Land-sea interaction and dynamic vegetation modelling

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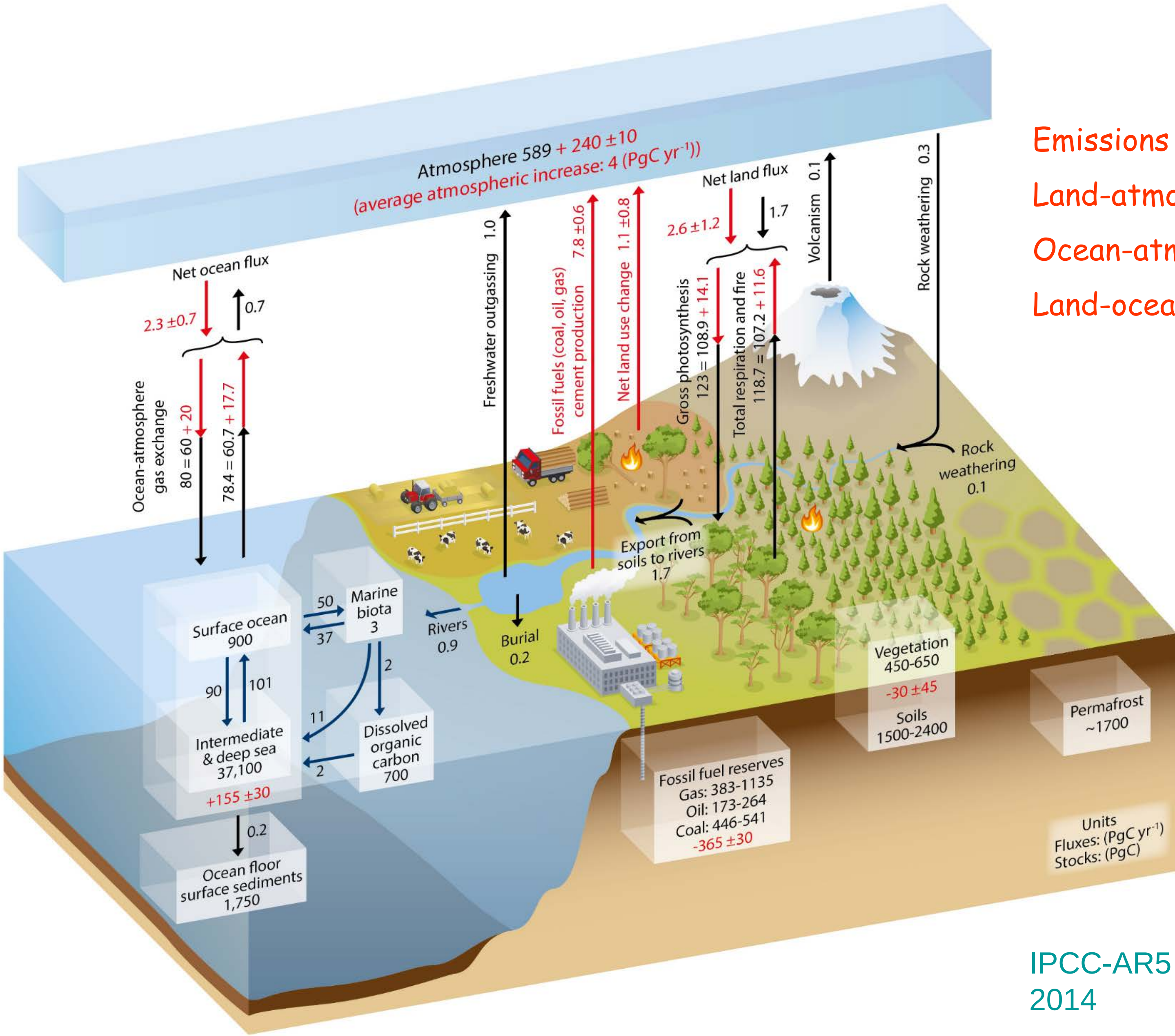
Lecture outline

- Land-sea-atmosphere connectivity in the global Earth system
- Carbon export from land to sea – possible impacts on coastal ecosystems and biogeochemistry
- Terrestrial vegetation and carbon cycling – recent trends and underlying causes
- Modelling climate change effects on vegetation and carbon cycling – introducing dynamic global vegetation models (DGVMs)
- Case study modelling land-sea carbon export and possible impacts on biogeochemistry of the Baltic Sea
- Future outlook: coupled models of regional Earth system dynamics

Supporting exercise (in own time)

- Modelling ecosystem response to climate change using the LPJ-GUESS DGVM

Compartments and fluxes of the global carbon cycle



Emissions = 9 PgC/yr

Land-atmosphere = -3 PgC/yr

Ocean-atmosphere = -2 PgC/yr

Land-ocean = 1 PgC/yr

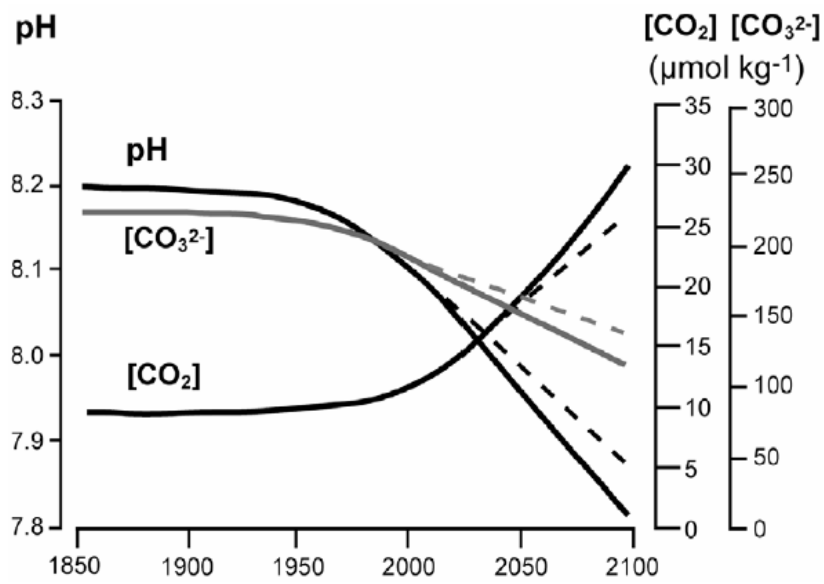
(data for 2000-2009)

IPCC-AR5
2014

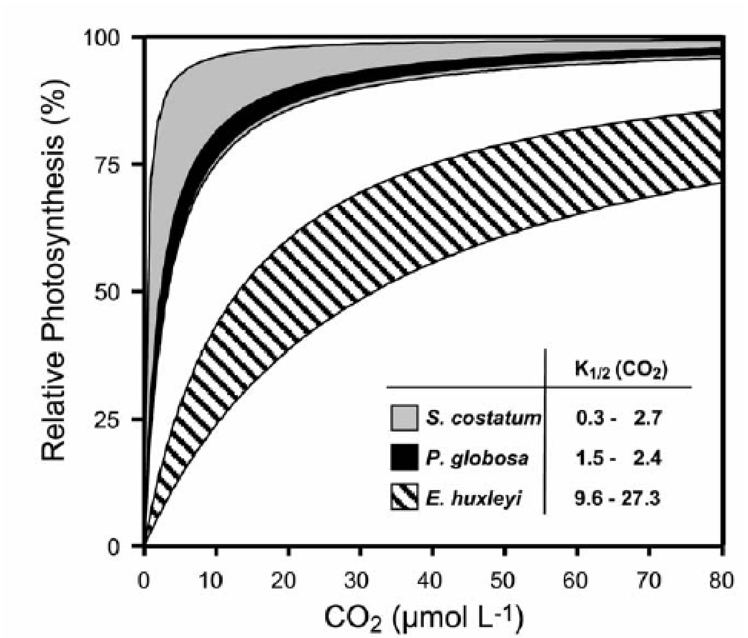
Effects of riverine C input to coastal seas*

*Riesebell 2004
J. Oceanography
60: 719-729

- Browner, more turbid water, steeper light attenuation
- Substrate for bacteria, increased respiration and pCO_2
- Lower pH, decreased carbonate saturation state, represses calcifying organisms
- Cascading effects on overall biogeochemistry and ecology
- Few detailed system-level studies

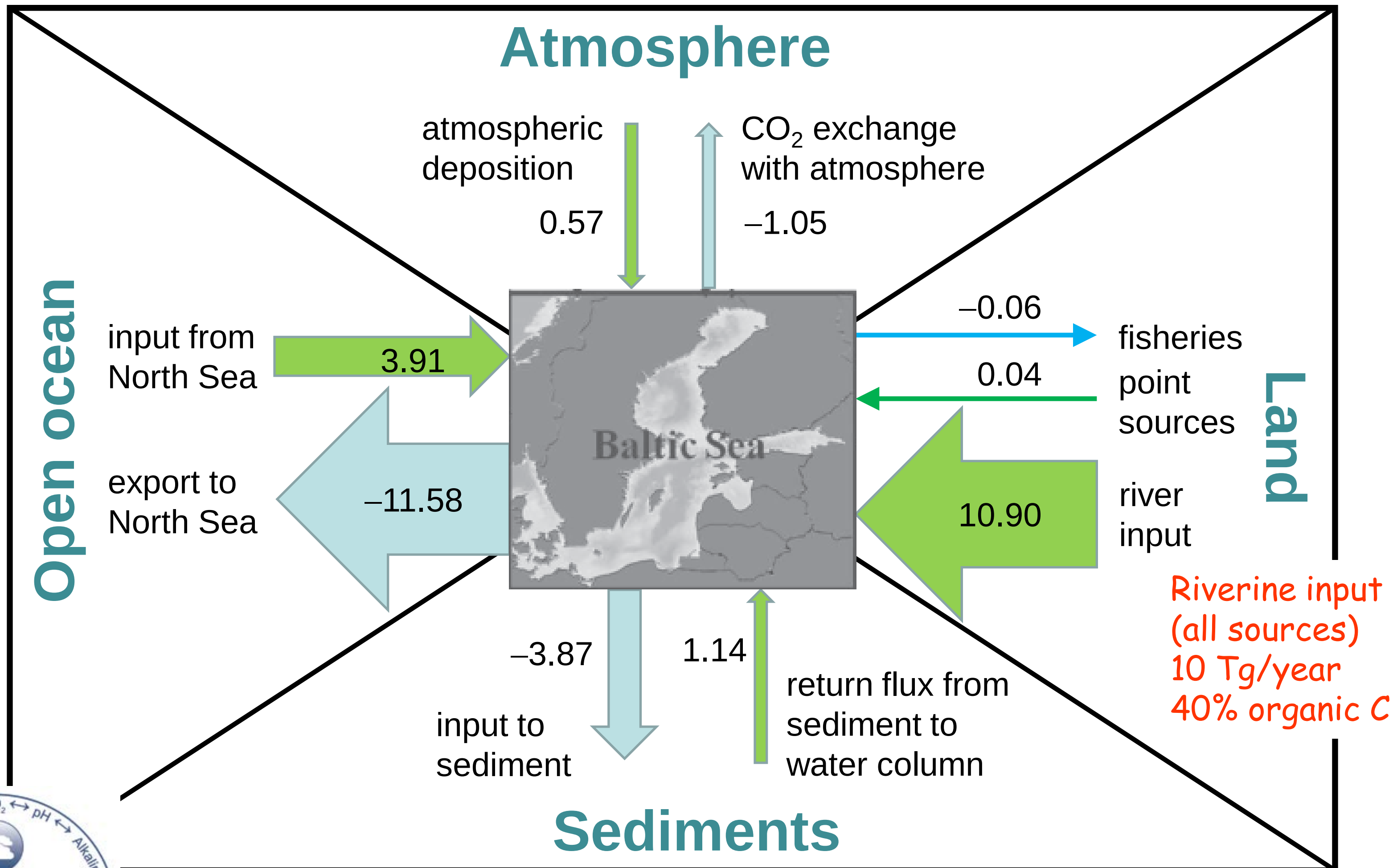


Effects of a BaU future emission scenario on global ocean CO_2, carbonate and pH (Houghton et al. 1995)



Increased water CO_2 concentration enhances production of some phytoplankton species

River runoff is the main source of C to the Baltic Sea*



Baltic - C

*Kulinski & Pempkoviak 2011
Biogeosciences 8: 3291-3230

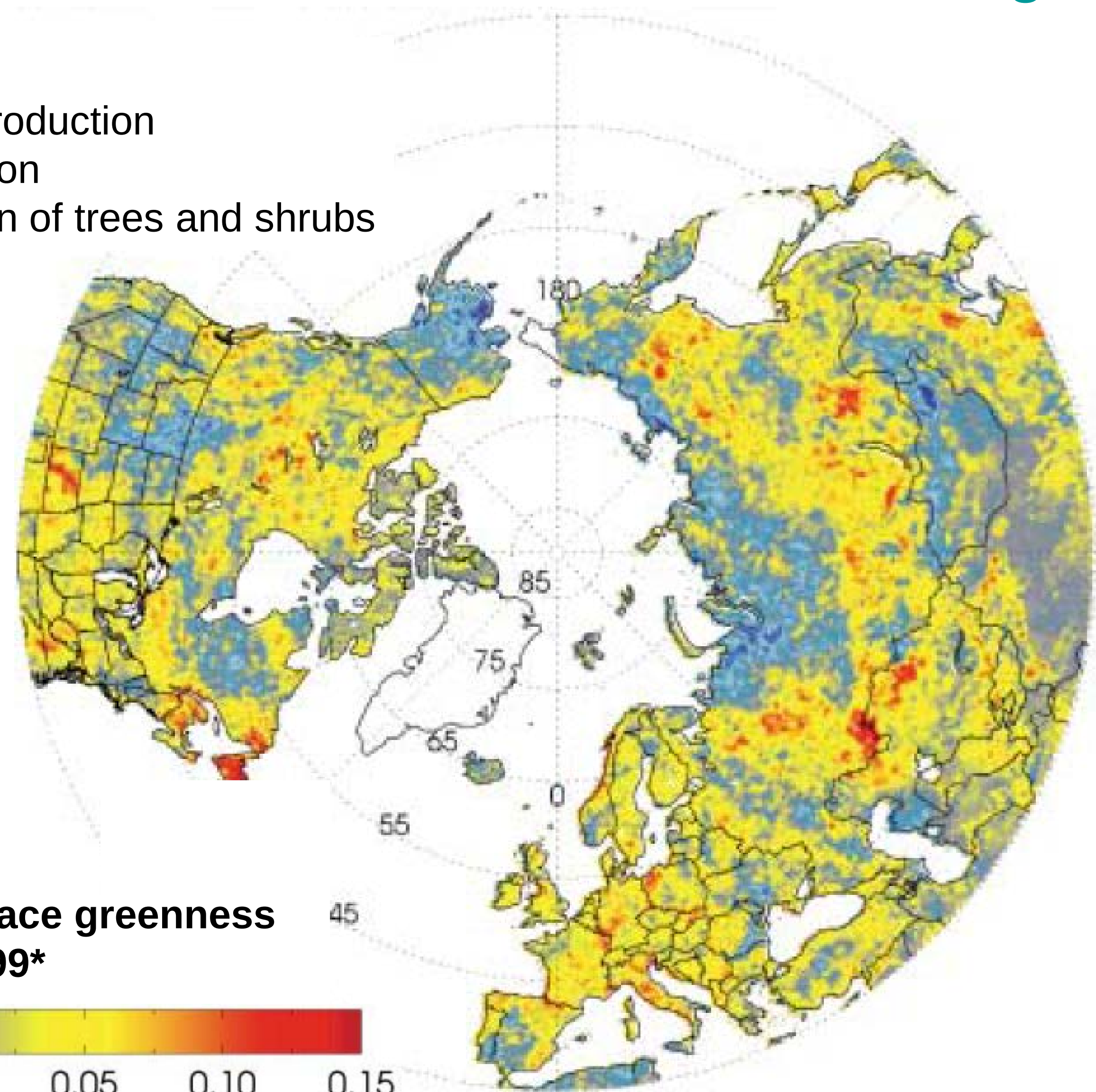
Vegetation cover and productivity have increased in concert with recent decades' climate warming

Likely causes:

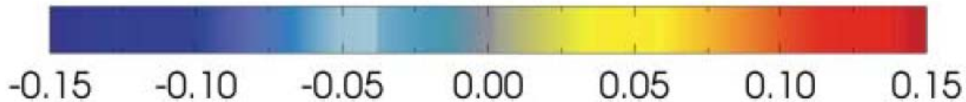
- increased primary production
- longer growing season
- expanded distribution of trees and shrubs

normalised difference vegetation index

$$NDVI = \frac{NIR - R}{NIR + R}$$

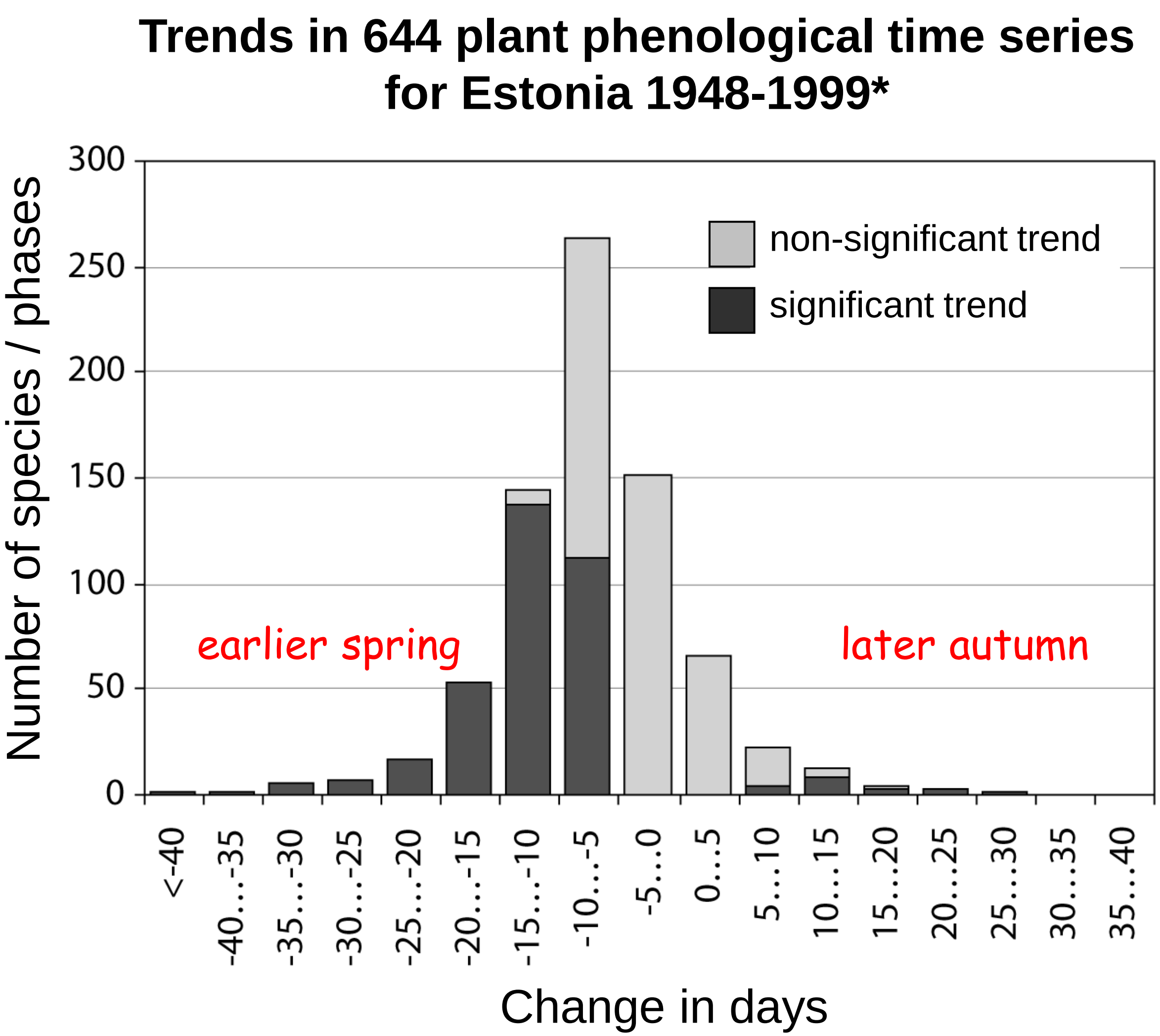


Change in land surface greenness 1982-1999*



*Tucker *et al.* (2001) *Int. J. Biometeorol.* 45: 184

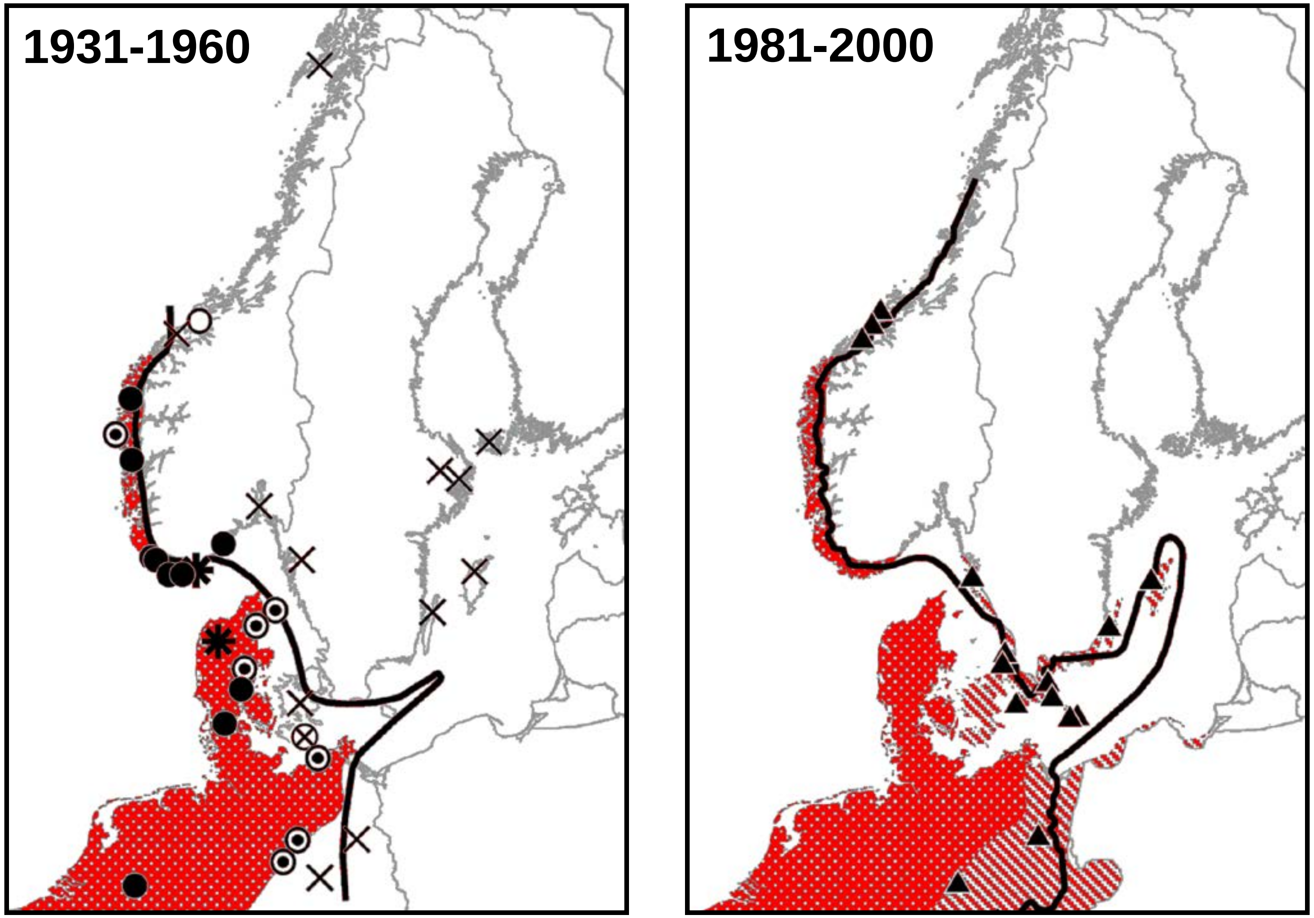
Earlier and longer growing season



*Ahas & Aasa (2004)

