition:

Areas that are inundated or saturated by surface or ground water… sufficient to support … vegetation typically adapted for saturated soil conditions
(U.S. Army Corps of Engineers)

Peatlands:

Accumulate thick organic soil layers

Global distribution of wetlands



Matthews and Fung, 1987, GBC

Northern peatland types

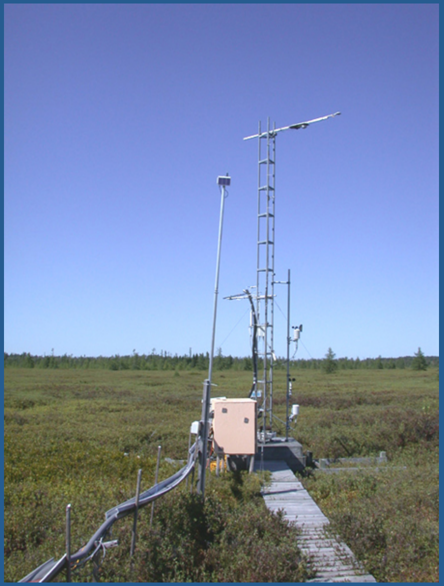
Fen
- Groundwater and surface water fed
- Usually shrubs or sedges dominate
- Peat results from anaerobic soil

Bog
- Rain-fed
- Nutrient-poor
- Often dominated by mosses
- Peat results from anaerobic soil

Tundra
- Permafrost soils
- Seasonal thawing leads to flooding of low areas
- Peat results from chronic freezing

Western Peatland (AB)

Lost Creek (WI)



Mer Bleue (ON)

Barrow (AK)
(Photo from specnet.info)

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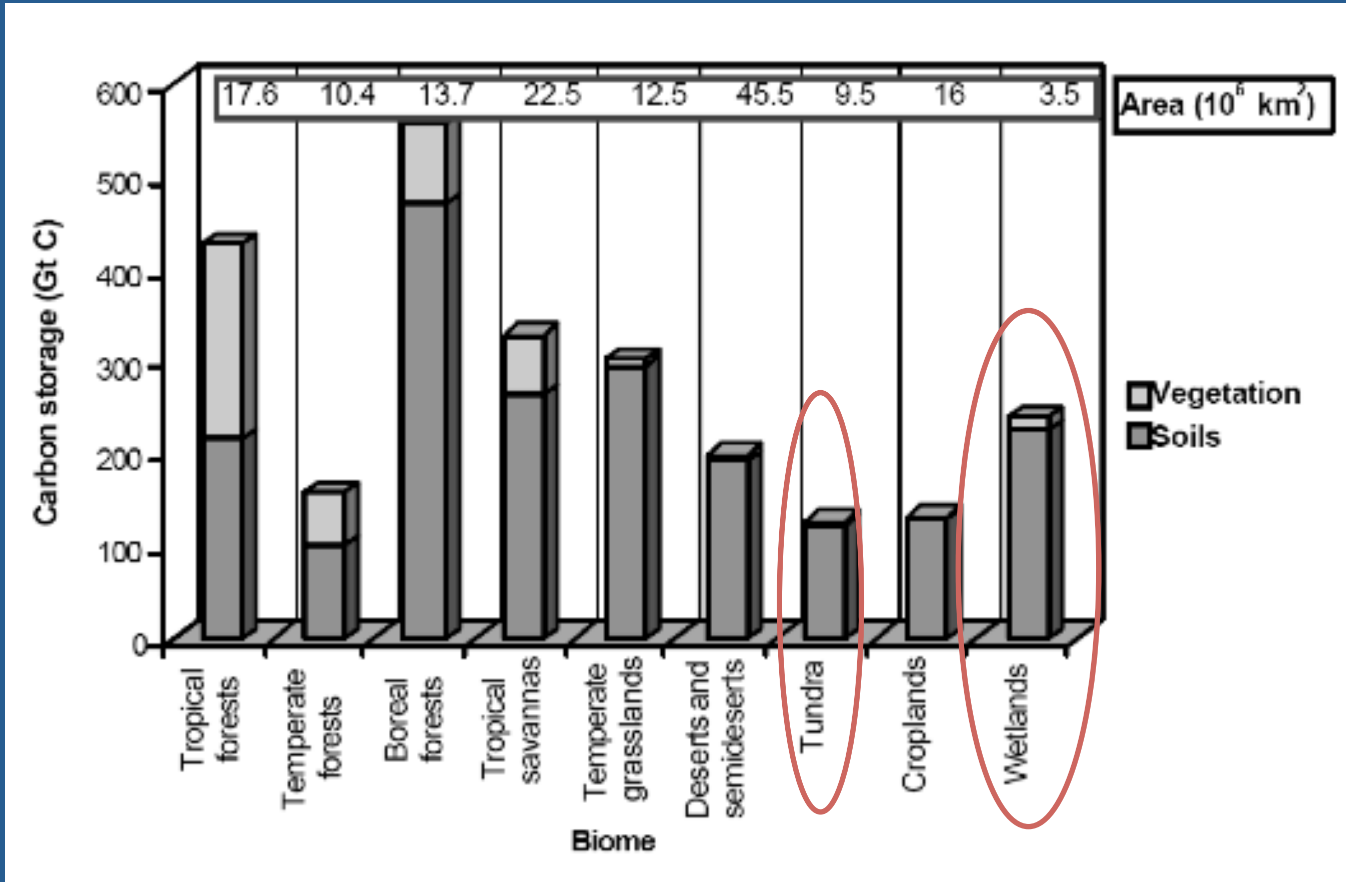
The global peatland carbon pool is large

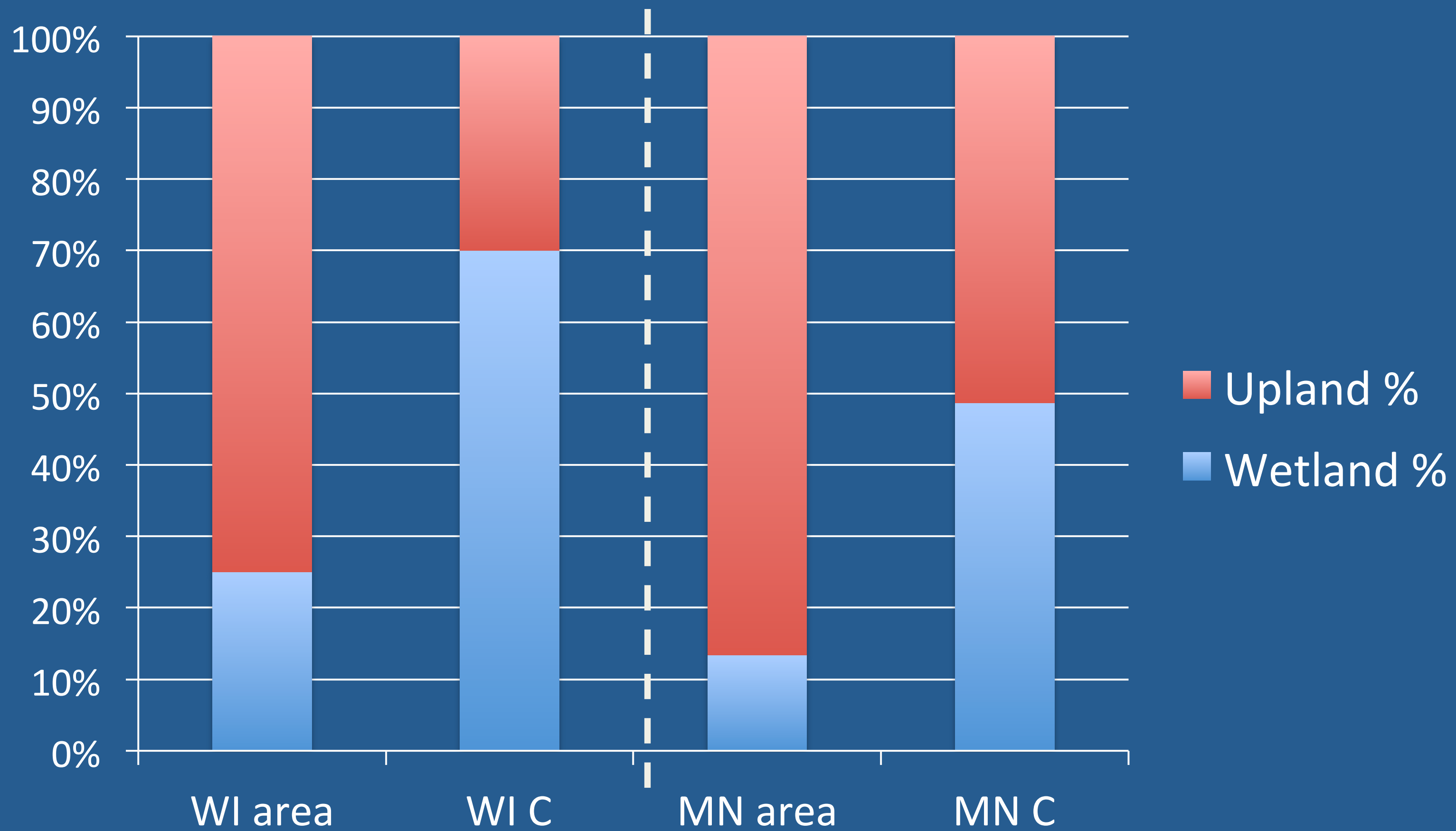
Boreal and subarctic wetlands contain between 120 and 500 Pg soil carbon (Mitra et al, 2005)

This is up to 1/3 of total global soil carbon pool (Gorham, 1991)



Mitra et al, 2005, Curr. Sci.

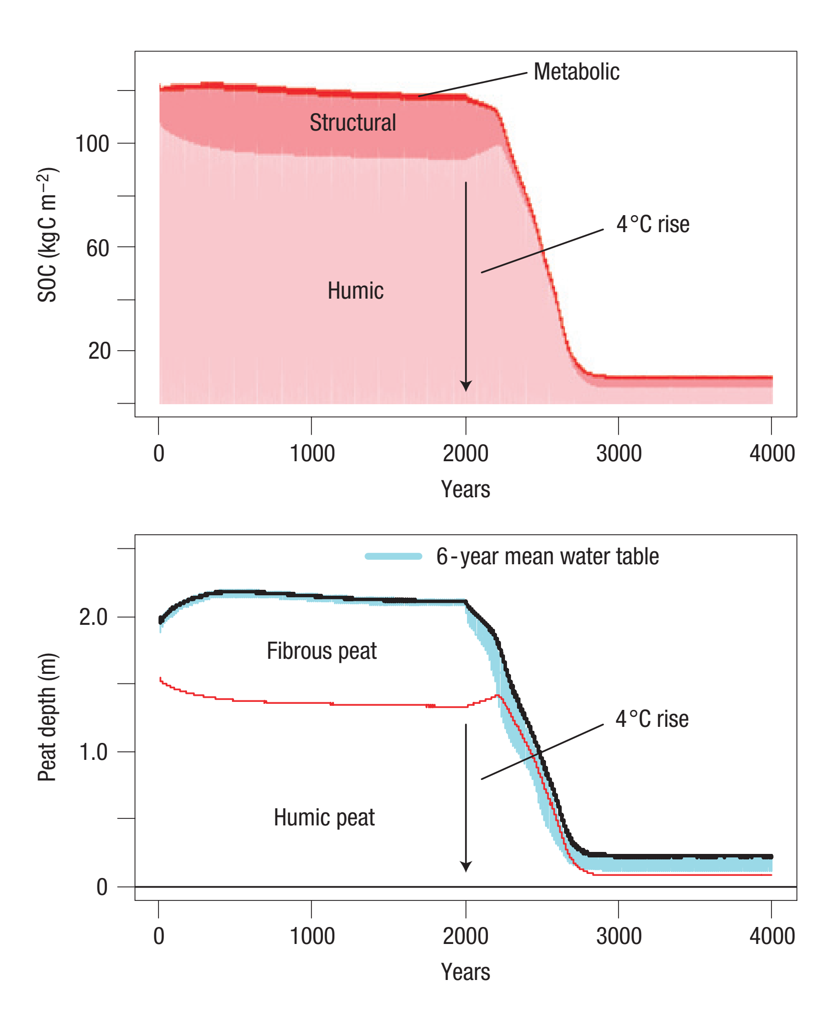
Wetlands in northern landscapes contain a large fraction of total C



WI: Buffam et al., GCB (2011); MN: Weishampel et al., For. Ecol. Man. (2009)
Fractions exclude lake area and carbon storage in lake sediments

Peatland carbon is vulnerable to climate and hydrological change

- Peat carbon is preserved by cool temperatures and flooded conditions
- Warming and drying can disrupt the process and lead to carbon loss



