Challenges and Opportunities for Carbon Sequestration in the Restoration of Wetlands

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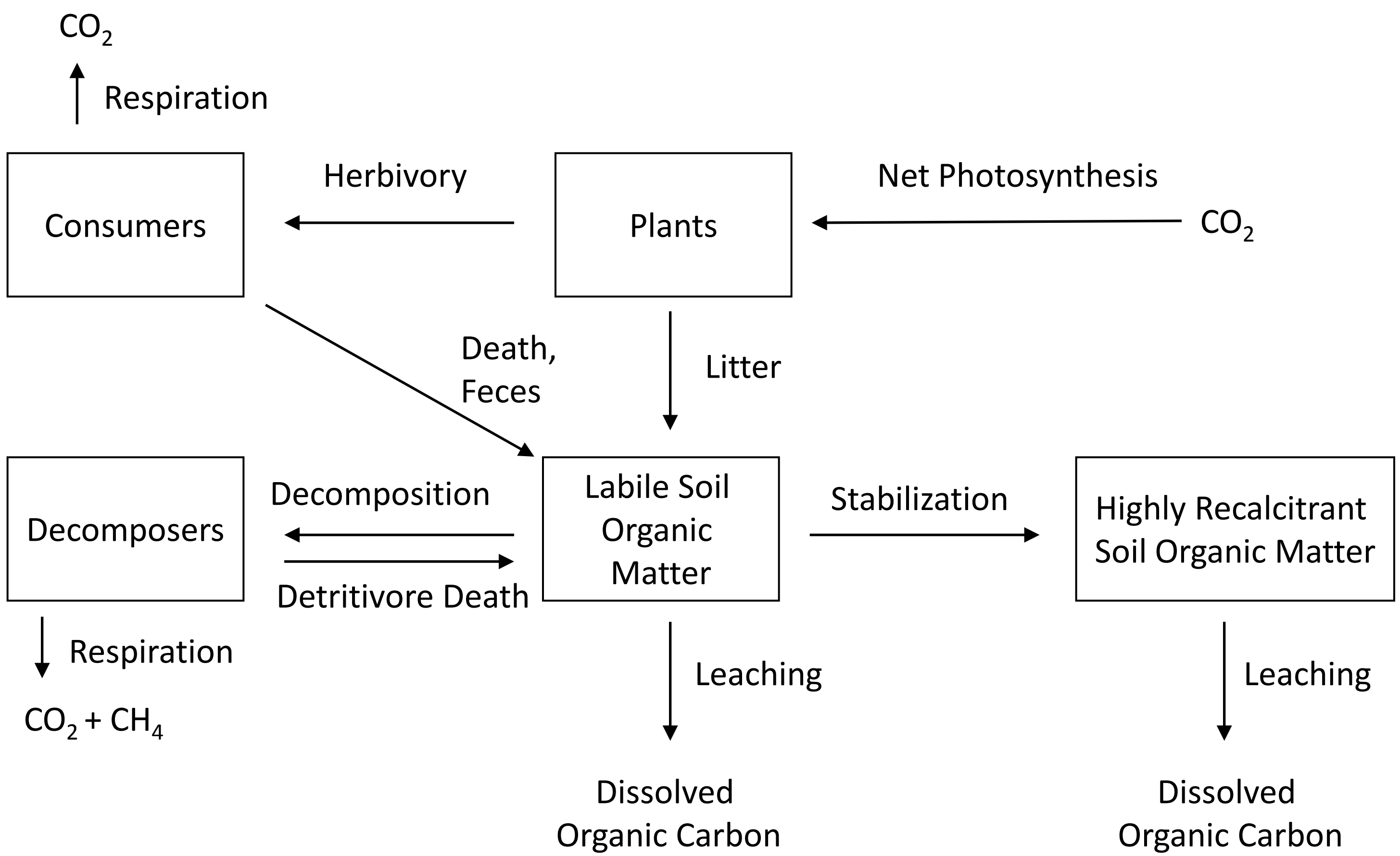
A Simplified Wetland Carbon Cycle