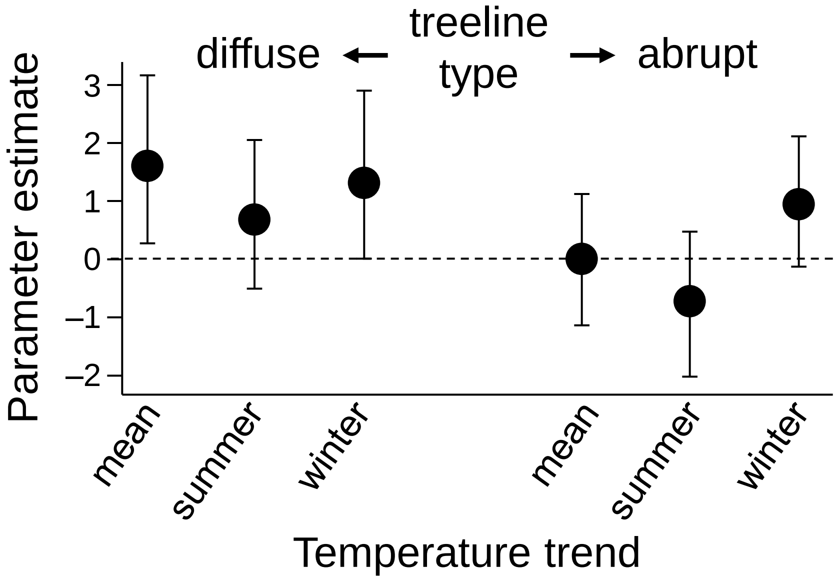
Species distributions track climate shifts

Changing distribution of holly, *Ilex aquifolium**

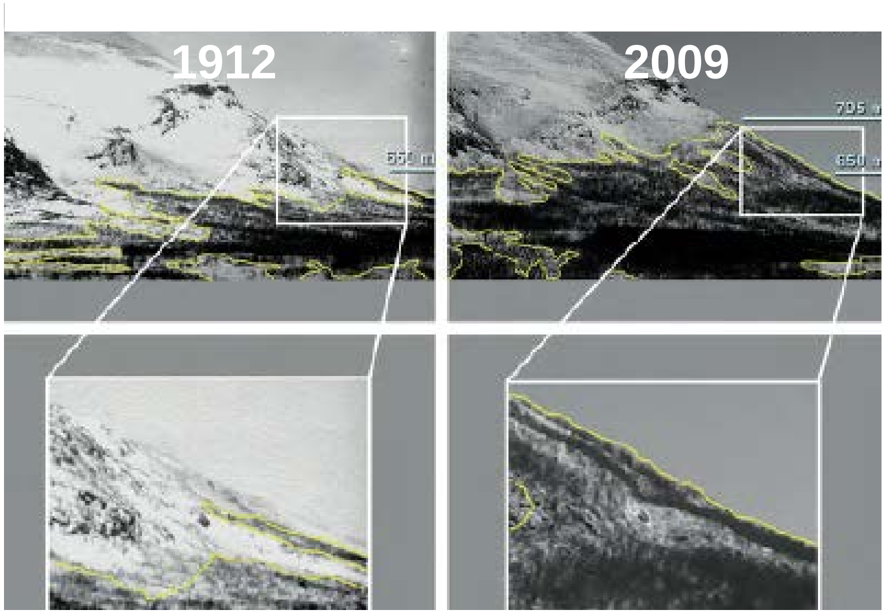


*Walther *et al.* 2005
Proceedings of the Royal Society B 272: 1427

Treelines are rising on average across the globe



Effect of temperature change on tree limit elevation shift for 166 near-treeline sites
+ = warming associated with upslope shift*

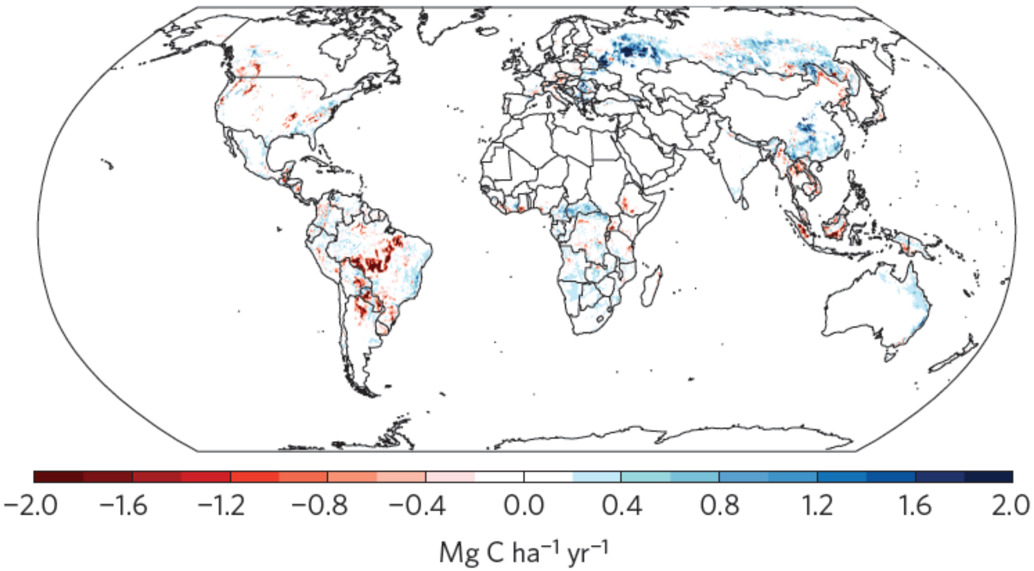


Treeline advance, Mt Nuolja, Sweden
(Van Bogaert et al. 2011. *J. Biogeog.*)

*Harsch et al. 2009, *Ecology Letters* 12: 1040

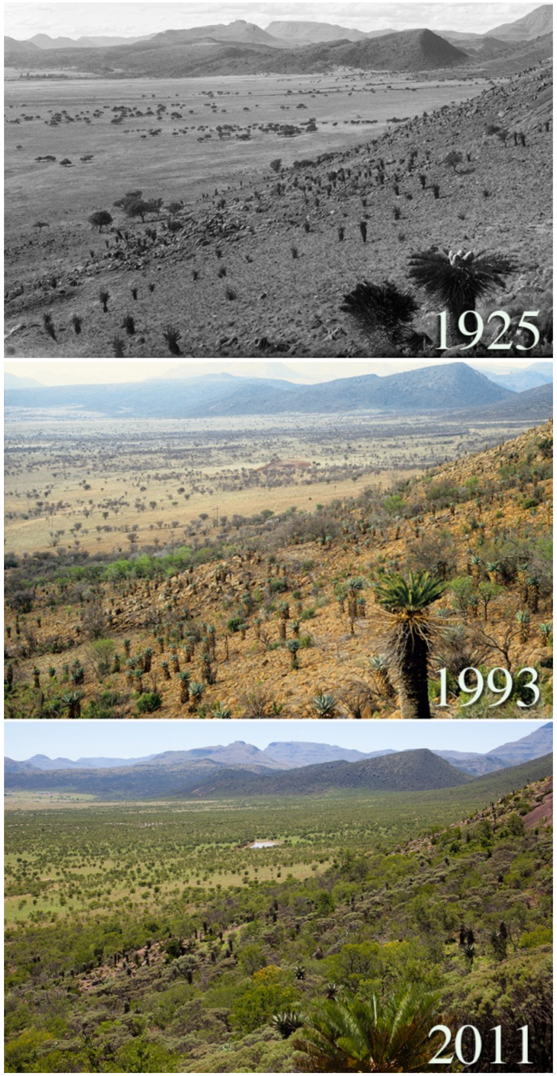
Woody biomass is increasing in many shrublands, savannahs and extra-tropical forests

Above-ground biomass change
1993-2012



Satellite passive microwave measurements
Liu et al. 2015
Nature Climate Change 5: 470-474

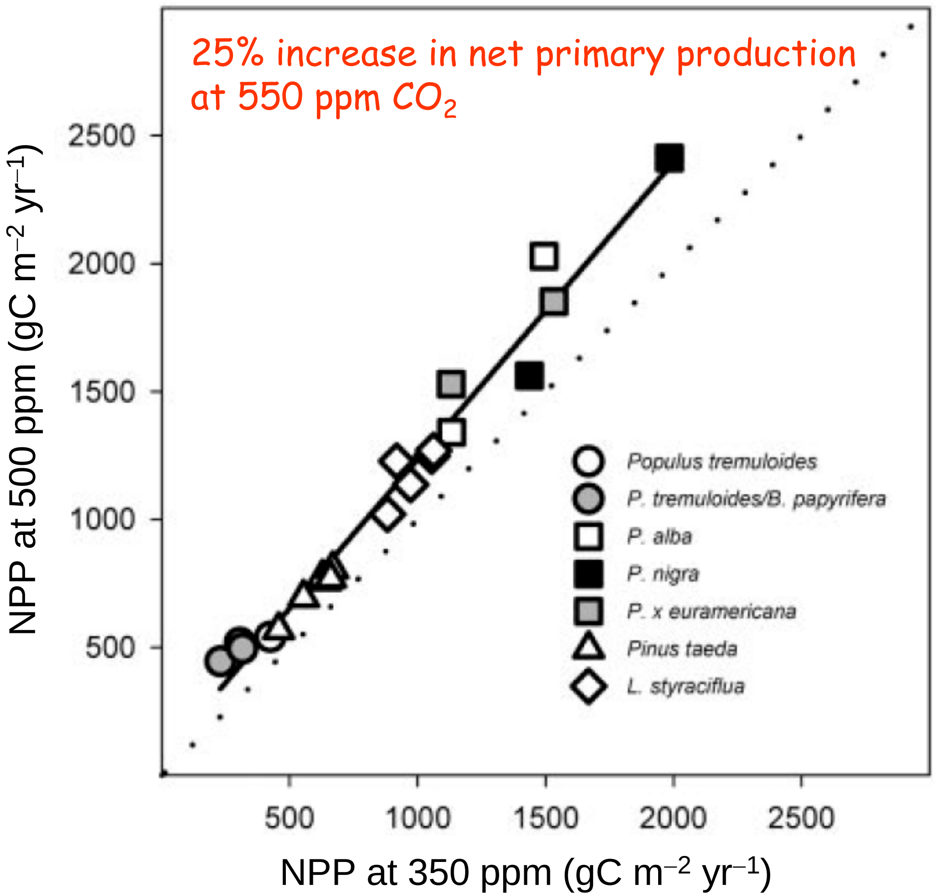
Likely causes include increased water-use efficiency under elevated CO_2



Eastern Cape Province
South Africa (Welz 2013)

CO_2 is food for plants

Increased atmospheric CO_2 → higher NPP, at least in short term ...



Norby et al. 2005
PNAS 102: 18052-18056

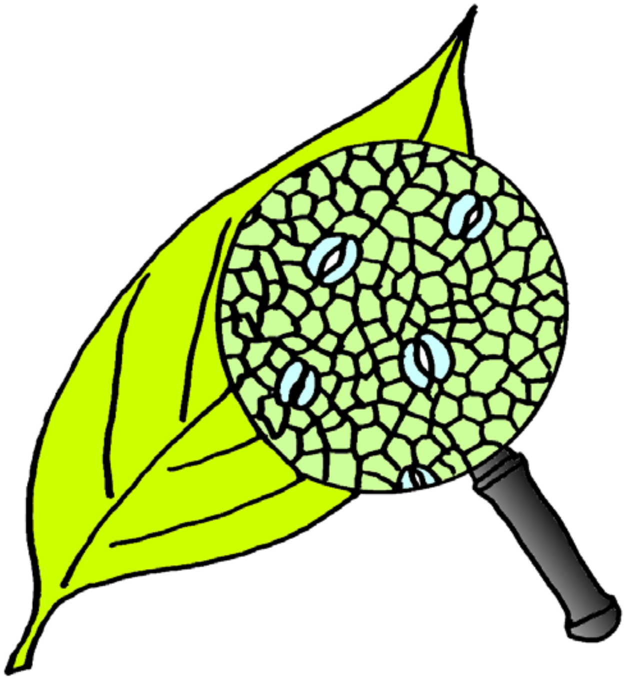
Duke forest FACE experiment
in North Carolina

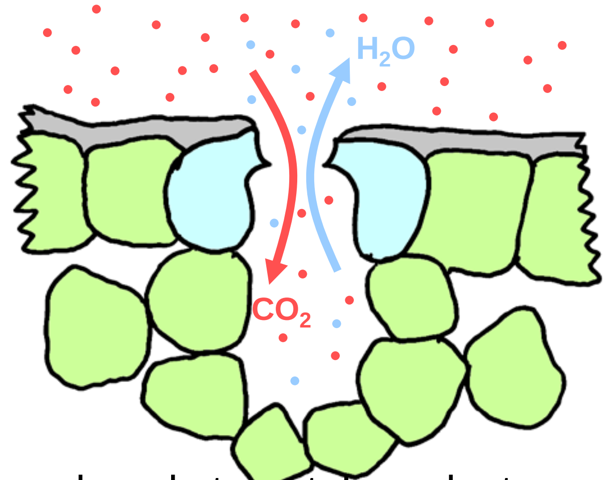
Net reaction of photosynthesis

$$CO_2 + H_2O + \text{sunlight} \longrightarrow CH_2O + O_2$$

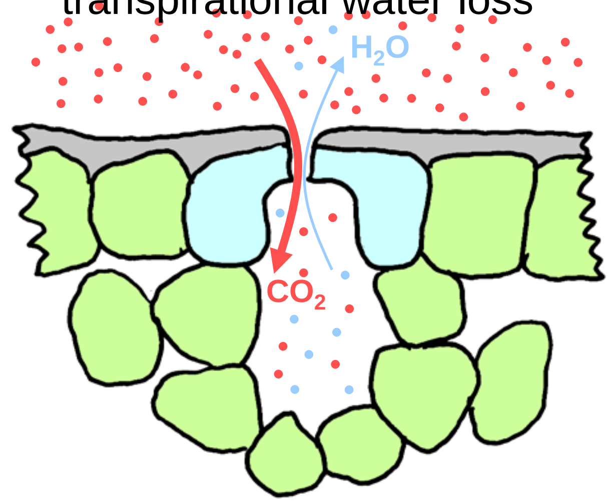
carbon dioxide | water | carbohydrate | oxygen

Reduced stomatal conductance under elevated CO_2 may enhance water-use efficiency (WUE)



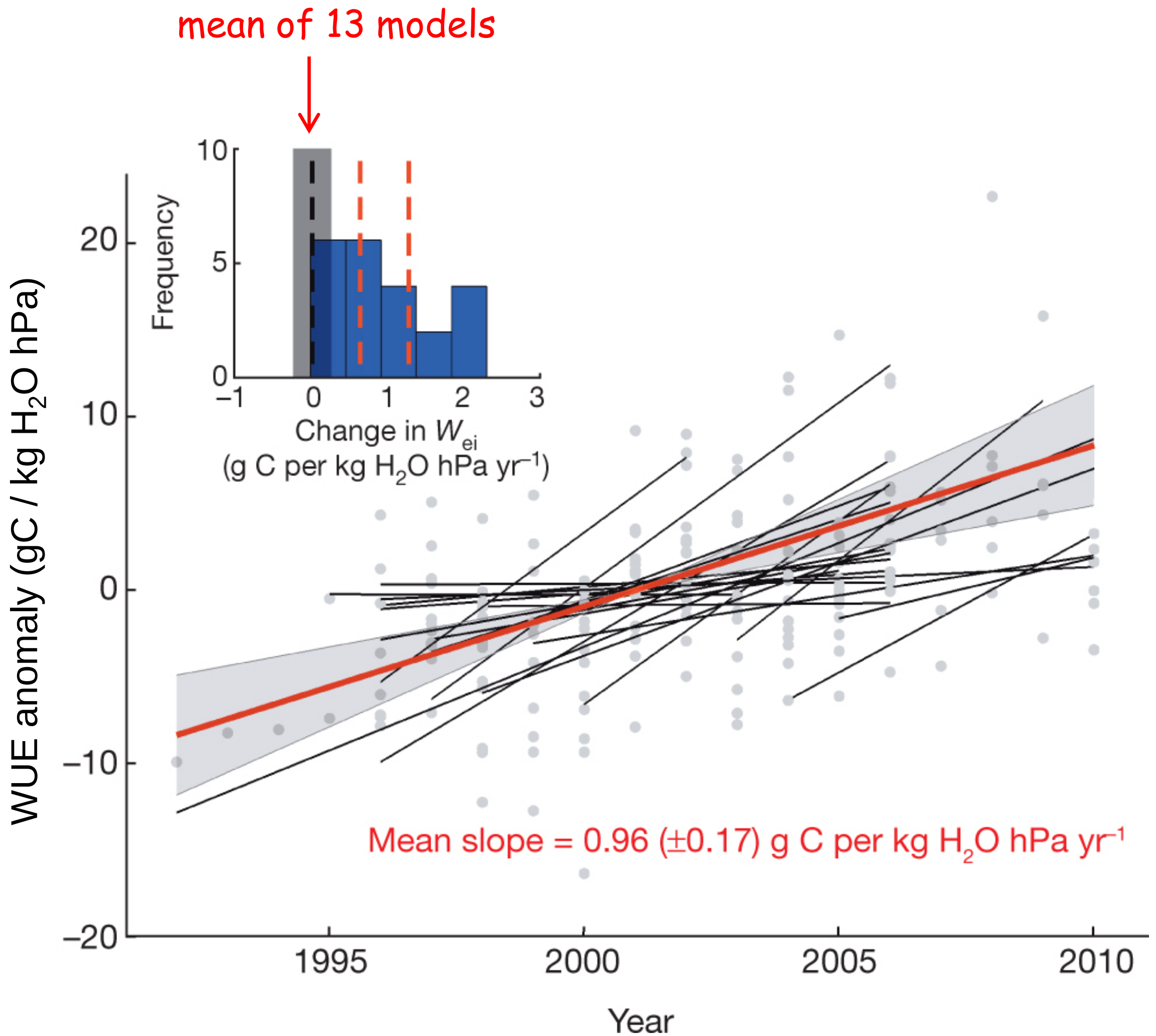


reduced stomatal conductance
in response to higher ambient CO_2 reduces
transpirational water loss



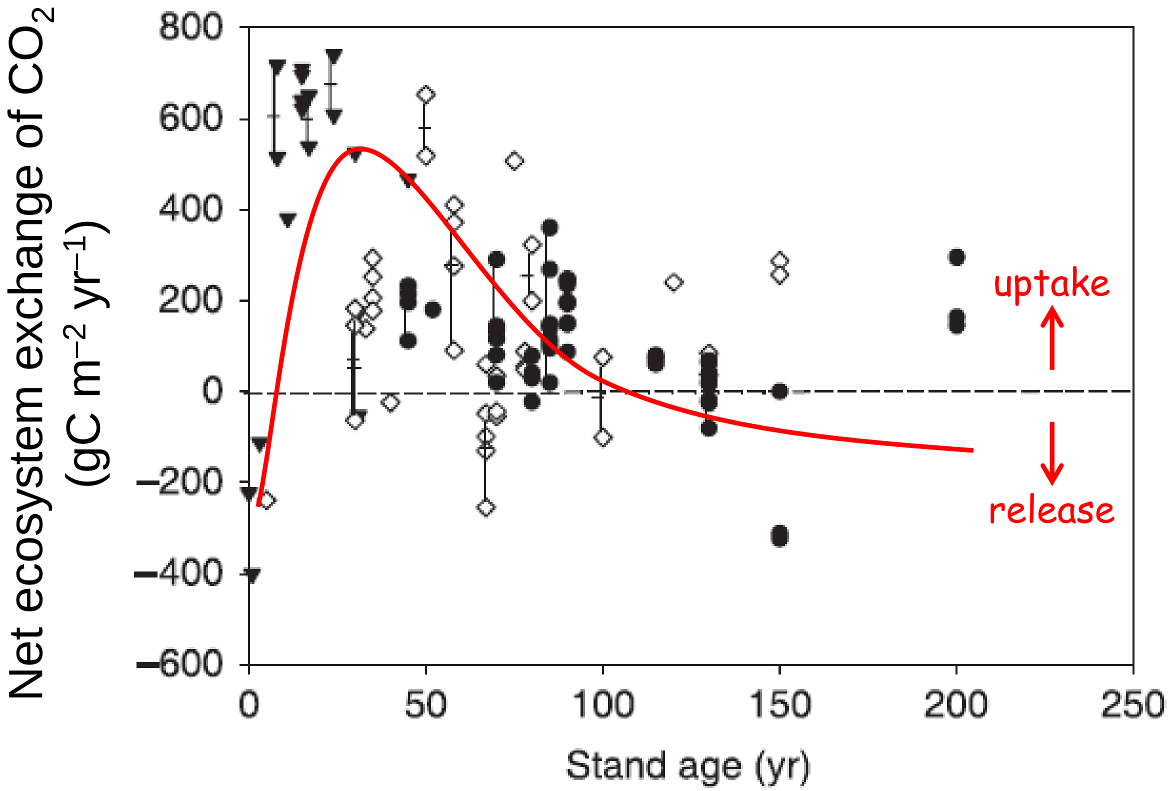
$$\text{WUE} = \frac{CO_2 \text{ uptake by photosynthesis}}{H_2O \text{ loss by transpiration}}$$

Forests around the world show a positive trend in water-use efficiency of growth*



*Keenan et al. 2013
Nature 499: 324-372

Carbon balance of woody ecosystems responds slowly to changes in structure, cover or distribution

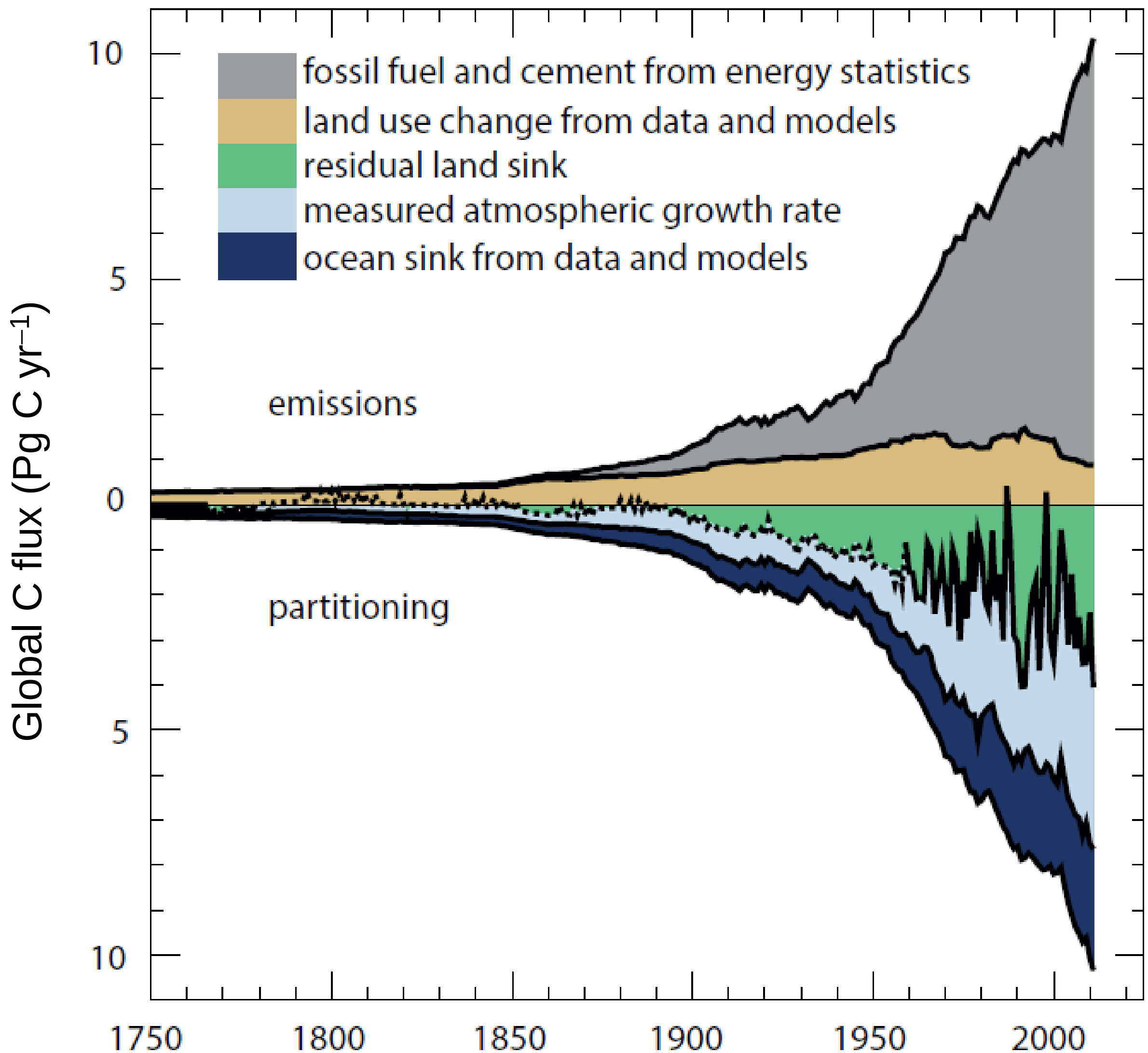


*Hyvönen et al. 2007
New Phytologist 173: 463-480

Young forests are a sink for CO_2, storing assimilated carbon in the stems of growing trees.

