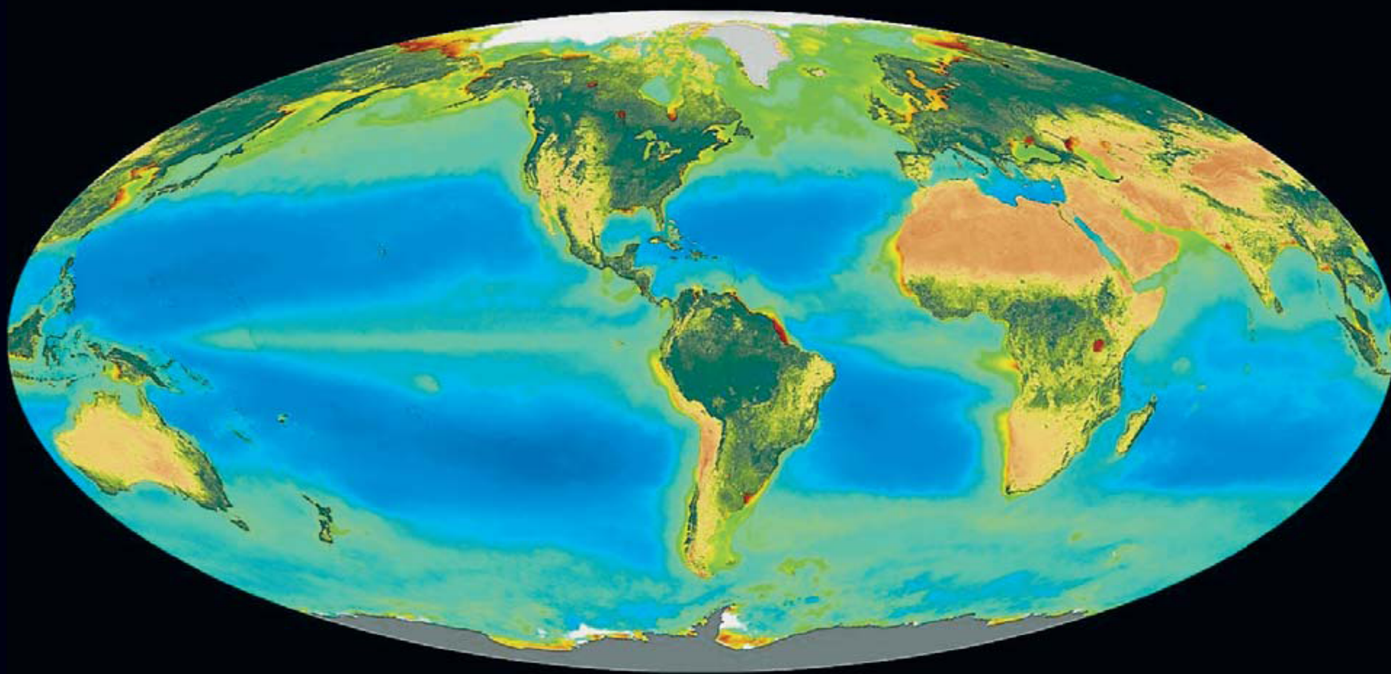
Carbon cycling in the land ocean atmosphere continuum

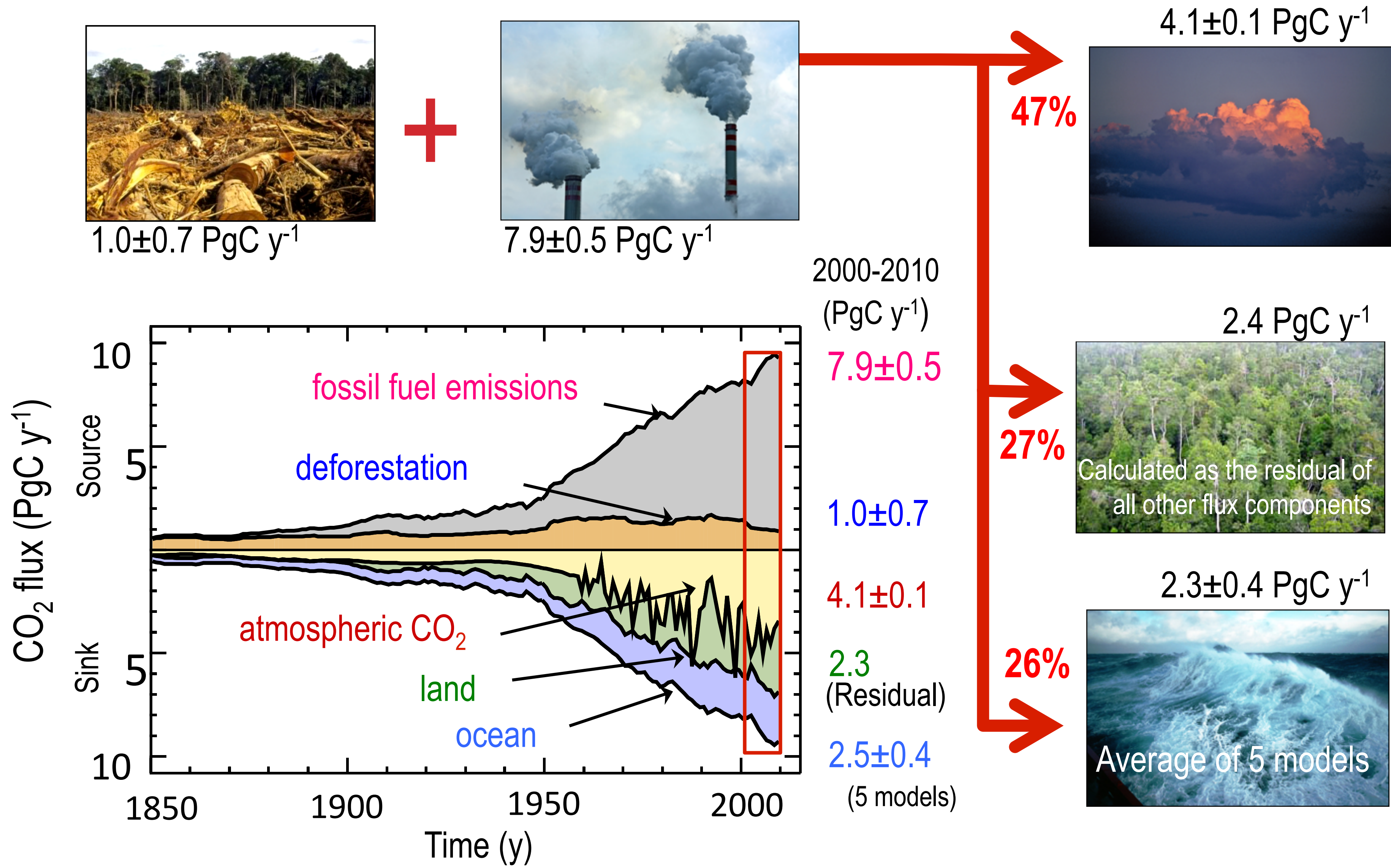


- B Guenet
- P. Regnier
- P. Raymond

- P. Friedlingstein
- F McKenzie
- N Gruber
- A. Andersson
- S. Arndt
- C. Arnosti
- A. Borges
- A. Dale
- A. Gallego-Sala
- Y. Goddéris
- F. Joos
- T. Ilyina
- J. Hartmann
- C. Heinze
- I. Janssens
- G. Laruelle
- D. LaRowe
- J. Leifeld
- R. Lauerwald
- S. Luyssaert
- F. Meysman
- G. Munhoven
- R. Spahni
- P. Suntharalingam
- M. Thullner

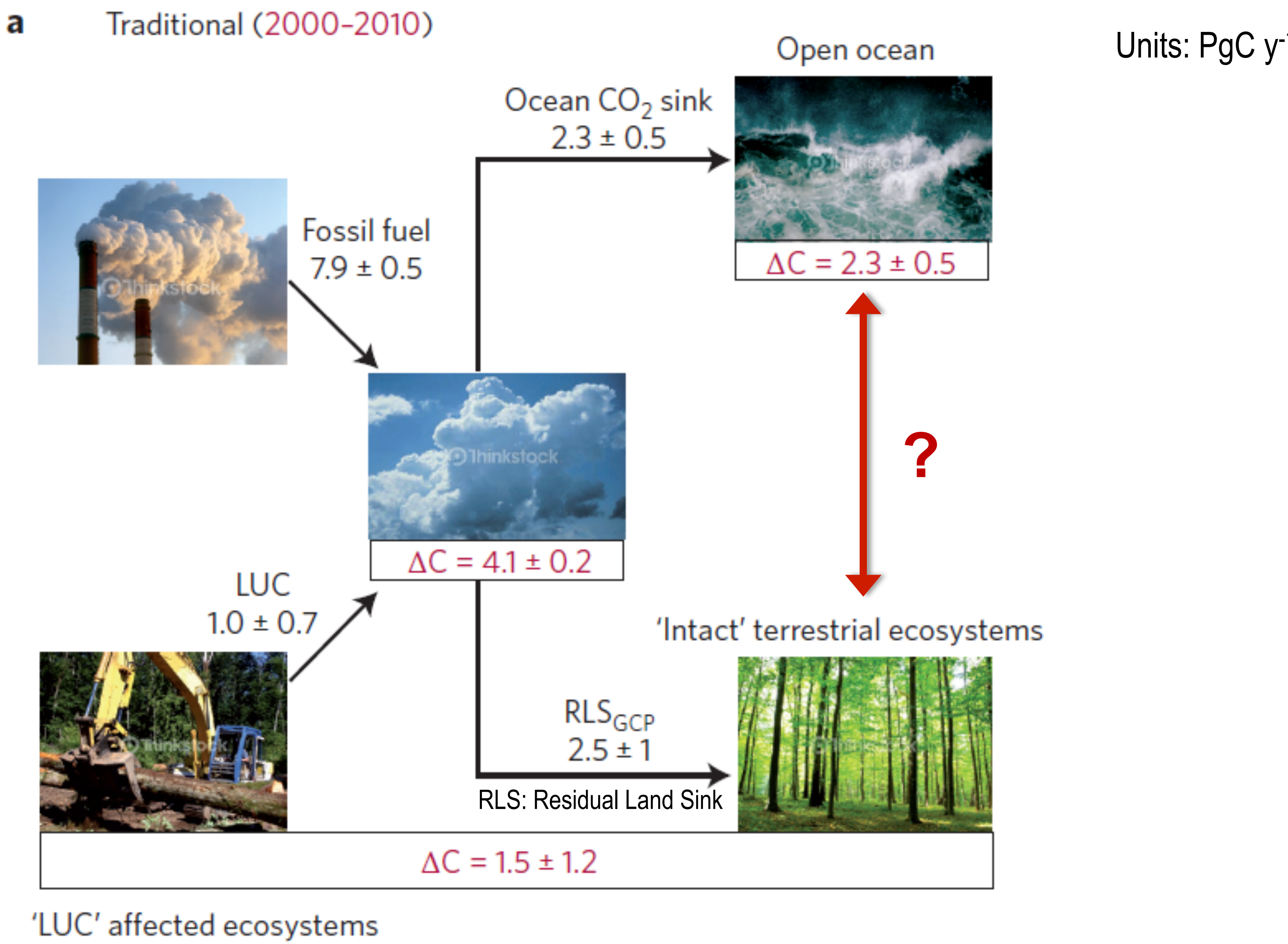
Philippe Ciais
LSCE, Gif sur Yvette, France

Fate of Anthropogenic CO_2 Emissions



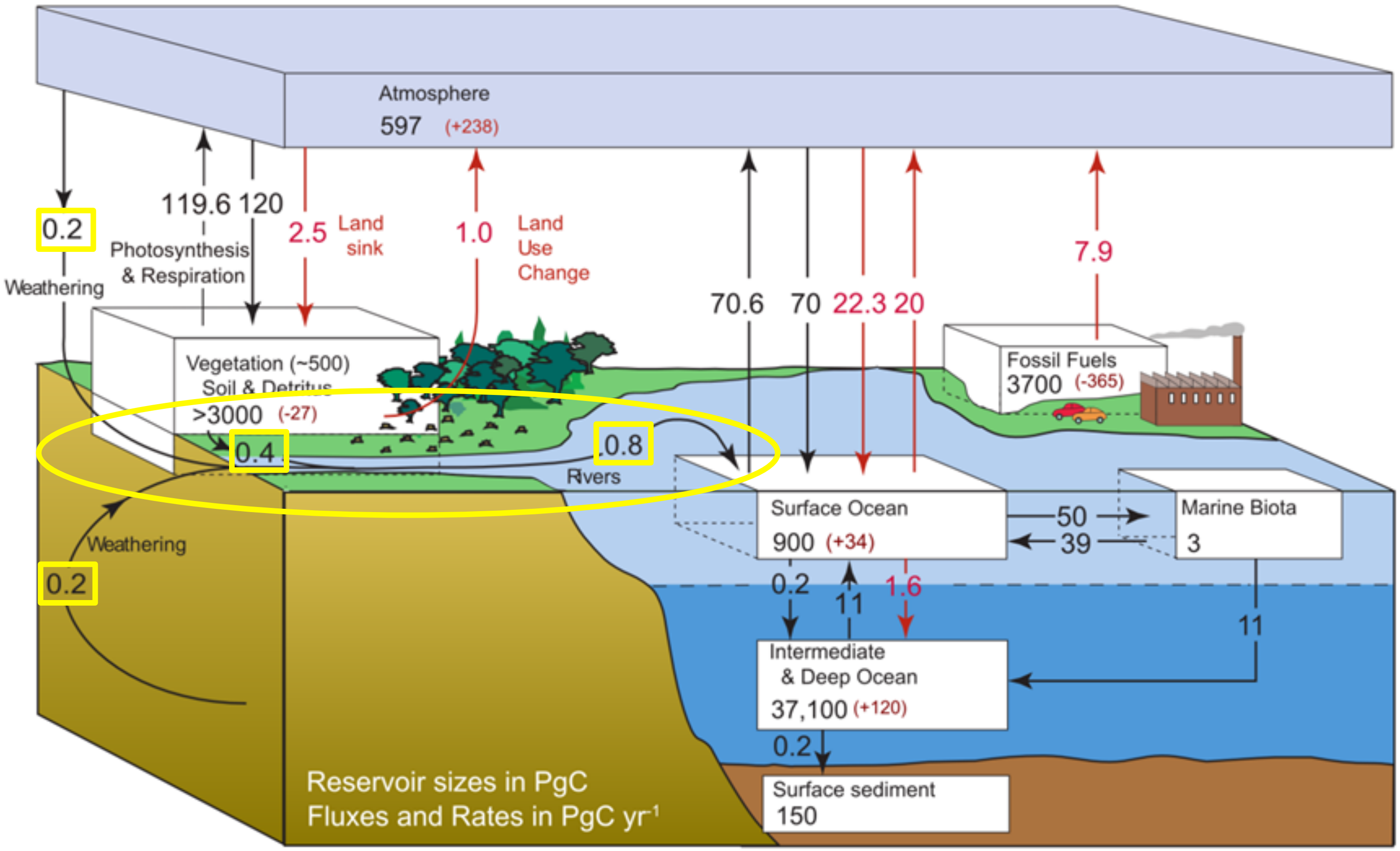
Global Carbon Project 2010; Updated from Le Quéré et al. 2009, Nature Geoscience; Canadell et al. 2007, PNAS

