

The terrestrial carbon cycle: processes and observations

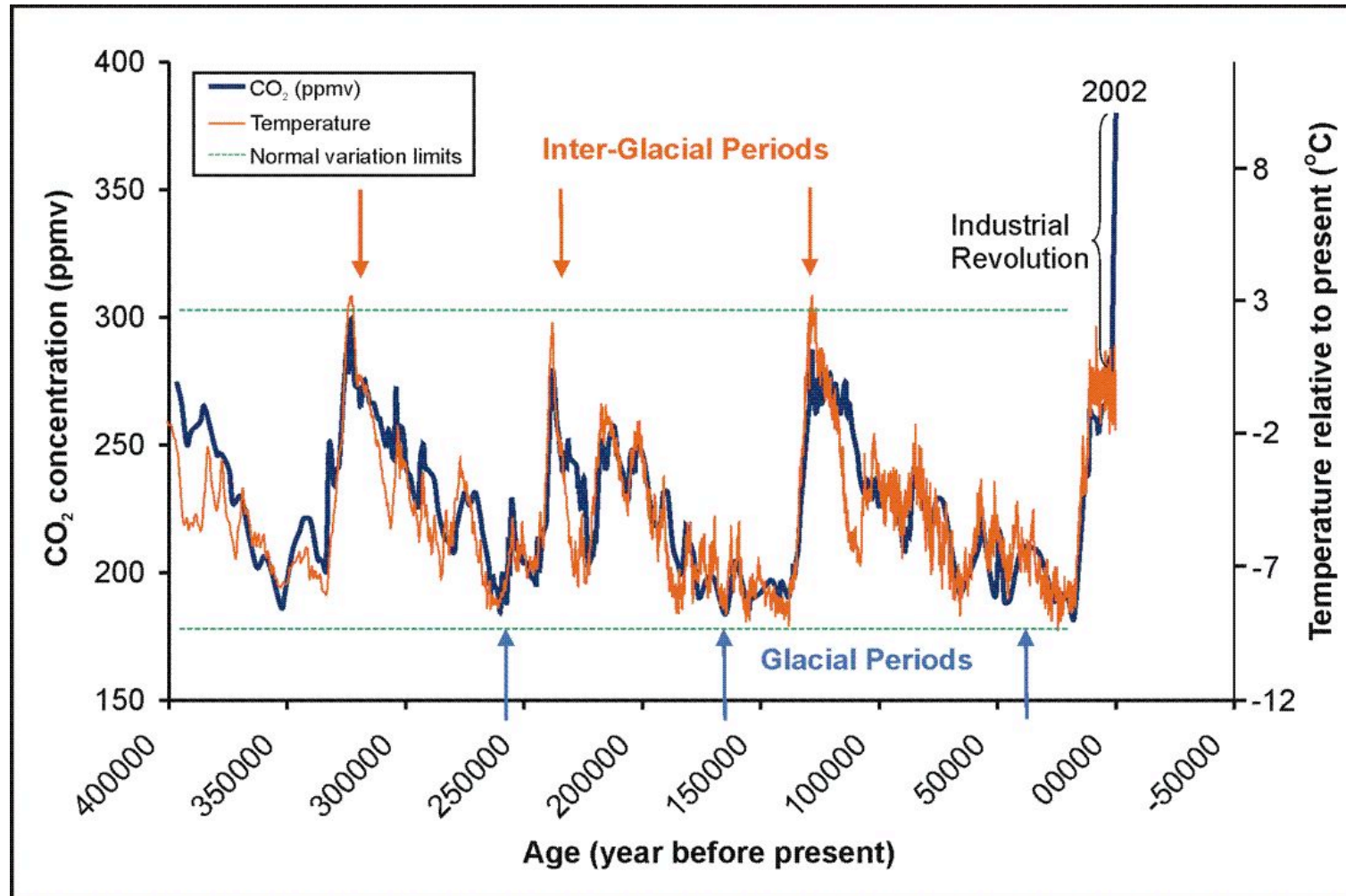
Shaun Quegan

Centre for Terrestrial Carbon Dynamics
National Centre for Earth Observation
& University of Sheffield

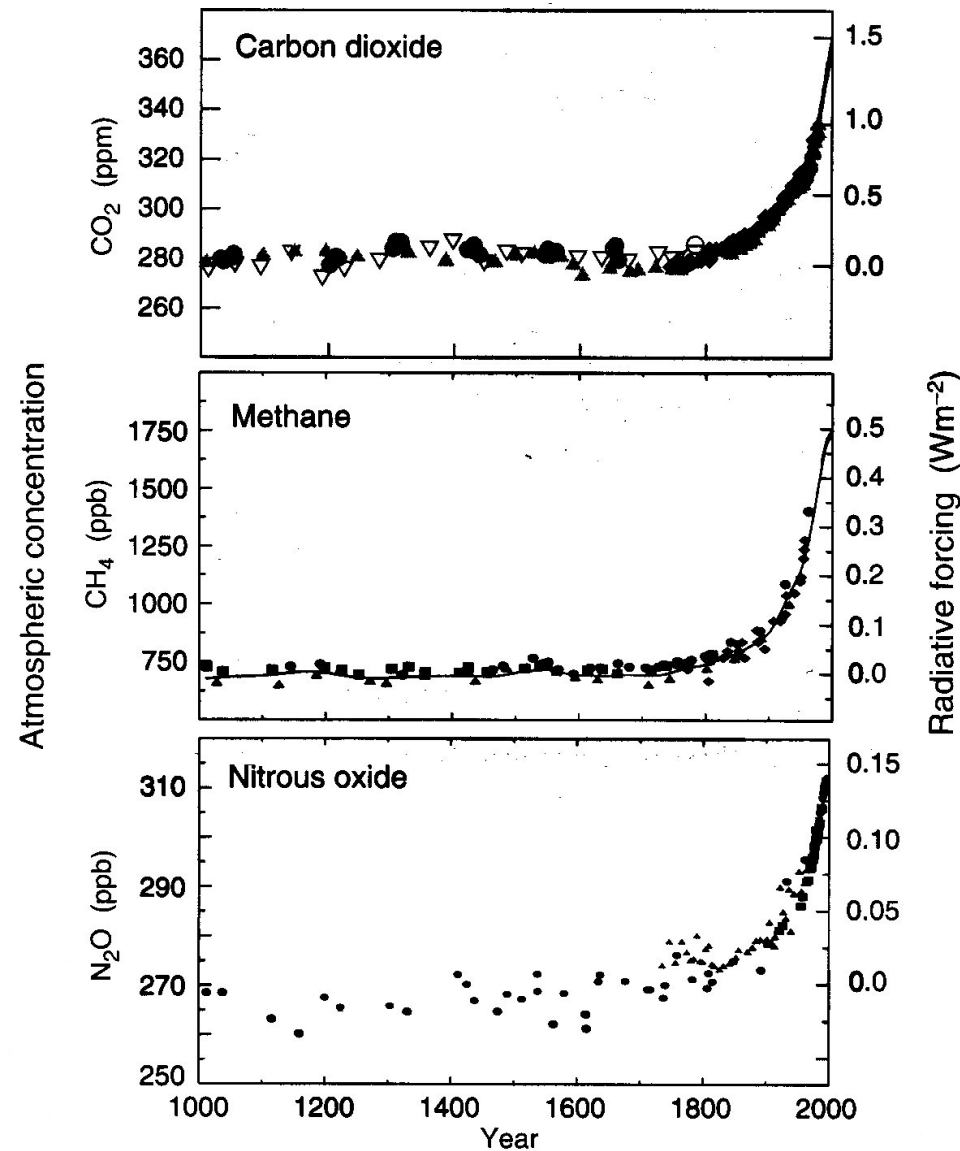
Lecture content

- u CO₂ and climate
- u The global C cycle and the role of the terrestrial biosphere: pools, fluxes and processes
- u Measuring land-atmosphere fluxes: global, regional, local
- u Uncertainties

Vostok: Past climate and CO₂



CO₂, NH₄ and N₂O in the last 1000 years



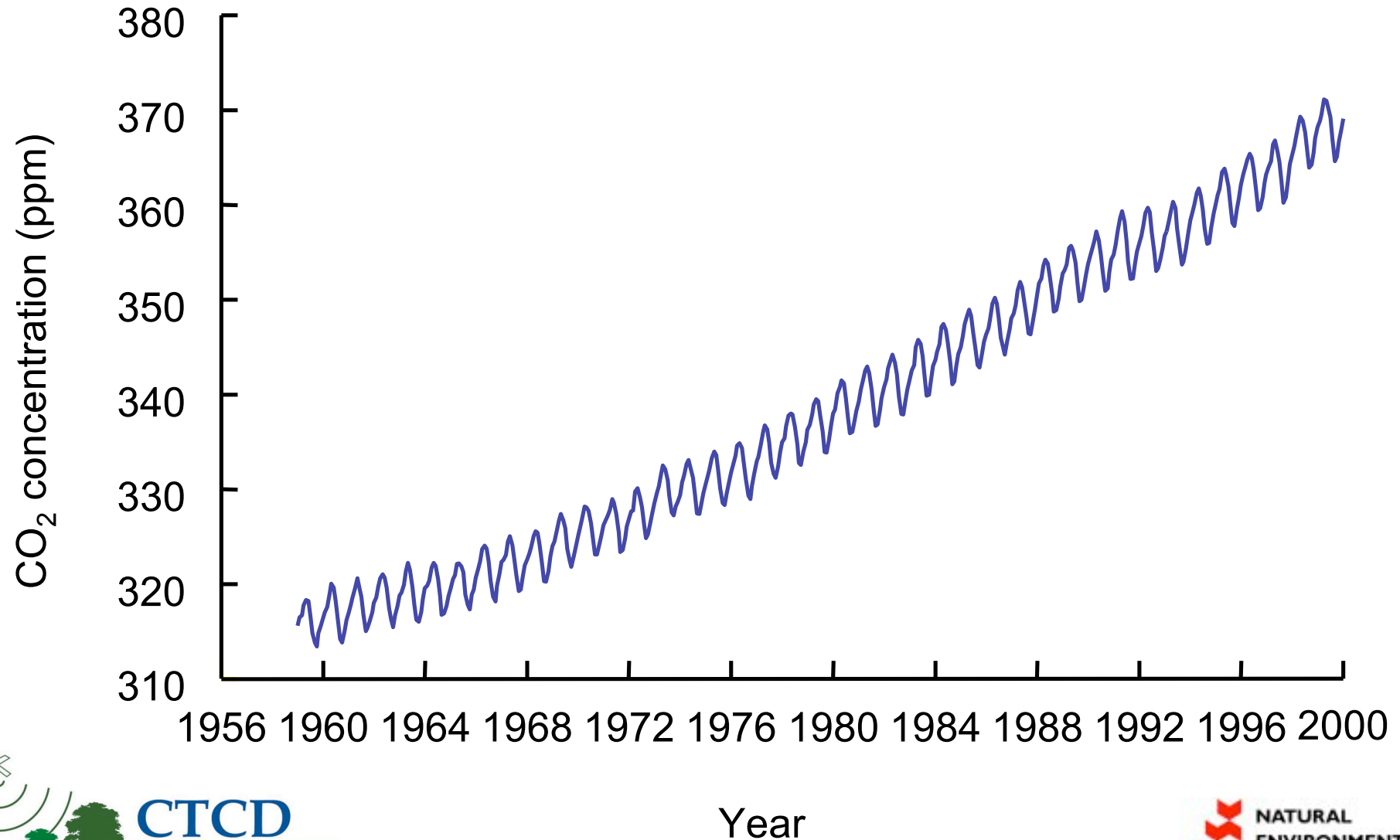
From: IPCC, Climate Change, 2001

Greenhouse gases (2)

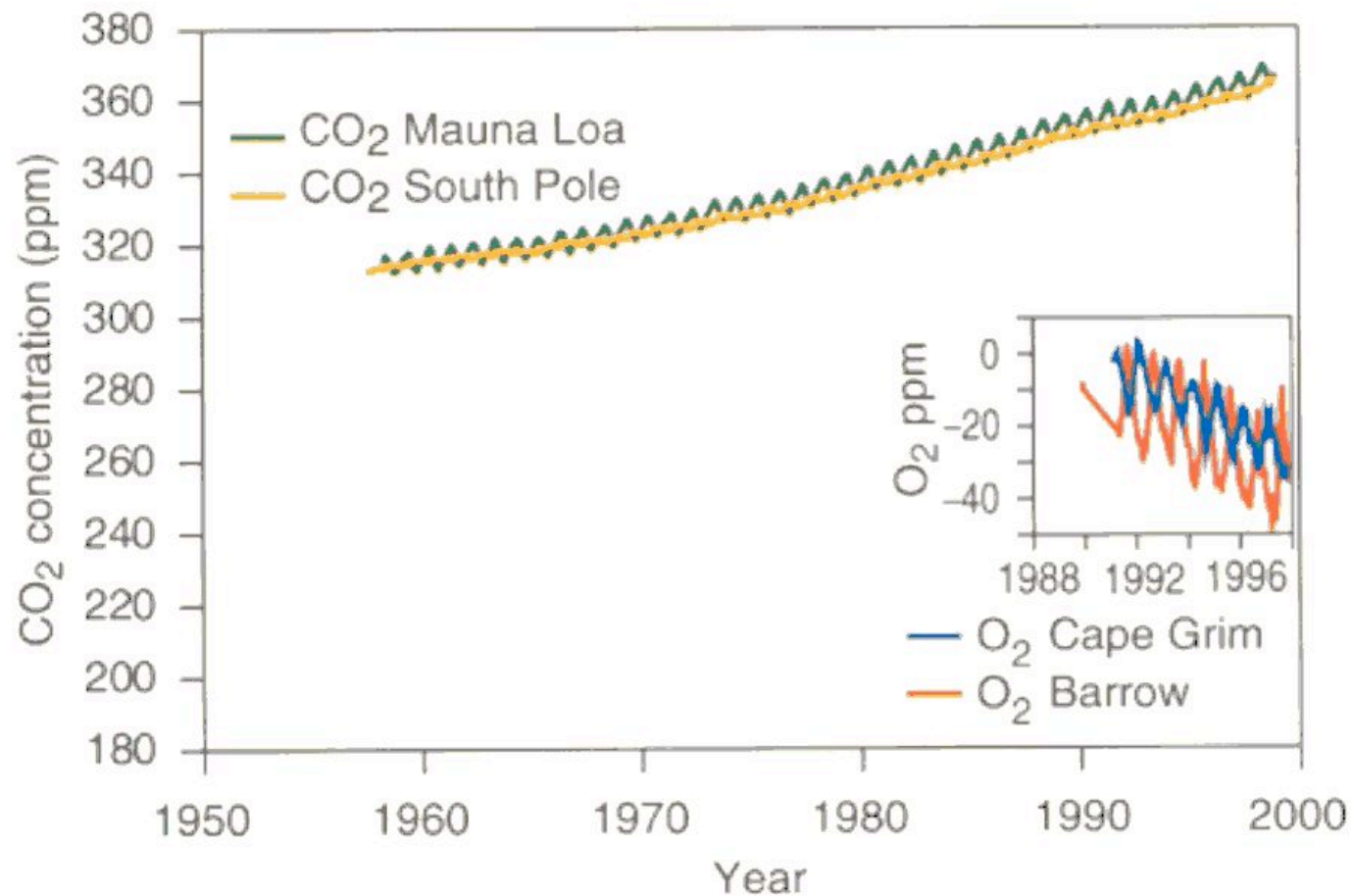
Gas	Radiative efficiency (Wm ⁻² ppb ⁻¹)	Lifetime (years)	Global Warming Potential		
			Time horizon		
			20 yrs	100 yrs	500 yrs
CO ₂			1	1	1
CH ₄	3.7×10^{-4}	12.0	62	23	7
N ₂ O	3.1×10^{-3}	114	275	296	156

