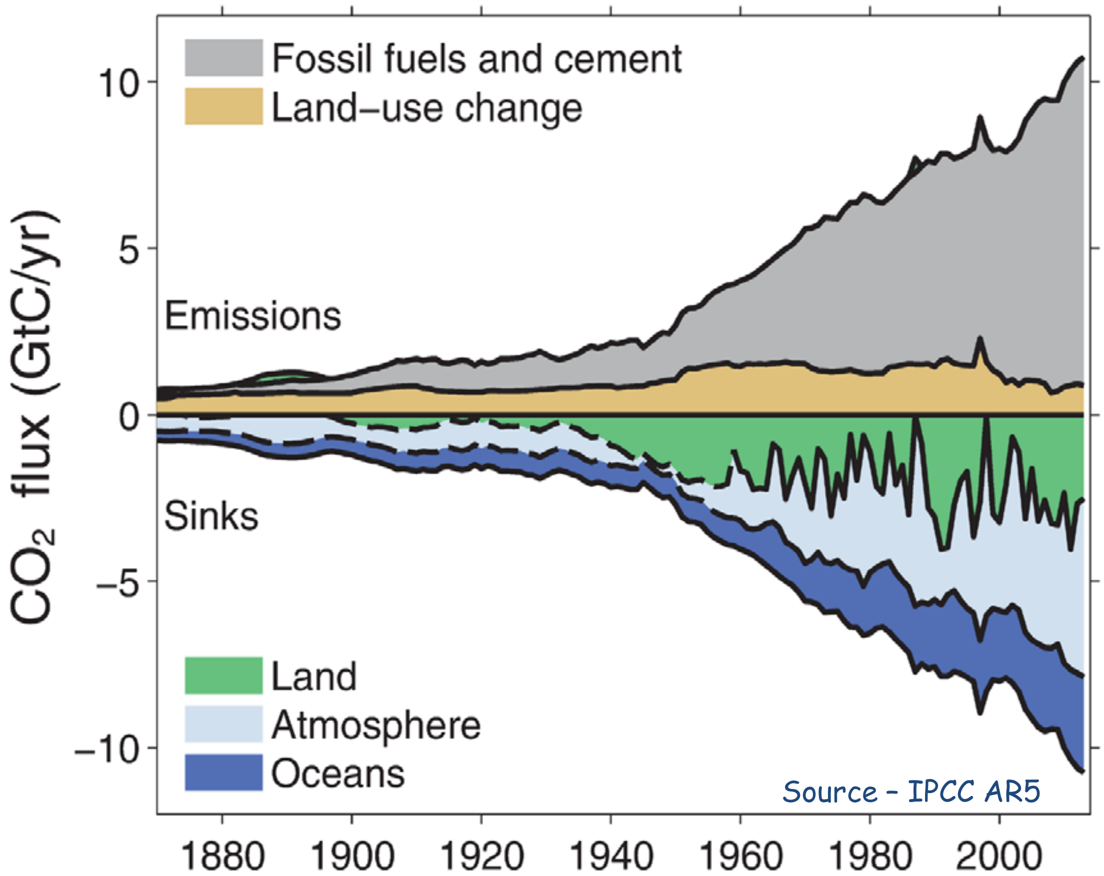
Observed regional carbon budgets imply reduced soil heterotrophic respiration.

Philippe Ciais [1,2], Thomas Gasser [1], Ronny Lauerwald [3], Shushi Peng [1,2], Peter A. Raymond [4], Yilong Wang [1], Josep G. Canadell [5], Glen P. Peters [6], Rob J. Andres [7], Jinfeng Chang [1,8], Chao Yue [1,9], A.Johannes Dolman [10], Vanessa Haverd [11], Jens Hartmann [12], Goulven Laruelle [3], AntonyW. King [7], Yi Liu [13,14], Sebastiaan Luyssaert [1], Fabienne Maignan [1], Prabir K. Patra [15], Anna Peregon [1], Pierre Regnier [3], Shilong Piao [2,16], Benjamin Poulter [17], Anatoly Shvidenko [18], Riccardo Valentini [19], Rong Wang [1], Albert I.J.M. van Dijk [20], Grégoire Broquet [1], Yi Yin [1], Jakob J. Zscheischler [21] and Dan Zhu [1].

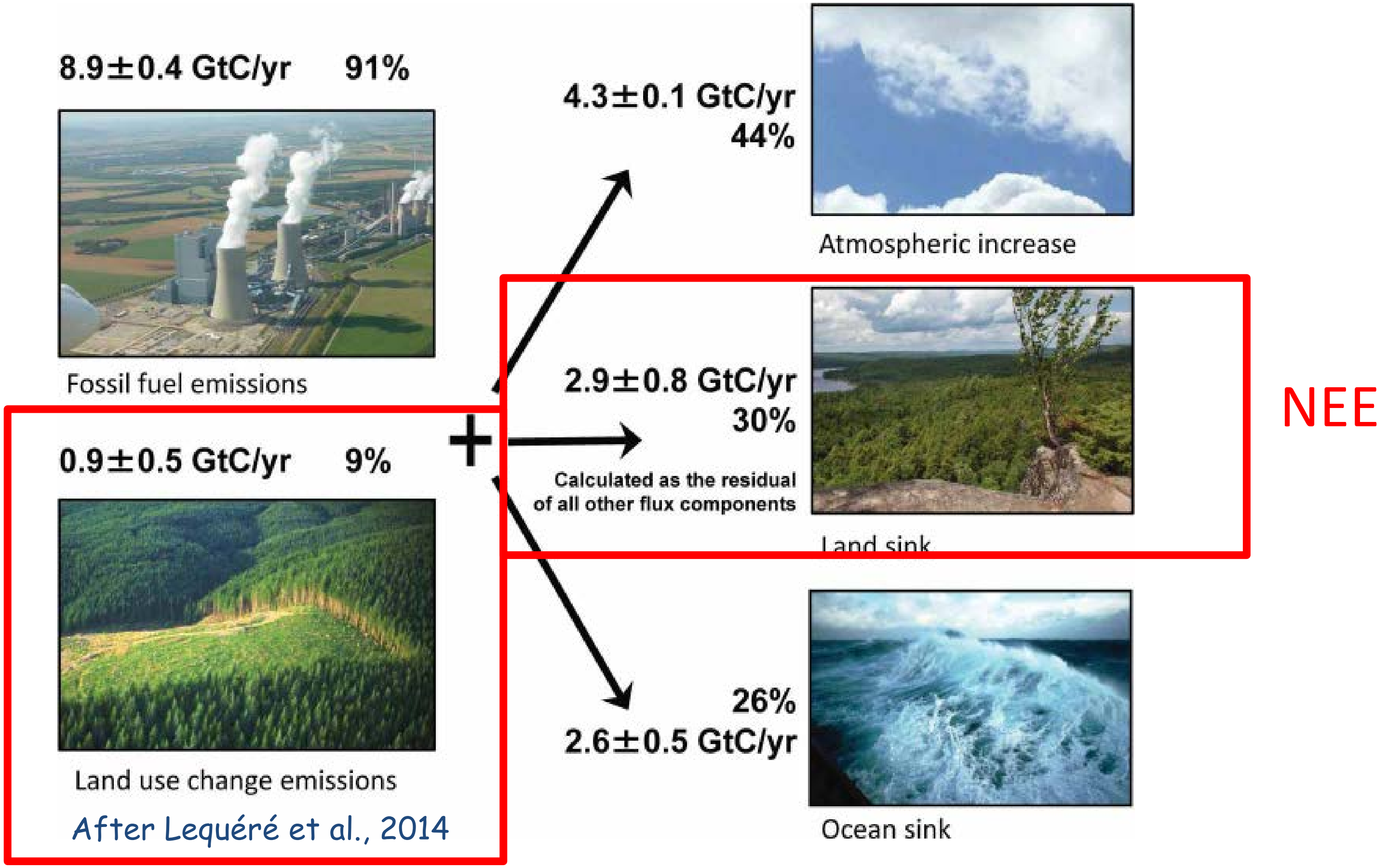
Carbon sinks offer to humanity a 50% discount on climate change



- The increase of CO_2 is caused by fossil fuel use and land use change
- Fossil fuel emissions soared from 2 GtC yr^{-1} in the 1960's to 10 GtC yr^{-1} today
- But the ocean and land carbon sinks absorbed on average ≈50% of emissions