Over time, **phenology and mortality augment soil carbon pools**, causing decomposition losses to balance CO_2 uptake

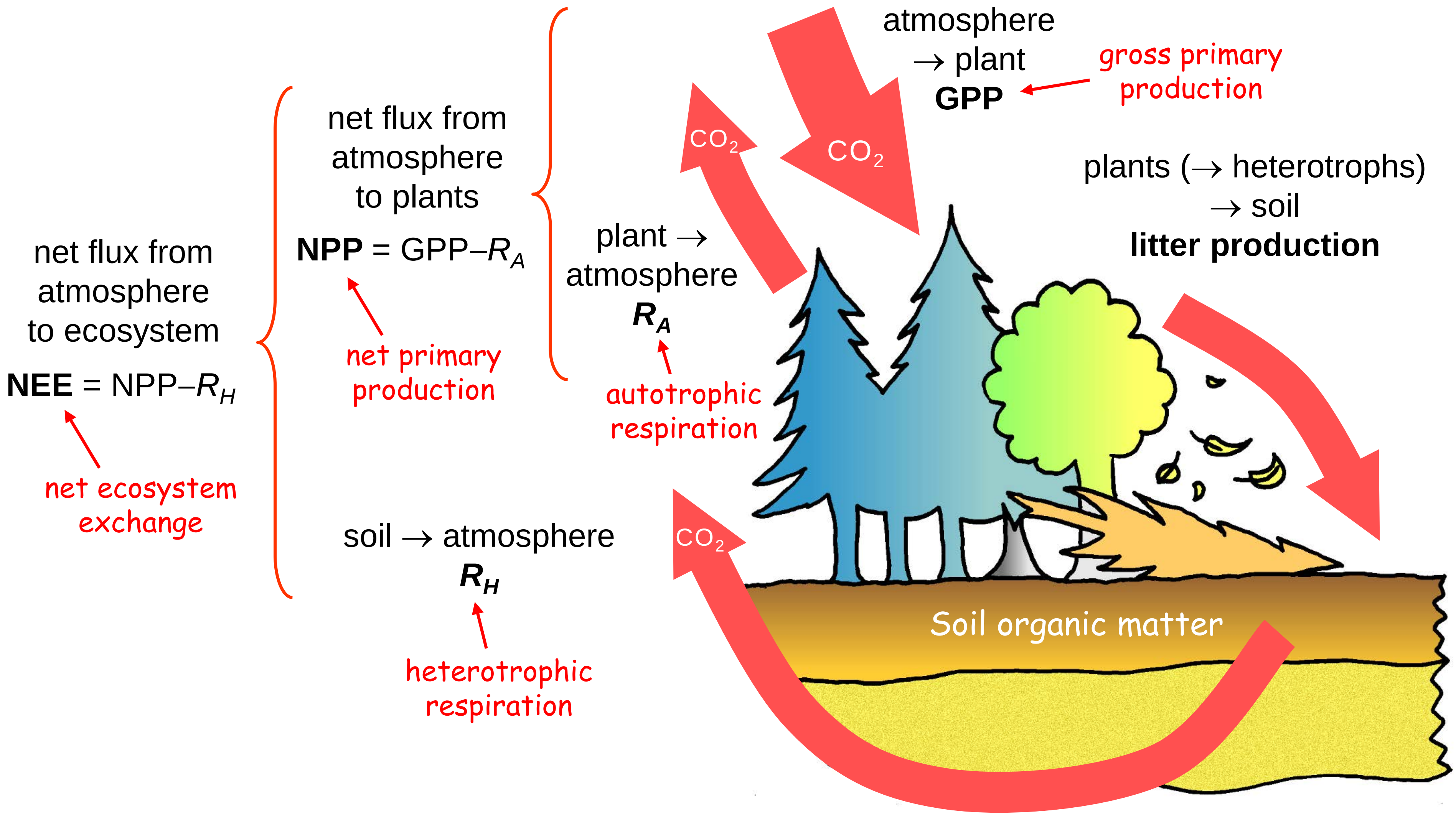
Land ecosystems are a sink for atmospheric CO_2 — a temporary anomaly not expected at steady state



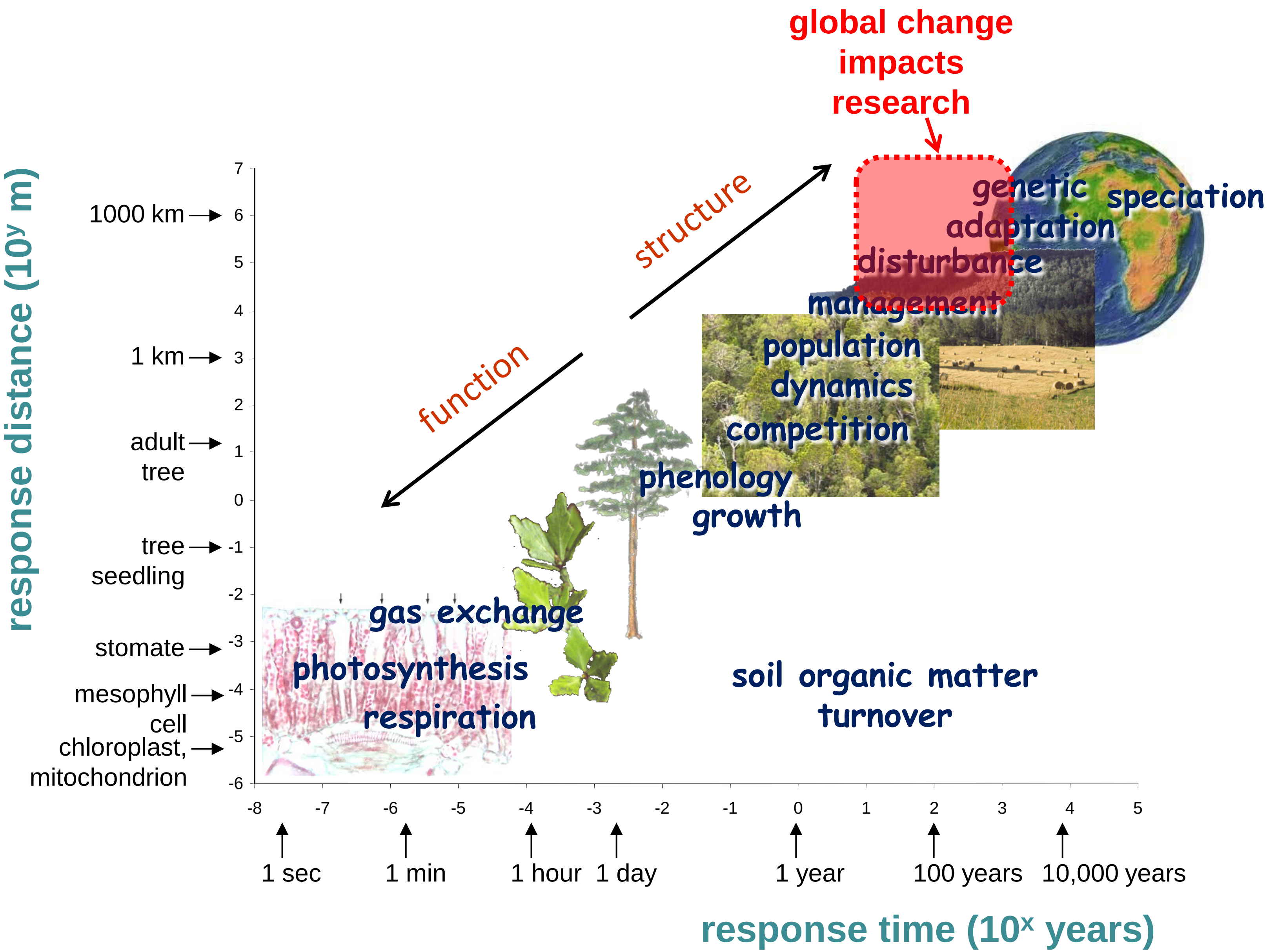
25% of C emissions are taken up by terrestrial ecosystems due to surplus of photosynthesis relative to respiration and emissions from wildfires

*Ciais *et al.* 2013. IPCC-AR5

Climate response of terrestrial ecosystems is intricately tied to their role in the global carbon cycle

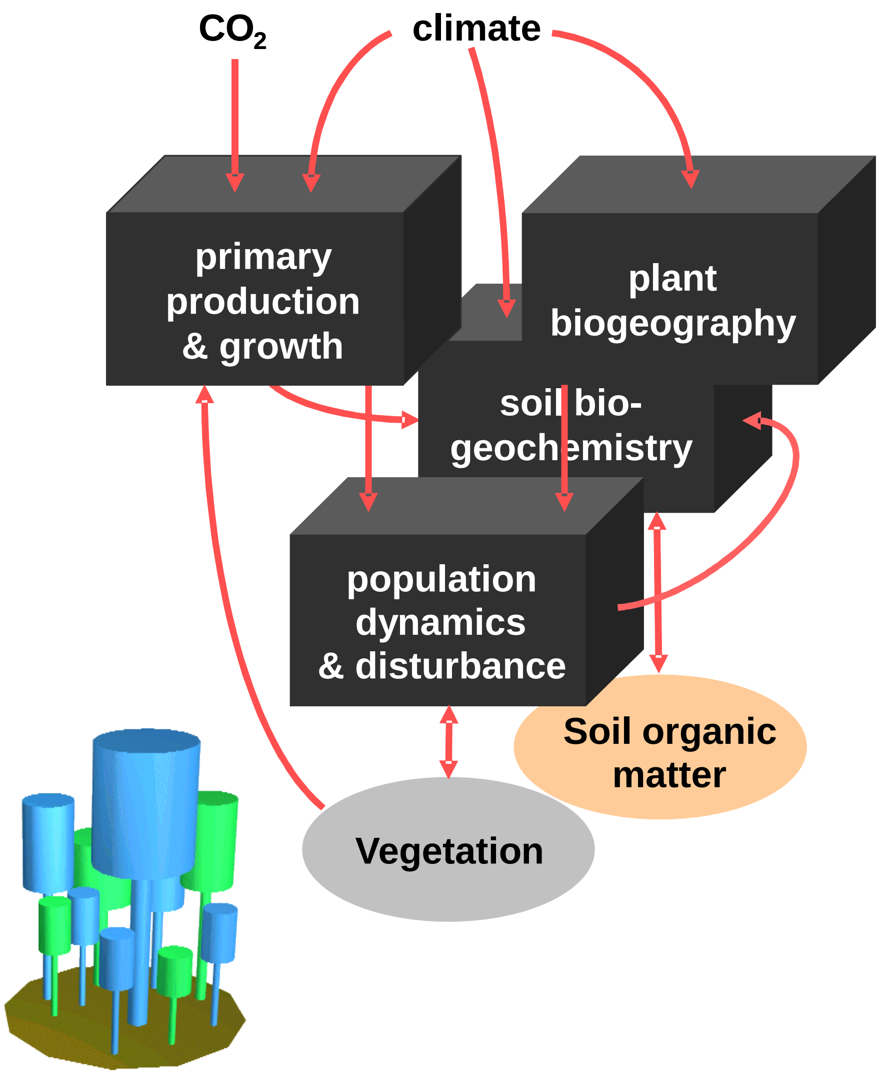


Scales of terrestrial ecosystem processes

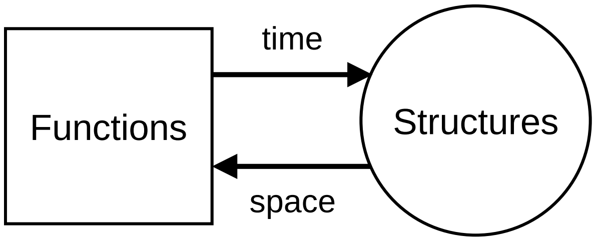


Dynamic Global Vegetation Model (DGVM)

globally-applicable coupled model of
terrestrial vegetation dynamics and ecosystem biogeochemistry



- link structure to function, accounting for feedbacks between them

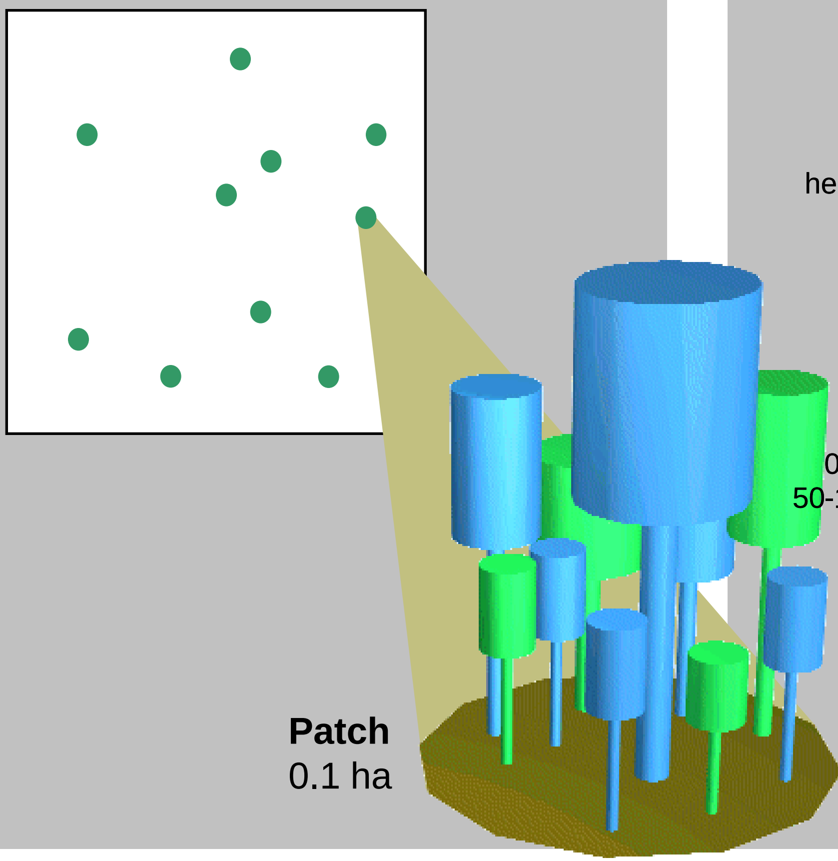


- link 'fast' (physiology, biogeochemistry) and 'slow' (demography, composition) ecosystem processes
- account for transient ecosystem dynamics when driving conditions (climate, CO_2) are changing rapidly
- based on generalised global (or biome-specific) parameterisations and plant functional types (PFTs)

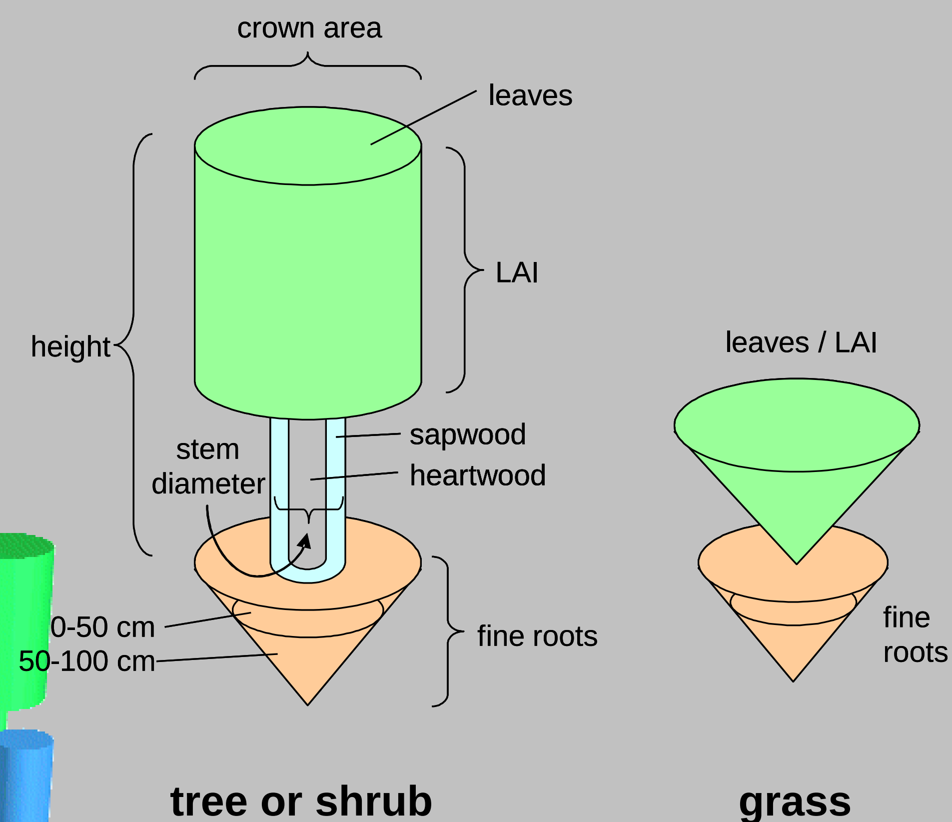
Vegetation representation in the LPJ-GUESS DGVM*

Modelled area (stand)
10 ha - 2500 km²

replicate patches in various
stages of development

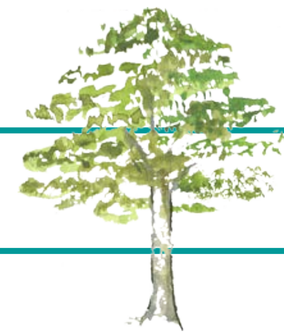


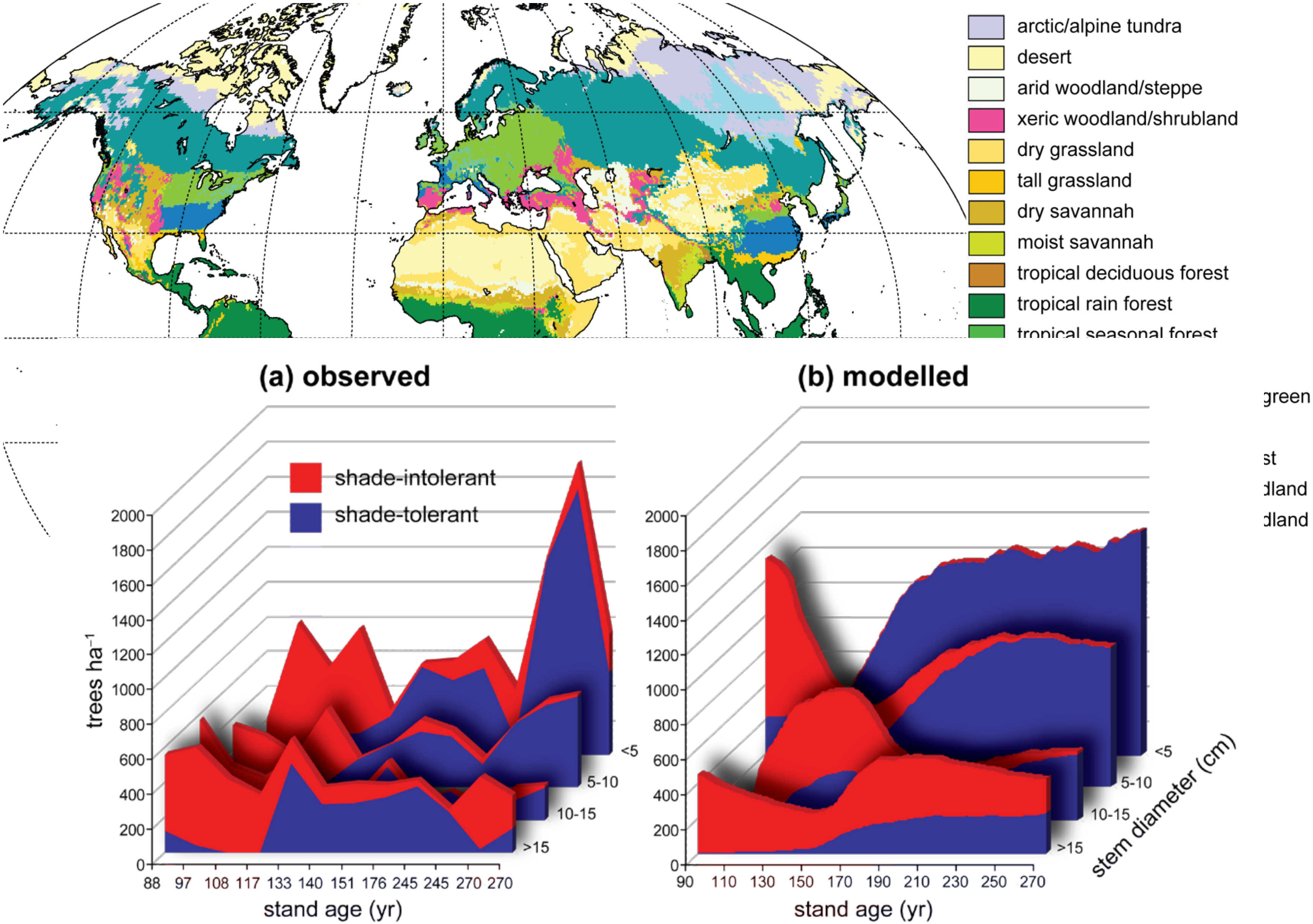
Average individual for plant functional type cohort in patch



*Smith et al. 2001
Global Ecology & Biogeography
10: 621-637

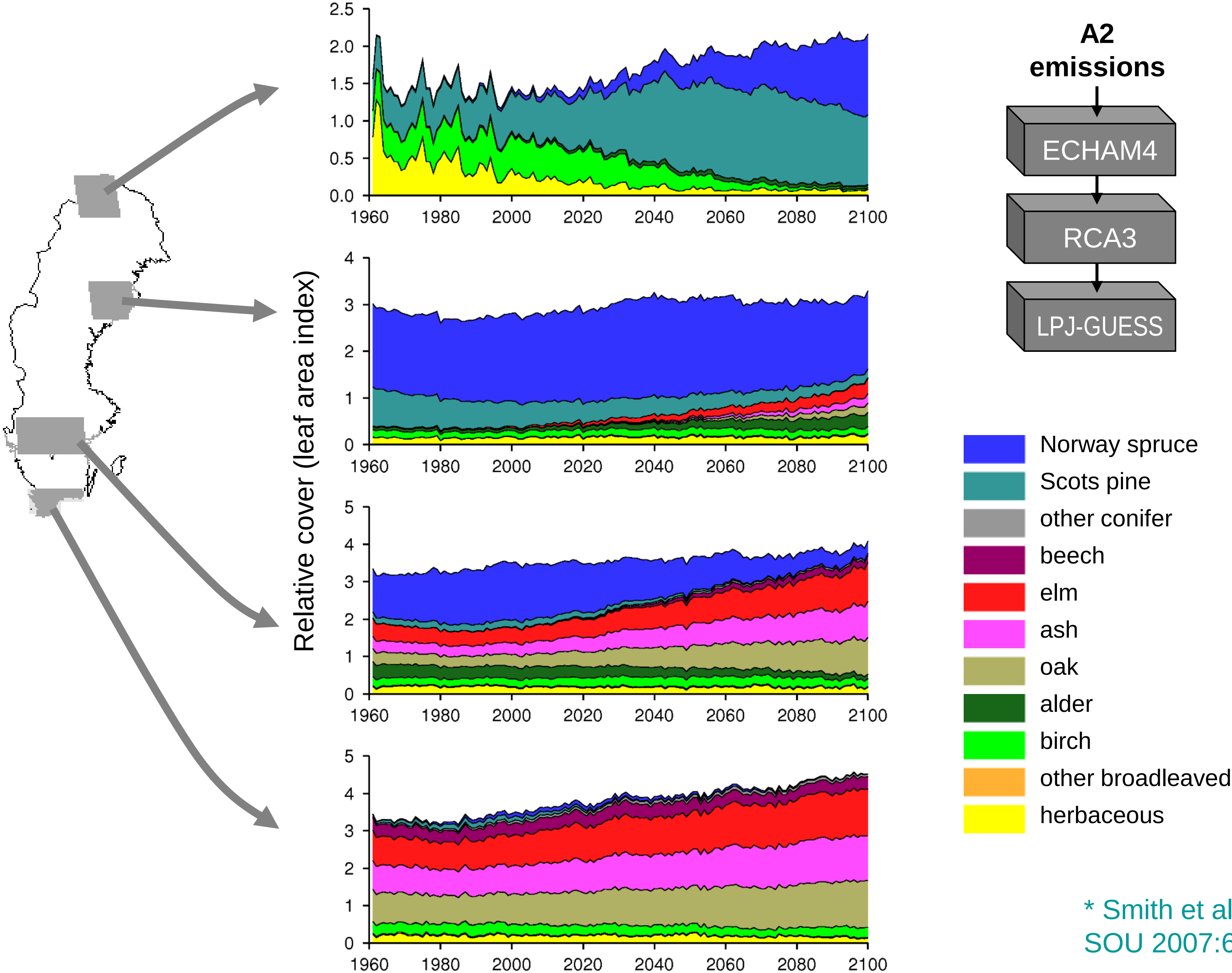
Trait differences influence functioning and interactions among plant functional types (groups of similar species)

