The Carbon Cycle

Dr Emily Lines

School of Geography, Queen Mary University of London

e.lines@qmul.ac.uk

Global carbon cycle

Carbon **stocks** and annual carbon exchange **fluxes**:

Prior to the Industrial Era (1750)

Additional 'anthropogenic' fluxes (averaged over 2000–2009)

Figures in PgC :
1 PgC = 10^{15} gC
1 PgC = 1 GtC

IPCC (2013)

Atmosphere 589 + 240 ±10
(average atmospheric increase: 4 (PgC yr^{-1}))

Net land flux

Net ocean flux

2.3 ±0.7   0.7

Ocean-atmosphere gas exchange

80 = 60 + 20   78.4 = 60.7 + 17.7

Freshwater outgassing   1.0

Fossil fuels (coal, oil, gas) cement production   7.8 ±0.6

Net land use change   1.1 ±0.8

2.6 ±1.2   1.7

Gross photosynthesis 123 = 108.9 + 14.1

Total respiration and fire 118.7 = 107.2 + 11.6

Volcanism   0.1

Rock weathering   0.3

Rock weathering   0.1

Export from soils to rivers 1.7

Surface ocean 900

Marine biota 3   50   37

Rivers 0.9

Burial 0.2

90   101

11   2

Intermediate & deep sea 37,100

Dissolved organic carbon 700   2

+155 ±30

0.2

Ocean floor surface sediments 1,750

Vegetation 450-650
-30 ±45
Soils 1500-2400

Permafrost ~1700

Fossil fuel reserves
Gas: 383-1135
Oil: 173-264
Coal: 446-541
-365 ±30

Units
Fluxes: (PgC yr^{-1})
Stocks: (PgC)

The *perturbation* of the global carbon cycle caused by anthropogenic activities.

(Figures in PgC/yr)

The land and ocean act as *sinks* of carbon, with a net increase annually.

Land sink larger, more variable over time, higher uncertainty.

Global carbon dioxide budget
(gigatonnes of carbon per year)
2003–2012

Fossil fuel & cement
8.6 ± 0.4

Atmospheric growth
4.3 ± 0.1

Land-use change
0.9 ± 0.5

Land sink
2.8 ± 0.8

Ocean sink
2.5 ± 0.5

Geological reservoirs

Produced by the International Geosphere-Biosphere Programme for the Global Carbon Project.
© Global Carbon Project 2010

Le Quéré, 2013
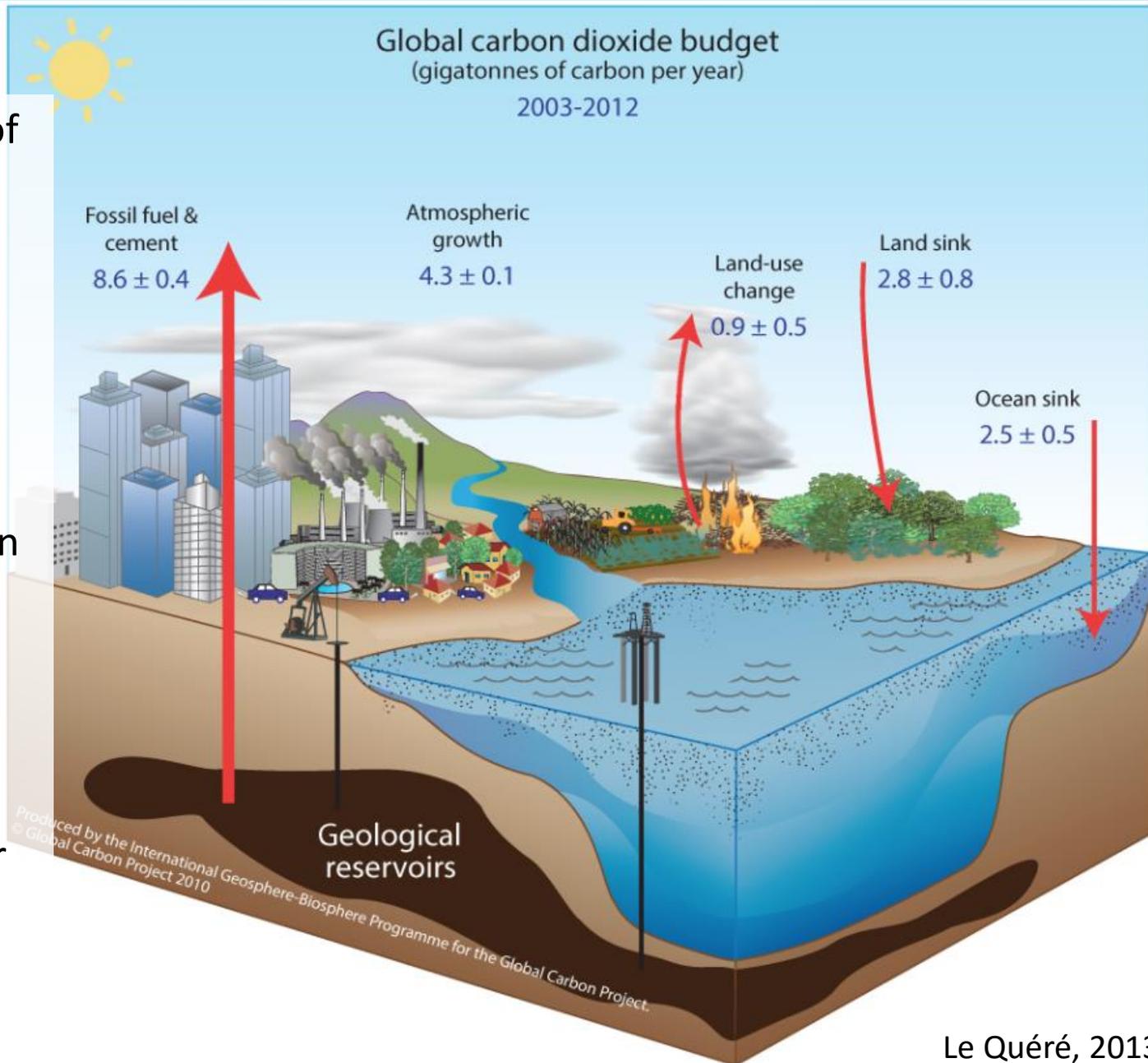
Primary production

- Primary production means the generation of biological material by plants via photosynthesis.

$$CO_2 + H_2O \xrightarrow{\text{light}} CH_2O + O_2 + H_2O$$

carbohydrate
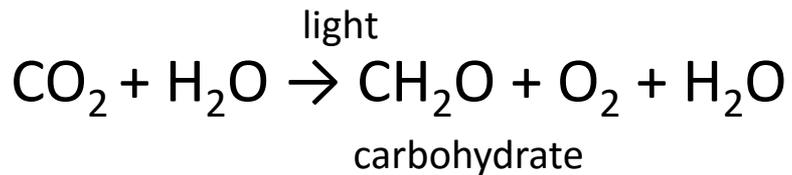
- Limited by light, nutrients, water, temperature.