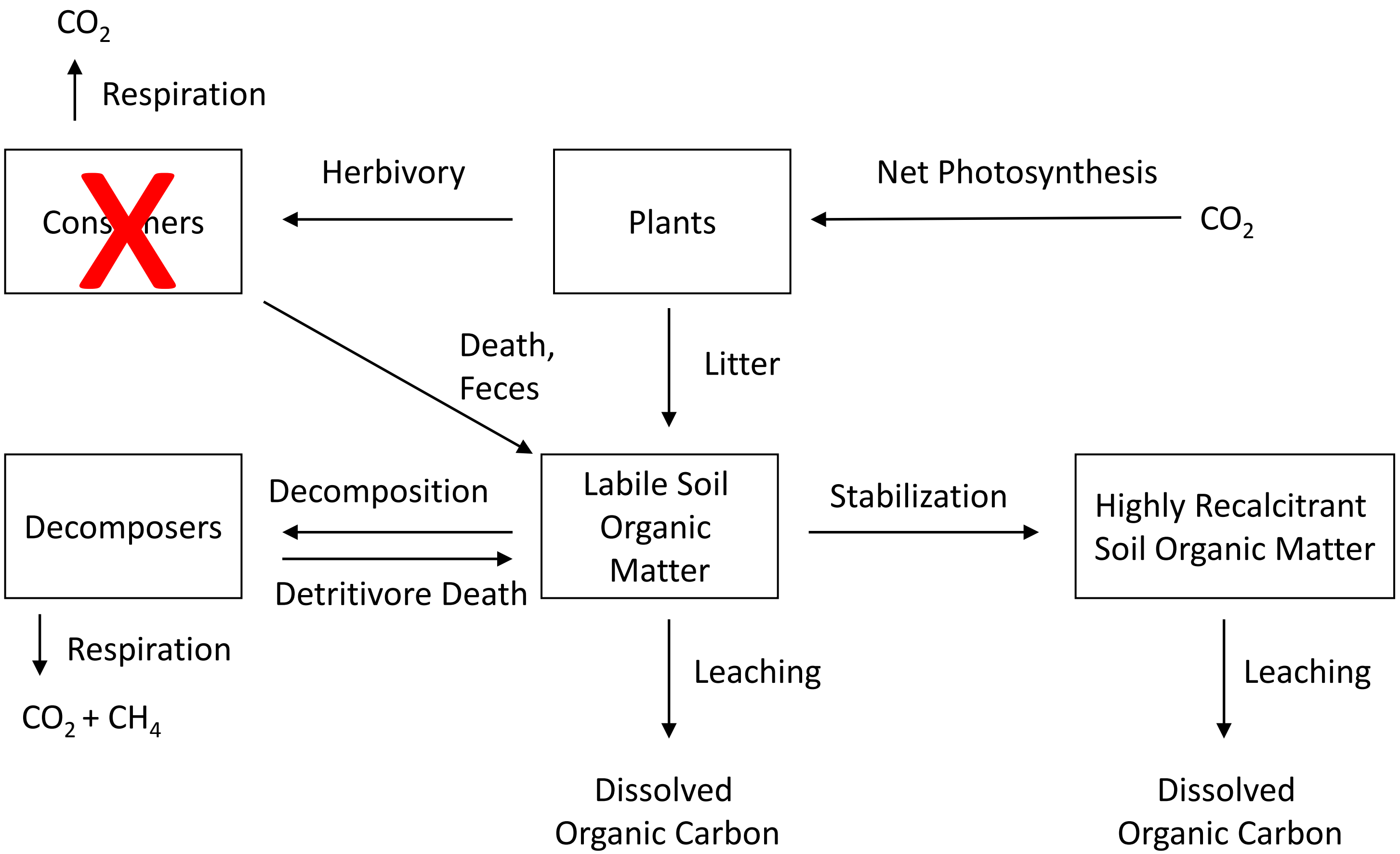


Boxes = C pools, arrows = C fluxes

CO_2 = Carbon dioxide, CH_4 = Methane

Herbivores and carnivores can be quite important in terms of their controls over plant community structure and biomass, but they are usually of minimal importance in themselves as a C pool, so they are usually ignored in terms of C sequestration.

A Simplified Carbon Cycle



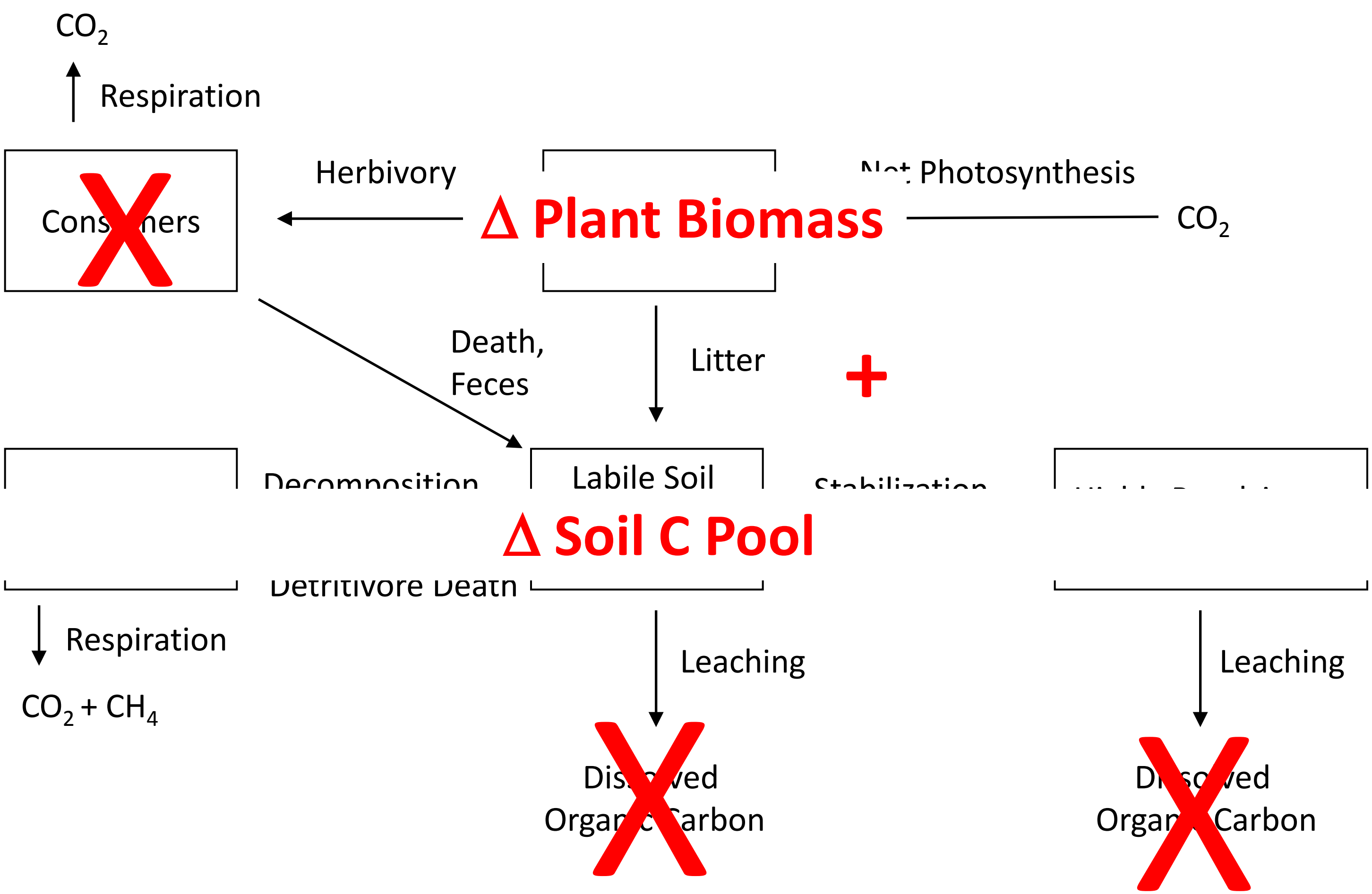
Boxes = C pools, arrows = C fluxes

CO_2 = Carbon dioxide, CH_4 = Methane

To estimate ecosystem C sequestration, the typical method is to ignore the fluxes and just measure the changes in plant and soil C pools.

Ecosystem C Balance (or Δ Ecosystem C Pool Sizes)

=



But this approach can be limited by an inability to measure the relatively slow changes in soil C pools with adequate precision.

If one assumes that all exported dissolved organic carbon is eventually oxidized to CO_2, it too can be ignored in a carbon mass balance. This is probably a safe assumption in most cases.

The increase in woody biomass is the only important plant biomass pool that continues to increase annually at an appreciable rate.

Consequently, plant biomass is inconsequential in herbaceous wetlands in terms of C sequestration.

Shrublands can have rapid biomass accumulation after restoration, but this is likely only important for a decade or so at most.

Young forests can sequester appreciable amounts of C over many decades. E.g., southeastern wetland forests sequester on average 0.50 Mg C ha^{-1} yr^{-1} (Bridgham et al. 2006).

