The Terrestrial Carbon Cycle: Measurements and Models

Shaun Quegan (+ CTCD, CarboEurope et al.)

NERC Centre for Terrestrial Carbon Dynamics & University of Sheffield

Lecture content

- CO_2 and climate
- The global C cycle and the role of the terrestrial biosphere: pools, fluxes and processes
- Measuring land-atmosphere fluxes
- Models of the terrestrial biosphere

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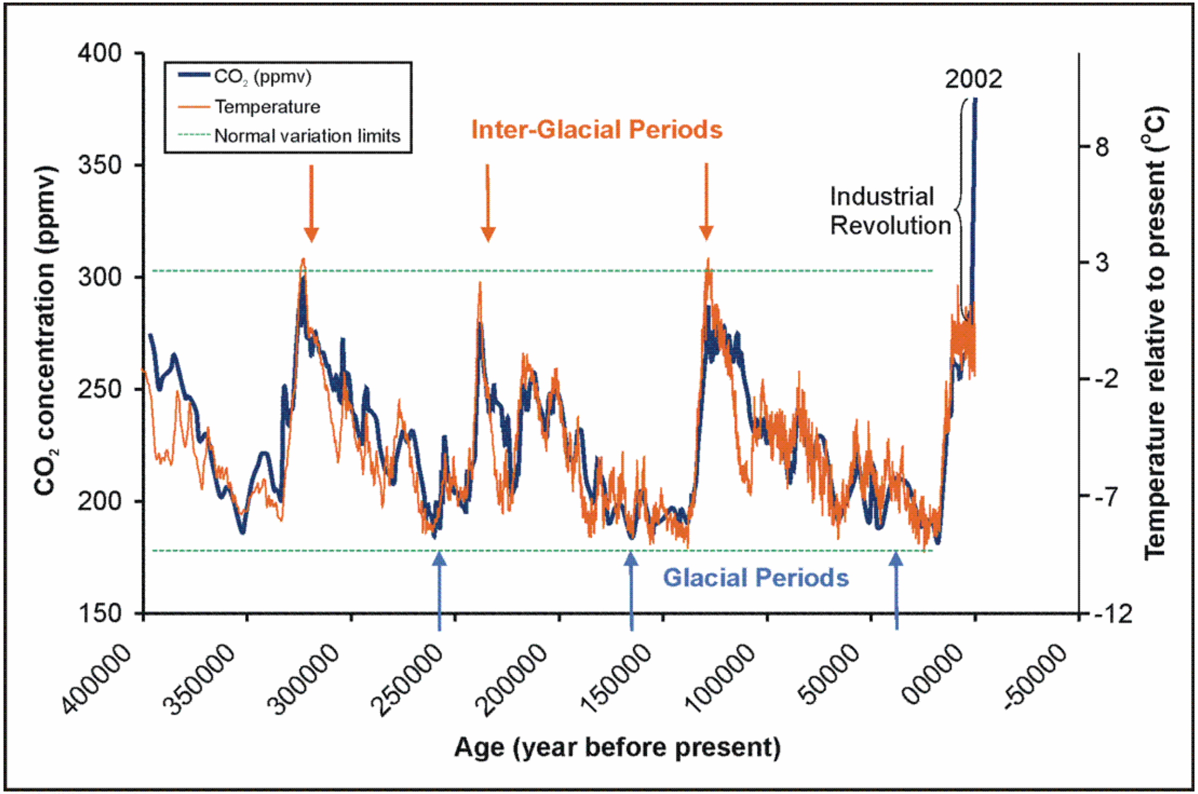
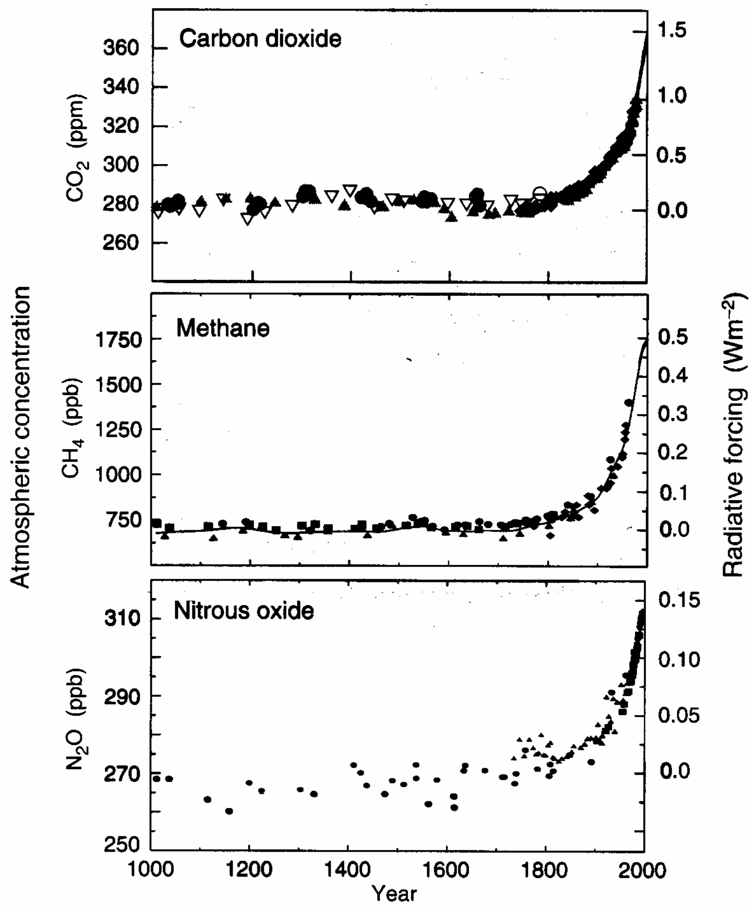
Vostok: Past climate and CO_2



Petit et al., Nature, 1999

CO_2, NH_4 and N_2O in the last 1000 years



From: IPCC, Climate Change, 2001

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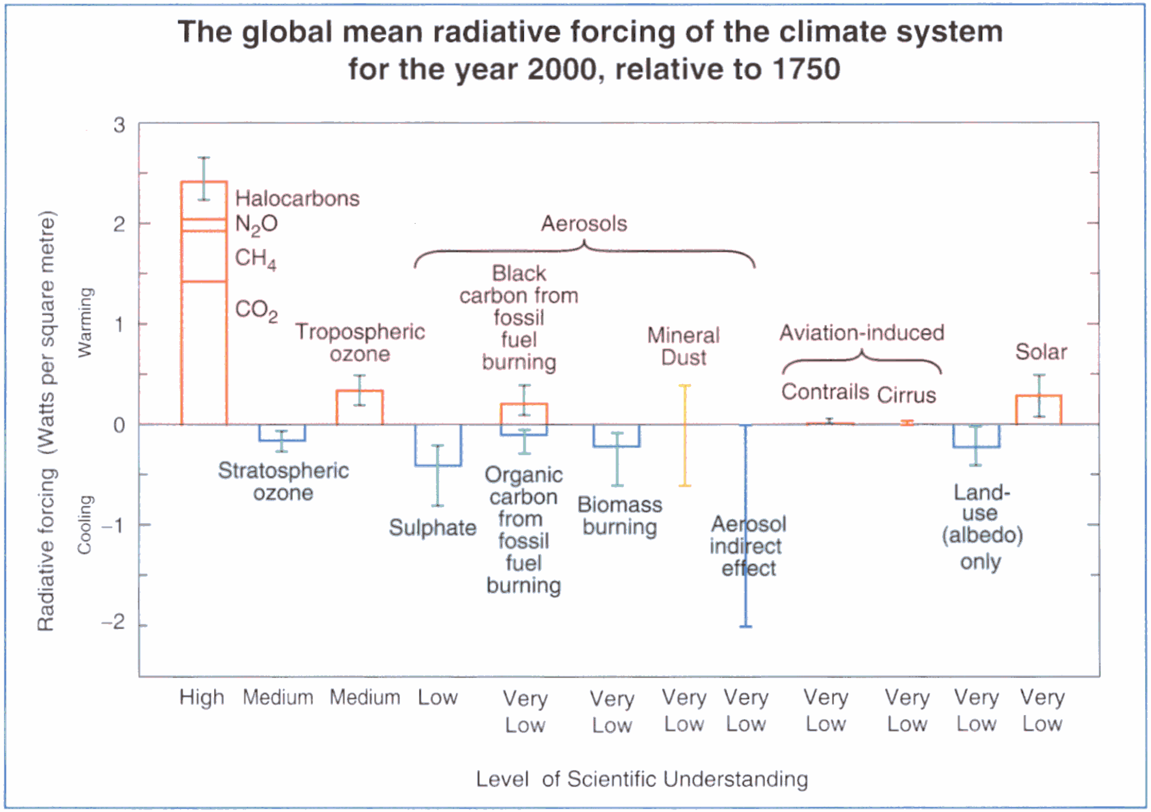
Greenhouse gases (1)



IPCC, Climate Change, 2001

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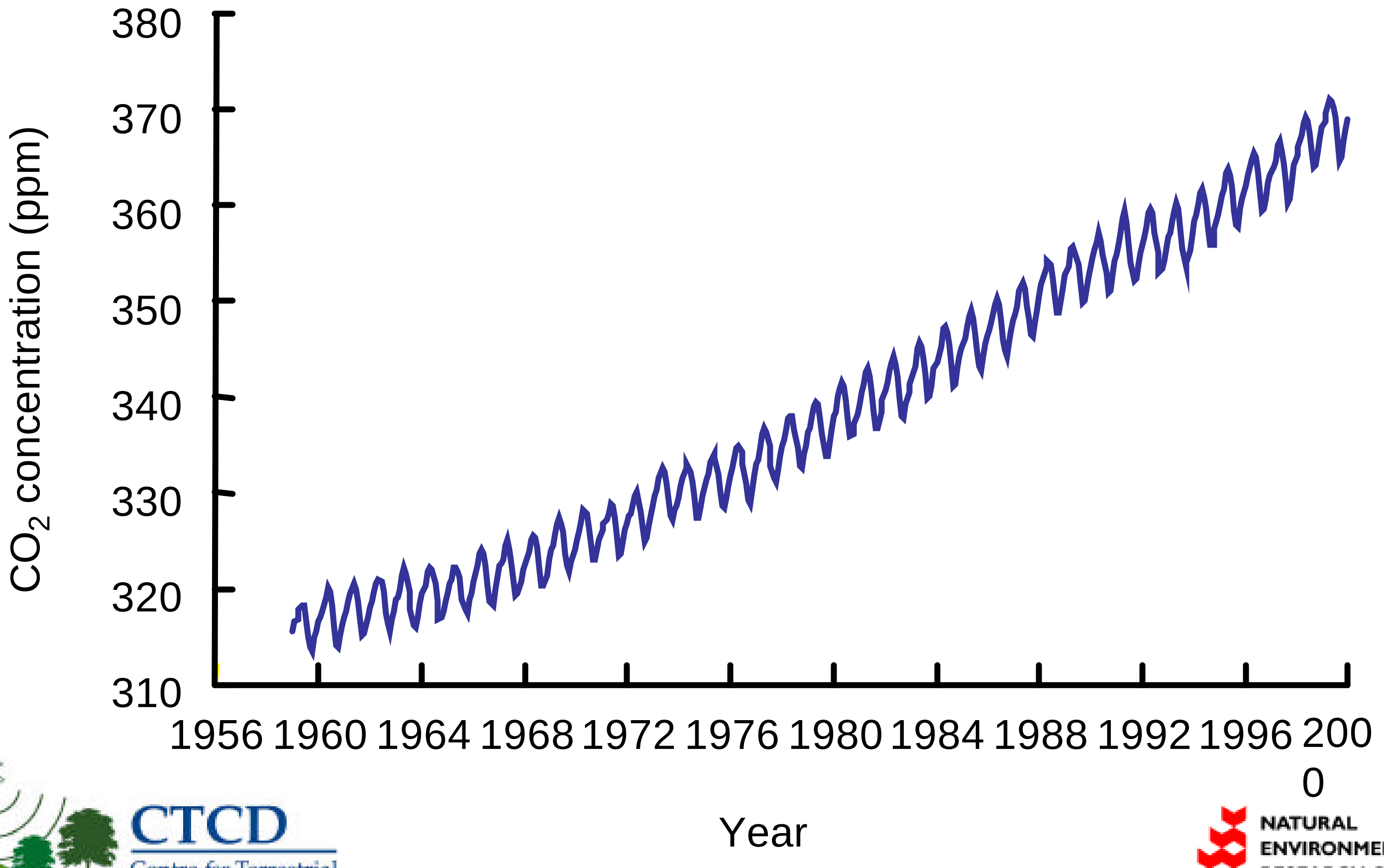
Mauna Loa C signal