Parameter				
bioclimatic distribution	boreal	temperate	boreal-temperate	no limits
optimal temp for photosynthesis (°C)	10-25	15-25	10-25	10-30
leaf phenology	evergreen	summergreen	summergreen	summergreen-raingreen
leaf:sapwood area ratio (m^2 cm^{-2})	0.3	0.4	0.4	-
crown spreading	150	250	250	-
allocation to stem growth	0.05	0.05	0.1	-
survival in shade	high	high	low	low
max longevity (yr)	900	900	300	-
max establishment rate (ha^{-1} yr^{-1})	1250	1250	2500	-



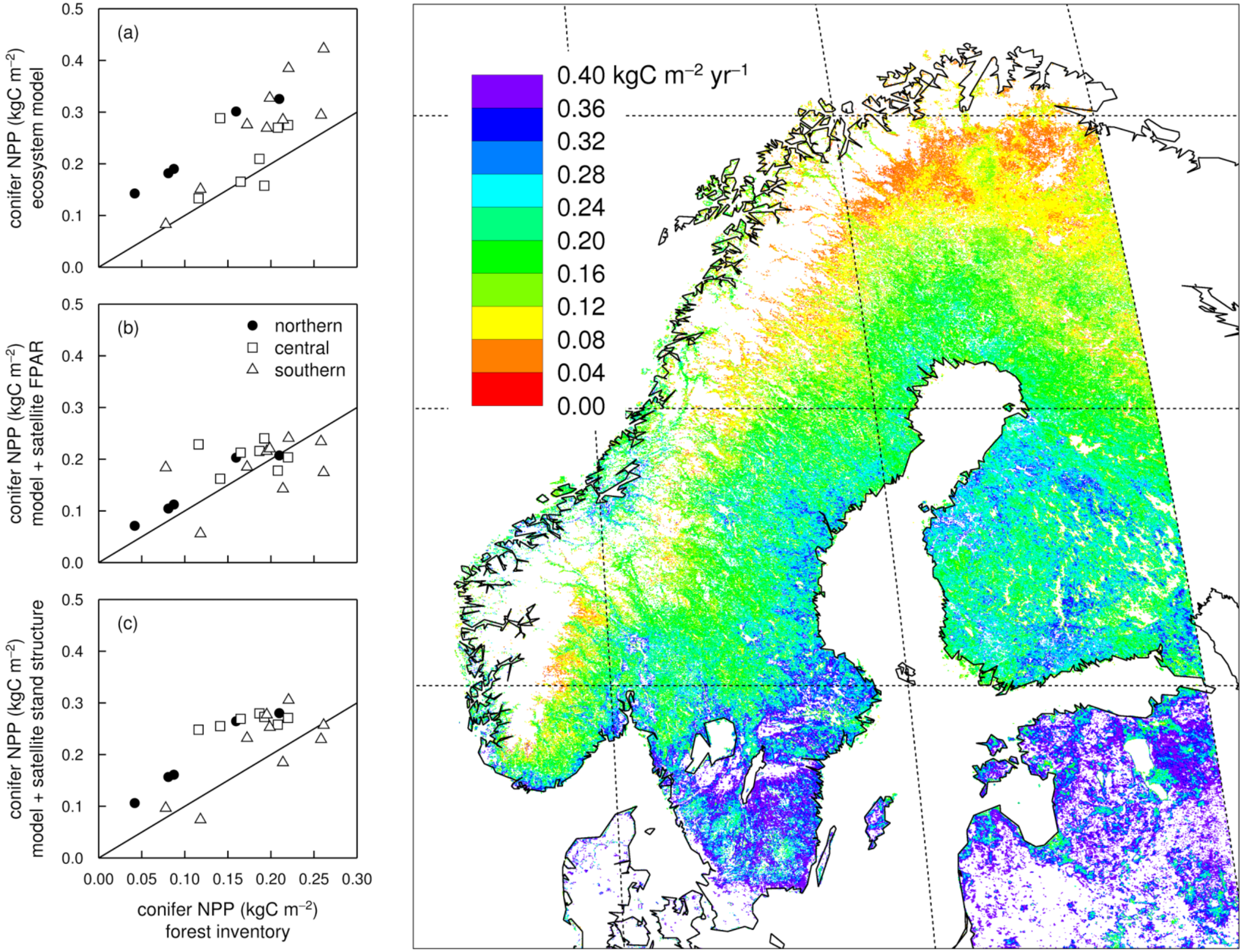
Smith et al. 2014
Biogeosciences 11: 2027-2054

Potential vegetation change in Sweden*



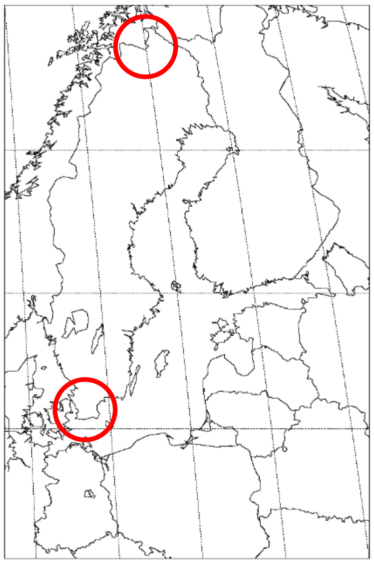
* Smith et al. 2007
SOU 2007:60

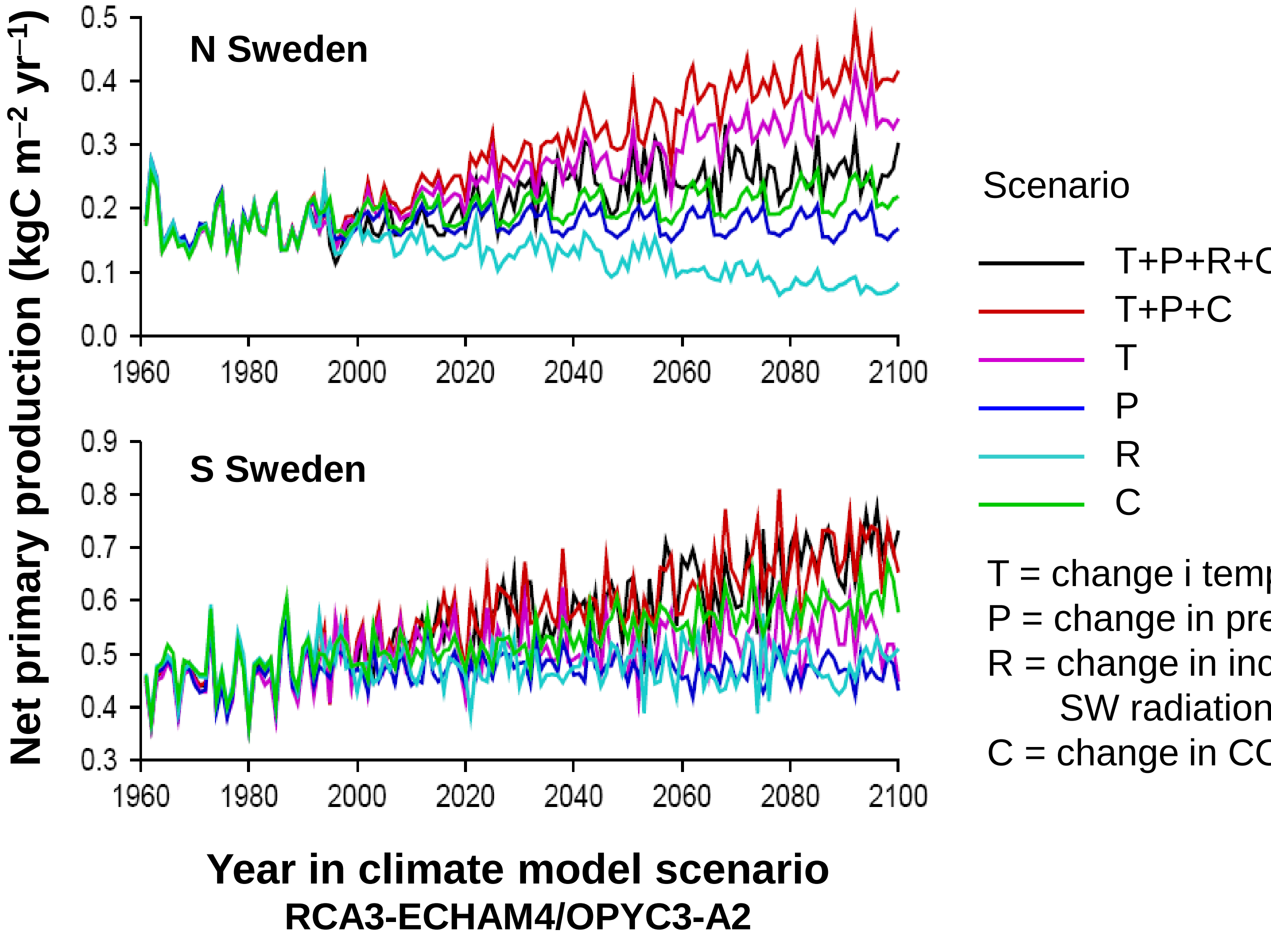
Conifer forest NPP 1996-2000*



*Smith et al. 2008. *Forest Ecology & Management* 255: 3985-3994

Climate and CO_2 effects on NPP*

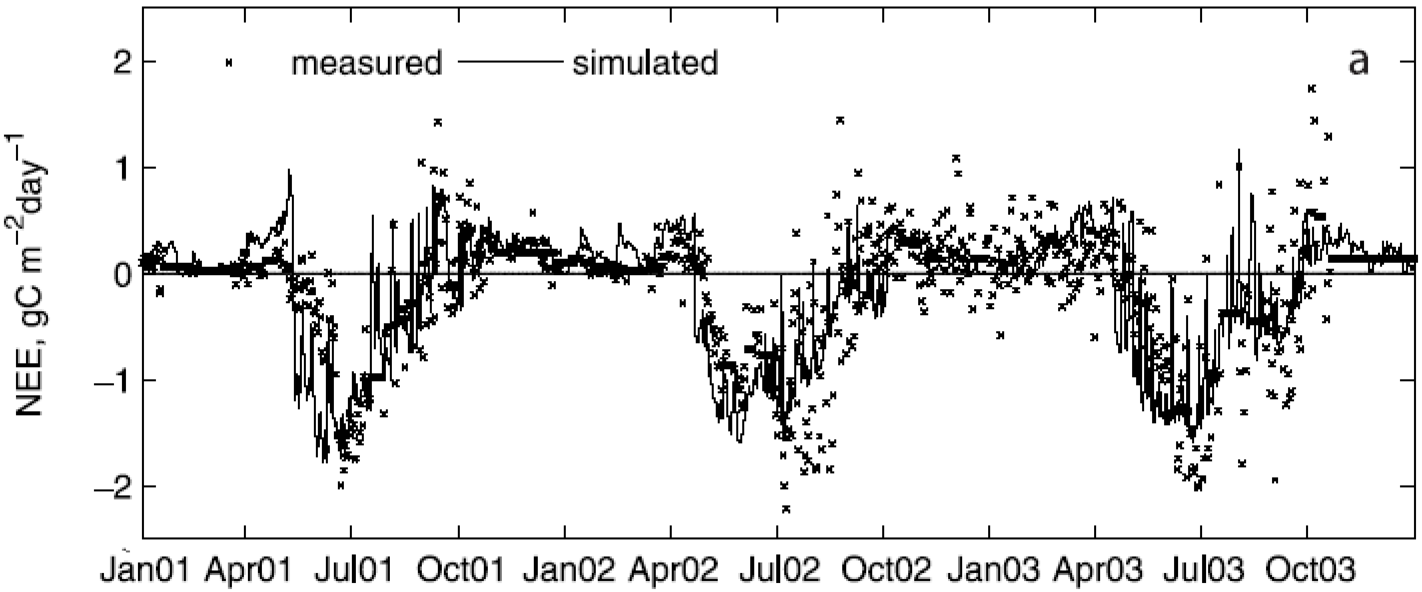


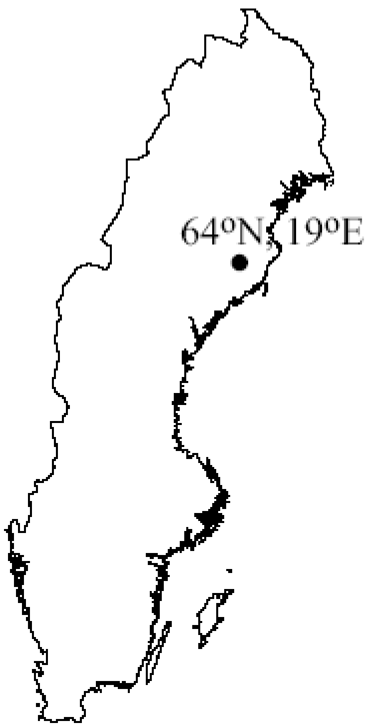


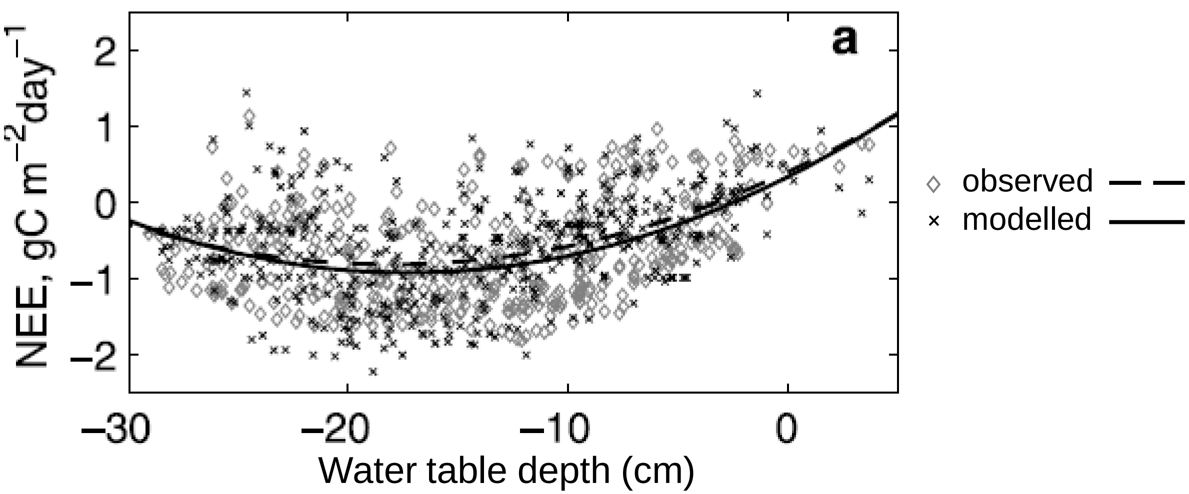
T = change i temperature
P = change in precipitation
R = change in incoming SW radiation
C = change in CO_2

* Smith et al. 2007
SOU 2007:60

Net ecosystem CO_2 exchange (NEE)
Degerö mire, northern Sweden*

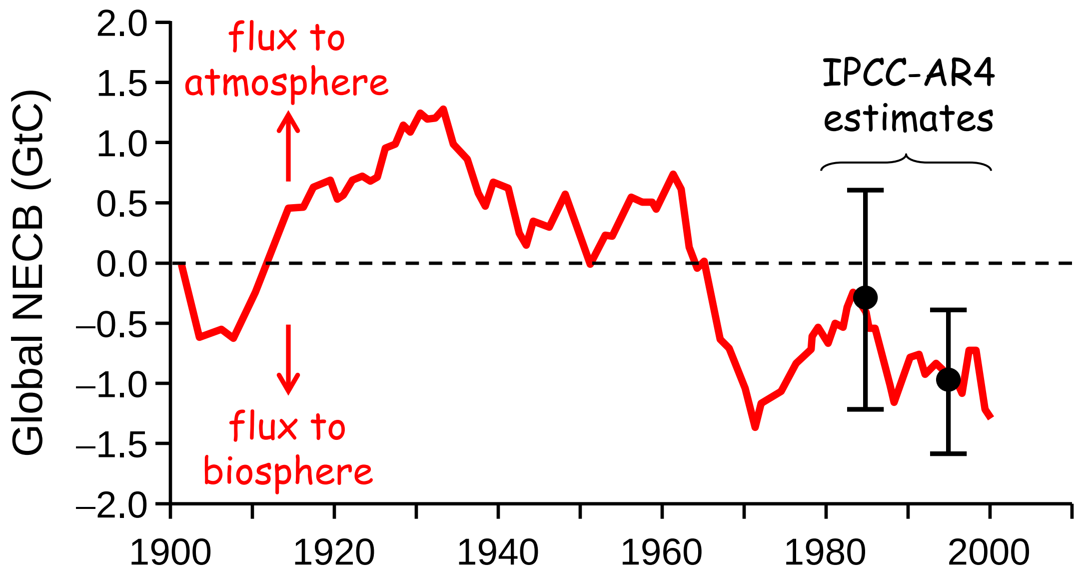


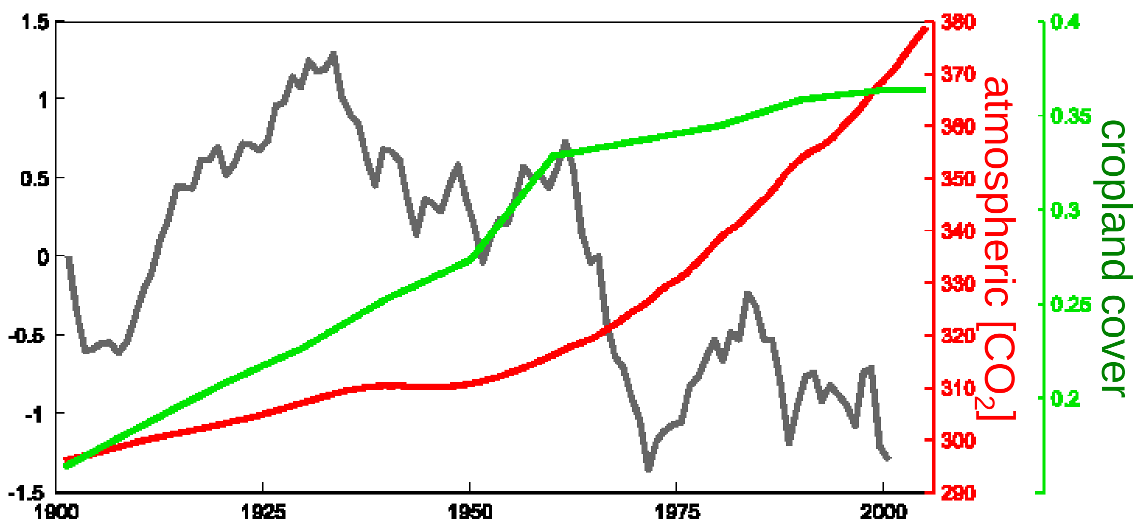




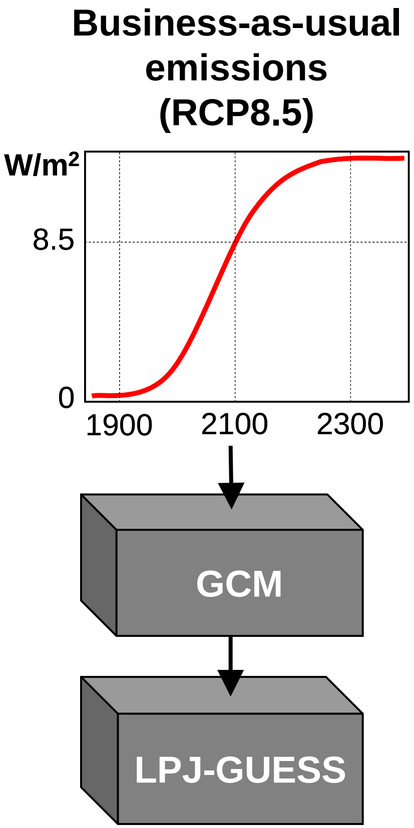
*Yurova et al. 2007
J. Geophysical Research 112

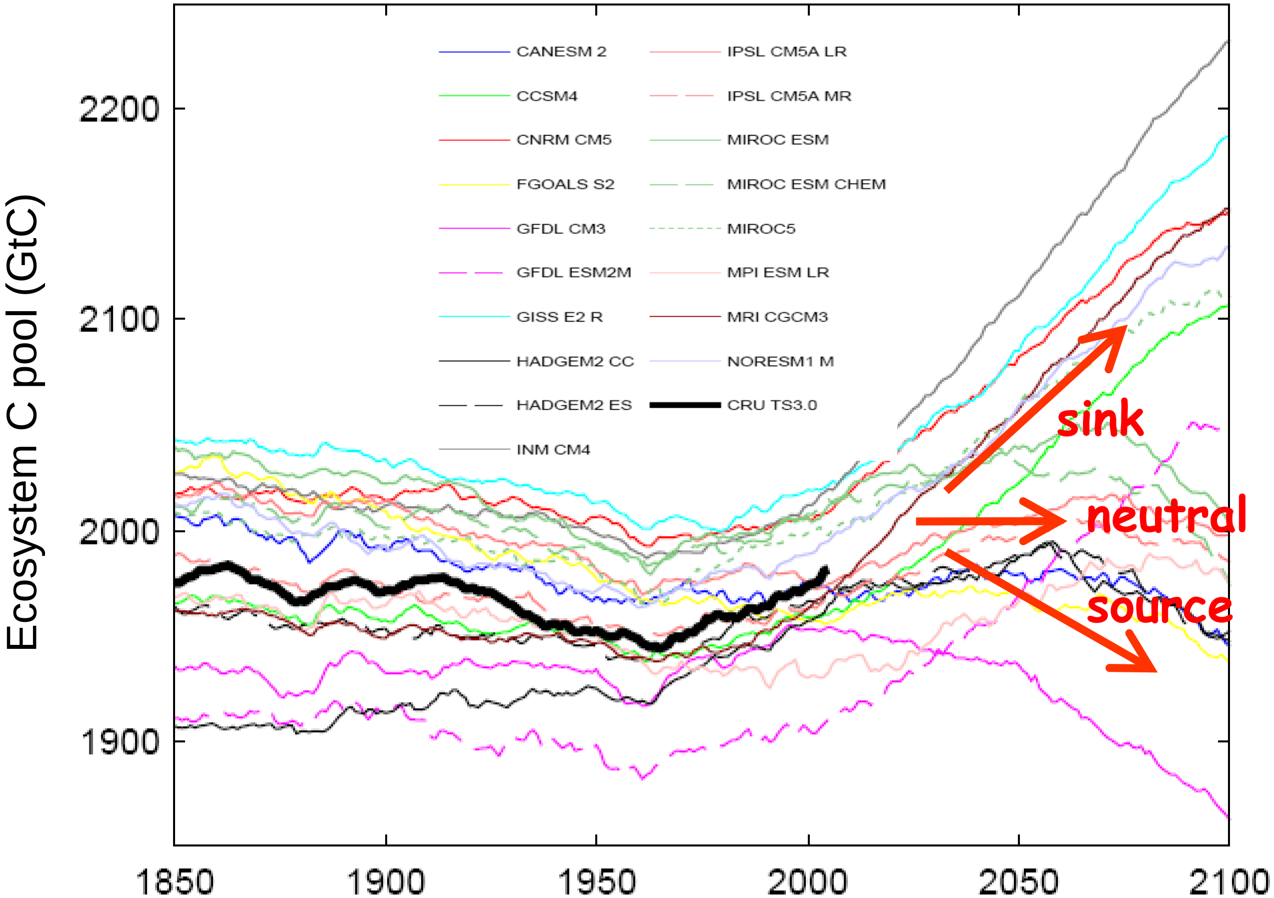
Globally, past net ecosystem C balance (NECB) reflects land use and CO_2 trends