Ise et al 2008

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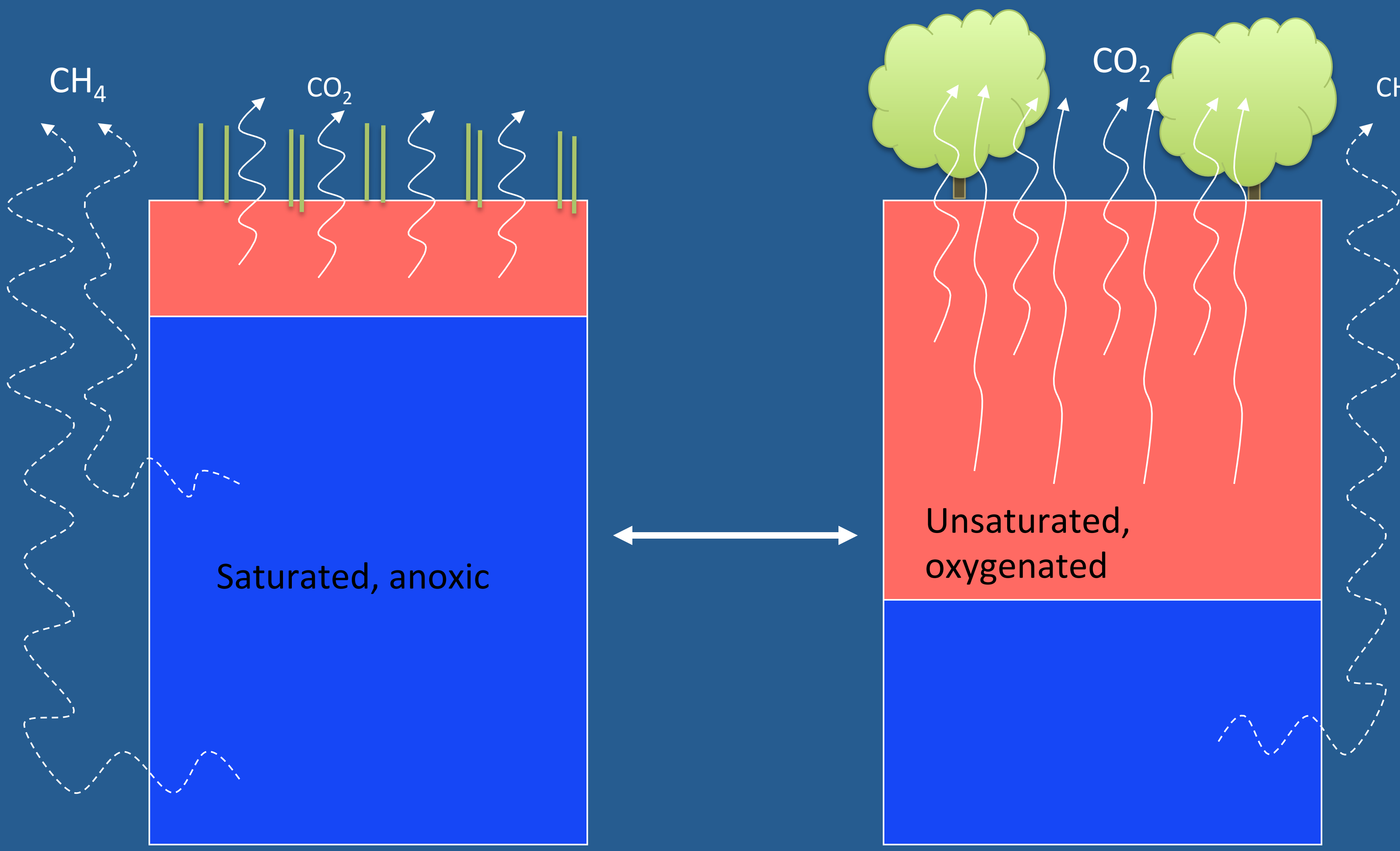
Effects of water table change

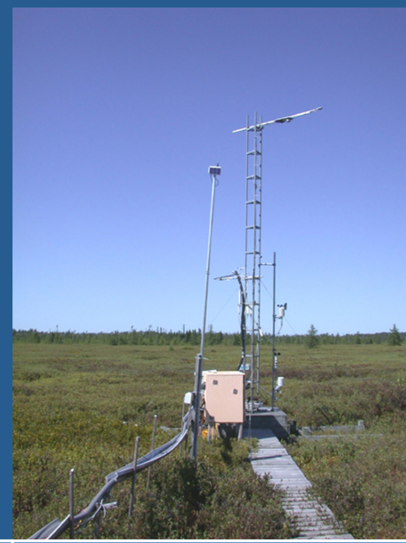


North American Carbon Program:
A site and model intercomparison project

- Three peatland eddy covariance flux sites
  - Plus four additional sites in a site comparison
- Seven ecosystem models
- Standardized meteorological driver data
- Time series of 3-8 years

Results presented in Sulman et al, GRL, 2010 and JGR-Biogeosciences, 2012

NACP Peatland Sites



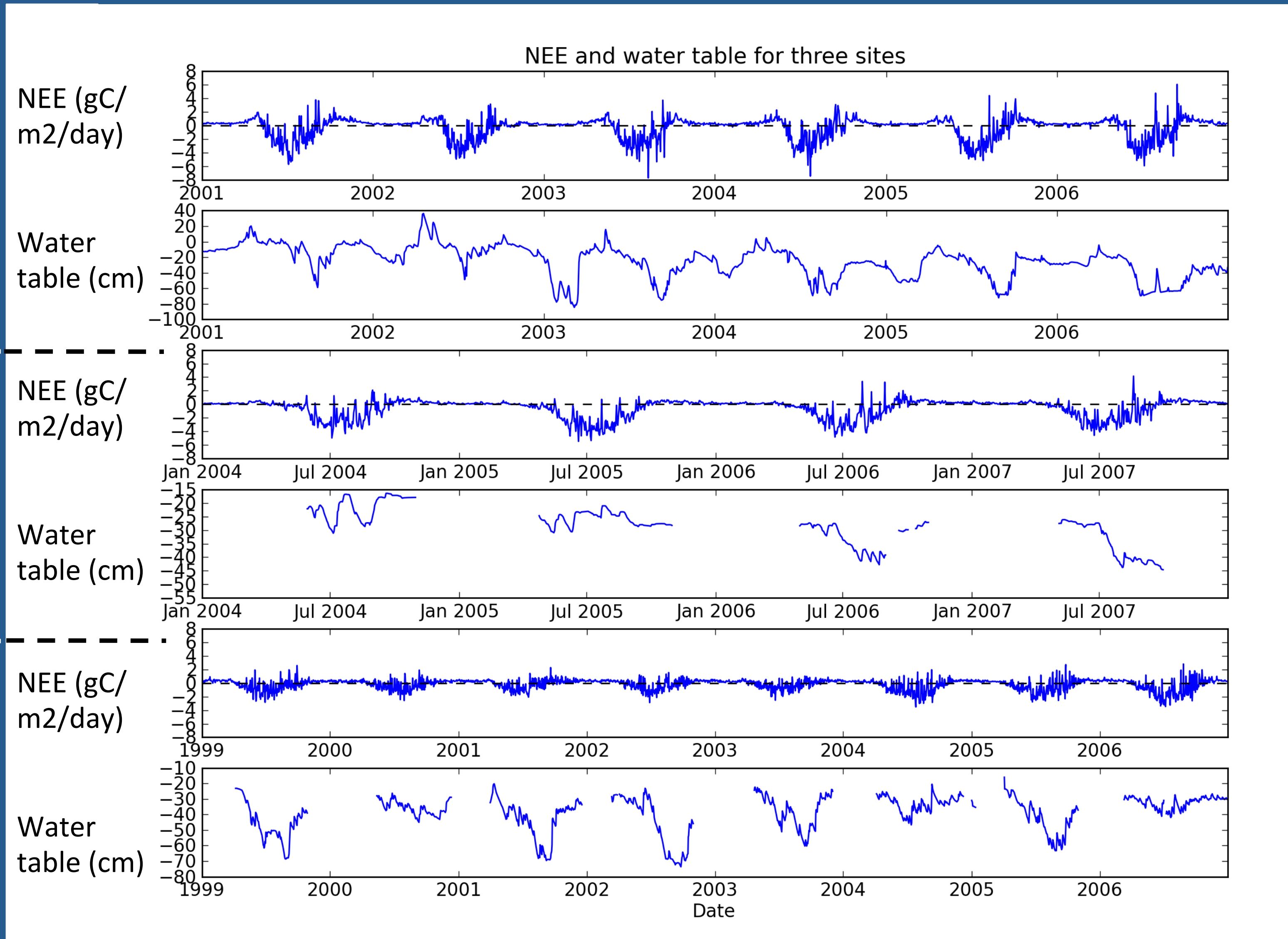
Site	Lost Creek shrub fen (WI)	Mer Bleue bog (ON)	Western Peatland treed fen (AB)
Vegetation	Primarily alder and willow	*Sphagnum* mosses with some shrubs	Stunted trees and shrubs, understory of mosses
Mean GEP	2.31 g/m2/day	1.68	2.36
Mean ER	2.10 g/m2/day	1.49	1.83

Example timeseries

Lost Creek Shrub fen

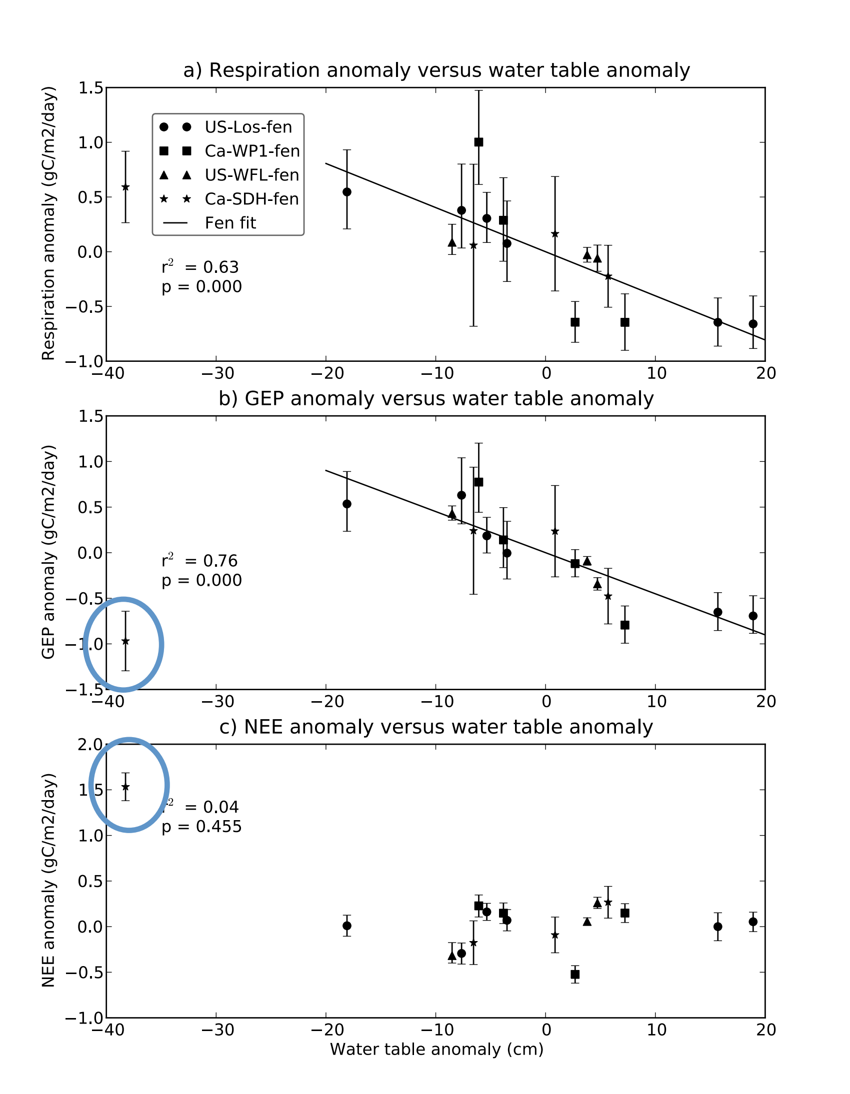
Western Peatland tree/sedge fen

Mer Bleue (Eastern Peatland) Bog



Hydrological effects in four fens

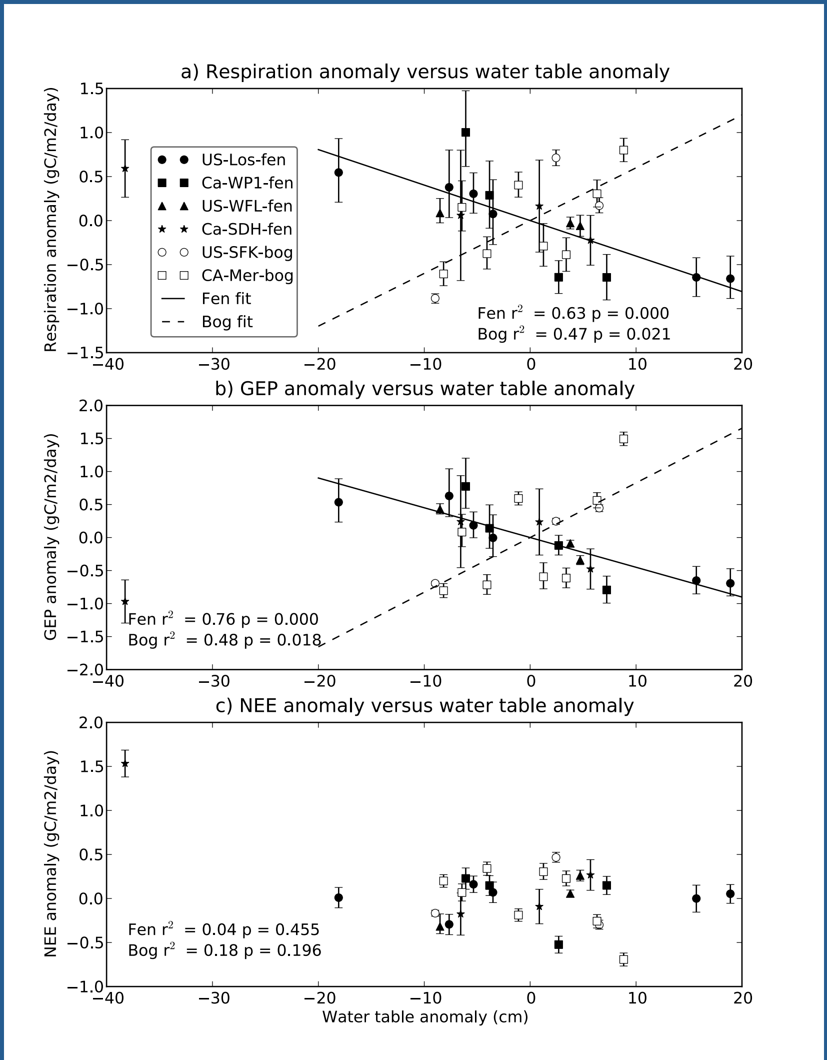
- Eddy-covariance summer carbon flux anomaly vs. water table anomaly for four northern fen sites
- Both ER and GEP increase with deeper water tables (long time scales)
- Drying over short time scale can lead to reduction in GEP and net CO_2 emission
- NEE has no significant correlation with water table



Sulman et al., GRL, 2010

Contrasting effects in bogs:

- Bog C fluxes (white symbols) have lower magnitude and opposite sign correlation with water table