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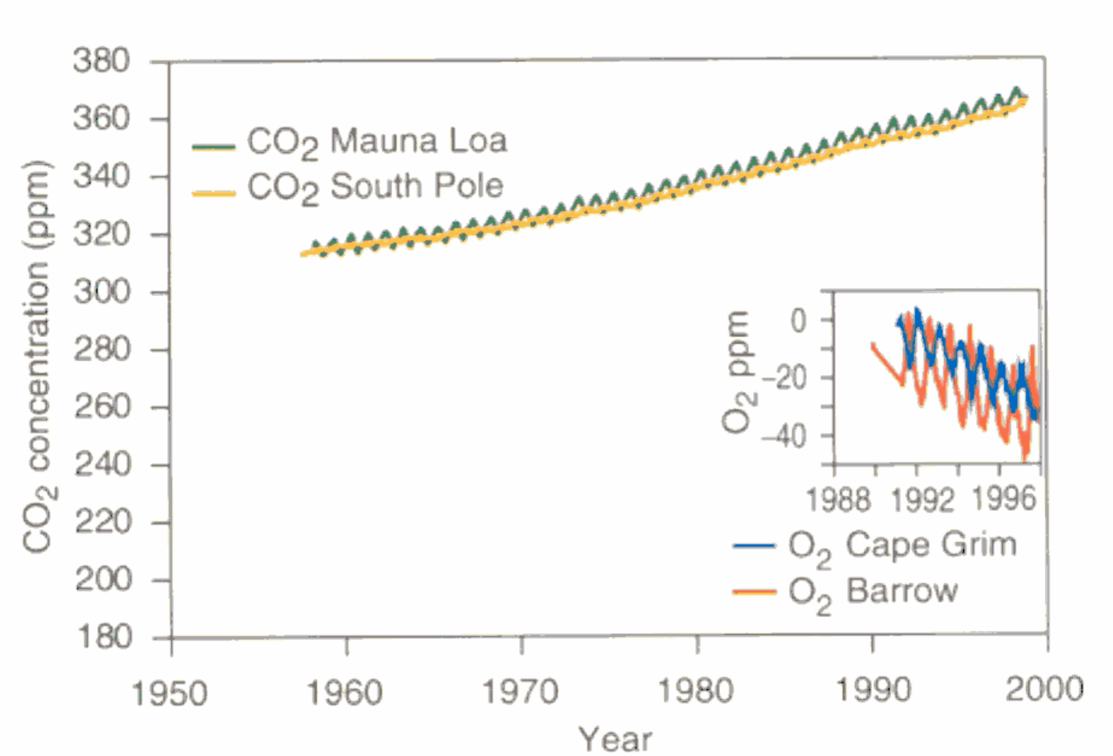
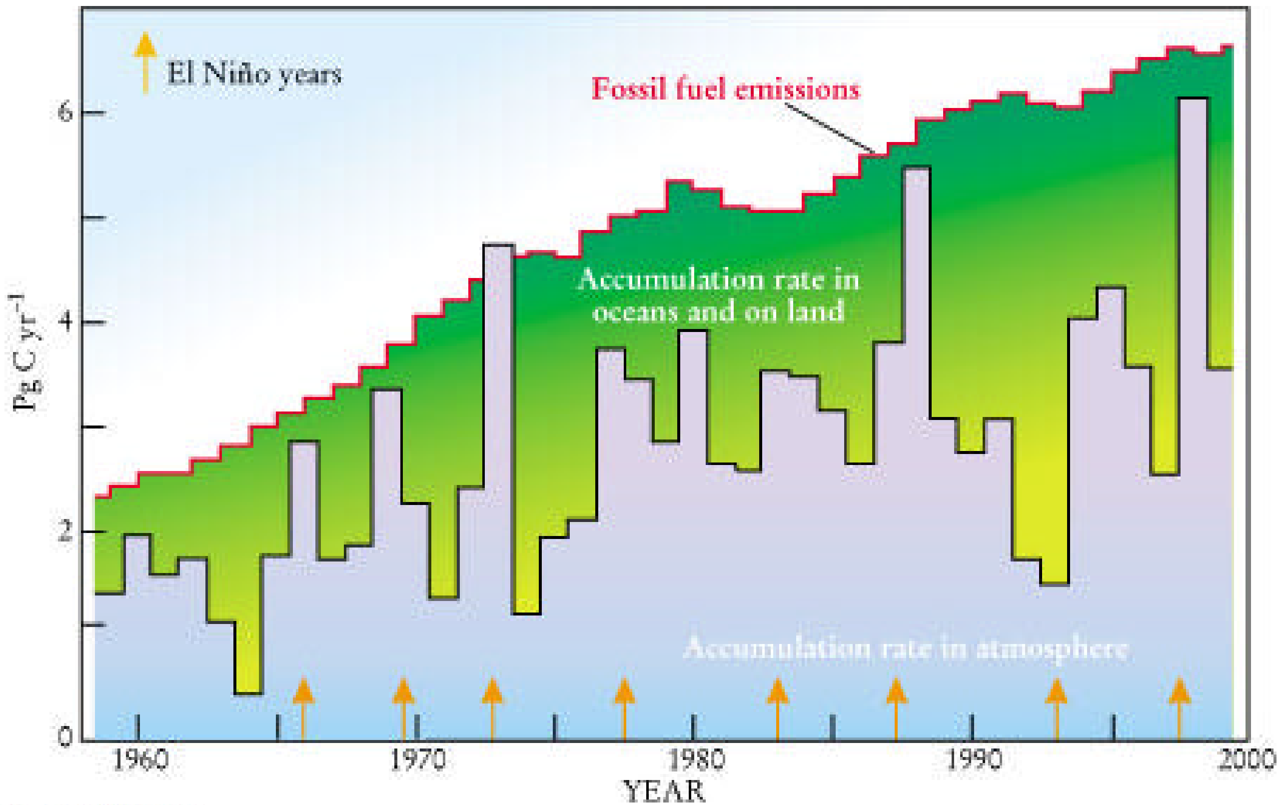
Keeling CO2 plots



IPCC, Climate Change, 2001

CO_2: emissions vs atmospheric increase



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From: 'Sinks for Anthropogenic Carbon', Physics Today, August 2002, Jorge L. Sarmiento and Nicolas Gruber

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

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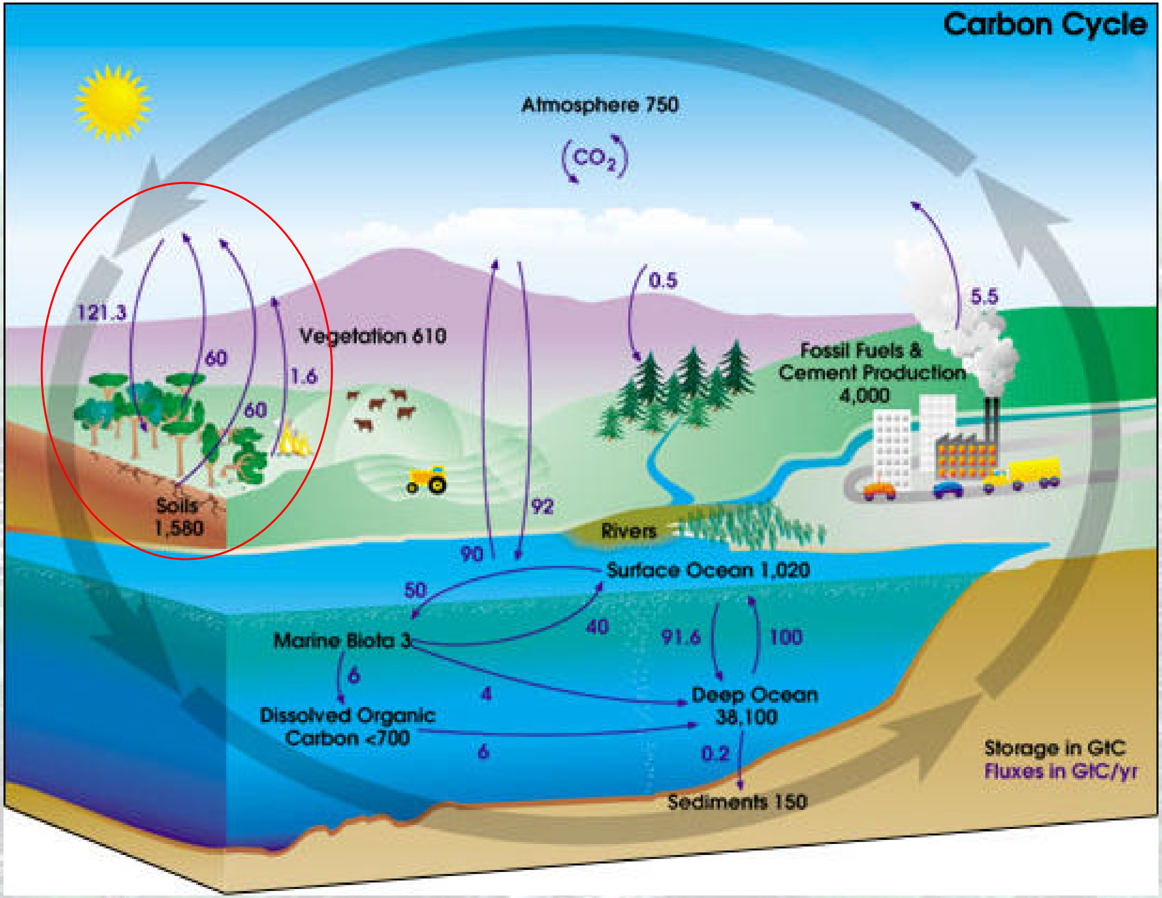
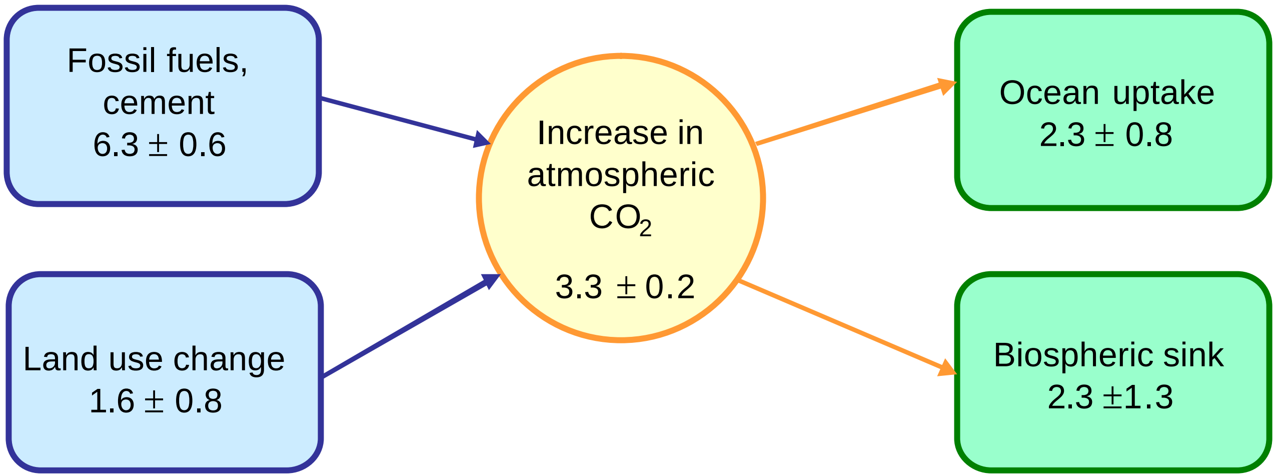
The Carbon Cycle



