An overview of the terrestrial carbon-cycle from a global modelling perspective

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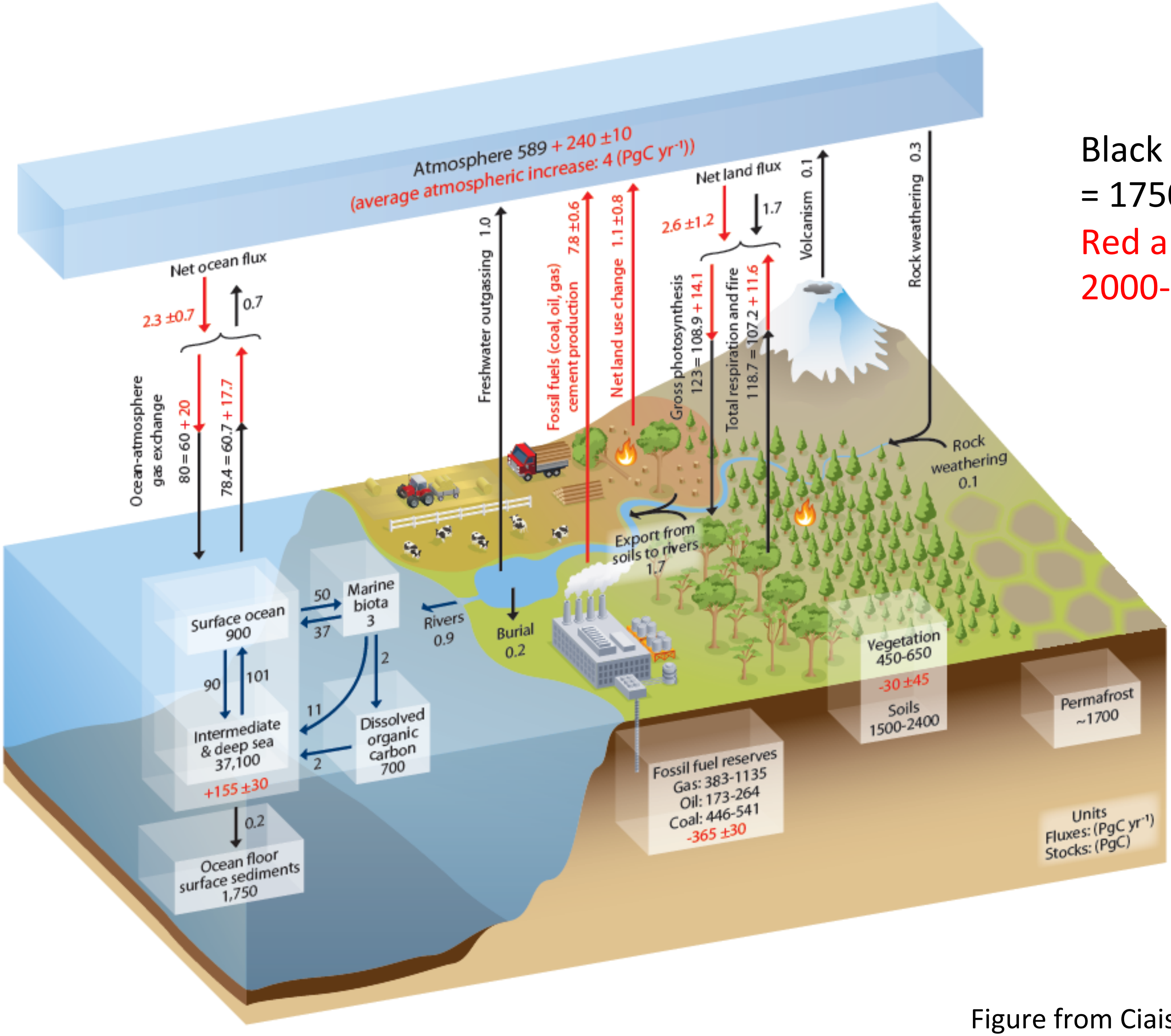
IMK-IFU: Atmospheric Environmental Research