Sulman et al., GRL, 2010

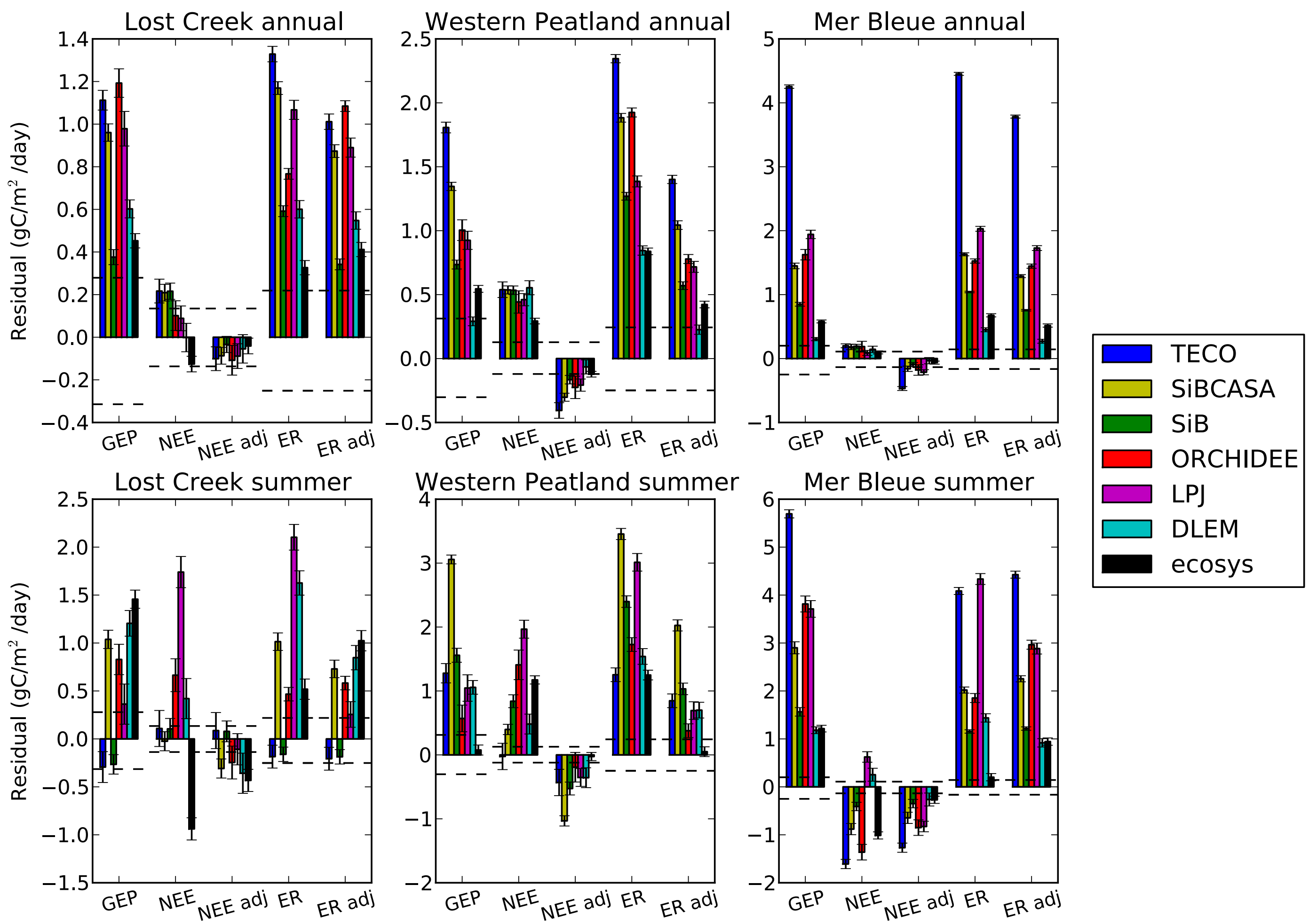
How well did models simulate peatland processes?

Model name	**Temporal resolution**	**Soil layers**	**Soil C pools**	**N cycle**	**Max soil moisture**
DLEM	Daily	**2**	3	Yes	Saturation
Ecosys	Hourly	8	9	Yes	Saturation (with water table)
LPJ	Daily	**2**	2	No	**Field capacity**
ORCHIDEE	30-min	**2**	8	No	**Field capacity**
SiB	30-min	10	None	No	Saturation
SiBCASA	30-min	25	9	No	Saturation
TECO	30-min	10	5	No	Saturation

All models overestimated GEP and

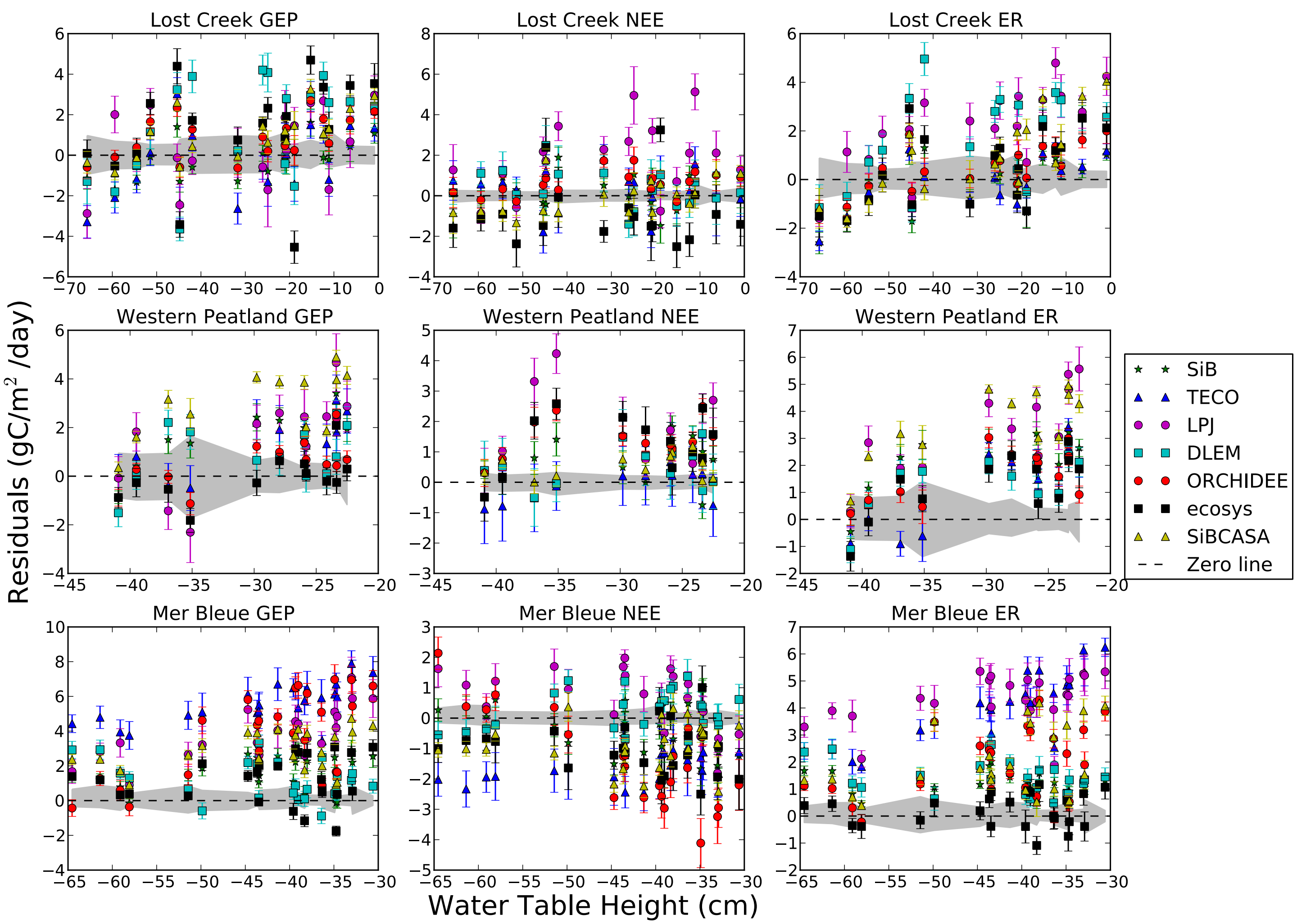
Annual

Summer



Sulman et al., JGR, 2012

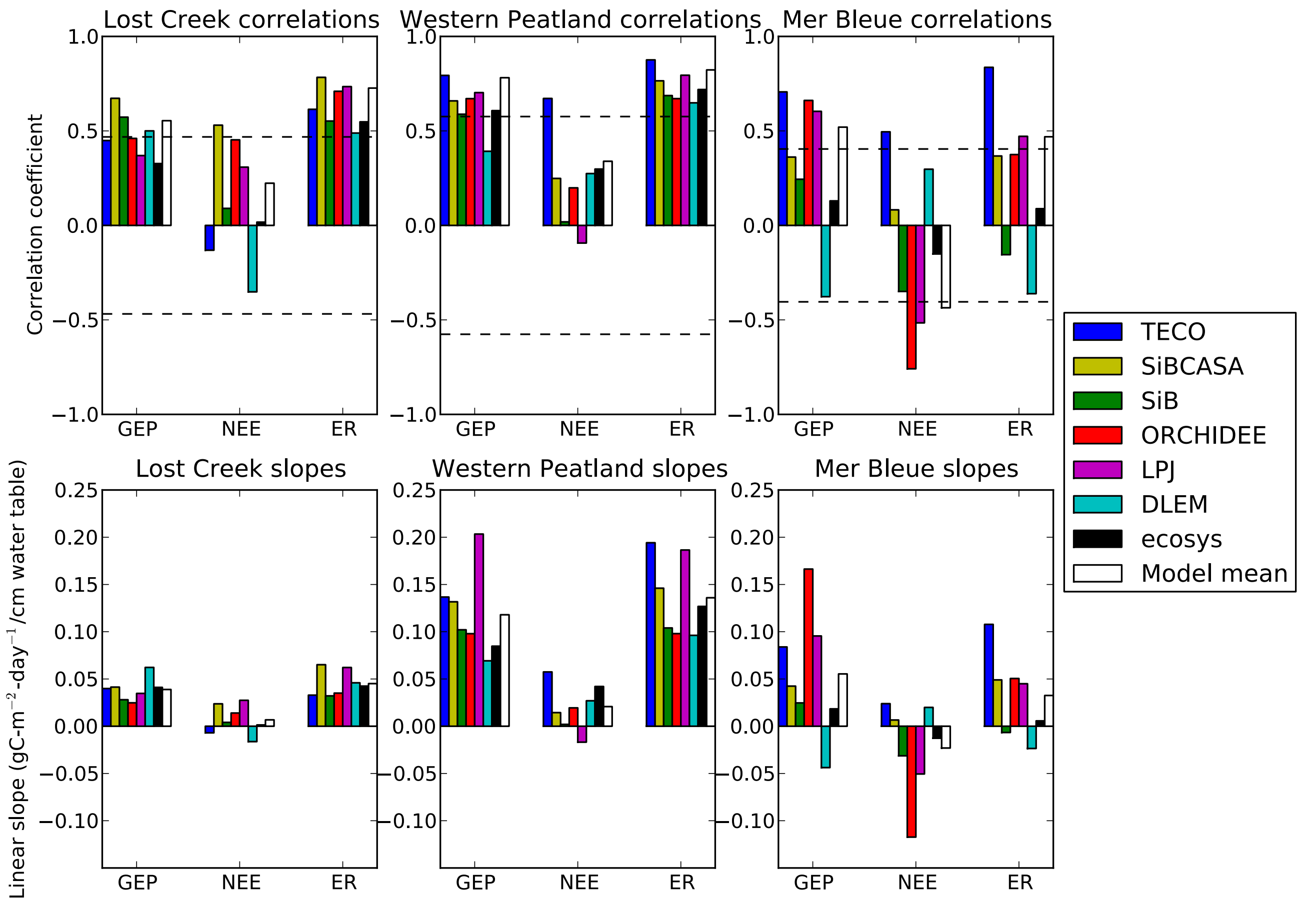
Monthly residuals were correlated with observed water table