IPCC, Climate Change, 2001

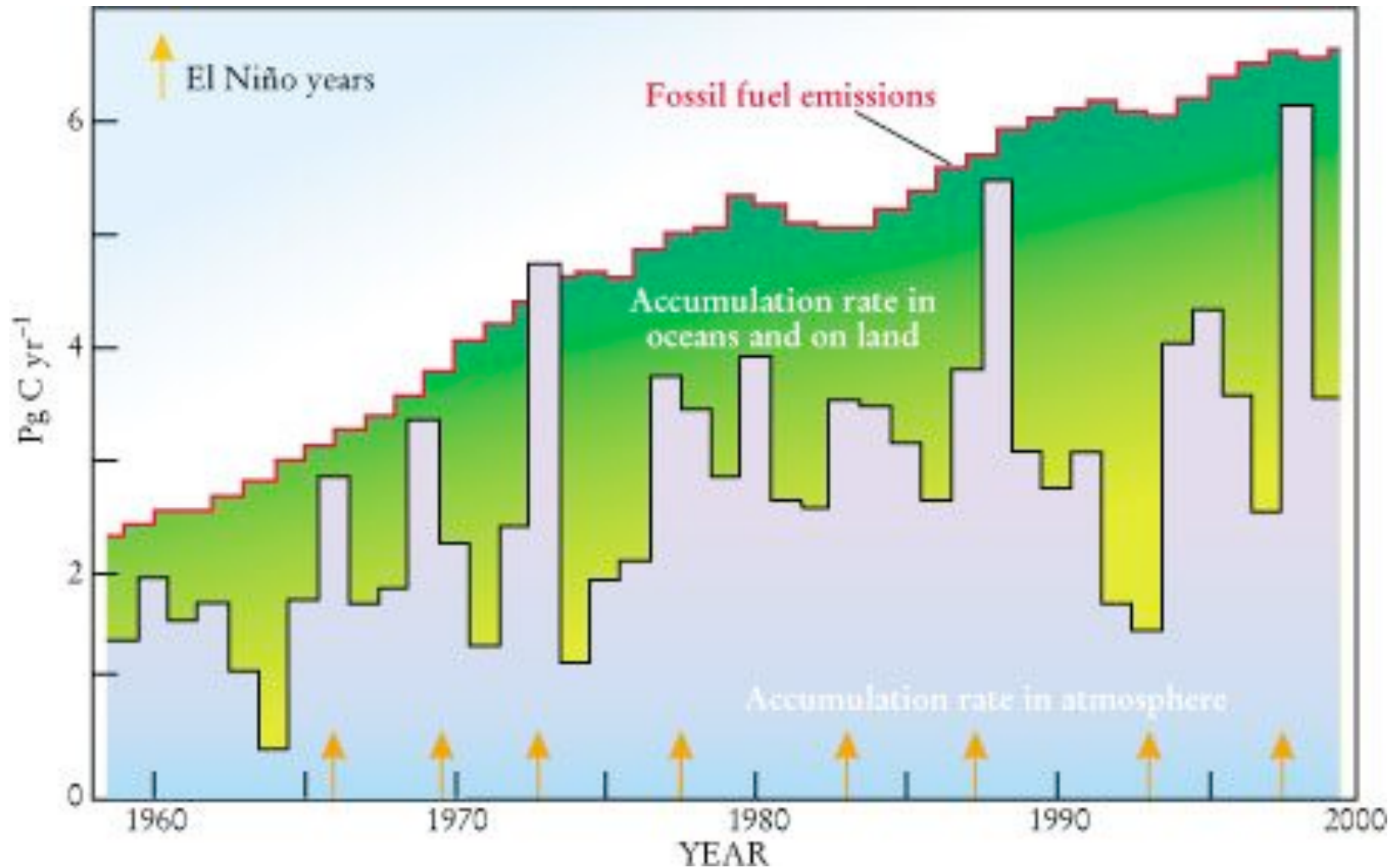
Mauna Loa C signal



Keeling CO2 plots

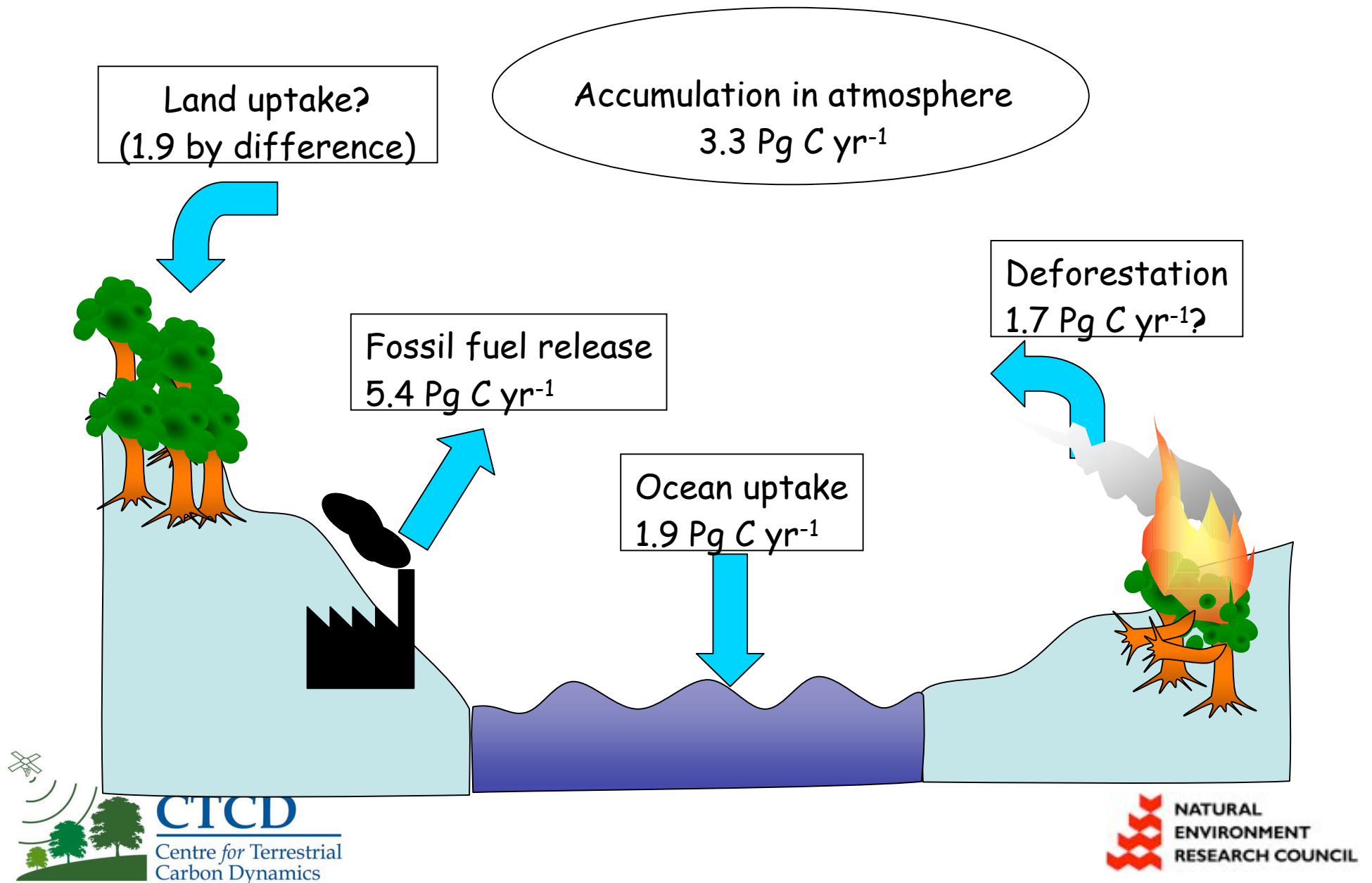


CO₂: emissions vs atmospheric increase

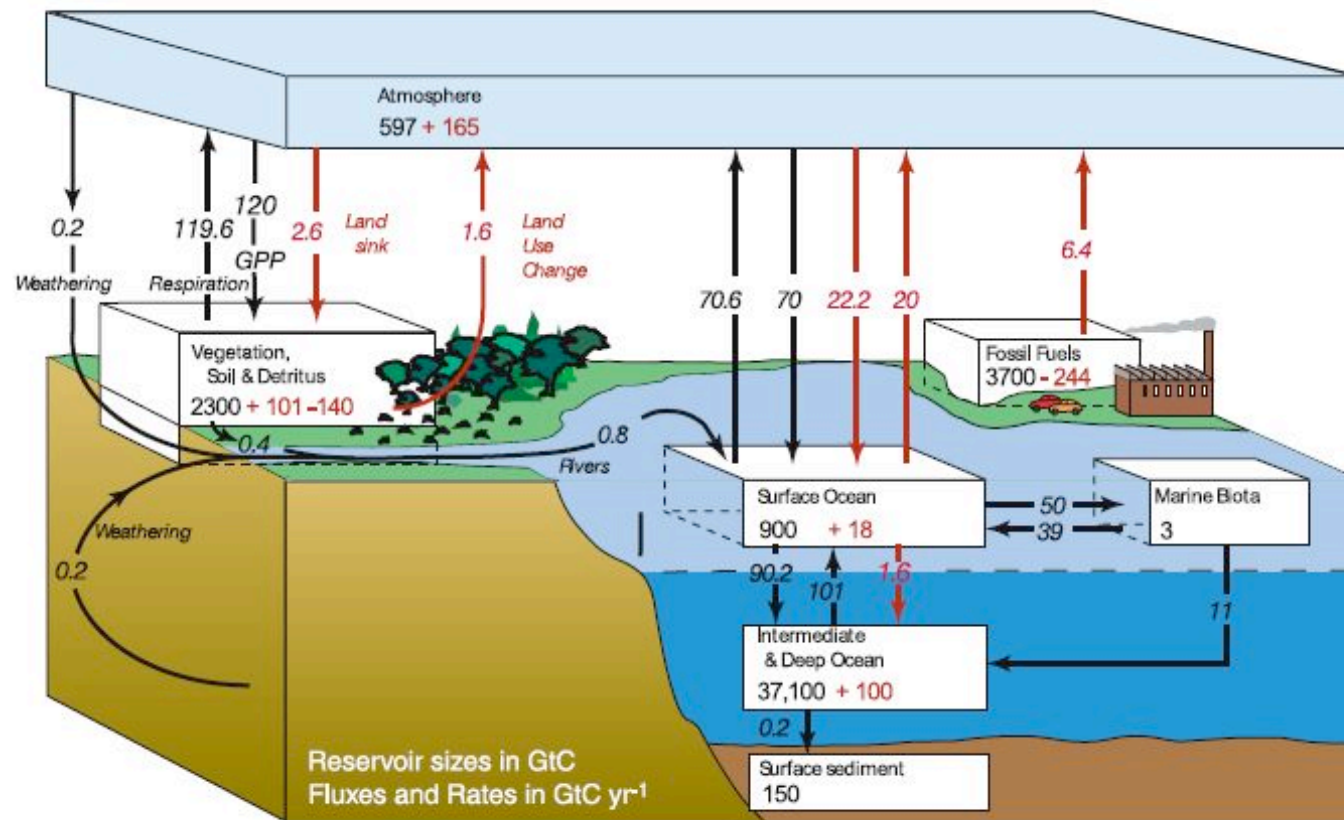


The global C cycle and the role of the terrestrial biosphere: pools, fluxes and processes

The C cycle: 1980s budget of anthropogenic carbon dioxide.

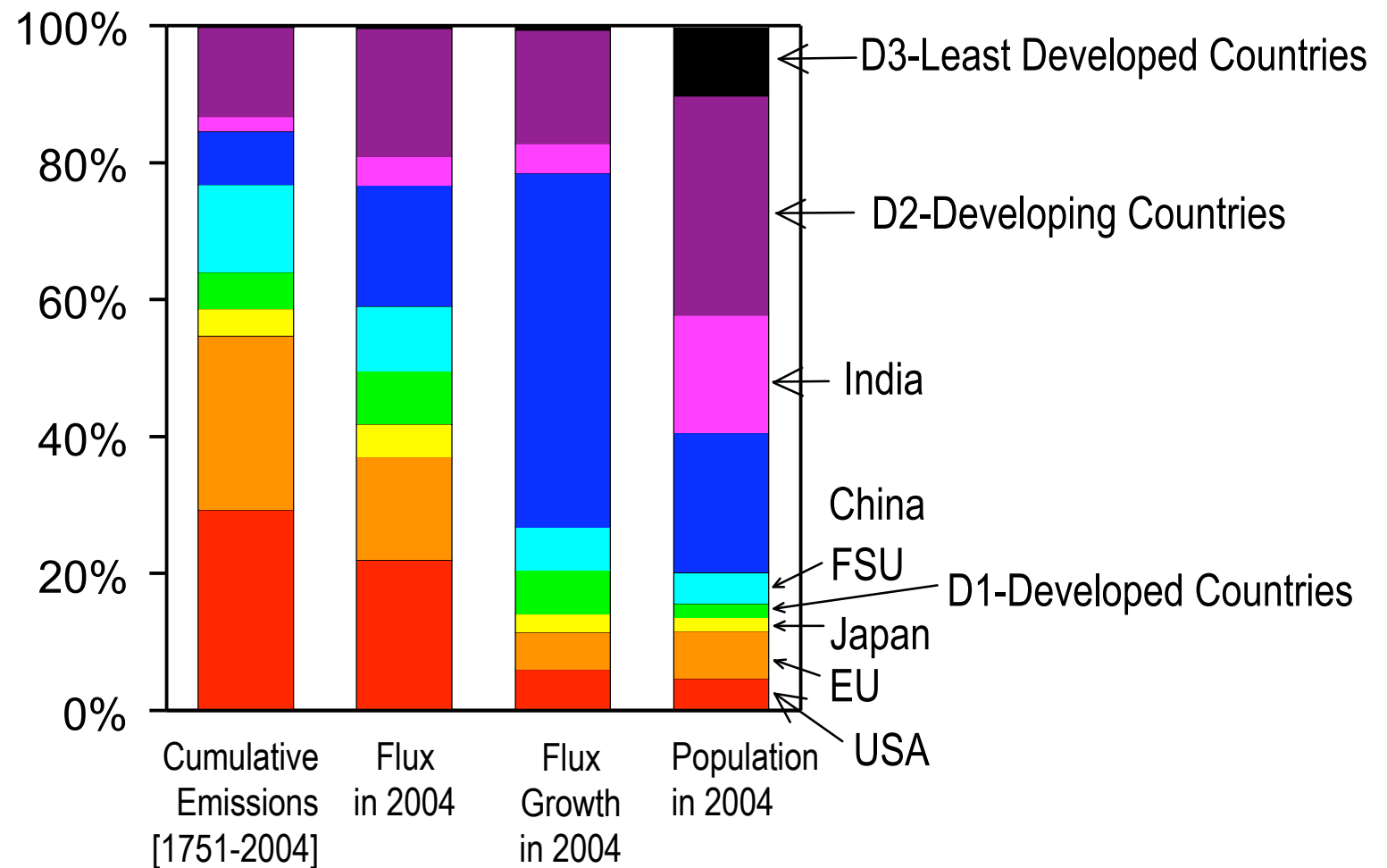


The Global Carbon Cycle

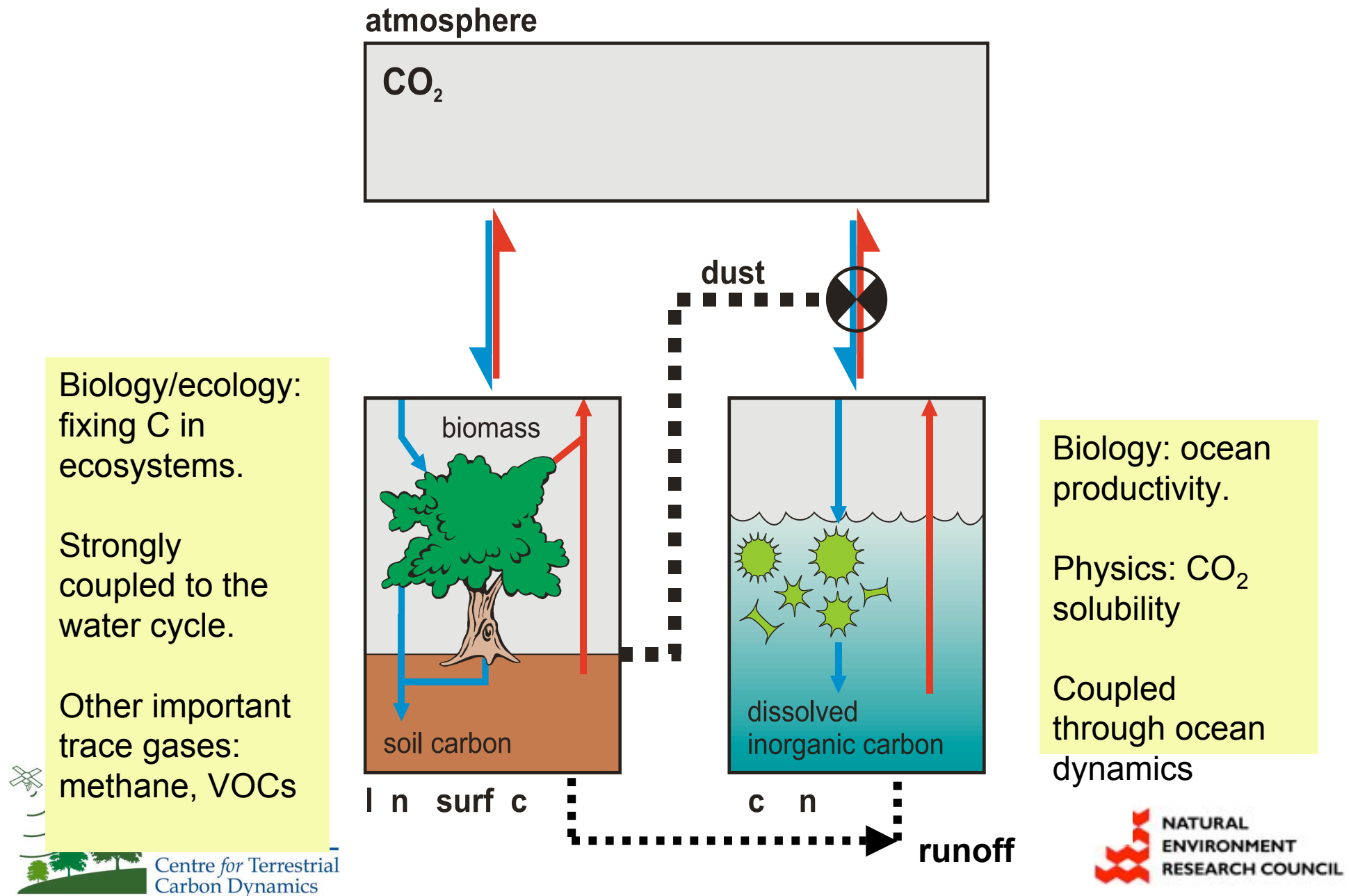


From IPCC 2007

Anthropogenic C Emissions: Regional Contributions



Domain coupling in the carbon cycle



Recent Carbon Trends and the Global Carbon Budget

updated to 2006

GCP-Global Carbon Budget team:

Pep Canadell, Philippe Ciais, Thomas Conway, Chris Field, Corinne Le Quéré, Skee Houghton,
Gregg Marland, Mike Raupach, Erik Buitenhuis, Nathan Gillett

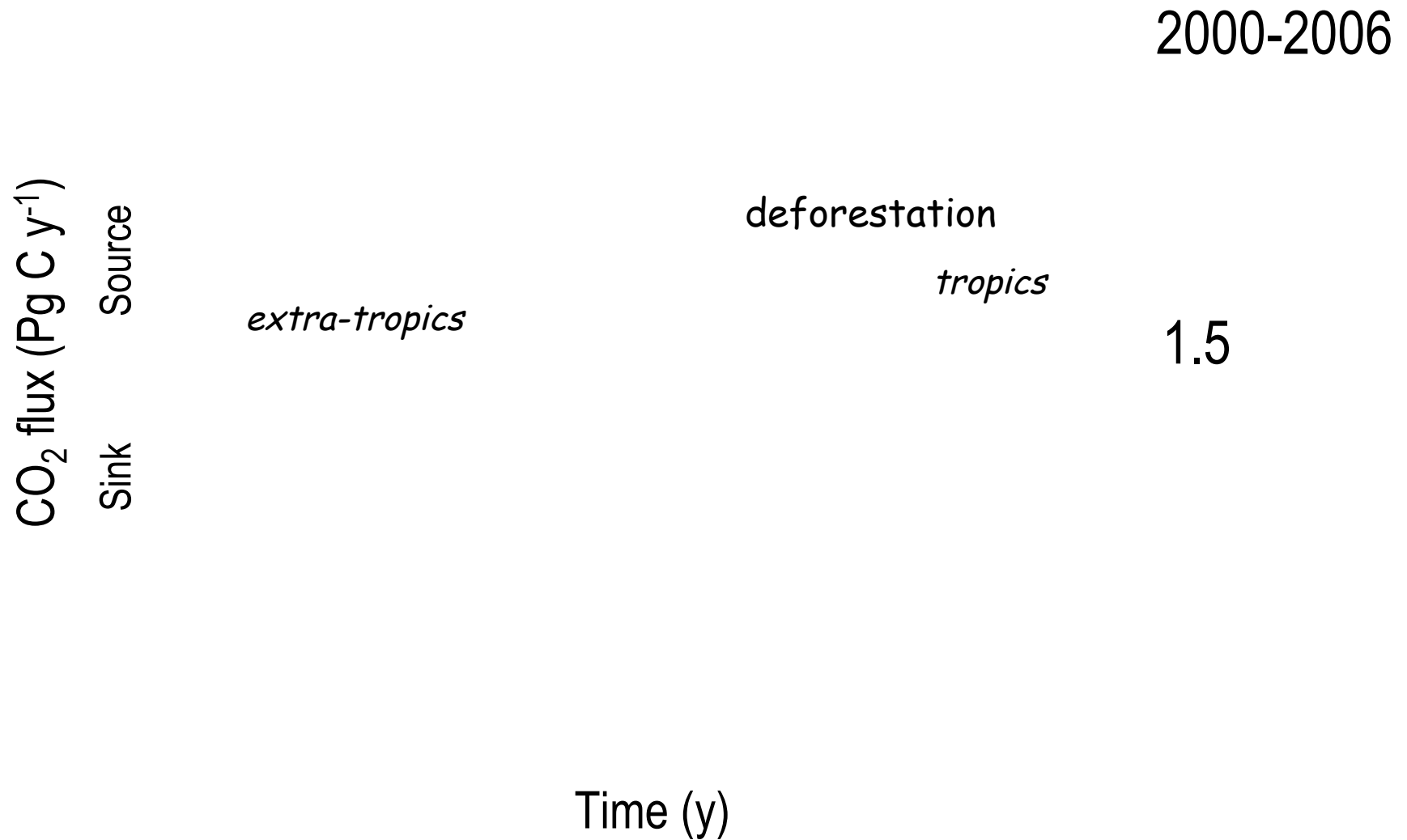
Last update: 15 November 2007



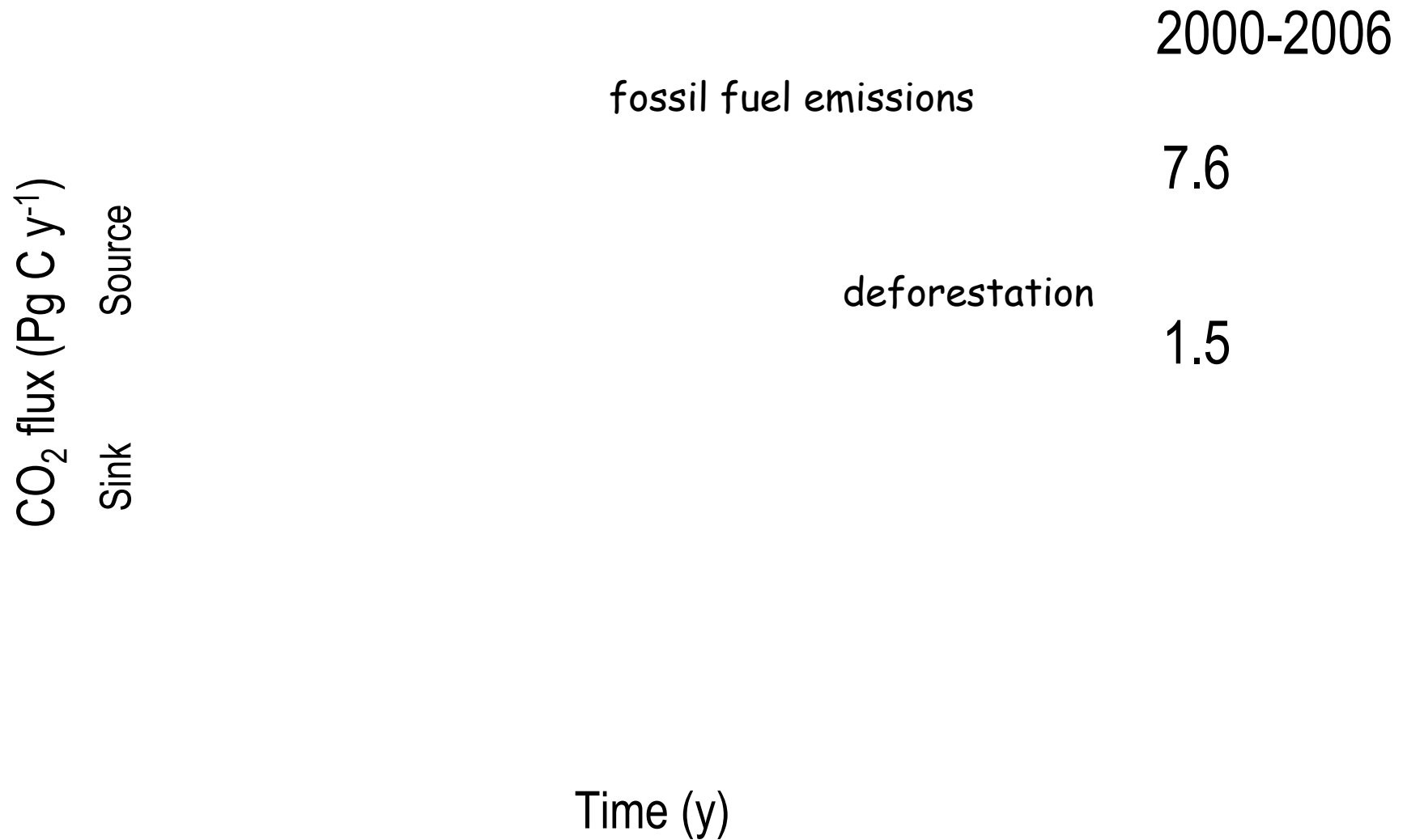
2.