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

Carbon Budget during 1989-98

(Gt C y^{-1}; Intergovernmental Panel on Climate Change, 2000)



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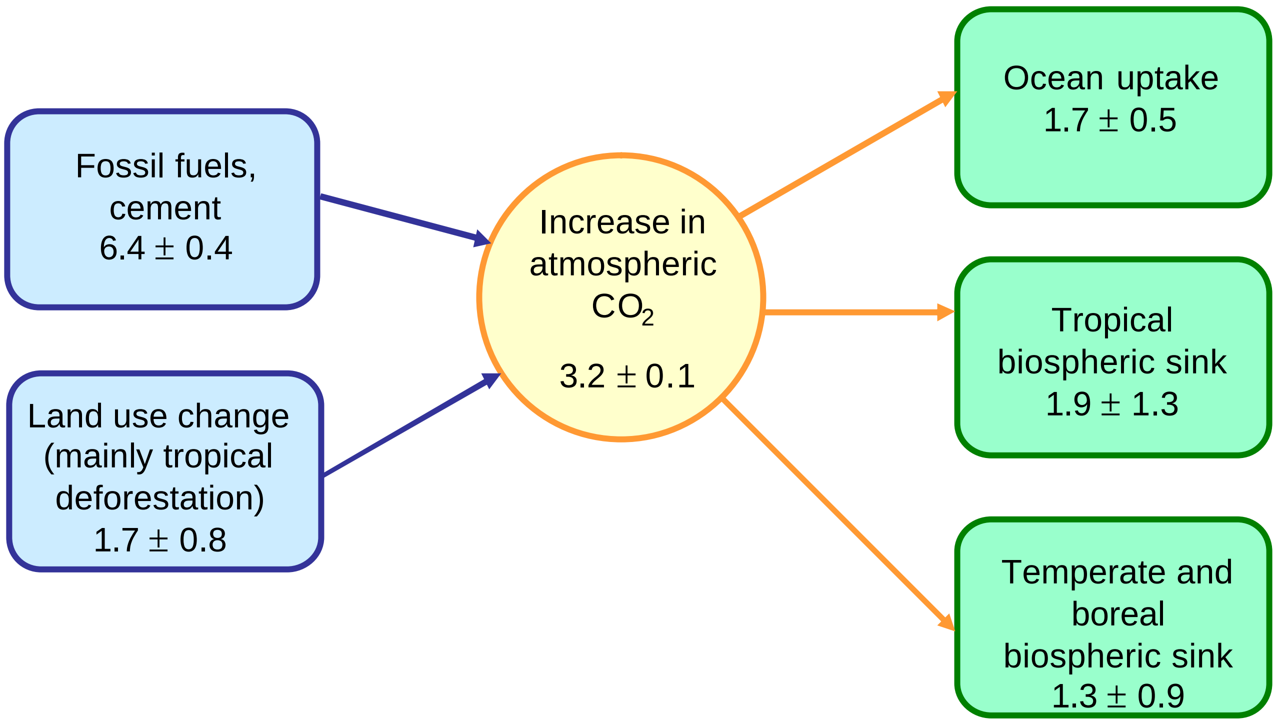
Carbon Budget in the 1990's

(Gt C y^{-1}; Royal Society Report, 2001)



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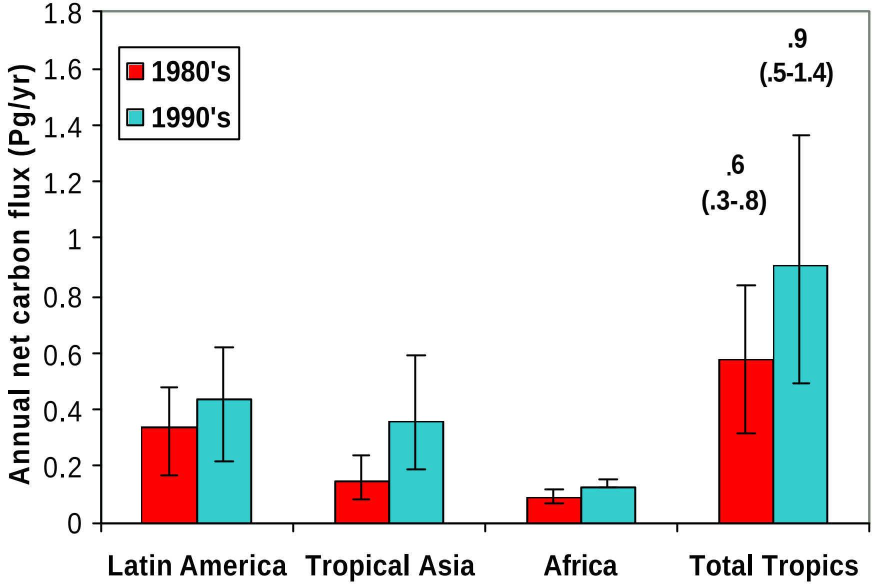
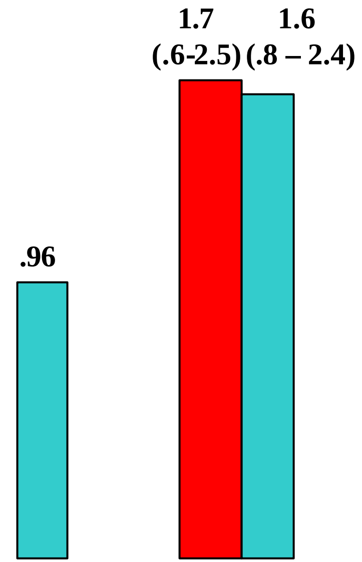
Estimated Carbon Flux from Tropical Deforestation and Regrowth for 1980s and 90s



(DeFries, et al., 2002)



Total Tropics

(Achard 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

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The importance of the land surface

The terrestrial biosphere is a crucial element of the carbon cycle

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

BUT, its

- status
- dynamics
- evolution

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

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The big questions

1. What role does the land surface play in modulating and controlling atmospheric CO_2?
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?

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Kyoto Protocol and C management on land

- **Urgent need to monitor sources and sinks of greenhouse gases (UN Framework Convention on Climate Change UNFCCC)**
- **The Kyoto Protocol allows the use of carbon sinks on land (essentially, planting new forests) to be offset against emissions**

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Measuring surface-atmosphere fluxes across scales

- Global (Keeling plots)
- Continental: atmospheric inversion

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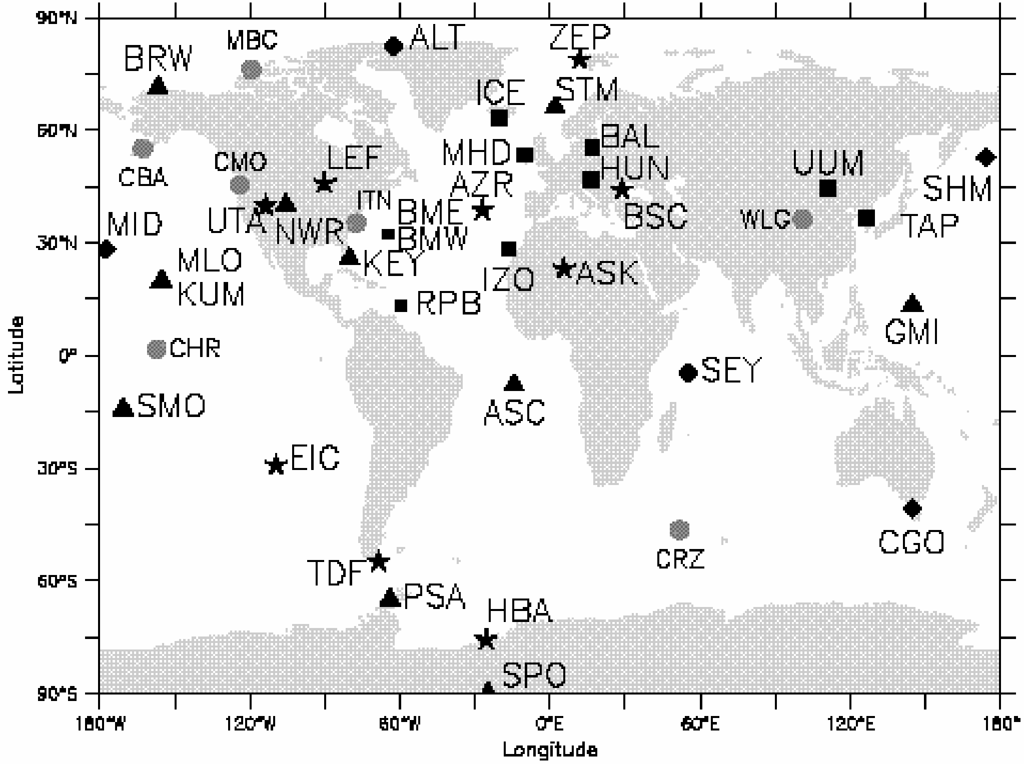
Inference of sinks from flask measurements



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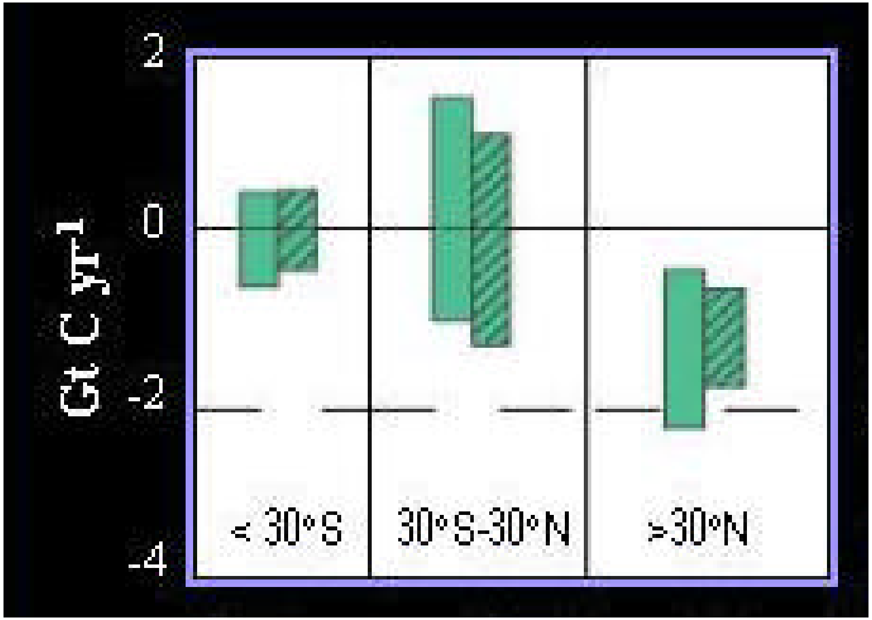
Current knowledge on carbon sources and sinks (from atmospheric inversions)



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

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1-2 Gigatons sequestered on land North of 30°; elsewhere, sources match sinks