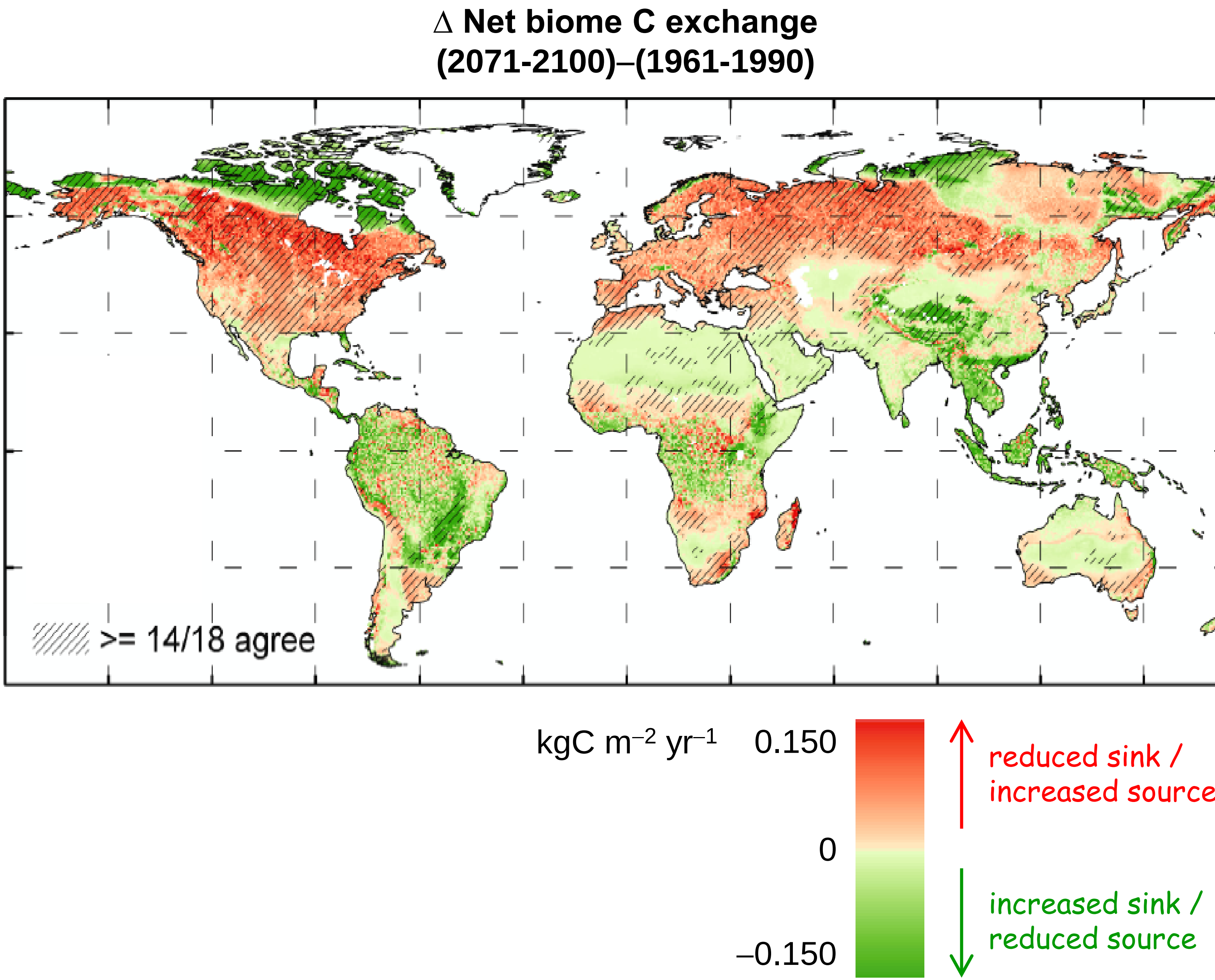
Future land ecosystem carbon balance*



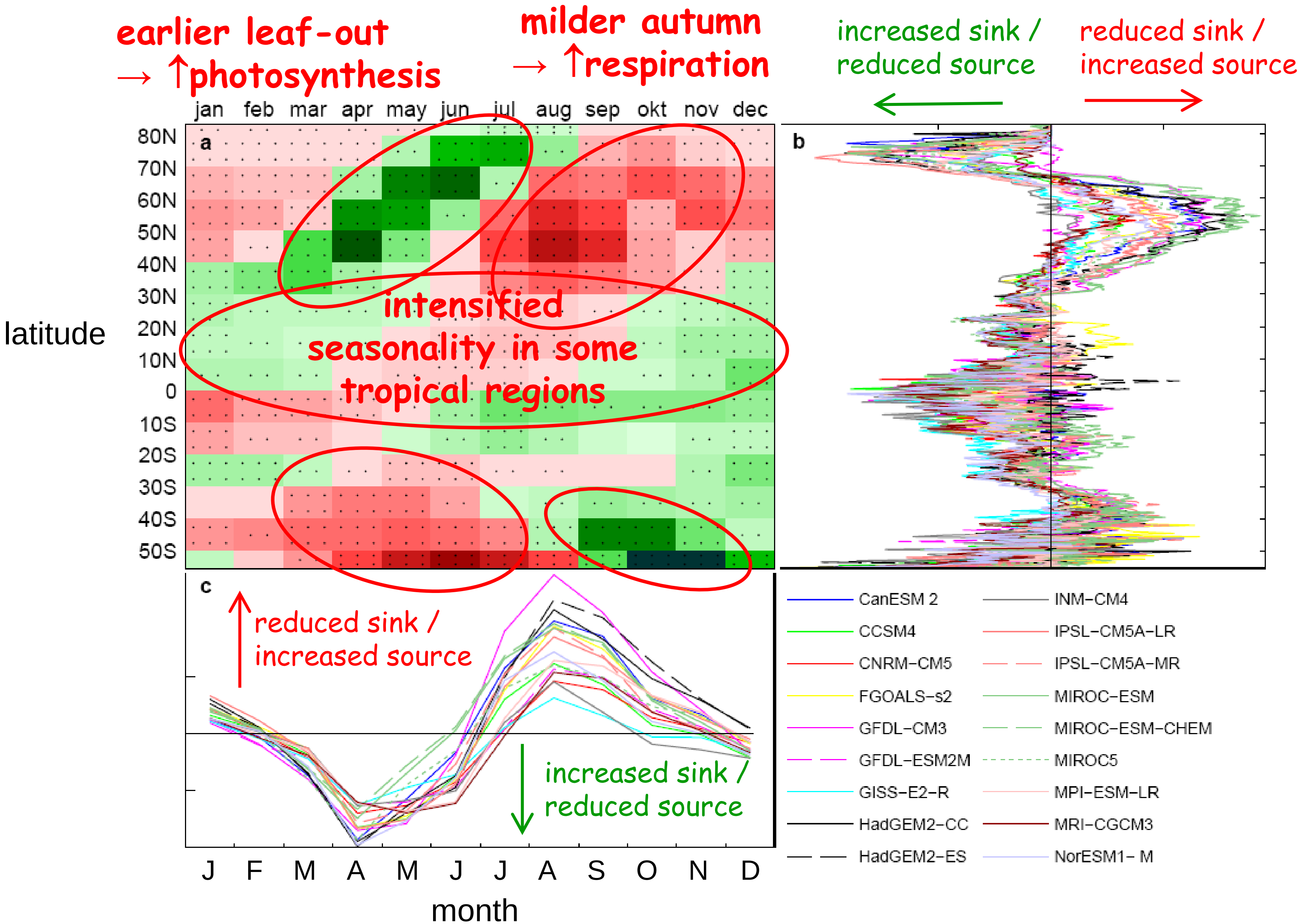


* Ahlström et al. 2012
Environmental Research Letters 7

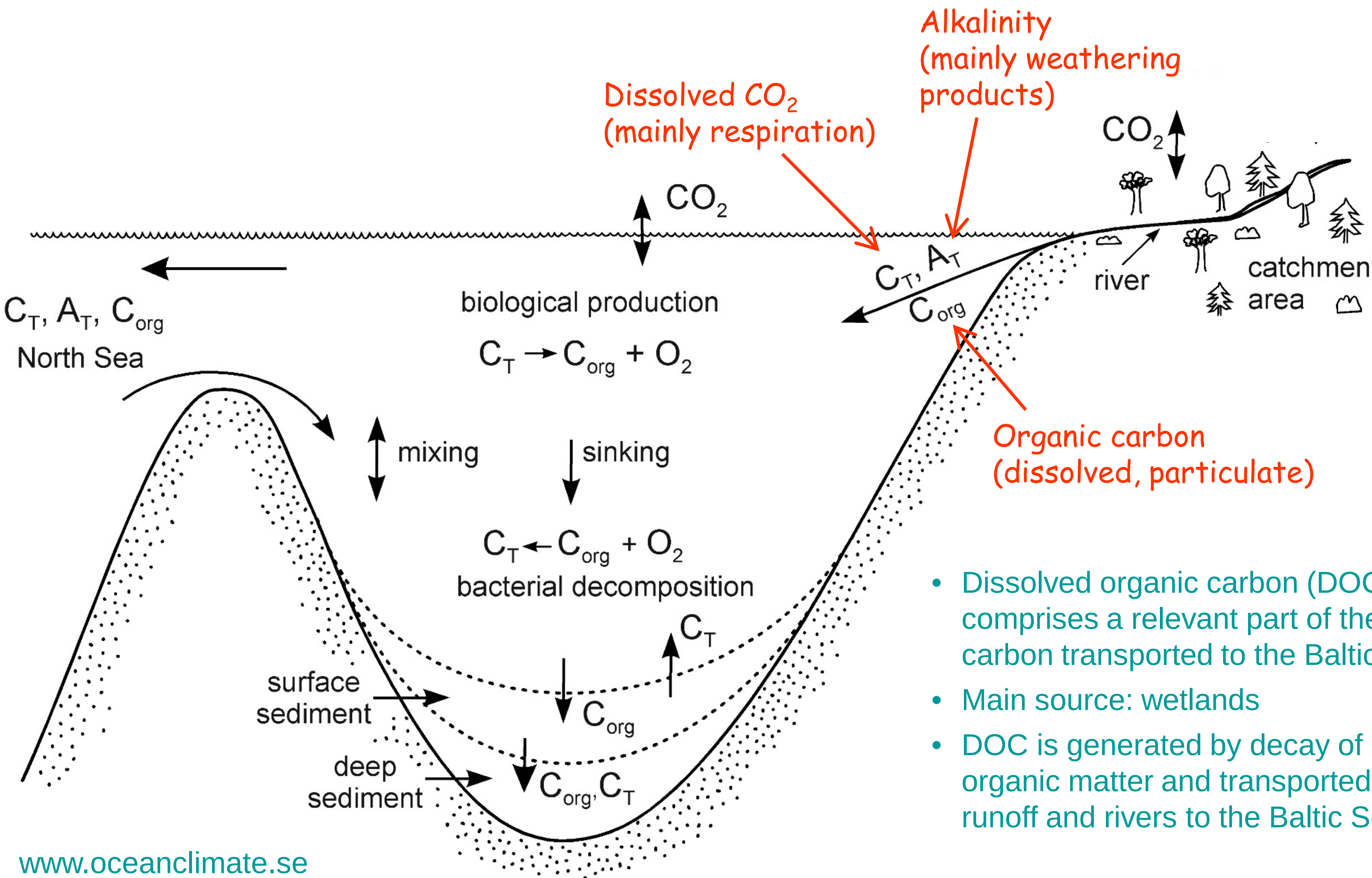
Robust sign of change for some regions



Some robust seasonal and regional trends



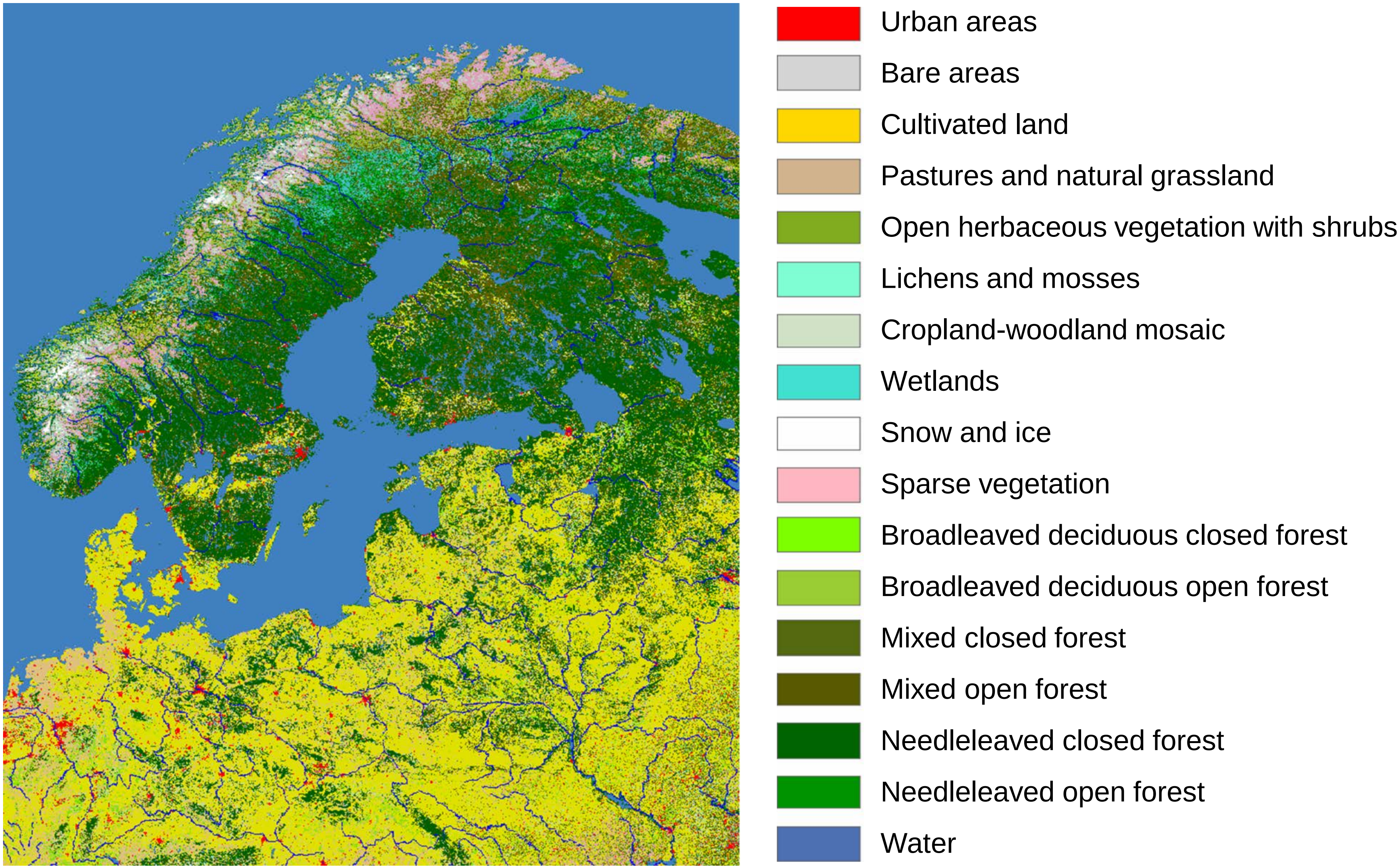
Carbon in runoff from land is a major input to Baltic Sea biogeochemistry



- Dissolved organic carbon (DOC) comprises a relevant part of the carbon transported to the Baltic Sea
- Main source: wetlands
- DOC is generated by decay of soil organic matter and transported by runoff and rivers to the Baltic Sea

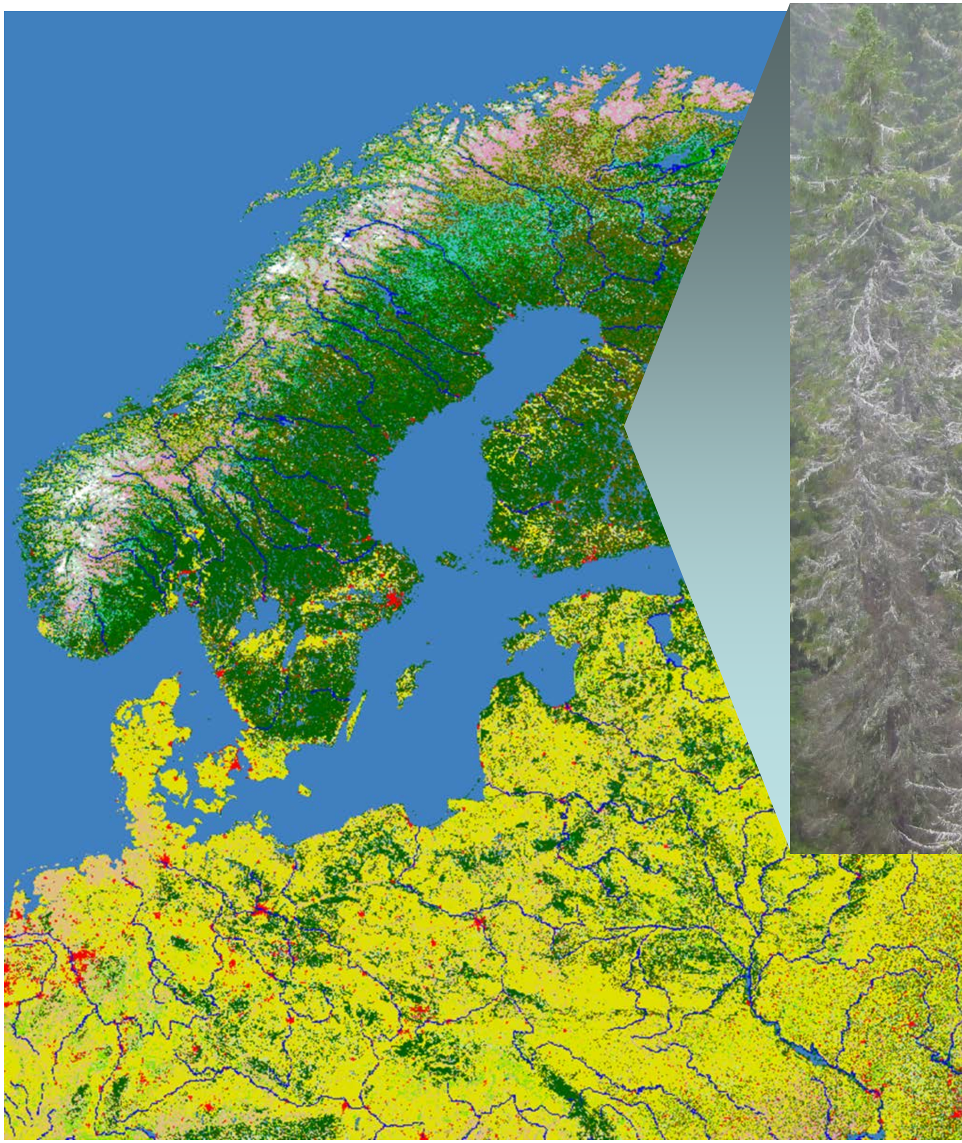
www.oceanclimate.se

Land cover of the Baltic Sea Basin



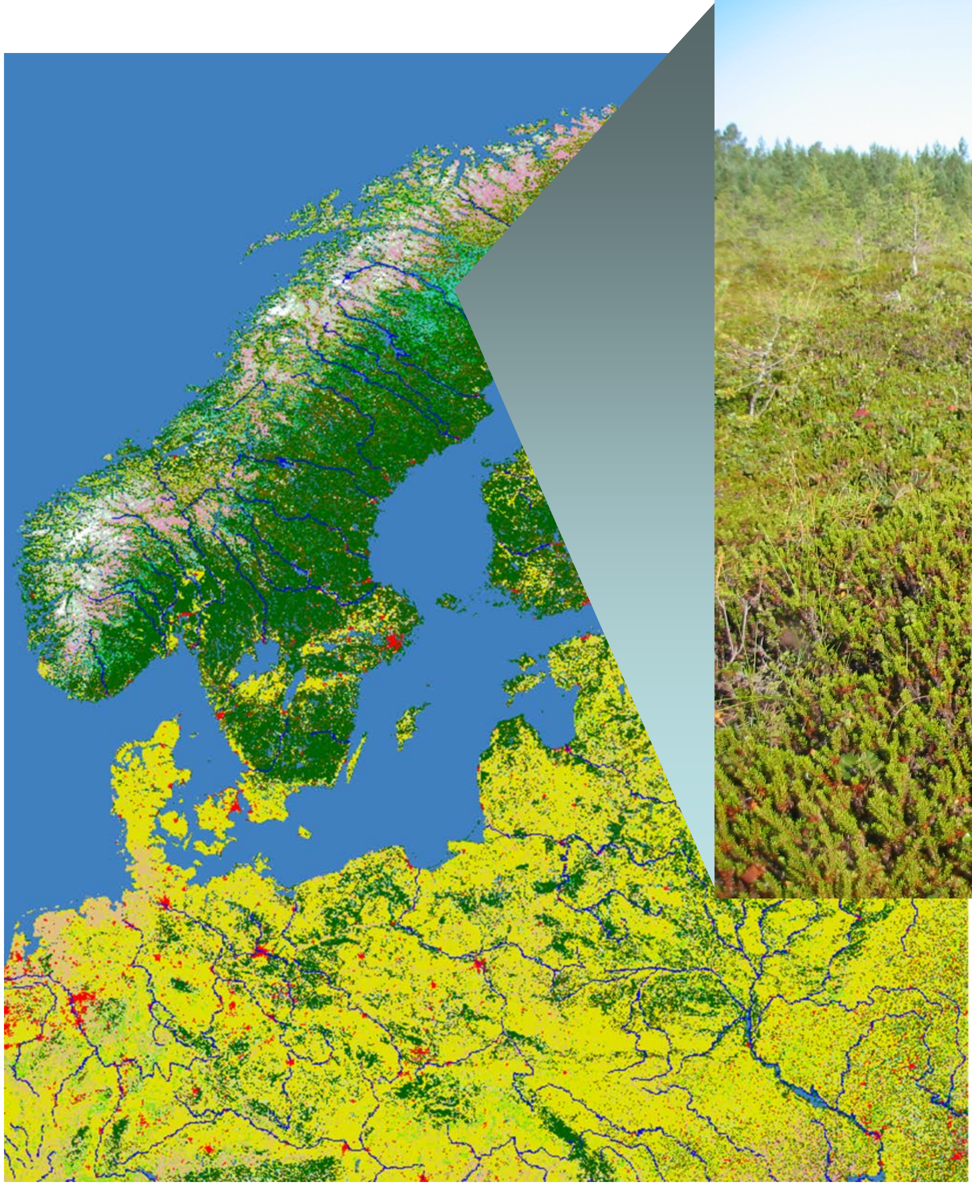
Ledwith (2003), GLC2000 project

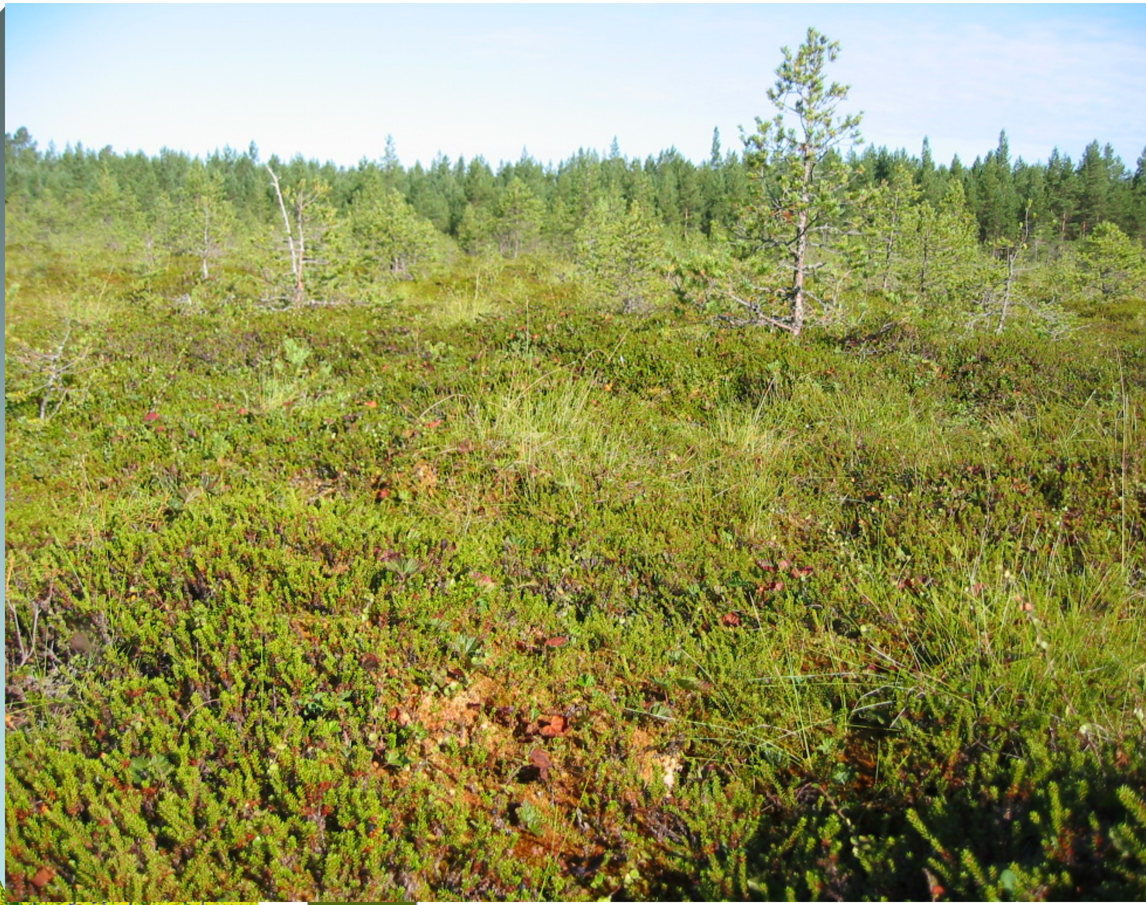
Land cover of the Baltic Sea Basin

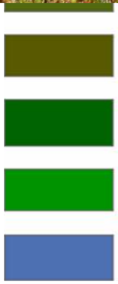


- Mixed open forest
- Needleleaved closed forest
- Needleleaved open forest
- Water