Correlations with water table

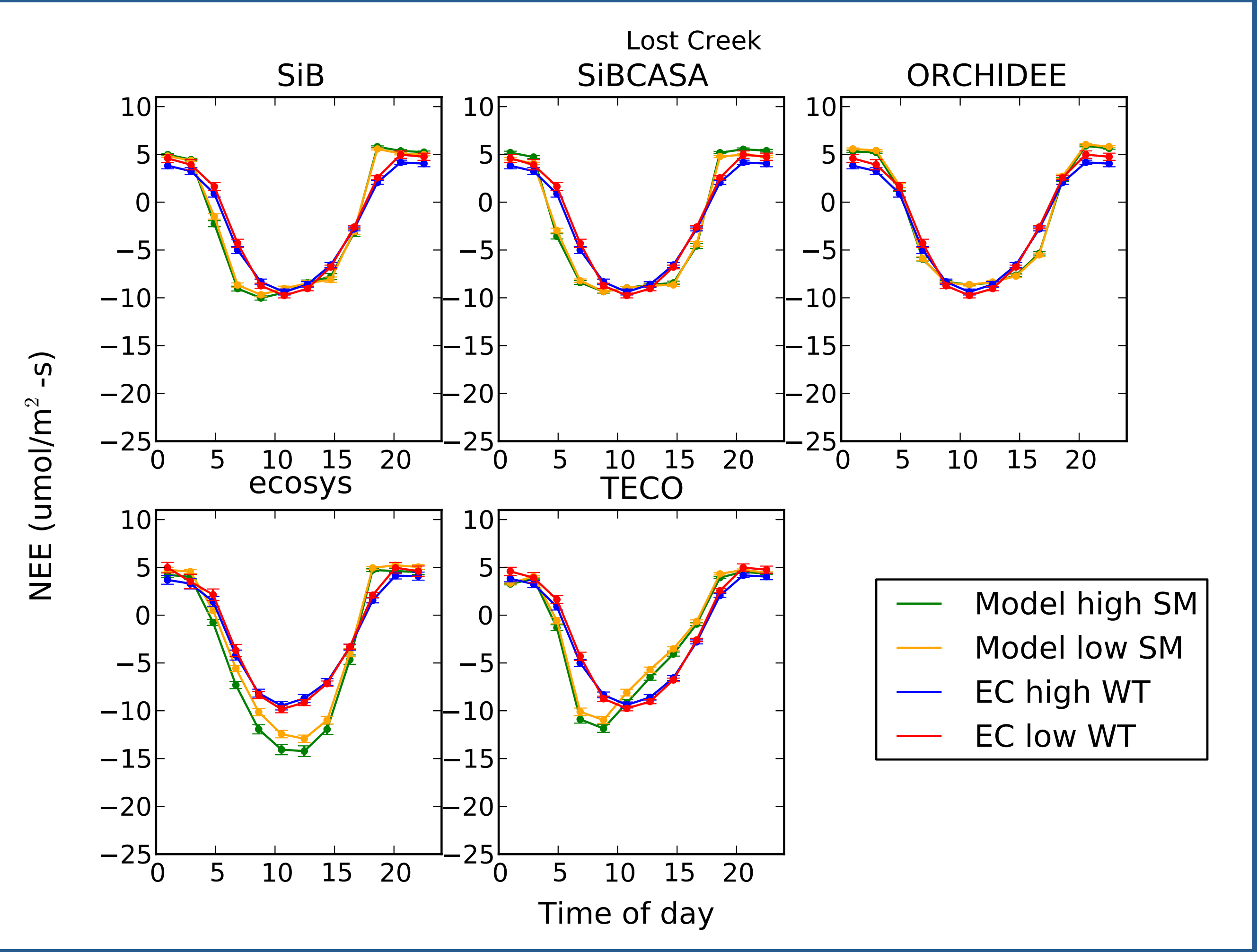
Correlation coefficient

Slope



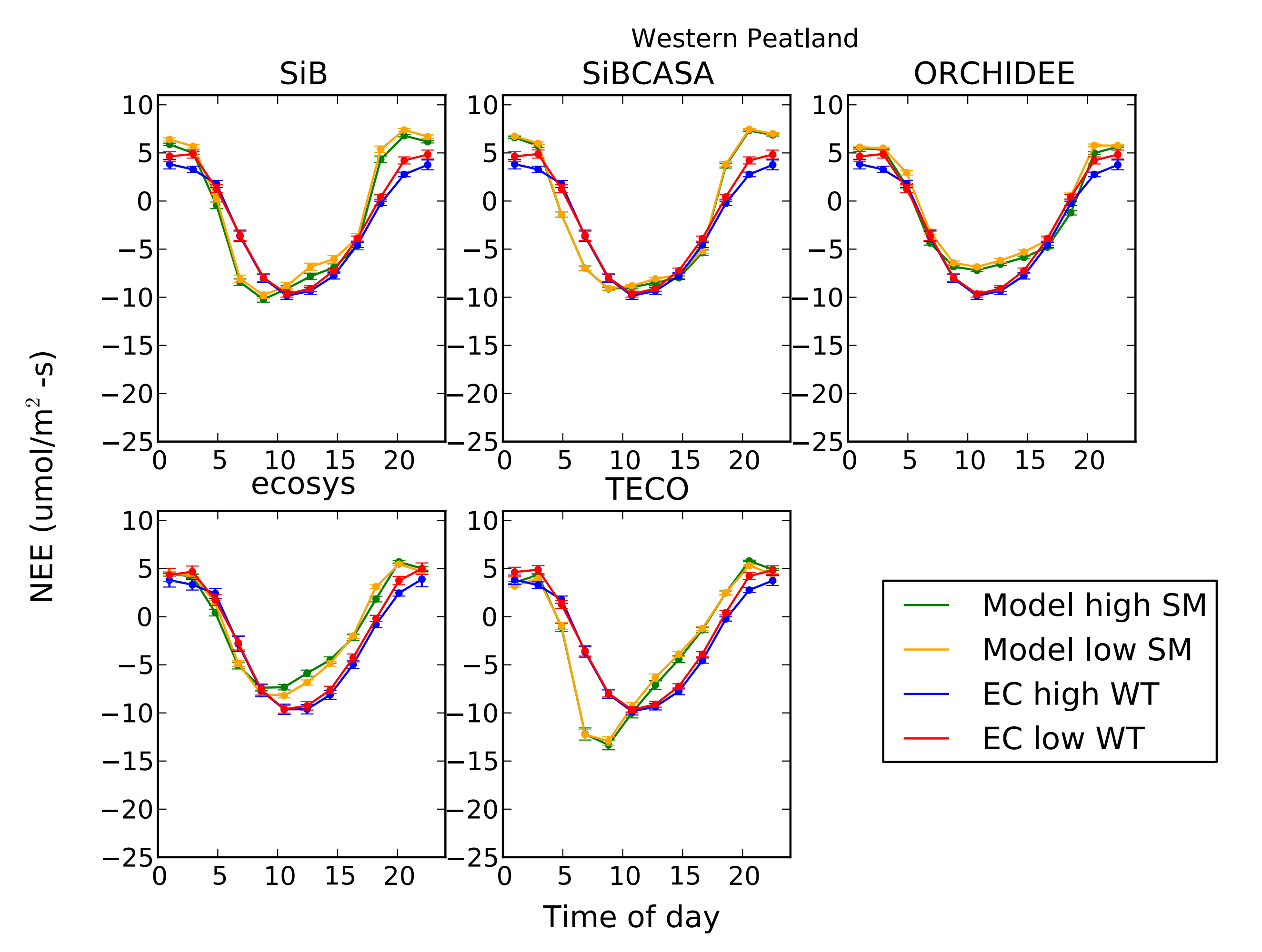
Diurnal cycles not bad at *fens*

Lost Creek

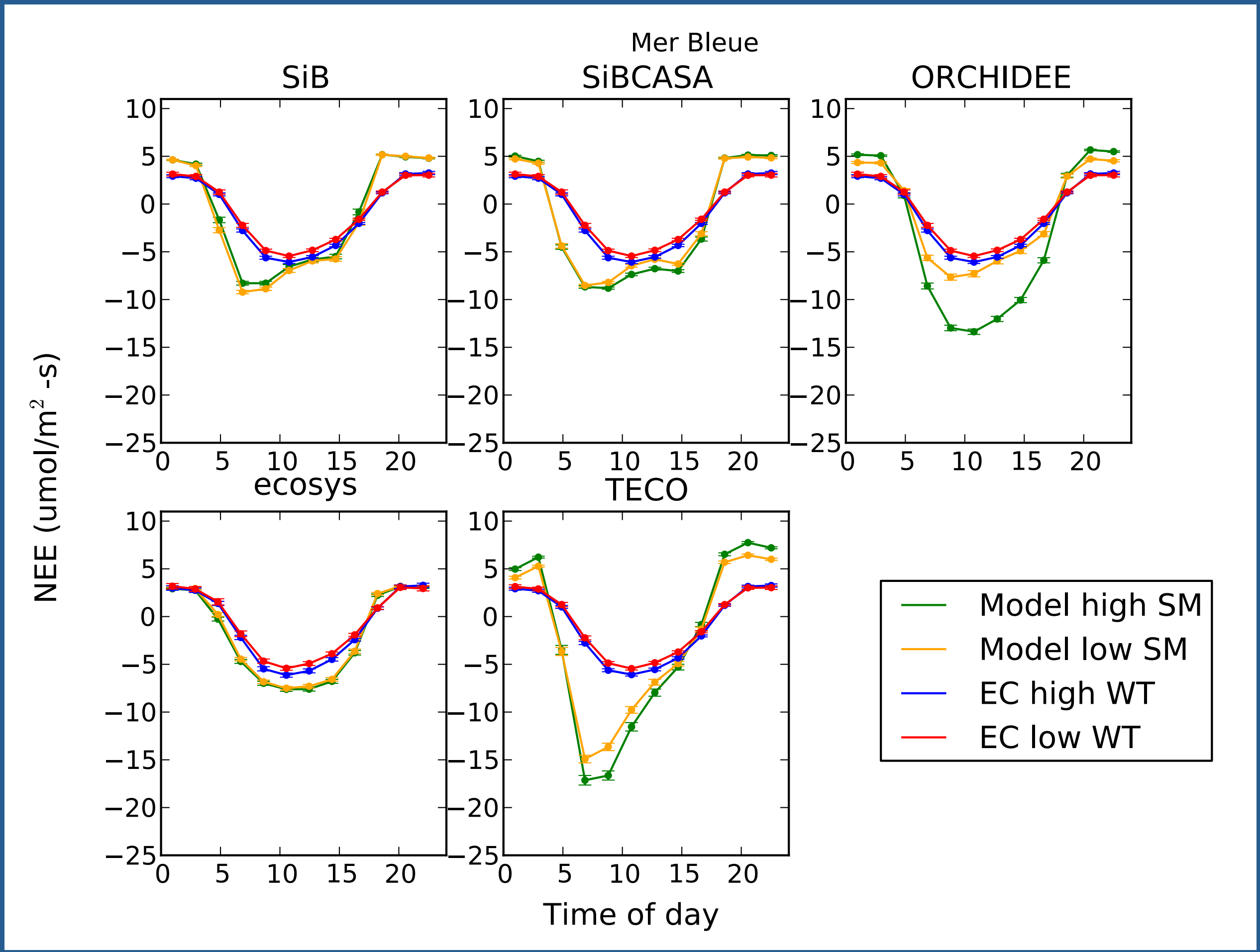


Diurnal cycles not bad at *fens*

Western Peatland



Diurnal cycles significantly worse at *bog*



Conclusions: Interannual time scales

- Fens and bogs have opposite responses to water table variations
- Ecosystem models overestimate peatland productivity and respiration
- Water table variations contribute significantly to model error
- Models perform better at bogs than fens

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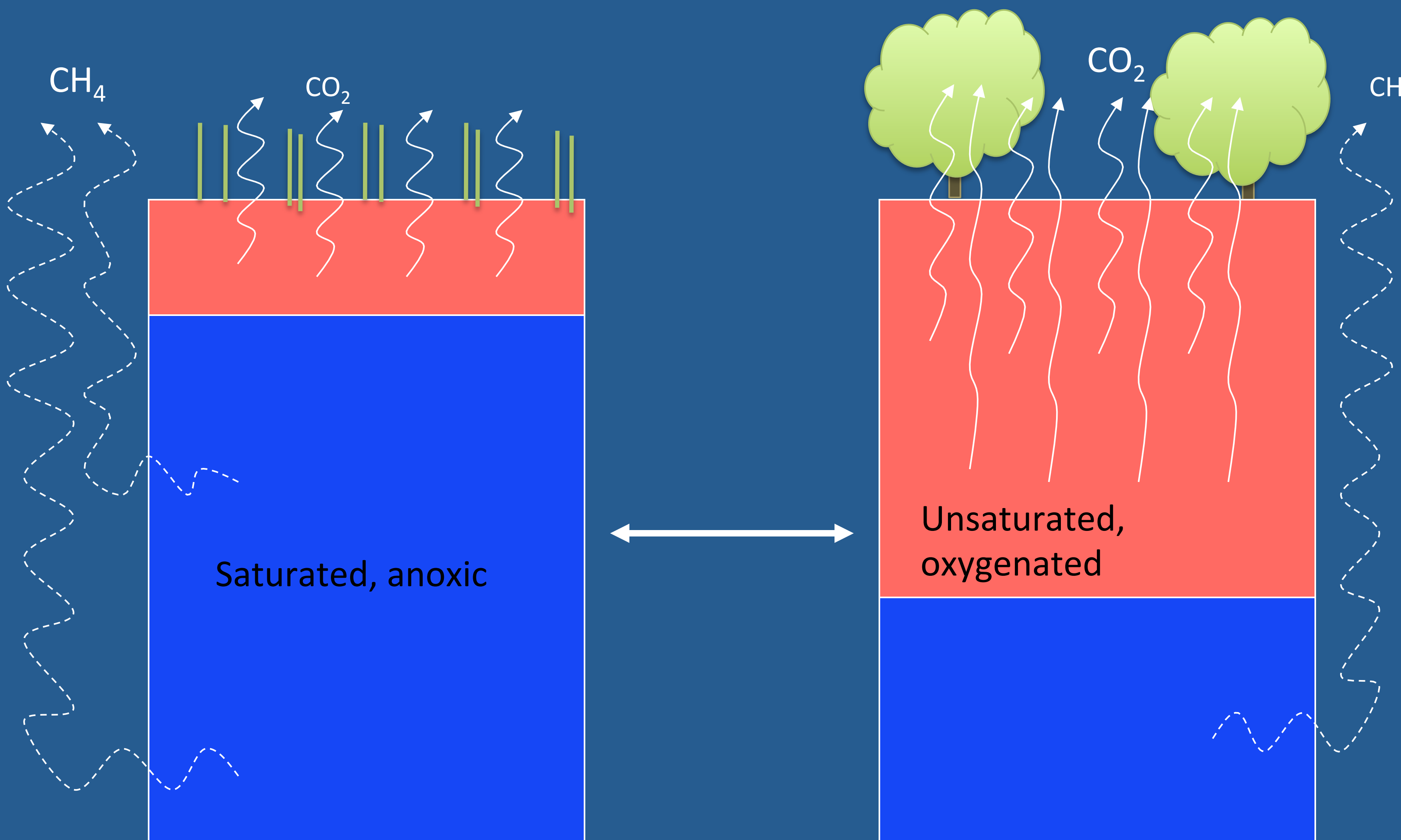
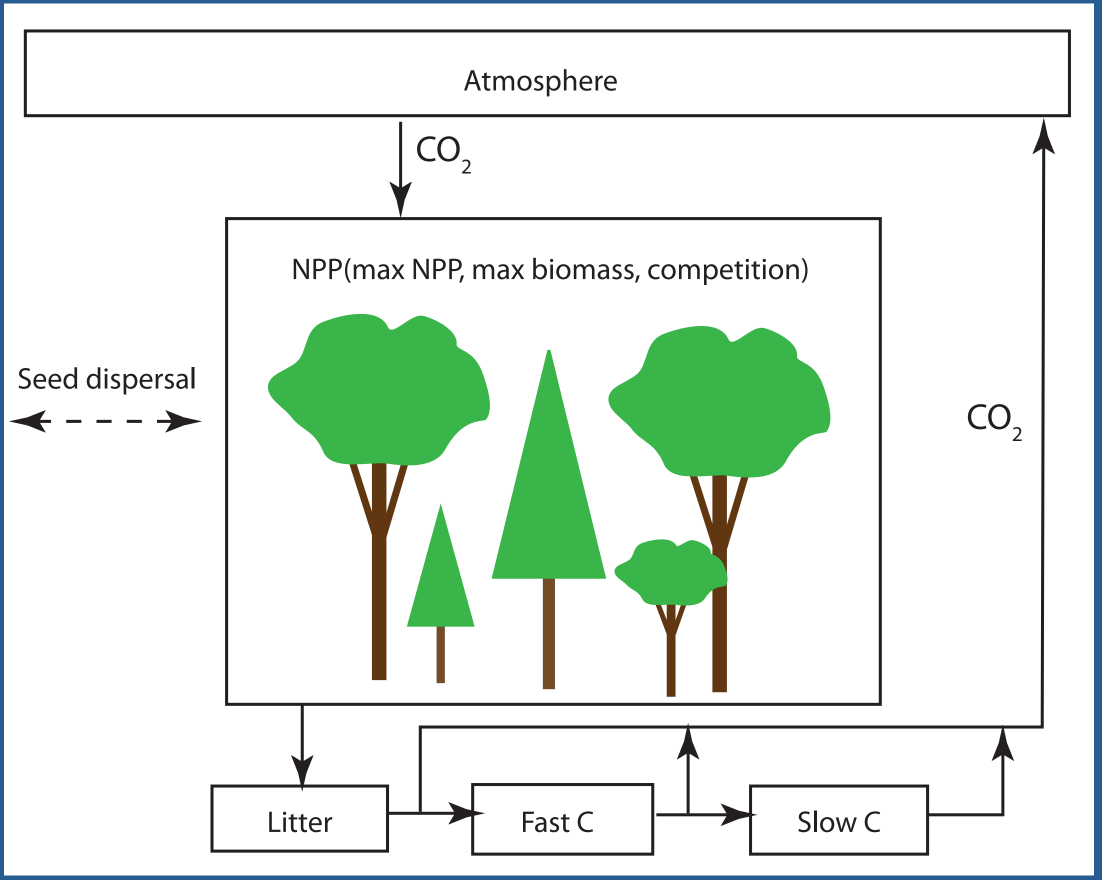
Effects of water table change