GPP = C taken up by plants through photosynthesis

NPP = GPP – respiration
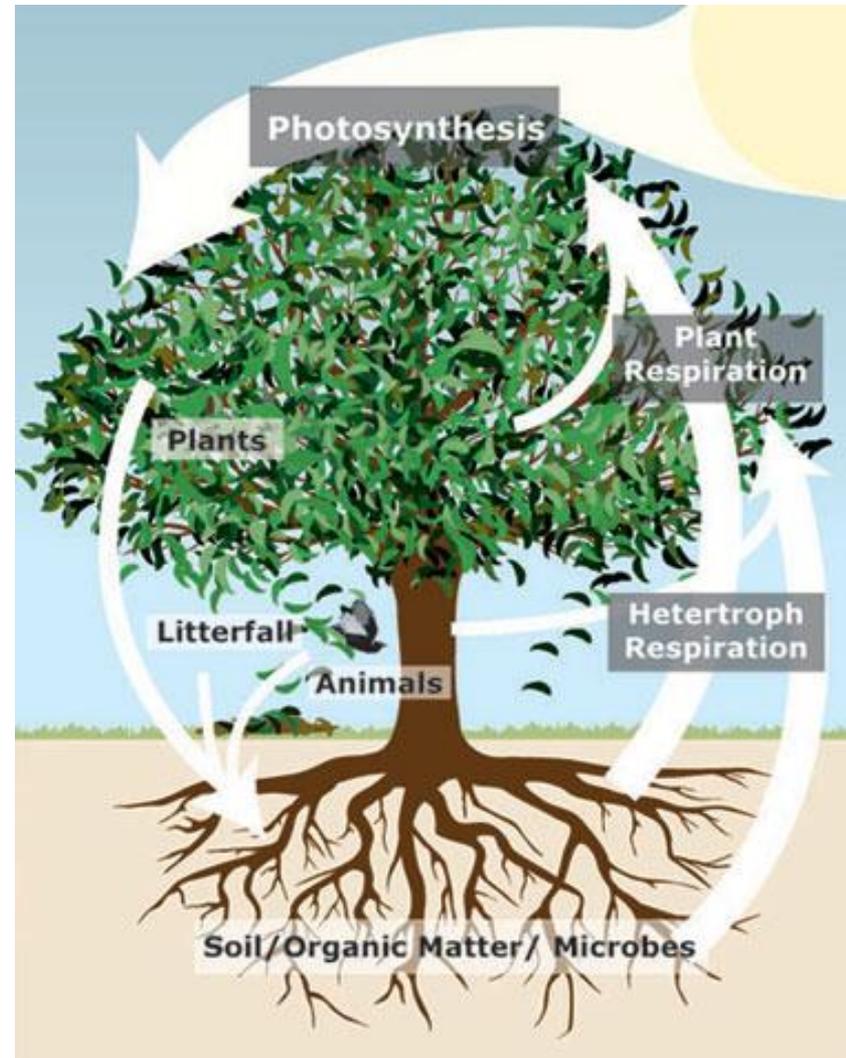
Scale up: Global terrestrial primary productivity

- Net primary productivity (NPP) = G(ross)PP - respiration

    = rate that Carbon is removed from the atmosphere by plants
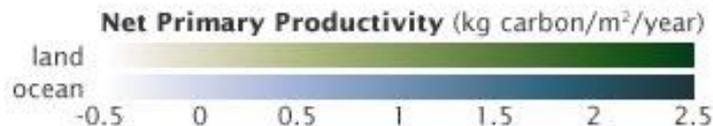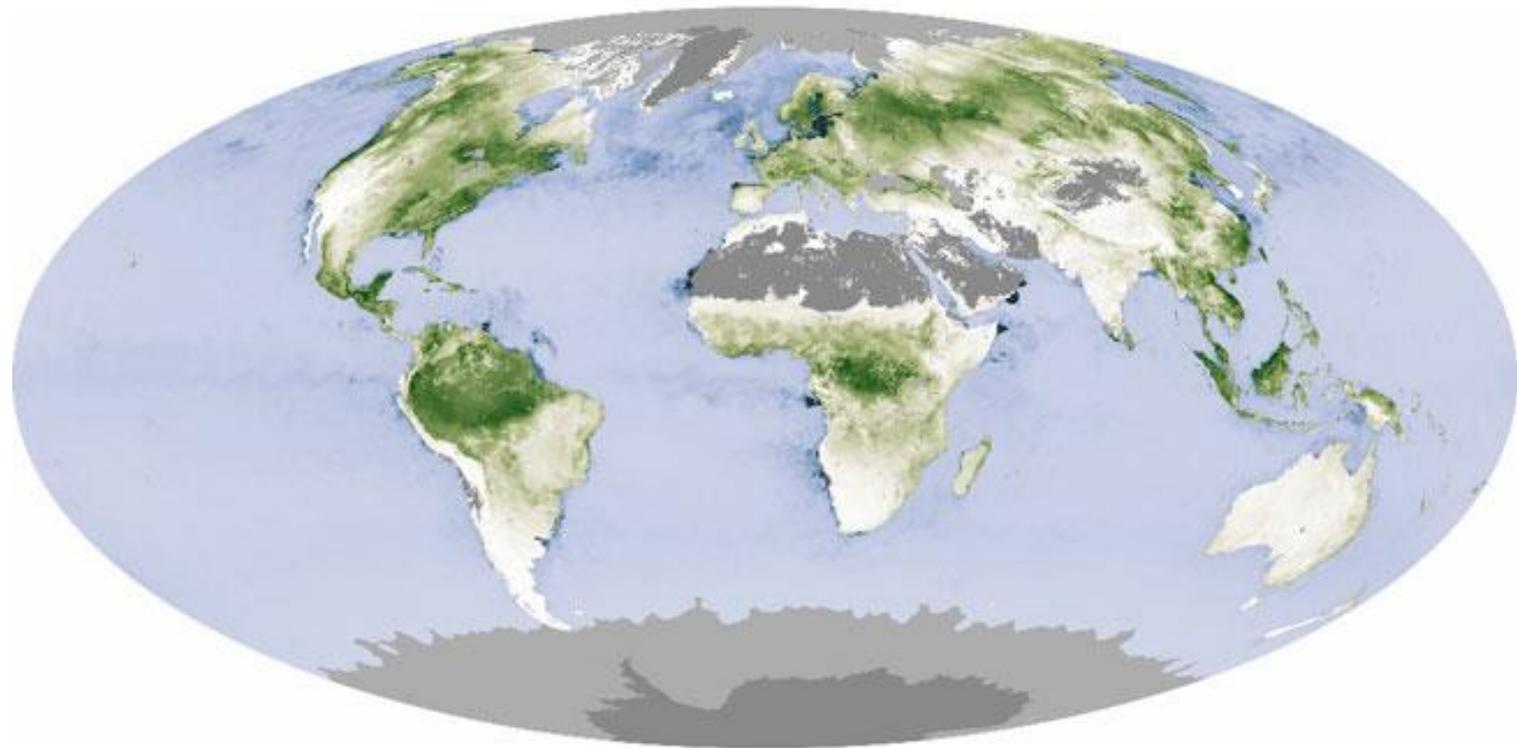
NASA Earth Observatory