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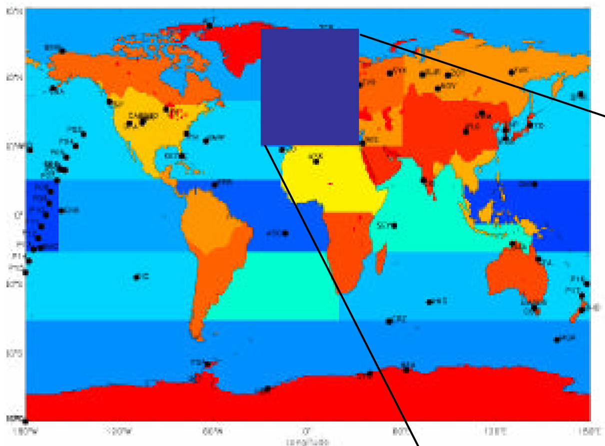
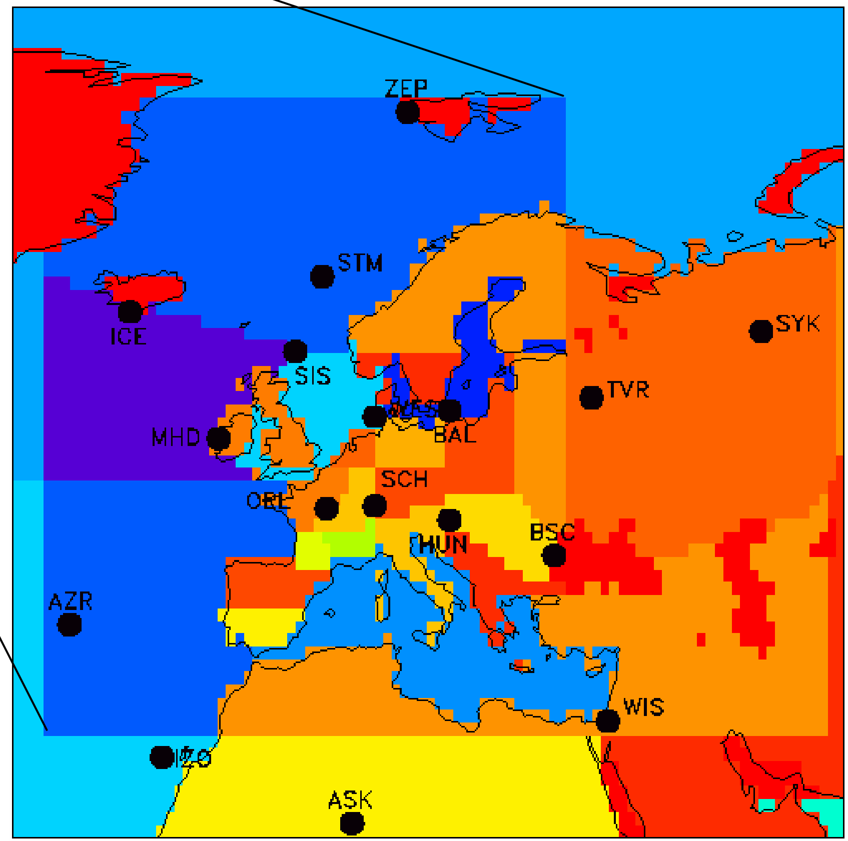
Russian Doll inversions
20 regions over Europe





Input data set:
112 stations, year 1998-2000

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

Slide from P. Ciais

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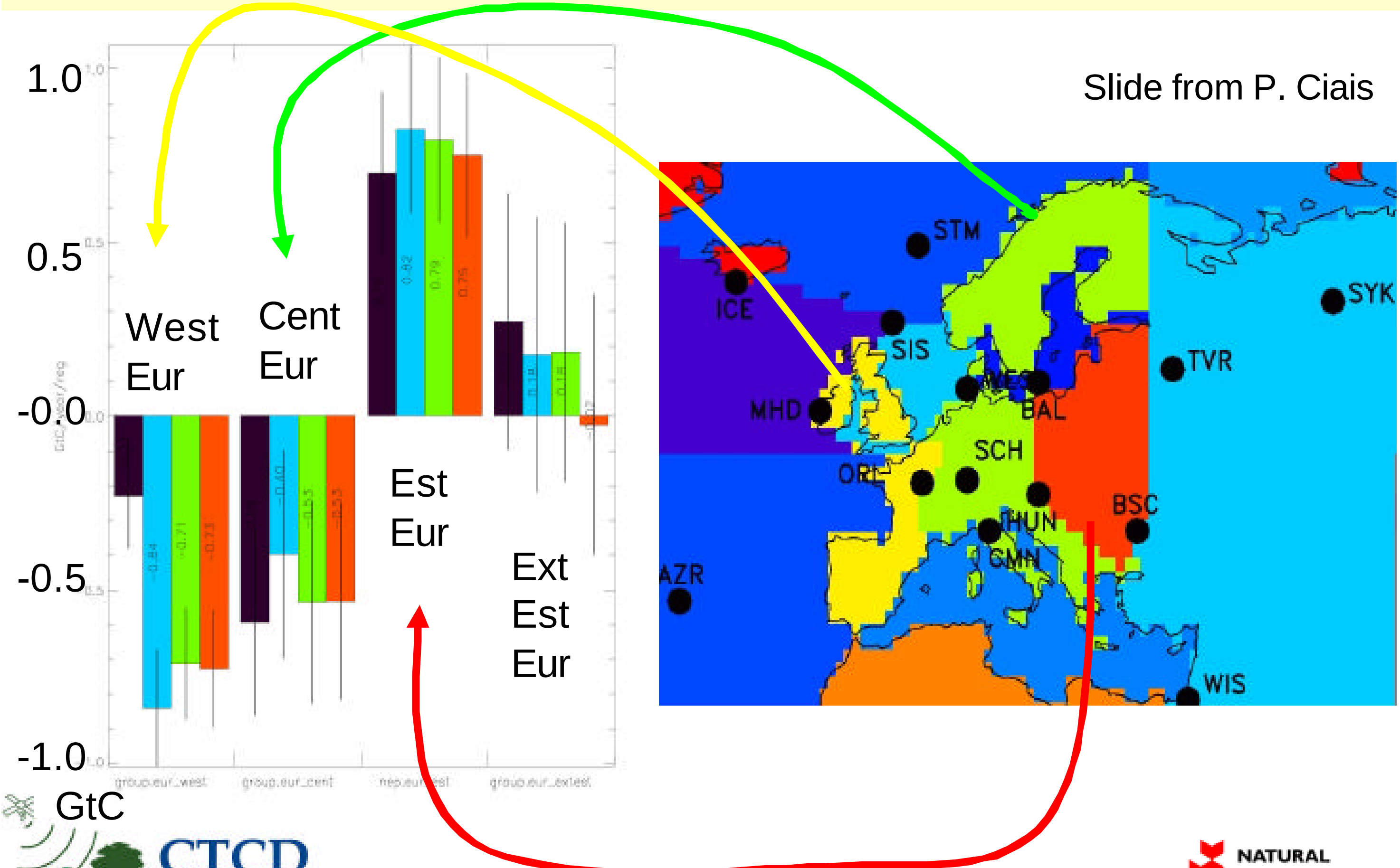
Annual optimized fluxes over Europe

Slide from P. Ciais



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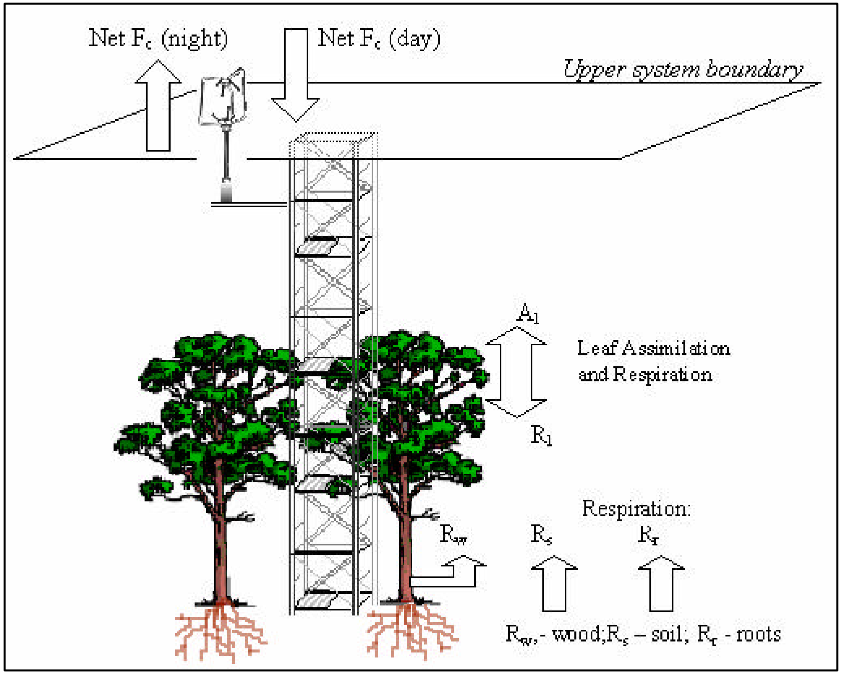
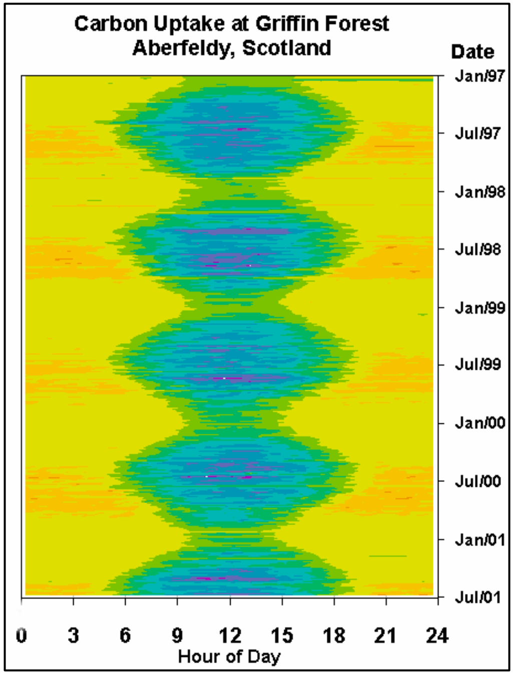
Eddy covariance CO_2 and H_2O fluxes: Provision of flux data for key target CTCD sites





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

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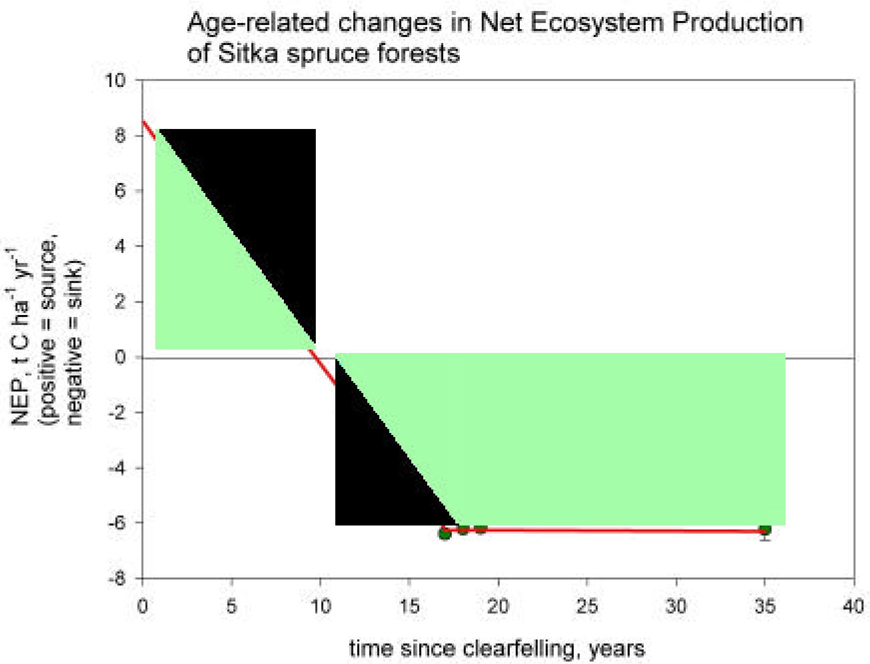
CarboAge NEP net C fluxes over one rotation. Spruce on a peaty gley: N. England (Mencuccini, Rayment & Grace *in prep*)