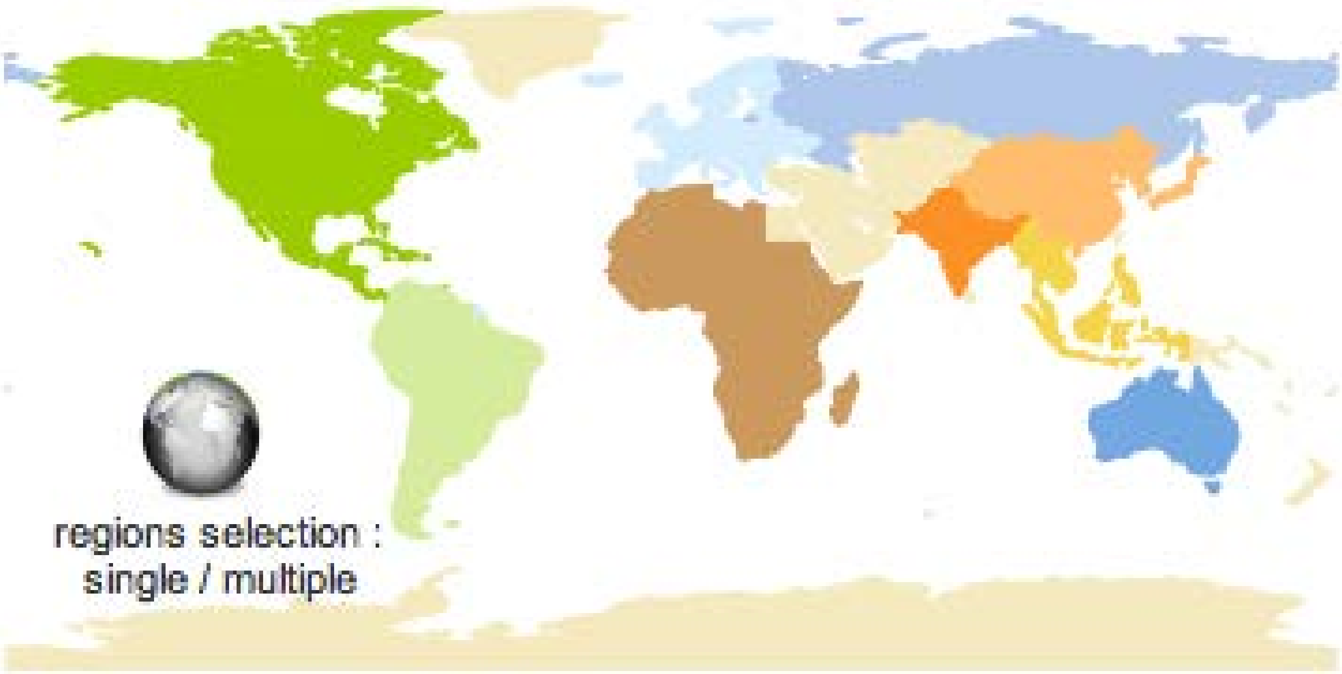
The global carbon budget

- Emissions of fossil fuels are estimated from energy use statistics

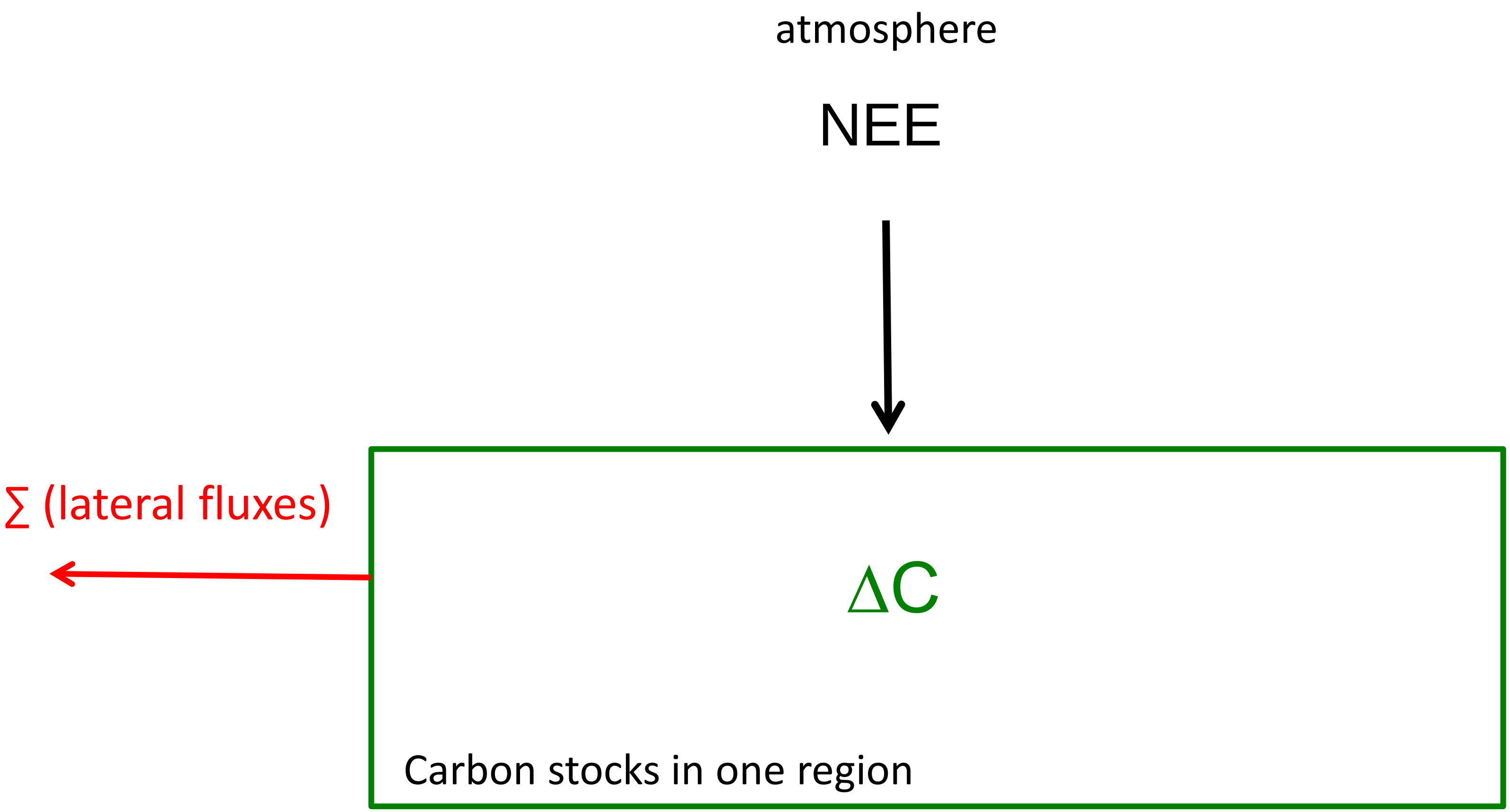


- The global ocean sink is constrained by ocean interior measurements
- But the global land sink cannot be quantified by land observations
- A bottom-up estimate of global NEE is still missing

Reccap regions

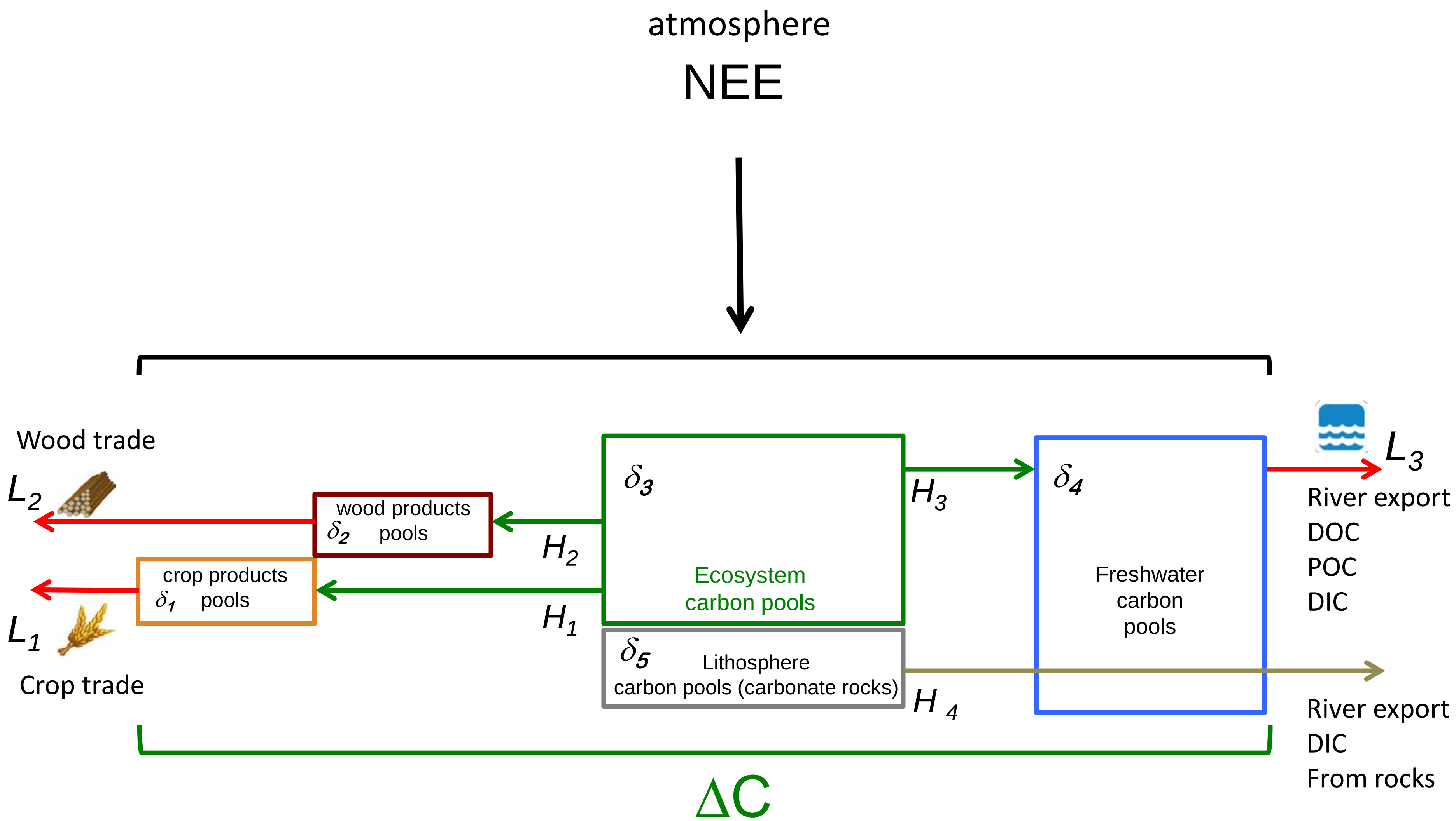


tan color = no data available



$NEE = \Delta C + \sum(\text{lateral fluxes})$

By convention negative if NEE removes C from the atmosphere and ΔC is negative if C is stored on land



Change in biomass and soil C pools estimated by inventories

Change of crop and wood product pools from

For Southeast Asia and South Asia, use of VOD satellite data

Data sources

ΔC : RECCAP publications (Biogeosciences)

- N America : King et al. BG 2015
- S America : Gloor et al. BG, 2012
- Africa : Valentini et al. BG 2012
- Europe : Luyssaert et al. BG 2013
- Russia : Dolman et al. BG 2012
- Australia : Haverd et al. BG 2012
- East Asia : Piao et al. BG 2013
- Sout Asia : Patra et al. BG 2012 + Liu et al. 2015
- **Southeast Asia Asia : new data from this study**