Land cover of the Baltic Sea Basin



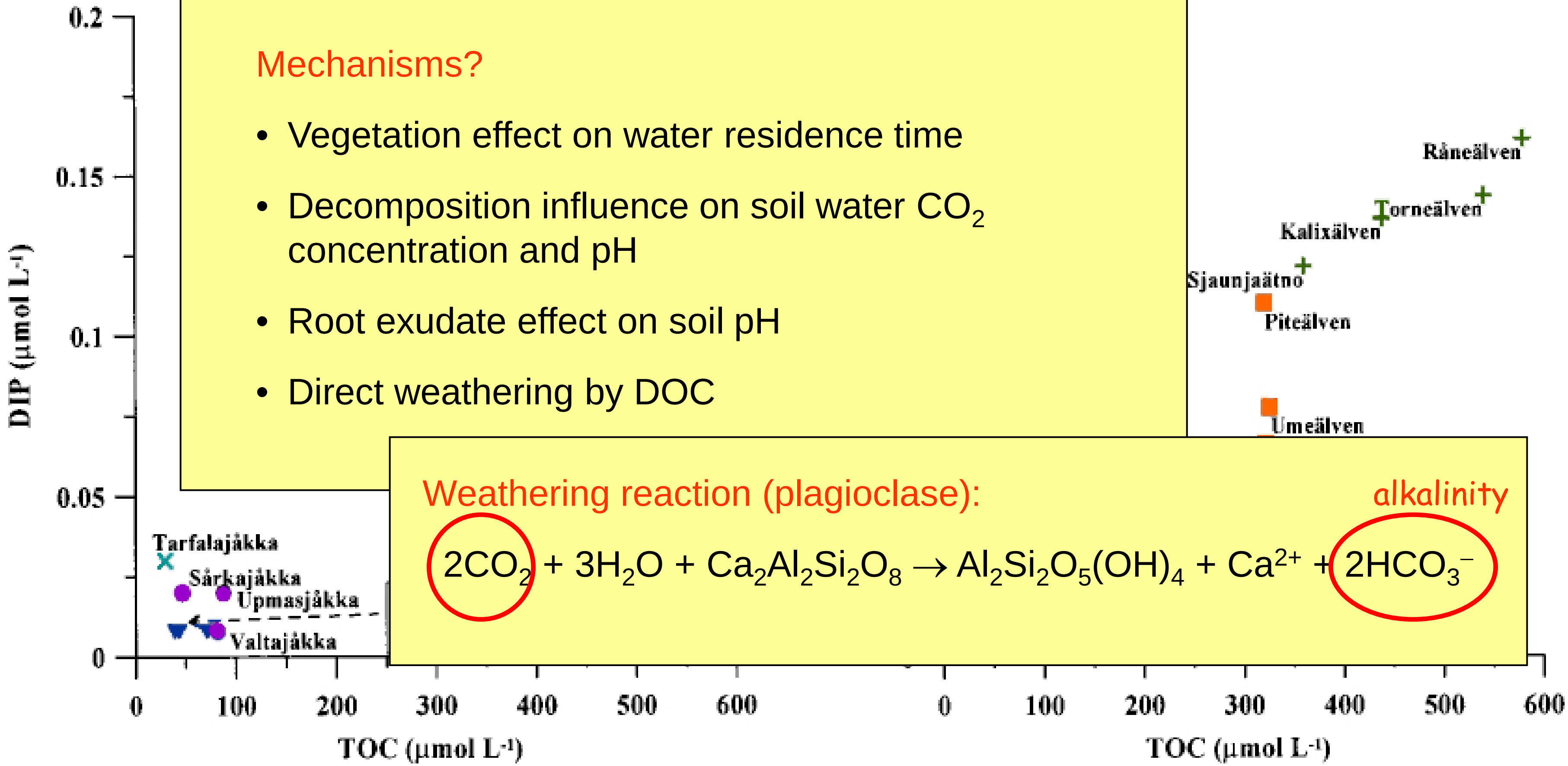




Land cover of the Baltic Sea Basin

Land cover of the Baltic Sea Basin

Vegetation cover/type affects export of organic carbon and weathering products*



Mechanisms?

- Vegetation effect on water residence time
- Decomposition influence on soil water CO_2 concentration and pH
- Root exudate effect on soil pH
- Direct weathering by DOC

Weathering reaction (plagioclase):

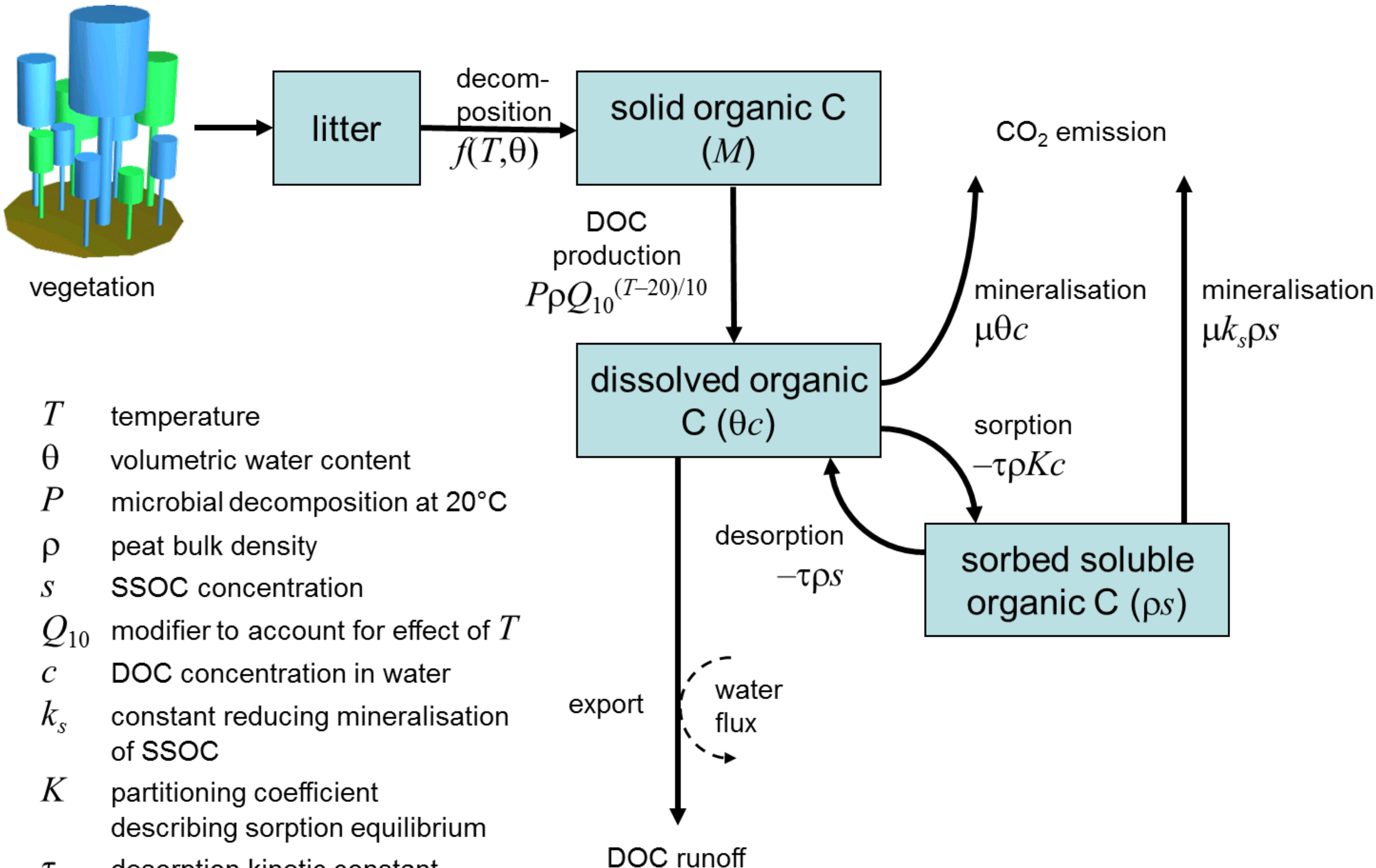
alkalinity

$$2CO_2 + 3H_2O + Ca_2Al_2Si_2O_8 \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^-$$

- high veg cover (more conifers & wetlands)
- high veg cover (less conifers & wetlands)
- large lakes/reservoirs
- open highland
- alpine + subalpine birch forest
- glacier

* Humborg et al. 2004
Limnology & Oceanography
49: 1871-1883.

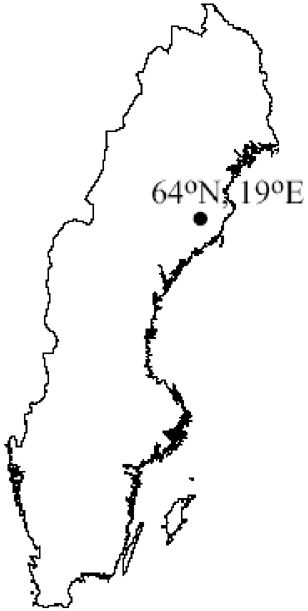
Dissolved organic carbon (DOC) production and export in the LPJ-GUESS DGVM*

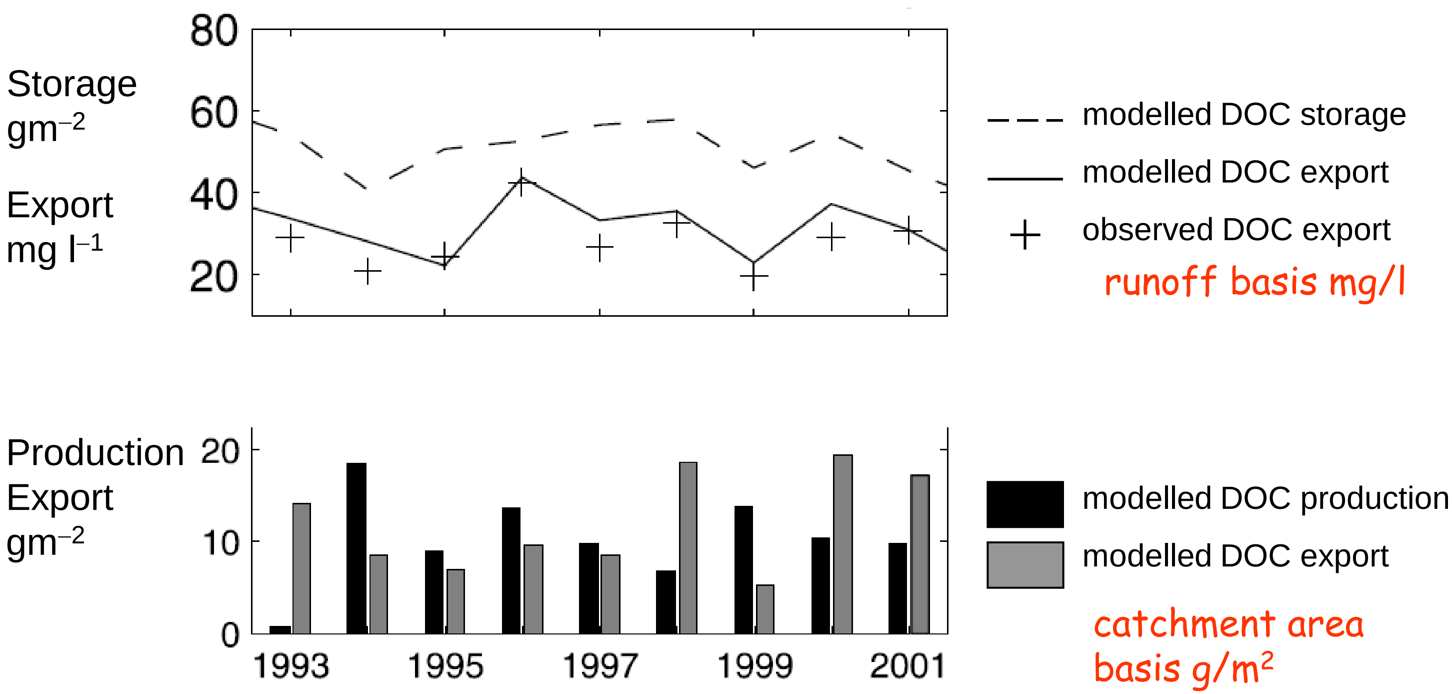


T	temperature
θ	volumetric water content
P	microbial decomposition at 20°C
ρ	peat bulk density
s	SSOC concentration
Q_{10}	modifier to account for effect of T
c	DOC concentration in water
k_s	constant reducing mineralisation of SSOC
K	partitioning coefficient describing sorption equilibrium
τ	desorption kinetic constant

*Yurova et al. 2008
Water Resources Res. 44

DOC production and export
Degerö mire, N Sweden*

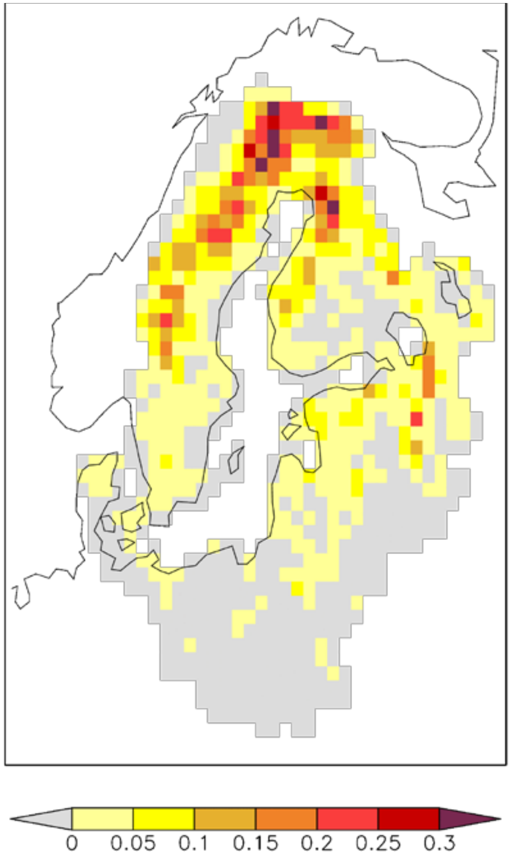




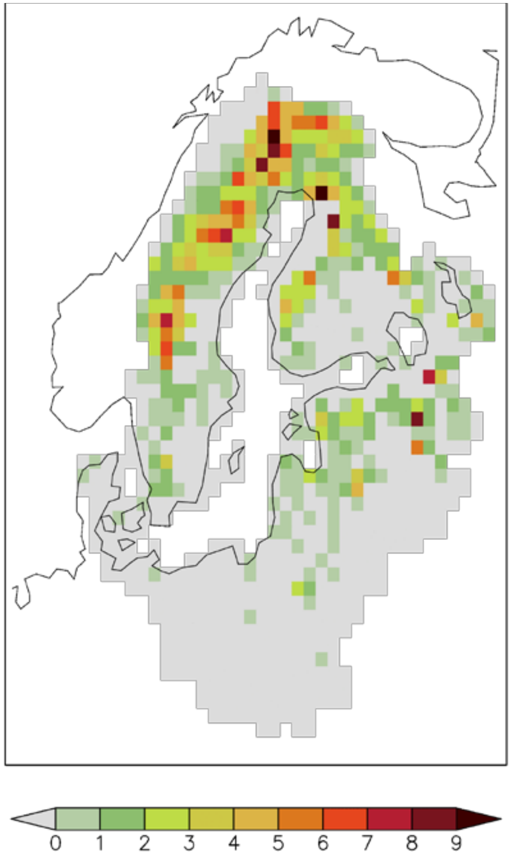
*Yurova et al. 2008
Water Resources Research 44

Simulated DOC production 1961-2005
Wetland sources

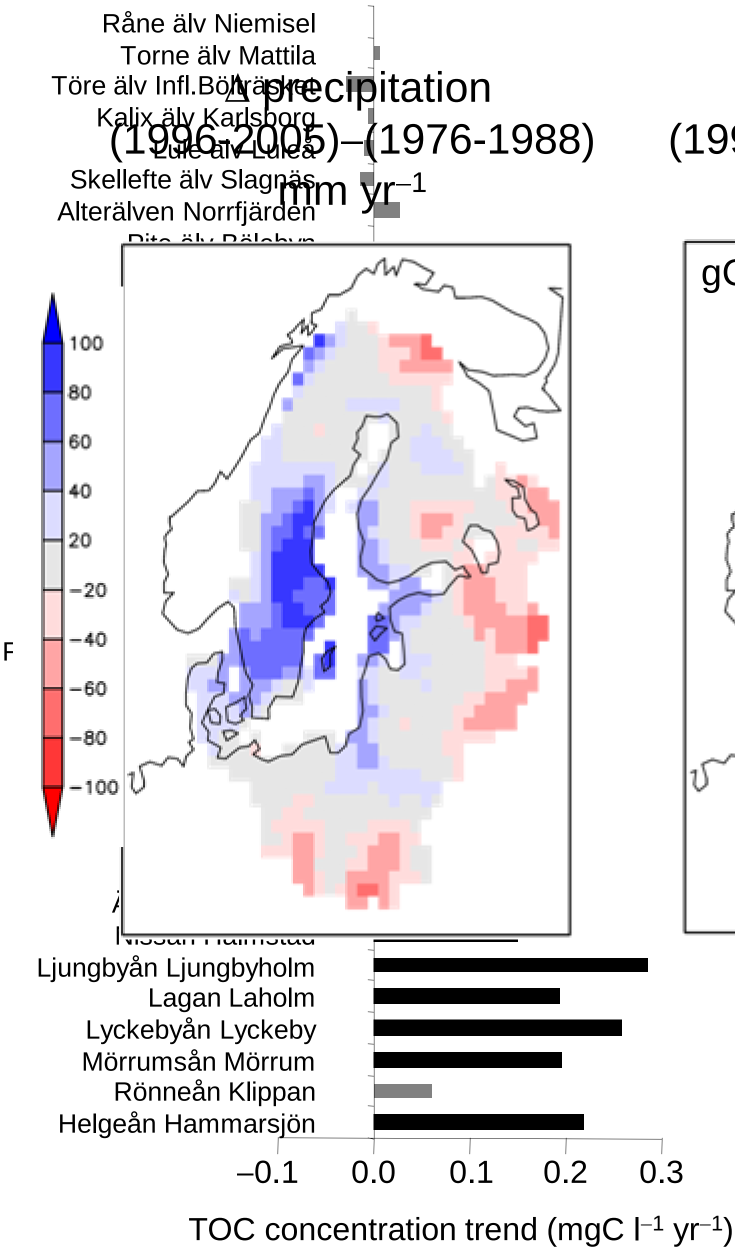
Wetland fraction of landscape

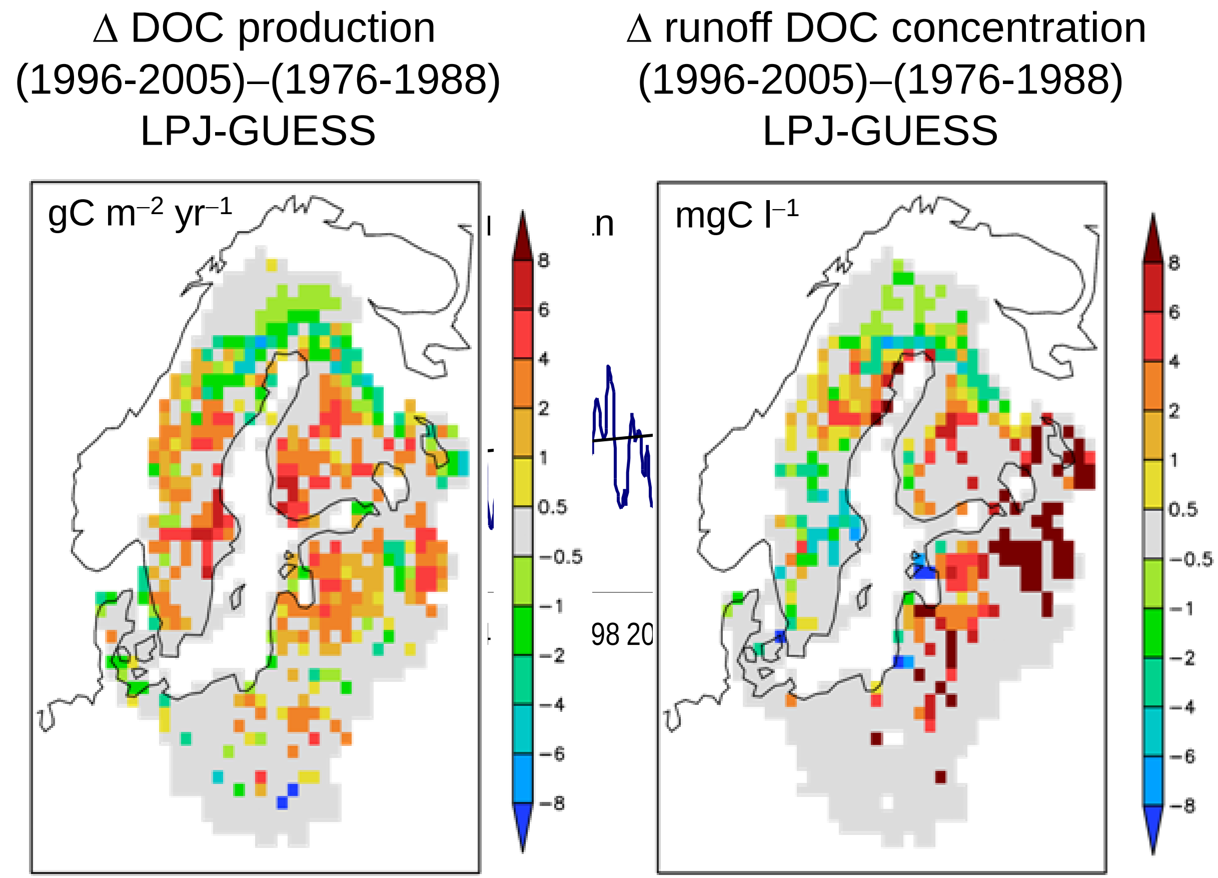


DOC in runoff gC m^{-2} yr^{-1}



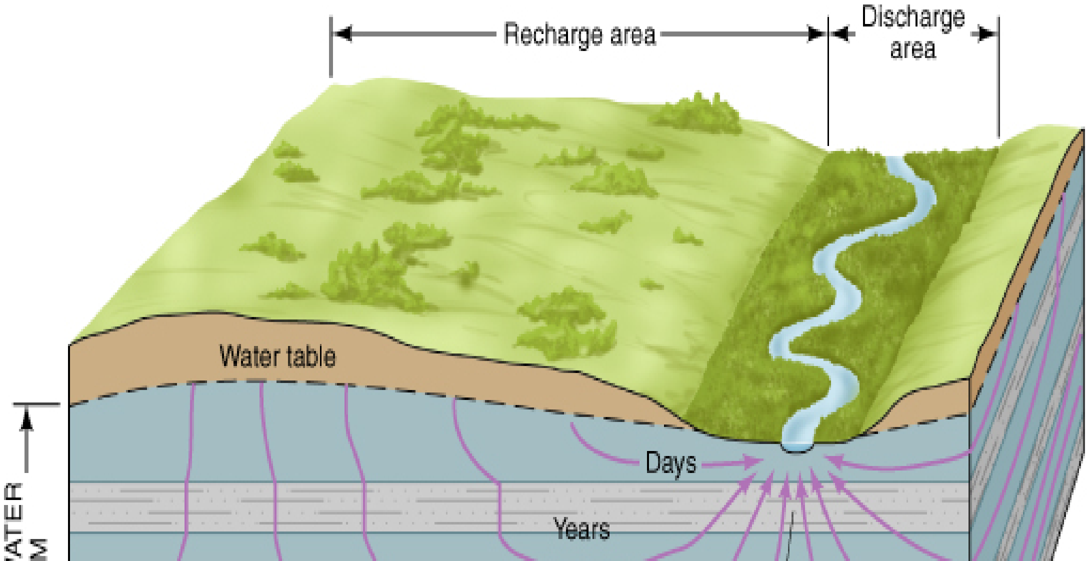
Simulated versus observed DOC concentration trends*