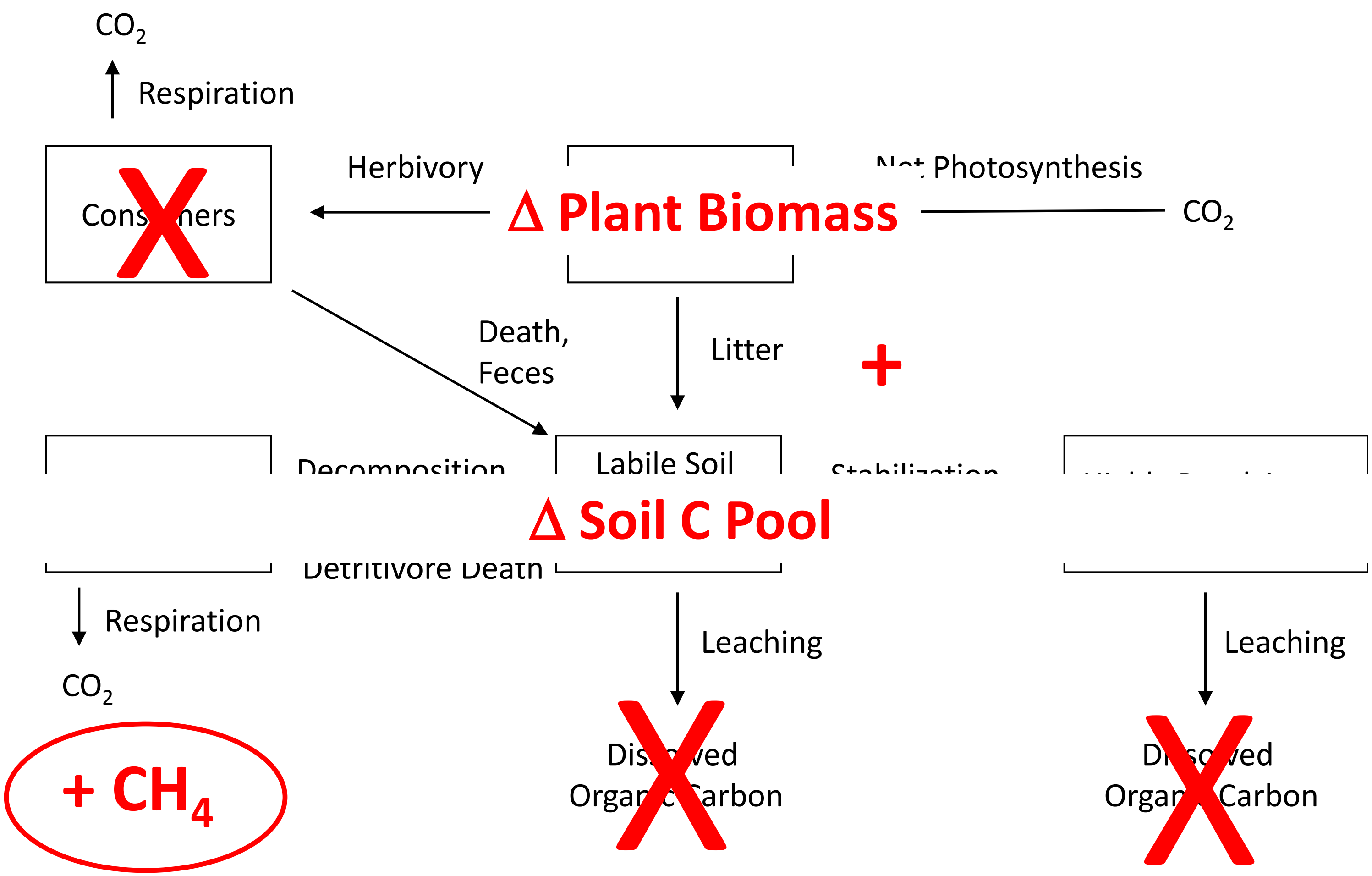
While this approach may be adequate for upland terrestrial ecosystems, it is inadequate for wetlands.

Why?

CH_4 has a global warming potential of 6.8 CO_2-C equivalents over a 100-year time frame!

The shorter the time period the higher the global warming potential of CH_4 (GWP = 19.6 for 20 yr, 2.1 for 500 yr).

Ecosystem C Balance =



Nitrous oxide (N_2O) is has a GWP of 81 CO_2-C equivalents in a 100-year time frame.

The limited studies to date have shown very low N_2O emissions in wetlands unless they have high soil nitrogen levels, e.g., from run-off or restoration of agricultural areas.

Wetland Radiative Balance (Accounting for GWP of CH_4 and N_2O)

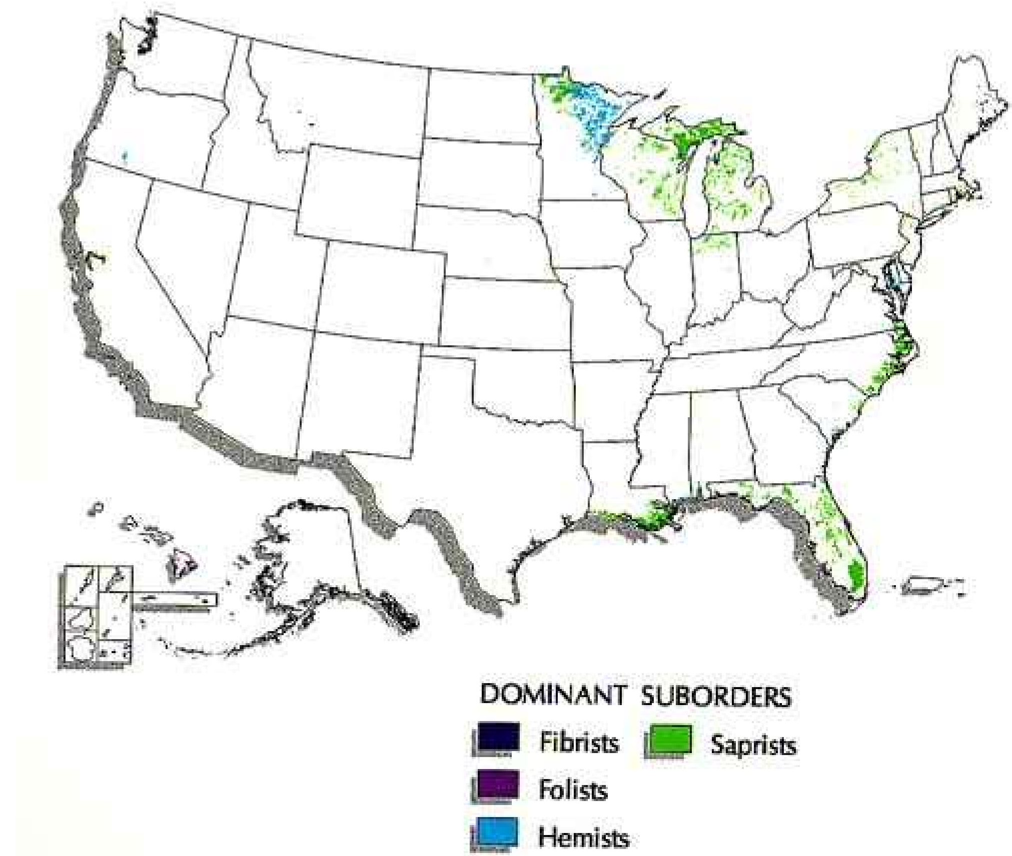
Radiative Balance = Δ Plant Biomass + Δ Soil C Pool – CH_4 flux – N_2O flux

All factors in the balance need to be in common units, e.g., kg CO_2-C ha^{-1} yr^{-1}