Lateral fluxes

- DOC, POC, DIC river transport to ocean :

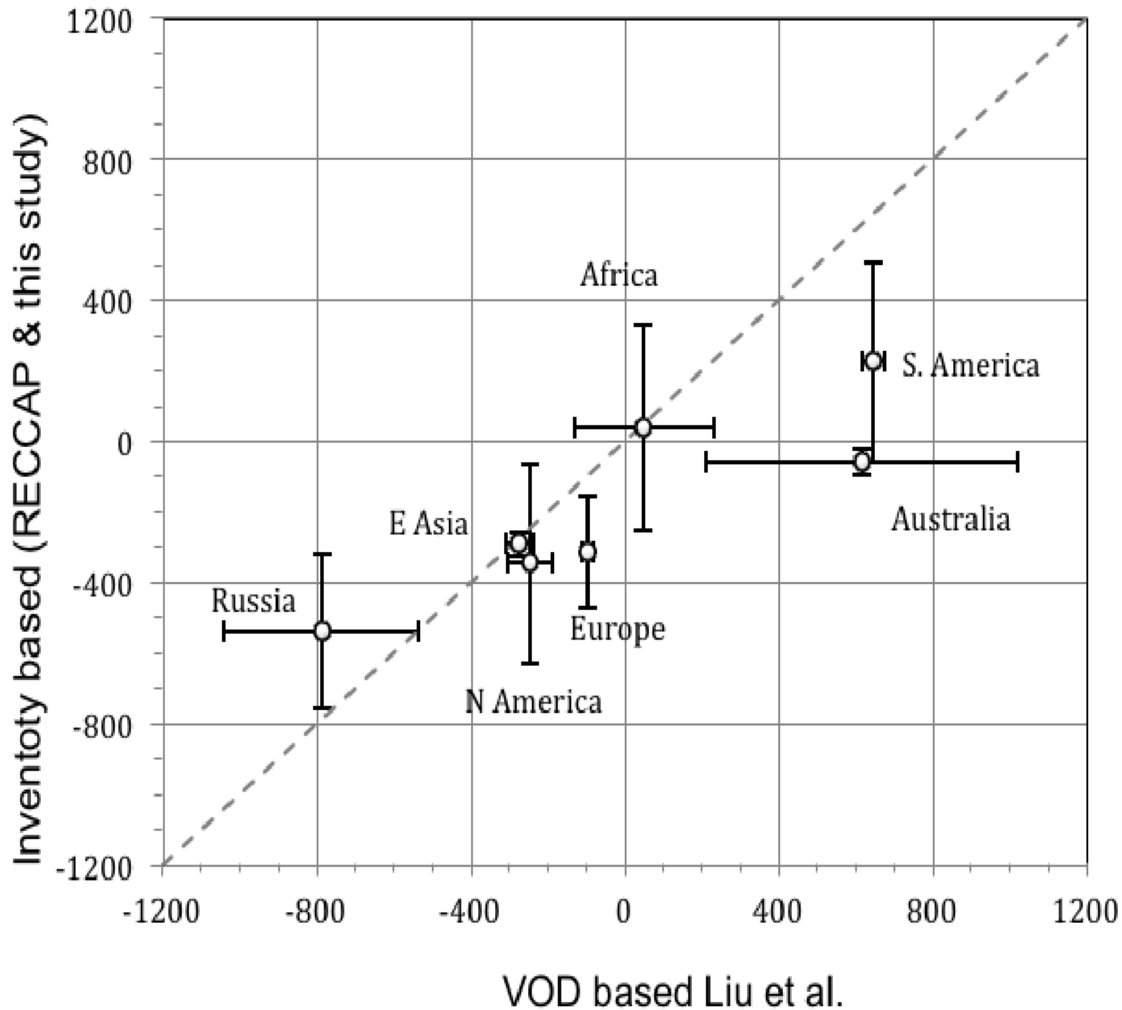
  Mayorga et al. 2010

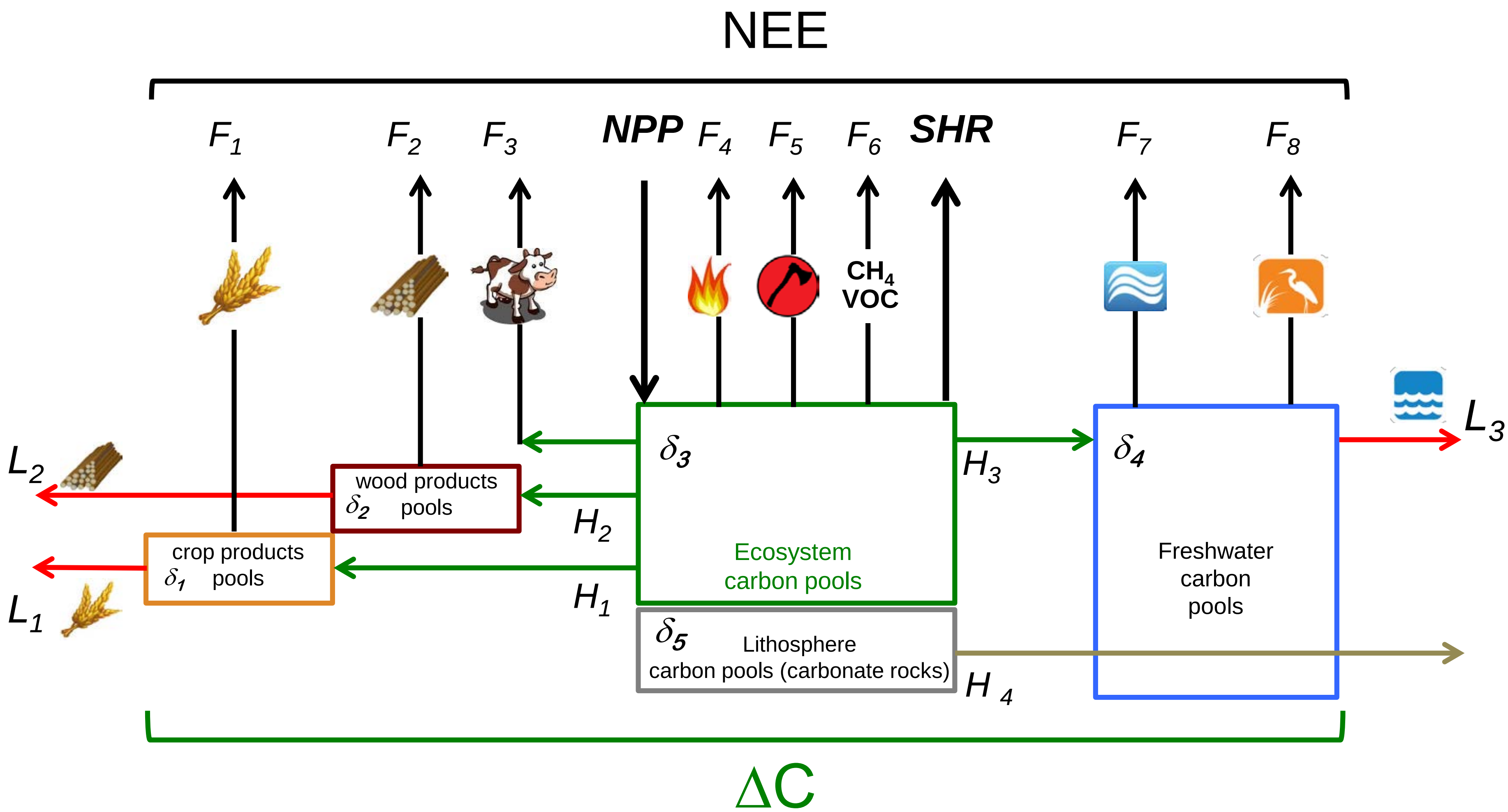
  Hartmann et al. 2009 Separate lithospheric component of DIC transport
- Crop and wood products harvest and trade

  Peters et al. BG 2012

	RECCAP publication / data source	Forest $\Delta C_{biomass}$	Forest ΔC_{soil}	Non-forest $\Delta C_{biomass}$	Non-forest ΔC_{soil}	ΔC_{LUC}	Δ wood product C
ica	King *et al.* 2015 (*10*) in their Table 1	(1)	(1)	(1)	(1)	(1)	(1)
	Luyssaert *et al.* 2012 (*11*) in their Table 1 : change in stocks from the sum of terms 9a-j + 10a-b + 11a-b in	(1)	(1)	(1)	(1)	(1)	(1)
	Dolman *et al.* (*13*) in their Table 5 corrected *	(1)	(1)	(1)	(1)	(1)	(1)
	No inventory data was reported by Patra *et al.* (*15*) so Liu *et al.* (*19*) was used	(2) #	ND	(2)	ND	(1)	(3)
	Piao *et al.* 2012 (*12*)	(1)	(1)	(1)	(1)	(1)	(1)
	New estimate from this study from Liu *et al.* (no RECCAP publication exists).	(2)	ND	(2)	ND	(2)	(3)
ica	Gloor *et al.* 2012 (*14*) in their Table 12	(1) ##	ND	ND	ND	(1)	(3)
	Valentini *et al.* (*17*) in their Table 11 completed by Liu *et al.* (*19*)	(1) ###	(1)	(2)	(2)	(1) ####	(3)
ia	Haverd *et al.* (*16*)	(1)	(1)	(1)	(1)	(1)	(1)

nature climate change


1200
800
400
0
-400
-800
-1200
Inventoty based (RECCAP & this study)
Africa
S. America
Australia
E Asia
Russia
Europe
N America
-1200
-800
-400
0
400
800
1200
VOD based Liu et al.