Sensitivity of productivity to limiting factors
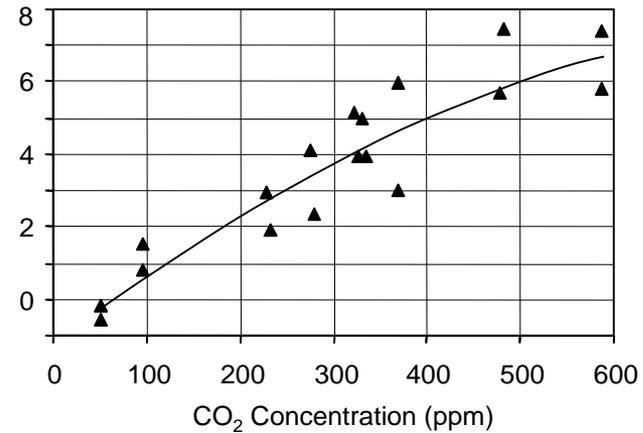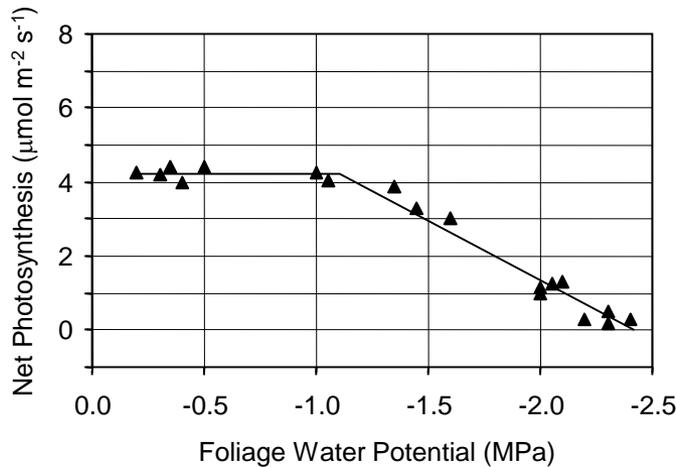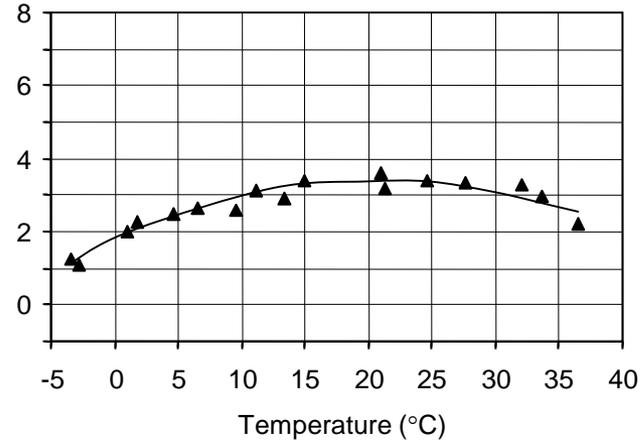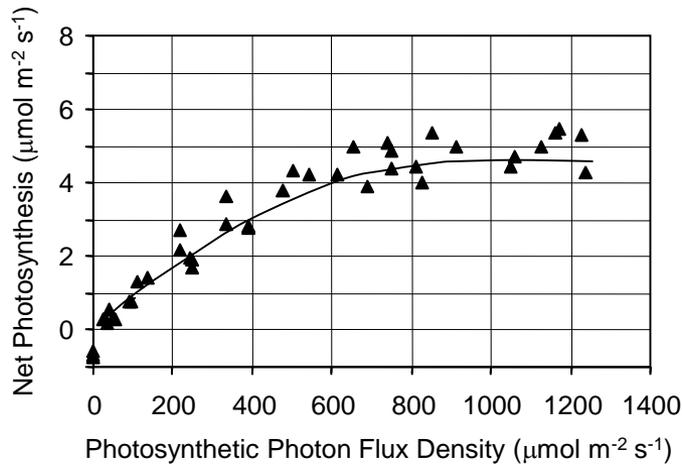
Bonan, 2014, *Ecological Climatology,* CUP.