Long-term drying: model analysis

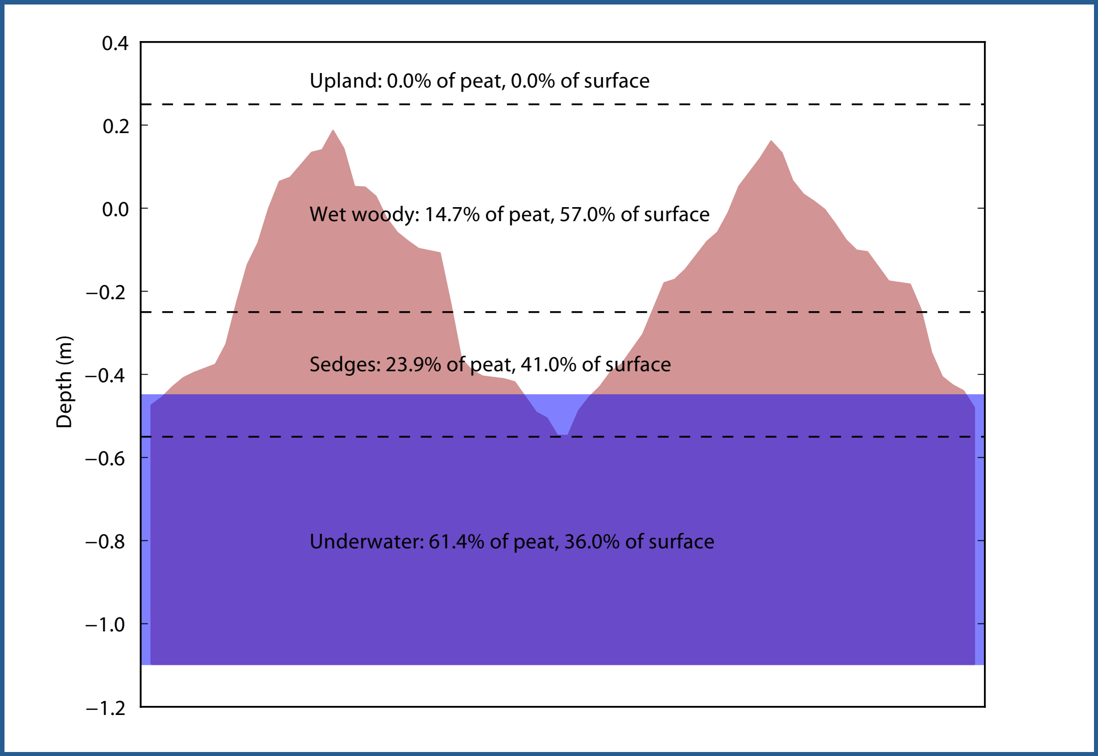
LANDIS-II model:

- Species cohort based forest succession model
- Yearly time step
- Tracks cohort biomass and two soil C pools
- Reproduction: Seed dispersal and establishment probability
- NPP: Species maximum NPP, maximum biomass, and competition



Simulating wetlands

- Plants divided by flood tolerance
- Wet fractions in grid cells determined with soil height distribution
- Growth parameters multiplied by habitat surface fraction in grid cell



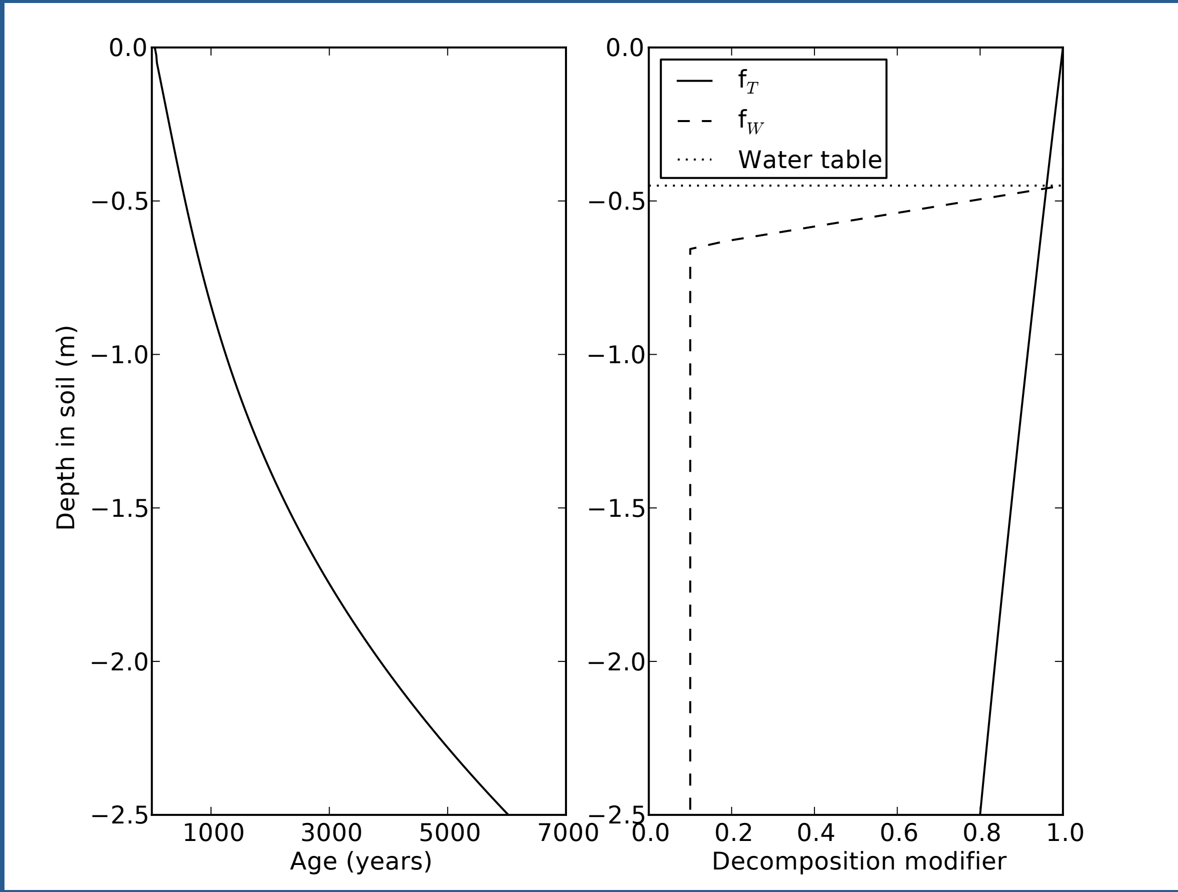
Bimodal hummock/hollow topography (Eppinga et al. 2008)

Soil decomposition model

- Decomposition rate *k* depends on age, temperature, and water table factors
- Mean k calculated from 100 soil columns sampled from topography distribution

$$k(t) = \frac{k_0}{1 + k_0 t}$$

$$k(z) = k(t) f_T(z) f_W(z)$$



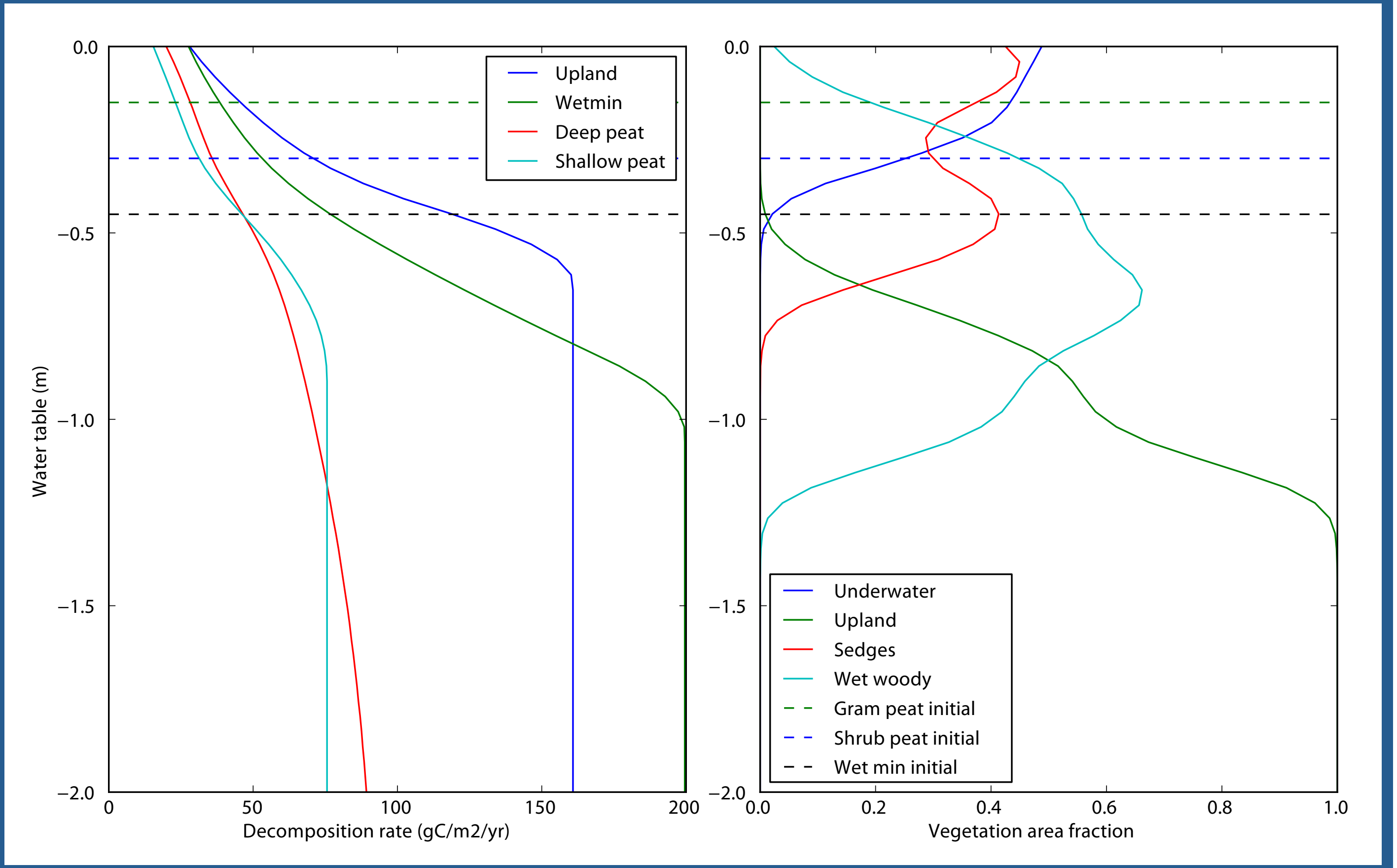
Model and profiles based on Frolking et al. 2001