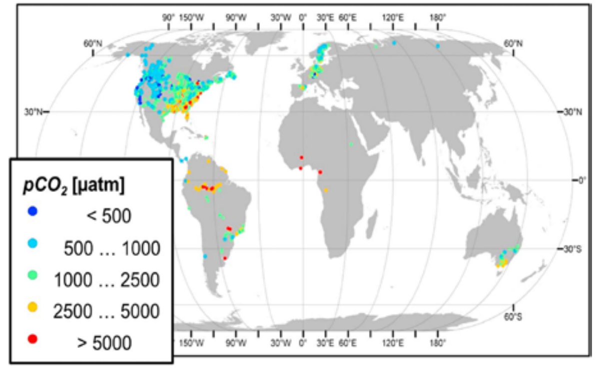

NEE
F_1
F_2
F_3
NPP
F_4
F_5
F_6
SHR
F_7
F_8
CH_4
VOC
L_2
L_1
L_3
δ_3
δ_4
H_3
wood products
δ_2 pools
H_2
crop products
δ_1 pools
H_1
Ecosystem
carbon pools
Freshwater
carbon
pools
δ_5 Lithosphere
carbon pools (carbonate rocks)
H_4
ΔC

Data sources - Component of NEE

- Fire emissions
  - GFEDv4 excluding deforestation fires
  - Agricultural residues burning; PKU emission inventory Wang et al. 2013
- LUC net emissions
  - RECCAP regional estimates, independent from Houghton et al.
- River outgassing
  - Raymond et al. 2014 Nature; rivers + lakes 2.1 PgC yr^{-1}
  - Lauerwald et al. 2015 GBC ; only rivers 0.65 PgC yr^{-1}
- Estuaries outgassing
- Grassland biomass intake and oxidation
- Crop and wood products decay
- CH_4, CO and BVOC emissions
  - Bousquet et al. atmospheric inversion
  - Guenther et al. BVOC emission model
- NPP
  - MODIS v5 MOD17A3.005-NPP
  - Excluding land use change grid cells with more than 5% LUC

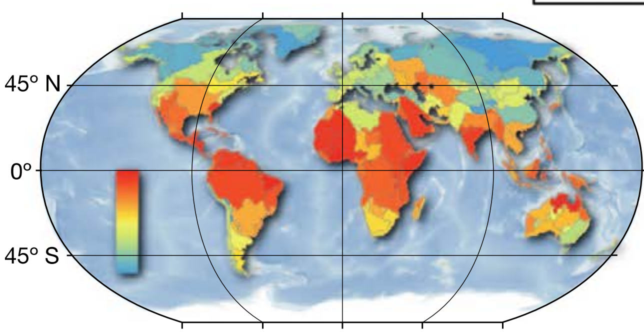
River CO_2 outgassing fluxes

Glorich pCO2 database

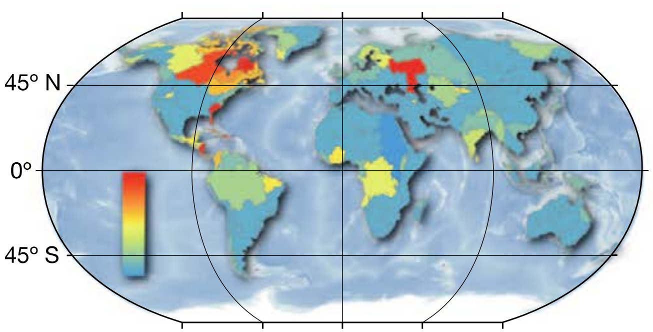


$1.8\ PgC\ y^{-1}$

Raymond et al.



River flux

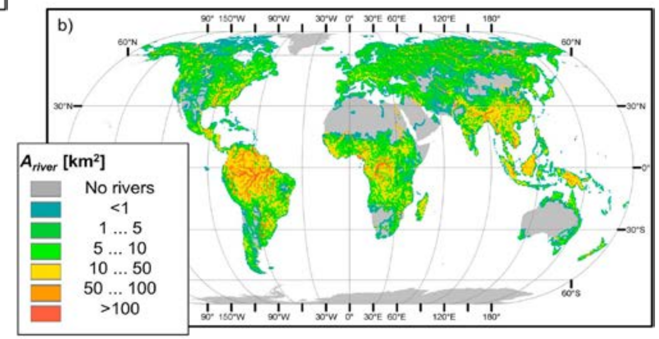


Lake flux

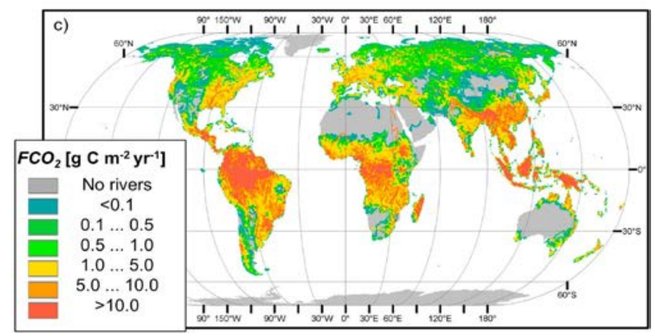
$0.65\ PgC\ y^{-1}$

Lauerwald et al. et al.

River area



River flux



Global carbon dioxide emissions from inland waters

Peter A. Raymond[1], Jens Hartmann[2]*, Ronny Lauerwald[2,3]*, Sebastian Sobek[4]*, Cory McDonald[5], Mark Hoover[1], David Butman[1,6], Rob Striegl[6], Emilio Mayorga[7], Christoph Humborg[8], Pirkko Kortelainen[9], Hans Durr[10], Michel Meybeck[11], Philippe Ciais[12] & Peter Guth[13]

Spatial patterns in CO_2 evasion from the global river network

Ronny Lauerwald[1,2,3], Goulven G. Laruelle[1,4], Jens Hartmann[3], Philippe Ciais[5], and Pierre A.G. Regnier[1]

[1]Department of Earth and Environmental Sciences, Université Libre de Bruxelles, Brussels, Belgium, [2]Institut Pierre-Simon Laplace, Paris, France, [3]Institute for Geology, University of Hamburg, Hamburg, Germany, [4]Department of Earth Sciences-Geochemistry, Utrecht University, Utrecht, Netherlands, [5]LSCE IPSL, Gif Sur Yvette, France

Data synthesis strategy – two sequential steps

1. Collect ΔC independent estimates from inventory approaches from RECCAP publications.

   Note that ΔC includes LUC

2. Calculate net export fluxes of each region from harmonized global datasets :

   Peters et al. 2012 for crop and wood products trade

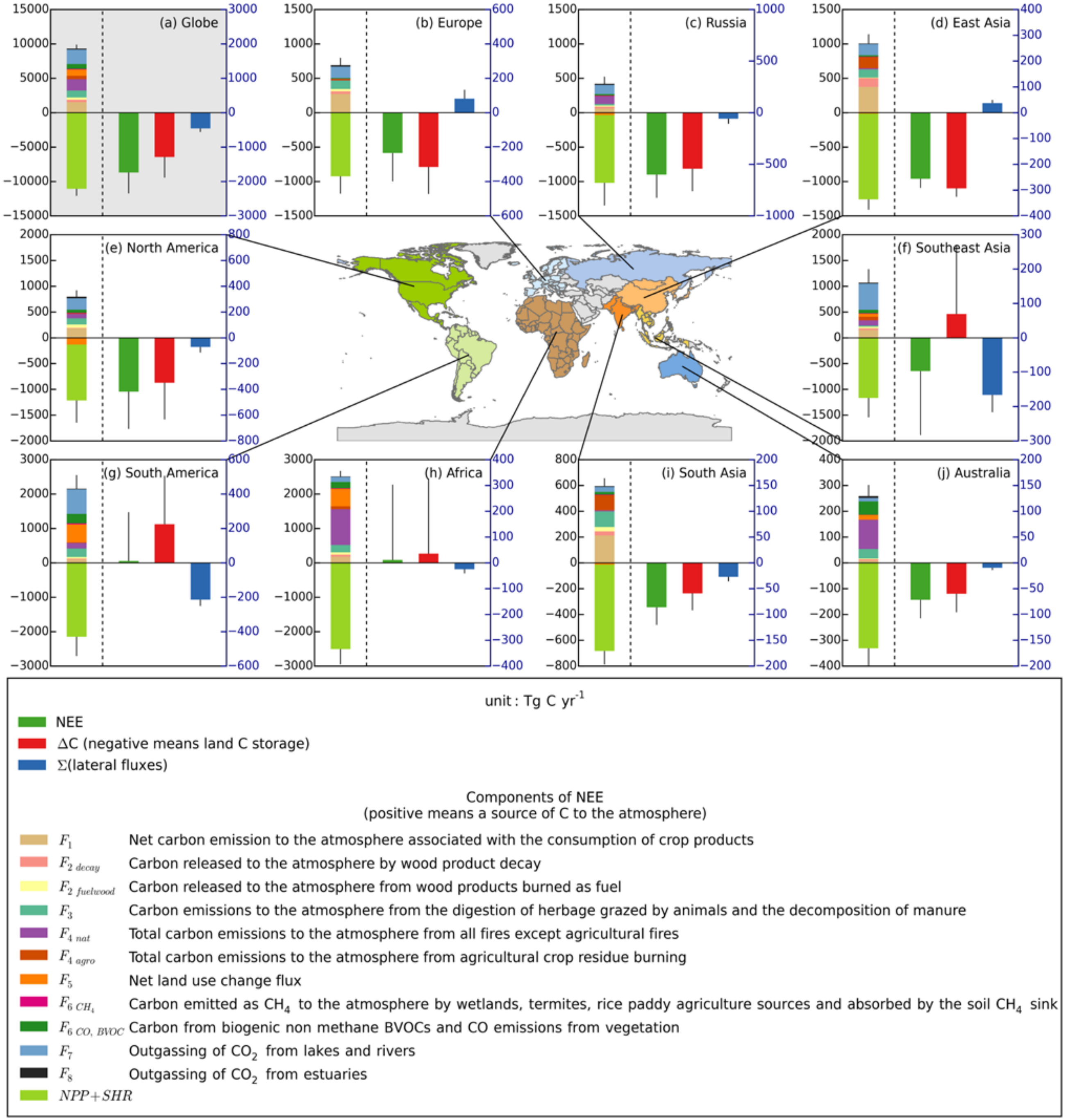
   Mayorga et al. 2010 and Hartmann et all. 2009 for river export to the ocean

   Separated DIC from carbonate rocks (Lauerwald et al. pers. com.)