Karlsruhe Institute of Technology

MICMoR/LUC4C Winter School

IMK-IFU, March 2015

Global carbon-cycle overview

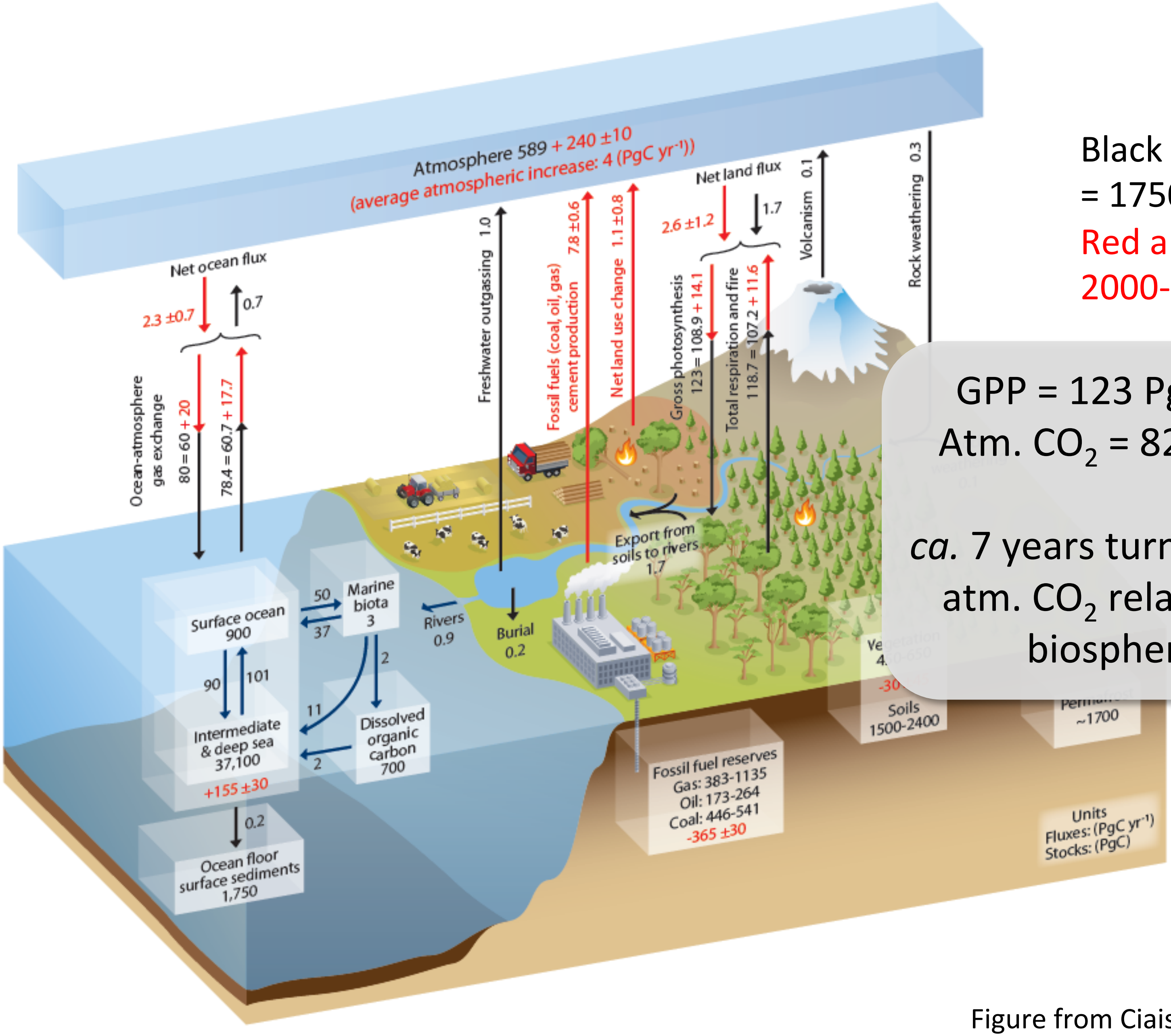


Black arrows = 1750

Red arrows = 2000-2009

Figure from Ciais et al. (2013)