Positive number = net gain in CO_2-C equivalents by ecosystem
Negative number = net loss in CO_2-C equivalents by ecosystem

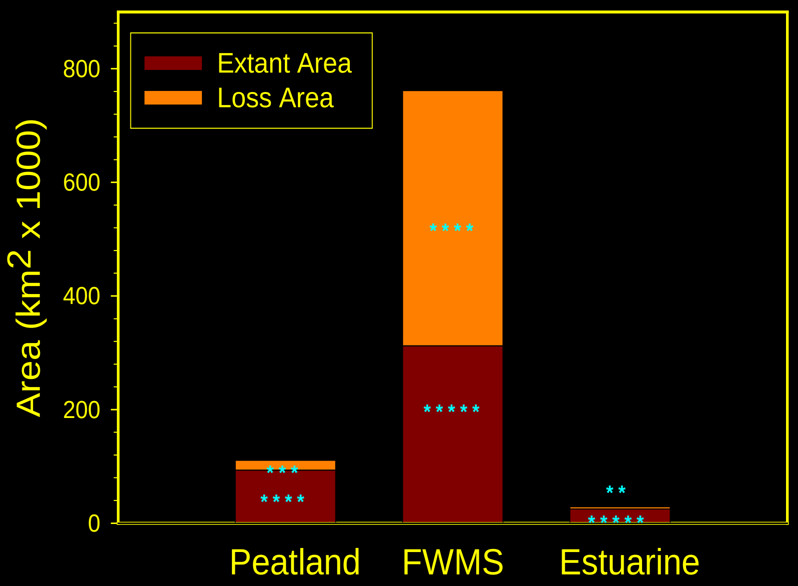
Peatlands (Histosols) require special consideration because of their massive soil C pools.

Average organic matter depth ~ 1 -2 m, but can be much greater.

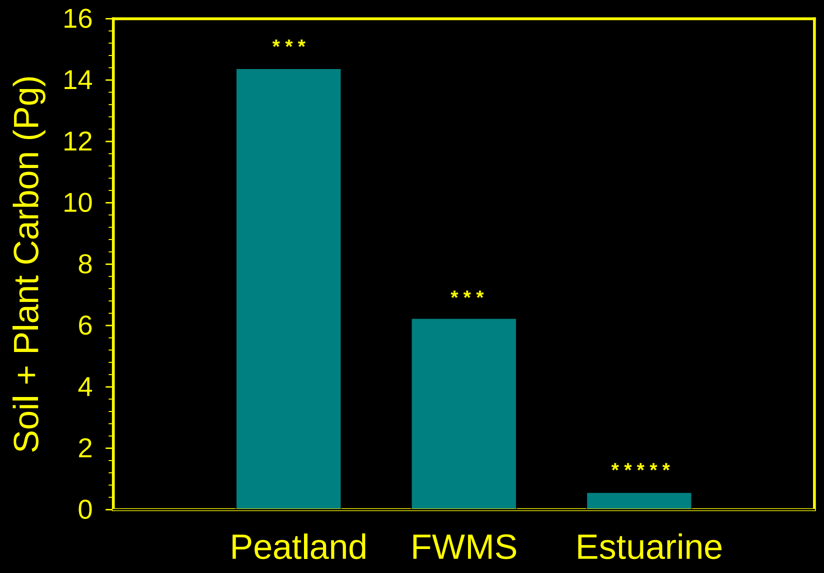


http://soils.usda.gov/technical/soil_orders/

Area of Extent and Loss in Conterminous U.S. Wetlands



Carbon Pools in Conterminous U.S. Wetlands



Total Conterminous U.S. Wetland Area = 430,670 km^2 (* * * * *)

Loss of Area = 470,424 km^2 (* * * *)

Total Conterminous U.S. Wetland C Pool = 21 Pg C (* * *)

FWMS = FreshWater Mineral Soil wetlands

Bridgham et al. 2006

- Drainage of peatlands causes massive subsidence and oxidation of the peat to CO_2.
- Restoration of peatland and 'stop loss' of this peat oxidation can be a highly beneficial component of peatland restoration activities.

Photo by Christian Fischer--http://en.wikipedia.org/wiki/File:Torfabbau-.jpg

This building at the Everglades Experiment Station was originally constructed at the land surface; latticework and stairs were added after substantial land subsidence.

http://sofia.usgs.gov/publications/circular/1182/

Wetland Radiative Balance = ΔPlant Biomass + ΔSoil C Pool – CH_4 flux – N_2O flux

A constant radiative balance has no warming or cooling effect on the Earth's climate.

It is the change in the change in the radiative balance over time that cause radiative forcing, or a change in the Earth's temperature.

E.g., Constant high CH_4 emissions from wetlands have a high radiative balance but zero radiative forcing. Drainage of wetland causes a reduction in CH_4 emissions and hence a cooling effect. Restoration of wetlands that results in higher CH_4 emissions has a warming effect (not taking into account other factors that would also affect the forcing).