Globally, what limits productivity?
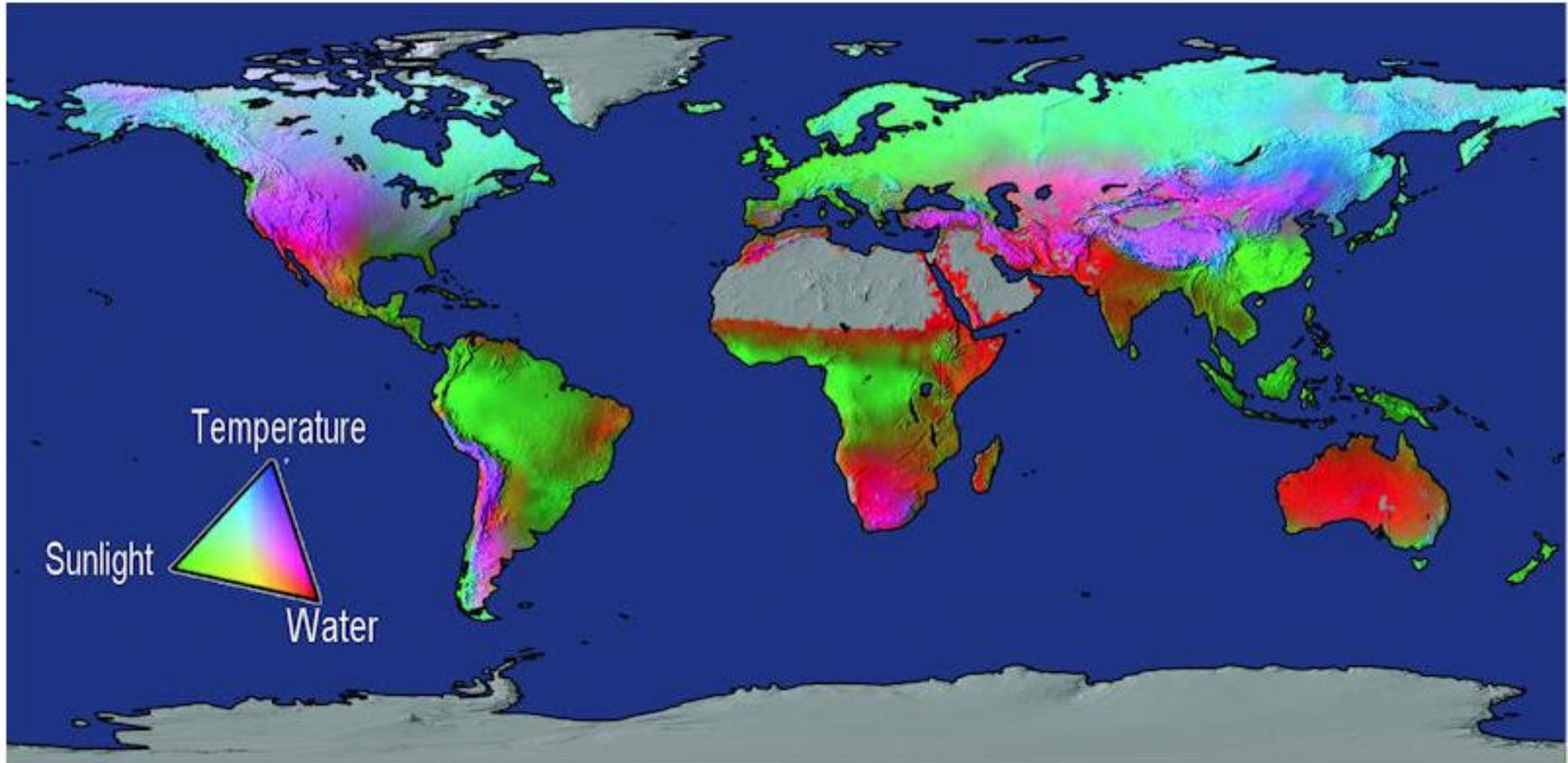
Geographic variation in climatic controls of terrestrial net primary production from water, temperature, and radiation limitations (Running et al. 2004)

Terrestrial carbon budget

GPP ≈ 120 GtC yr^{-1}

Plant respiration ≈ 60 GtC yr^{-1}

Decomposition ≈ 50 GtC yr^{-1}

Disturbance (natural, human) ≈ 9 GtC yr^{-1}

Short-Term Carbon Uptake

Medium-Term Carbon Uptake

Long-Term Carbon Uptake

NPP ≈ 60 GtC yr^{-1}

NEP ≈ 10 GtC yr^{-1}

NBP ≈ ±1 GtC yr^{-1}
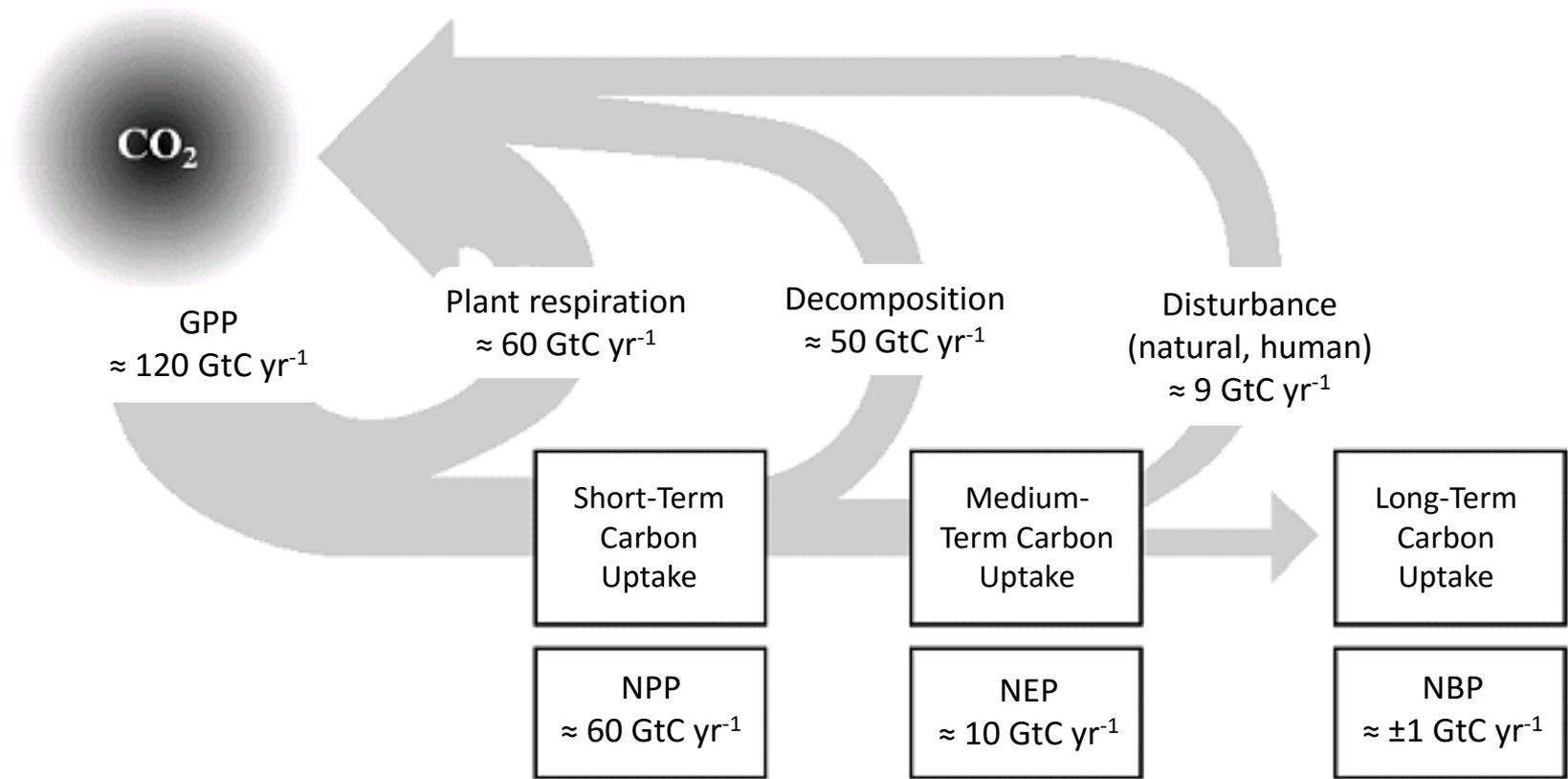
IPCC: adapted from Steffen et al., 1998