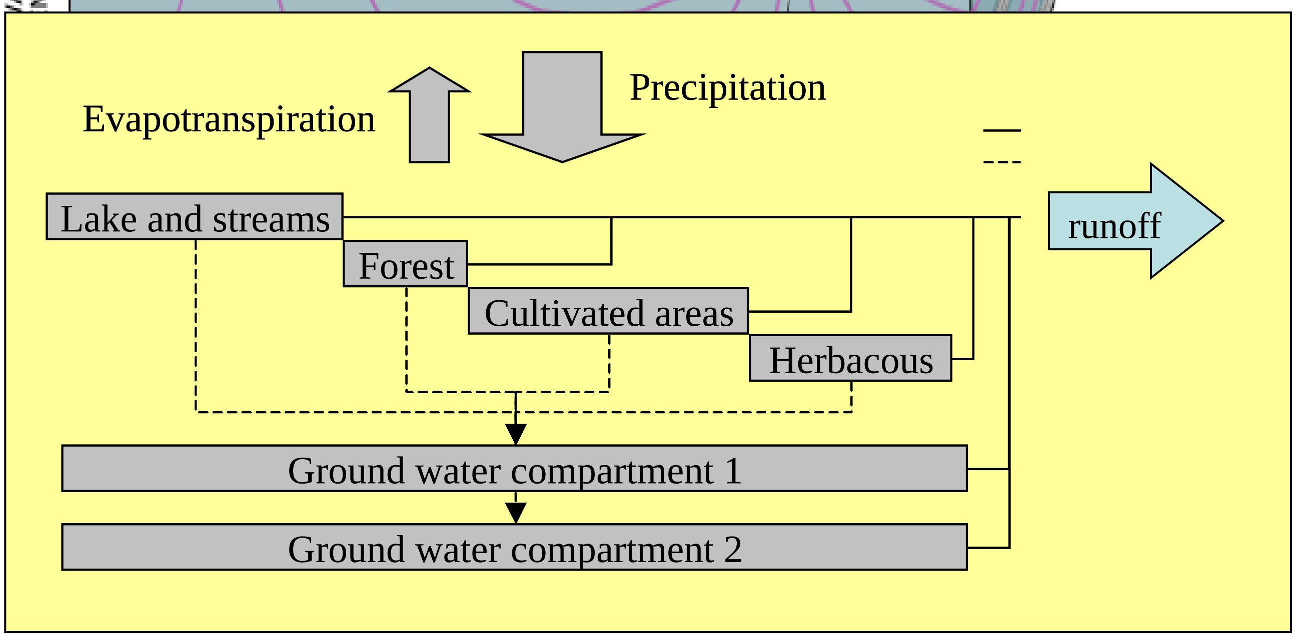


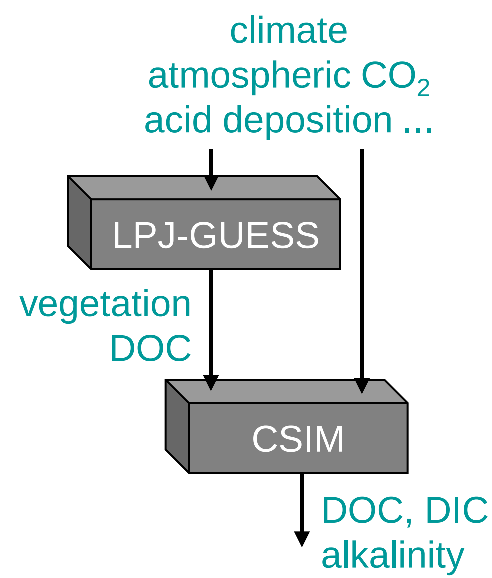
*Measurements: T. Wällstedt
Modelling: Guy Schurgers
(wetlands only)

Scaling up: root zone to catchment



- CSIM catchment hydrochemistry model*
- based on generalised watershed loading functions (GWLF)
- basic model assumption
  → water flow path is the most important factor regulating river chemistry

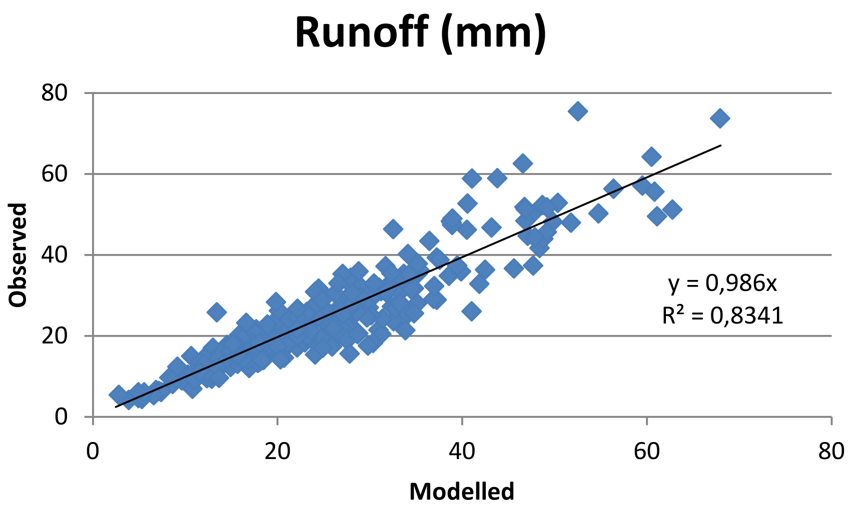


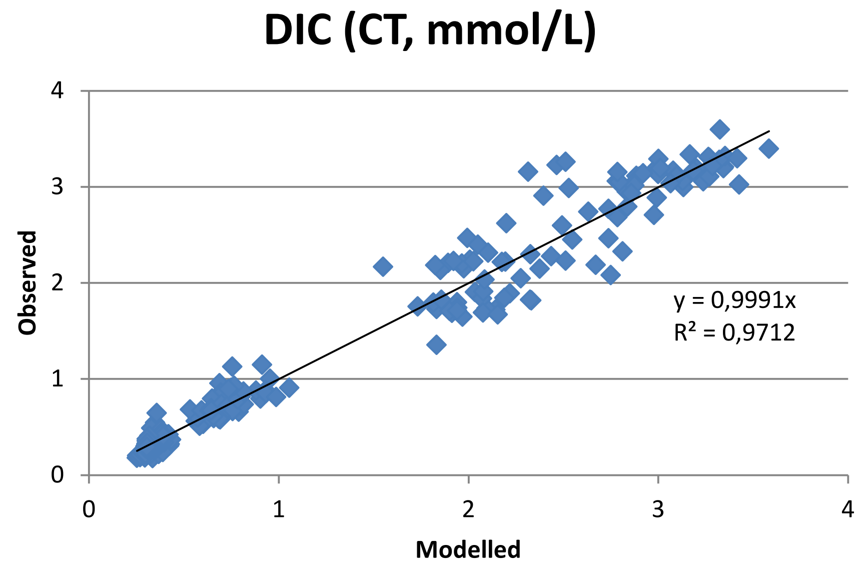


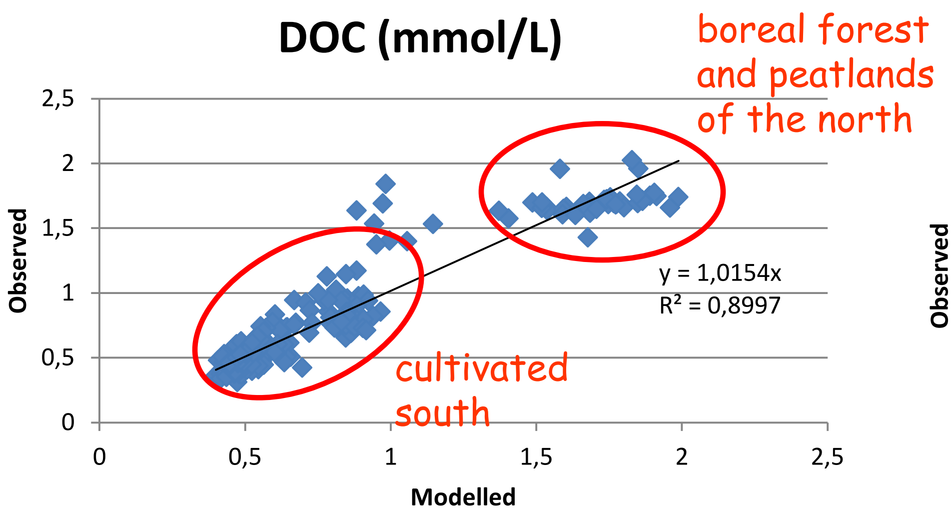
*Mörth et al. 2007. *Ambio* 36: 124

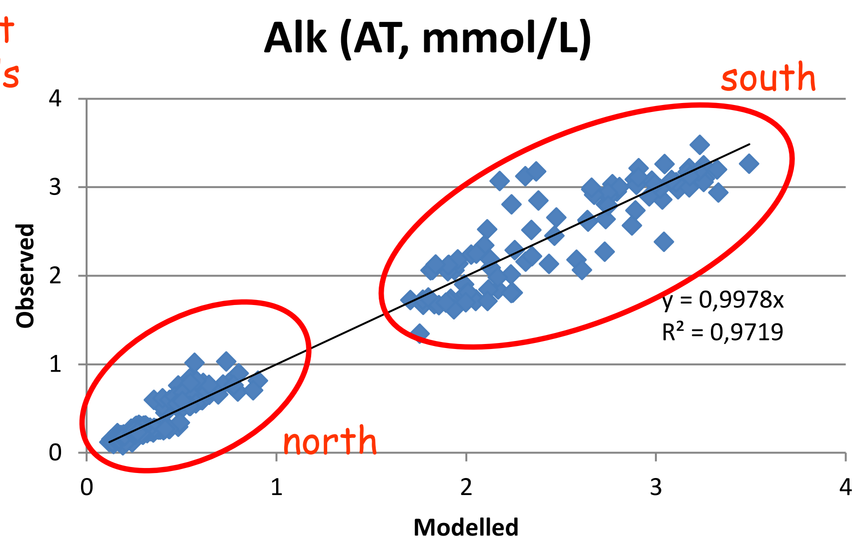
Calibration results 1996-2000

point = watershed



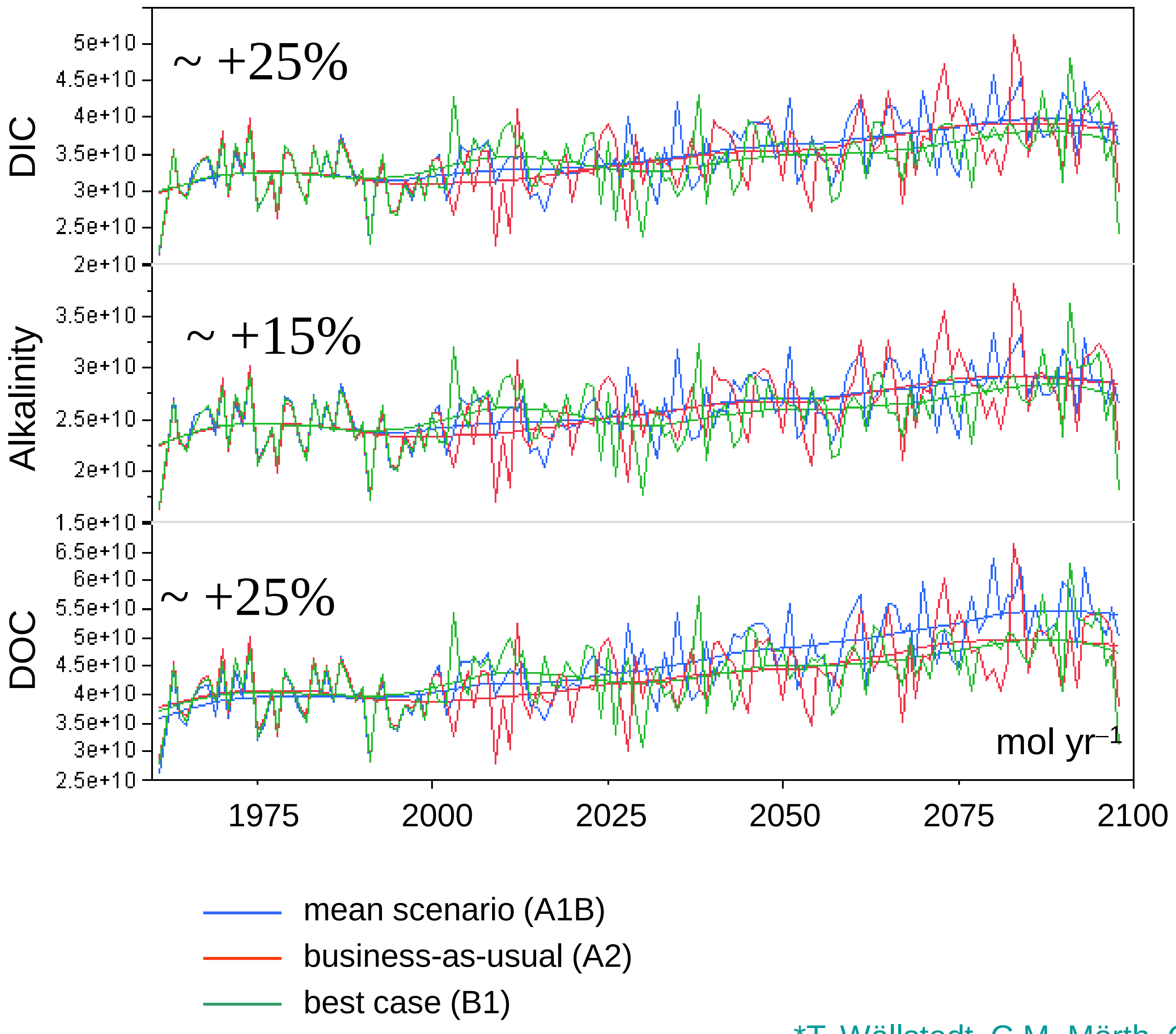




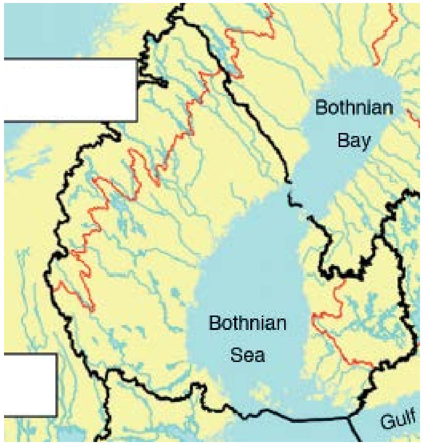


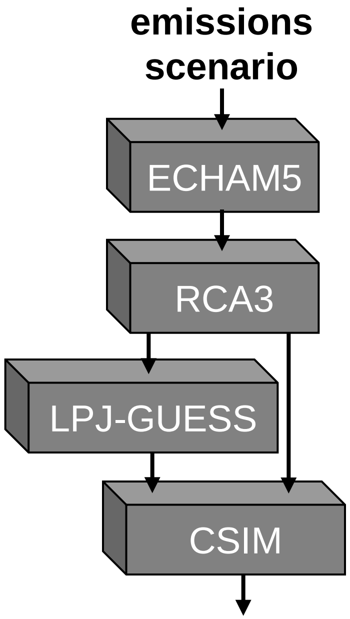
*T. Wällstedt, C.M. Mörth, C. Humborg et al. unpublished

Future climate scenarios



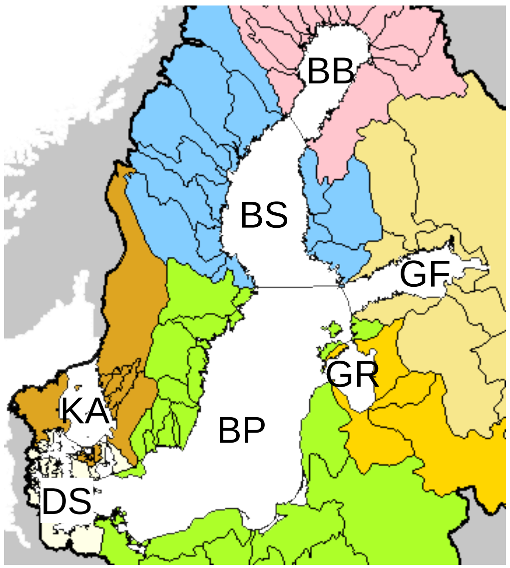
Runoff to Bothnian Sea



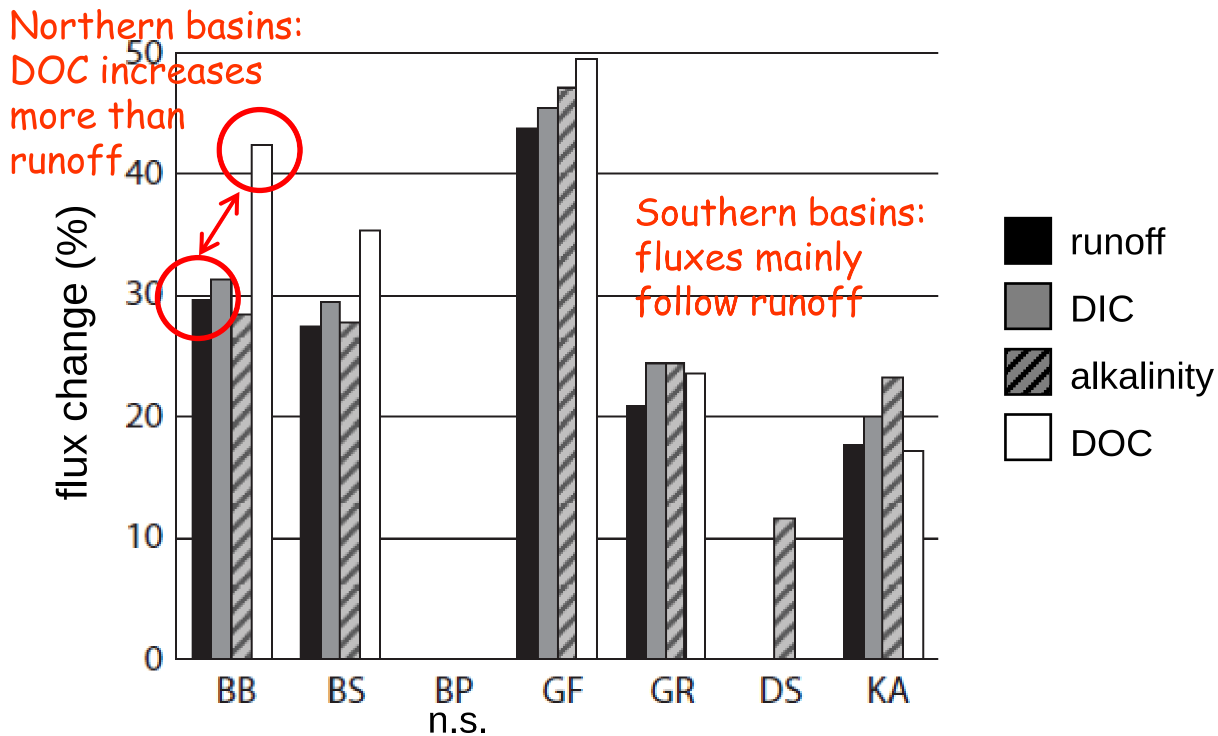


*T. Wällstedt, C.M. Mörth, C. Humborg et al. unpublished

Future impacts on biogeochemical export to the Baltic Sea*



Change in riverine export × sub-basin
(2069-2098)-(1996-2005)
business-as-usual (A2) scenario