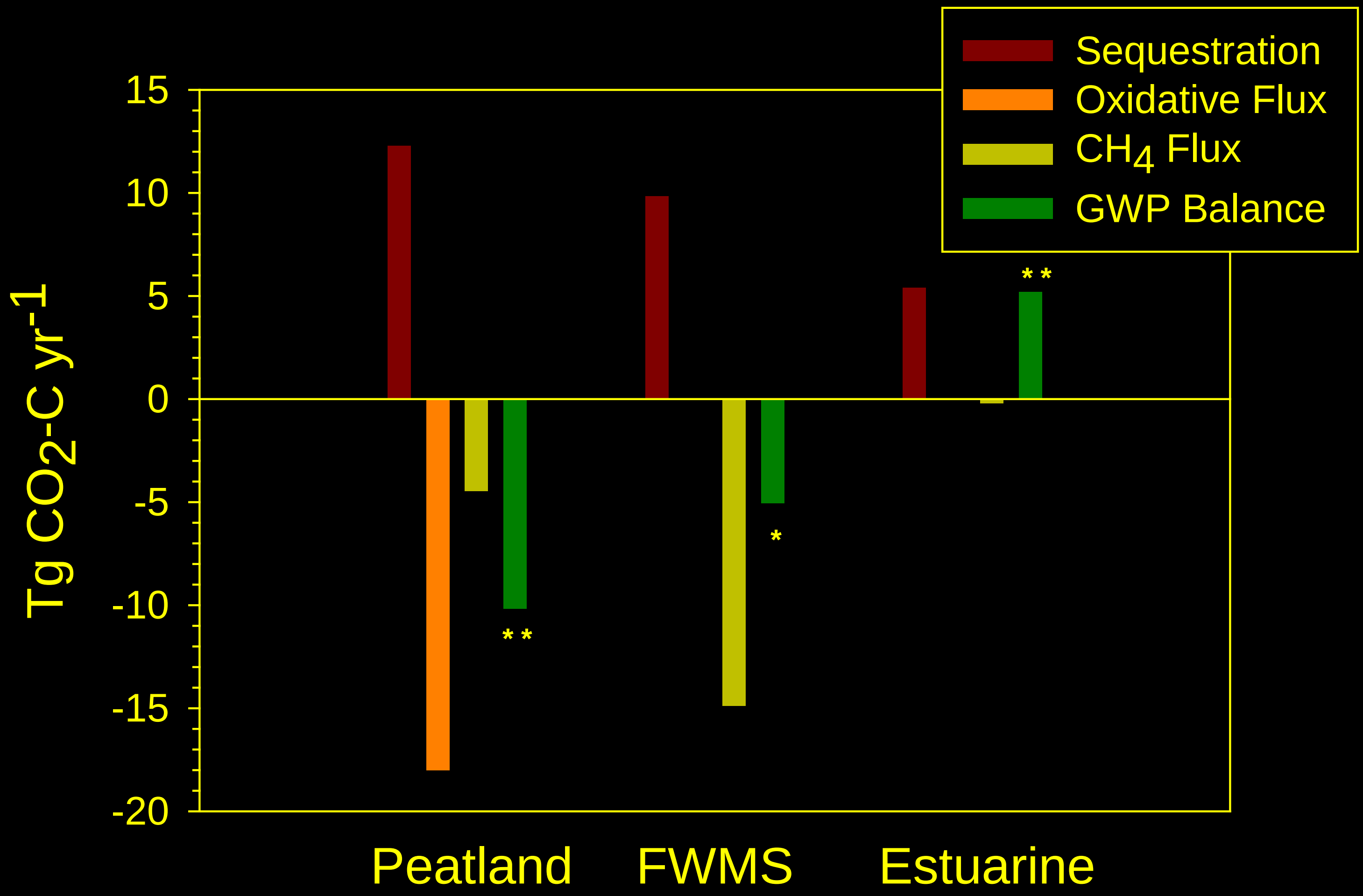
Radiative Forcing = Pre-Implementation CO_2-C Balance – Post-Implementation CO_2-C Balance

or:

Radiative Forcing = Δ Plant Biomass + Δ Soil C Sequestration Rate + Δ Peat Oxidation + Δ CH_4 flux + Δ N_2O flux

Positive number = net cooling effect
Negative number = net warming effect

Current GWP Balance in Conterminous U.S. Wetlands



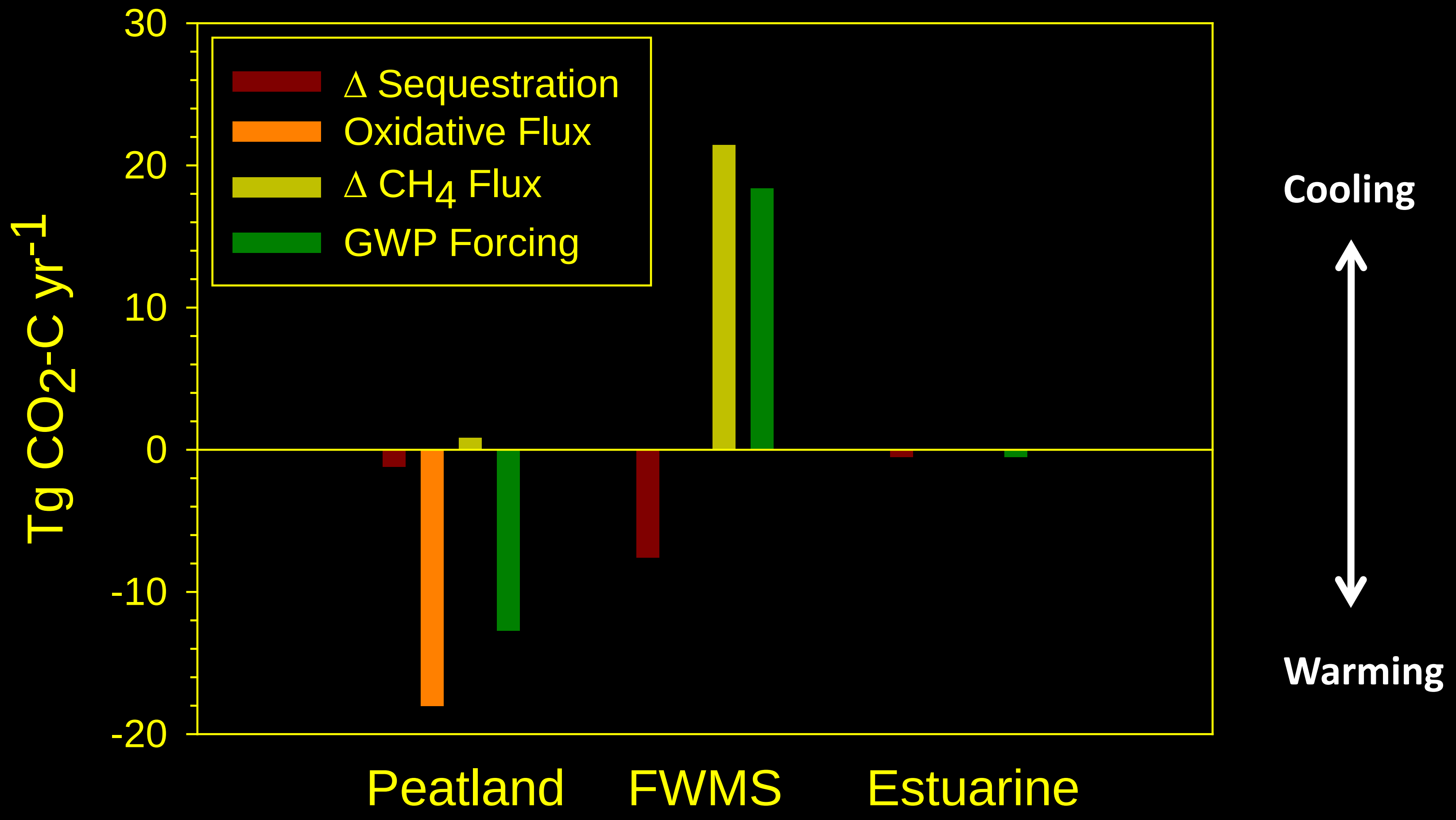
Total Conterminous U.S. Wetland GWP Balance

= -10 Tg CO_2-C yr^{-1} (*)

Note: Positive number = net flux into wetland, negative number = net flux from wetland

(Bridgham et al. 2006)

Historical GWP Forcing in Conterminous U.S. Wetlands



Total Conterminous U.S. Wetland GWP Forcing

= 5.2 Tg CO_2-C yr^{-1} (*), i.e. small net cooling

(Bridgham et al. 2006)

Difficulties in Estimating Sedimentation Rates

- Rates in the literature are widely variable.
- Some portion of C stored during sedimentation is allochthonous, i.e. originating from erosion in uplands, and some portion is autochthonous, i.e. derived from within the ecosystem.
- At a landscape scale, allochthonous C is only sequestered to the extent that decomposition is slower in the wetland sink than in the upland source. No data exist to evaluate this important caveat.