Terrestrial carbon stocks

Carbon stored by biome (Gigatonnes of C)

547.8	Tropical, Subtropical Forests
285.3	Tropical and Subtropical Grasslands, Savannas, Shrublands
178.0	Deserts and Dry Shrubland
183.7	Temperate Grasslands, Savannas Shrublands
314.9	Temperate Forest
384.2	Boreal Forest
155.4	Tundra

0.98 Lakes
1.47 Rock and Ice

Source: UNEP - WCMC, 2009.

- Tundra
- Boreal forest
- Temperate forest
- Temperate grasslands, savannas and shrublands
- Desert and dry shrublands
- Tropical and subtropical grasslands, savannas and shrublands
- Tropical and subtropical forests

Source: adapted from Olson *et al.*, 2001.

UNEP (2009)

Estimates for the total amount of terrestrial carbon (biomass + soil) stored in each biome.

Tropical/subtropical forests store the most (548 Gt C), followed by boreal forest (384 Gt C).

The amount of carbon stored in soils is *several times* the amount stored in biomass.
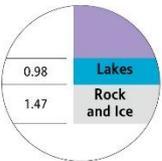
Biome characteristics: tropical rainforests

- Most important biome for C stores and fluxes
- Dominated by broadleaved *evergreen* species
- Very high biodiversity
- Very high productivity

- Reliably hot and wet (little seasonal variability)
- Consistent light source
- Poor and thin soils

# Full carbon cycle for a mature tropical forest in Amazonia (Caxiuanã, Brazil)

GPP
NPP = Above & below-ground
Respiration = auto- & hetero-tropic, above & belowground biomass, & soils

Canopy litterfall
Woody mortality
Fine root detritus

Outflow of DOC
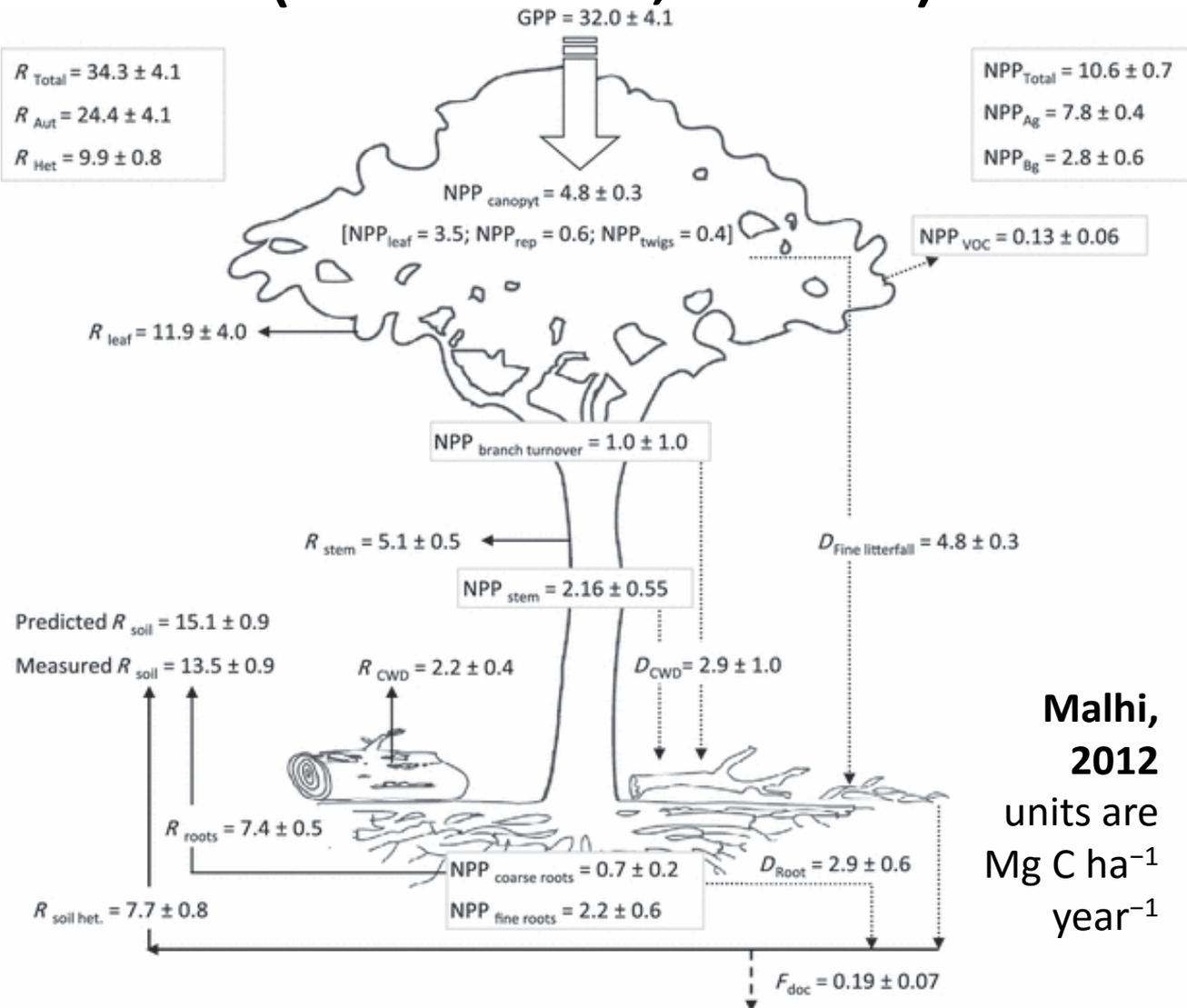
Malhi, 2012
units are Mg C ha^{-1} year^{-1}