Soil decomposition and plant community dependence on water table

Peatland pools:
Shallow peat scenario:
- 18.5 kgC/m2
- 45 cm depth

Deep peat scenario:
- 100kgC/m2
- 2.5 m depth

Low sensitivity at deeper depths is due to older C



Soil decomposition rate dependence on water table

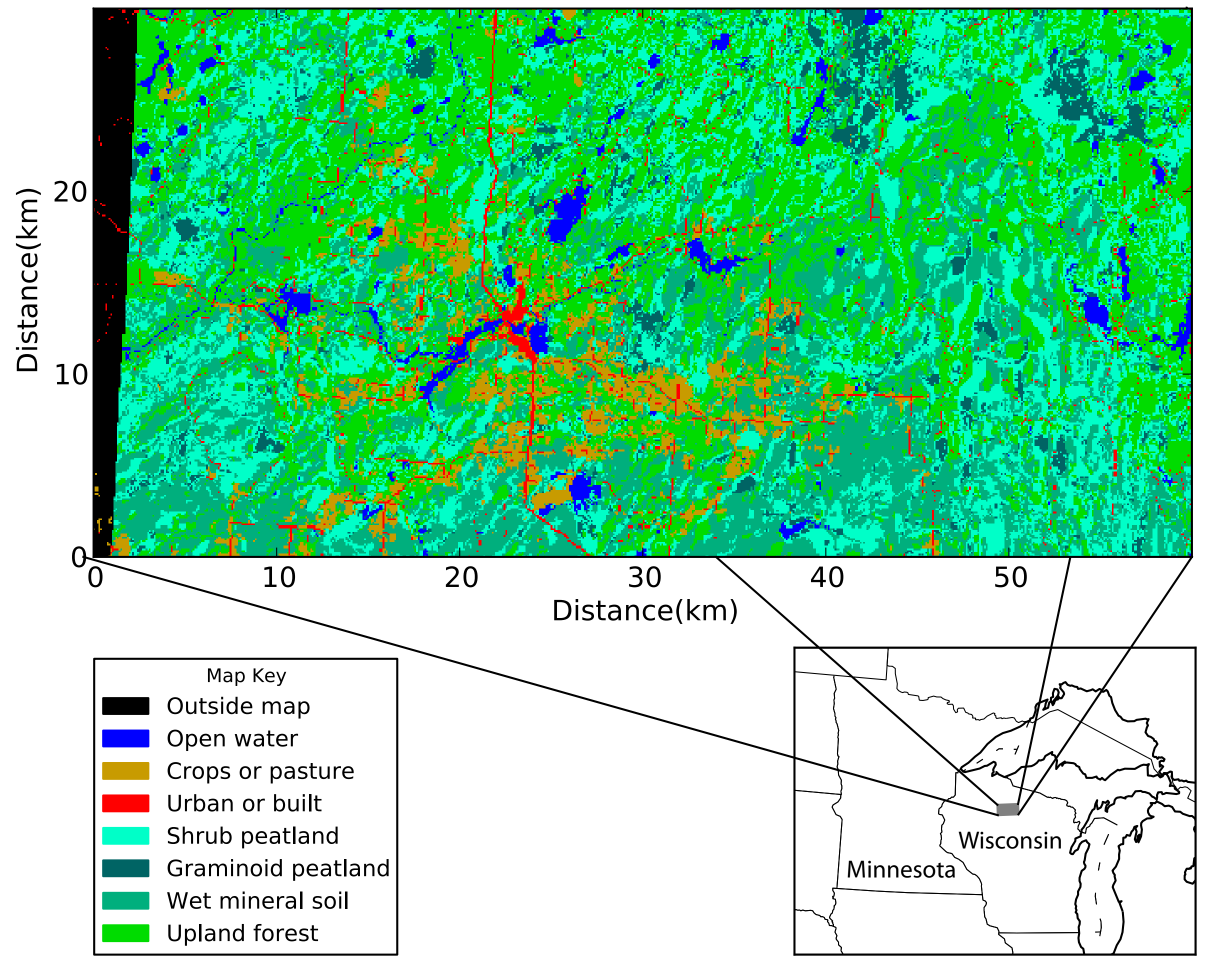
Vegetation fraction dependence on water table

Modeled landscape: Northern Wisconsin

Price County, near Phillips, WI

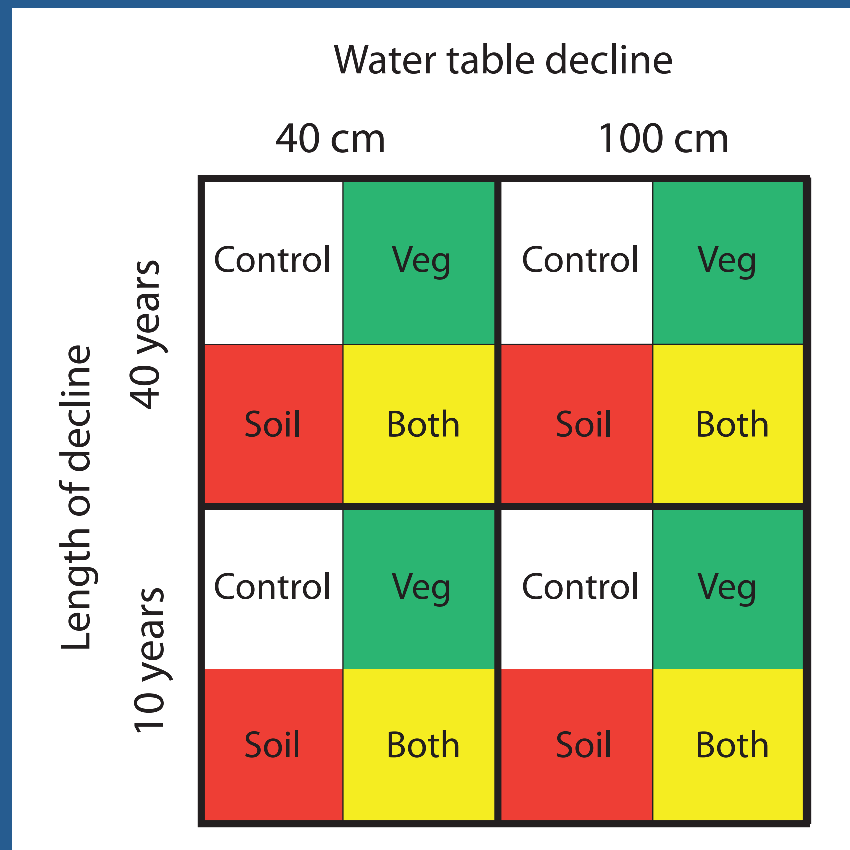
Categorized based on remote sensing and soil inventories

Ecoregion	Active area fraction
Upland	38%
Mineral wetland	27%
Shrub peat	29%
Graminoid peat	5%



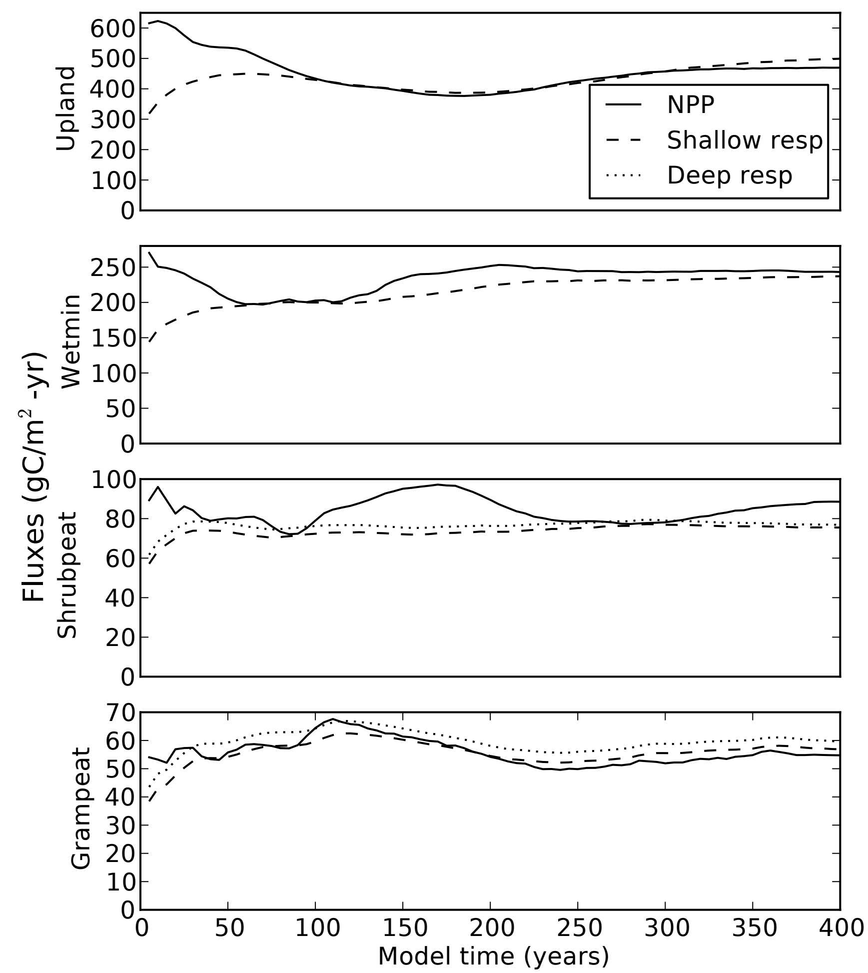
Summary of simulations

- Moderate and severe levels of water table decline
- Fast and slow water table decline
- Separation of plant and soil effects
- These combinations were applied to both shallow and deep peat scenarios



Model results: control simulation fluxes

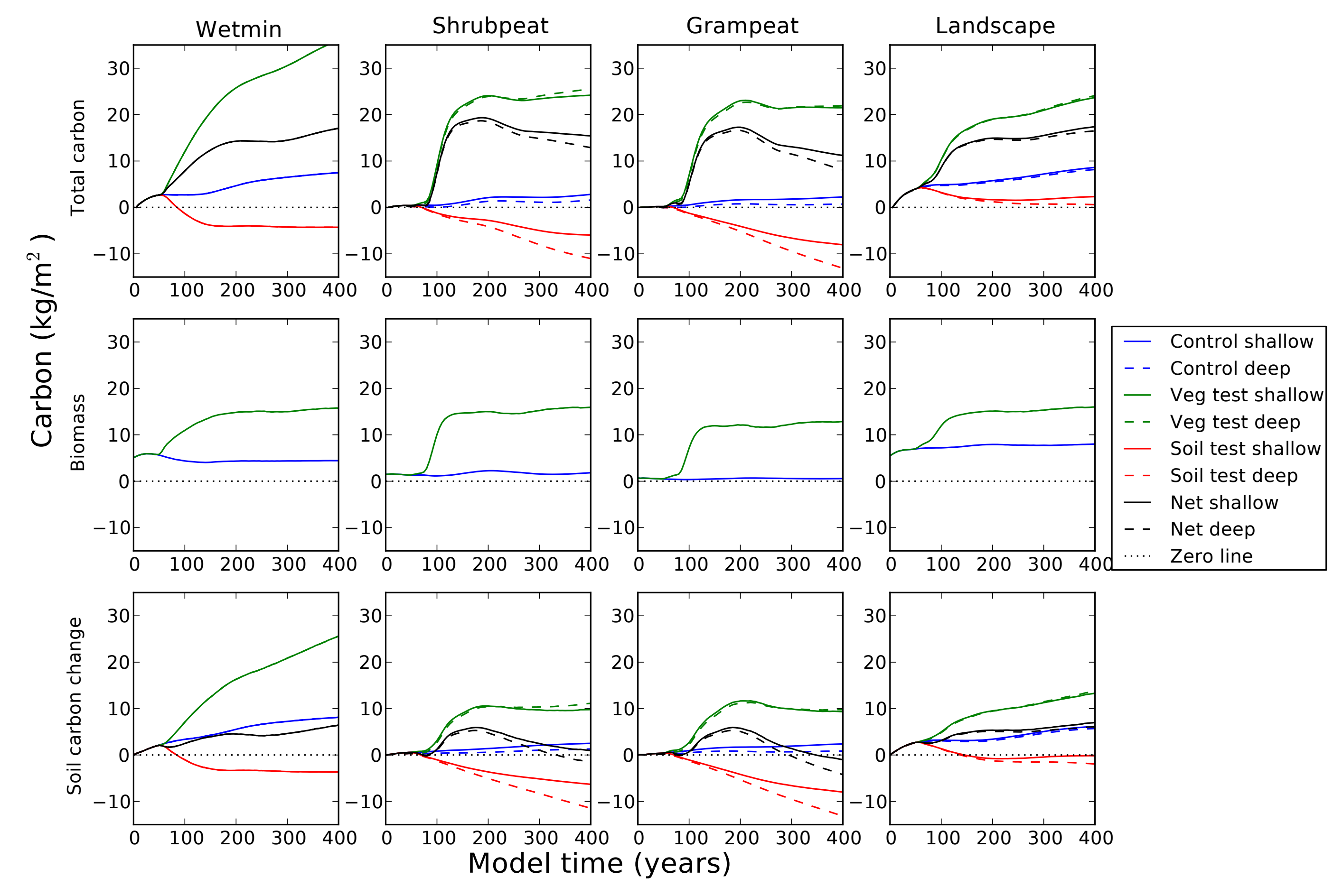
- Four ecoregions:
  - Upland forest
  - Mineral woody wetland
  - Peat shrub wetland
  - Peat graminoid wetland
- Upland was most productive
- Productivity declines and respiration increases as forest ages



Water table effects on carbon balance

Water table decline caused:

- Increased soil decomposition
- Increased biomass accumulation
- Net effect: Short term increase in carbon, followed by long-term losses



Scenario: 100 cm WT decline over 40 years

Water table effects on carbon balance

Peatlands:

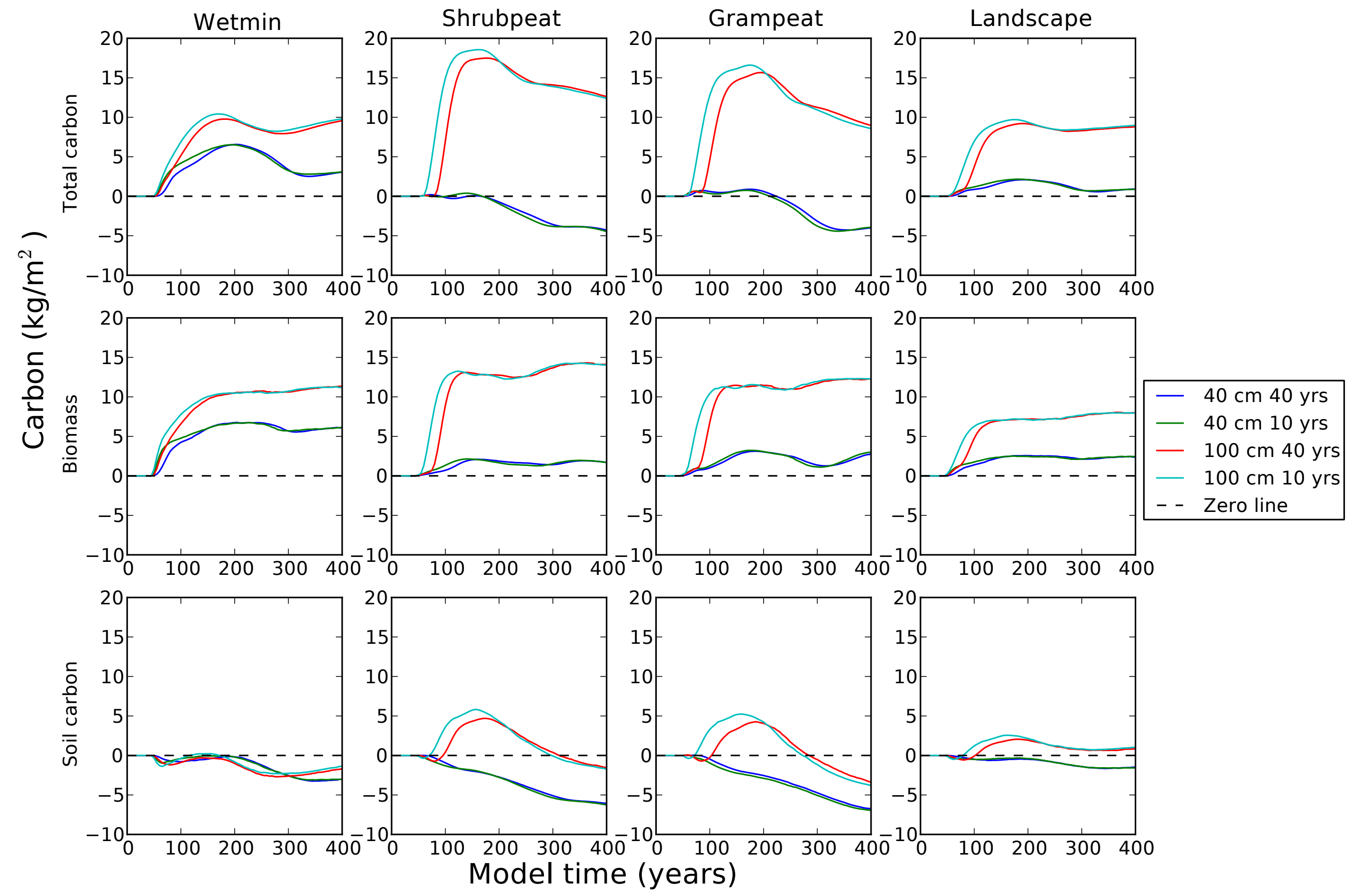
- 100 cm declines:
  - Short term: C gain
  - Long term: C loss
- 40 cm declines
  - Short term: C neutral
  - Long term: C loss

Mineral wetlands:

- C gain for both

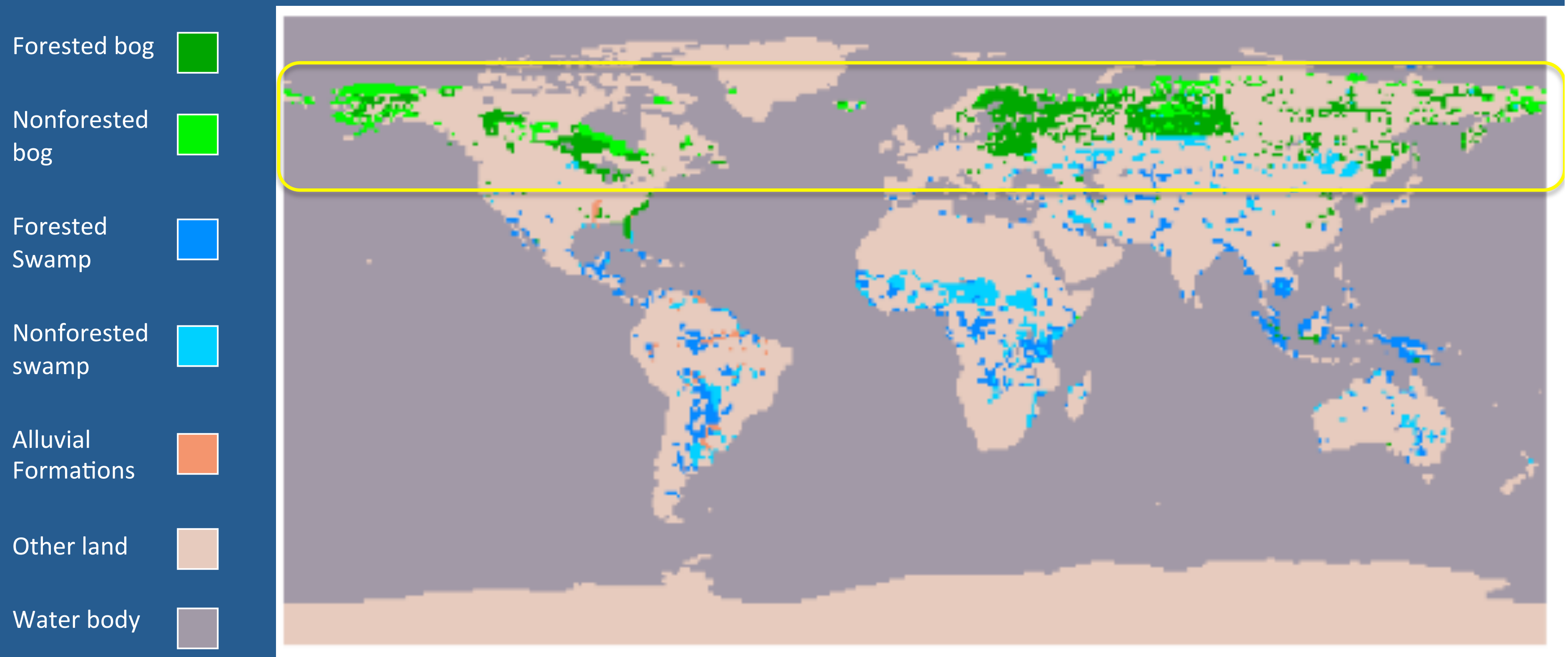
Whole landscape

- Short-term: C increase
- Long-term: C steady
- Time scale of decline made little difference



Net change from control run for shallow peat simulations: Different water table scenarios

Simple global upscaling



Matthews and Fung, 1987, GBC

Boreal and subarctic wetland area ≈ 2-4x10^{12} m^2 (Mitra et al 2005)

Simple global upscaling

- Boreal/subarctic wetland area ≈ 2-4x10^{12} m^2 (Mitra et al 2005)
- Modeled changes:
  - Soil C loss of 5 kgC/m^2
  - Biomass C gain of 5-10 kgC/m^2
- Anthro emissions ≈ 4-8 PgC/year (IPCC 2007)
- Global equivalent
  - Loss of 10-20 PgC (1-5% additional emissions over 100 yrs)
  - Gain of 30-60PgC (4-15% lower emissions over 100 yrs)

Conclusions: Century time scales

- Plant community responses dominate response to drying
- Moderate drying leads to C loss in peatlands
- Severe drying leads to short-term C gain followed by losses
- Drying leads to C gain in non-peat wetlands
- Drying leads to significant C gain at landscape scale
- Magnitudes are significant at global scales

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Additional complications and future applications

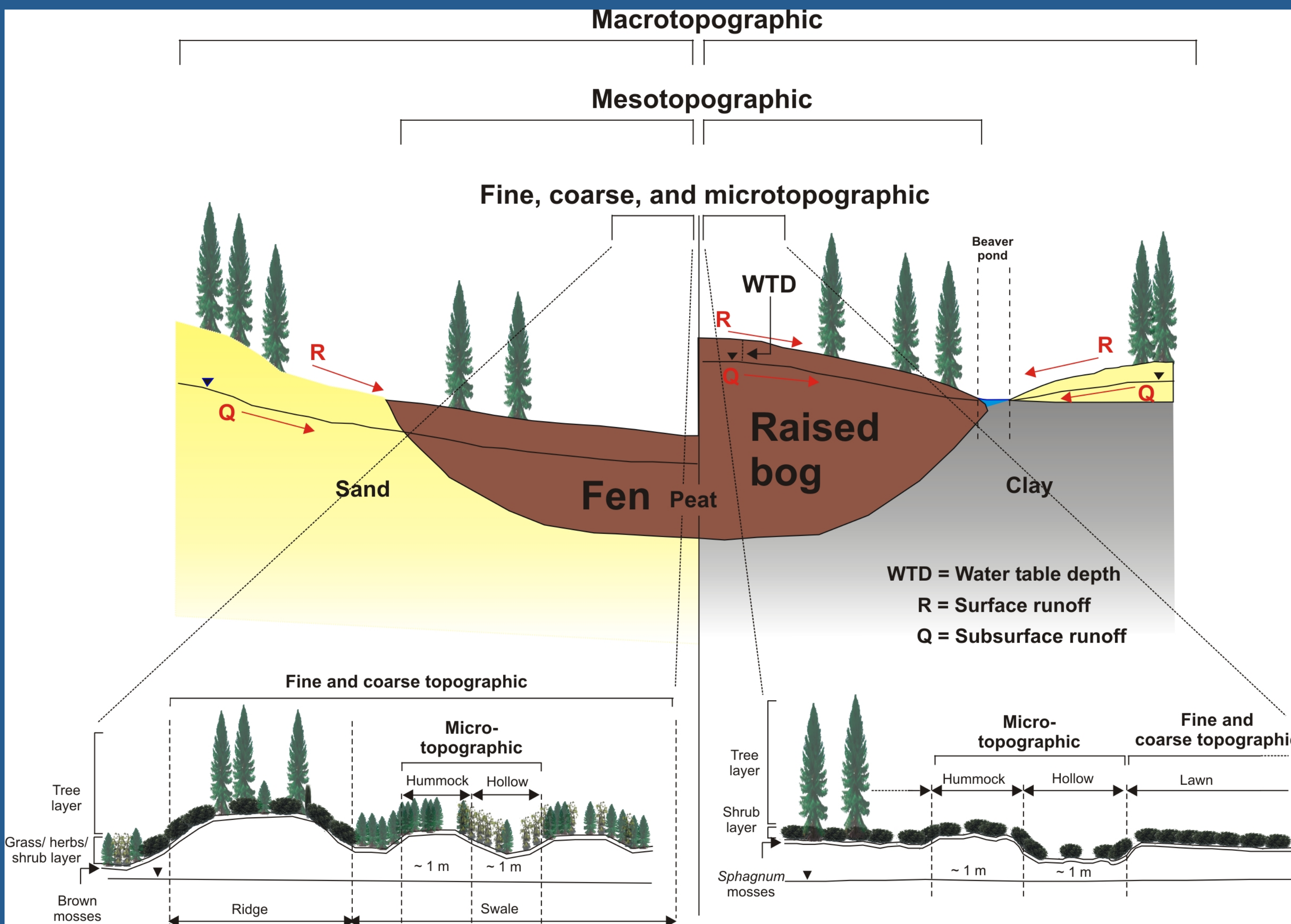
- Topography
- Non-CO_2 carbon fluxes
- Changes in soil properties over time
- Climate-driven hydrology

Peatland topography

Männikjärve bog, Estonia

J. S. Aber, 2001.
Accessed from http://www.emporia.edu/earthsci/estonia/estonia.htm, 1/13/2011.
See Aber et al., *Suo*, 2002

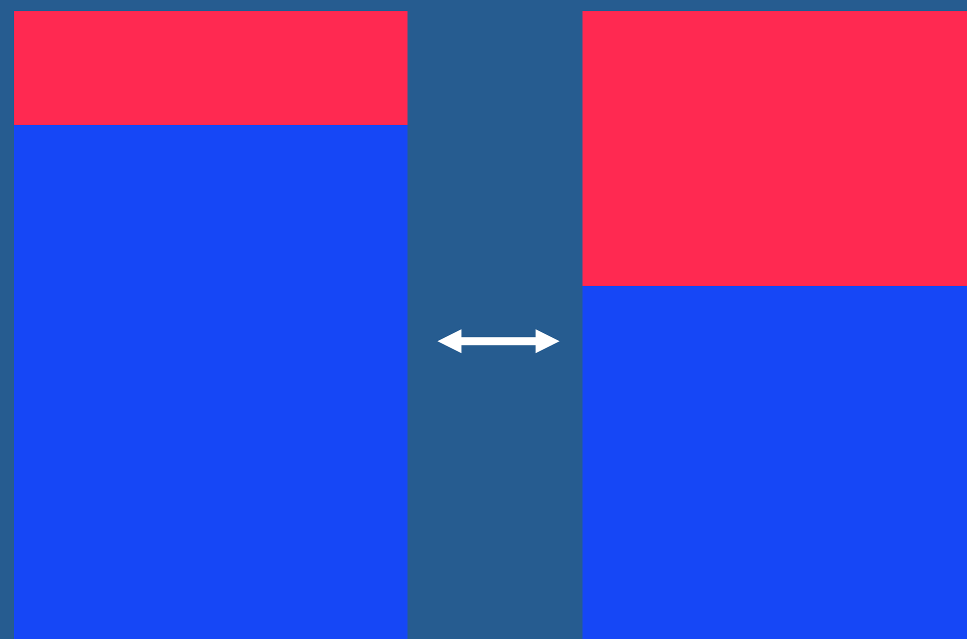
Peatland topography



Sonnentag, PhD thesis (2008)

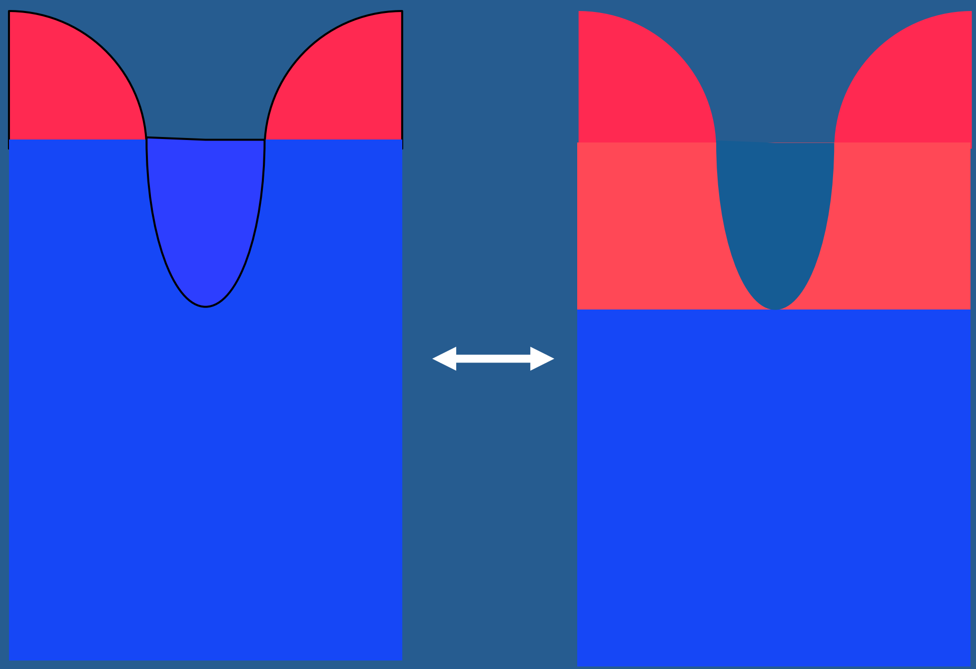
Microtopography in wet peatlands

What does water table depth mean, really?