Σ NEP » 149.3 tC /ha over 40 years, i.e., 3.7 t C ha^{-1} y^{-1}

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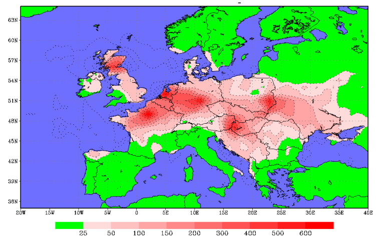
Regional observations tool-kit

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



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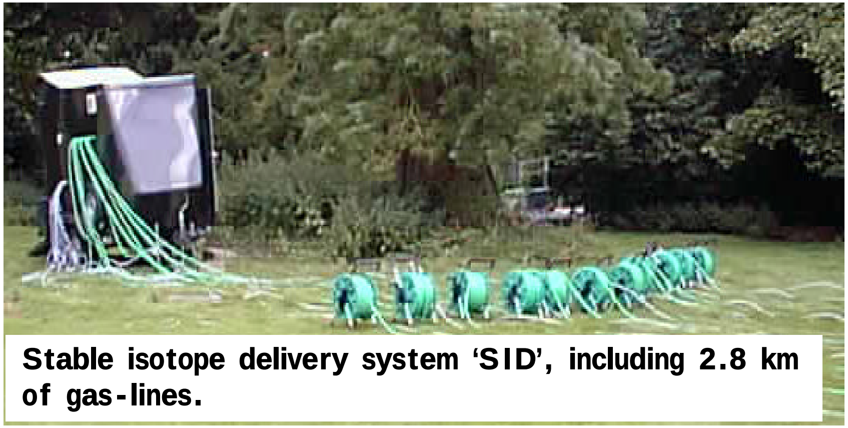
Pulse areas isolated above- and below-ground

$^{13}CO_2$ pulse/flux chambers.



Stable isotope delivery system 'SID', including 2.8 km of gas-lines.

Pulse delivery system

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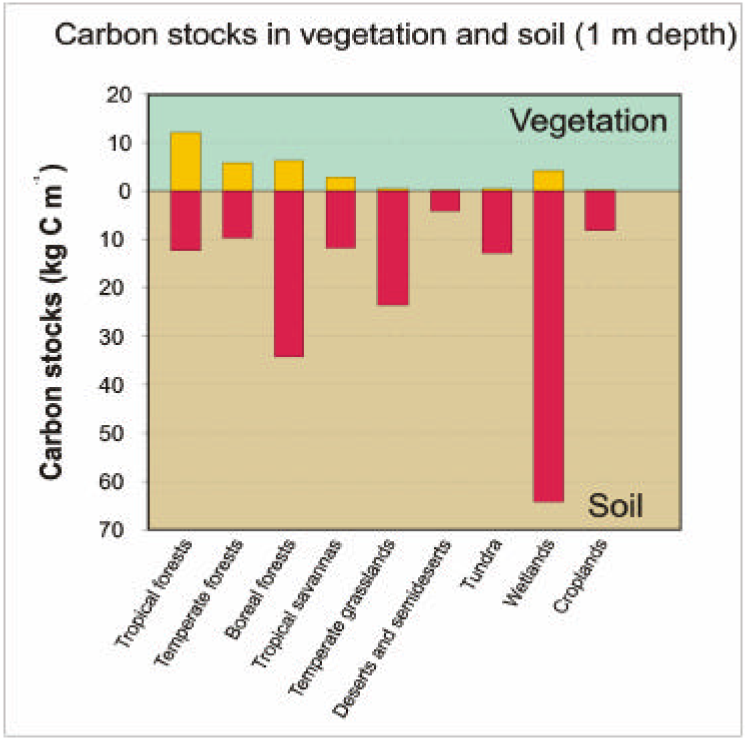
Proportion of carbon in vegetation and soils

1) Importance of soils in terrestrial C dynamics



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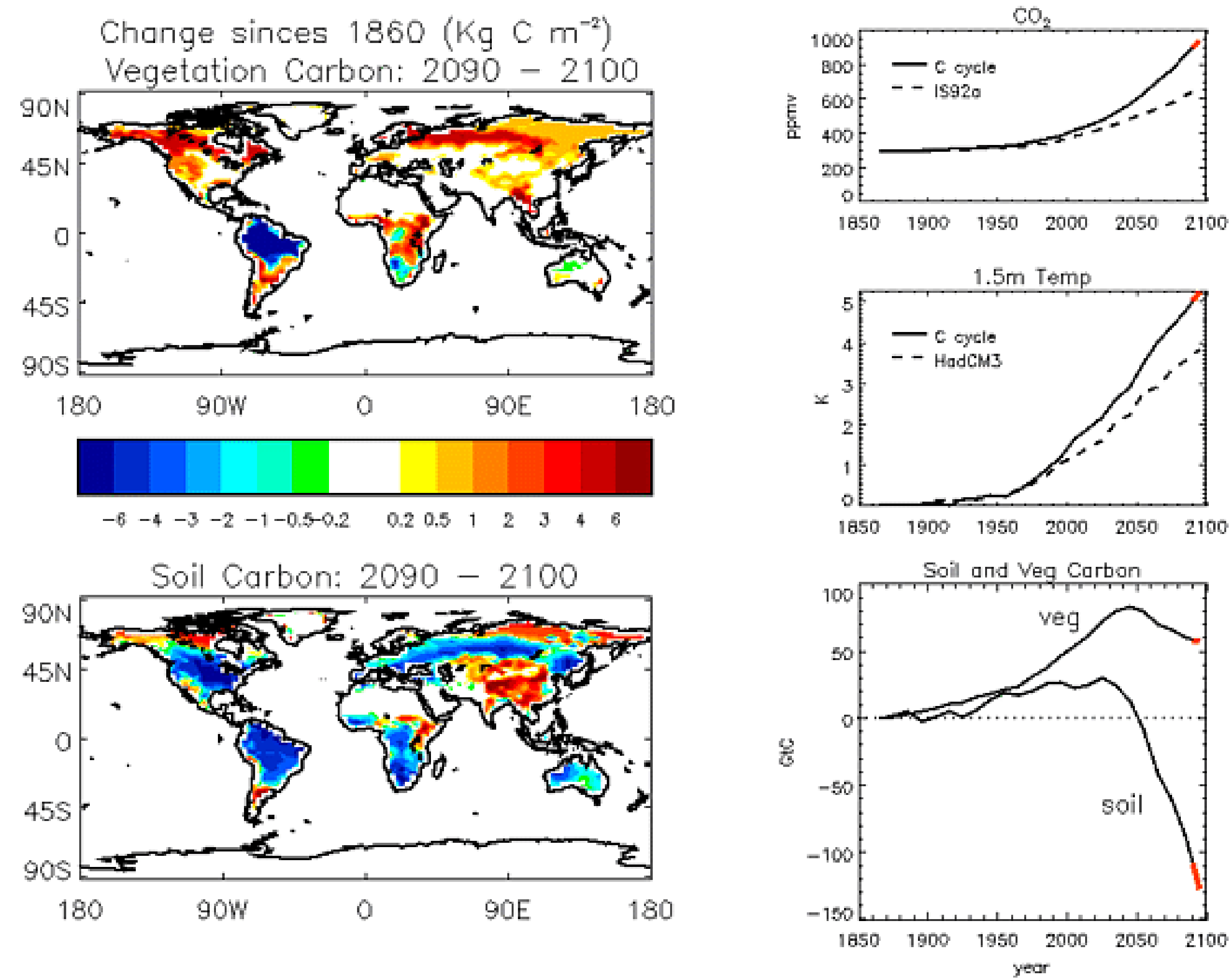
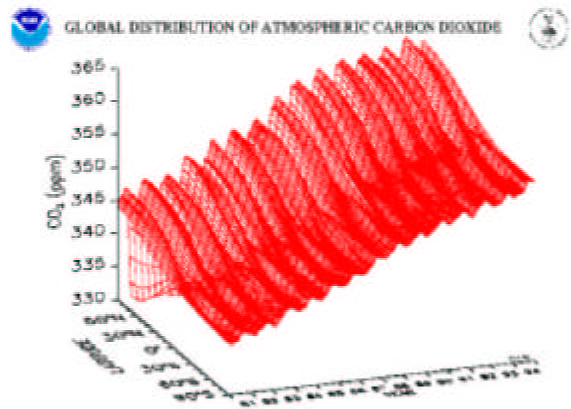
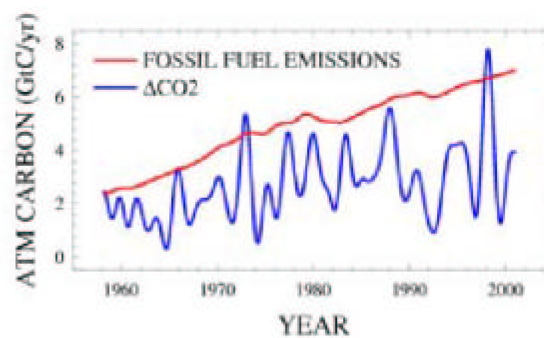
Climate Change Experiments with Carbon Cycle Feedbacks



An Uncertain Future: Where are the Missing Carbon Sinks?

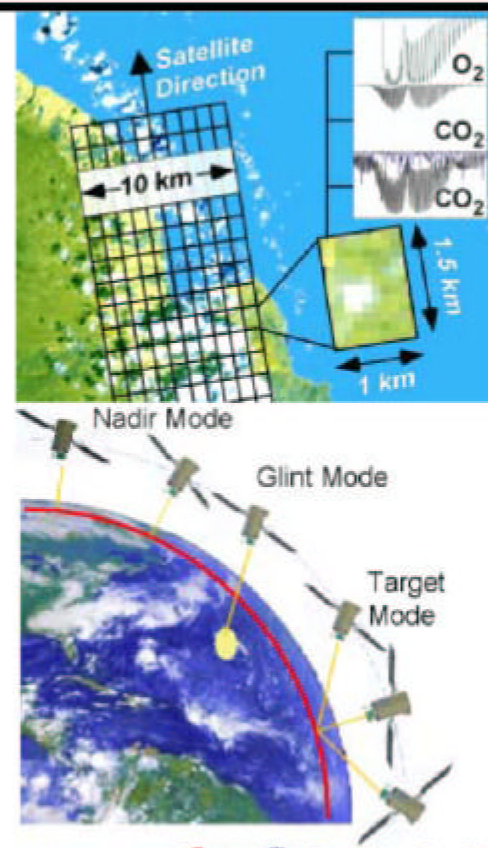
- **Only half of the CO_2 released into the atmosphere since 1970 years has remained there. The rest has been absorbed by land ecosystems and oceans**
  - What are the relative roles of the oceans and land ecosystems in absorbing CO_2?
  - Is there a northern hemisphere land sink?
    - What are the relative roles of North America and Eurasia
- **What controls carbon sinks?**
  - Why does the atmospheric buildup (blue) vary with uniform emission rates (red)?
  - How will sinks respond to climate change?
- **Reliable climate predictions require an improved understanding of CO_2 sinks**
  - Future atmospheric CO_2 increases
  - Their contributions to global change





OCO Spatial Sampling Strategy

- **OCO is designed provide an accurate description of X_{CO2} on regional scales**
  - Atmospheric motions mix CO_2 over large areas as it is distributed through the column
  - Source/Sink model resolution limited to 1°x1°
- **OCO flies in the A-train, 15 minutes ahead of the Aqua platform**
  - 1:15 PM equator crossing time yields same ground track as AQUA
  - Global coverage every 16 days
- **OCO samples at high spatial resolution**
  - Nadir mode: 1 km x 1.5 km footprints
    - Isolates cloud-free scenes
    - Provides thousands of samples on regional scales
  - Glint Mode: High SNR over oceans
  - Target modes: Calibration



Inventory methods

Mass balance: $$\Delta C = \Delta B_A + \Delta B_B + \Delta L + \Delta S$$

ΔC carbon sequestration by vegetation and soil,

B biomass (A: above and B: below ground),

L litter,

S soil carbon

Weaknesses:

Regional: not representative.