$GPP = 32.0 \pm 4.1$

$R_{Total} = 34.3 \pm 4.1$
$R_{Aut} = 24.4 \pm 4.1$
$R_{Het} = 9.9 \pm 0.8$

$NPP_{Total} = 10.6 \pm 0.7$
$NPP_{Ag} = 7.8 \pm 0.4$
$NPP_{Bg} = 2.8 \pm 0.6$

$NPP_{canopyt} = 4.8 \pm 0.3$
$[NPP_{leaf} = 3.5; NPP_{rep} = 0.6; NPP_{twigs} = 0.4]$

$NPP_{VOC} = 0.13 \pm 0.06$

$R_{leaf} = 11.9 \pm 4.0$

$NPP_{branch\ turnover} = 1.0 \pm 1.0$

$R_{stem} = 5.1 \pm 0.5$

$D_{Fine\ litterfall} = 4.8 \pm 0.3$

$NPP_{stem} = 2.16 \pm 0.55$

Predicted $R_{soil} = 15.1 \pm 0.9$
Measured $R_{soil} = 13.5 \pm 0.9$

$R_{CWD} = 2.2 \pm 0.4$

$D_{CWD} = 2.9 \pm 1.0$

$R_{roots} = 7.4 \pm 0.5$

$NPP_{coarse\ roots} = 0.7 \pm 0.2$

$D_{Root} = 2.9 \pm 0.6$

$R_{soil\ het.} = 7.7 \pm 0.8$

$NPP_{fine\ roots} = 2.2 \pm 0.6$

$F_{doc} = 0.19 \pm 0.07$

Case study: tropical forest carbon cycling

- Most productive terrestrial forests
  - **Primarily** because they don't have a 'dormant' period (rather than because warmer/more diverse).
  - Productivity is fairly constant through the year.
  - Soils are poor, thin (old) and nutrient cycling is fast.

- Variation in GPP between tropical forests:
  - Not likely due to variation in light/climate
  - Certainly some effect of soil/leaf phosphorus availability
  - Possibly other micronutrients: calcium, sodium, potassium
  - Forest age (carbon use efficiency – NPP/GPP – lower in older forests)

Climate change and the terrestrial carbon cycle
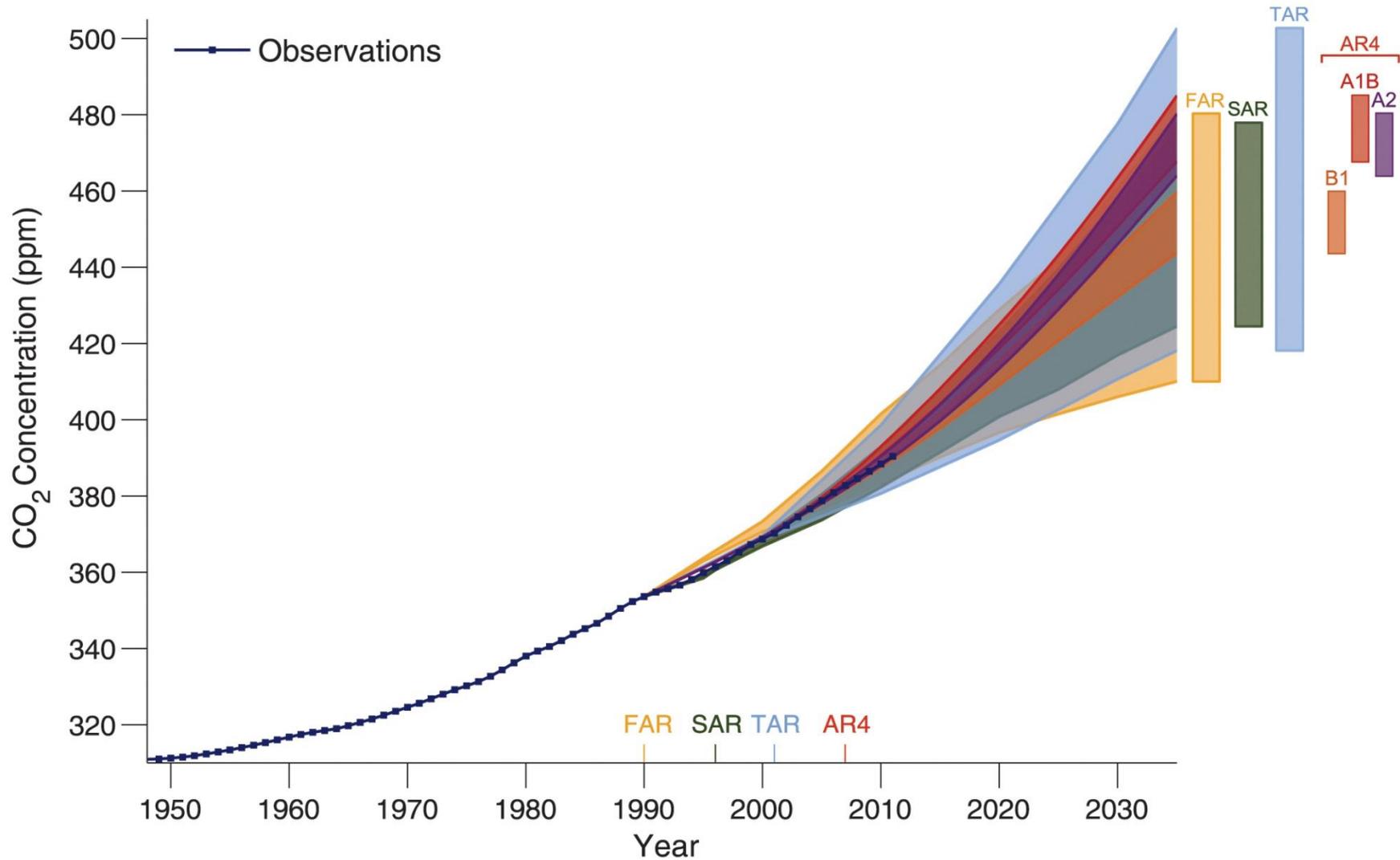
IPCC
(2014)