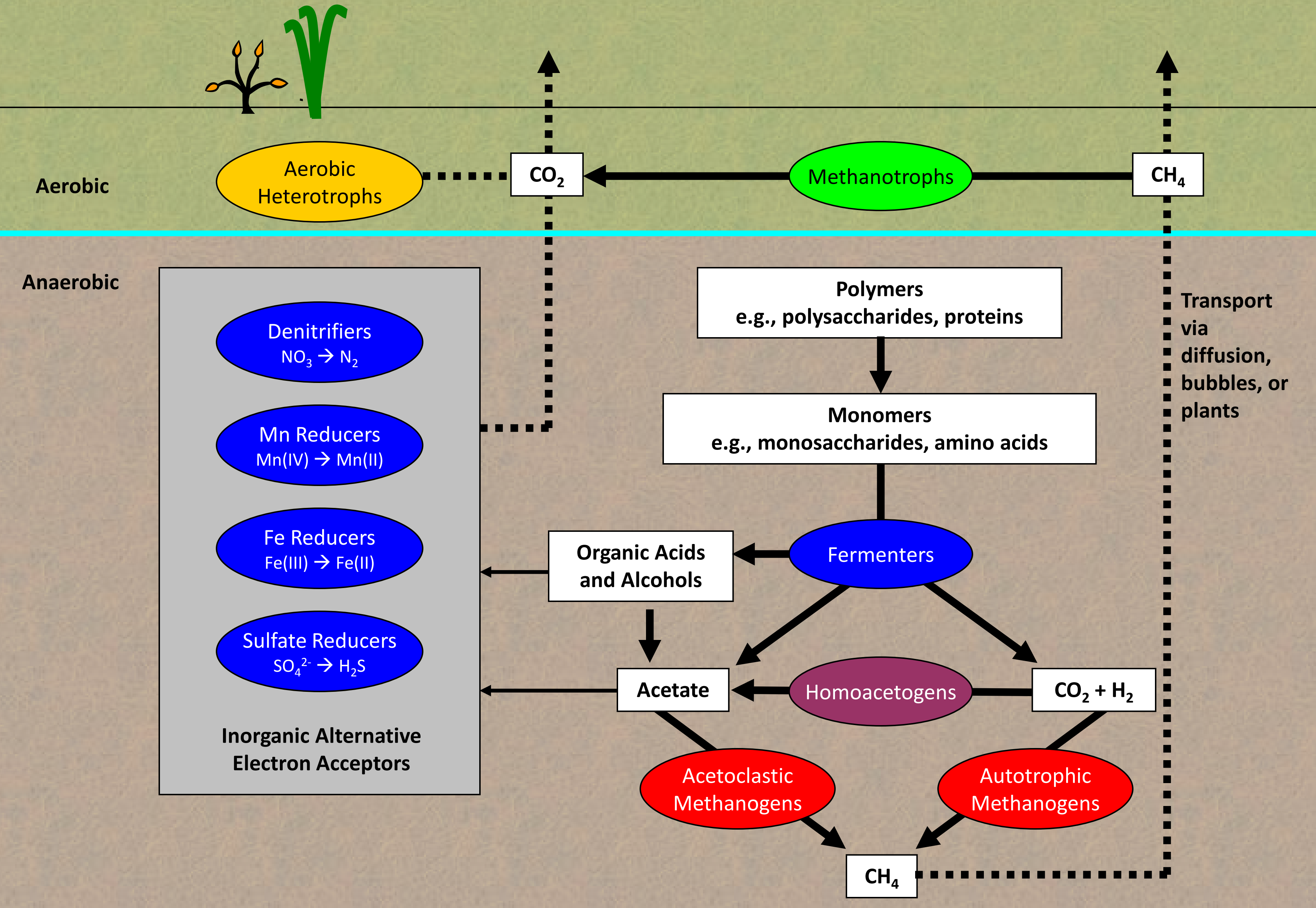
Difficulties in Estimating Sedimentation Rates

- **To estimate the true landscape-scale sequestration of allochthonous C requires landscape modeling of both sediment transport and decomposition rates in both the source and sink areas.**
- **The above caveat doesn’t exist in peatlands, where all soil C is autochthonous, or derived from within the ecosystem.**

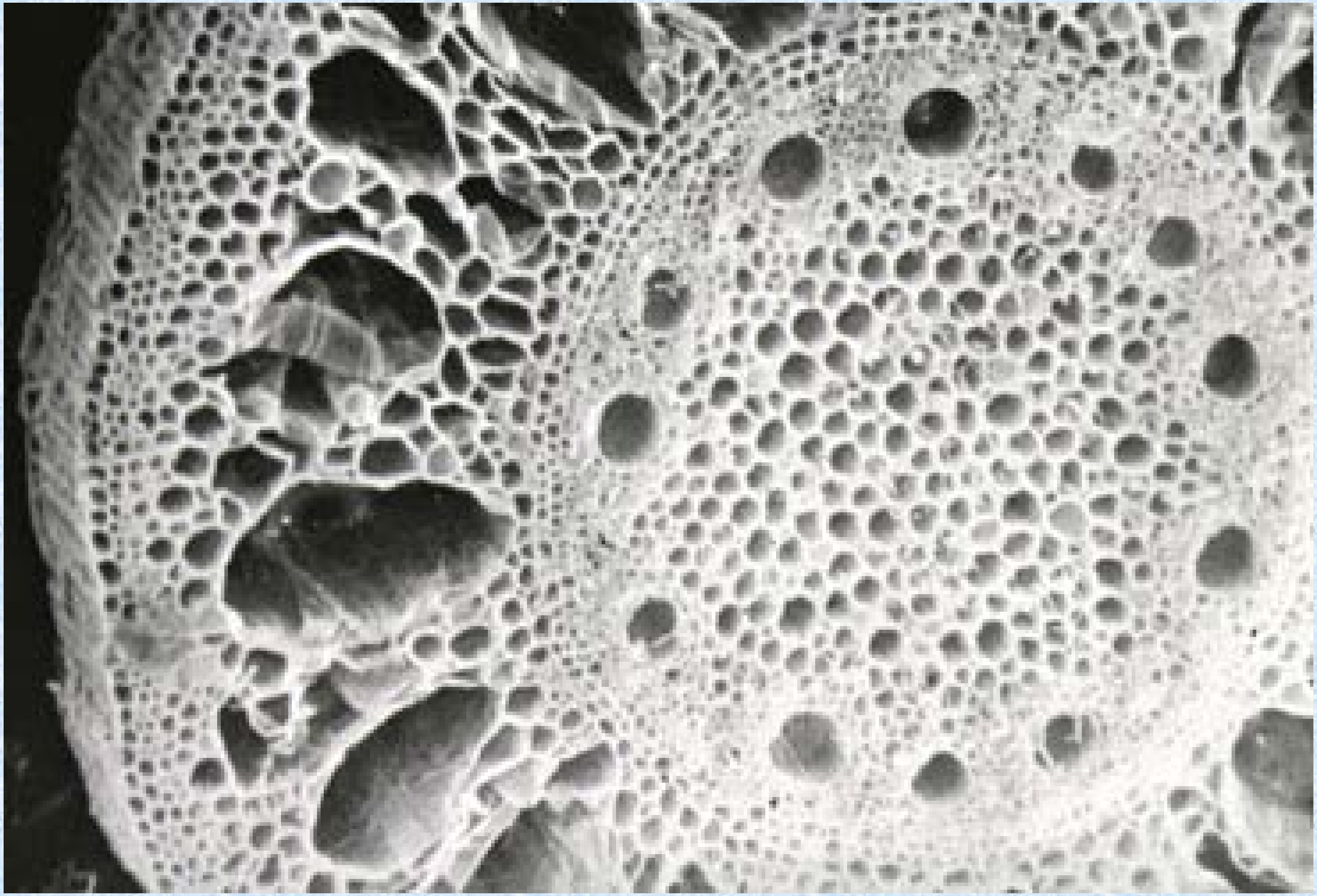
Since CH_4 emissions are so problematic in wetland restorations (if a primary goal is for a net negative radiative forcing), how do you try and reduce them?