Global: incomplete, inconsistent, cannot measure annual and inter-annual variability in NEP

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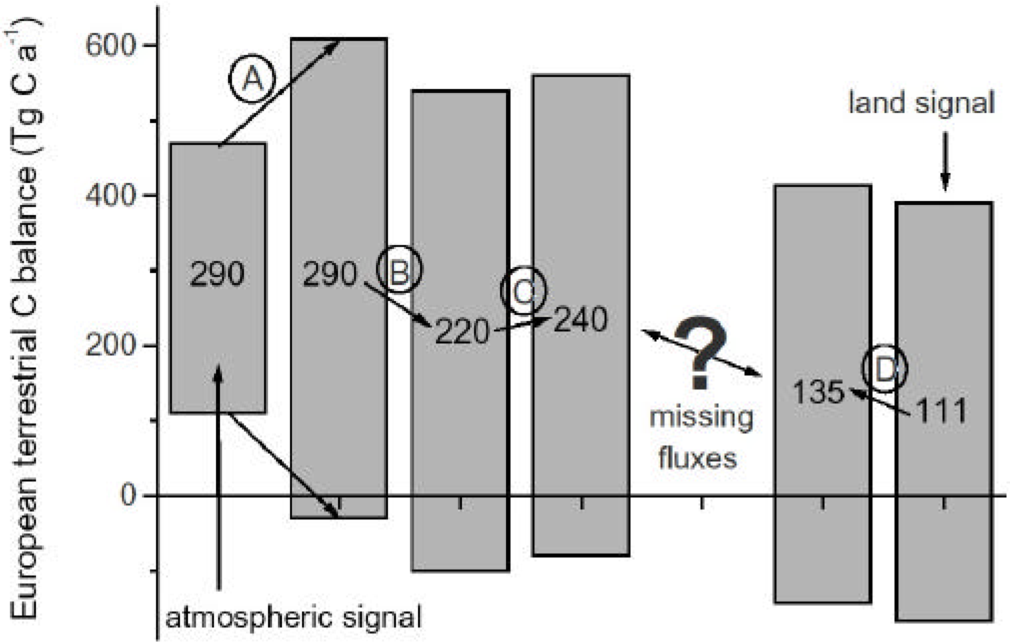
Reconciling Top-Down and Bottom-Up Estimates of the European Terrestrial Carbon Balance - State-of-the-Art



Corrections attributed to:
A Fossil emission uncertainty
B Non-CO_2 emissions
(a.o. CO)
C Trade product flows
D Wood products

Janssens et al., Science, in revision, 2003

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Models of the terrestrial biosphere: a process-based approach

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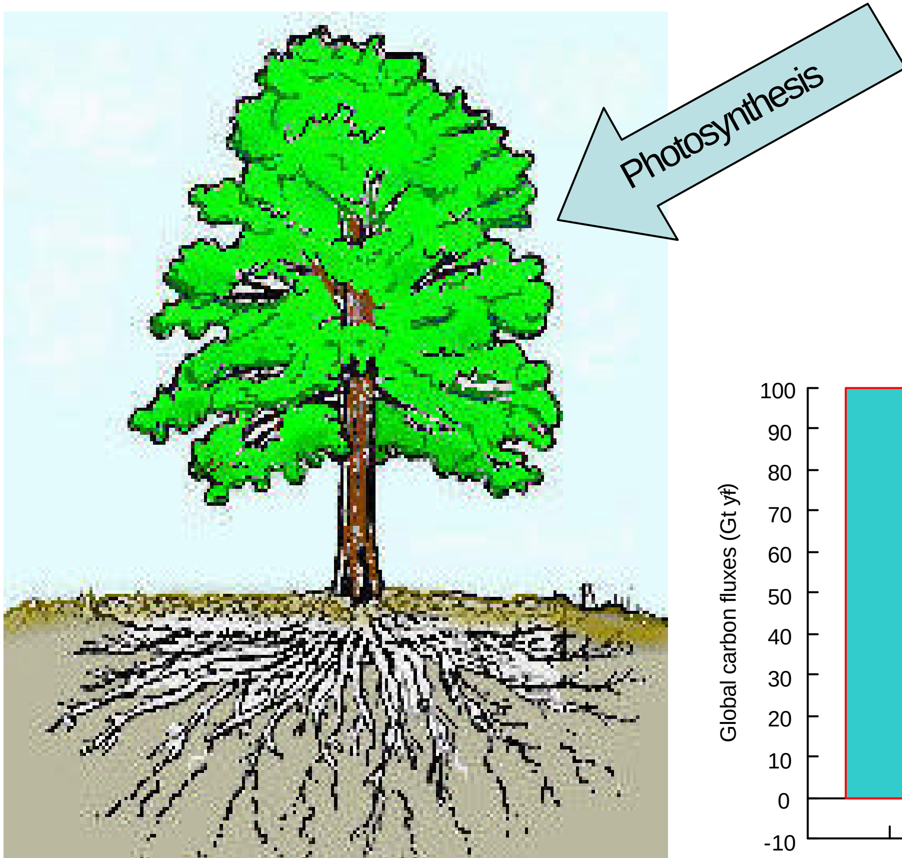
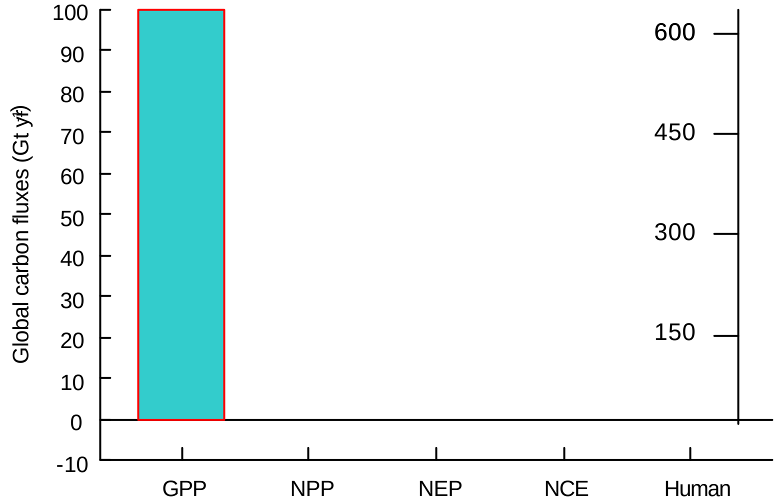
Gross Primary Production



Global Carbon Exchange

(gC m^{-2} yr^{-1})



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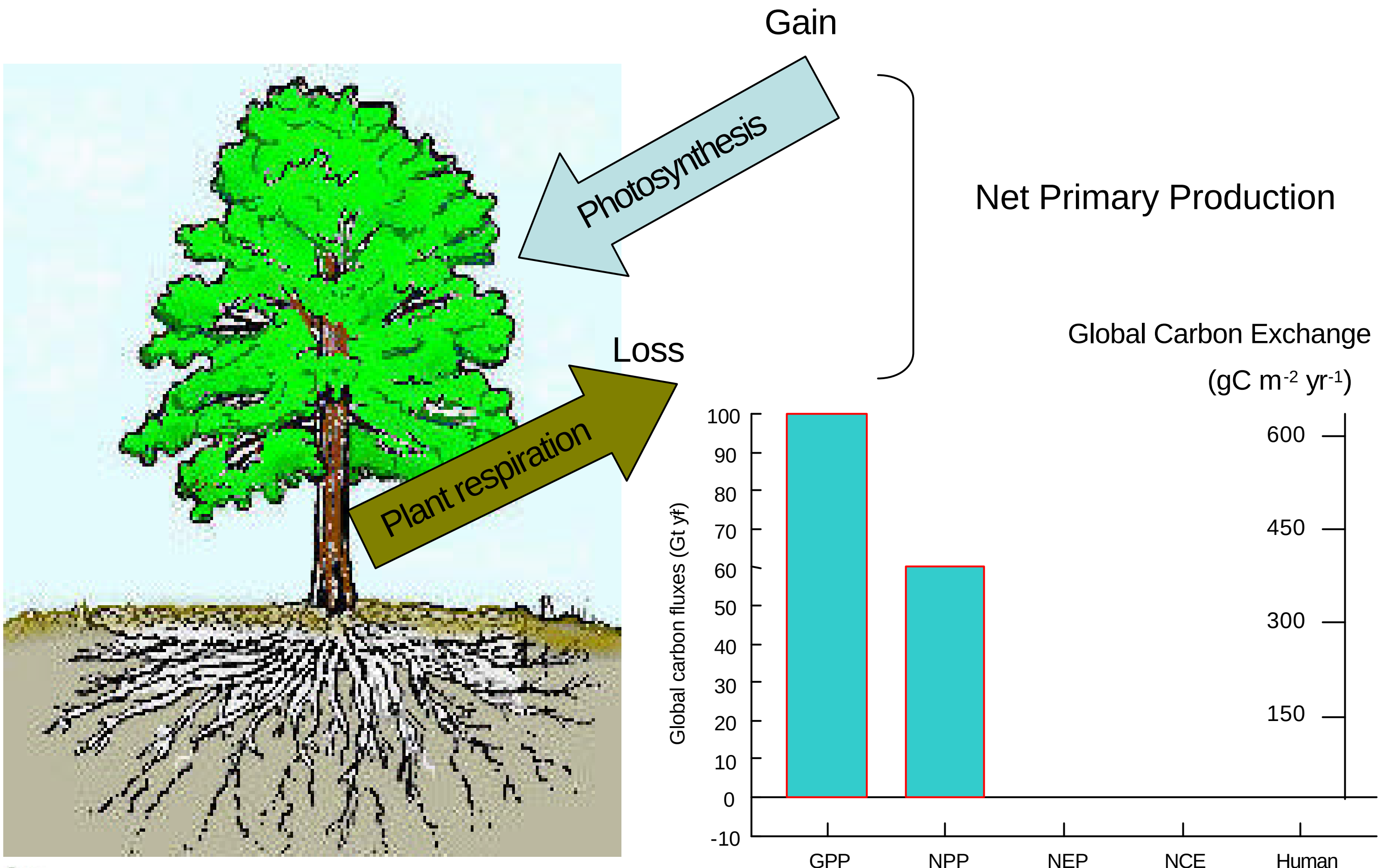