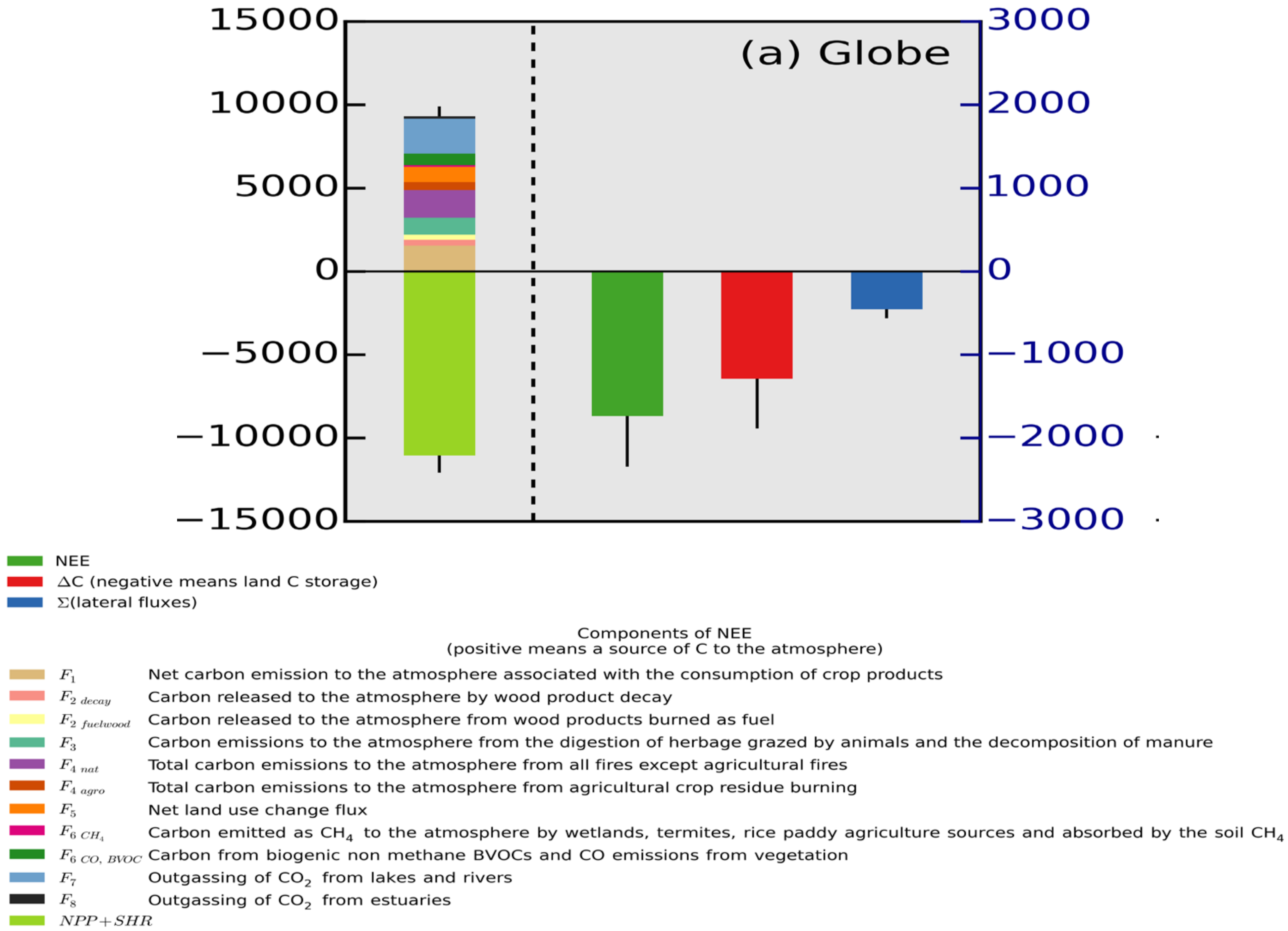
Calculate NEE : $\boxed{\text{NEE} = \Delta\text{C} + \sum \text{exports}}$

Calculate soil hetetrotrophic respiration (SHR) as a residual :

$$\boxed{\text{SHR} = \text{NPP} - \text{NEE} – \text{wood, crop, grass products consumption} – \text{fire} – \text{LUC} - \text{outgassing}}$$



(a) Globe
(b) Europe
(c) Russia
(d) East Asia
(e) North America
(f) Southeast Asia
(g) South America
(h) Africa
(i) South Asia
(j) Australia
unit : Tg C yr-1
NEE
ΔC (negative means land C storage)
Σ(lateral fluxes)
Components of NEE
(positive means a source of C to the atmosphere)
F_1 Net carbon emission to the atmosphere associated with the consumption of crop products
$F_{2\ decay}$ Carbon released to the atmosphere by wood product decay
$F_{2\ fuelwood}$ Carbon released to the atmosphere from wood products burned as fuel
F_3 Carbon emissions to the atmosphere from the digestion of herbage grazed by animals and the decomposition of manure
$F_{4\ nat}$ Total carbon emissions to the atmosphere from all fires except agricultural fires
$F_{4\ agro}$ Total carbon emissions to the atmosphere from agricultural crop residue burning
F_5 Net land use change flux
$F_{6\ CH_4}$ Carbon emitted as CH_4 to the atmosphere by wetlands, termites, rice paddy agriculture sources and absorbed by the soil CH_4 sink
$F_{6\ CO,\ BVOC}$ Carbon from biogenic non methane BVOCs and CO emissions from vegetation
F_7 Outgassing of CO_2 from lakes and rivers
F_8 Outgassing of CO_2 from estuaries
$NPP+SHR$


15000
10000
5000
0
−5000
−10000
−15000
3000
2000
1000
0
−1000
−2000
−3000
(a) Globe
NEE
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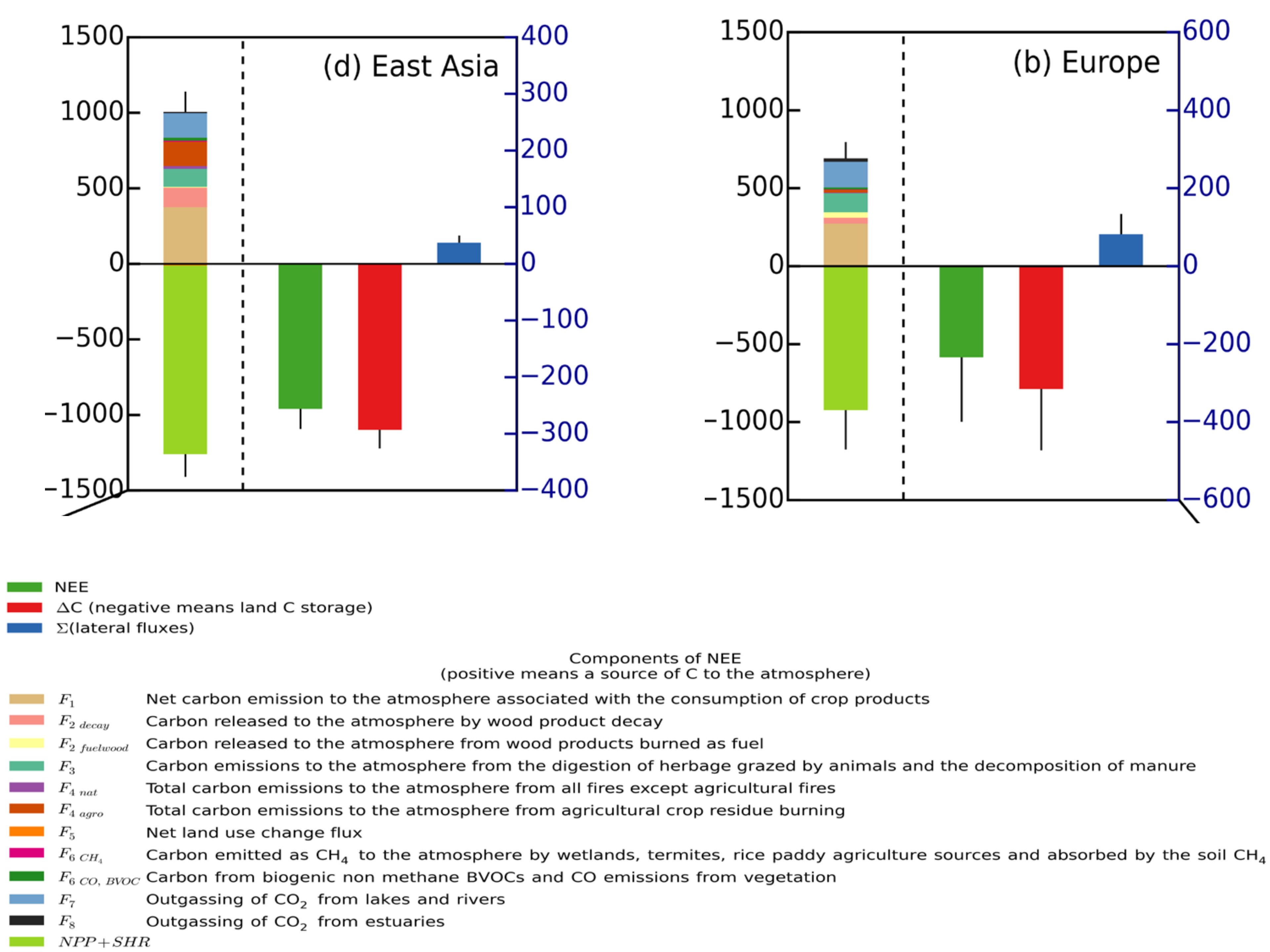
(d) East Asia
(b) Europe
1500
1000
500
0
−500
−1000
−1500
400
300
200
100
0
−100
−200
−300
−400
600
400
200
0
−200
−400
−600
NEE
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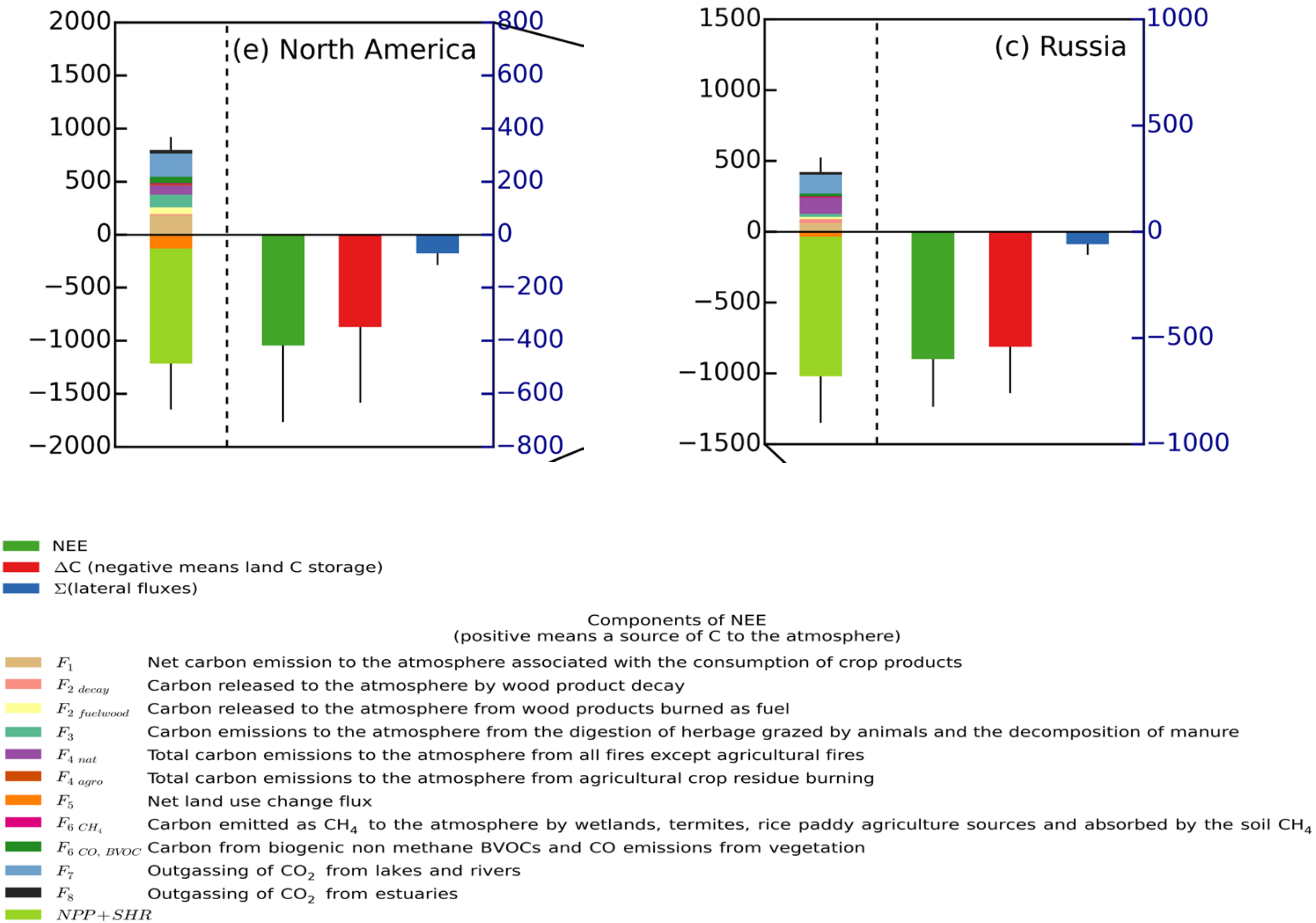
$NPP+SHR$