This requires a basic understanding of the mechanisms of CH_4 production, transport, and oxidation in the soil column.

Pathways of Aerobic and Anaerobic C Cycling in Wetlands



Aerenchyma in plant roots and stems allow for rapid CH_4 transport from the soil to the atmosphere without exposure to methanotrophic bacteria, and hence minimizes CH_4 oxidation and maximizes CH_4 emissions.



http://www.uoguelph.ca/~mgoss/five/410_N06.html

How to Reduce CH_4 Emissions in Wetland Restorations

- **Less labile C in soil (but hard to control).**
- **Water table far from the soil surface during much of the growing season.**
- **Lack of herbaceous plant species with aerenchyma.**
- **High porewater sulfate concentrations (e.g., marine-influenced wetlands), or potentially high concentrations of other alternative electron acceptors.**
- **Low soil temperatures (but hard to control).**

But many of these actions may reduce the many other ecosystem services that wetlands provide. Minimizing CH_4 emissions may not provide the most positive environmental and societal benefits to wetland restorations.

Brief Overview of Methods for C Sequestration in Wetlands

- **Standard forestry methods are used for determining the increase in plant biomass over time.**

Δ Soil C Pool = Δ soil column height (cm) + Δ bulk density (g soil/cm^3 soil) + Δ % soil C

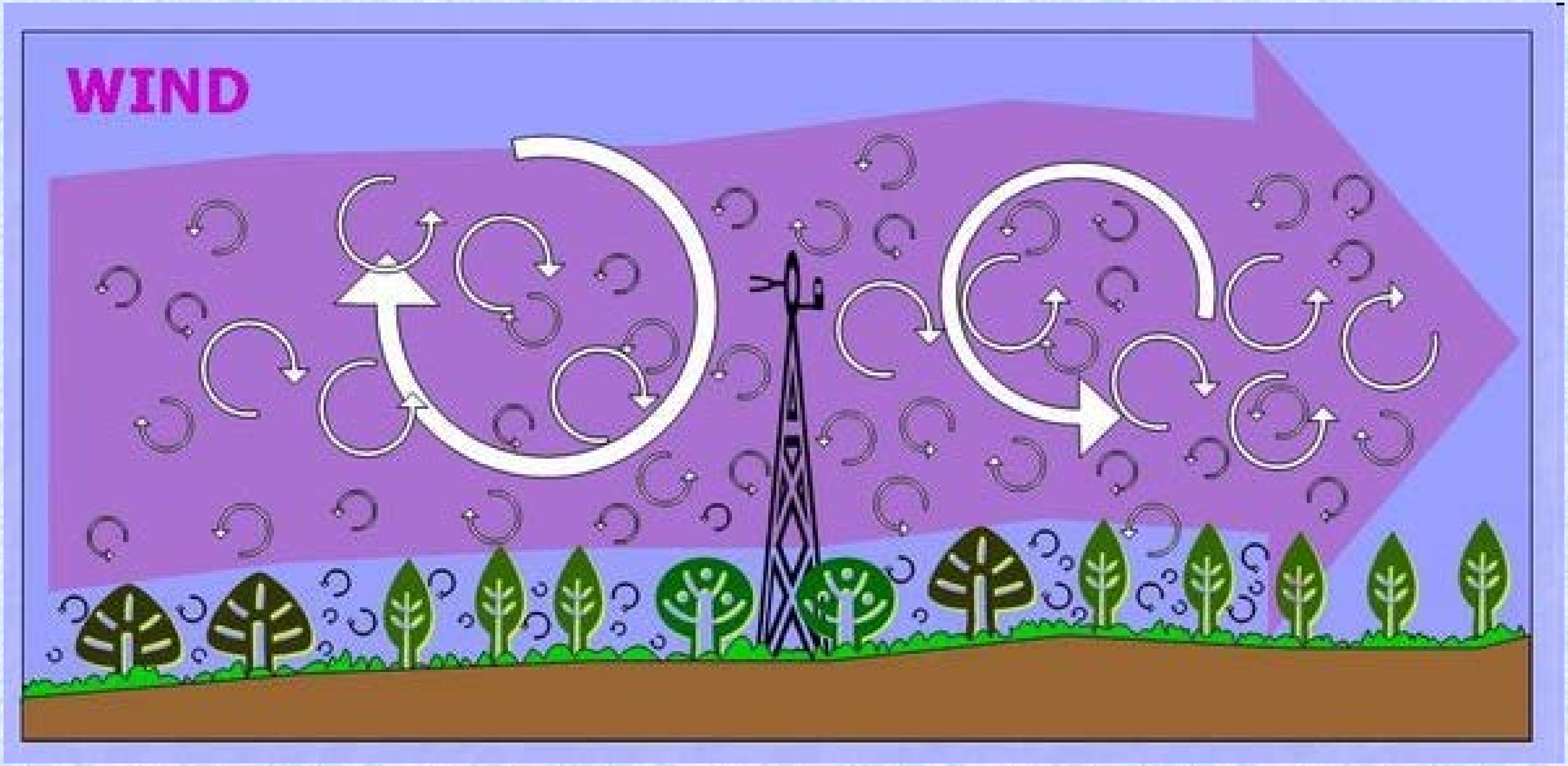
Surface Elevation Tables (SETs) are one of several commonly used methods to measure sedimentation rates. They can also determine erosion rates.

http://www.pwrc.usgs.gov/set/

CH_4 emissions are typically measured with static flux chambers by taking several headspace gas samples over 1-2 hours, storing the samples in gas tight vials, and running the samples quickly on a gas chromatograph in the lab.