The perturbation of the global carbon cycle (1850-2006)

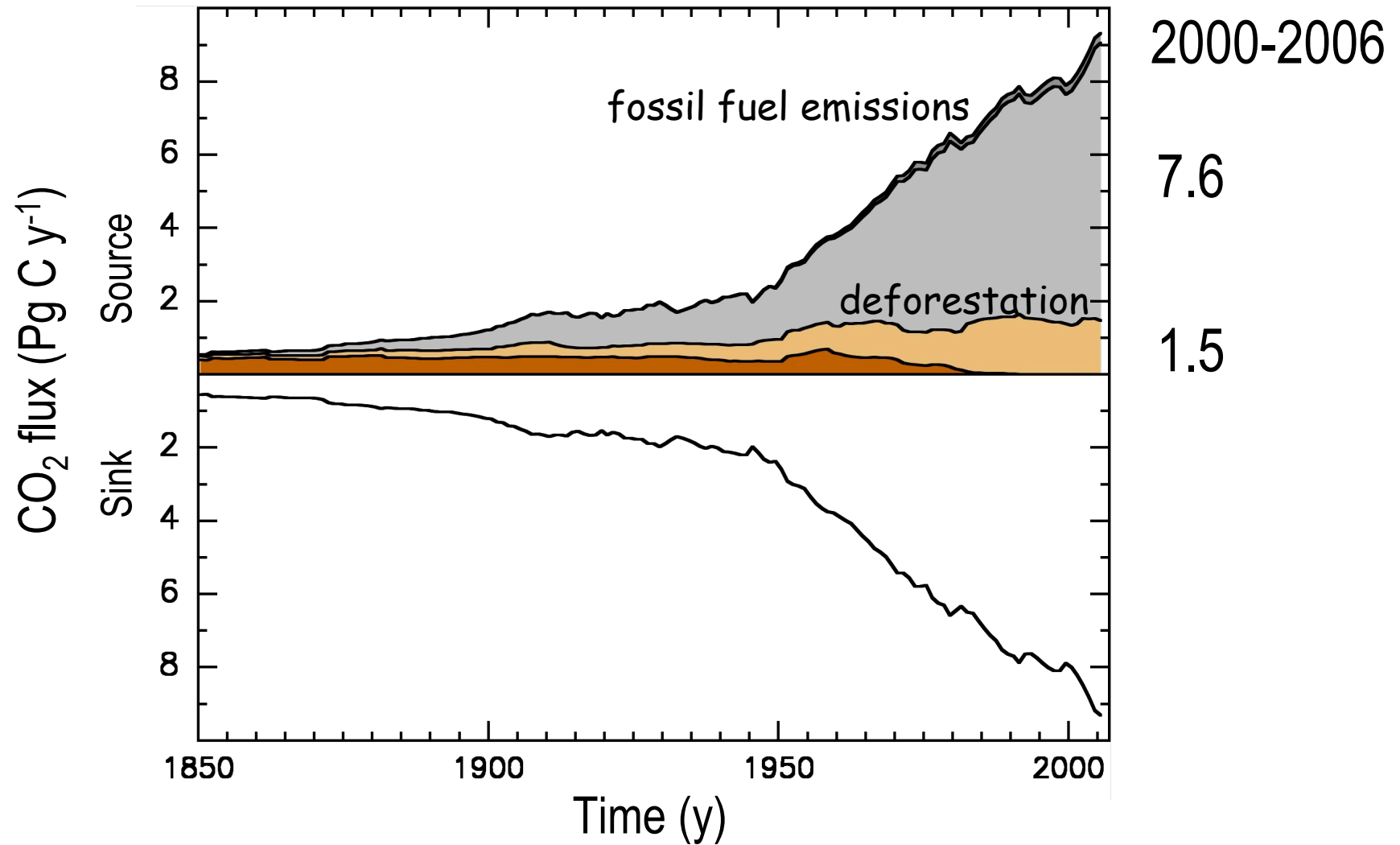
Perturbation of Global Carbon Budget (1850-2006)



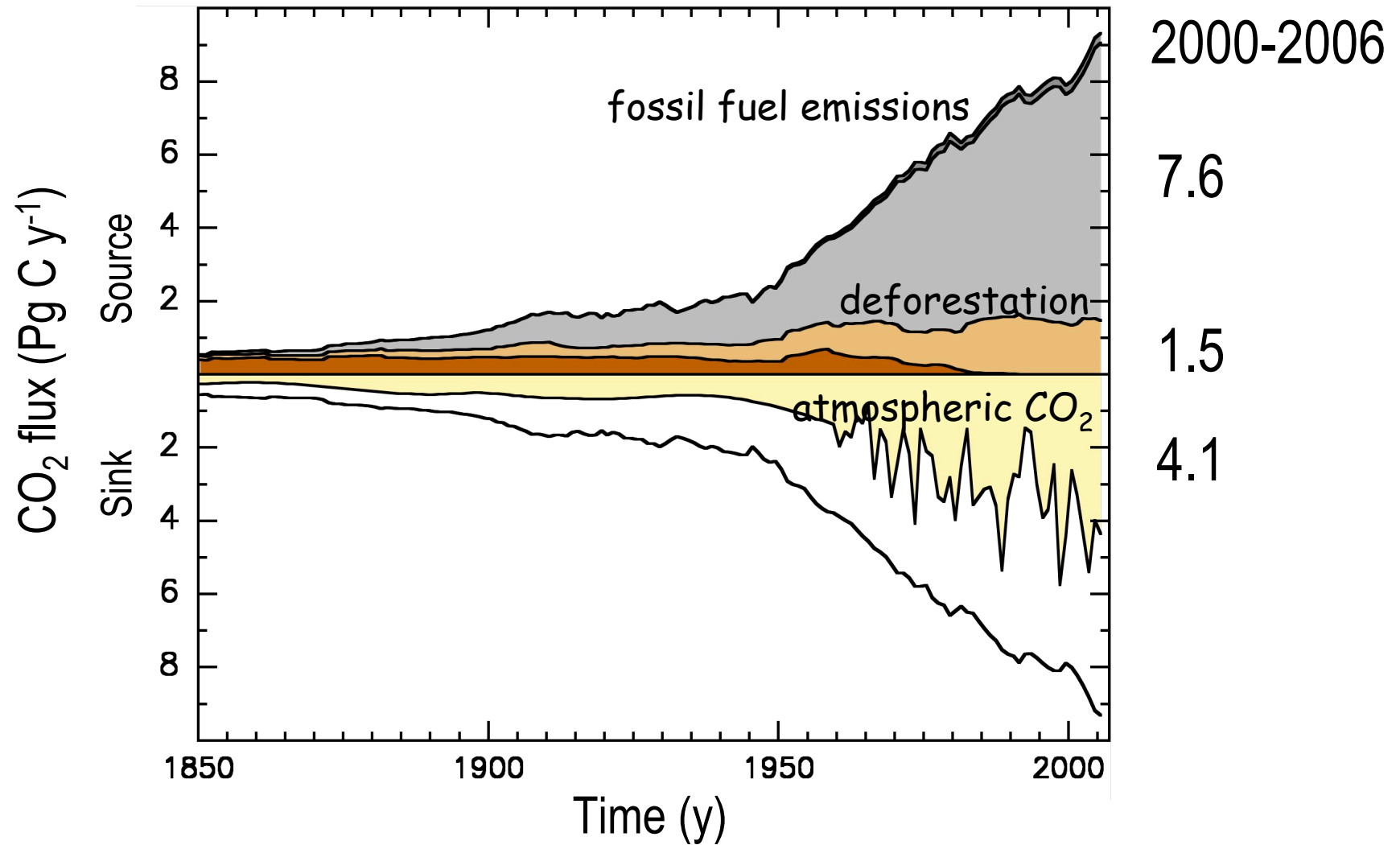
Perturbation of Global Carbon Budget (1850-2006)



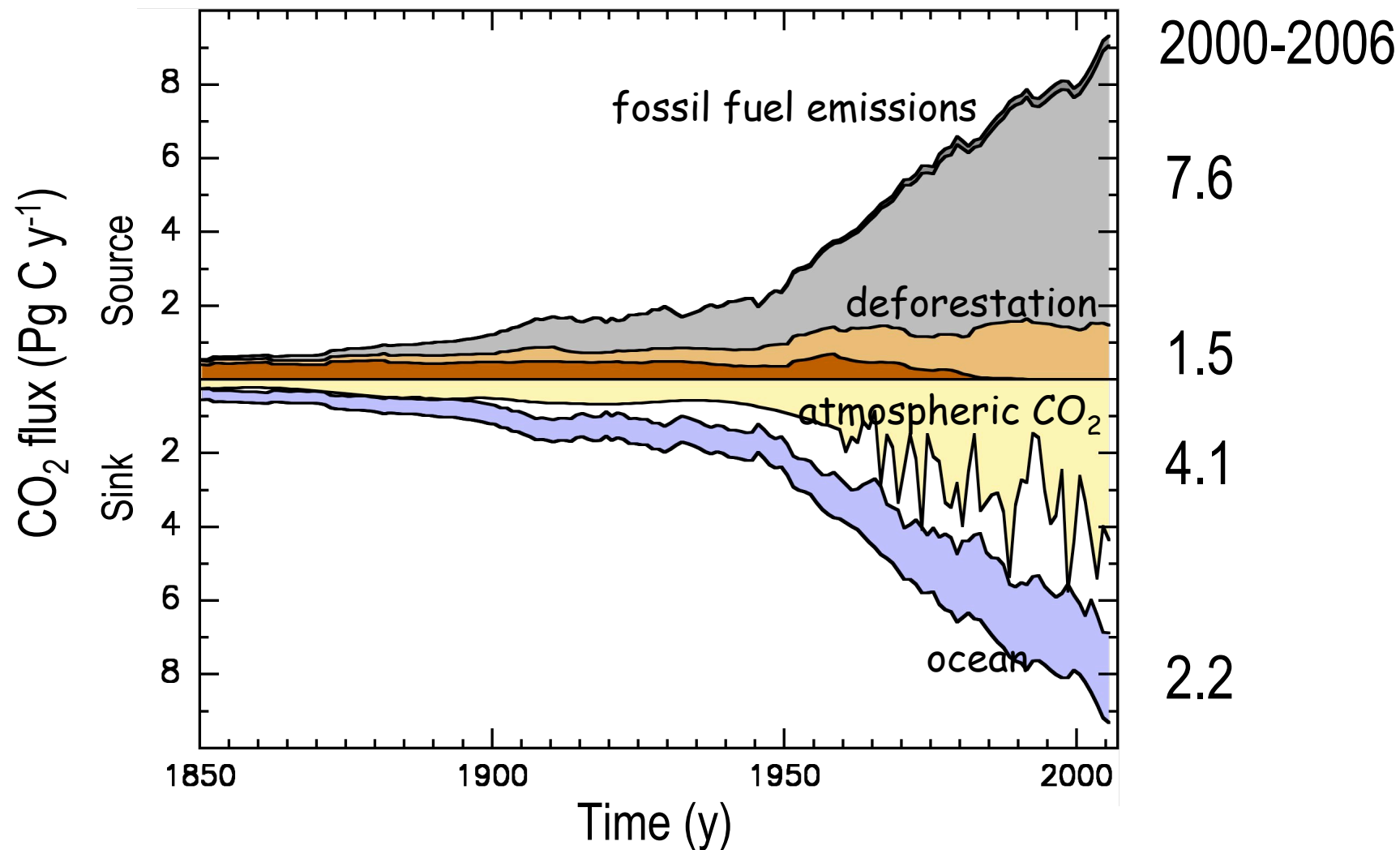
Perturbation of Global Carbon Budget (1850-2006)



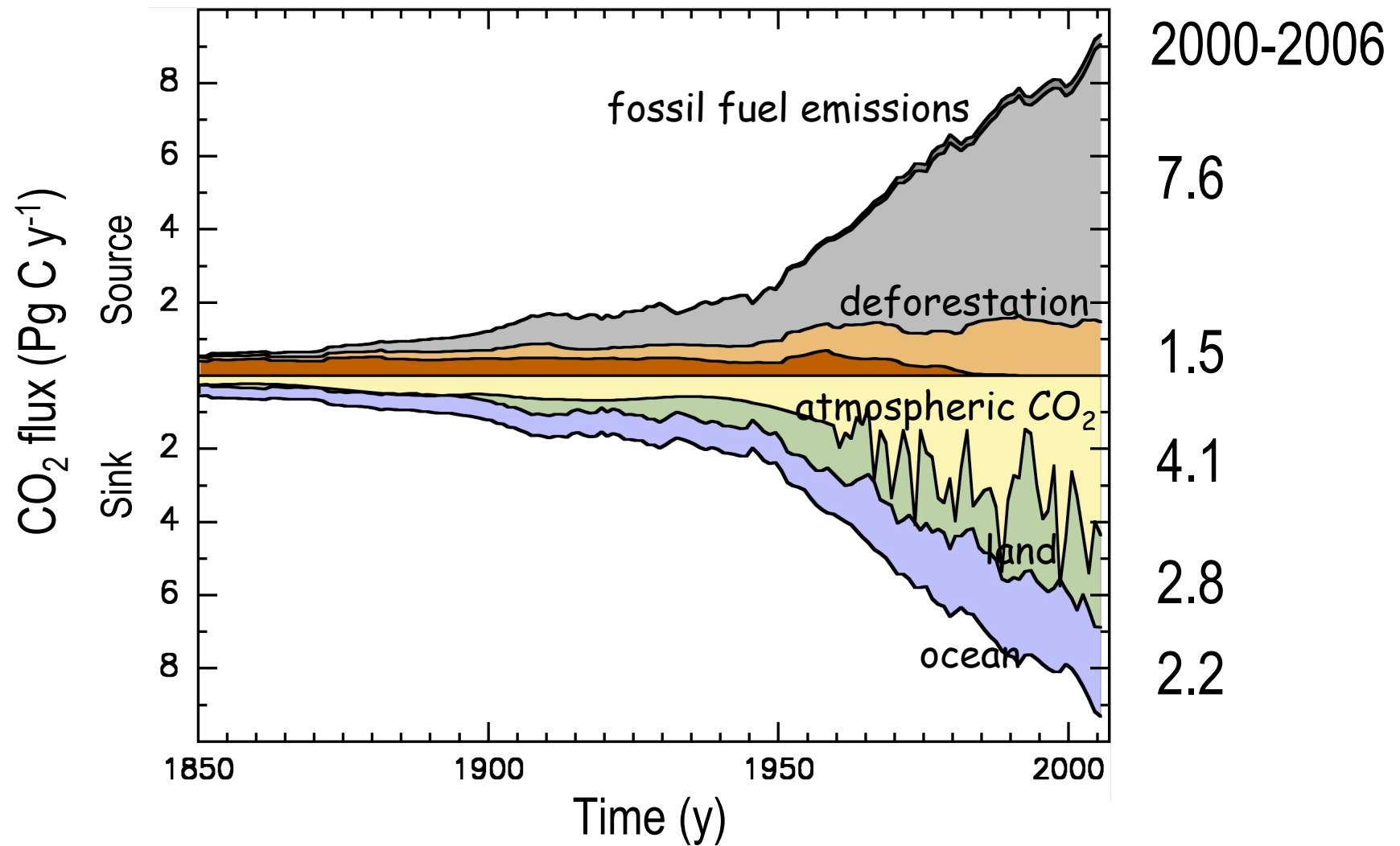
Perturbation of Global Carbon Budget (1850-2006)



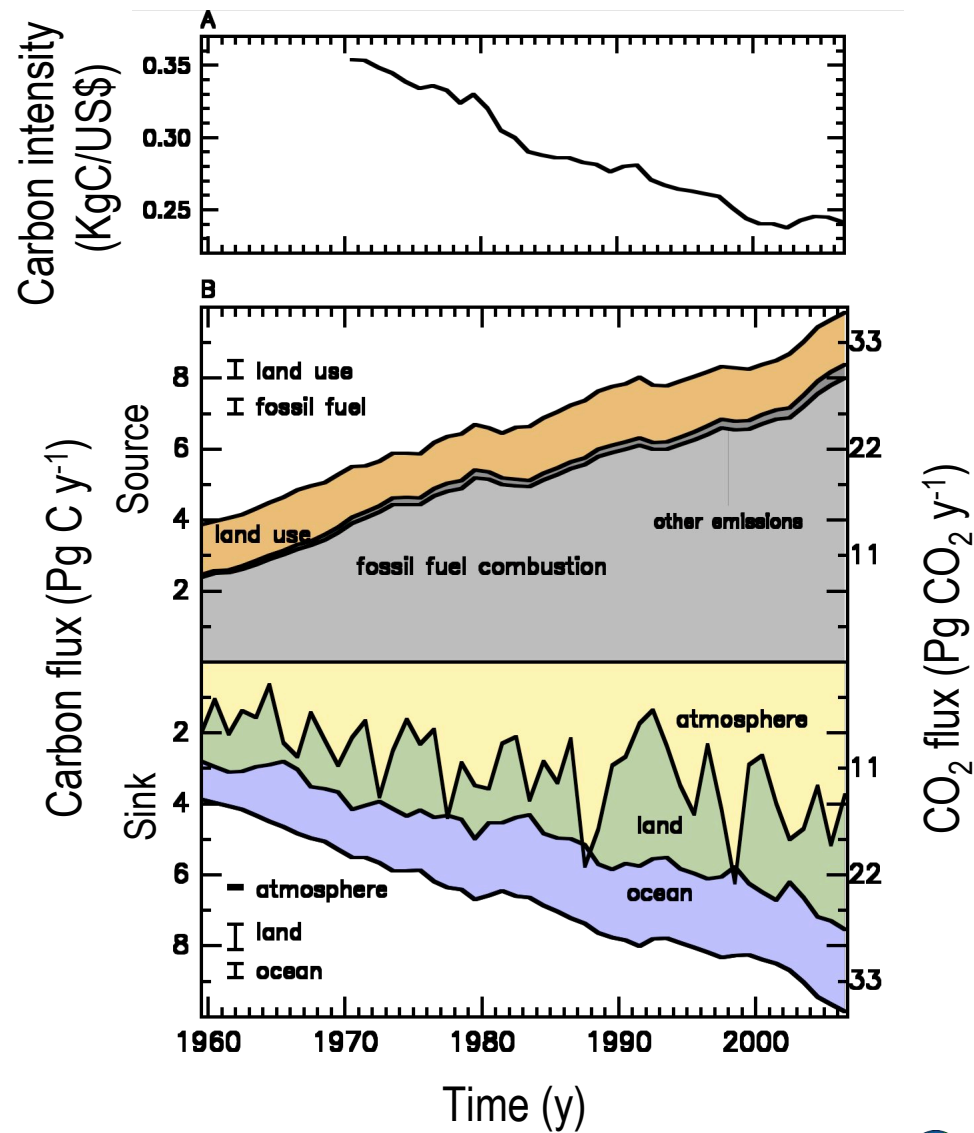
Perturbation of Global Carbon Budget (1850-2006)



Perturbation of Global Carbon Budget (1850-2006)



Perturbation of the Global Carbon Budget (1959-2006)



Canadell et al. 2007, PNAS

The big questions

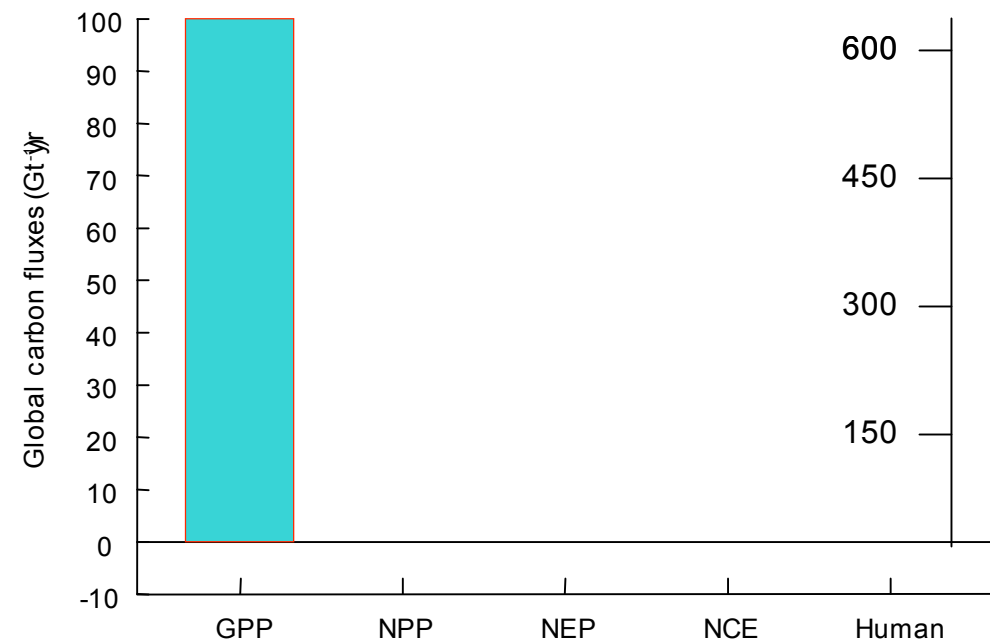
1. What role does the land surface play in modulating and controlling atmospheric CO₂?
2. Where are the major sources and sinks, and what is their likely long-term behaviour?
3. What are the key processes, and how will they interact in a changing climate?
4. What observing networks are needed to monitor and understand the carbon cycle?
5. Can we manage the system?