(e) North America
2000
1500
1000
500
0
−500
−1000
−1500
−2000
800
600
400
200
0
−200
−400
−600
−800
(c) Russia
1500
1000
500
0
−500
−1000
−1500
1000
500
0
−500
−1000
NEE
ΔC (negative means land C storage)
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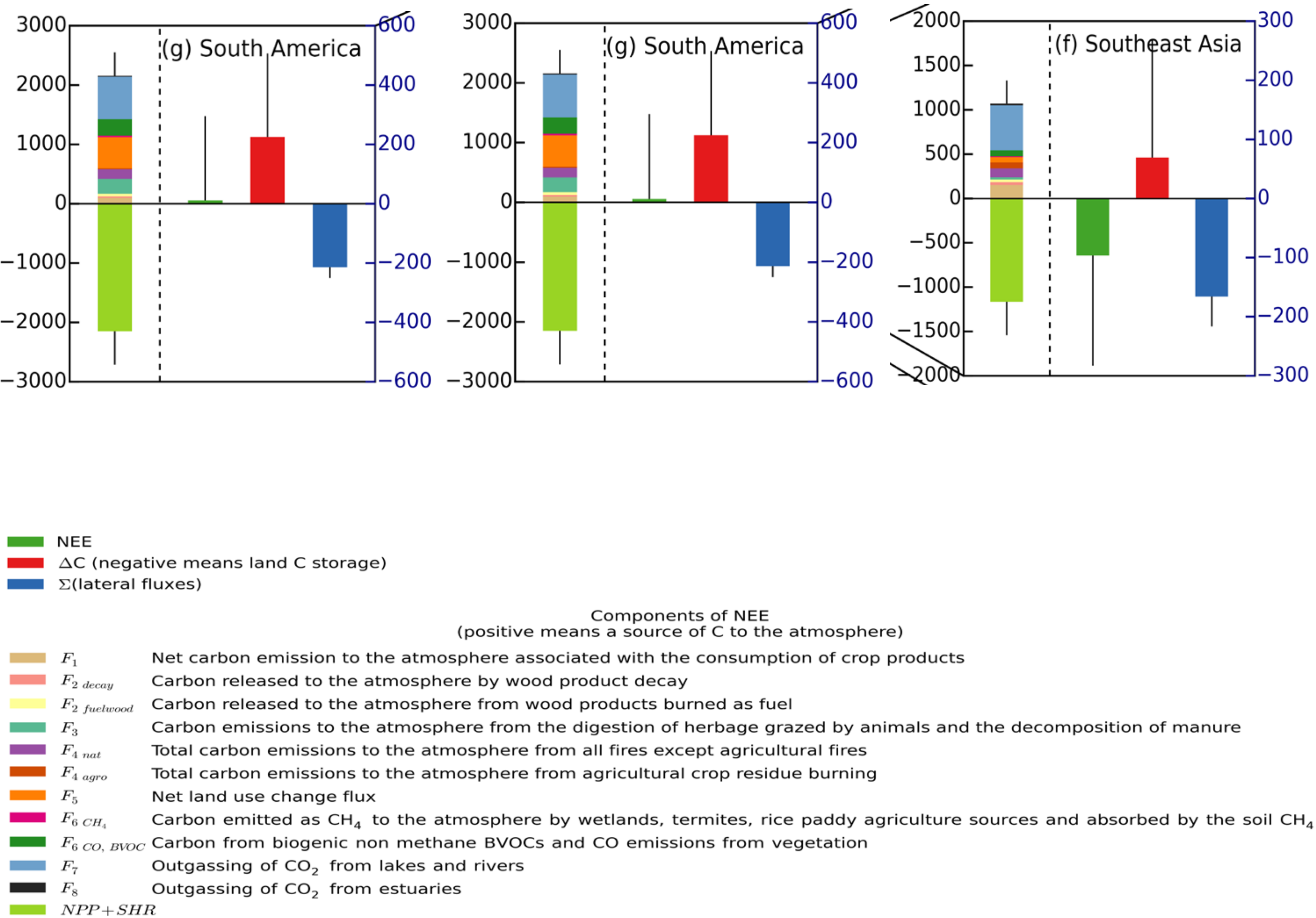
$NPP + SHR$



(g) South America
(g) South America
(f) Southeast Asia
3000
2000
1000
0
−1000
−2000
−3000
600
400
200
0
−200
−400
−600
1500
500
−500
−1500
300
100
−100
−300
NEE
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F_8 Outgassing of CO_2 from estuaries
$NPP+SHR$