Photos by S. Bridgham

Eddy Covariance or Eddy Flux Measurements



Calculates vertical turbulent fluxes of water, CO_2, CH_4, etc. within atmospheric boundary layers.

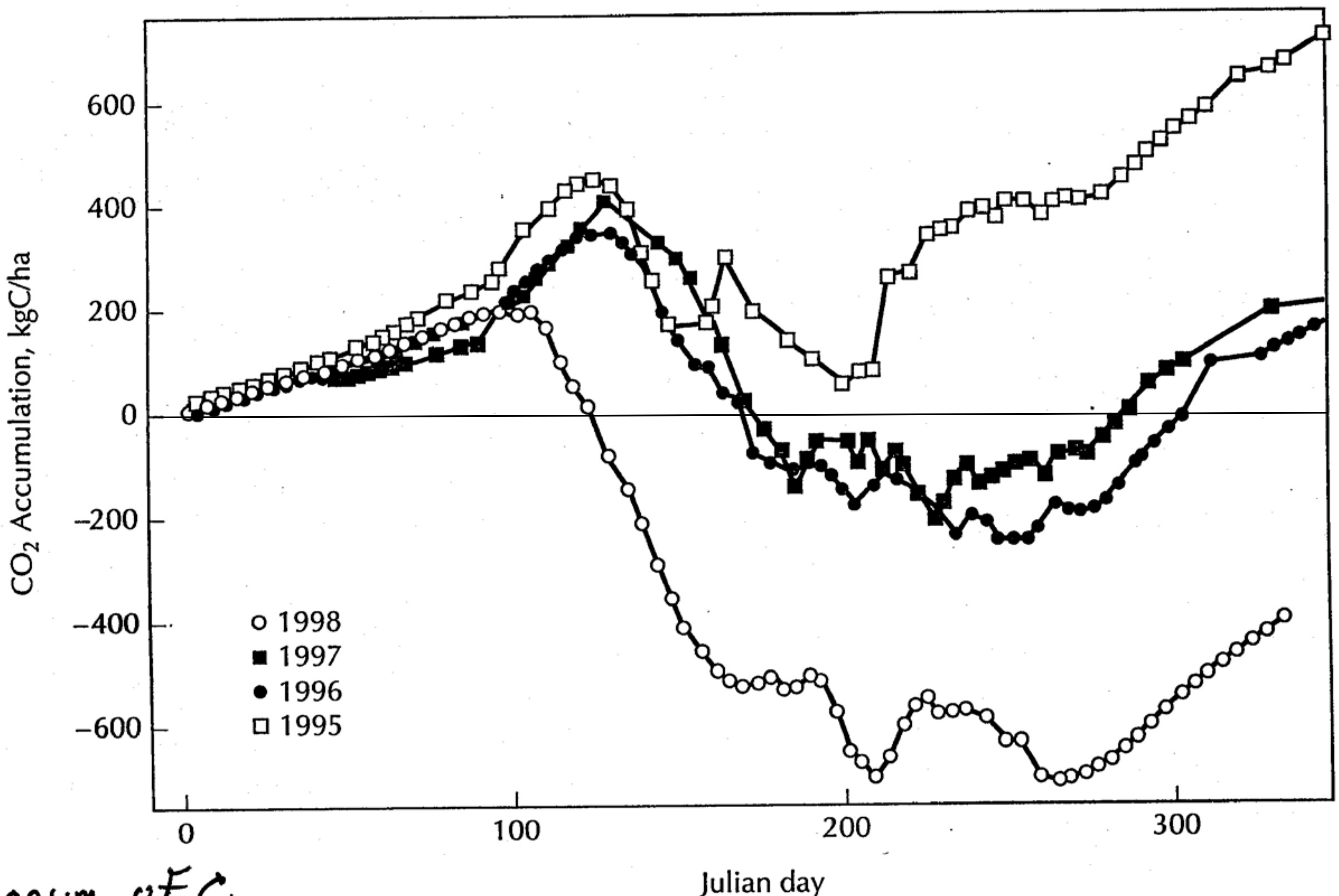
http://en.wikipedia.org/wiki/Eddy_covariance

Eddy Flux Tower in British Wetland Meadow

Photo by Colin Lloyd--http://www.bgc-jena.mpg.de/public/carboeur/archive/files/LloydC_TM_SoLicor_2-13Jul00.jpg

Eddy covariance system consisting of an ultrasonic anemometer and infrared gas analyzer (IRGA).

Photo from http://en.wikipedia.org/wiki/Eddy_covariance



+ = accum. of C
− = loss of C

FIGURE 3.8 Eddy covariance data for 4 years of net ecosystem exchange data for a mature black spruce stand in Ontario, Canada. (Fan et al. 1995)

Aber & Melillo 2001

Net Ecosystem Exchange (NEE) is a Viable Cutting Edge Technology

- NEE = Plant Gross Primary Productivity – Ecosystem Respiration
- Continuous stream of data (logged ~ every 30 minutes) and then annualized.
- Open-path CH_4 analyzers are also now commercially available, allowing the analysis of both NEE and CH_4 flux.

Net Ecosystem Exchange (NEE) is a Viable Cutting Edge Technology

- **Tower height gives a 'footprint' in prevailing wind direction ranging from 10's of meters to miles.**
- **Well developed technology, but $$$ set up and requires large amount of expertise to run. Towers can be transportable.**
- **Does not measure leaching of dissolved organic C, loss of C due to herbivory, etc., and these may be of at least modest importance. This matters because Δ C flux rather than the Δ C pools is being estimated.**

Conclusions

- **The viability of restoring wetlands for C sequestration is poorly verified and requires better quantification of the pertinent aspects of the C budget and trace gas fluxes before it becomes an accepted practice.**
- **Restoration of different types of wetlands will almost certainly have very different effects on radiative forcing.**

Restoration of marine-dominated wetlands for C sequestration is likely justified because of their typical low CH_4 emissions and high soil C sequestration rates.

Restoration of some riverine forested wetlands for C sequestration may be justified if they have high woody biomass accumulation and only seasonal flooding, often during a spring cool season. Site dependent?

http://www.tpwd.state.tx.us/publications/pwdpubs/pwd_rp_t3200_1057b/index.phtml

Photo by Bob Misso, USFWS (http://www.pixdatabase.com/photo/5805/)

In the restoration of peatlands, the 'stop loss' of oxidation of the peat profile may offset CH_4 emissions, although this may be somewhat site dependent.

- **Restoration of freshwater, mineral soil wetlands dominated by herbaceous plants may not be justified based upon carbon sequestration.**

A freshwater marsh in OR restored for salmon habitat.

- **The effects of wetlands on radiative forcing is relatively minor compared to the many other ecosystem services that they provide. Thus, wetlands of all types should be restored irrespective of their radiative forcing.**
- **Design of wetland restorations to maximize a positive radiative effect may minimize other important ecosystem services.**

Questions?

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