Gross Primary Production

Photosynthesis



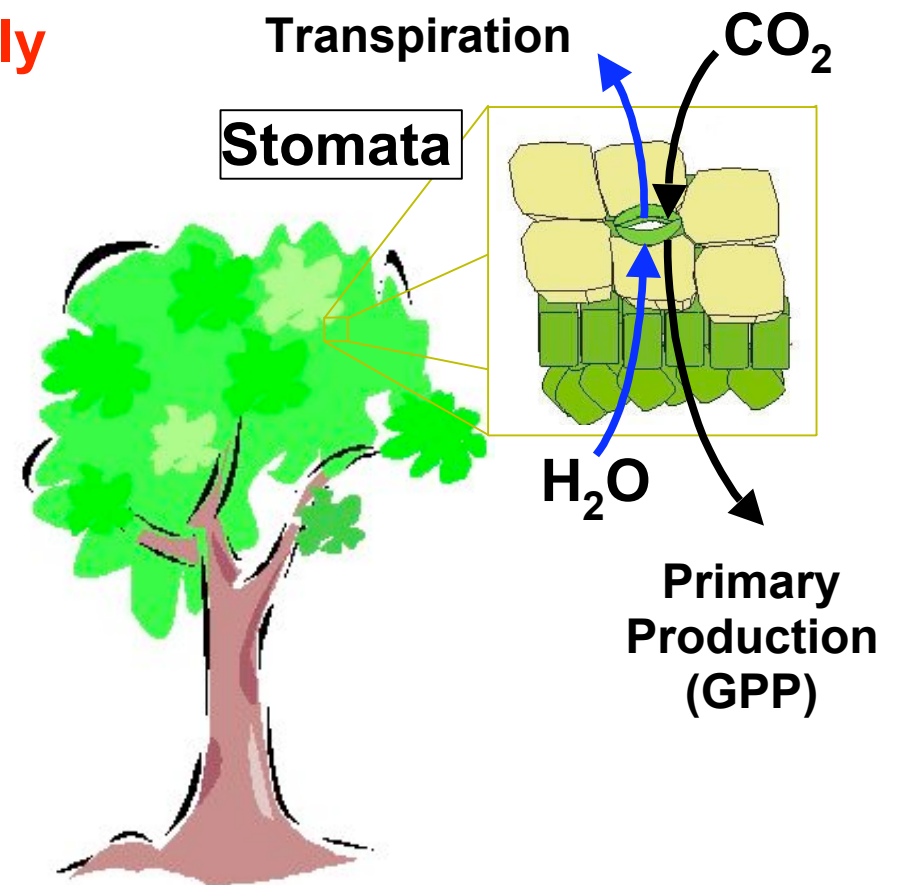
Global Carbon Exchange
($\text{gC m}^{-2} \text{yr}^{-1}$)

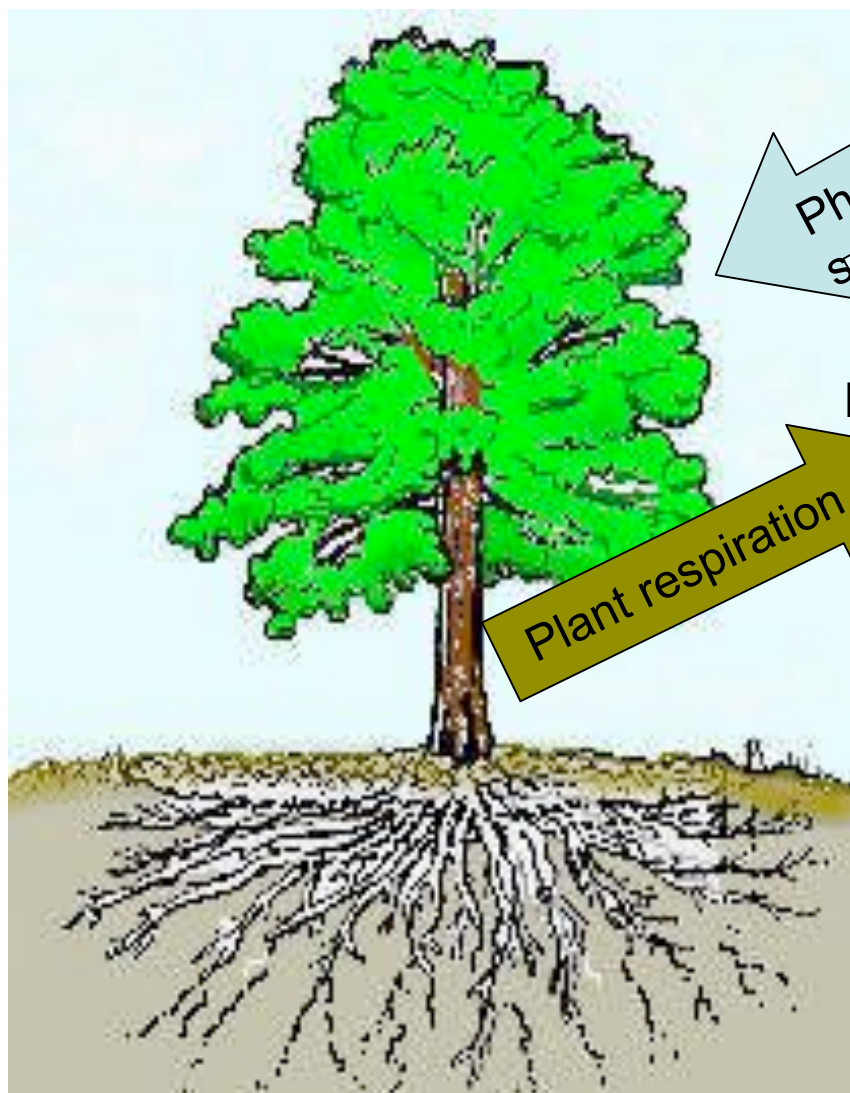


Water and carbon cycles

- **Water and carbon cycles are closely linked**

- Stomata control CO_2 and H_2O exchange
- Soil moisture controls stomatal aperture
- Leaf area controls rain interception
- Soil moisture controls leaf area
- Soil moisture controls C decomposition





Photosynthesis

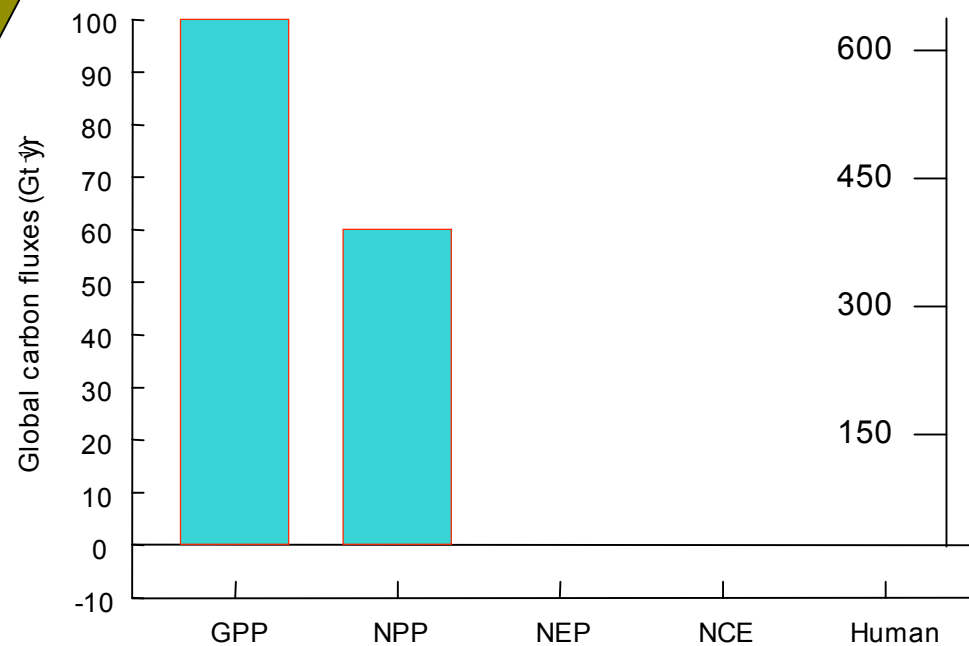
Gain

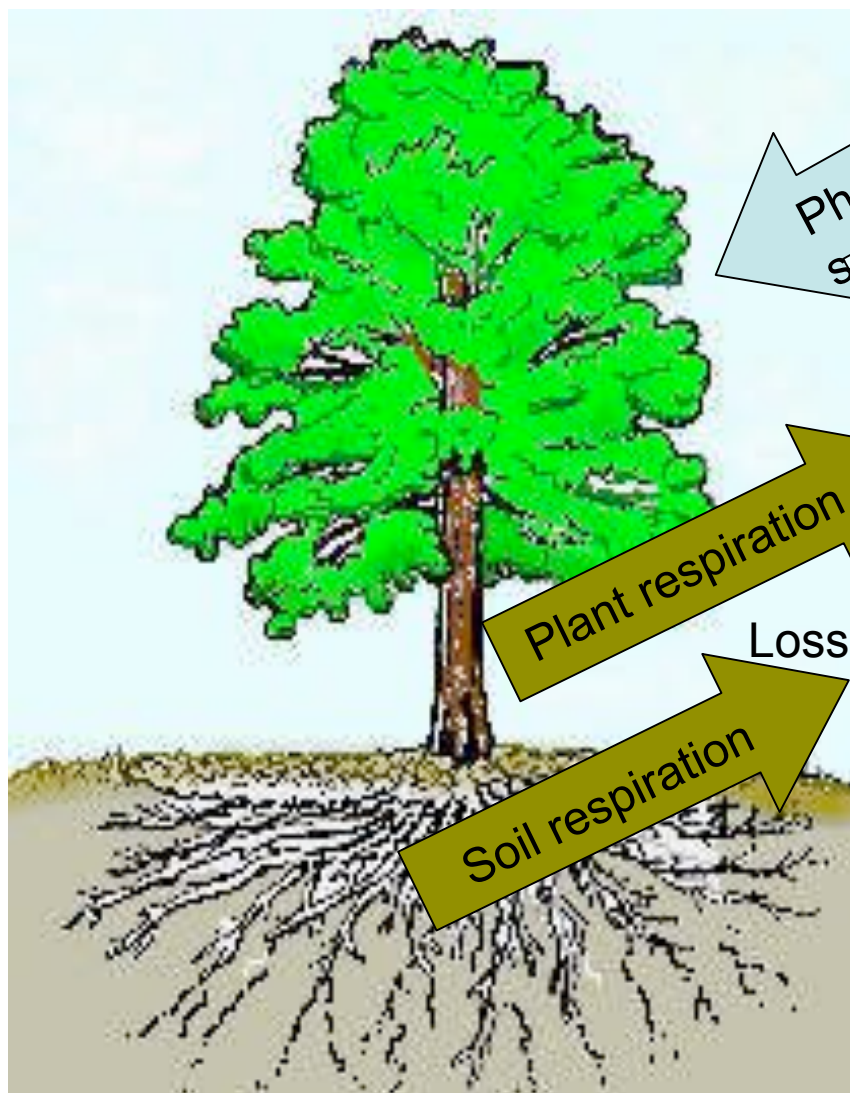
Plant respiration

Loss

Net Primary Production

Global Carbon Exchange
(gC m⁻² yr⁻¹)

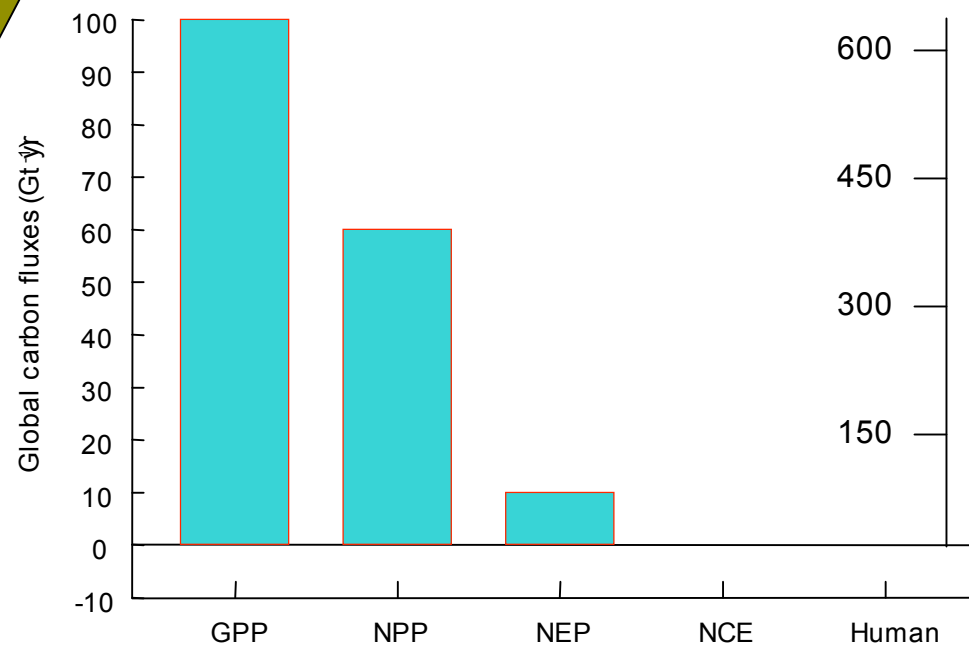




Net Ecosystem Production

Loss

Global Carbon Exchange
(gC m⁻² yr⁻¹)





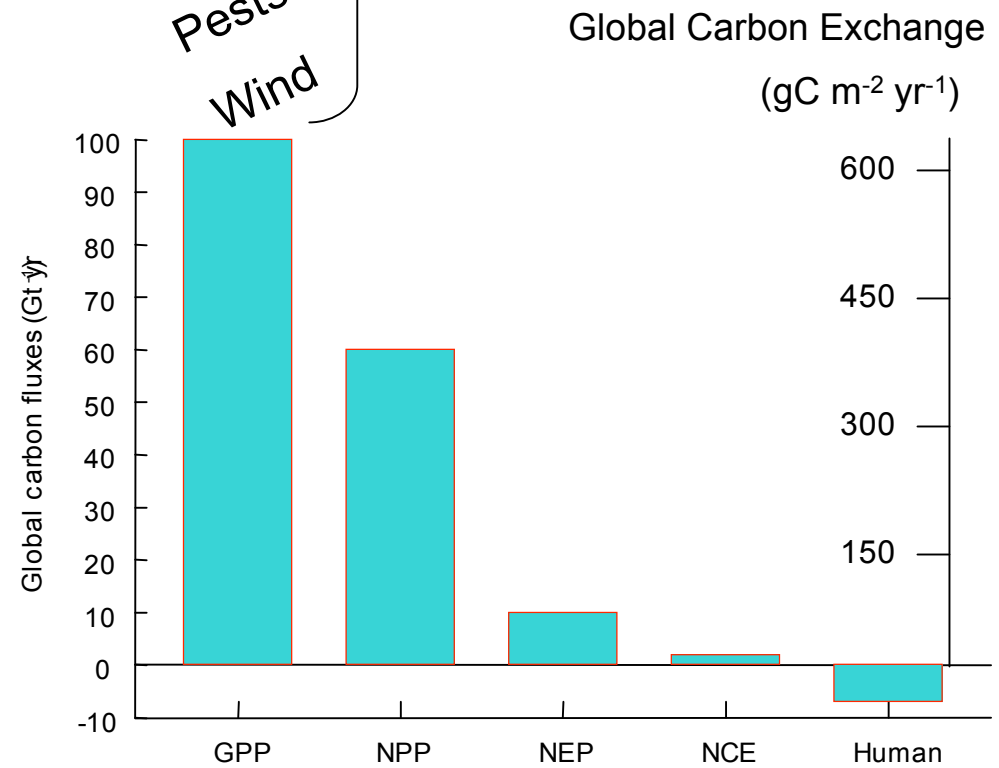
Losses

Fire

Pests

Wind

**Net Biome Production
= - Net Carbon Exchange**

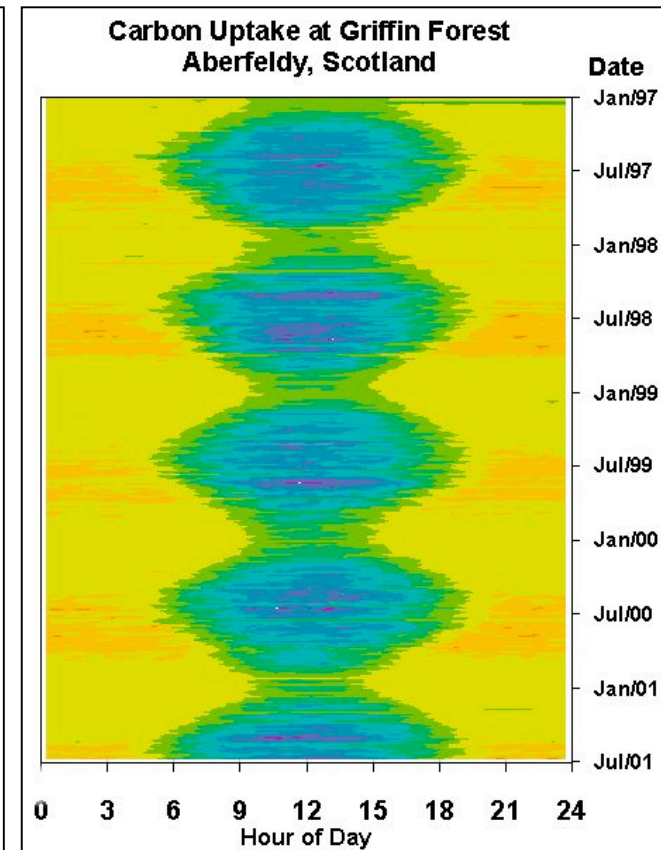
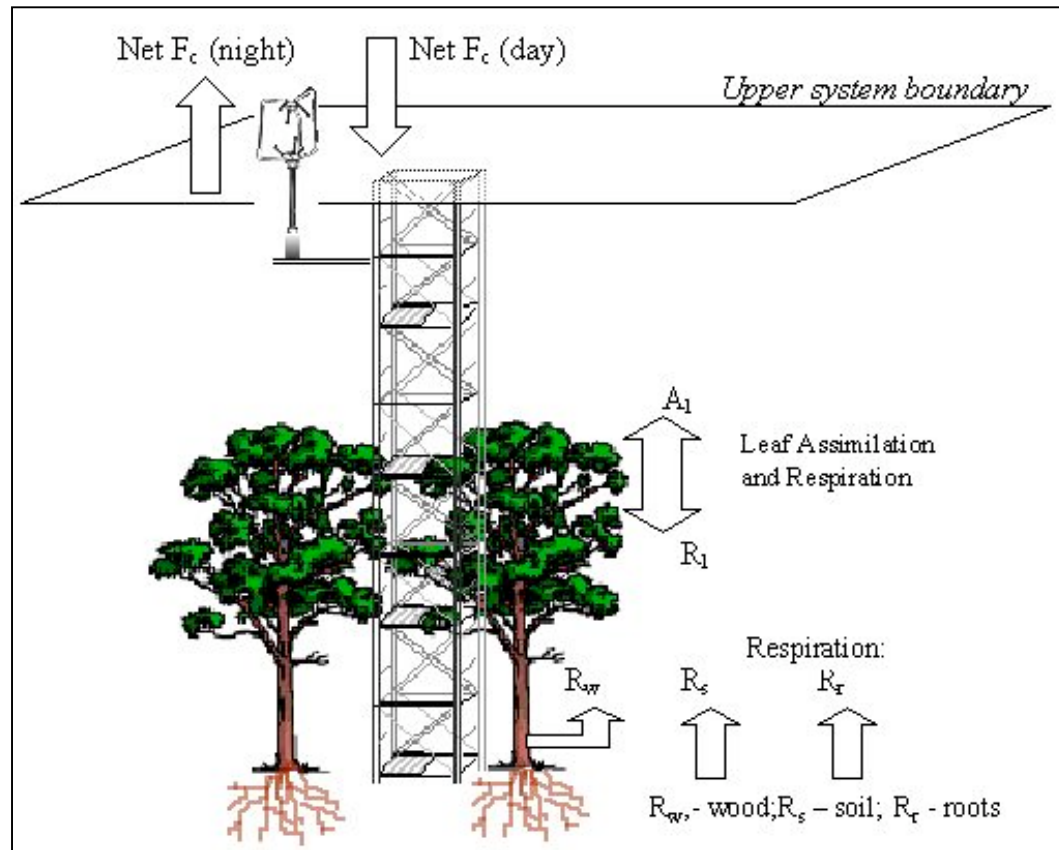