Global bottom-up NEE 2000-2009

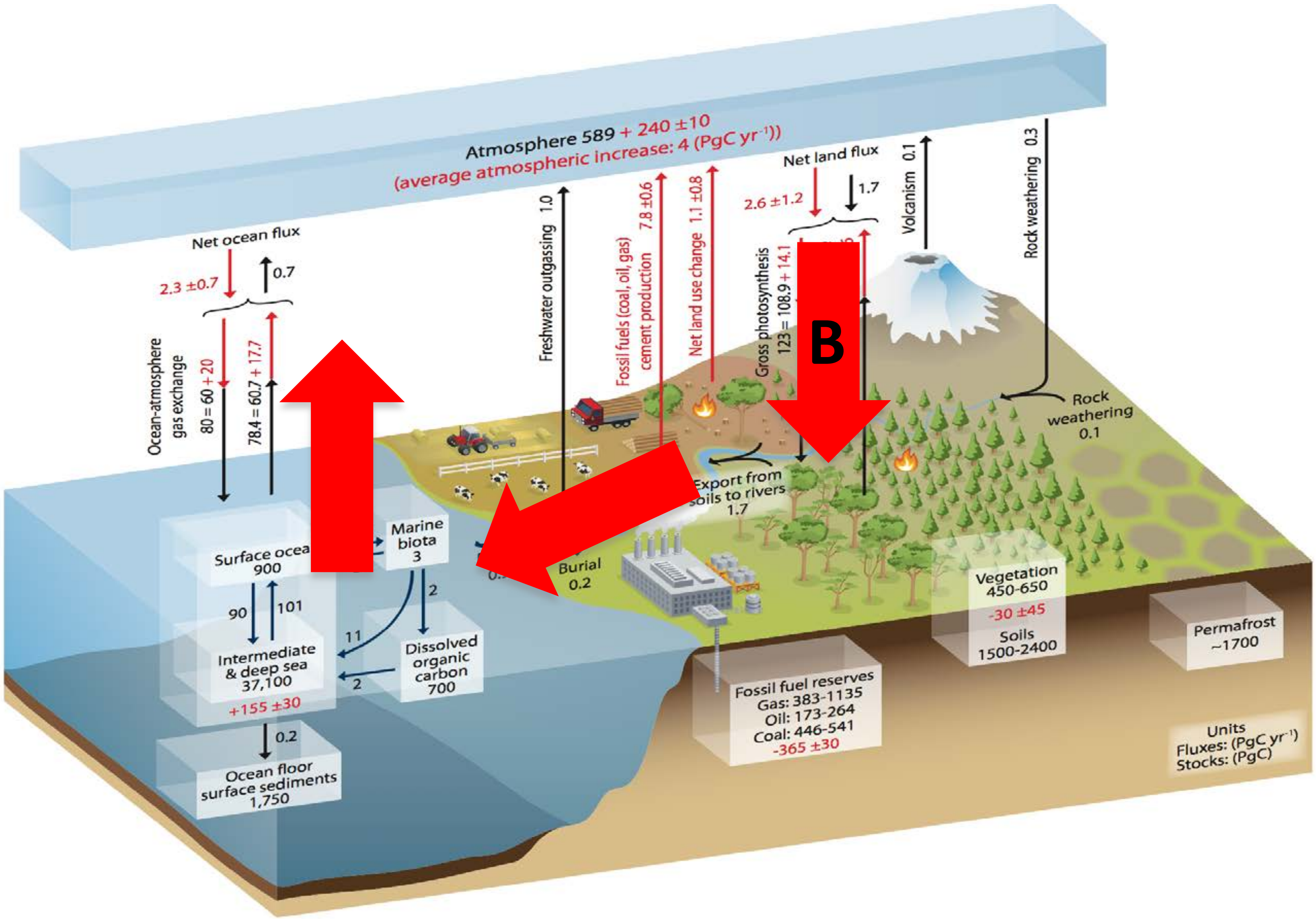
$NEE_{bottom\ up} = 1.8 \pm 0.6$

$NEE_{top\ down} = 1.4 \pm 0.9$

$LUC_{bottom\ up} = 0.9 \pm 0.2$

$LUC_{Houghton} = 1.0 \pm 0.6$

$PgC\ yr^{-1}$



B = background land CO_2 uptake during pre-industrial; this C is transported by rivers and outgassed in the ocean