The GCP carbon budget (IPCC)



Regnier et al, Nature Geoscience, 2013

The present-day global C cycle (IPCC AR4)



Natural fluxes

Anthropogenic perturbation

Land-ocean fluxes

Modified from N. Gruber; pers. com

A new C budget for inland waters

commentary

The boundless carbon cycle

Tom J. Battin, Sebastiaan Luyssaert, Louis A. Kaplan, Anthony K. Aufdenkampe, Andreas Richter and Lars J. Tranvik

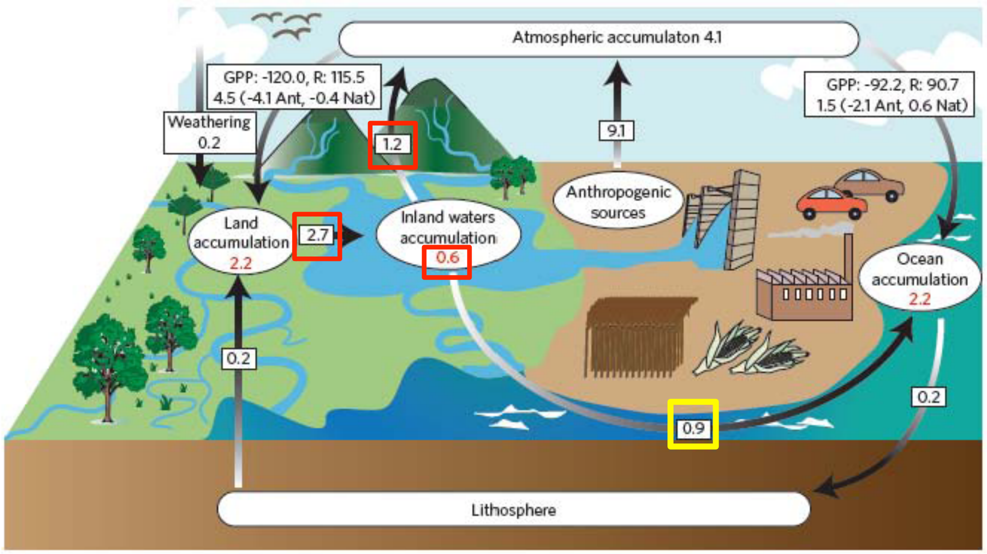


Figure 1 | The 'boundless carbon cycle'. The schematic highlights carbon fluxes through inland waters[5], and also includes pre-industrial[2] and anthropogenic[3] fluxes. Values are net fluxes between pools (black) or rates of change within pools (red); units are Pg C yr^{-1}; negative signs indicate a sink from the atmosphere. Gross fluxes from the atmosphere to land and oceans, and the natural (Nat) and anthropogenic (Ant) components of net primary production — the net uptake of carbon by photosynthetic organisms — are shown for land and oceans. Gross primary production (GPP) and ecosystem respiration (R) are poorly constrained[18,19]; we therefore modified respiration to close the carbon balance. Non-biological dissolution of anthropogenic carbon dioxide by the oceans is included in these fluxes[2]. Fluxes to the lithosphere represent deposition to stable sedimentary basins, and the flux from the lithosphere to land represents erosion of uplifted sedimentary rocks[2].

suggest that inland waters transport, mineralize and bury ~2.7 Pg C yr^{-1} (ref. 5; Fig. 1). This is similar to the size of the terrestrial carbon sink for anthropogenic emissions of 2.8 Pg C yr^{-1} (ref. 3).

NATURE GEOSCIENCE | VOL 2 | SEPTEMBER 2009

Present-day fluxes versus anthropogenic perturbation

BREVIA

Freshwater Methane Emissions Offset the Continental Carbon Sink

David Bastviken,[1*] Lars J. Tranvik,[2] John A. Downing,[3] Patrick M. Crill,[4] Alex Enrich-Prast[5]

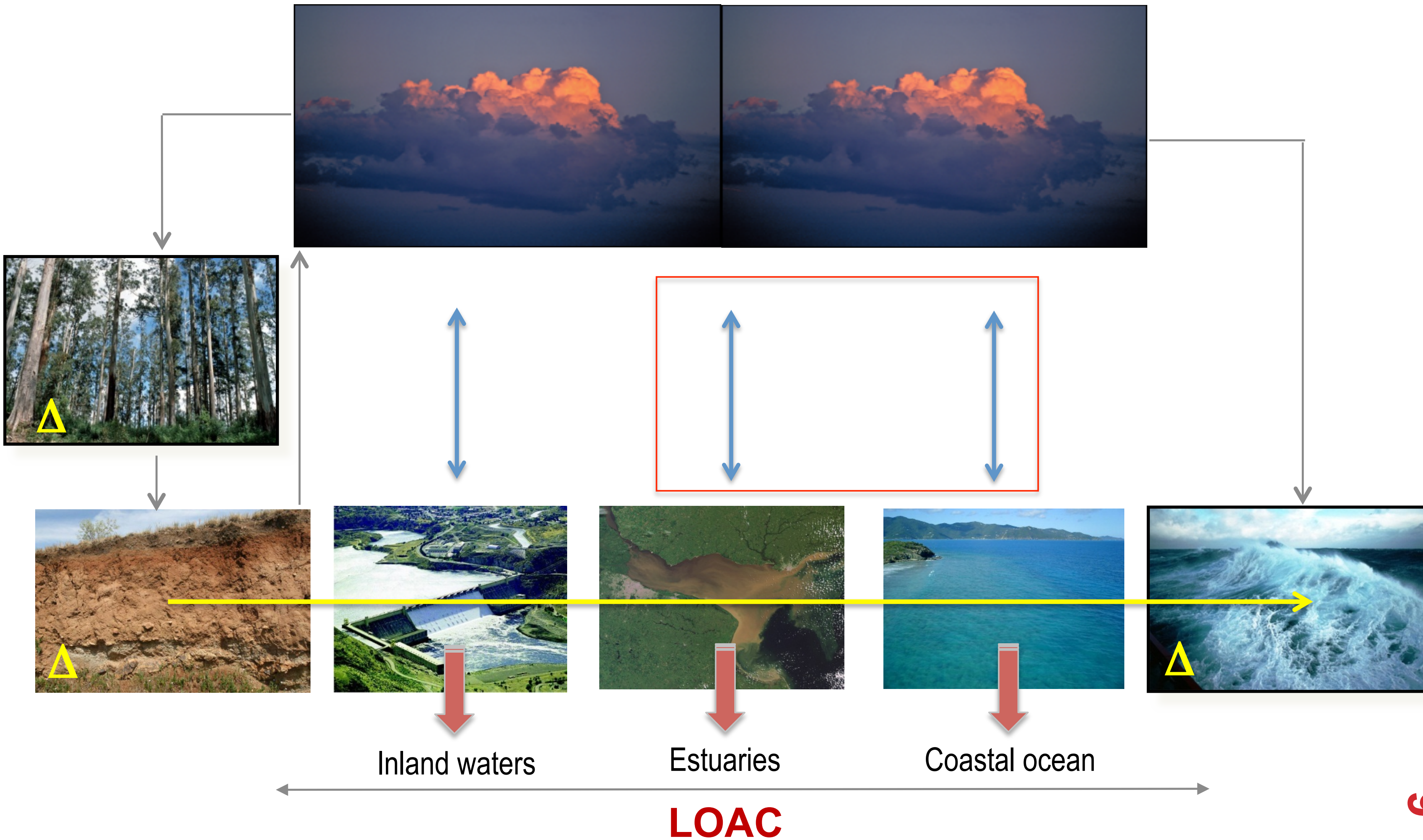
A cornerstone of our understanding of the contemporary global carbon cycle is that the terrestrial land surface is an important greenhouse gas (GHG) sink (*1*, *2*). The global land sink is estimated to be 2.6 ± 1.7 Pg of C $year^{-1}$ (variability ± range, excluding C emissions because of deforestation) (*1*). Lakes, impoundments, and rivers are parts of the terrestrial landscape, but they have not yet been included in the terrestrial GHG balance (*3*, *4*). Available data suggest, however, that freshwaters can be substantial sources of CO_2 (*3*, *5*) and CH_4 (*6*). Over time,

over century time scales. This study indicates that global CH_4 emissions expressed as CO_2 equivalents correspond to at least 25% of the estimated terrestrial GHG sink.

7 JANUARY 2011 VOL 331 SCIENCE

Closing the global C budget:

The land-ocean aquatic continuum (LOAC)



CO_2 flux estimates: air-estuary & air-coastal ocean

Present-day

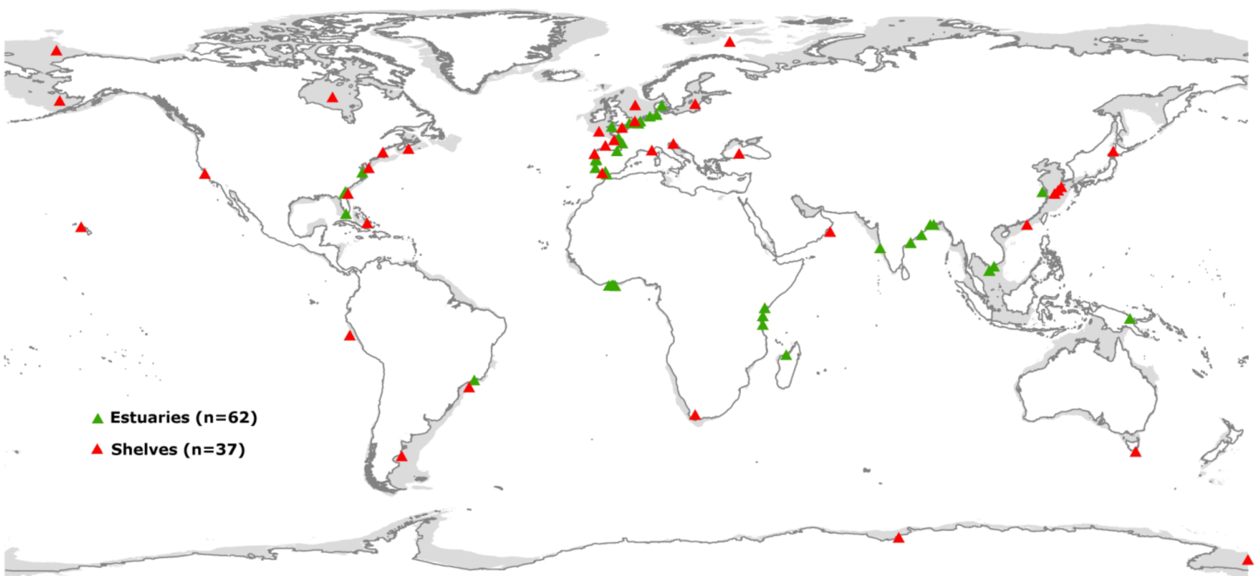
Estuaries

CO_2 flux ($PgC\ yr^{-1}$)	Reference
0.38	Borges (2005)
0.40	Borges et al. (2005)
0.50*	Chen and Borges (2009)
0.27	**Laruelle et al. (2010)**
0.25	Cai (2011)