Measuring surface-atmosphere fluxes: local scales

Measuring NEE from flux towers



Eddy covariance CO₂ and H₂O fluxes: Provision of flux data for key target CTCD sites

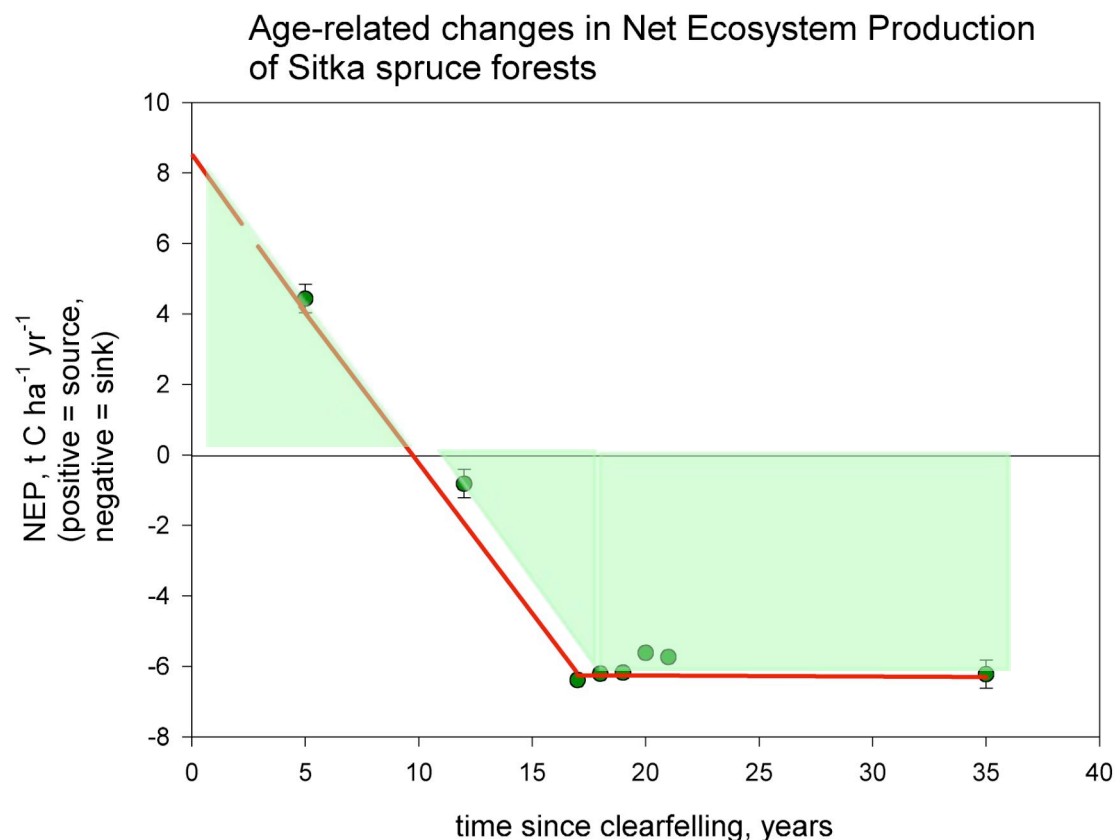


Losses	Gains
g C m ⁻² hour ⁻¹	
	0.64 – 0.80
	0.48 – 0.64
-0.48 – -0.32	0.32 – 0.48
-0.32 – -0.16	0.16 – 0.32
-0.16 – 0.0	0.0 – 0.16

CarboAge NEP net C fluxes over one rotation.

Spruce on a peaty gley: N. England

(Mencuccini, Rayment & Grace *in prep*)

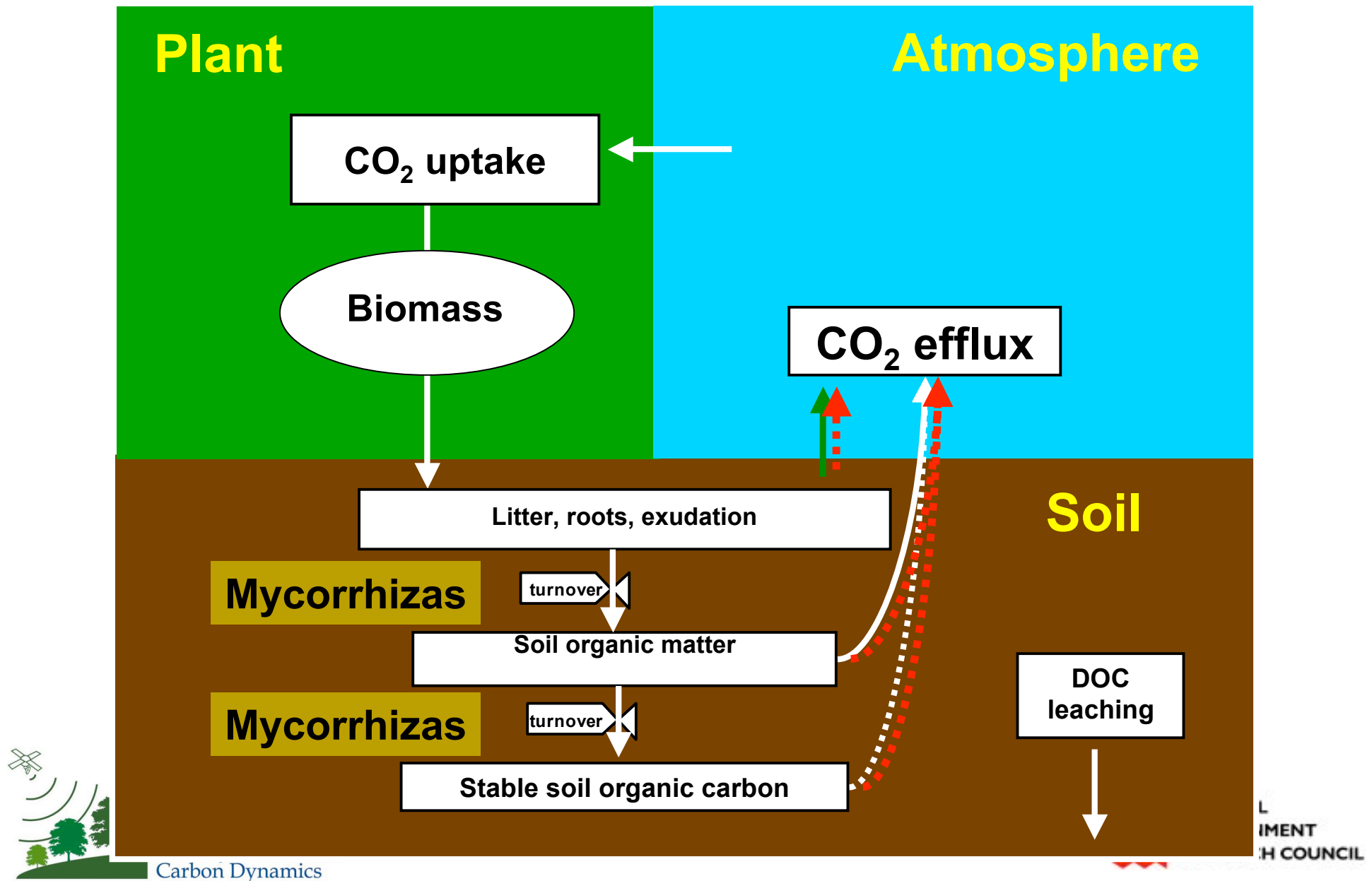


**S NEP ≈ 149.3 tC
/ha over 40 years,
i.e., 3.7 t C ha⁻¹ y⁻¹**

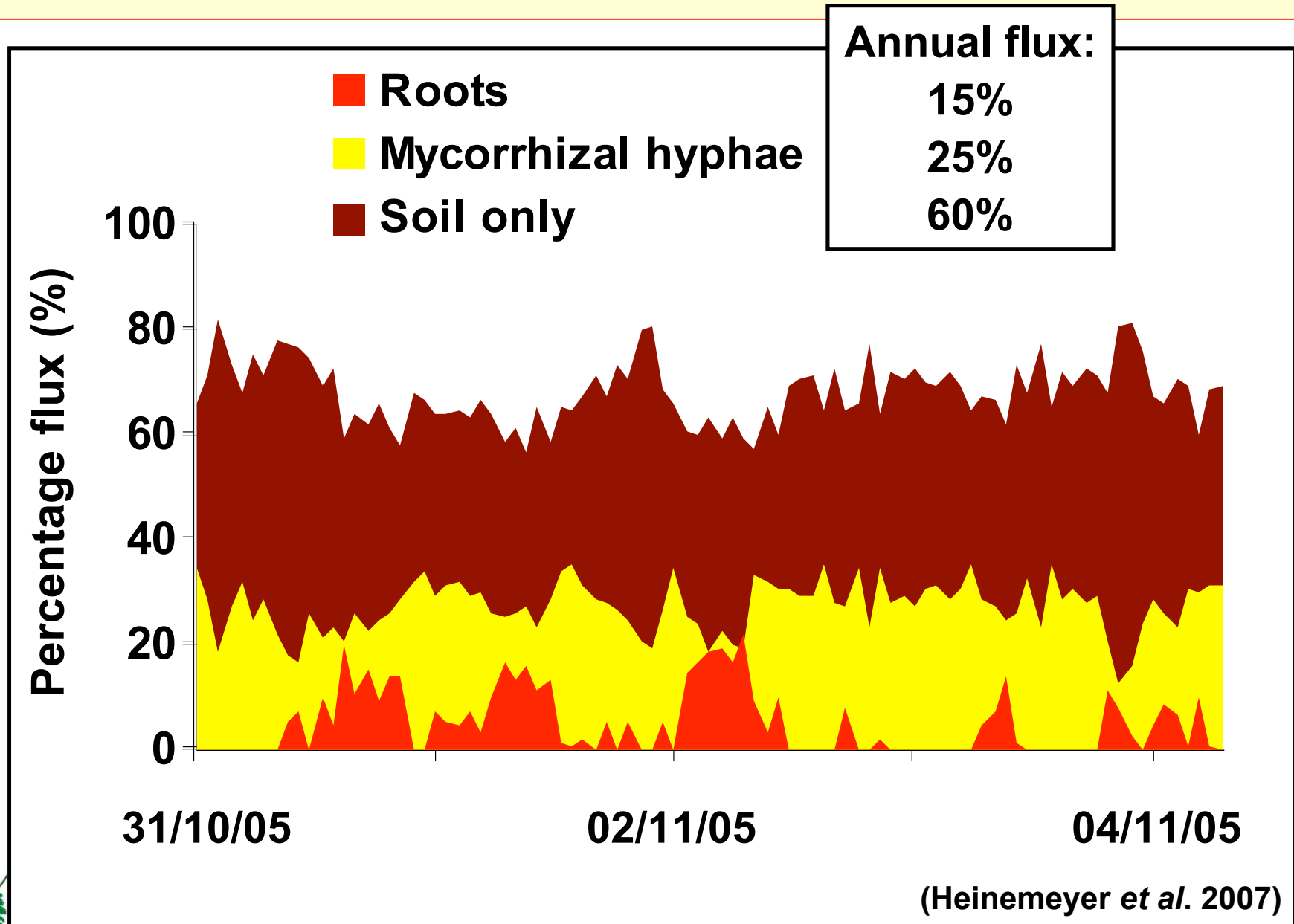
York: forest carbon cycle



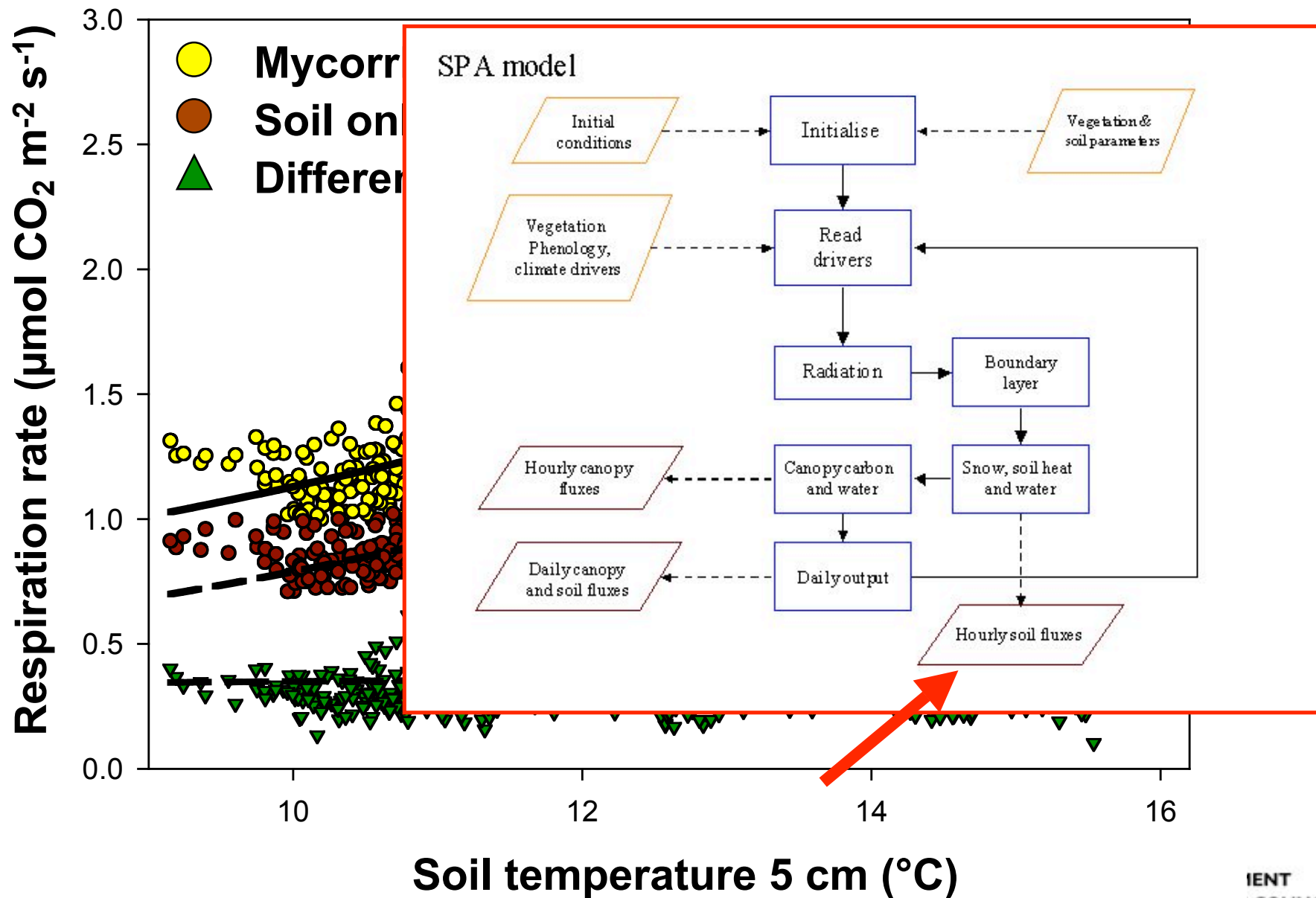
Soil respiration: a component flux



Flux proportions



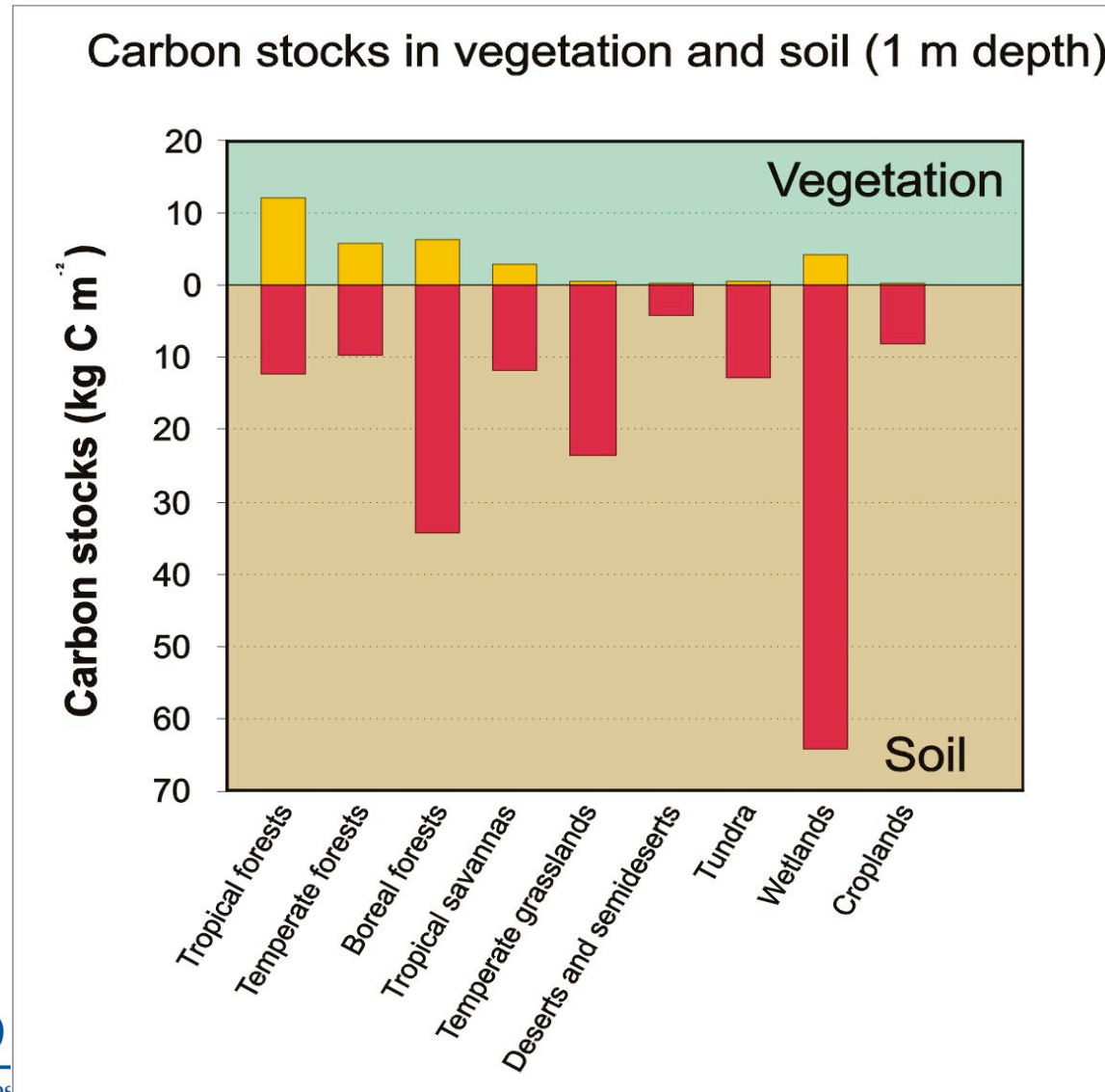
Temperature sensitivity



Global C stocks in vegetation and soils

Biome	Area (10 ⁶ km ²)	Carbon Stocks (Gt C)		
		<i>Vegetation</i>	<i>Soils</i>	<i>Total</i>
Tropical forests	17.6	212	216	428
Temperate forests	10.4	59	100	159
Boreal forests	13.7	88	471	559
Tropical savannas	22.5	66	264	330
Temperate grasslands	12.5	9	295	304
Deserts & semi-deserts	45.5	8	191	199
Tundra	9.5	6	121	127
Wetlands	3.5	15	225	240
Croplands	16.0	3	128	131
Total	151.2	466	2011	2477