Global carbon-cycle overview



Black arrows = 1750

Red arrows = 2000-2009

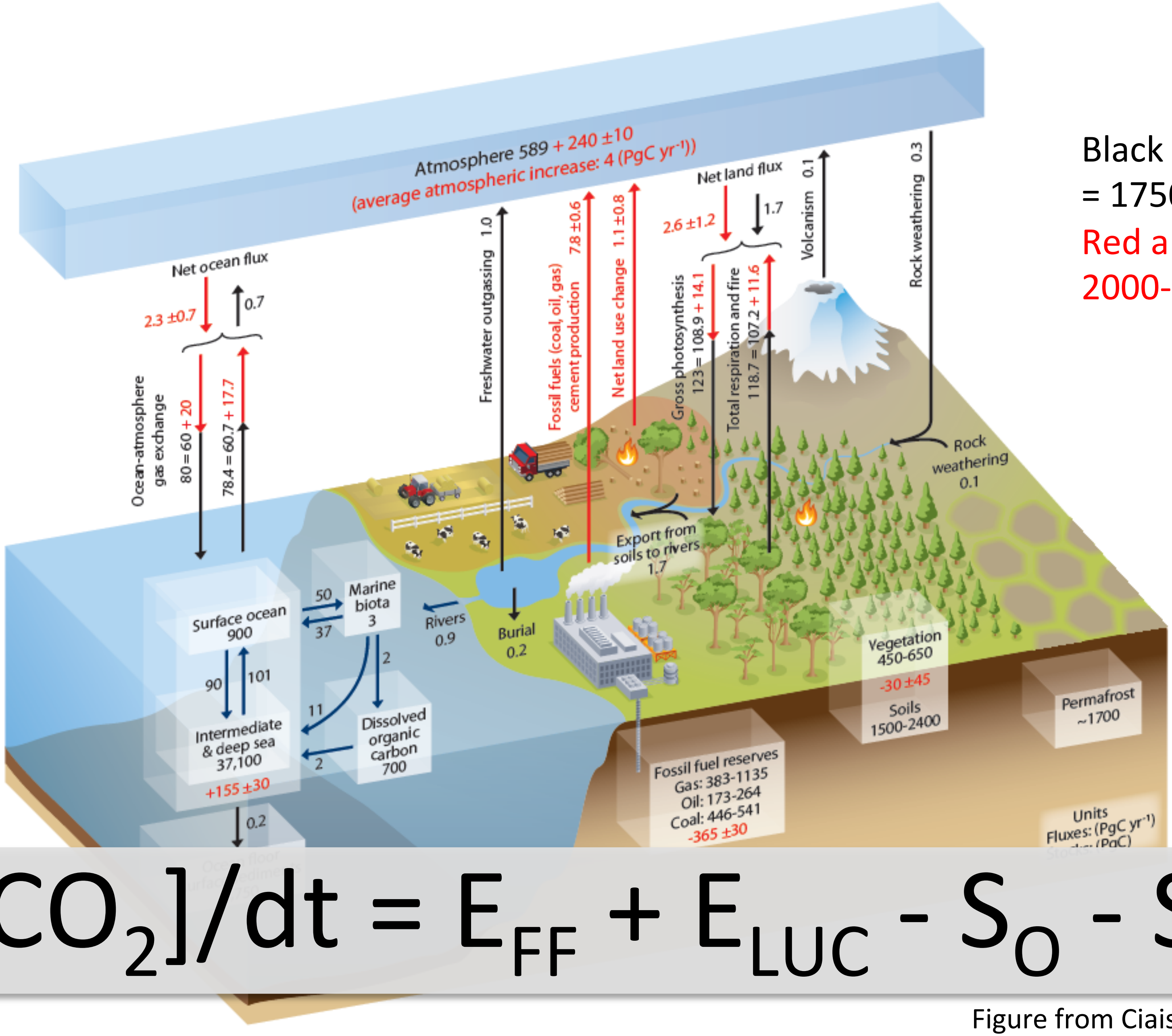
GPP = 123 Pg C a^{-1}

Atm. CO_2 = 829 Pg C

ca. 7 years turnover for atm. CO_2 relative to biosphere

Figure from Ciais et al. (2013)