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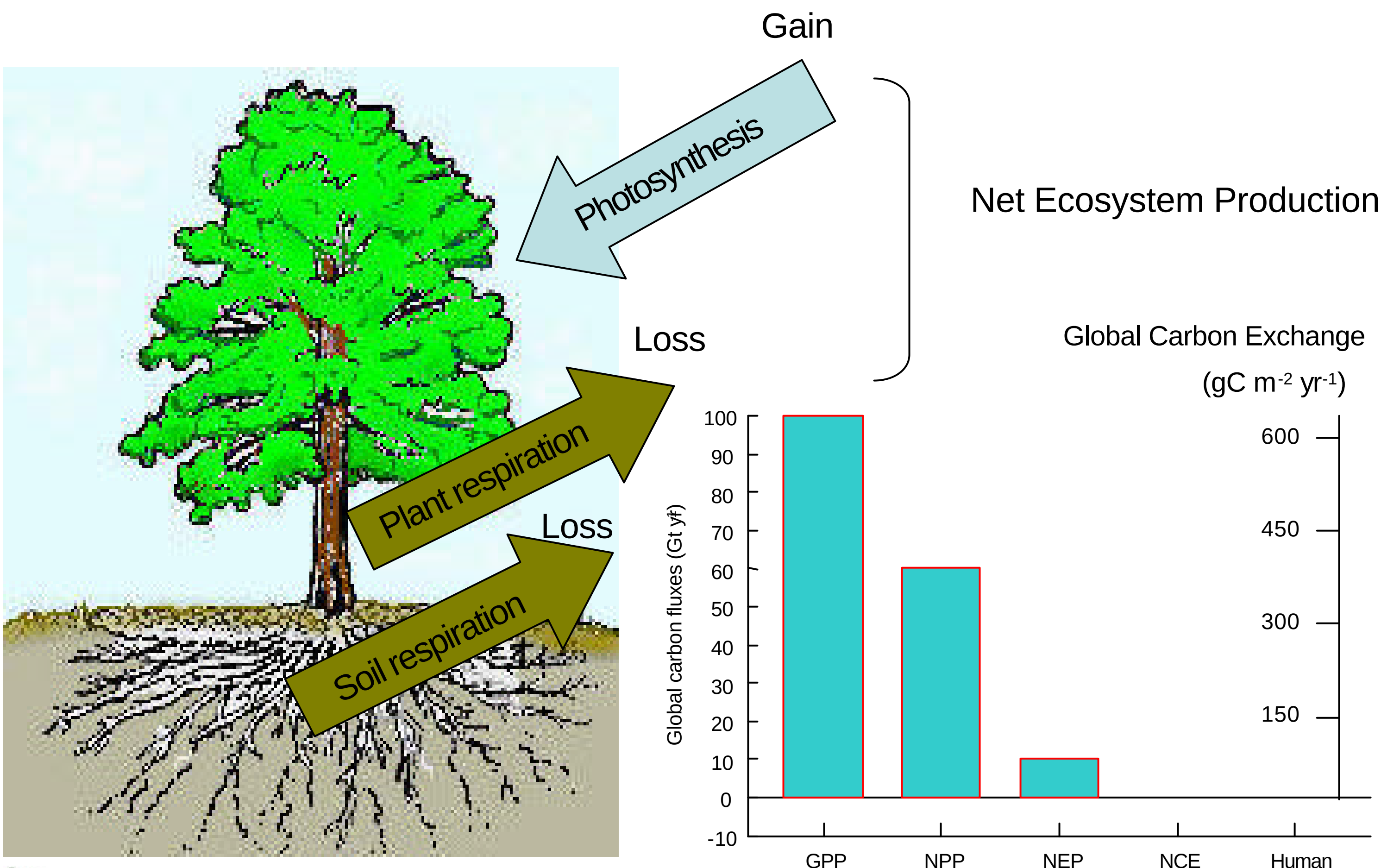

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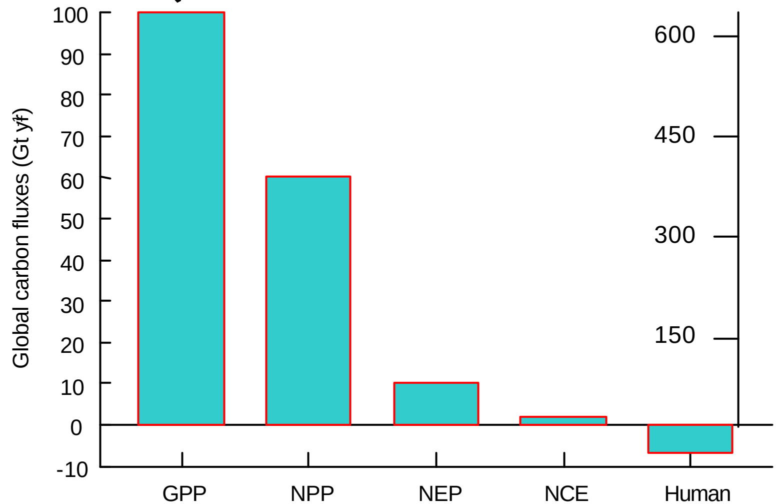
Losses

Net Carbon Exchange

Global Carbon Exchange

(gC m^{-2} yr^{-1})



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Modelling the Terrestrial Carbon Balance

Coupling dynamics and allocation processes:

Process equation : $\Delta C = GPP - R_P - R_H - D$

GPP gross primary production (photosynthesis),
R respiration (*P*: plant and *H*: heterotrophic),
D carbon loss by disturbance.

Allocation equation : $\Delta C = \Delta B_A + \Delta B_B + \Delta L + \Delta S$

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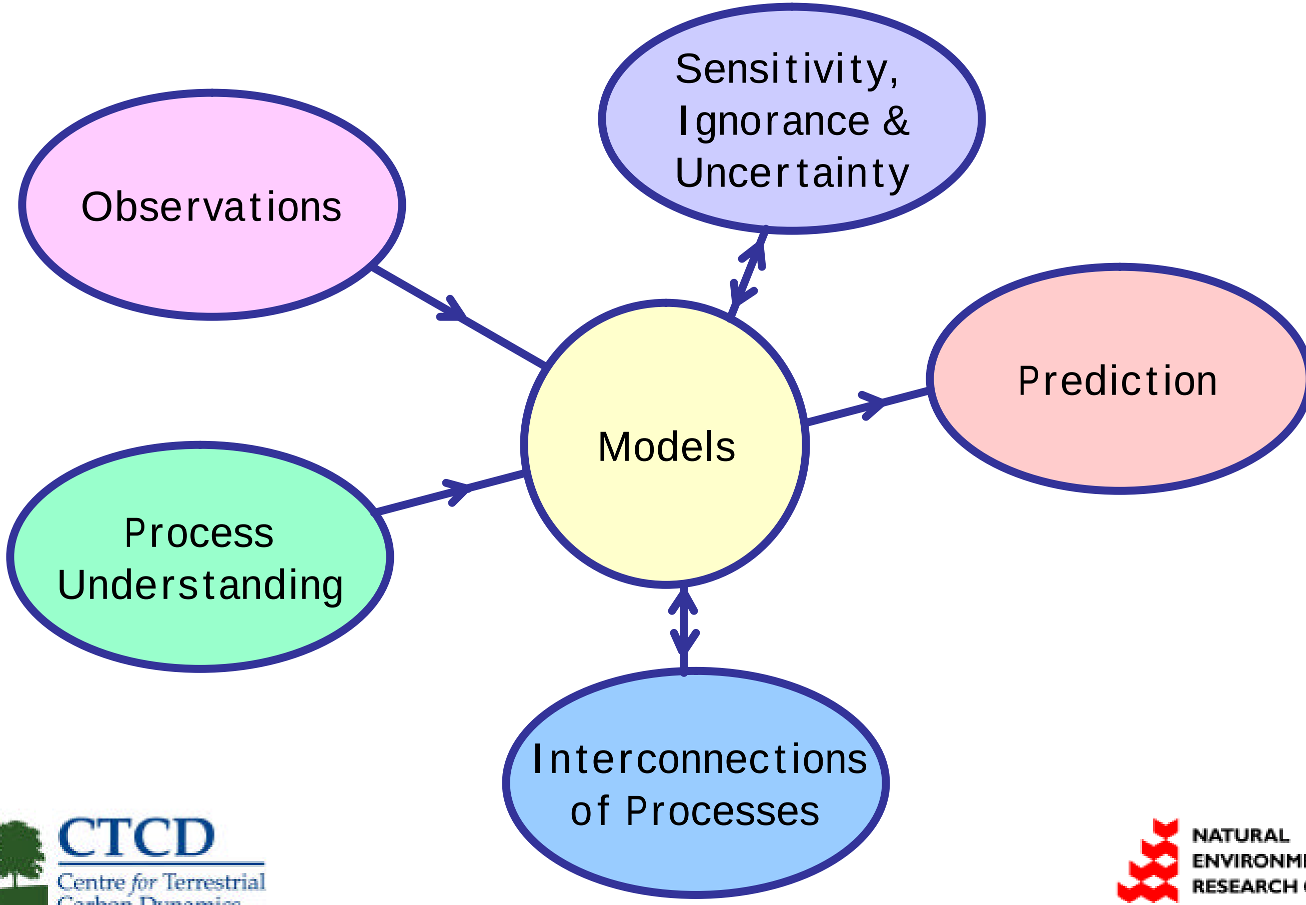
A Systems Approach Implies Models



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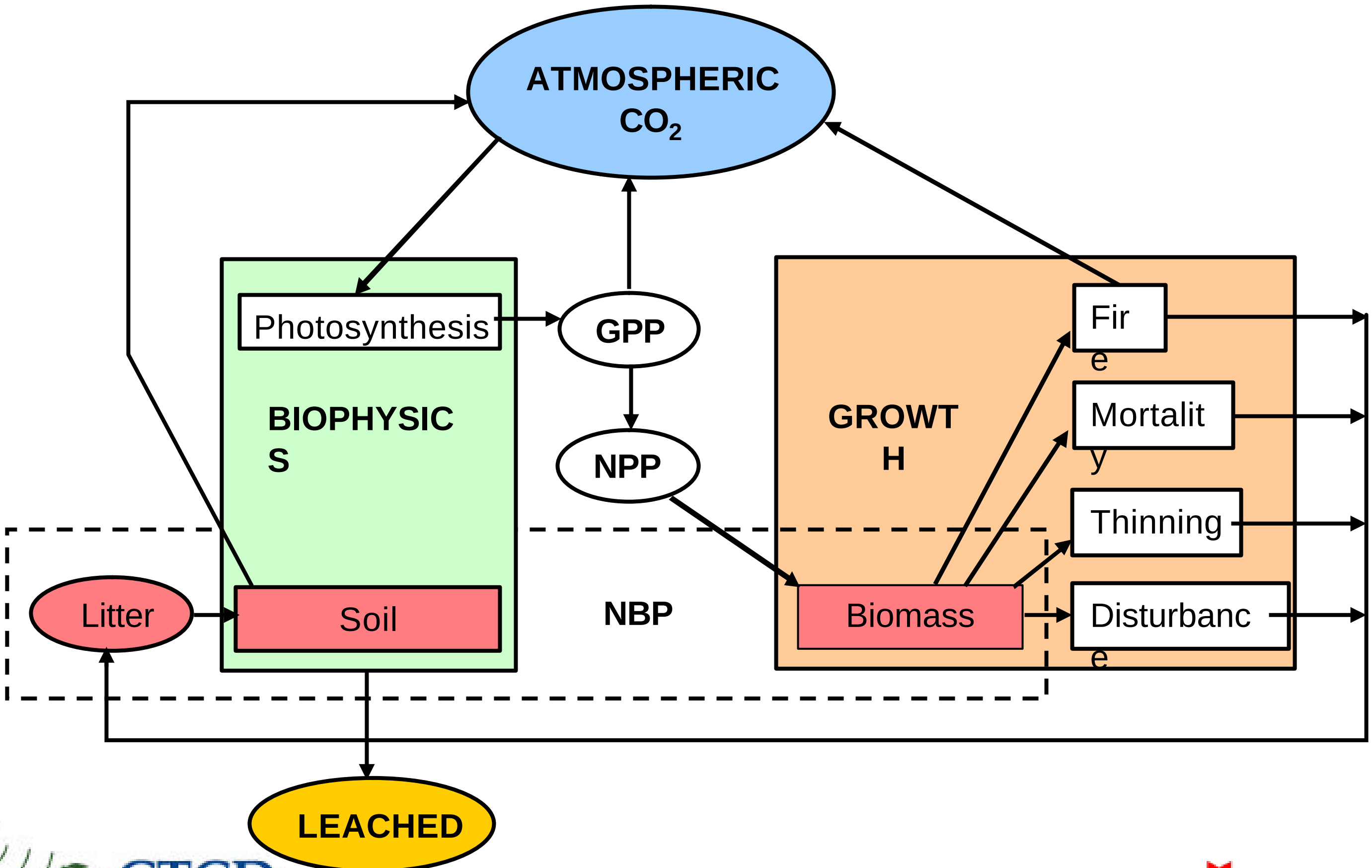
The SDGVM carbon cycle