* Including Salt marshes and Mangroves

Continental Shelves

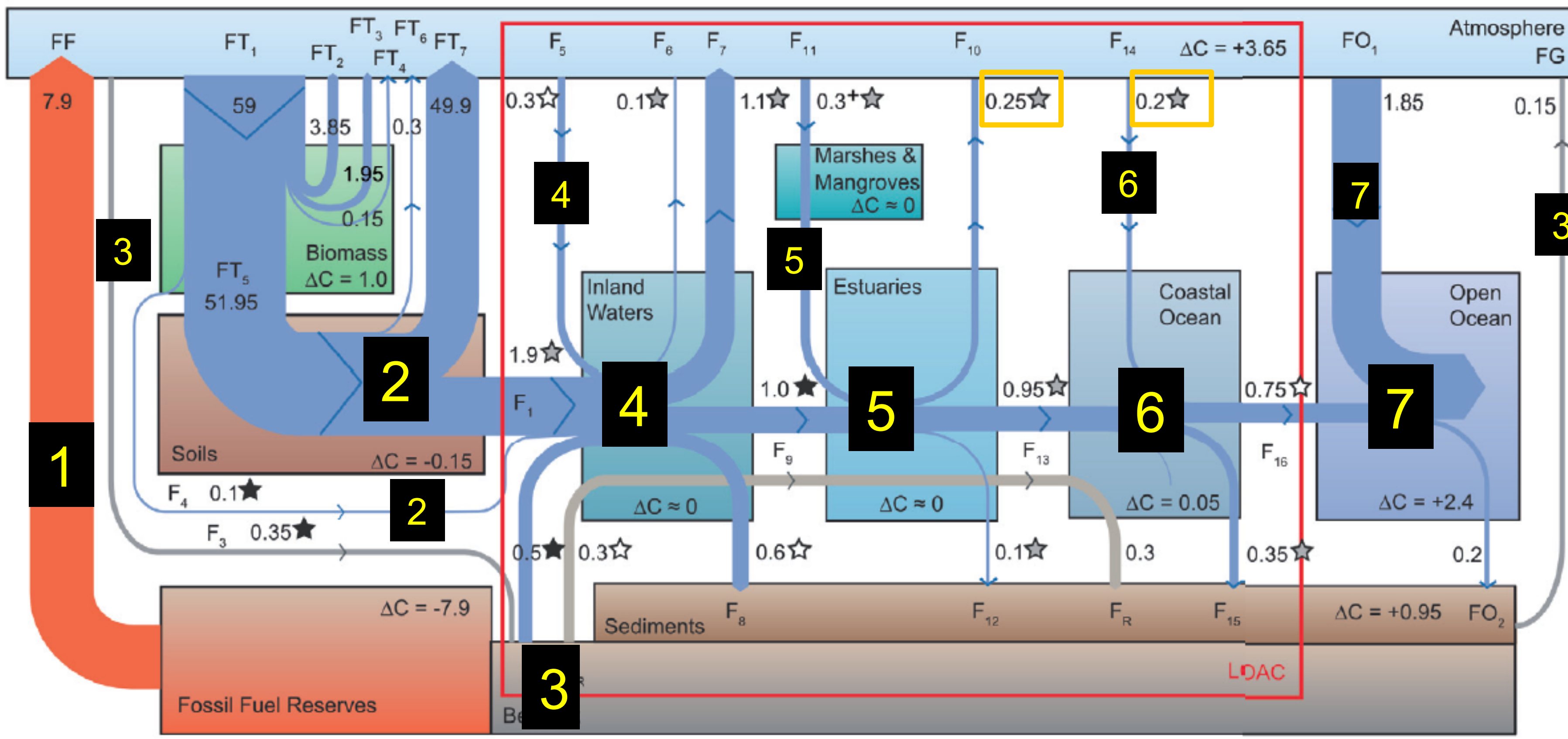
CO_2 flux ($PgC\ yr^{-1}$)	Reference
-0.95	Tsunogai et al. (1999)
-0.40	Thomas et al. (2004)
-0.37	Borges (2005)
-0.45	Borges et al. (2005)
-0.22	Cai et al. (2006)
-0.34	Chen and Borges (2009)
-0.22	**Laruelle et al. (2010)**
-0.24	Cai (2011)
-0.18	Wanninkhof et al. (2012)



Estuaries: 0.25 $PgC\ yr^{-1}$

Shelves: -0.2 $PgC\ yr^{-1}$

The carbon budget for the land-ocean continuum

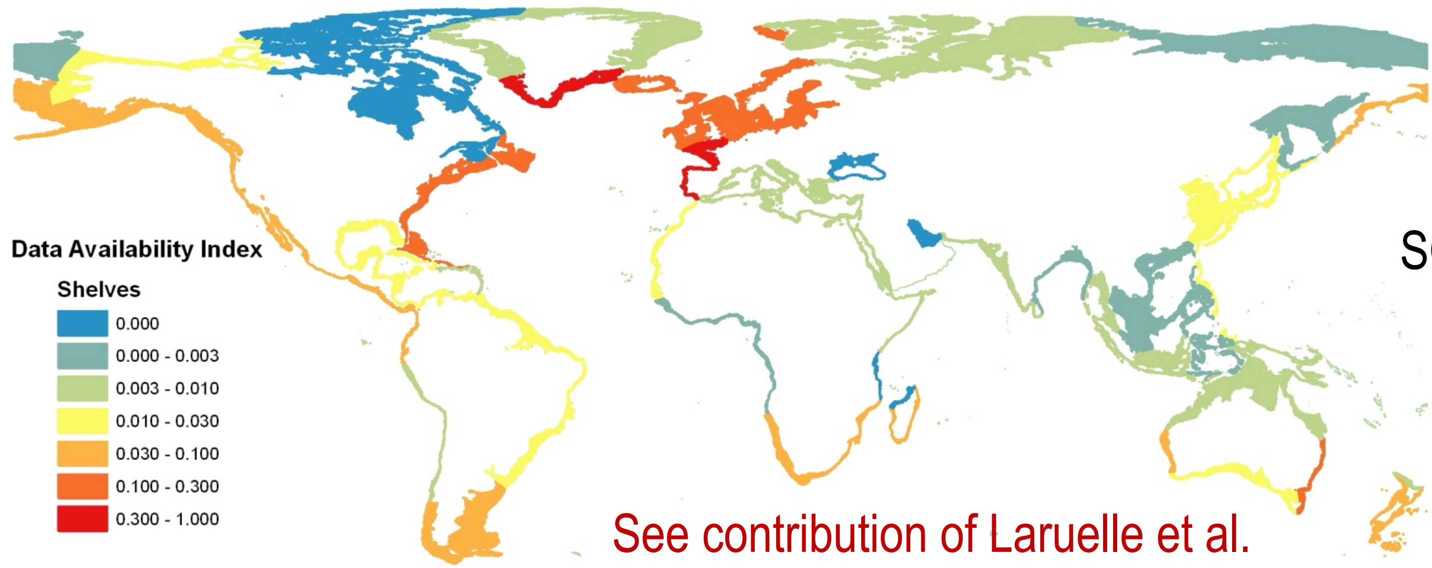


The stars in panel **a** indicate the confidence interval associated to the flux estimates, based on *The First State of the Carbon Cycle Report*[99]. A black star means 95% certainty that the actual estimate is within 50% of the estimate reported; a grey star means 95% certainty that the actual value is within 100% of the estimate reported; a white star corresponds to an uncertainty greater than 100%.

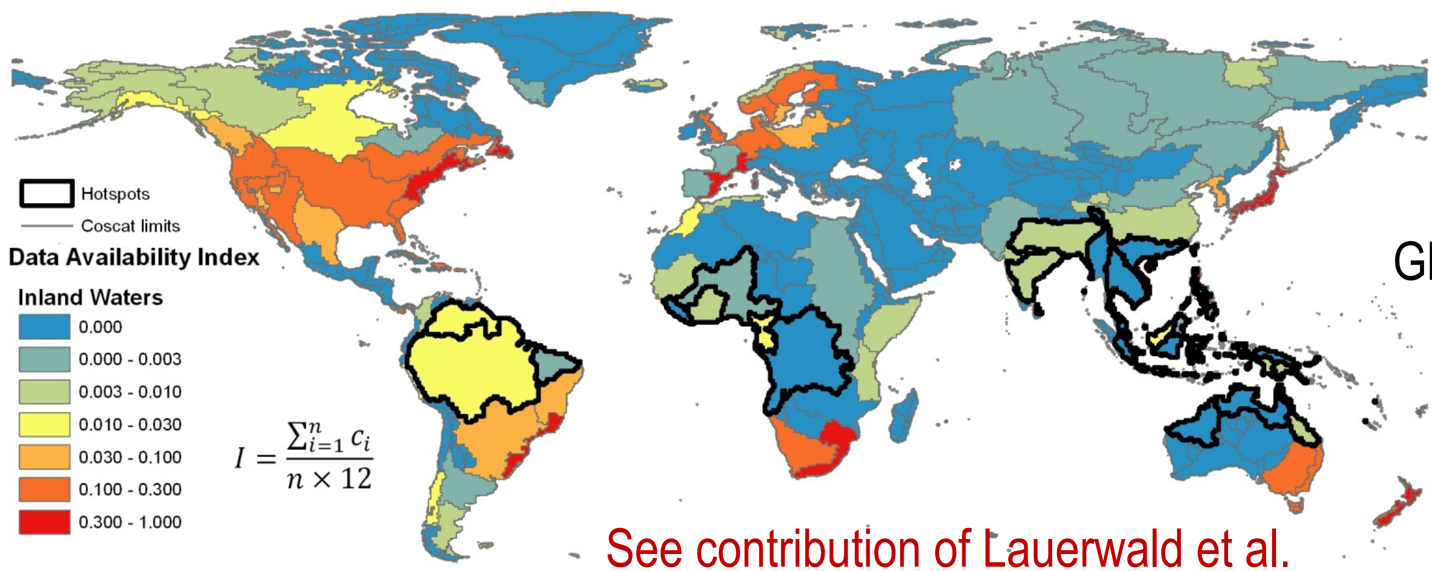
Present-day

Regnier et al, Nature Geoscience, 2013

CO_2 data coverage for the LOAC



SOCAT



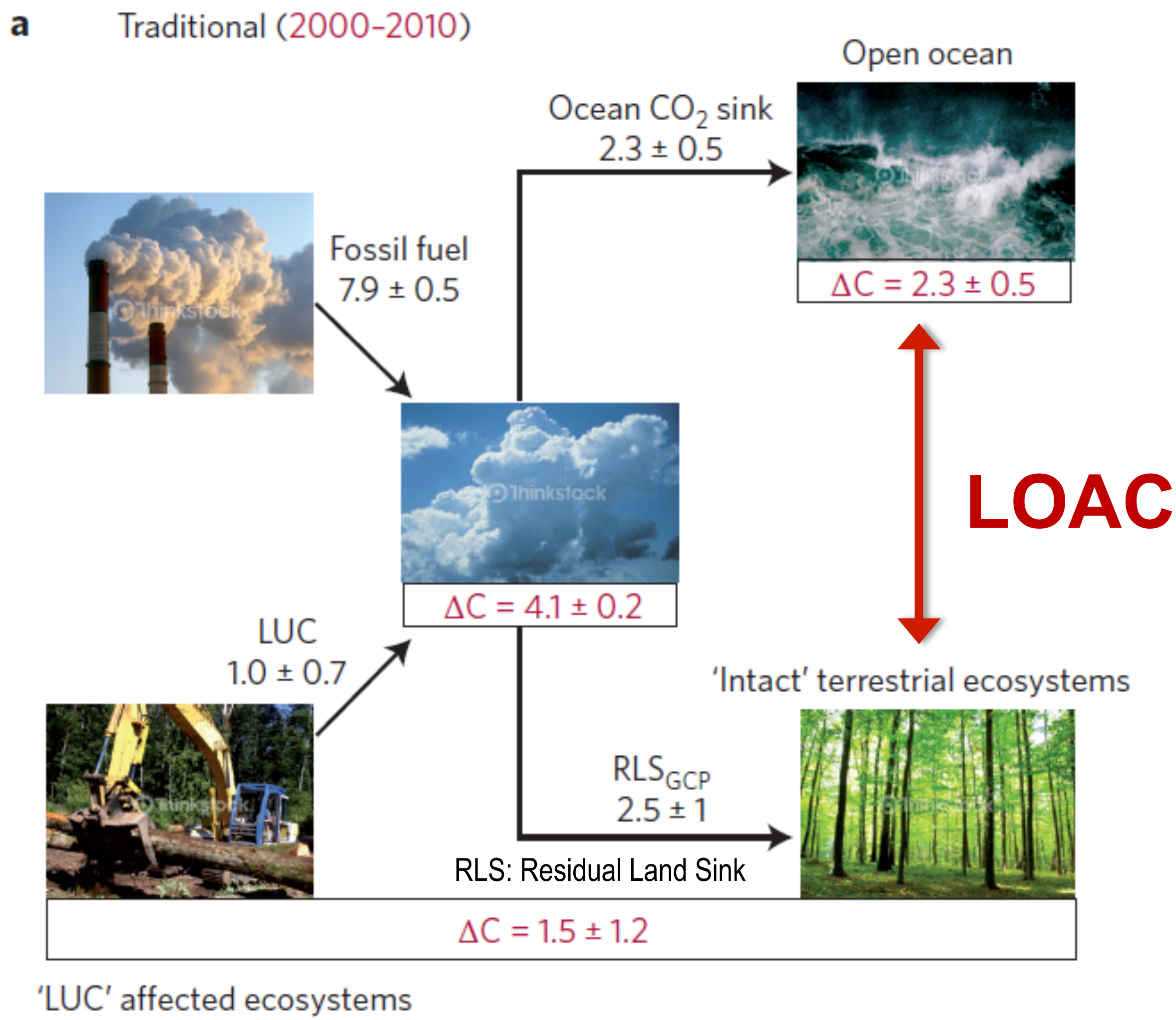
GLORICH

Regnier et al., Nature Geoscience, 2013; Laruelle et al., HESS, 2013

Closing the anthropogenic C budget:

The land-ocean aquatic continuum (LOAC)

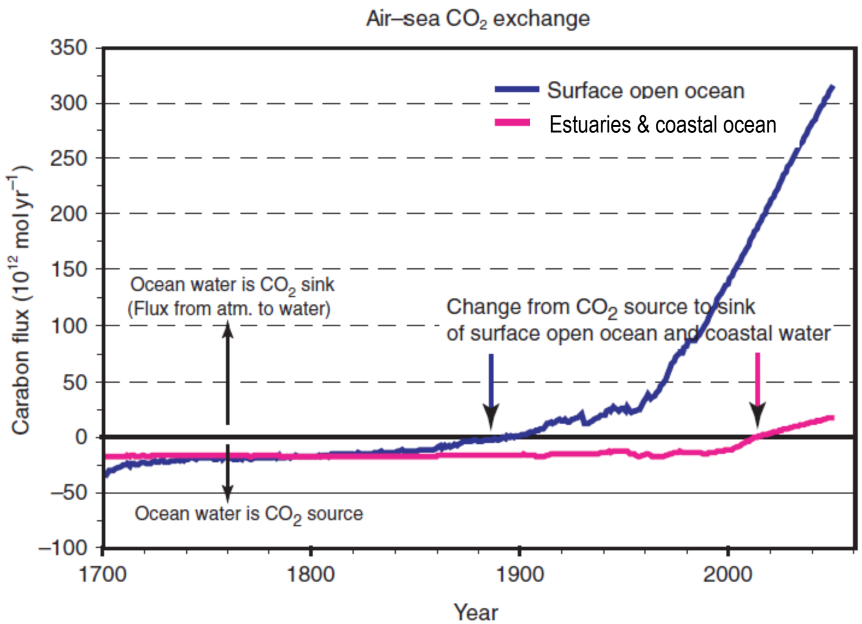
Units: PgC y^{-1}



Regnier et al, Nature Geoscience, 2013

Example: Coastal ocean CO_2 fluxes

Change between present-day and 'pre-industrial' (1750) deduced from box model simulations



~0.2 PgC yr^{-1}

Estuaries & coastal ocean

Mackenzie, F.T., De Carlo, E.H. & Lerman, A. Coupled C, N, P, and O Biogeochemical Cycling at the Land-Ocean Interface, in: Treatise on Estuarine and Coastal Science, Chapter 5.10, Elsevier, 2012.