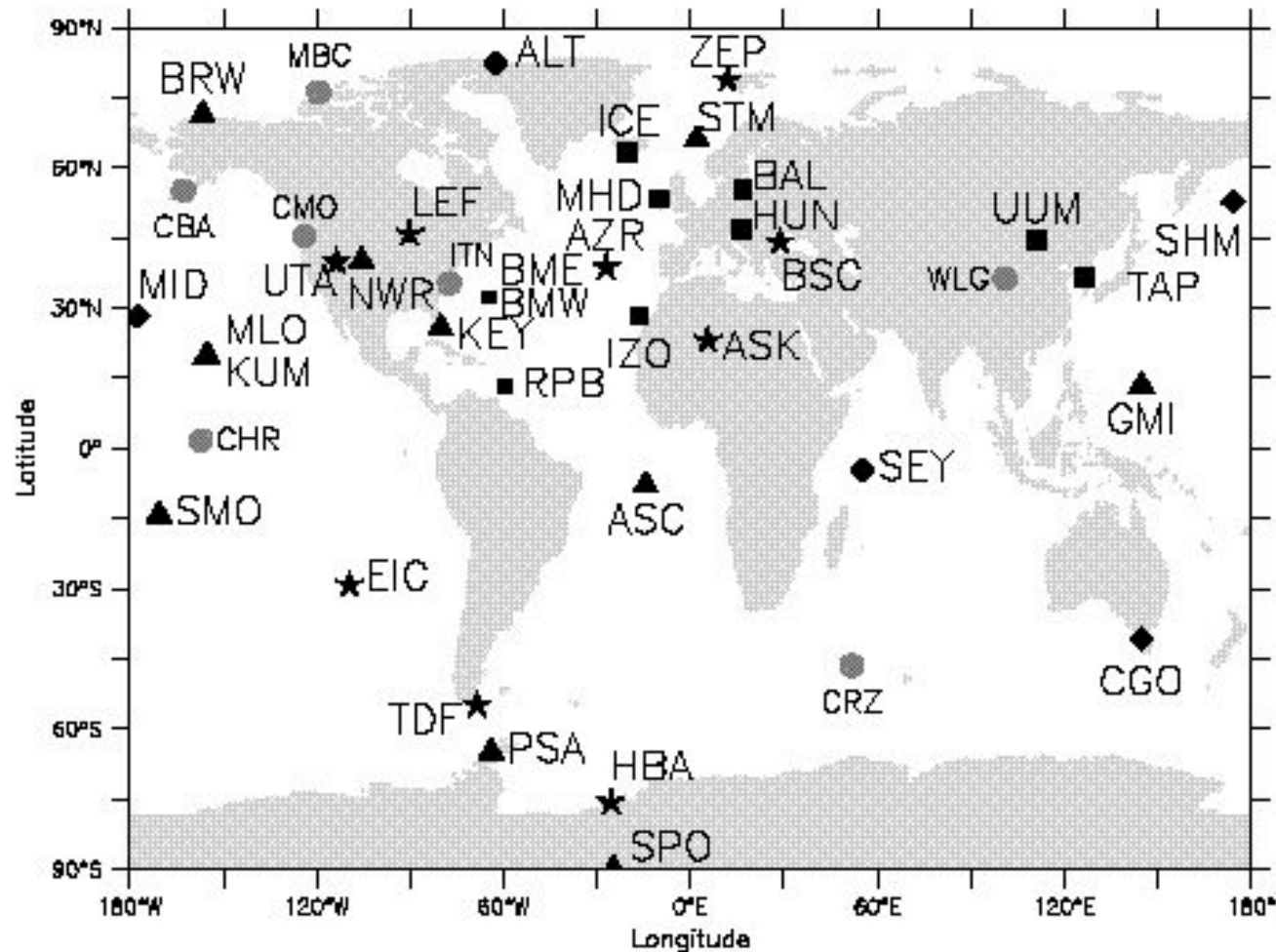
Proportion of carbon in vegetation and soils



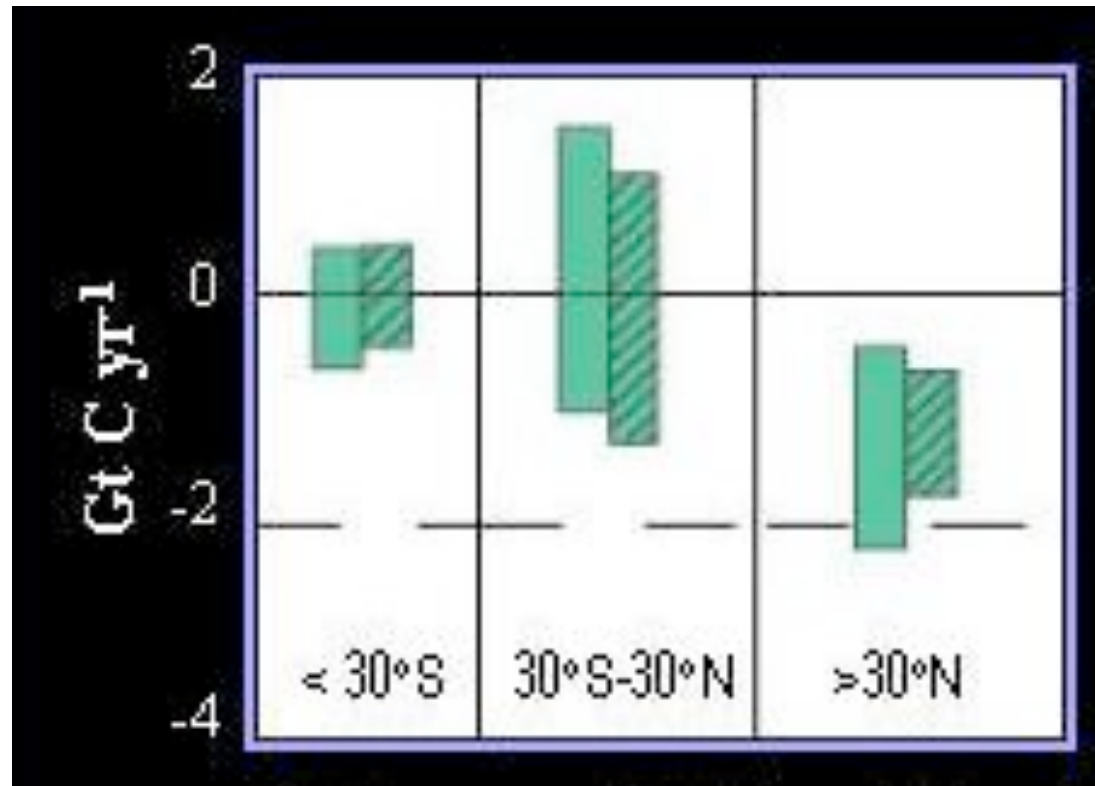
Measuring surface-atmosphere fluxes: regional scales

Atmospheric inversion

Inference of sinks from flask measurements



Current knowledge on carbon sources and sinks (from atmospheric inversions)



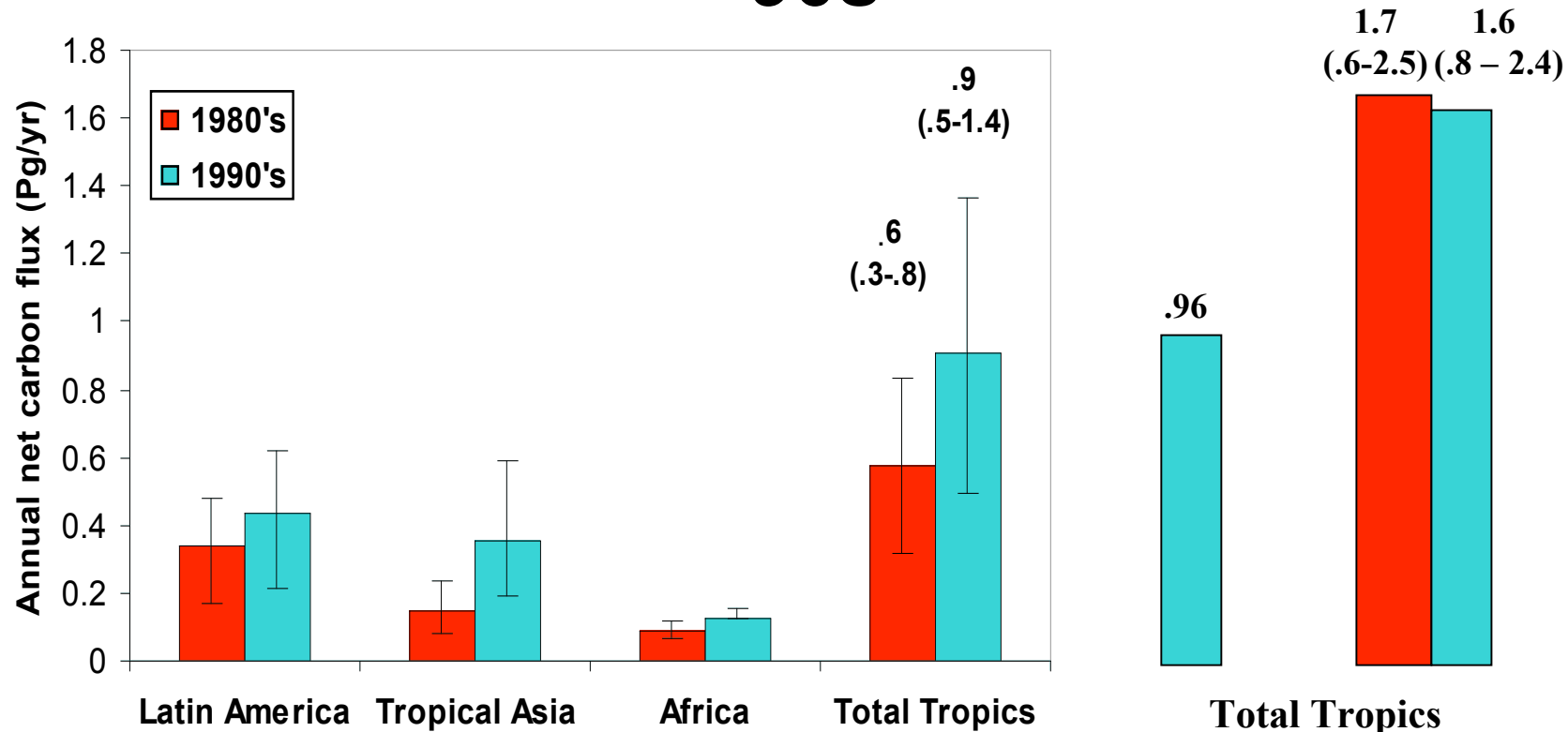
Land carbon sinks (<0) and sources (>0) for the 1980s (plain bars) and for 1990-1996 (hatched bars) (Heimann et al., 2001)

Compilation of atmospheric inversion results for Northern Hemisphere and Southern Hemisphere Land sink (slide from Emanuel Gloor)

	Gurney et al. 2002 1992-96	Jacobson et al. 2007 1992-96	Rödenbeck et al. 2003 1992-96 1996-99		Baker et al. 2006 1992-1996	Stephens et al. 2007 1992-96		
<i>Transport Model</i>	12 Models T3L1	12 Models T3L1	TM3	TM3	12 Models T3L2	{TM3, UCI, JMA} T3L1* T3L2		TM3 T3L2
<i>Atmosphere Land Flux</i>								
S Hem (<20S)	-0.2±1.1	-2.4±2.0	0.0±0.2	0.1±0.2	-1.2	0.1±1.1		
Tropics	1.1±1.3	4.2±2.7	-1.0±0.4	-0.8±0.4	1.6	0.7±1.4	-0.1±0.8	1.0
N Hem (>20N)	-2.3± 0.6	-2.9±1.0	-0.7±0.2	-0.4±1.0	-2.7	-2.2±0.6	-1.5±0.6	-2.2
	-1.4	-1.1	-1.8	-1.3	-2.3	-1.4		

Disturbance fluxes

Estimated Carbon Flux from Tropical Deforestation and Regrowth for 1980s and 90s



(DeFries, et al., 2002)

(Achar et al., 2002)

IPCC estimates based on FAO stats

“Bottom up” estimates based on satellite observations indicate substantially lower fluxes than estimates based on national statistics

		Houghton 2003	De Fries et al. 2002	Achard et al. 2002
1980s	Land use change	2.0 (0.9 to 2.8)	0.6 (0.3 to 0.8)	
	Residual land sink	-2.3 (-4.0 to -0.3)	-0.9 (-3.0 to 0.0)	
1990s	Land use change	2.2 (1.4 to 3.0)	0.9 (0.5 to 1.4)	1.0 ± 0.2
	Residual land sink	-3.4 (-5.0 to -1.8)	-2.1 (-3.4 to -0.9)	-2.2 (-3.2 to -1.2)

Conclusions

- u The land surface plays a central role in the global carbon cycle, but is the least well-known and understood component of the cycle.
- u Quantifying atmosphere-land carbon fluxes requires measurements at many different scales.
- u The carbon cycle is reasonably well characterised at the global scale, though its likely evolution is hard to predict
- u There are very large uncertainties in our regional scale quantification of the carbon cycle

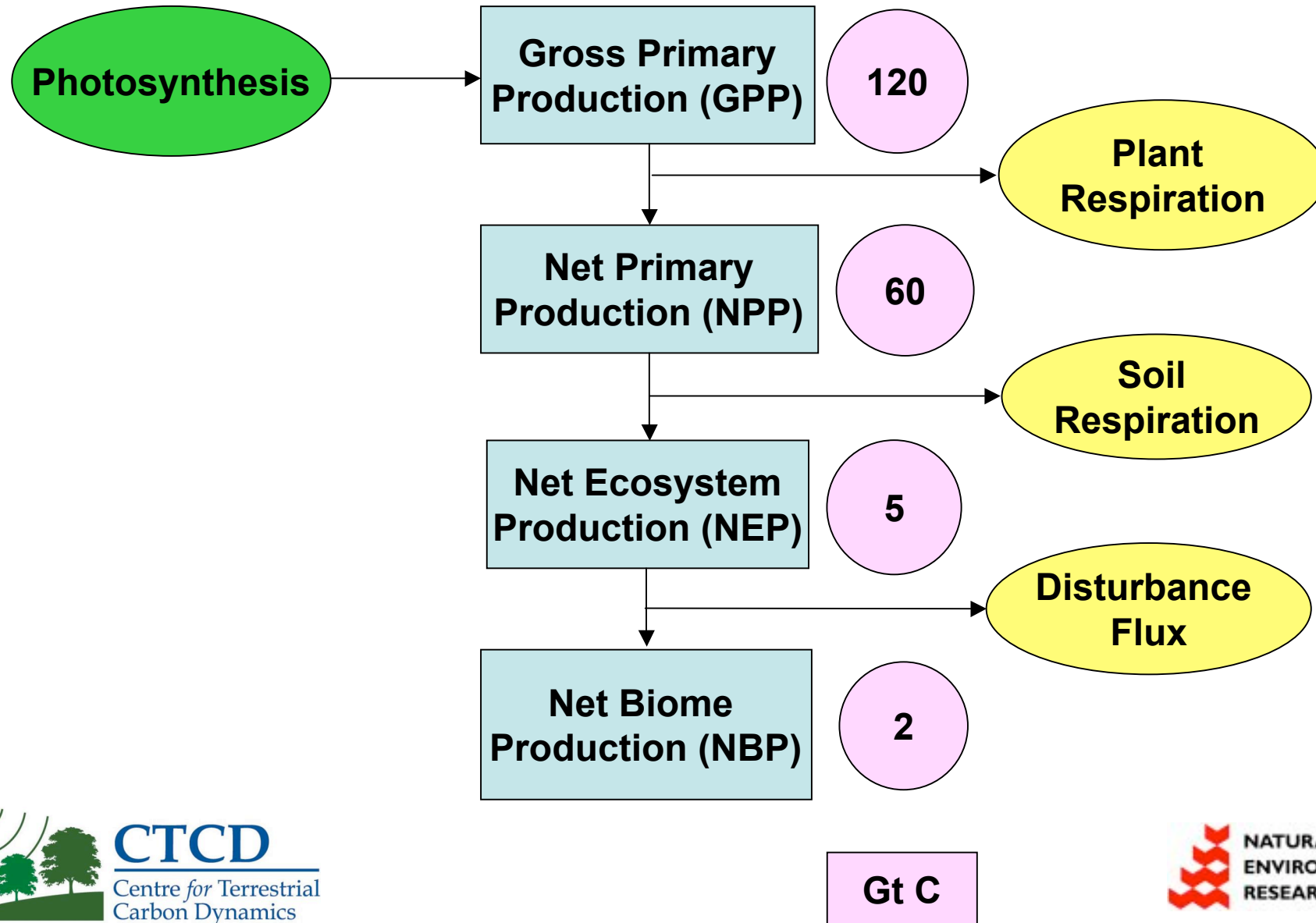
The C cycle in the Earth system

- u The large-scale modification of land cover is inextricably bound up with modifications of the carbon cycle. Effects:
 - resources available to humans
 - climate modification by altering albedo
 - primary cause of loss of biodiversity.
 - u Changes in the carbon cycle have major effects on the water cycle affecting
 - river runoff (i.e. freshwater supply),
 - soil moisture and
 - water transport to the atmosphere (globally, the volume of transpired water is nearly equal to the total river runoff).
- These changes feed back on vegetation growth.
- u All aspects of the Earth system (land, ocean, atmosphere, cryosphere) are involved in the C cycle.

The C cycle in the Earth system

- u The basic driver of anthropogenic climate change is the imbalance between fluxes of CO₂ and CH₄ to and from the atmosphere;
 - u Management of the carbon cycle, as enshrined in the Kyoto Protocol, is the only international treaty focused on slowing climate change. Principal mechanisms:
 - reduce emissions
 - increase the carbon stored in forest ecosystems.
- Current negotiations seek to include reduction in deforestation and forest degradation in the post-2012 KP.
- u Lack of quantitative understanding of feedbacks between climate and the land carbon cycle is a major area of uncertainty in climate prediction (IPCC 2007).

Carbon Fluxes



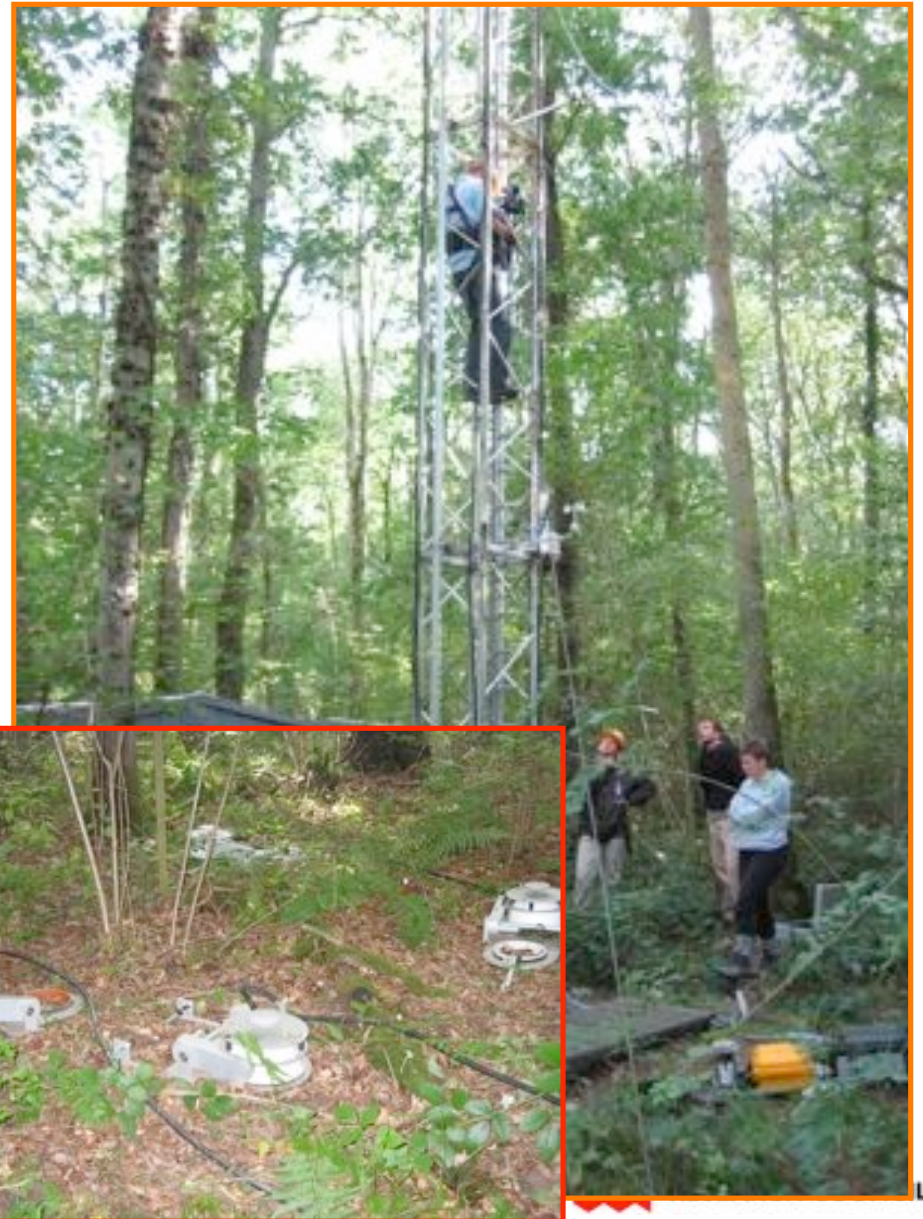
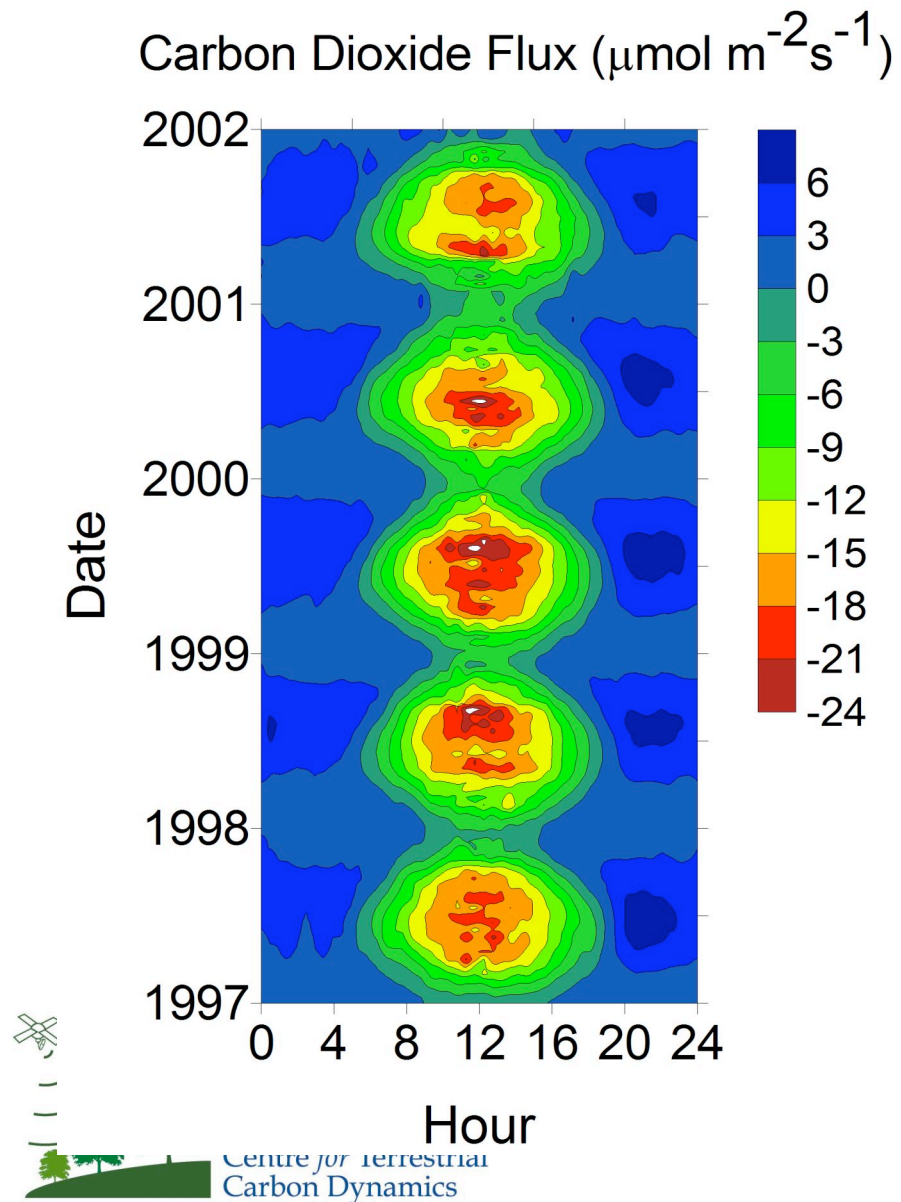
Reducing uncertainties in the C budget

Our objective: To greatly improve our estimates and predictions of the terrestrial carbon cycle by effectively combining Earth Observation measurements with biospheric process models and other data.