Global carbon-cycle overview



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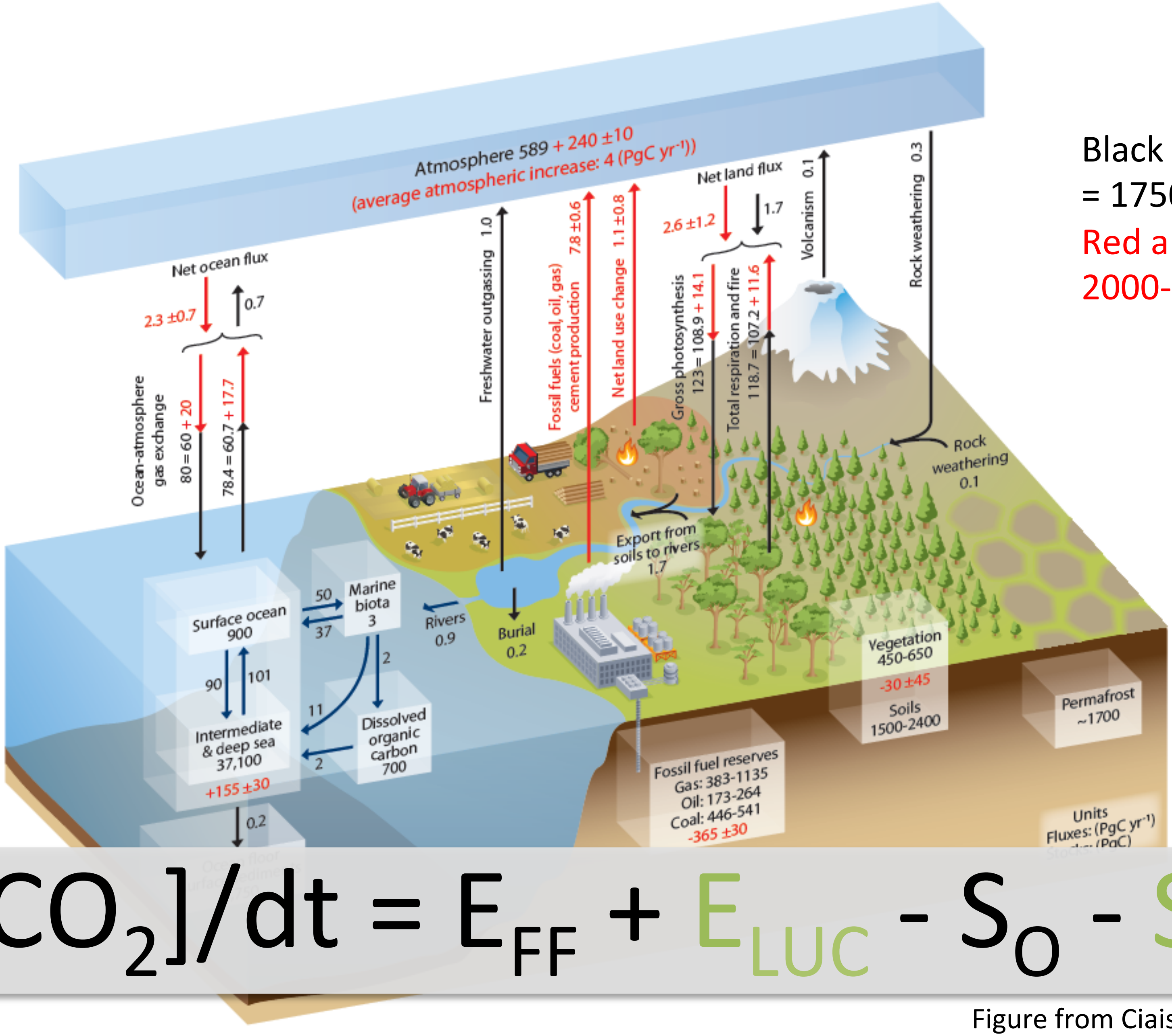
$$d[CO_2]/dt = E_{FF} + E_{LUC} - S_O - S_L$$