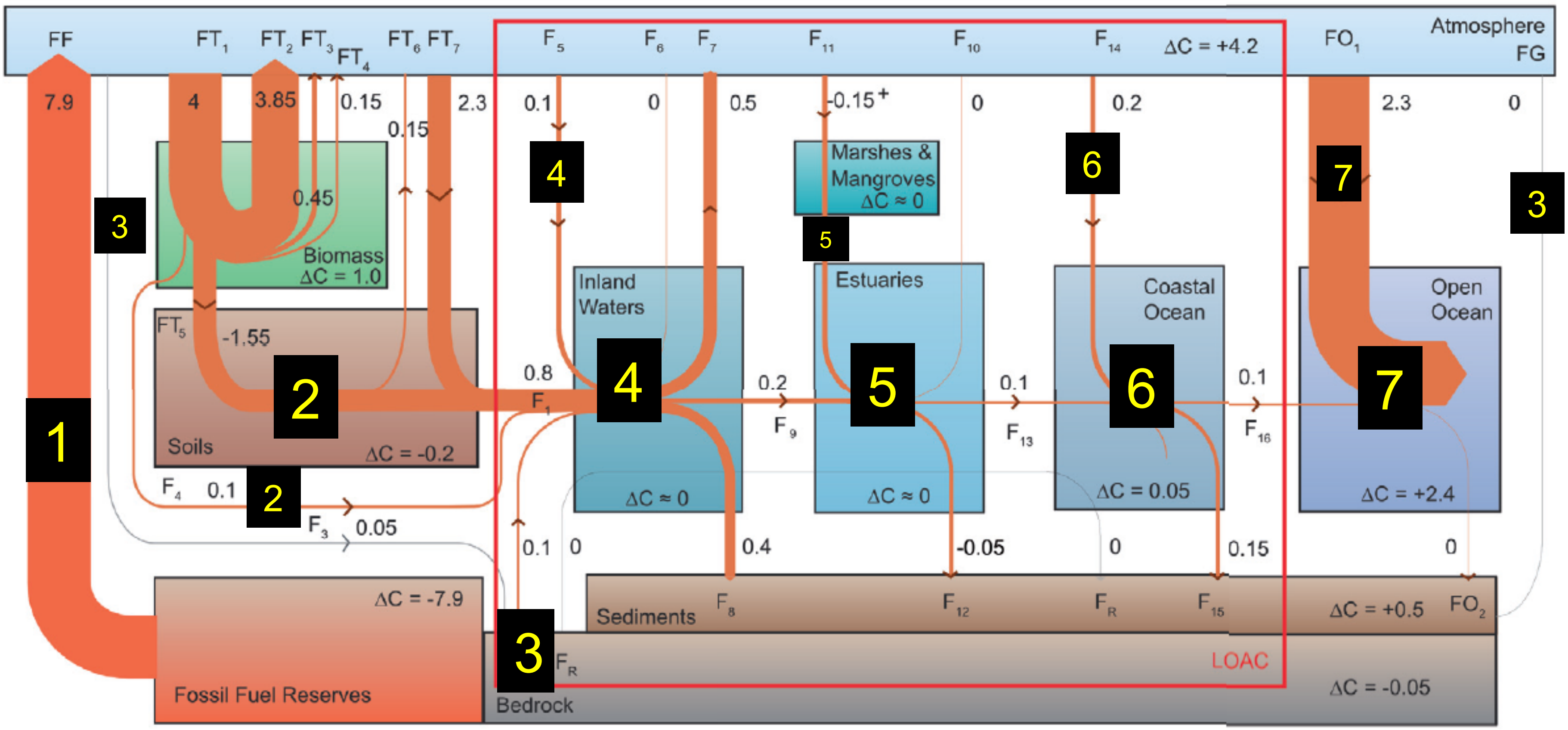
- Jin et al., 2008; Gruber & Galloway, 2008: **0.1 PgC yr^{-1}**

- Liu et al., 2010: Anthropogenic perturbation of **0.5 PgC yr^{-1}**

Liu K.-K. et al. (eds.), Carbon and Nutrient Fluxes in Continental Margins, Global Change – The IGBP Series, 3, Springer-Verlag Berlin Heidelberg, doi:10.1007/978-3-540-92735-8 1, (2010).

c ANTHROPOGENIC PERTURBATION

Regnier et al, Nature Geoscience, 2013

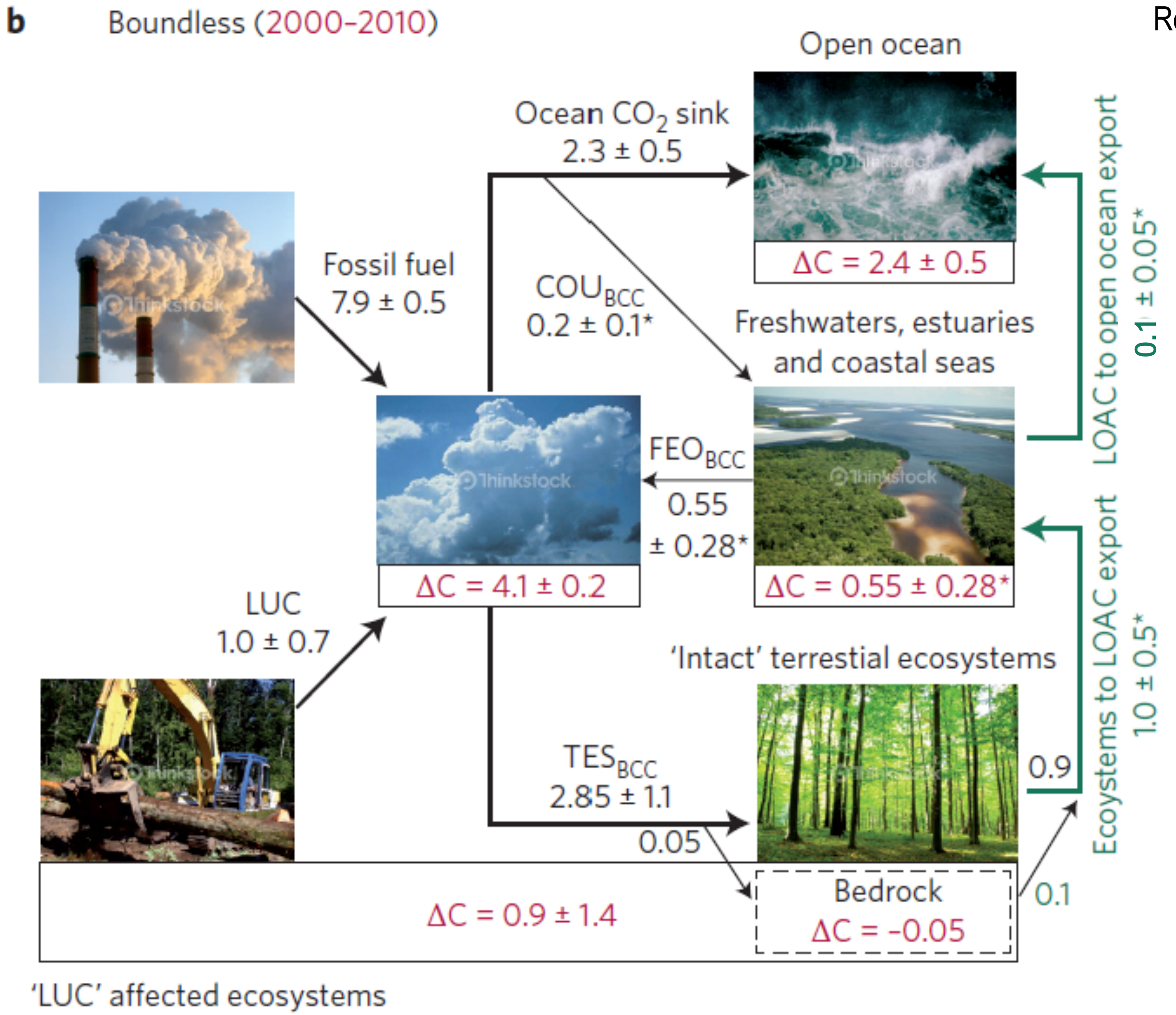


F_{14}	Atmospheric CO_2 uptake by coastal waters
F_{15}	Total C burial in coastal ocean sediments
F_{16}	Total C export from the coastal to the open ocean
FO_1	Air-sea CO_2 flux in the open ocean
FO_2	Total C burial in open ocean sediments

Perturbation

The anthropogenic CO_2 budget with the LOAC

Regnier et al, Nature Geoscience, 2013



Units: PgC y^{-1}

FEO: Freshwater & Estuary Outgassing
COU: Coastal Ocean Uptake
TES: Terrestrial Ecosystem Sink

Uncertainties on fluxes are from the GCP, except for the LOAC fluxes (identified by an asterisk) where indicative estimates are given based on the categorization proposed in *The First State of the Carbon Cycle Report* (converted to values assuming Gaussian distribution)

Conclusions

- Substantial amounts (2.5 PgC yr^{-1}) of atmospheric carbon are transported laterally along the land-ocean aquatic continuum (LOAC) from upland terrestrial ecosystems into the ocean

- **The anthropogenic perturbation may have increased the flux of C to the LOAC by as much as 1 PgC yr^{-1}.**

- Most of this additional carbon input to upstream rivers is emitted back to the atmosphere as CO_2 (0.55 PgC yr^{-1}) or sequestered in sediments along the aquatic continuum (0.55 PgC yr^{-1}), leaving a small perturbation carbon input (0.1 PgC yr^{-1}) to the open ocean.

Conclusions

- **According to our analysis, terrestrial ecosystems store ~0.9 Pg C yr^{-1} at present, which is in agreement with results from forest inventories (Pan et al, Science, 2011), but significantly less than the 1.5 Pg C yr^{-1} previously estimated when land carbon storage is calculated as a "residual" ignoring changes in lateral carbon fluxes**

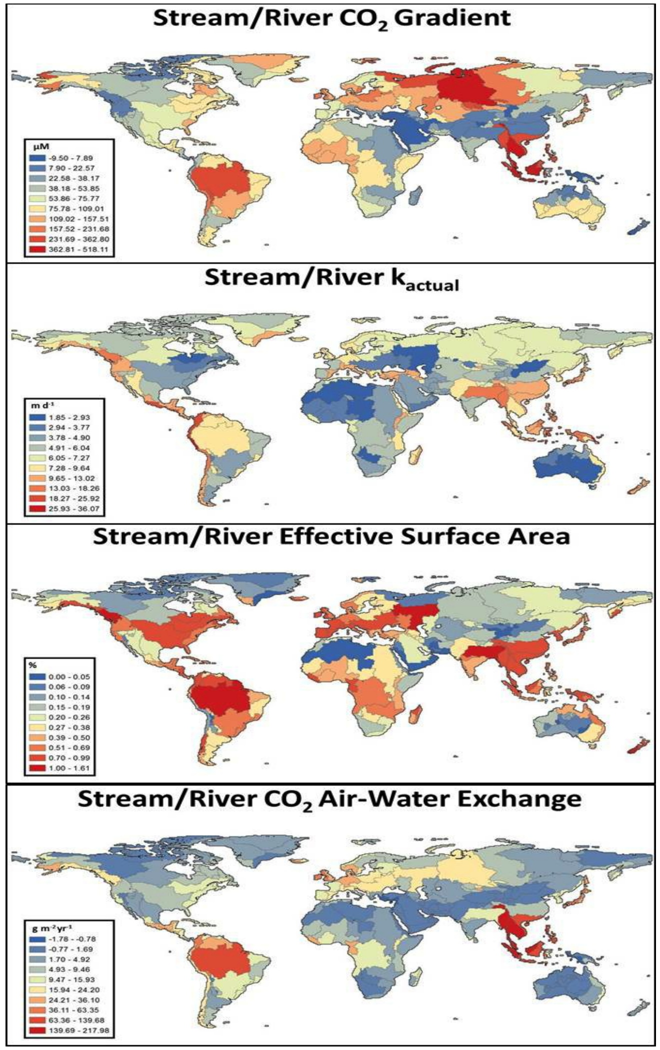
- Carbon fluxes along the land–ocean aquatic continuum need to be included in global carbon dioxide budgets and ESMs

Towards geospatial estimates CO_2 flux from inland waters

pCO2 from GLORICH database (aggregated on COSCAT hydro-regions)