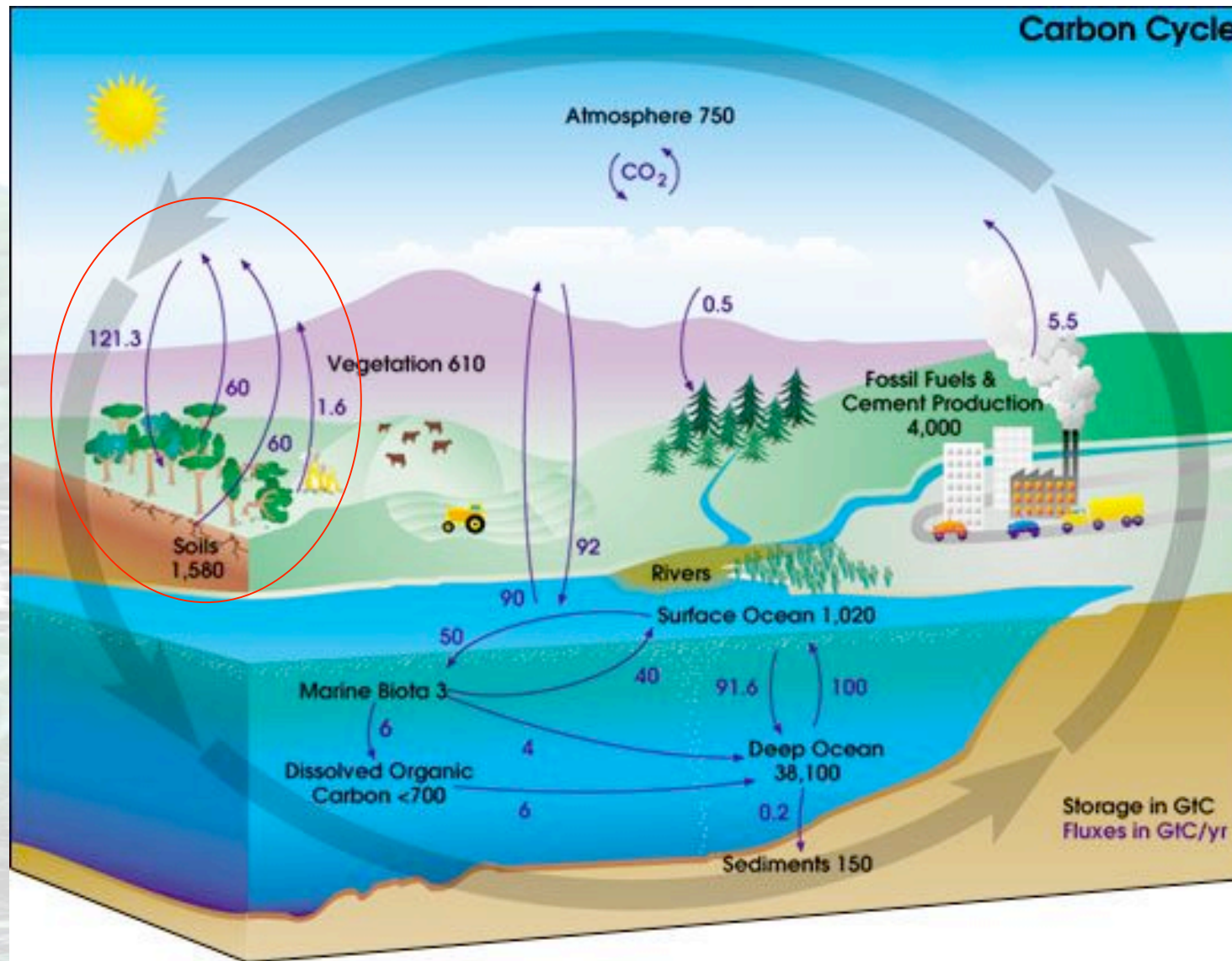
Key science questions:

1. where are the carbon sources and sinks, how do they vary and what processes underlie them?
2. why is the equatorial land surface carbon neutral, despite rapid deforestation (and how rapid is this)?

Alice Holt: forest carbon cycle

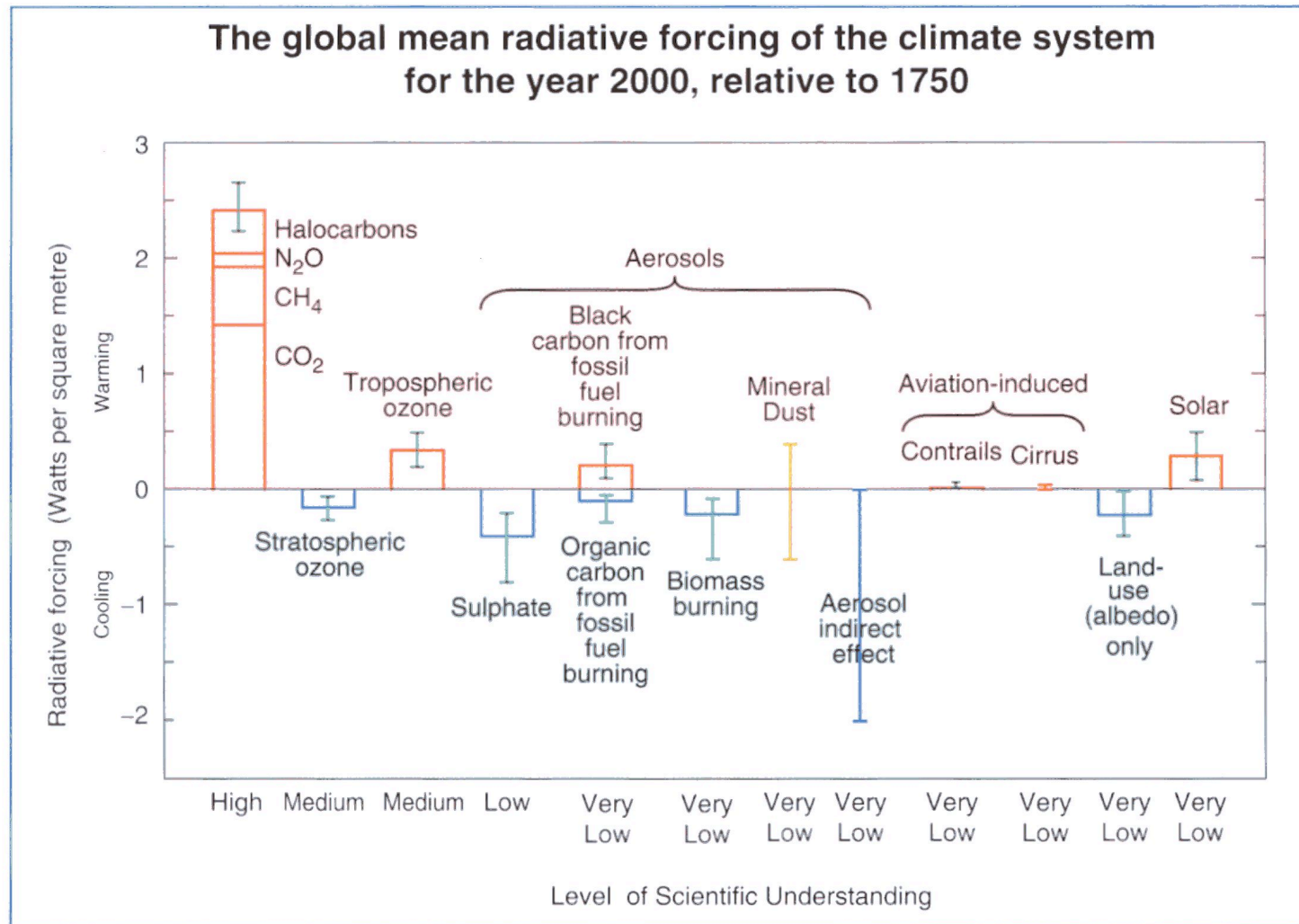


The Carbon Cycle

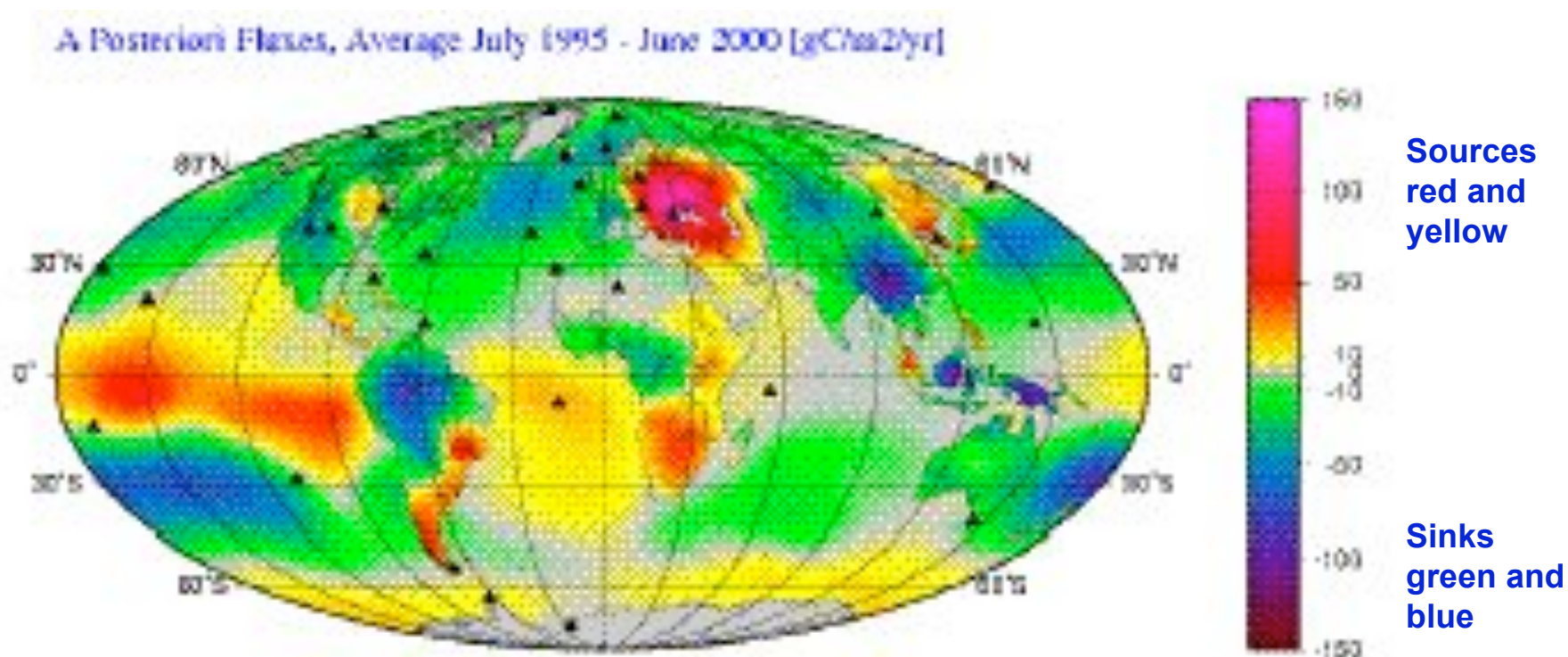


http://earthobservatory.nasa.gov/Library/CarbonCycle/carbon_cycle4.html

Greenhouse gases (1)

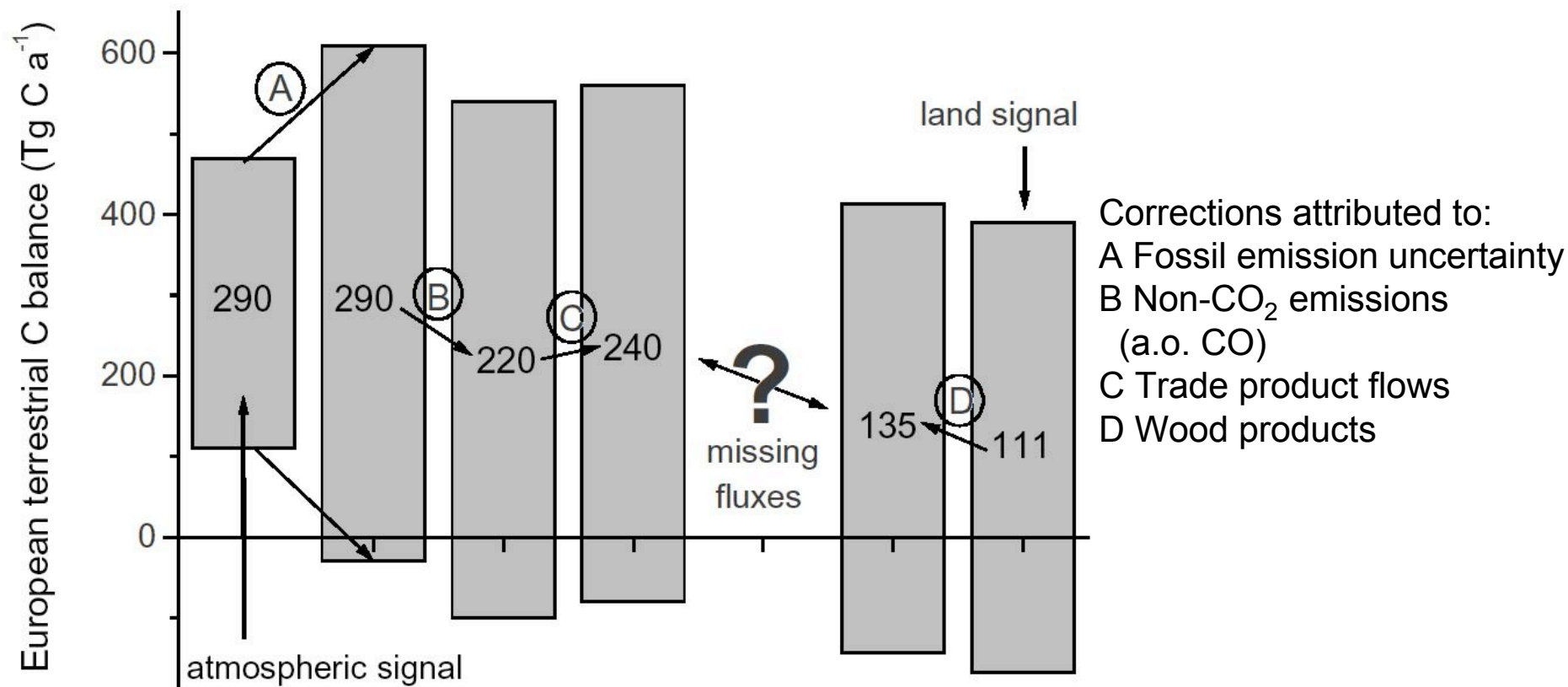


Global distribution of sinks over the period 1982-2001 (flask inversion method)

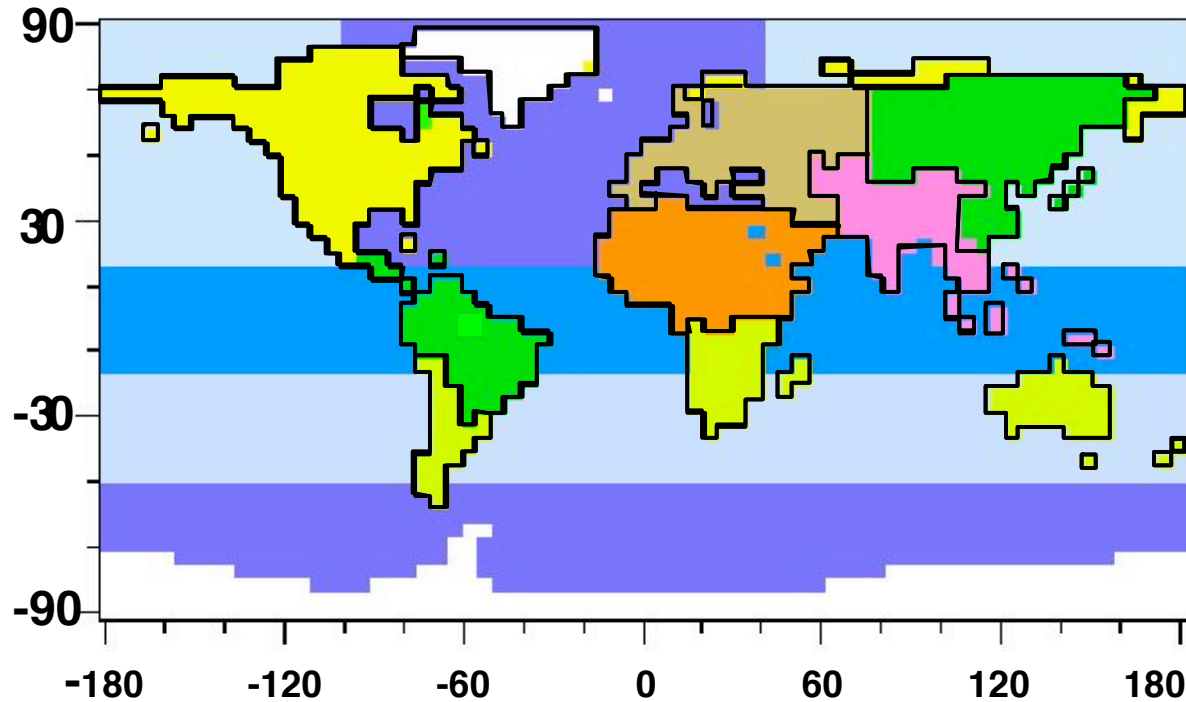


Roedenbeck et al. (2003) Atmos Chem Phys Discussions 3, 2575-2659.

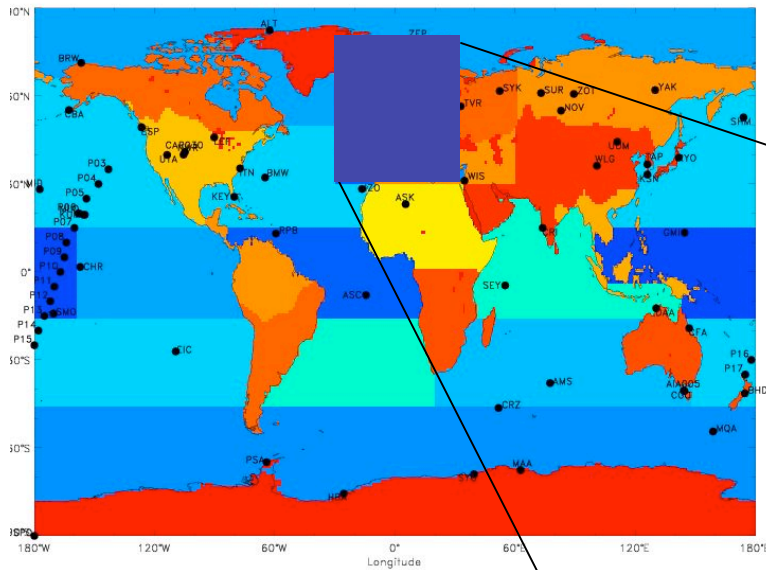
Reconciling Top-Down and Bottom-Up Estimates of the European Terrestrial Carbon Balance - State-of-the-Art



Atmospheric Inversion using ground-based measurements to locate CO₂ sources and sinks: what we can do now



- Discrimination of sources/sinks between latitude bands is relatively easy
- Localising sinks in the same latitude bands is subject to wide error.
- Fluxes over ocean basins are easier to constrain than continental fluxes over large regions.