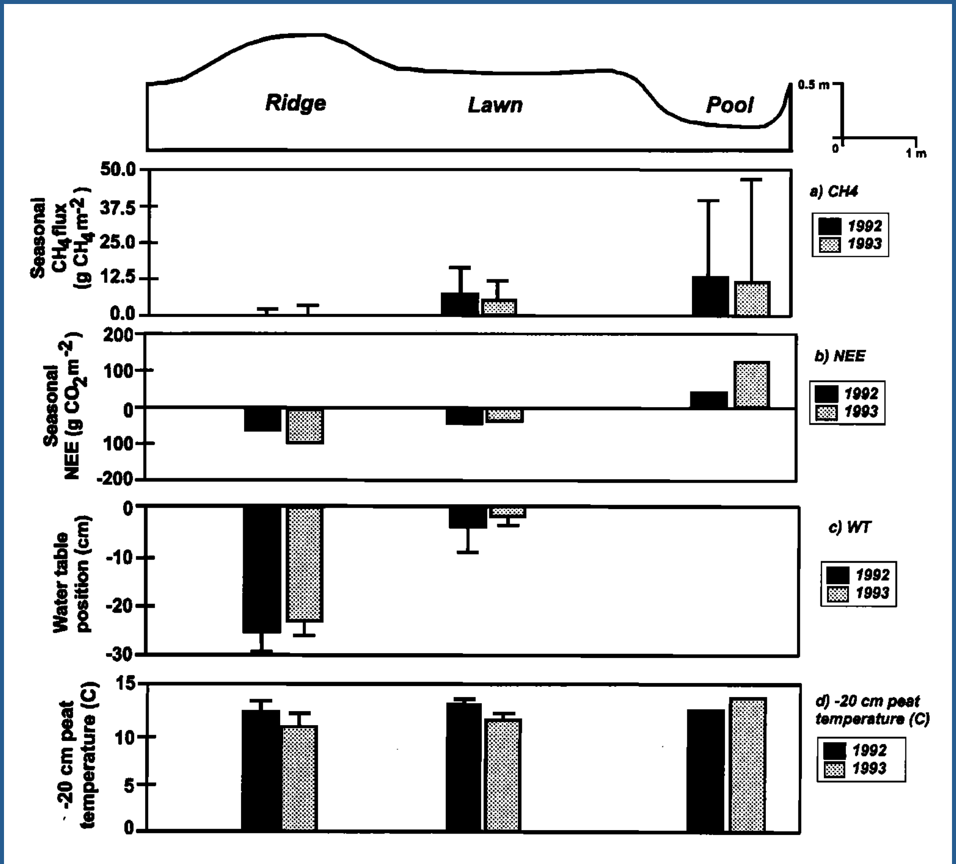
Microtopography in wet peatlands

- Water table can vary by tens of cm at small scales
- Mean water table at a peatland does not capture the real range of variability
- Topographical variations lead to micro-ecosystems within the peatland



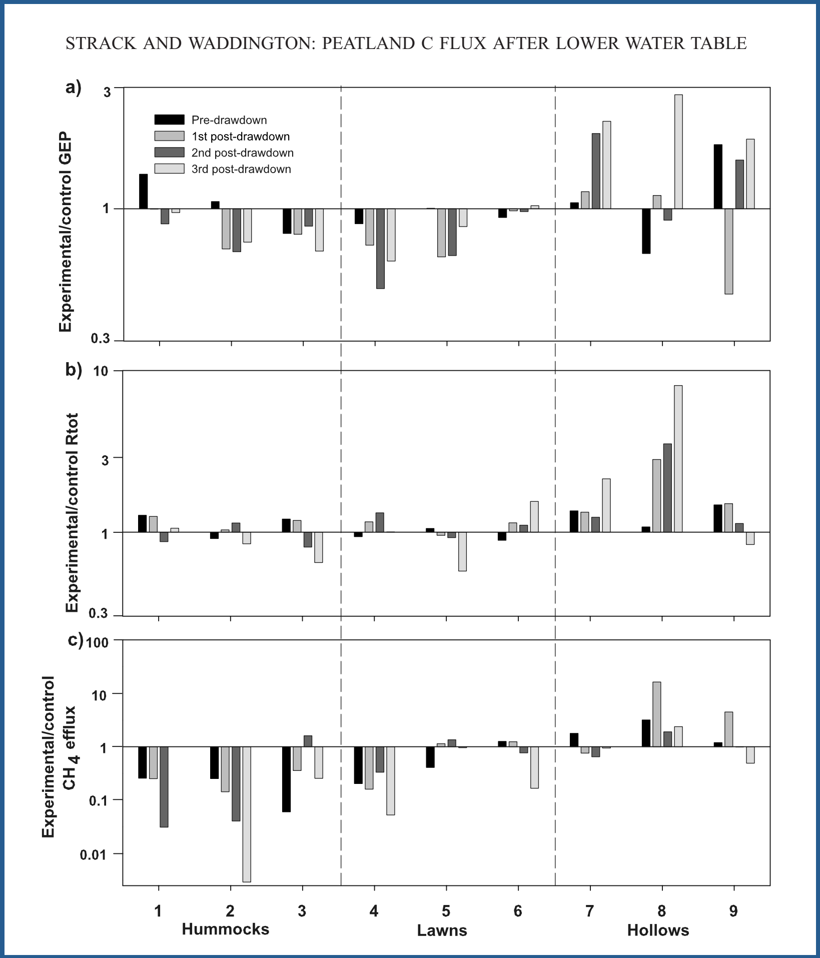
Measured effects

CH_4 and CO_2 fluxes



Waddington and Roulet, Glob. Biogeochem. Cy., 1996

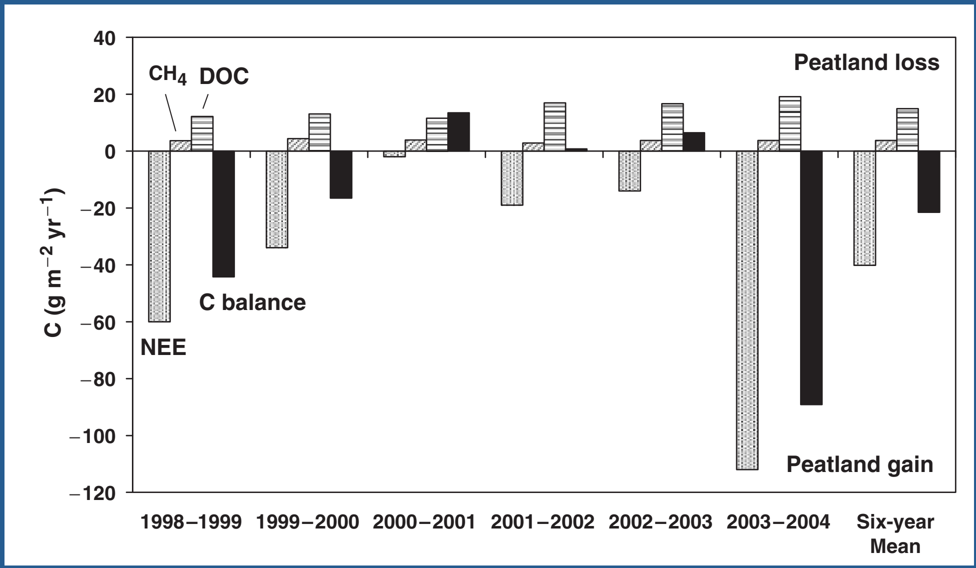
Effects of lowered water table



Strack and Waddington, Glob. Biogeochem. Cy., 2007

Non-CO_2 carbon fluxes
An example: Mer Bleue bog

- NEE was larger than other factors, but ignoring DOC and CH_4 would lead to overestimate of net carbon uptake
- High inter-annual variability leads to high uncertainty



Roulet et al., Glob. Change Biol., 2007

Northern Wisconsin landscape

Results for northern Wisconsin

Wetland litter
+ wetland runoff
= 17.7% of wetland NEE

Litter
+ runoff
+ methane
= 28% of wetland NEE

Forest litter
+ runoff
= 2.6% of forest NEE

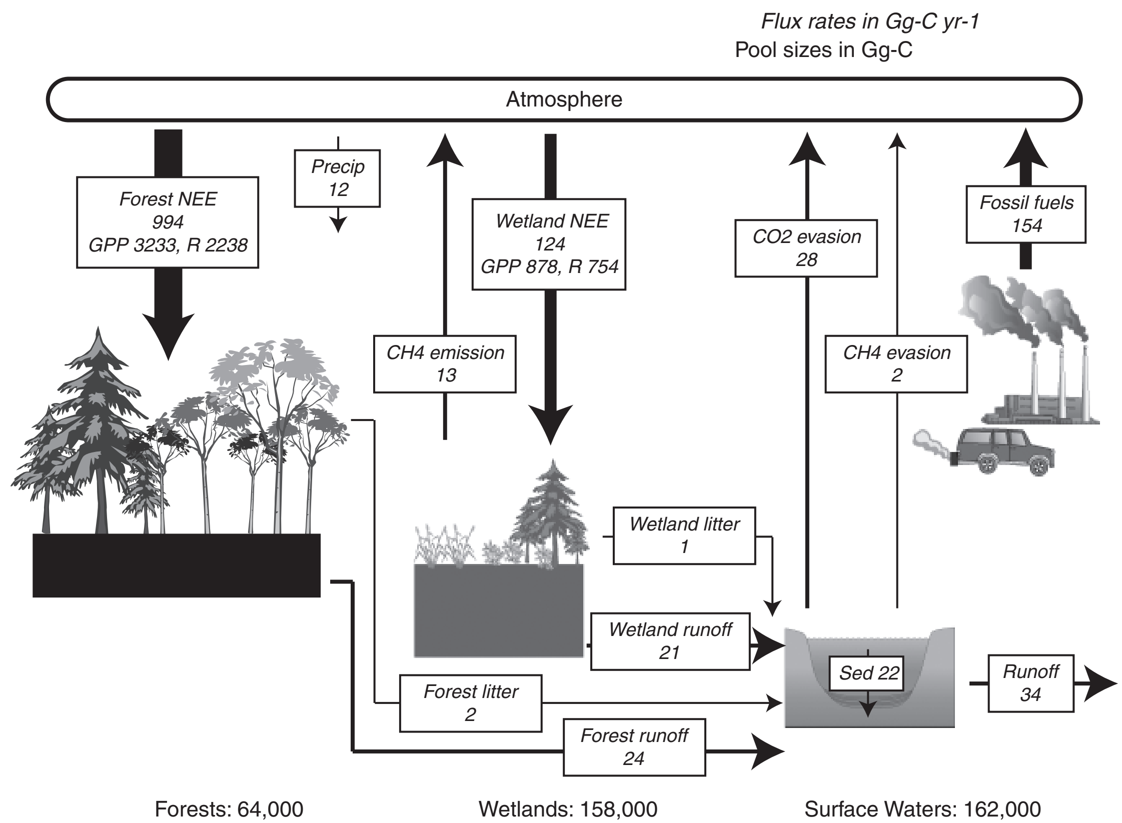


Fig. 2 Schematic showing the three major ecosystem types of the Northern Highlands Lake District (NHLD), along with best estimates of C flux rates and pool sizes. These estimates are associated with varying degrees of uncertainty (Tables 1–5). Forests make up 54% of the NHLD area, wetlands 28% (including 20% peatlands and 8% other wetlands), and lakes 13%. NEE, net ecosystem exchange; GPP, gross primary production; R, respiration.

Buffam et al., Glob. Change Biol., 2011

Future model improvements

- Dynamic soils
  - Peat layers treated as age cohorts
  - Soil subsidence and changes in bulk properties
- Interactive hydrology
  - Couple to climate-driven hydrological model
  - Landscape topography driven by digital elevation map
- Improved biology
  - Nitrogen cycle
  - Productivity coupled to climate
  - Explicit species biological responses to flooding
- Climate feedbacks
  - Albedo
  - Latent and sensible heat fluxes
  - Carbon cycle coupled to climate

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Summary of results

- Peatland **community types** and **succession** control carbon cycle responses to hydrological change
- Model simulations **overestimate productivity and respiration** and **miss hydrology-driven variability** in peatlands
- Responses to hydrological change vary greatly depending on **time scale**

How might wetlands surprise us?

- Slow and fast hydrological changes can have opposite effects on carbon fluxes
- Different types of northern wetlands can have opposite responses to similar forcings
- Tundra, northern wetlands, coastal wetlands, and tropical wetlands could have different behaviors
- Multiple micro-ecosystems within a peatland due to topography could lead to higher resilience than expected

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