Gas exchange dependency on stream order

Stream area regressed from precipitation and temperature



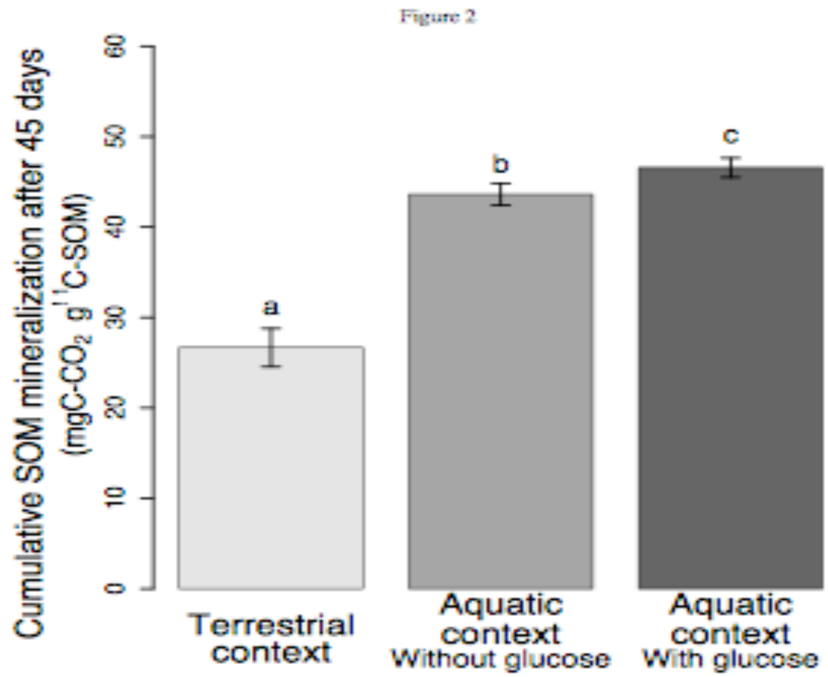
Raymond et al. Nature in press

Rivers outgassing:
2.2 PgC yr^{-1}
[1.8 – 2.6] 95% CI

Lakes and reservoirs:
0.32 PgC yr^{-1}
[0.06 – 0.84]

Considerably higher than previous estimates, due to larger gas exchange

C mineralization rates are (perhaps) higher under aquatic conditions



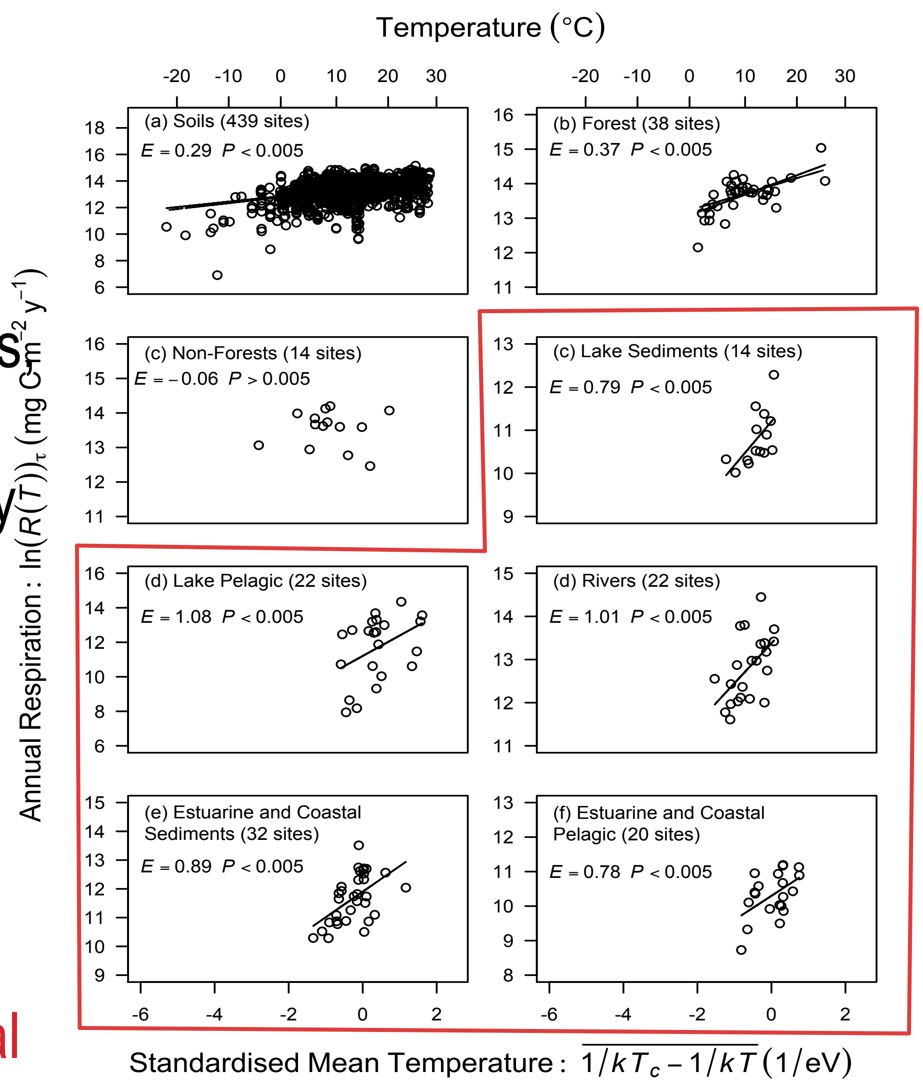
Guenet et al. 2013

Comparison of mineralization rates of the same incubated soil samples either preserved as « terrestrial » or mixed and stirred with water as « aquatic »

Temperature response is also (perhaps) higher in aquatic systems

"over a time span of days, the temperature sensitivity of ecosystem respiration is remarkably similar for estuaries, lakes, oceans, rivers, forests and non-forested terrestrial systems, and converges on an activation energy identical to that of the respiratory complex (~0.65 eV) aka Q10 = 2.5

By contrast, annual ecosystem respiration exhibits a substantially greater temperature-dependence in aquatic (~0.65 eV) relative to terrestrial ecosystems (~0.32 eV) aka Q10 = 1.6"



Yvon-Durocher et al. Nature 2012

Temperature-controlled organic carbon mineralization in lake sediments

Cristian Gudasz[1], David Bastviken[2], Kristin Steger[1], Katrin Premke[1], Sebastian Sobek[1] & Lars J. Tranvik[1]

Evidence for the respiration of ancient terrestrial organic C in northern temperate lakes and streams

S. Leigh McCallister[a,1] and Paul A. del Giorgio[b]

[a]Department of Biology and Environmental Studies, Virginia Commonwealth University, Richmond, VA 23284; and [b]Groupe de Recherche Interuniversitaire en Limnologie (GRIL), Dépt. des sciences biologiques, Université du Québec à Montréal, Montréal, QC, Canada H3C 3P8

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Carbon dynamics in lakes of the boreal forest under a changing climate

Glenn Benoy, Kevin Cash, Edward McCauley, and Frederick Wrona

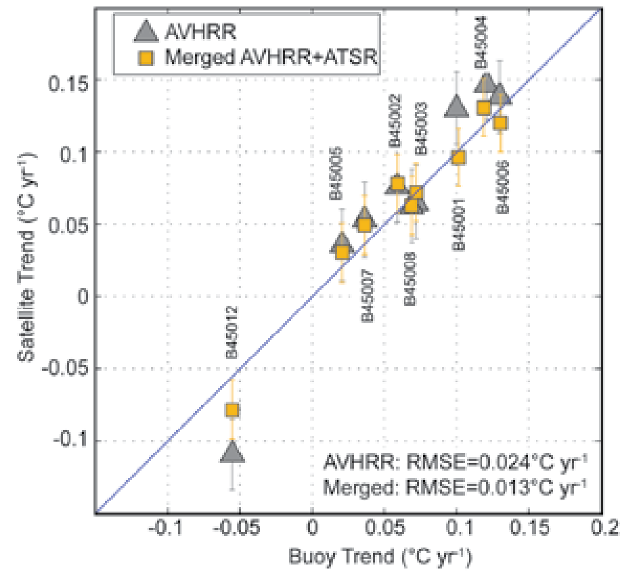
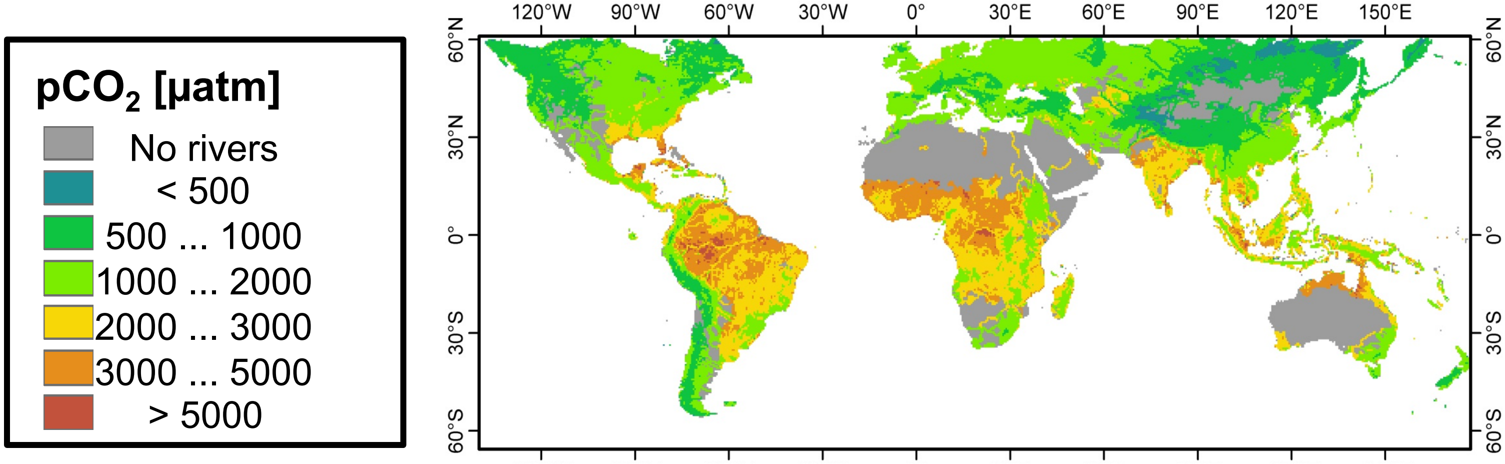


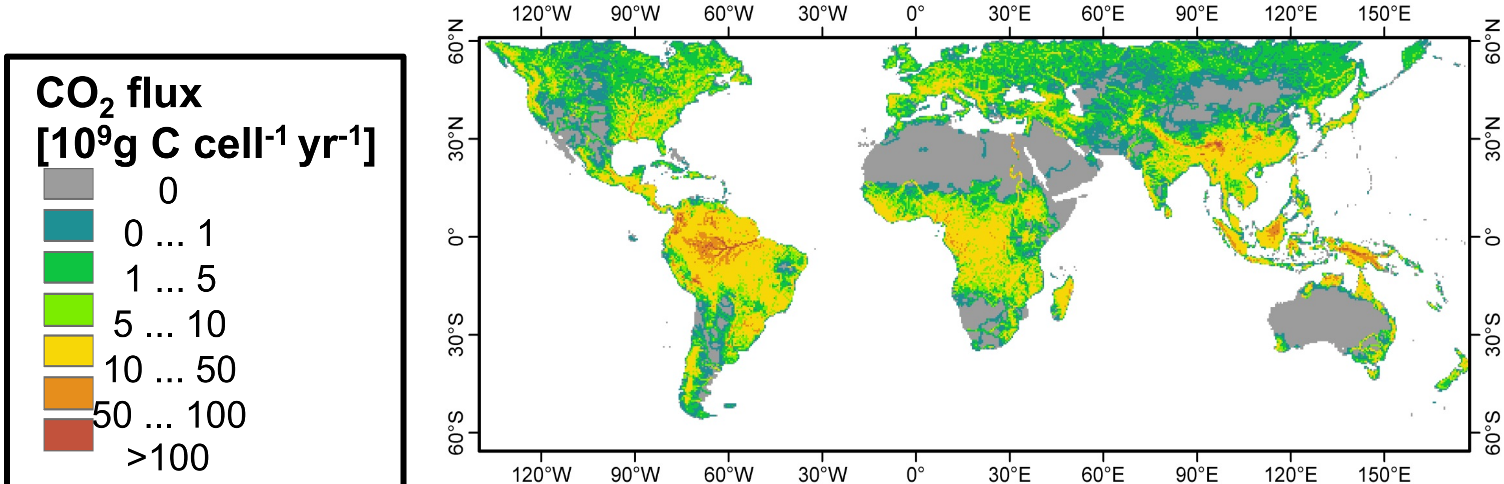
Fig. 2.9. Comparison of 1985–2009 Jul–Sep nighttime lake surface temperature trends derived from satellite data with those obtained from hourly measurements at nine buoys in the Great Lakes.