Terrestrial biosphere: sink or source in the future?
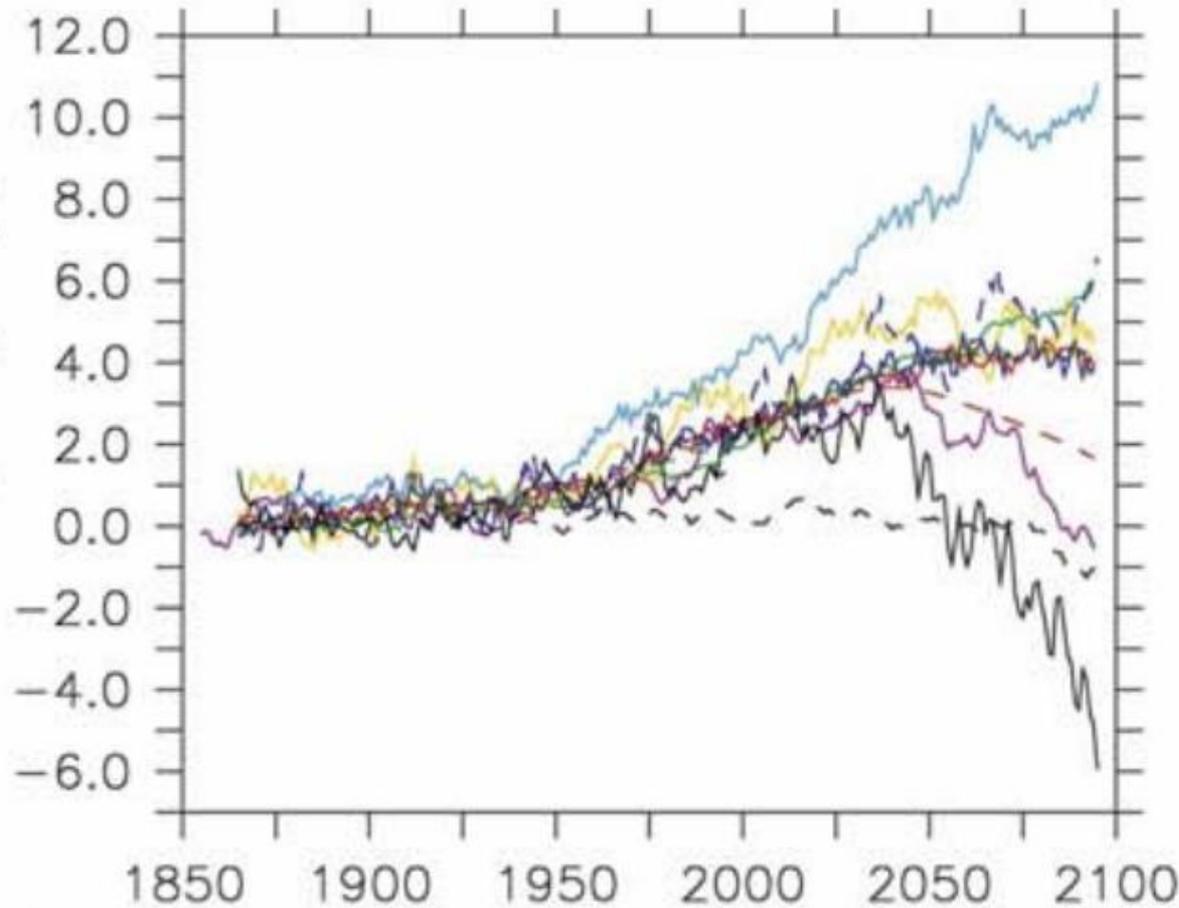
Land carbon fluxes for the coupled runs (GtC yr^{-1}) as simulated by the HadCM3LC (solid black), IPSL-CM2C (solid red), IPSL-CM4-LOOP (solid yellow), CSM-1 (solid green), MPI (solid dark blue), LLNL (solid light blue), FRCGC (solid purple), UMD (dash black), UVic-2.7 (dash red), CLIMBER (dash green), and BERN-CC (dash blue).

Friedlingstein et al. (2006)

Experimental approaches: what's the impact of increased atmospheric CO_2?

Free-Air CO_2 Enrichment (FACE) experiments

Grow plants in the field (i.e. 'real-world' conditions) at a **controlled elevated atmospheric CO_2 concentration**.