Global bottom-up NEE 2000-2009

B = background land CO_2 uptake

B = 0.45

$NEE_{bottom\ up} - B = 1.3 \pm 0.6$

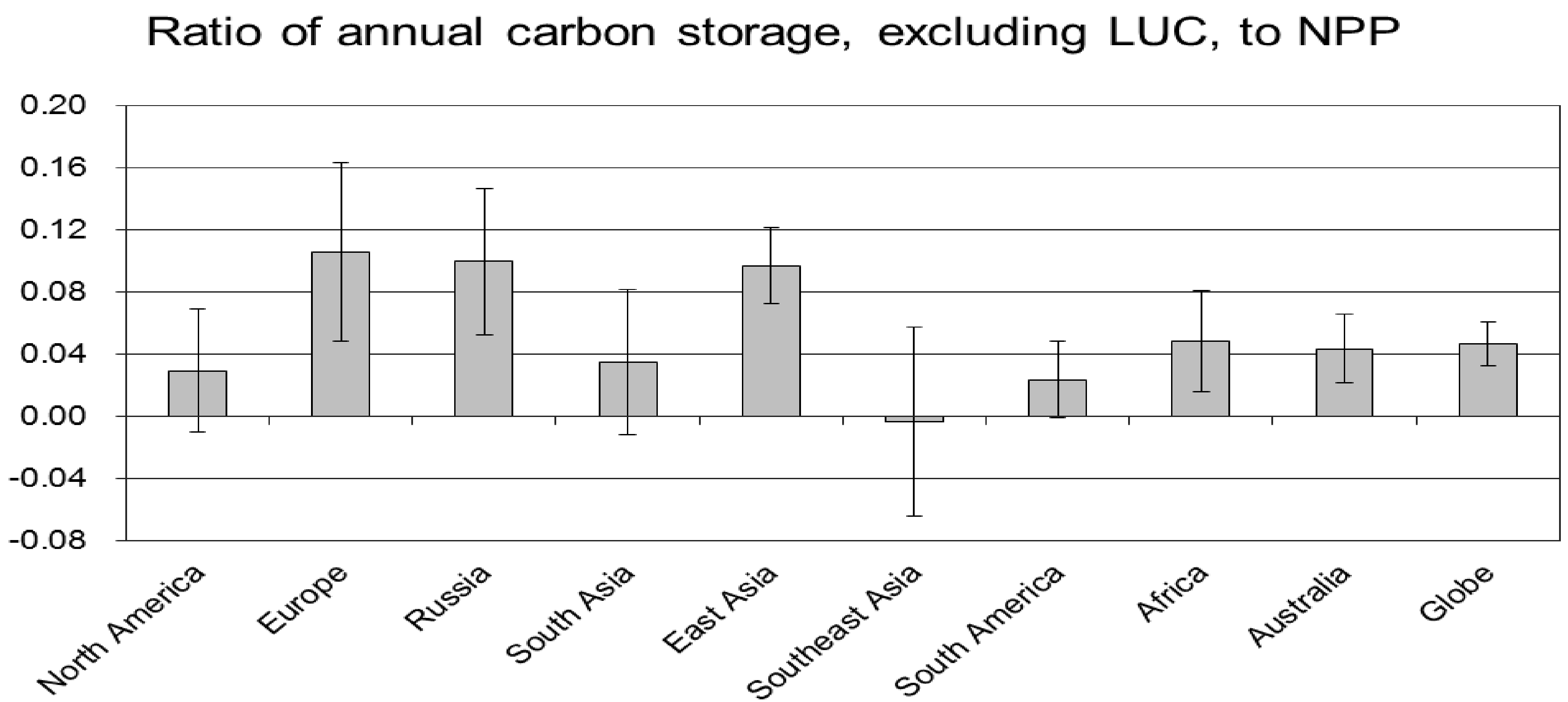
$NEE_{top\ down} = 1.4 \pm 0.9$

$LUC_{bottom\ up} = 0.9 \pm 0.2$

$LUC_{Houghton} = 1.0 \pm 0.6$

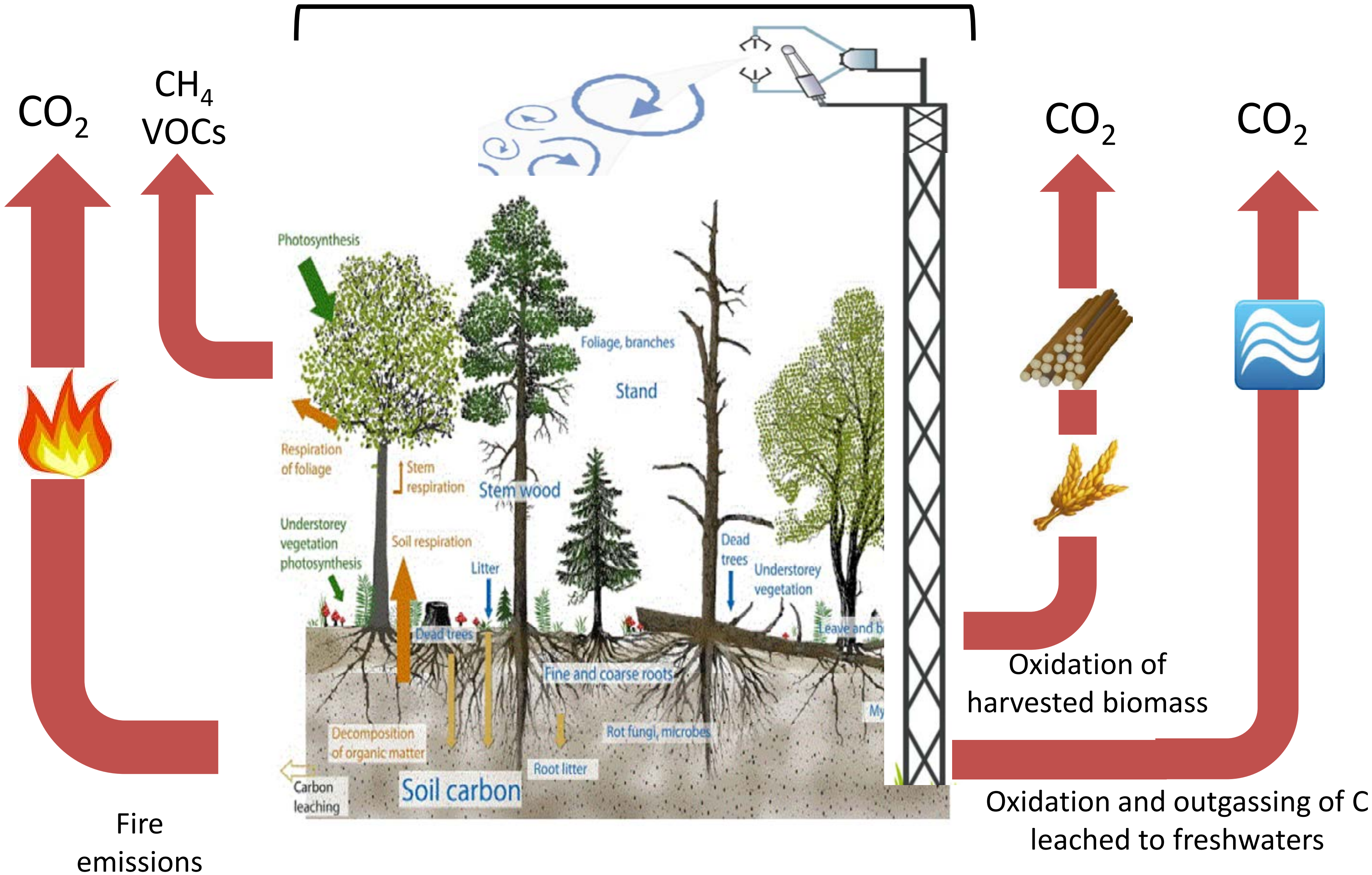
PgC yr^{-1}

Carbon storage efficiency of NPP
Excluding land use change



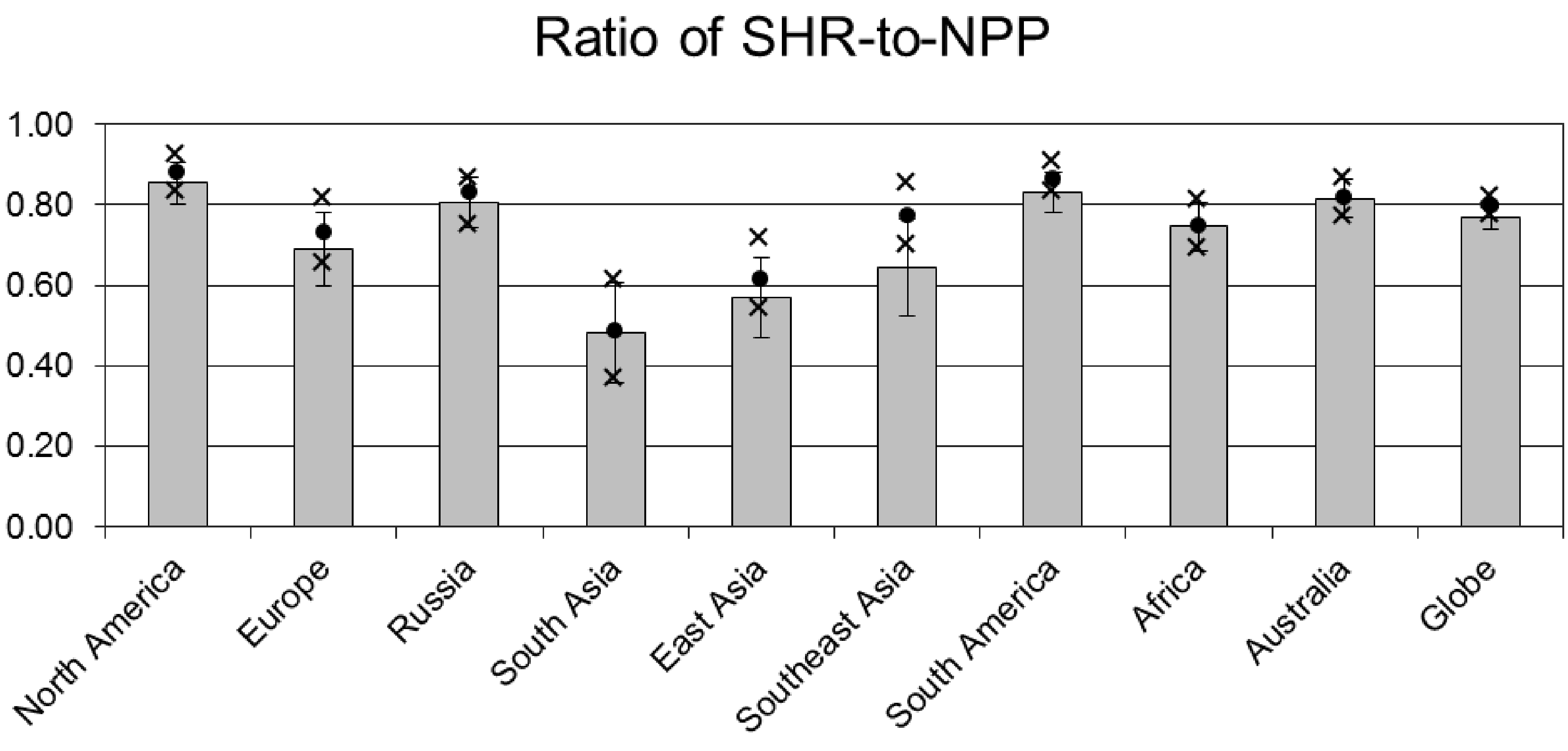
Measured by eddy covariance :

NEE = NPP + soil heterotrophic respiration



Soil heterotrophic respiration-to-NPP ratios

Global mean value ranges from 77 to 80%
Asian Regions tend to have a lower ratio than other regions because of intensively ecosystem management ?
IPCC TAR => 90%
Trendy models ≈ 80% in all regions



Lateral fluxes and future scenarios

A larger fraction of NPP not returned to the soil imply :

-Smaller change of soil C per ppm atmospheric CO_2 (β_{soil})

-Smaller change of soil C per ° C warming (γ_{soil})

Compared to ESMs with only NPP, some fire, LUC, HR

Which effect is the strongest ?

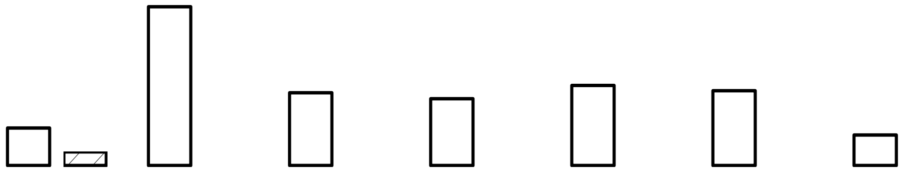
A compact Earth System Model (OSCAR) with all biogeochemical feedbacks was emulated to reproduce six CMIP5 ESMs

Two runs – "all NPP to the soil" & " RECCAP NPP to SHR ratio" were performed

Models	Lateral fluxes included in CMIP5 simulations					
	Fires	**LUC & wood products**	**Harvest of crop**	**Grazing**	**Non-CO_2 Biogenic C-fluxes**	**Rivers**
BCC-CSM-1.1	False	False	False	False	False	False
CanESM2	False	False	False	False	False	False
CESM1-C	True	True	False	False	False	False
HadGEM2-ES	False	True	False	False	False	False
IPSL-CM5A-LR	True	True	True	False	False	False
MPI-ESM-LR	True	True	False	False	False	False
NorESM1-ME	True	True	True	False	False	False

	Proxy used to assess relative change						
	NPP	**Fires**	**LUC & HWP**	**Harvest**	**Grazing**	**CH_4 fluxes**	**Rivers**
Backcast (1850, 1900, 1950)	CMIP5 (7 models)	CMIP5 (4 models)	CMIP5 (5 models)	LUH data	LUH data	constant	This study (see text)
Reference (2000-2010)	RECCAP	RECCAP	RECCAP	RECCAP	RECCAP	RECCAP	RECCAP
Forecast (2050, 2100)	CMIP5 (7 models)	CMIP5 (4 models)	CMIP5 (3 models)	LUH data	LUH data	constant	This study (see text)
	Global values relative to reference period						
1850	1.00	1.14	0.53	0.14	0.11	1.00	0.85
2000-2010	1	1	1	1	1	1	1
2050	1.87	2.05	1.14	1.06	1.05	1.00	1.31
2100	1.72	1.87	0.75	1.12	1.03	1.00	1.75

Lateral fluxes and future scenarios



ge

Lateral fluxes and future scenarios

With minus without NEE components not related to soil respiration changes of CO_2 and T between 2100 and 2010

$\Delta CO_2 = 19 – 77$ ppm

$\Delta T = 0.1 – 0.4\,^\circ C$

An important characteristic of RCP8.5 are transformative changes the biomass use for energy purposes from presently traditional (non-commercial) use in the developing world to commercial use in dedicated bio-energy conversion facilities (for power and heat) in the future. Globally the contribution of bioenergy is increasing in RCP8.5 from about 40 EJ in 2000 to more than 150 EJ by 2100. The vast majority of this biomass is harvested in forests, resulting in increased land-requirements for secondary managed forests. While total area of forests is declining in RCP8.5 (Fig. 8), the share of managed forests and harvested areas for biomass are thus increasing considerably. The latter grows from about 17 million ha to more than 26 million ha by 2100. Uncertainties in the interpretation of the underlying

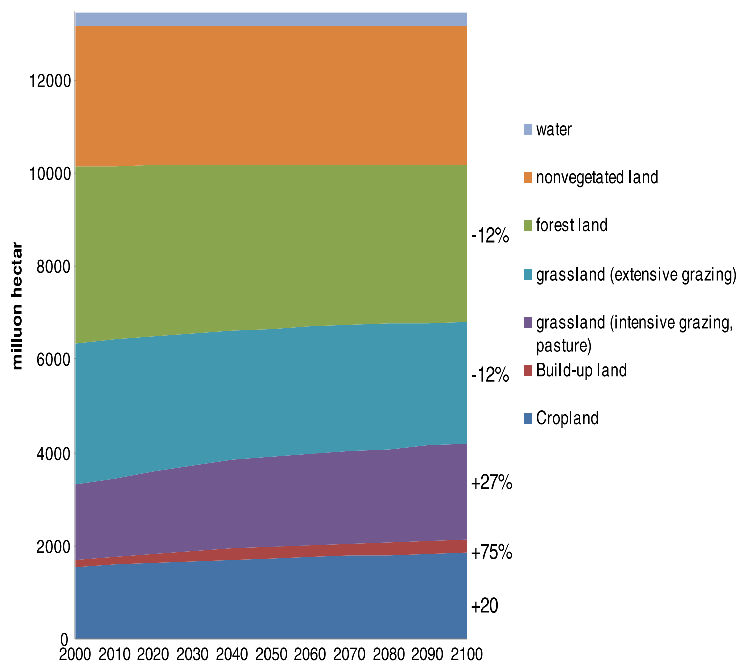


Fig. 8 Global land use by category in RCP8.5