State of the Climate Report
BAMS 2010

Predicted pCO_2 and FCO_2 at 0.5° resolution

Georeferenced estimates obtained from a machine learning algorithm based upon GLORICH data and climate drivers

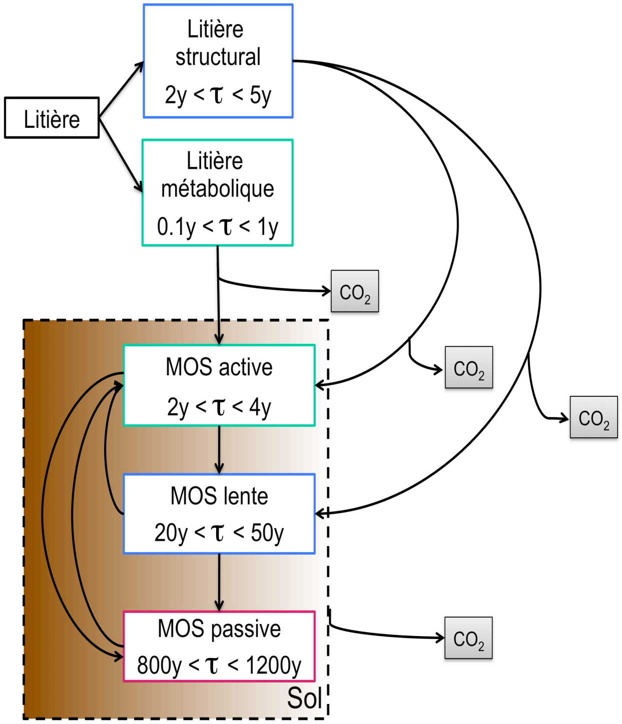




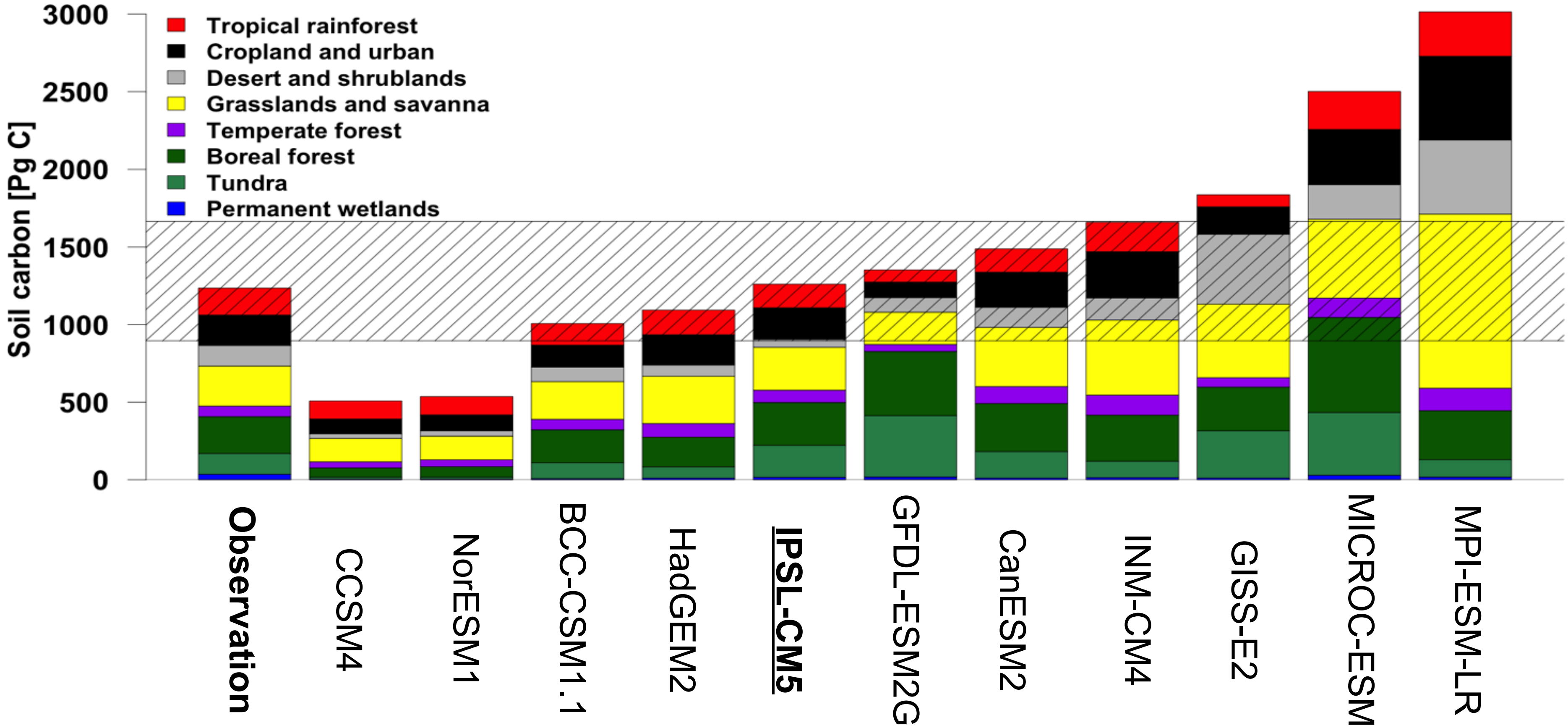
Lauerwald et al. In prep

HOW TO IMPROVE SOIL CARBON MODELING IN LINKAGE WITH THE BOUNDLESS CARBON CYCLE

Results from ORCHIDEE model (but relevant to other land carbon models)



CMIP5 MODELS DO NOT REPRESENT SOIL CARBON STOCKS WELL



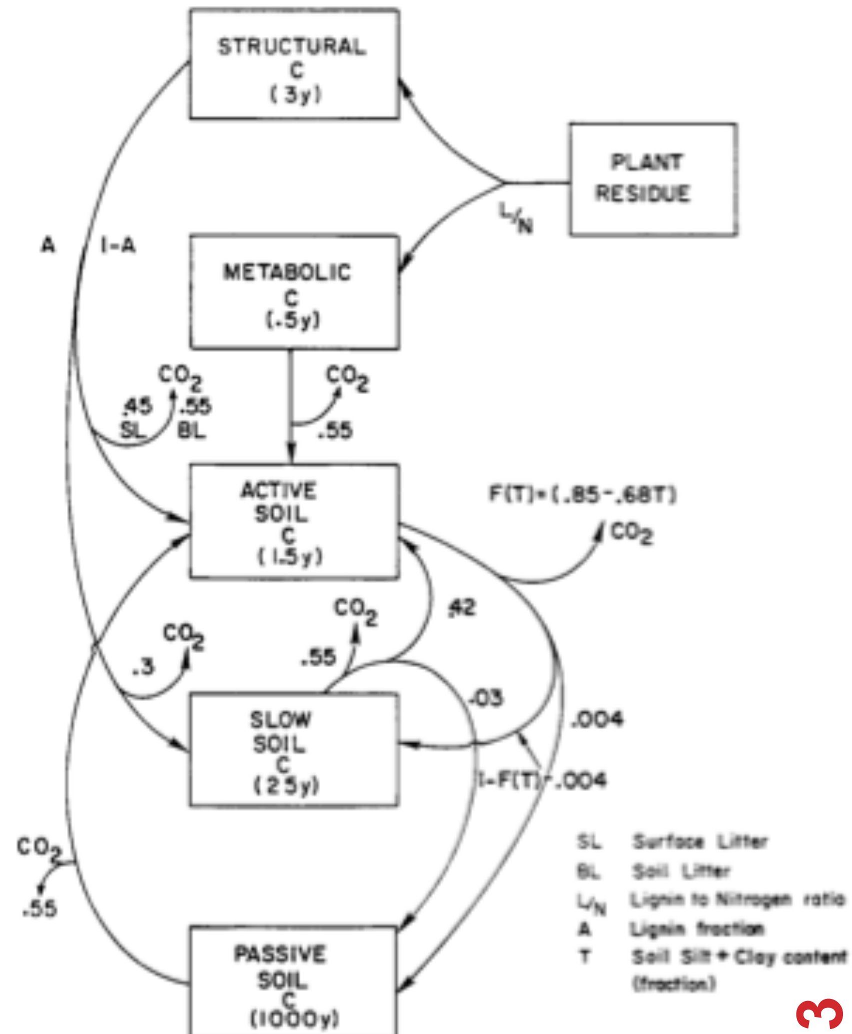
Todd-Brown et al. (2013)

CENTURY (PARTON ET AL., 1988)

The standard version of ORCHIDEE still runs with a 25 years old model.

CENTURY assumes implicitly that microbial biomass is not a driver of decomposition

Designed for the 20 first cm whereas a substantial part of the C is stored in the deep layers (Jobbagy and Jackson, 2000)



CENTURY (PARTON ET AL., 1988)

CENTURY has been designed for systems at equilibrium state

$$\frac{\partial SOC}{\partial t} = I - k \times SOC \times \theta \times \tau$$

Several processes are not or not well represented

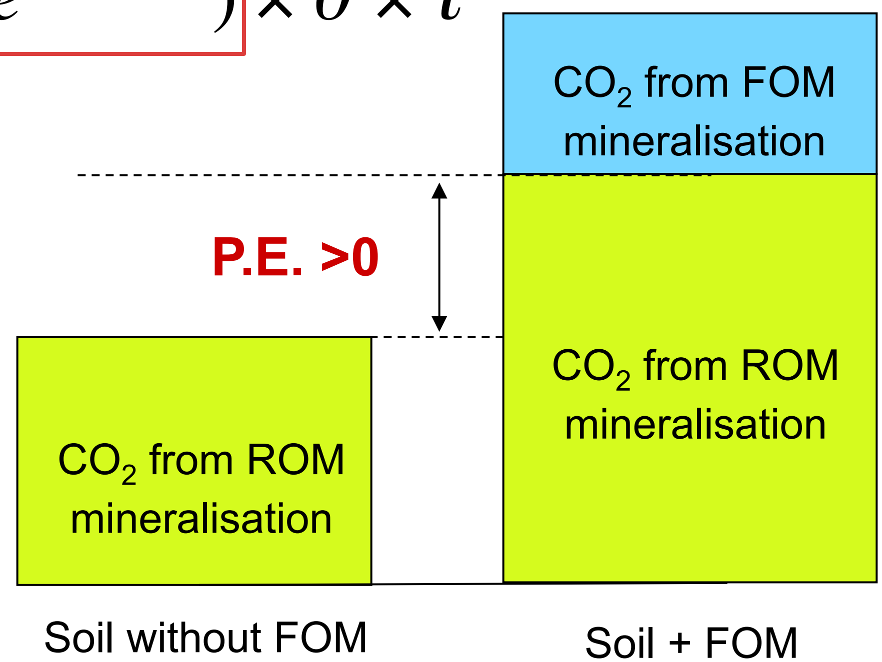
- Biology: **priming effect**, **effect of moisture**, effect of temperature, N mining, predations on decomposers
- Physics: no representation of the soil structure and its effect on decomposition, **very simple representation of texture**
- Chemistry: **Pools represented not measurable**.

PRIMING EFFECTS

Based on Wutzler and Reichstein (2008) and adapted by Guenet et al., (2013)

$$\frac{\partial SOC}{\partial t} = I - k_{SOC} \times SOC \times \boxed{(1 - e^{-c \times FOC})} \times \theta \times \tau$$

- This approach is able to reproduce priming effect
- Assumes that microbial biomass is always in equilibrium with FOC (Xia et al., *In prep*)