The Duke Forest FACE experiment

http://www.bnl.gov/face/DukeForest-FACE.asp

Direct and indirect threats from climate change: tipping points
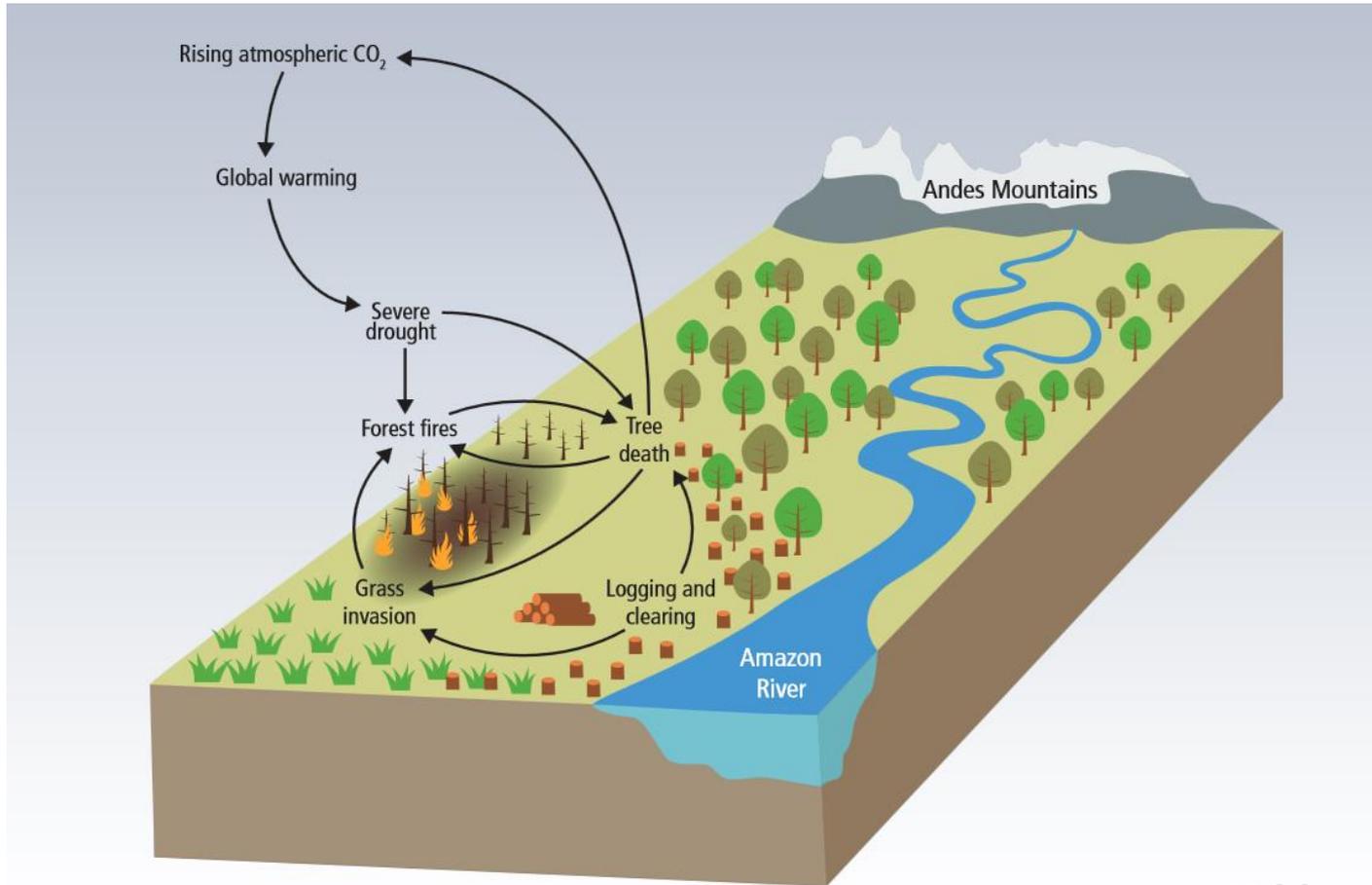
IPCC

Tipping points in the Amazon?

Met Office (Hadley Centre) predicts forest loss due to climate change alone, driven by changes in rainfall patterns.

"If droughts continue to occur at 5–10-year frequency, or increase in frequency, large areas of Amazonian forest canopy likely will be exposed to the persistent effect of droughts and the slow recovery of forest canopy structure and function"
                    -(Saatchi et al. 2012)
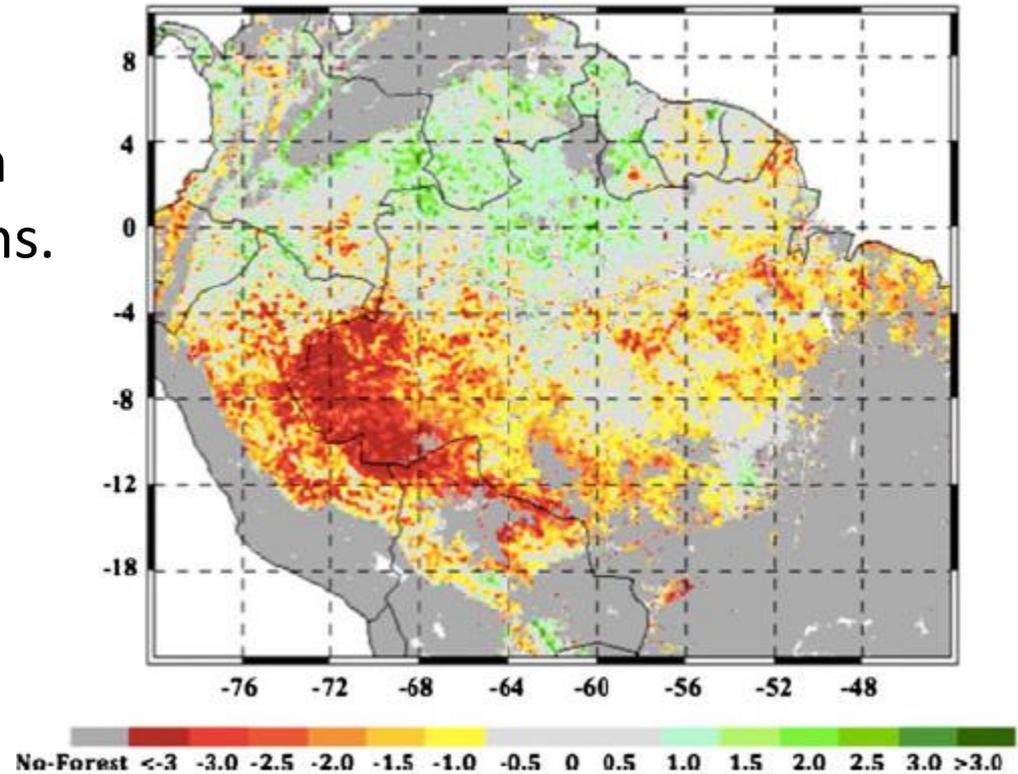
Spatial extent of canopy water stress showing the severity of the 2005 Amazonian drought based on forest canopy water stress, Saatchi et al (2012)

Apps in fieldwork to measure trees

Example: Theodolite iPhone app for measuring tree heights (primary determinant of C storage)

https://www.heacademy.ac.uk/resource/understanding-potential-new-roles-mobile-computer-technologies-teaching-geography-fieldwork

http://www.enhancingfieldwork.org.uk/

questions?