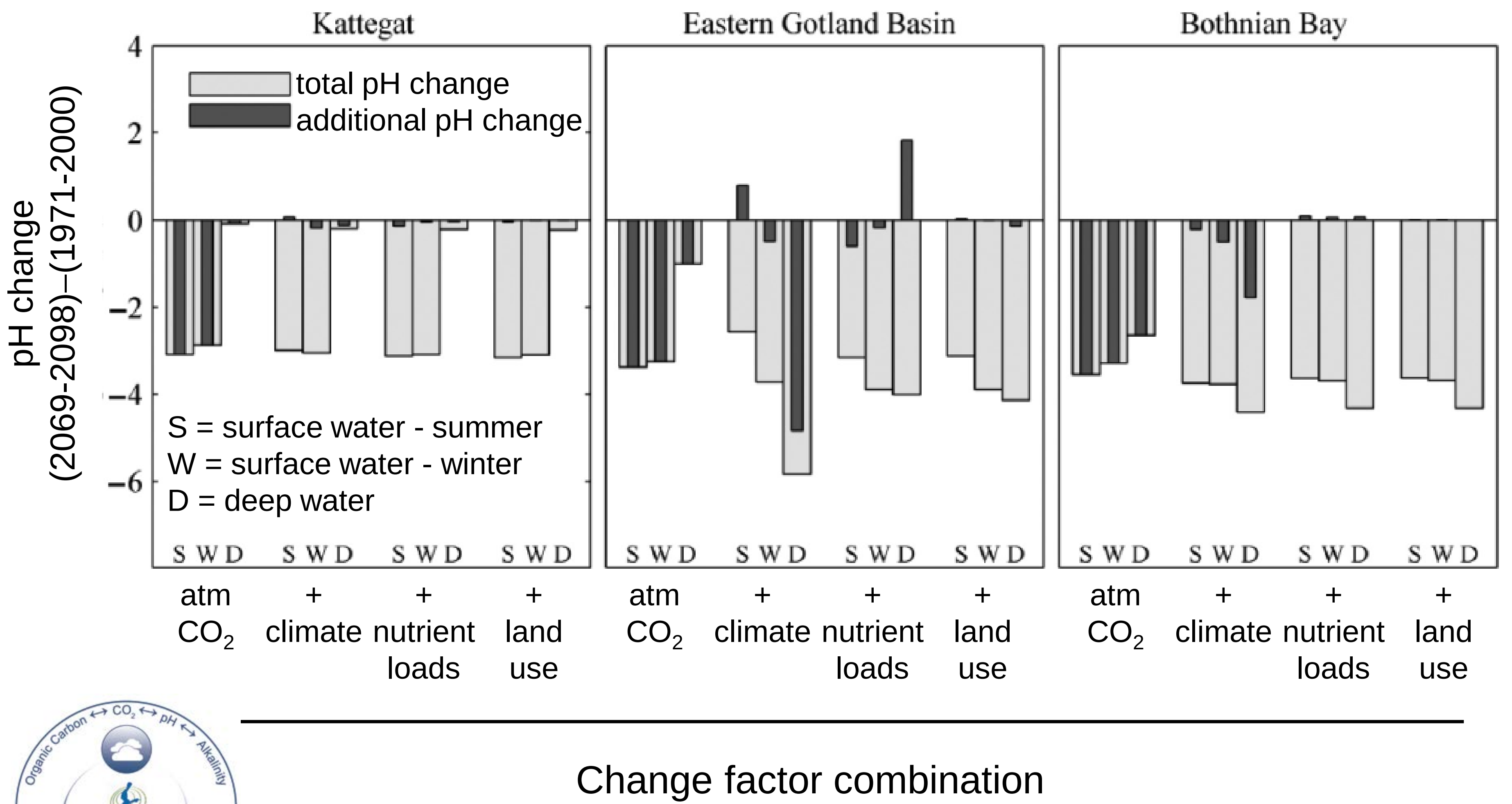


Baltic - C

*Omstedt et al. 2012
Tellus 64B: 19586

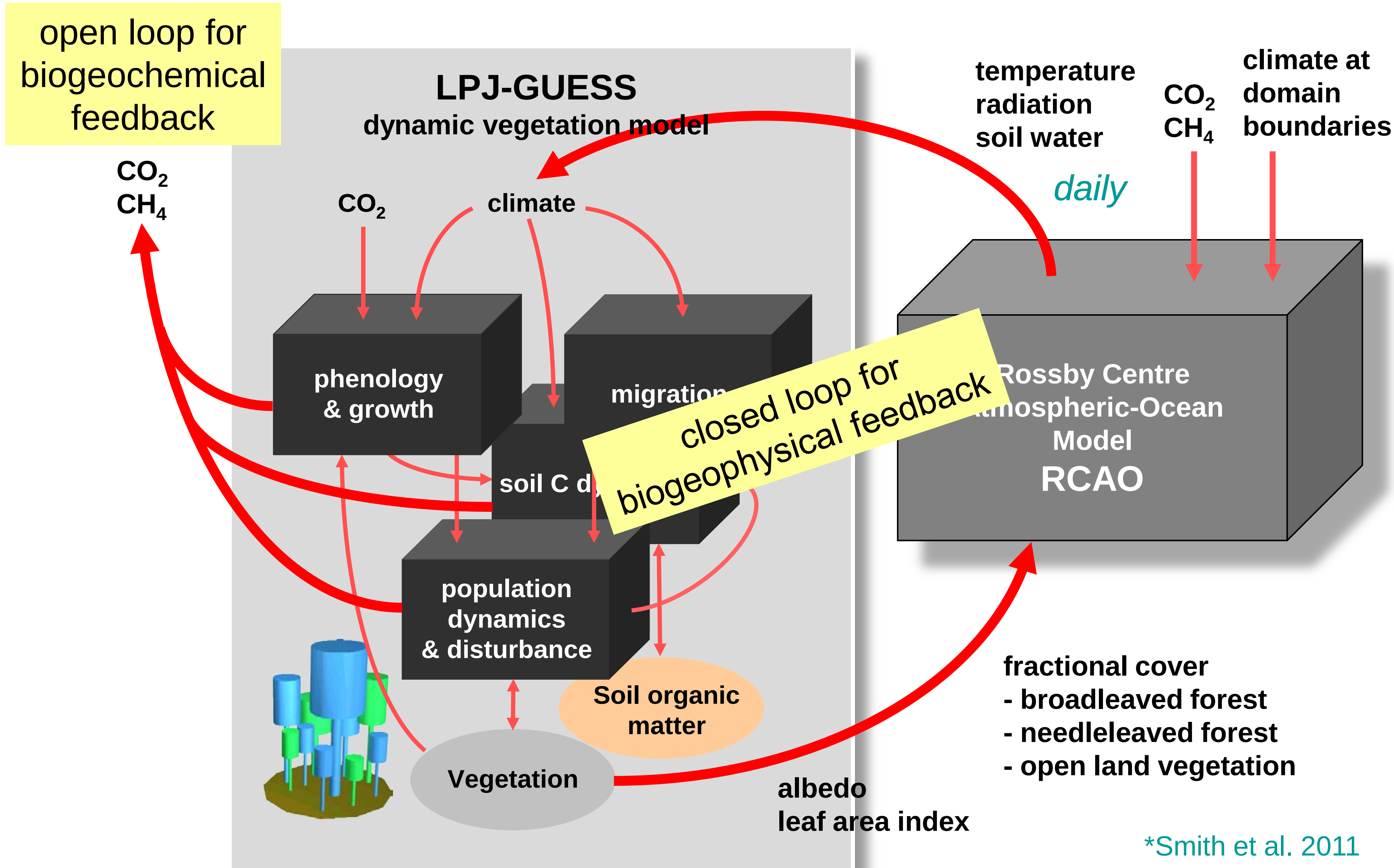
Simulated effects on seawater pH*

PROBE-Baltic oceanography-biogeochemistry model



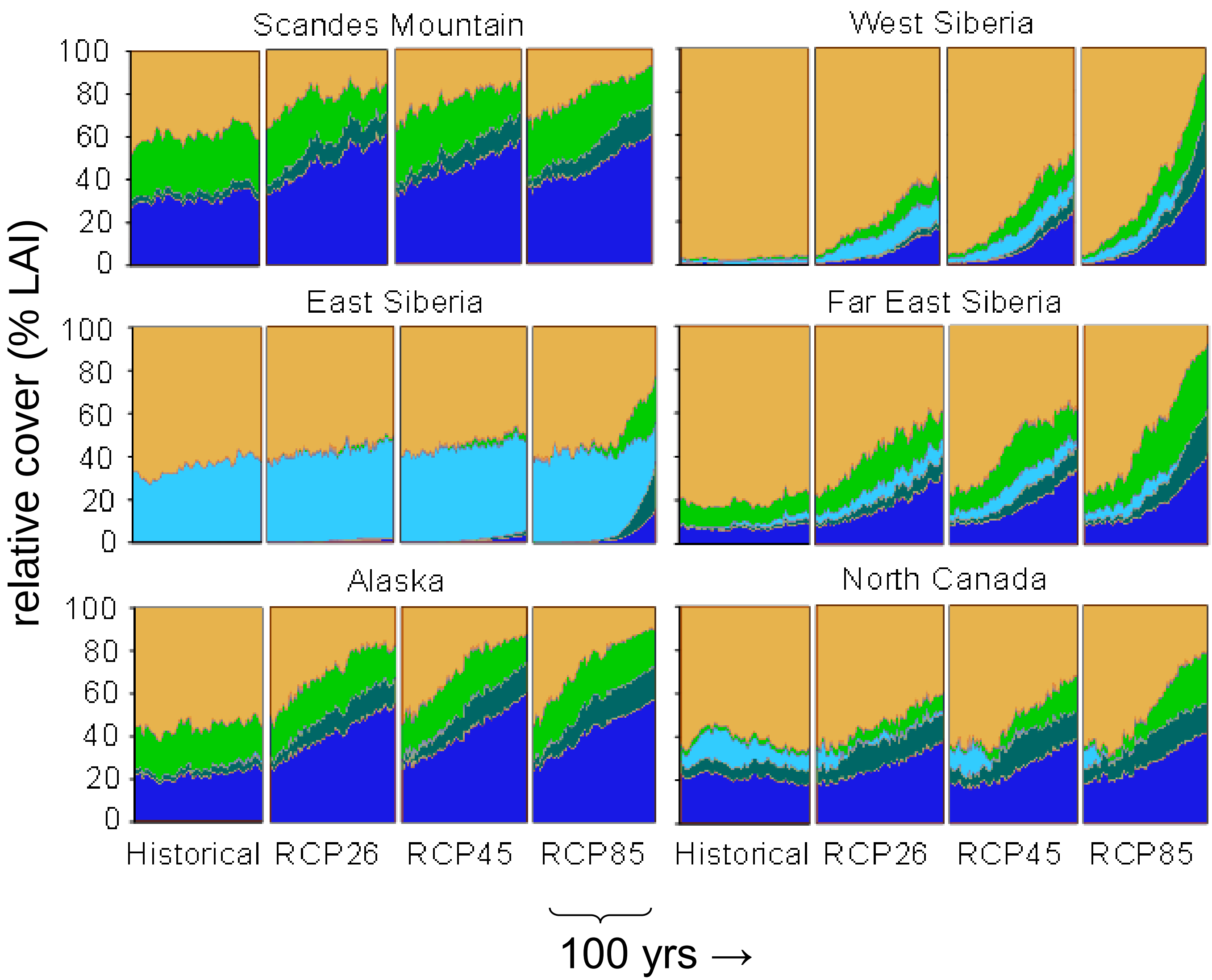
*Omstedt et al. 2012
Tellus 64B: 19586

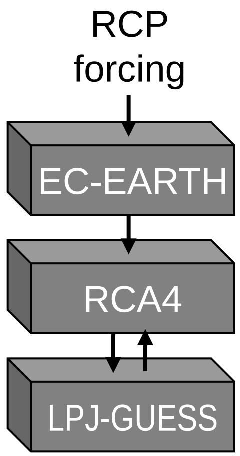
Future prospect: regional Earth system model coupling land-atmosphere-ocean*



*Smith et al. 2011
Tellus 63A: 87-106

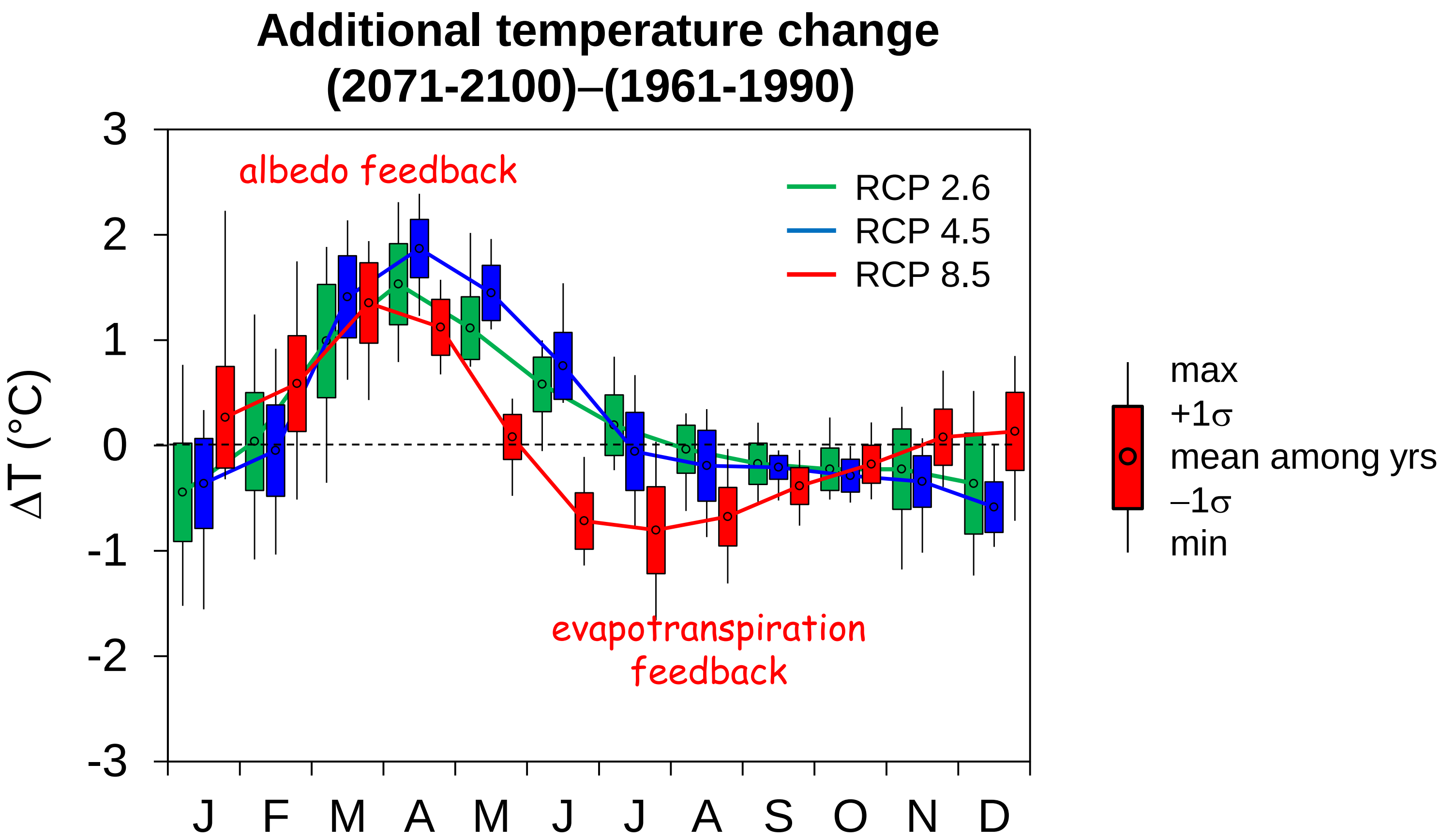
Vegetation change across the boreal zone and Arctic*





*W. Zhang et al.
in prep.

Albedo warming in spring, evapotranspiration cooling in summer

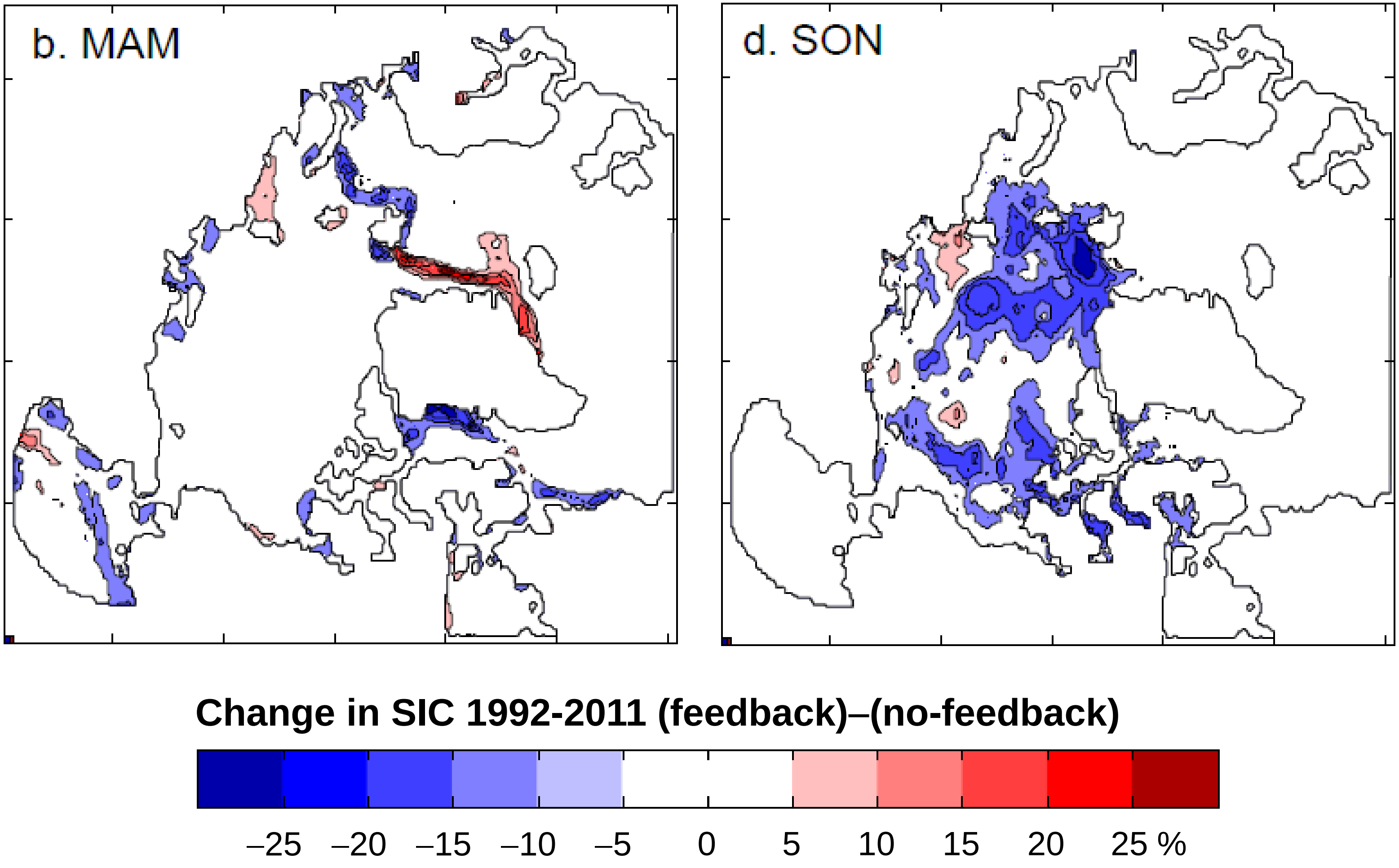


- Seasonality shift – longer growing season, earlier temperature peak
- Evaporative cooling evens out growing season temperature profile

  → favours further shrub encroachment and treeline advance

*W. Zhang et al. in prep.

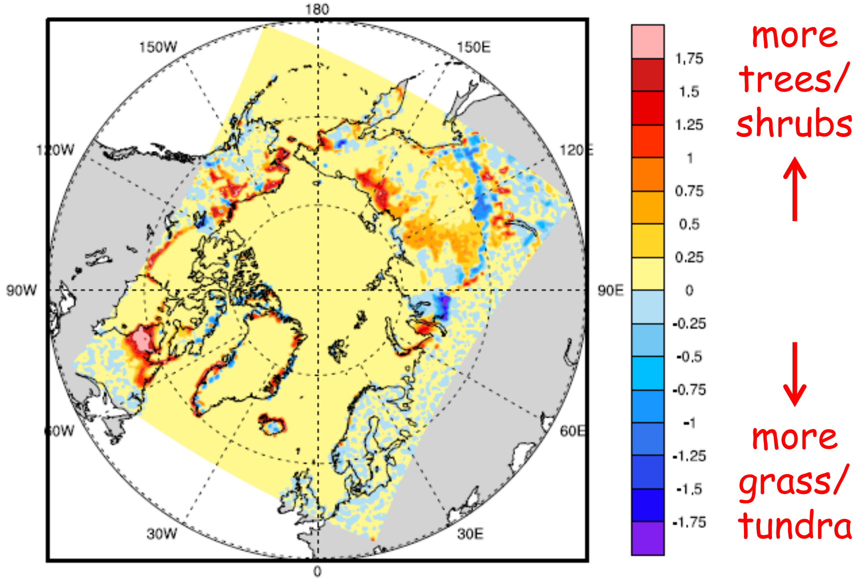
Vegetation-atmosphere feedback reduces sea ice cover*



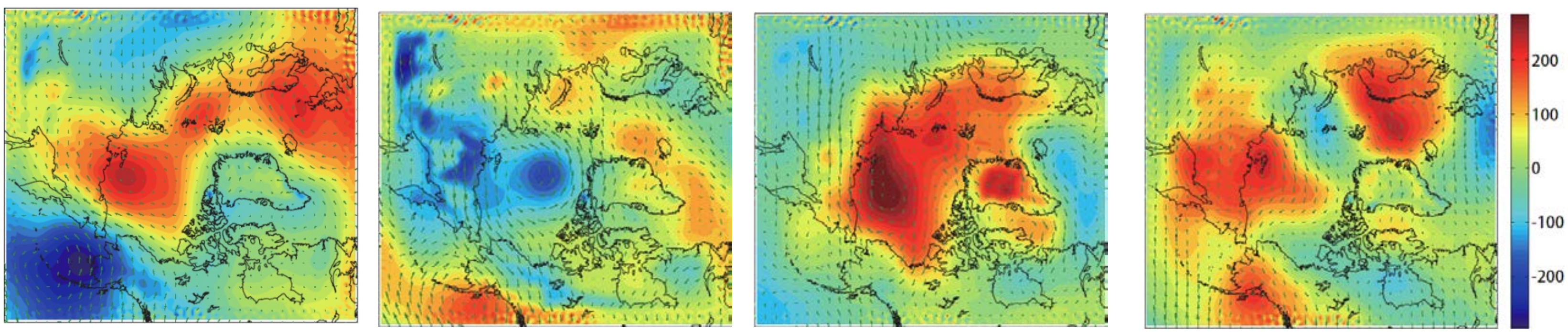
*W. Zhang et al. in prep.

Causality?

Veg.
change
(2007-11)
–(1992-96)

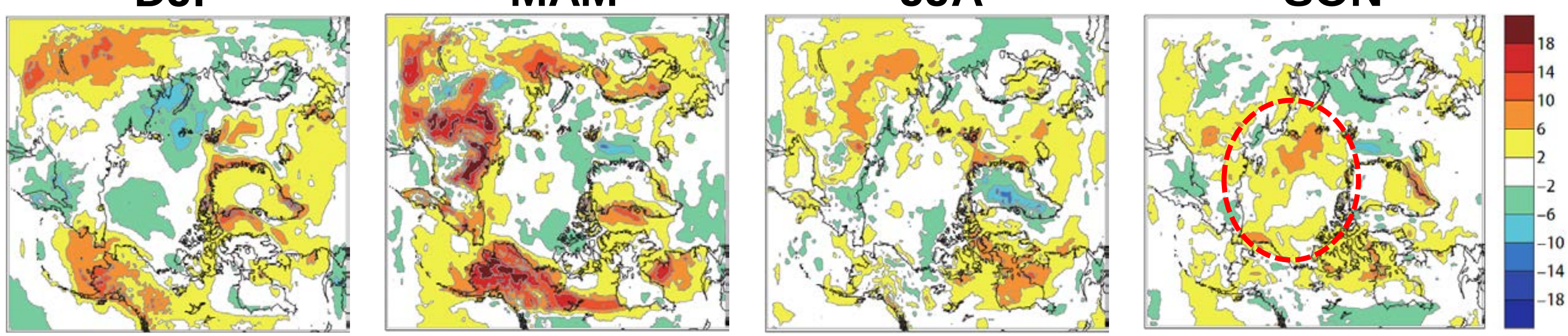


ΔSLP
(Pa)
(fb)–(no-fb)



DJF **MAM** **JJA** **SON**

ΔLR
(Wm^{-2})
(fb)–(no-fb)



Summary of main points

- Land, sea and atmosphere are part of the Earth system, coupled via biogeochemical (especially carbon), hydrological and energy fluxes. River runoff carbon fluxes are in the ballpark 10% of anthropogenic emissions.
- Vegetation patterns and ecosystem functions are changing in response to climate change and elevated CO_2
- Models that resolve processes at a wide range of scales are needed to describe potential future changes. DGVMs are built for this purpose.
- Increasing temperatures and CO_2 will likely lead to vegetation distributional shifts, effects on carbon cycling will vary by climate zone and uncertainties due to forcing are large.
- System models accounting for land-sea carbon exports and impacts on marine biogeochemistry are emerging. One example for the Baltic Sea suggests 21st Century changes in climate, vegetation and CO_2 concentrations will lead to lower pH in the Baltic Sea
- Regional Earth system models that fully couple land-sea-atmosphere matter and energy fluxes may be needed to resolve complex responses to multiple drivers