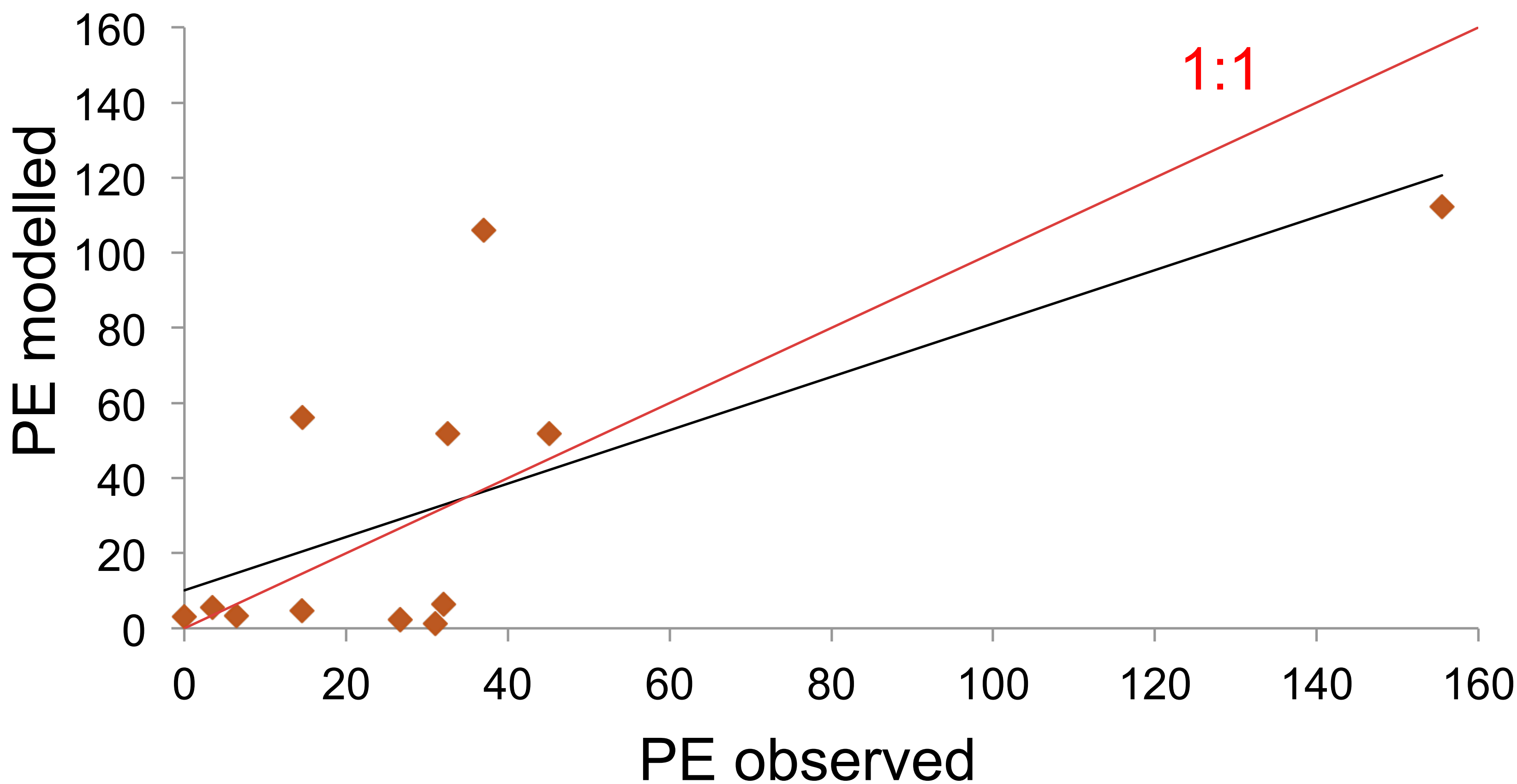
Adapted from Kuzyakov *et al.*, 2000

Caveat – extrapolate short term data to long term response

EVALUATION OF PRIMING PARAMETERIZATION

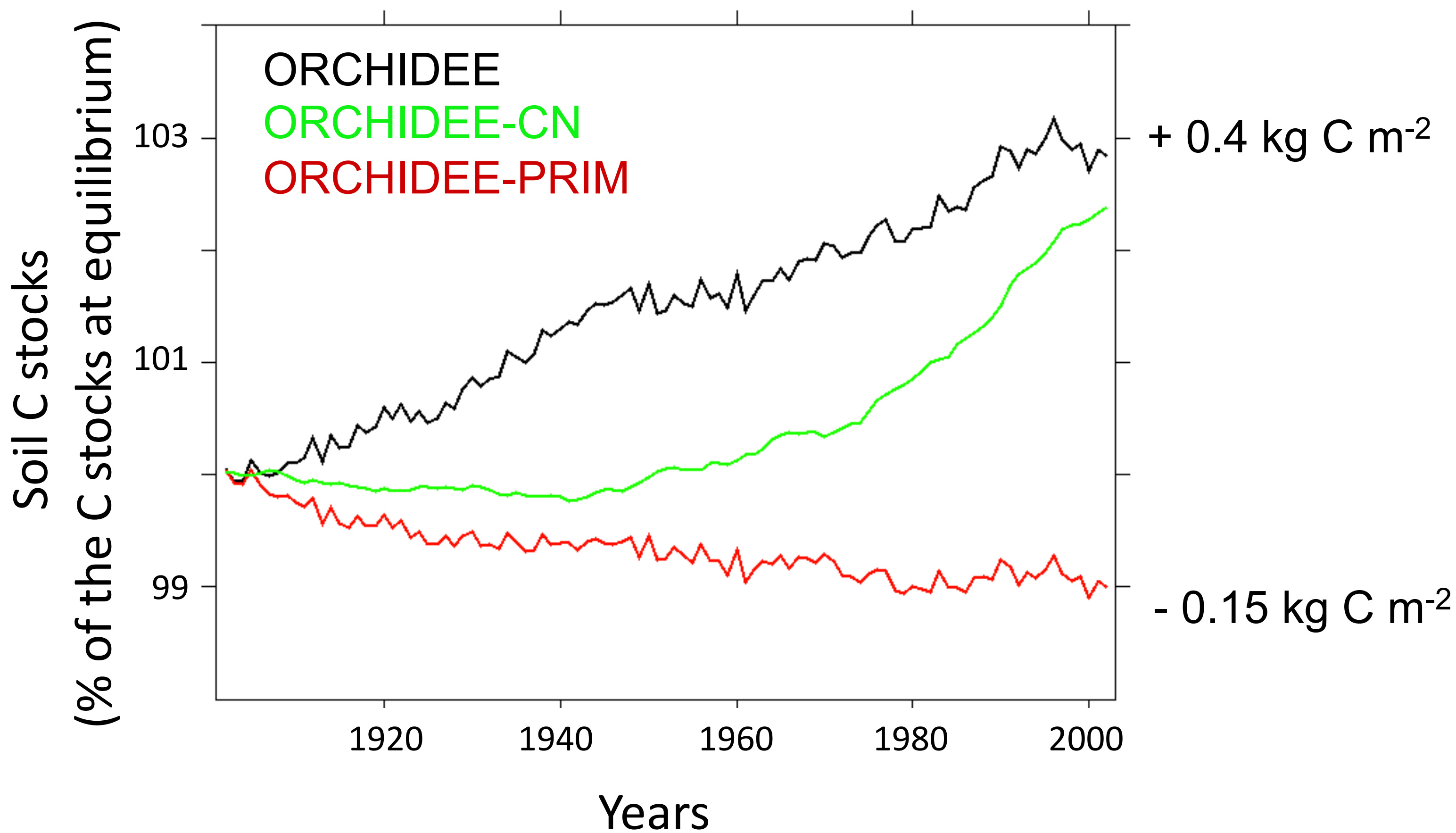
Parameters optimized against soil incubation data

Evaluated within ORCHIDEE against litter manipulation experiments



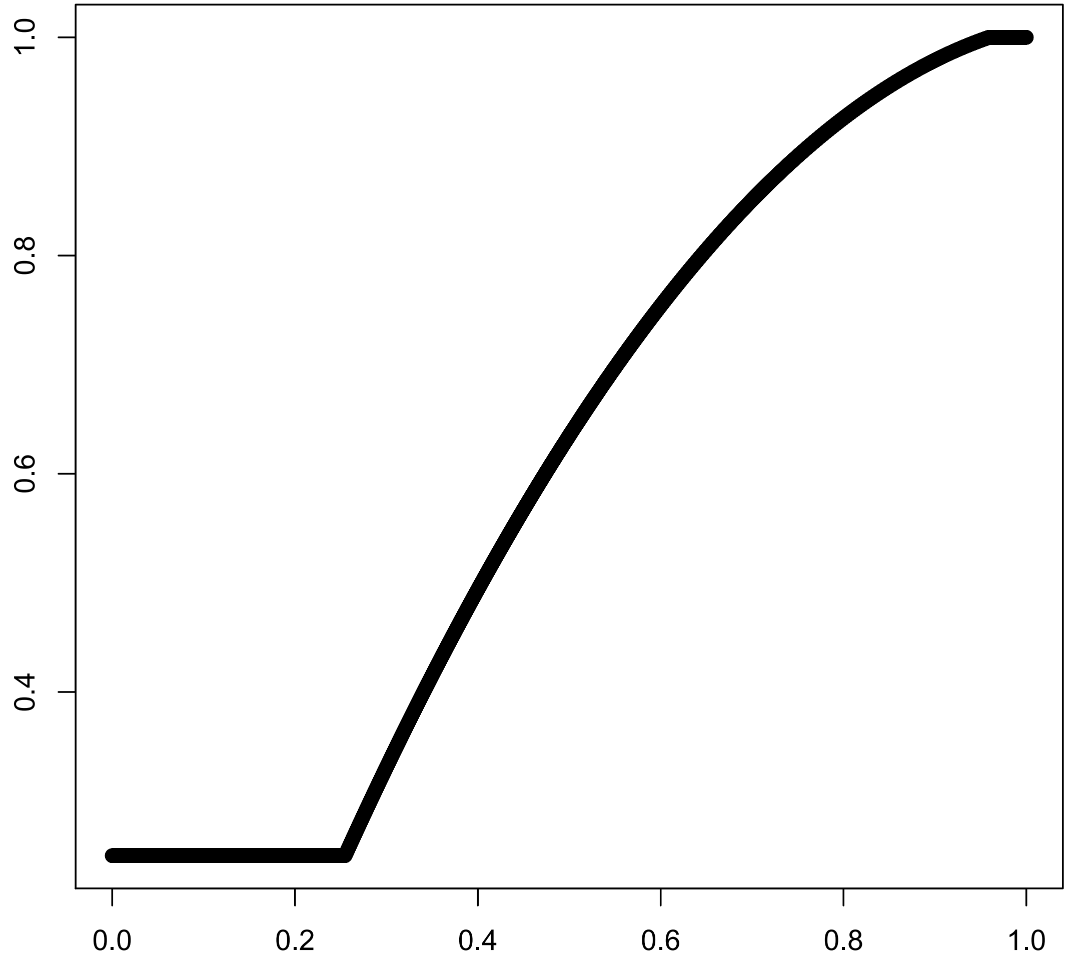
LARGE SCALE EFFECTS OF PRIMING IN A GLOBAL RUN

Priming modifies deeply the modelled SOC change trajectory



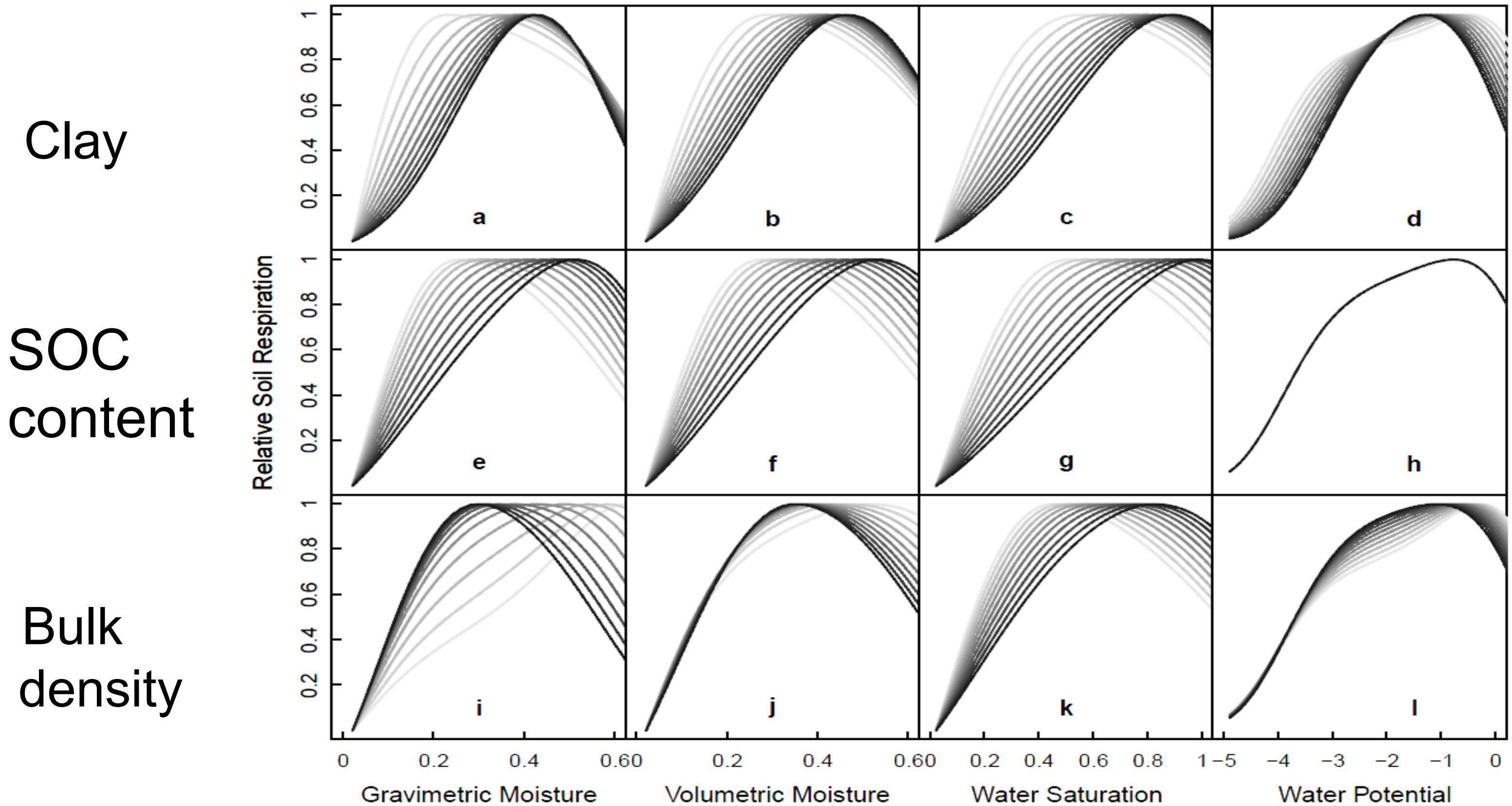
MOISTURE EFFECT ON DECOMPOSITION

Moisture effect only depends on soil moisture.



Current soil moisture function used in the ORCHIDEE model

MOISTURE EFFECTS ON DECOMPOSITION COVARY WITH OTHER SOIL PROPERTIES



Moyano et al., 2012

Darker lines represent higher values of a given property. Variations are shown for :

- Clay content from 100 to 1000 g kg (a–d)
- Organic carbon from 5 to 50 mg gsoil (e–h)
- Soil bulk density from 0.6 to 1.6 g cm (i–l)

SOIL CARBON [VERTICAL] DISCRETIZATION

None of the models used for CMIP5 represent the soil C profiles.