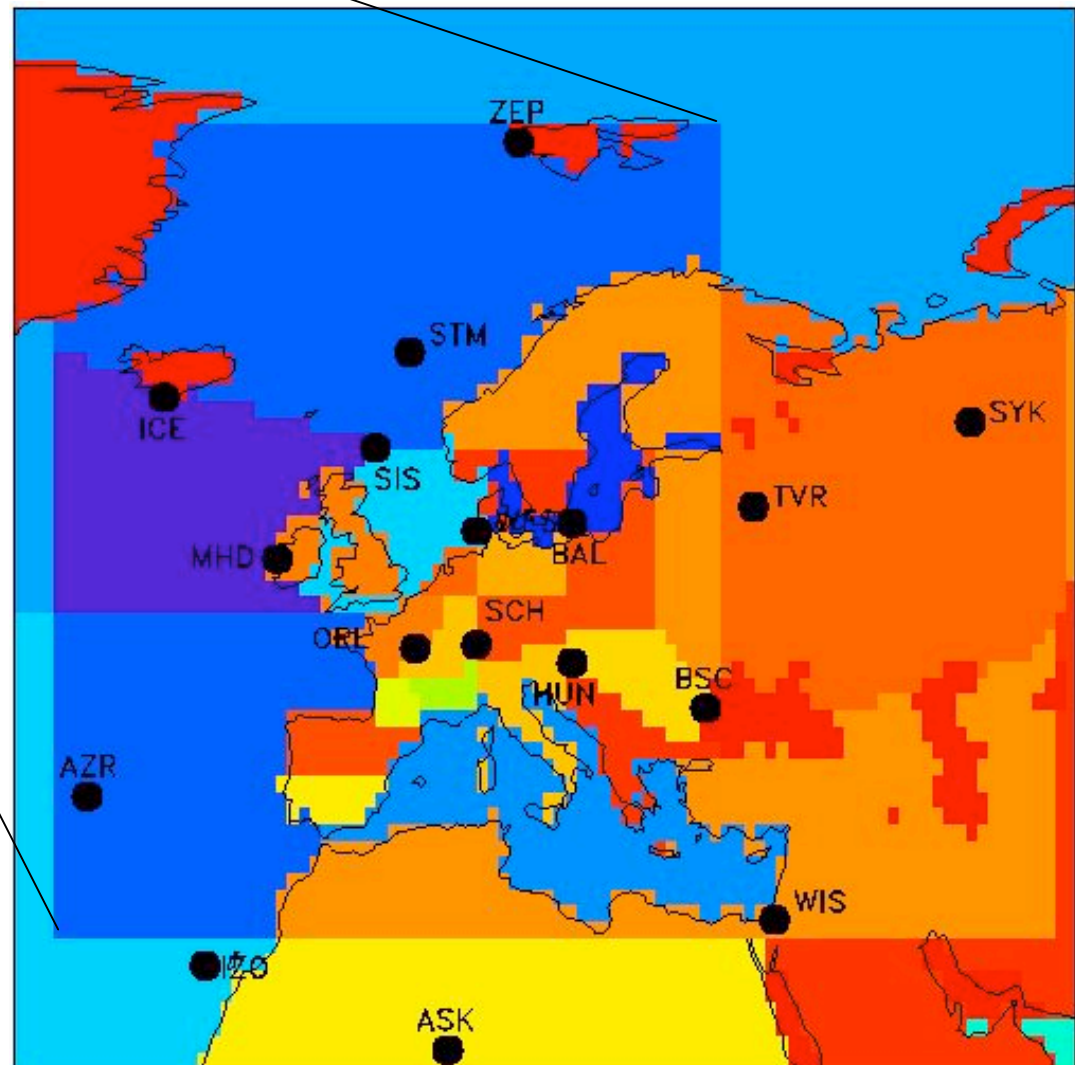


Russian Doll inversions 20 regions over Europe

Input data set:
112 stations, year 1998-2000

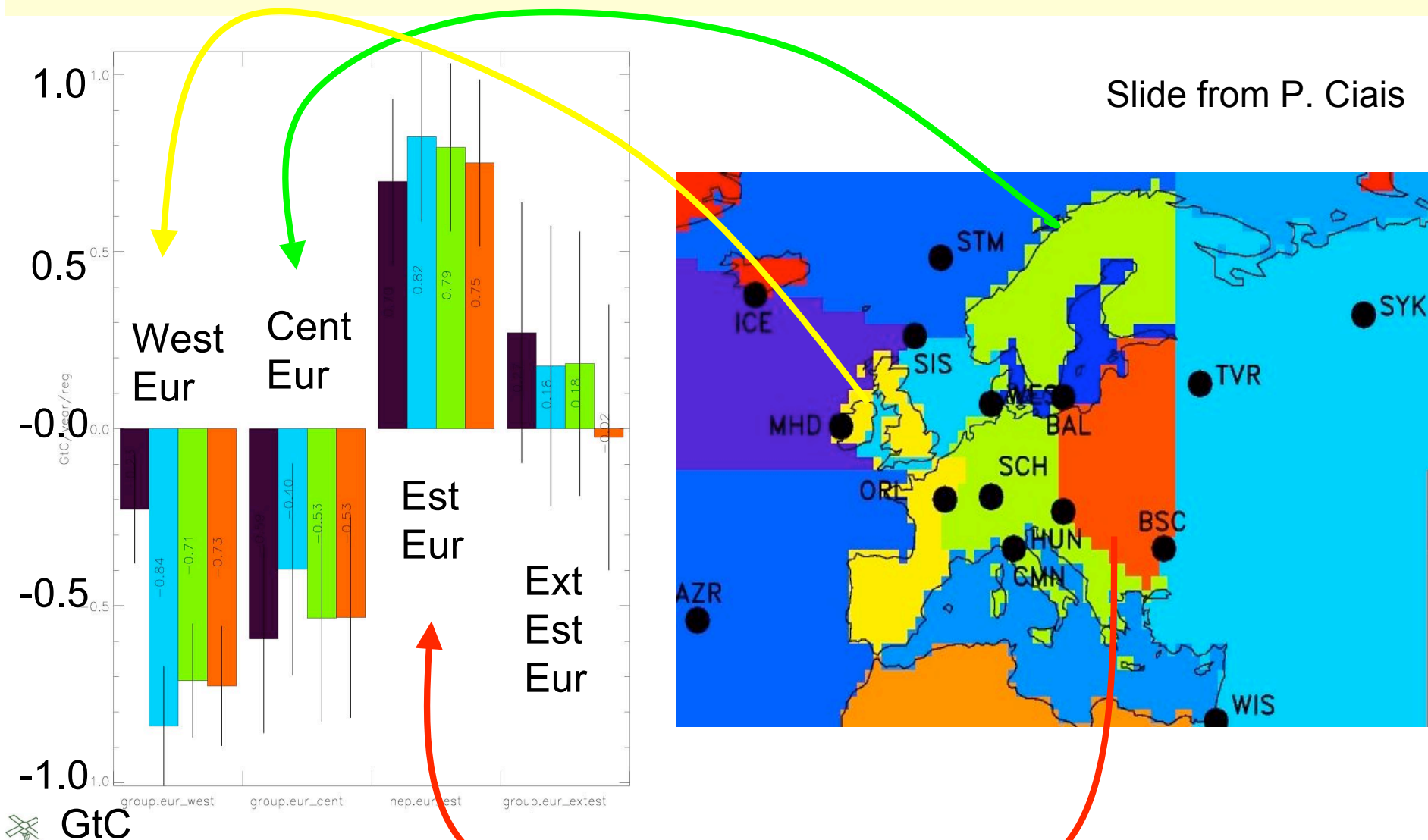
Gurney et al. data set:
76 stations, year 1992-1996

Slide from P. Ciais



Annual optimized fluxes over Europe

Slide from P. Ciais



GtC

The importance of the land surface

The terrestrial biosphere is a crucial element of the carbon cycle

- υ as a source
- υ as a sink
- υ as an instrument of policy

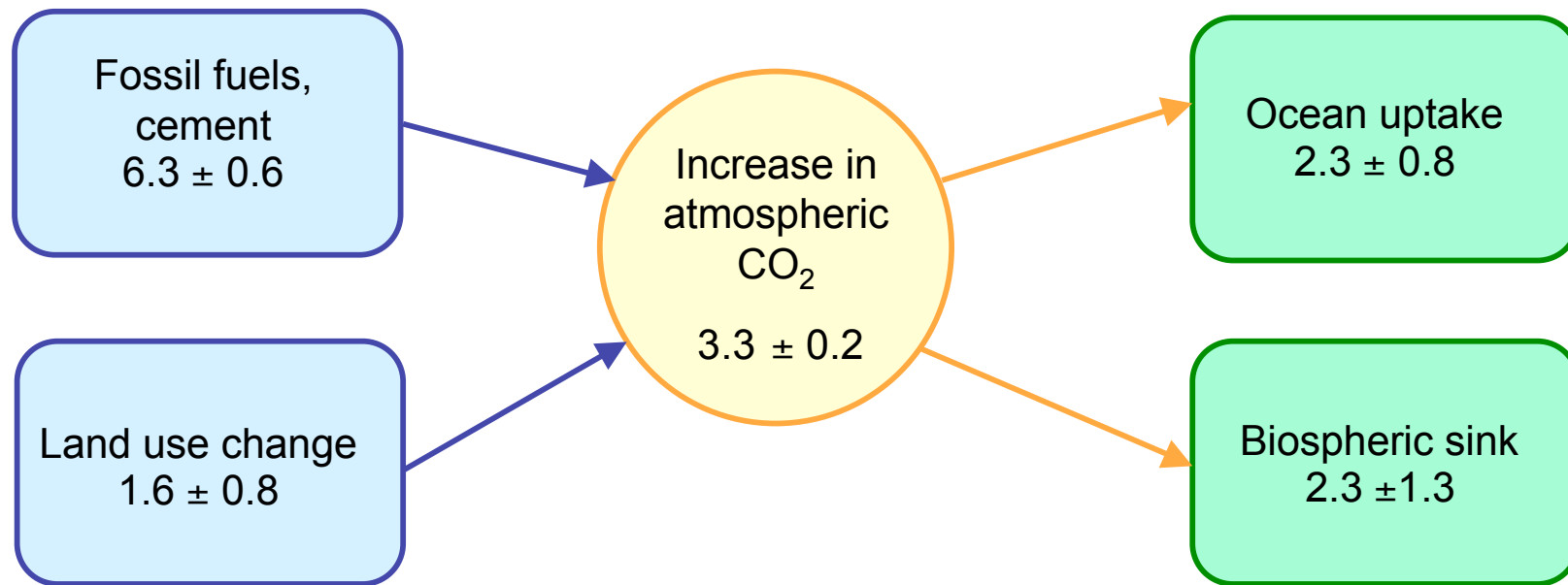
BUT, its

- υ status
- υ dynamics
- υ evolution

are the least understood and most uncertain elements in the carbon cycle, at all scales.

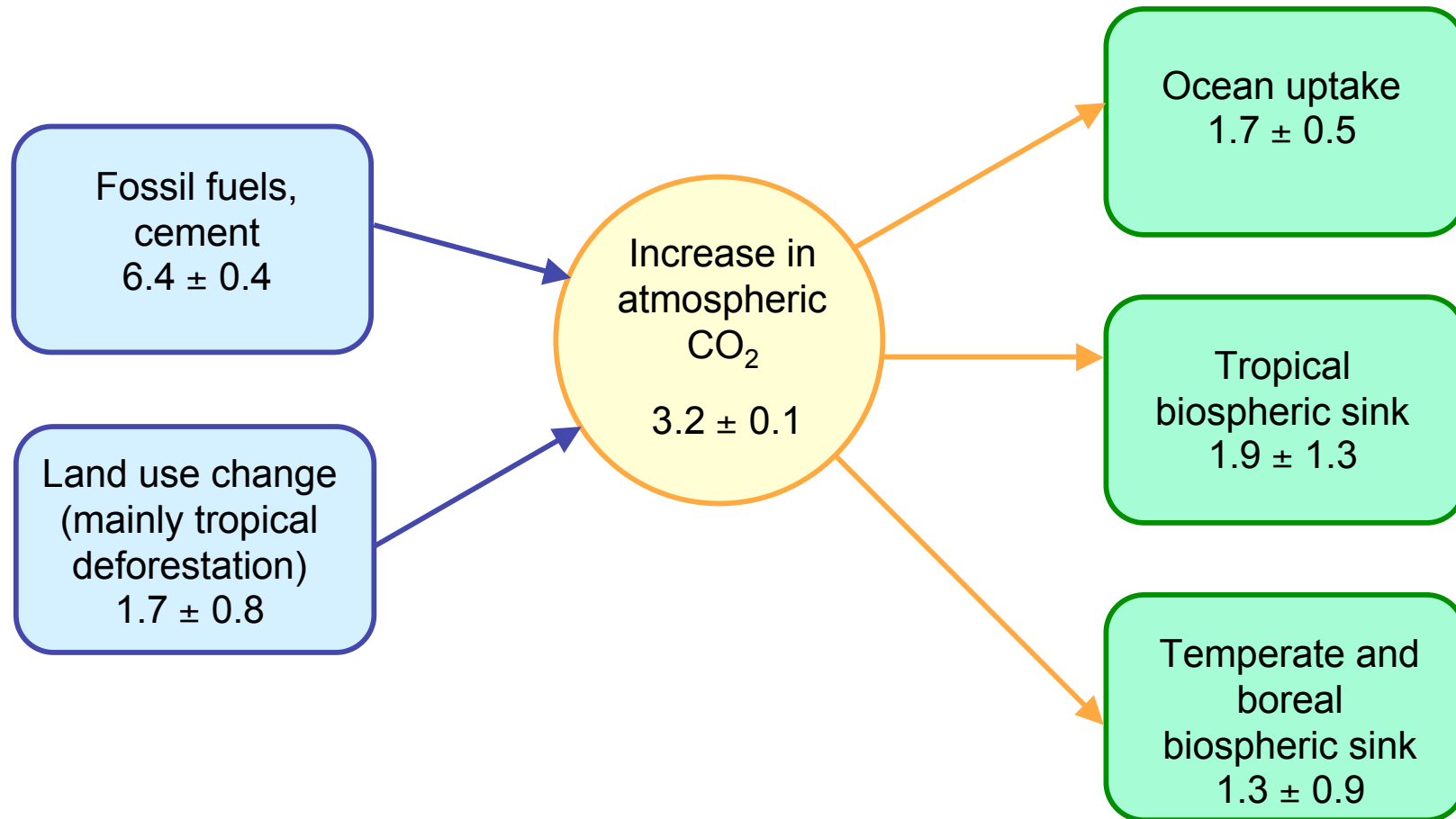
Carbon Budget during 1989-98

(Gt C y⁻¹; Intergovernmental Panel on Climate Change, 2000)



Carbon Budget in the 1990's

(Gt C y⁻¹; Royal Society Report, 2001)



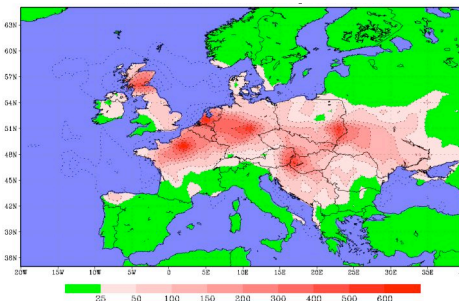
Global soil C stocks

(C stocks in Gt C = Pg C = 10^{15} g C)

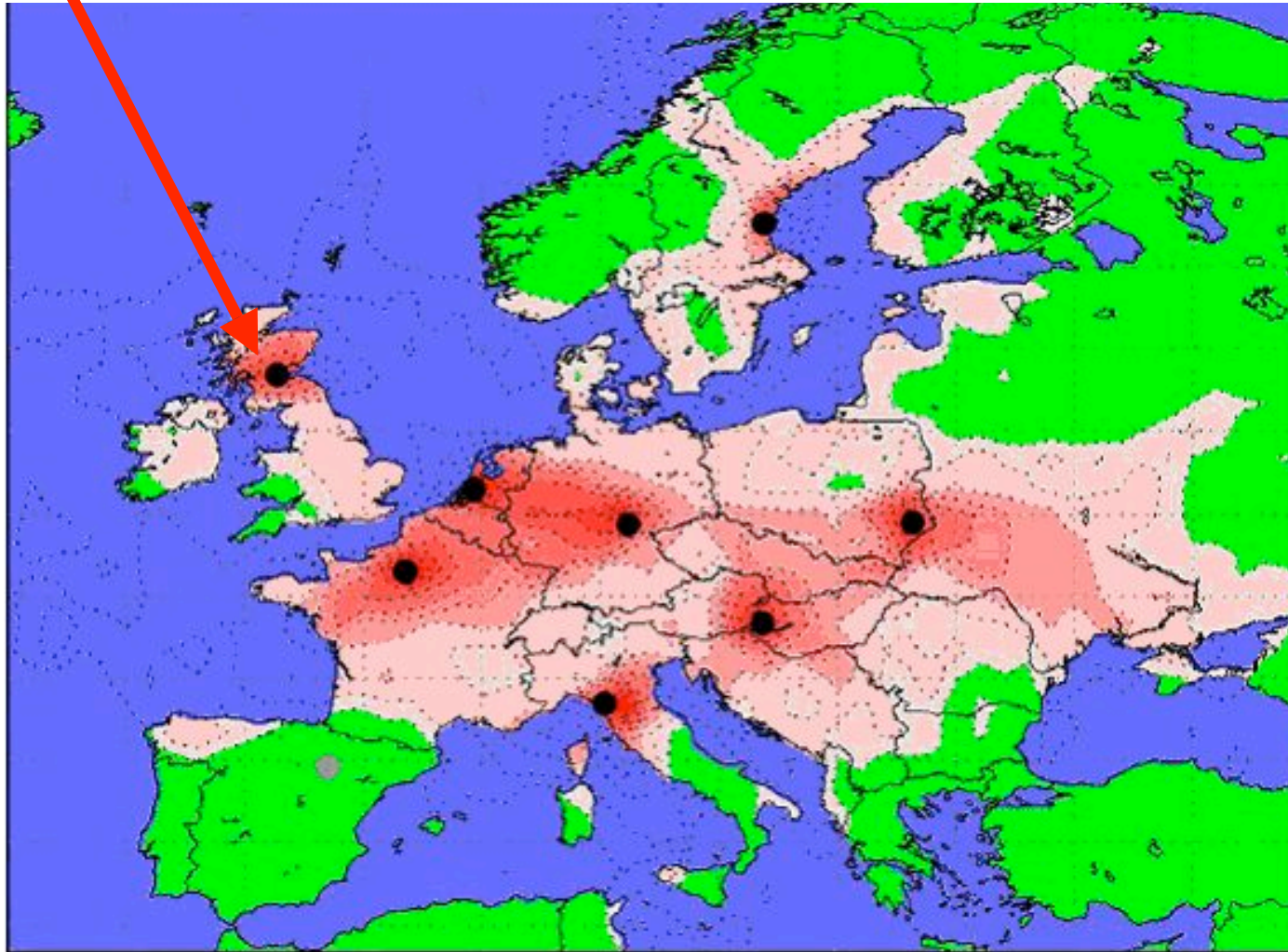
Biome		IGBP * 100 cm IPCC 2001	IGBP 100 cm GLCM 2000 #	WBGU [‡] 100 cm IPCC 1990	ISLSCP II- 150 cm GLCM 2000 #	ISLSCP II 30 cm GLCM 2000 #
Forest	Tropical & subtropical	213	209	216	275	109
	Temperate	153	97	100	131	43
	Boreal	338	174	471	255	62
Savanna & grassland	Tropical & sub tropical	247	206	264	276	98
	Temperate	176	171	295	236	80
Desert & semi desert		159	199	191	276	86
Tundra		115	106	121	158	42
Boreal		165	76	-	110	29
Croplands		-	76	128	101	36
Wetlands		-	147	225	211	53
Bare		-	36	-	50	16
Total C stock		1566	1497	2011	2079	654

Regional observations tool-kit

- u Allows estimates of the carbon balance over large regions using inverse modelling
- u Quantifies interannual variations in fluxes in response to climate variability
- u Multiple species approach



Tall Tower Angus



Hourly CO₂ exchange estimates for Scotland