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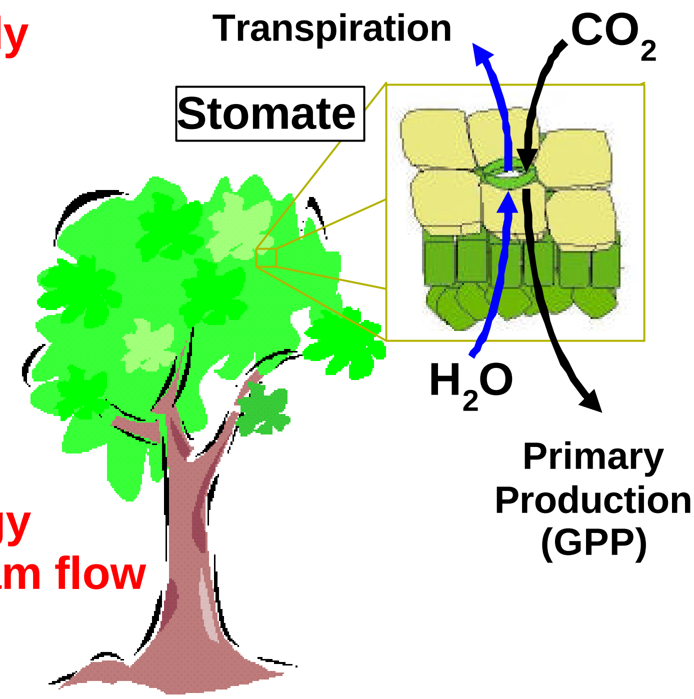
Water and carbon cycles

- **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**



- **Validating the hydrology and energy transfer parts of models using stream flow data**

- **Widely available**
- **Contain information about whole catchment**
- **Accurate**

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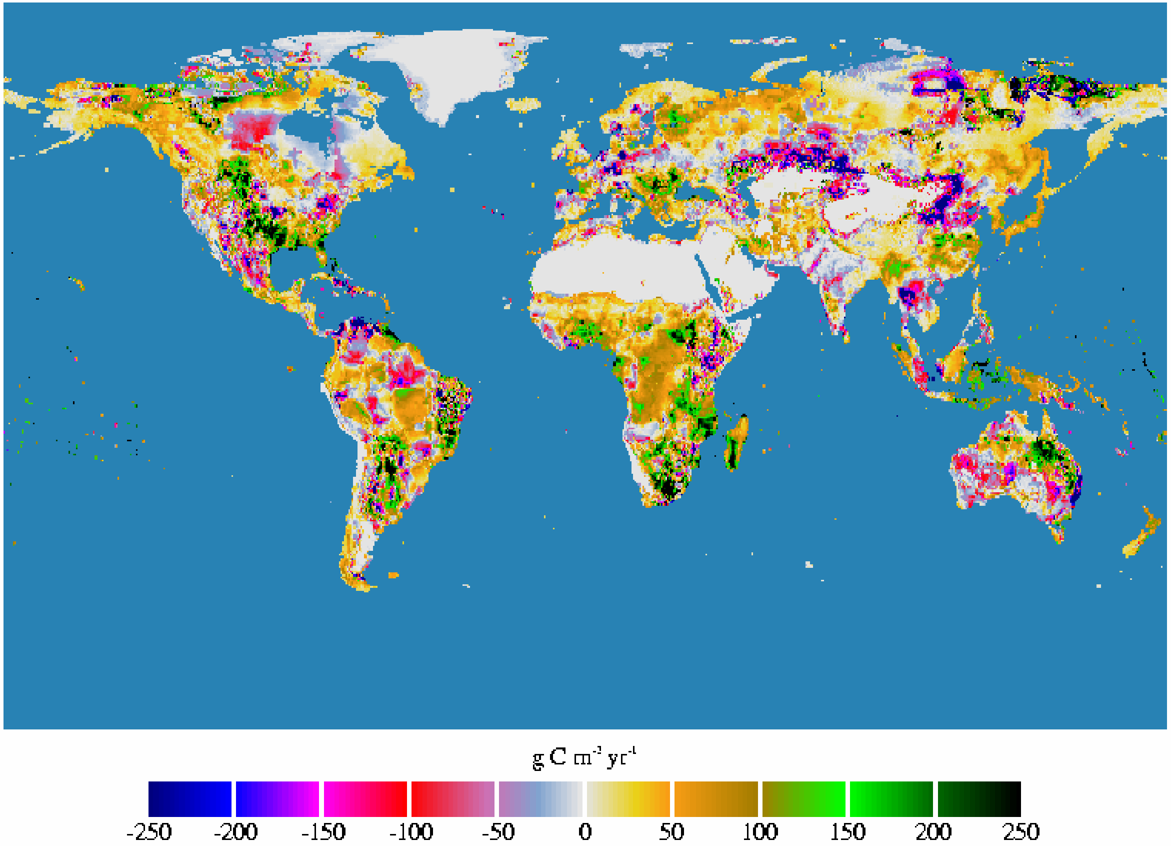
NCE 1991 with crop adjustment



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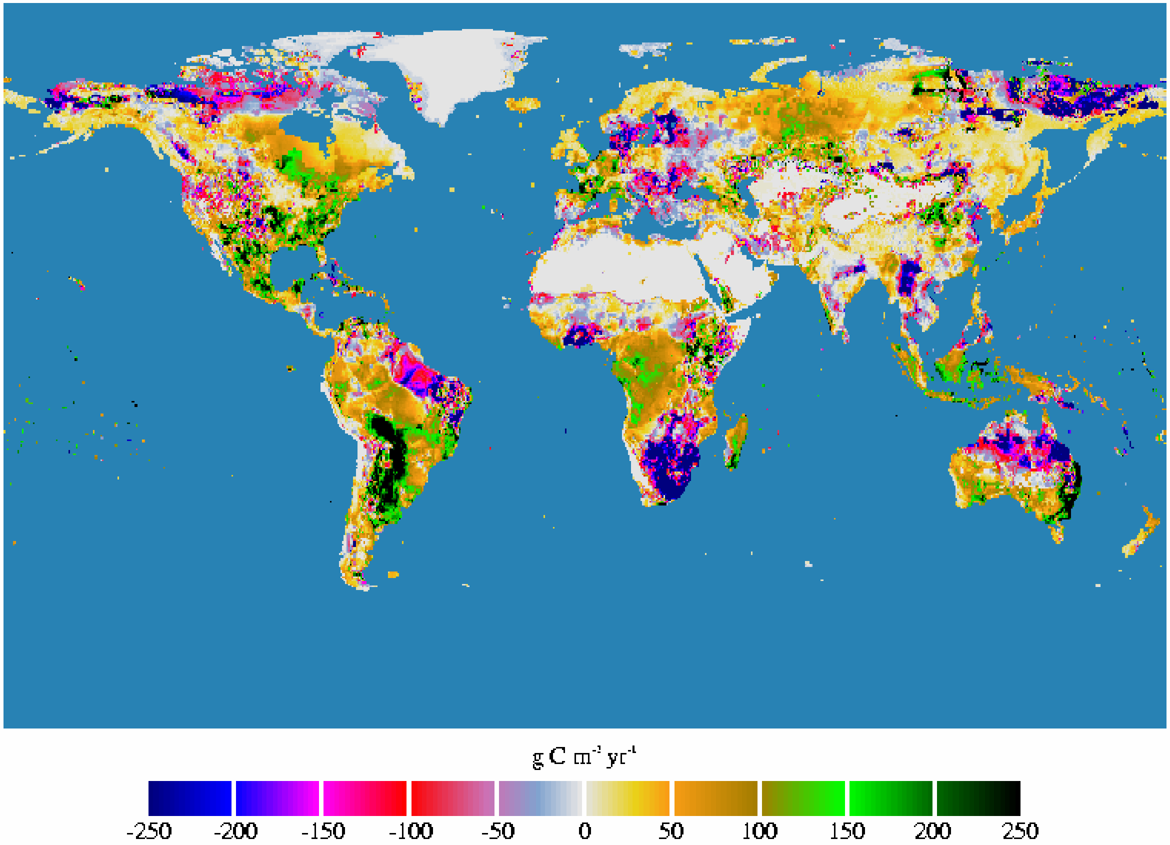
NCE 1992 with crop adjustment



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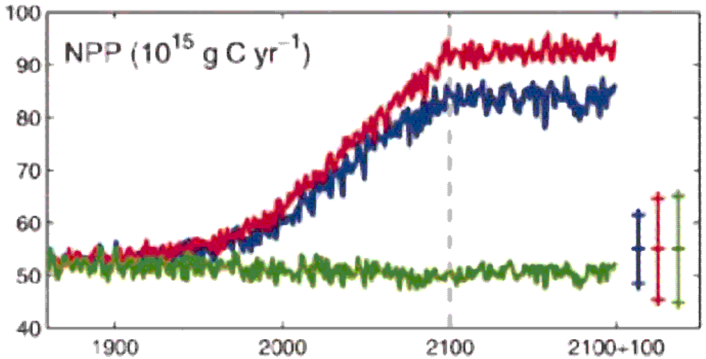
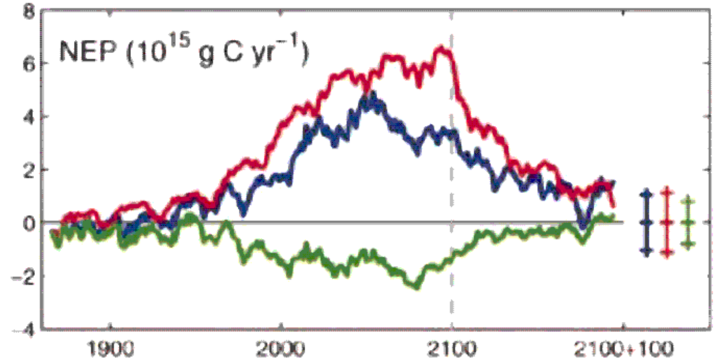
Predicted Response of Vegetation to Atmospheric Changes

Net Primary Production



Net Ecosystem Production



blue	CO_2 & T
red	CO_2 only
green	T only

SDGVM calculations use Hadley Centre climate predictions for 2000 – 2100:

doubling of CO_2;
mean global temp. increase from 13.3º C to 17º C.

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Conclusions

- The land surface plays a central role in the global carbon cycle, but is the least well-known and understood component of the cycle.
- Quantifying atmosphere-land carbon fluxes requires measurements at many different scales.
- Understanding the reasons for these fluxes and their likely evolution under a warming climate requires biospheric models; these models need data on carbon processes and pools.
- Models provide the framework for integrating knowledge and data, including measurements of many different types from satellite sensors.

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Logos