A substantial part of the soil C stored in deep layers (Jobbagy and Jackson, 2000)

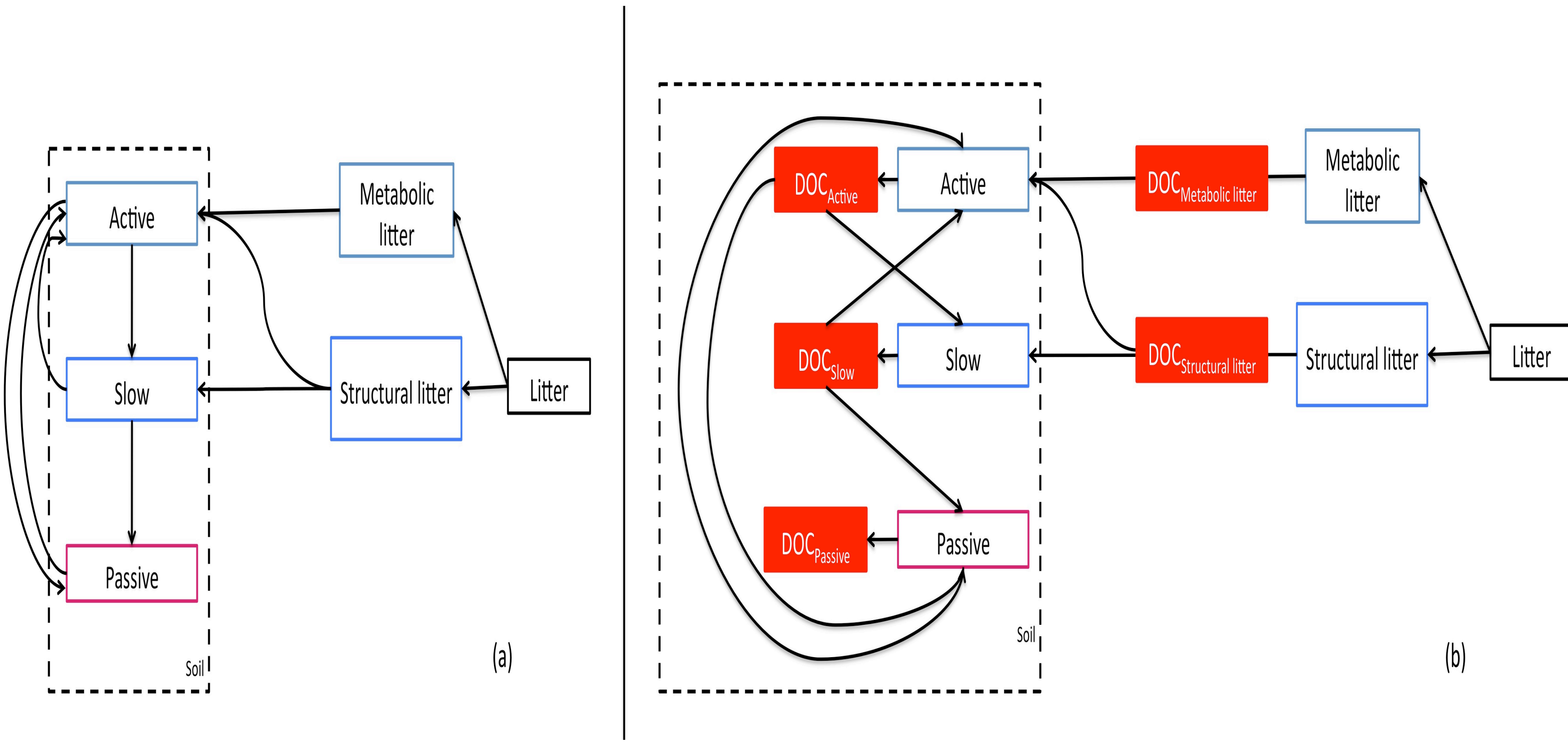
Deep C dynamic different from surface C (Fontaine et al., 2007)

In ORCHIDEE none of the C is lost by drainage or runoff despite the importance of allochtonous C in aquatic ecosystems functionning (Cole et al., 2007, Bianchi et al., 2011)

SOIL CARBON DISCRETIZATION

Soil C discretized using the same layers than hydrology scheme (11 layers)

A new pool introduced (DOC)



SOIL CARBON DISCRETIZATION

Adsorption of DOC following the Langmuir equation

$$RE = \frac{k \times Q_{\max} \times DOC_{free}}{1 + k \times DOC_{free}} - b$$

- DOC transported within the profile following the water movements (Futter et al., 2007) and exported following runoff and the drainage fluxes

- POC transported using the second Fick's law

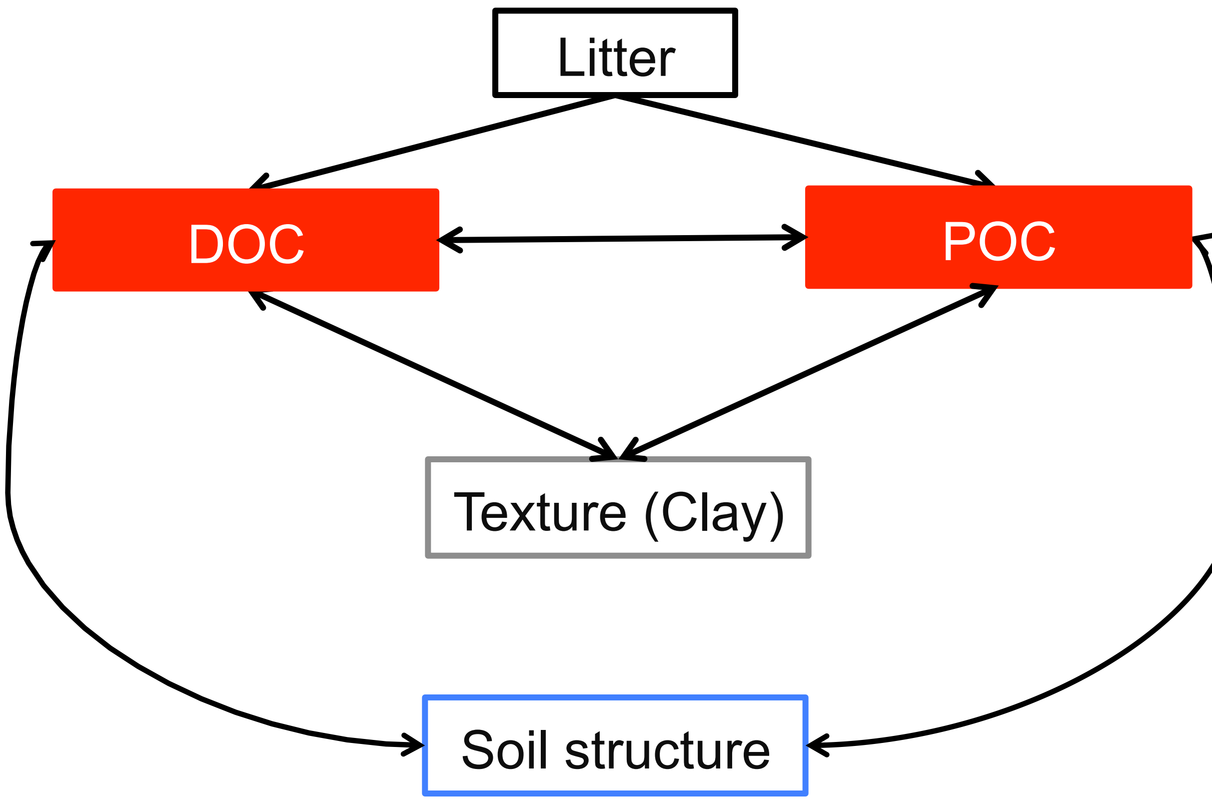
$$F_D = -D \times \frac{\partial^2 C}{\partial z^2}$$

- Work in progress to define D and the Langmuir equation parameters as a function of different variables (clay, pH, SOC).

PERSPECTIVES

CO_2 and O_2 diffusion in the soil profile.

Leaving the non-measurable pools approach to represent real mechanisms



PERSPECTIVES

Better representation of the tillage effects

- **Change parameters values for accelerating decomposition**
- **Take into account the different tillage techniques**
- **Impacts of tillage on decomposition depends upon soil properties (texture, SOC, pH etc.)**
- **Crop harvest residues decomposed in tilled layers instead of being decomposed in surface**

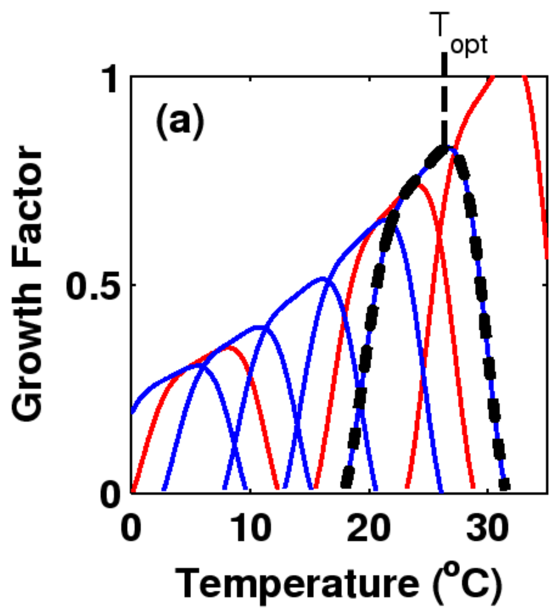
Erosion not represented for the moment

- **Williams (1995) developed a soil loss equation**
- **Soil Lost = 1.292 * EI * K * CM * P * LS * CFRG**
  - EI is rainfall erosion index
  - K is the soil erodibility factor
  - CM is the cover and management factor
  - P is the practice factor
  - LS is the topographic factor
  - CFRG is the coarse fragment factor

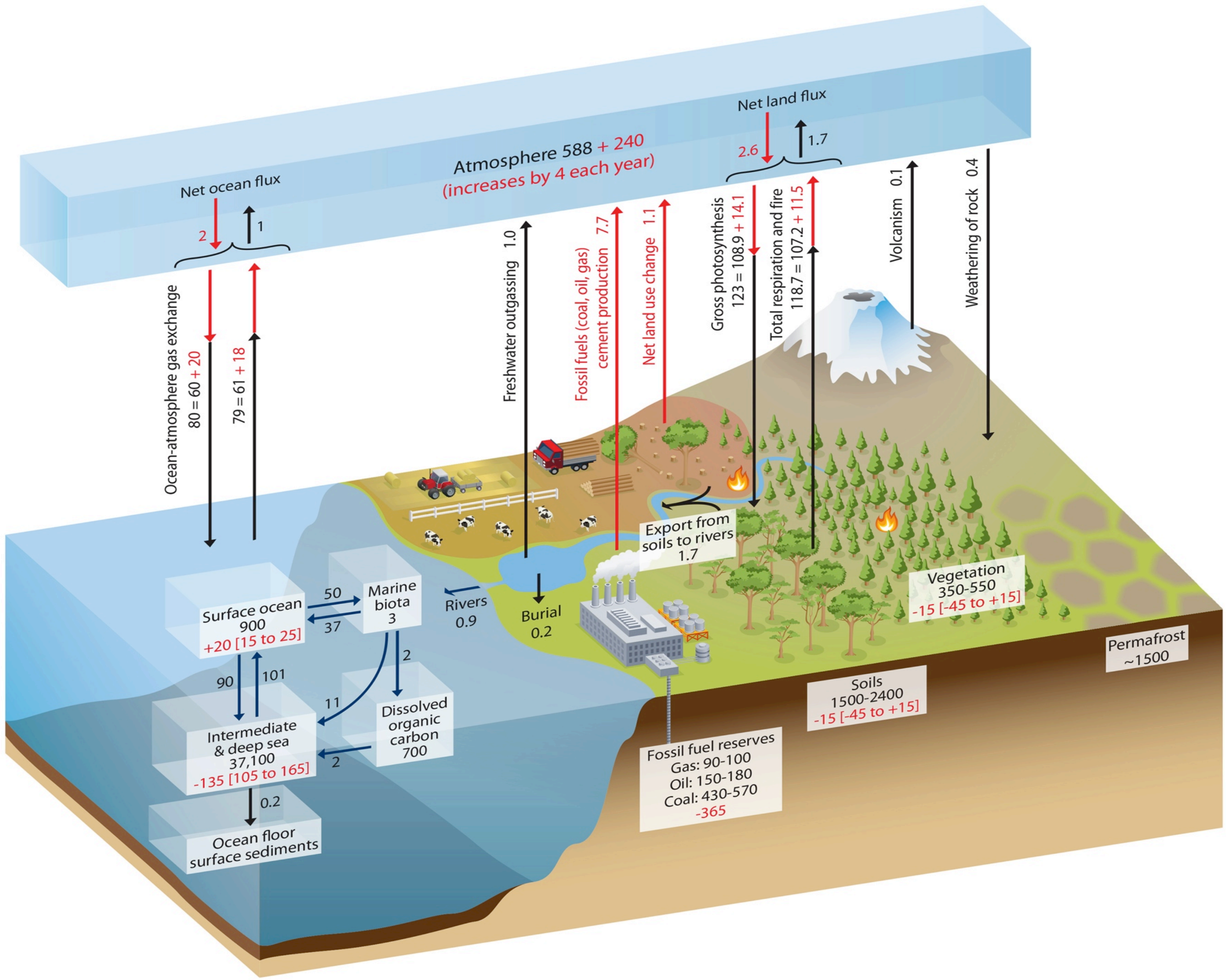
PERSPECTIVES

The N cycle – beyond C:N stoichiometry

Explicit representation of the microbial biomass and of the microbial community structure



Actinomycètes
β-protéobacteria
Actinobacteria
Bacteroidetes
Fibrobacter
Acidobacter
Ascomyceta
Verrucomicrobia


Atmosphere 588 + 240
(increases by 4 each year)
Net ocean flux
2
1
Net land flux
2.6
1.7
Ocean-atmosphere gas exchange
80 = 60 + 20
79 = 61 + 18
Freshwater outgassing 1.0
Fossil fuels (coal, oil, gas) cement production 7.7
Net land use change 1.1
Gross photosynthesis 123 = 108.9 + 14.1
Total respiration and fire 118.7 = 107.2 + 11.5
Volcanism 0.1
Weathering of rock 0.4
Export from soils to rivers 1.7
Rivers 0.9
Burial 0.2
Surface ocean 900 +20 [15 to 25]
50
37
Marine biota 3
90
101
2
11
Intermediate & deep sea 37,100 -135 [105 to 165]
Dissolved organic carbon 700
2
0.2
Ocean floor surface sediments
Vegetation 350-550 -15 [-45 to +15]
Permafrost ~1500
Soils 1500-2400 -15 [-45 to +15]
Fossil fuel reserves
Gas: 90-100
Oil: 150-180
Coal: 430-570
-365