Figure from Ciais et al. (2013)

Global carbon-cycle overview



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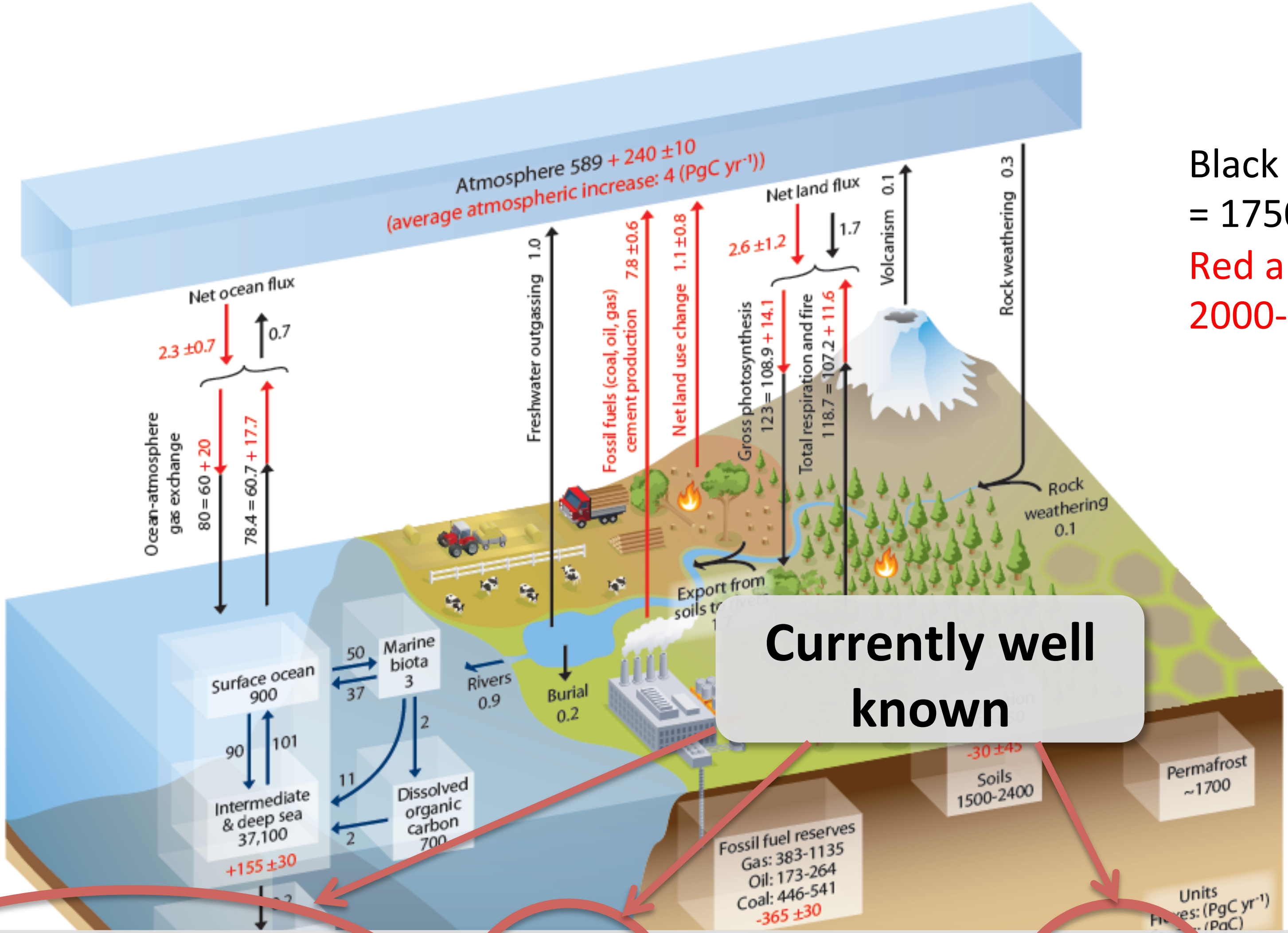


Currently well known

Black arrows = 1750

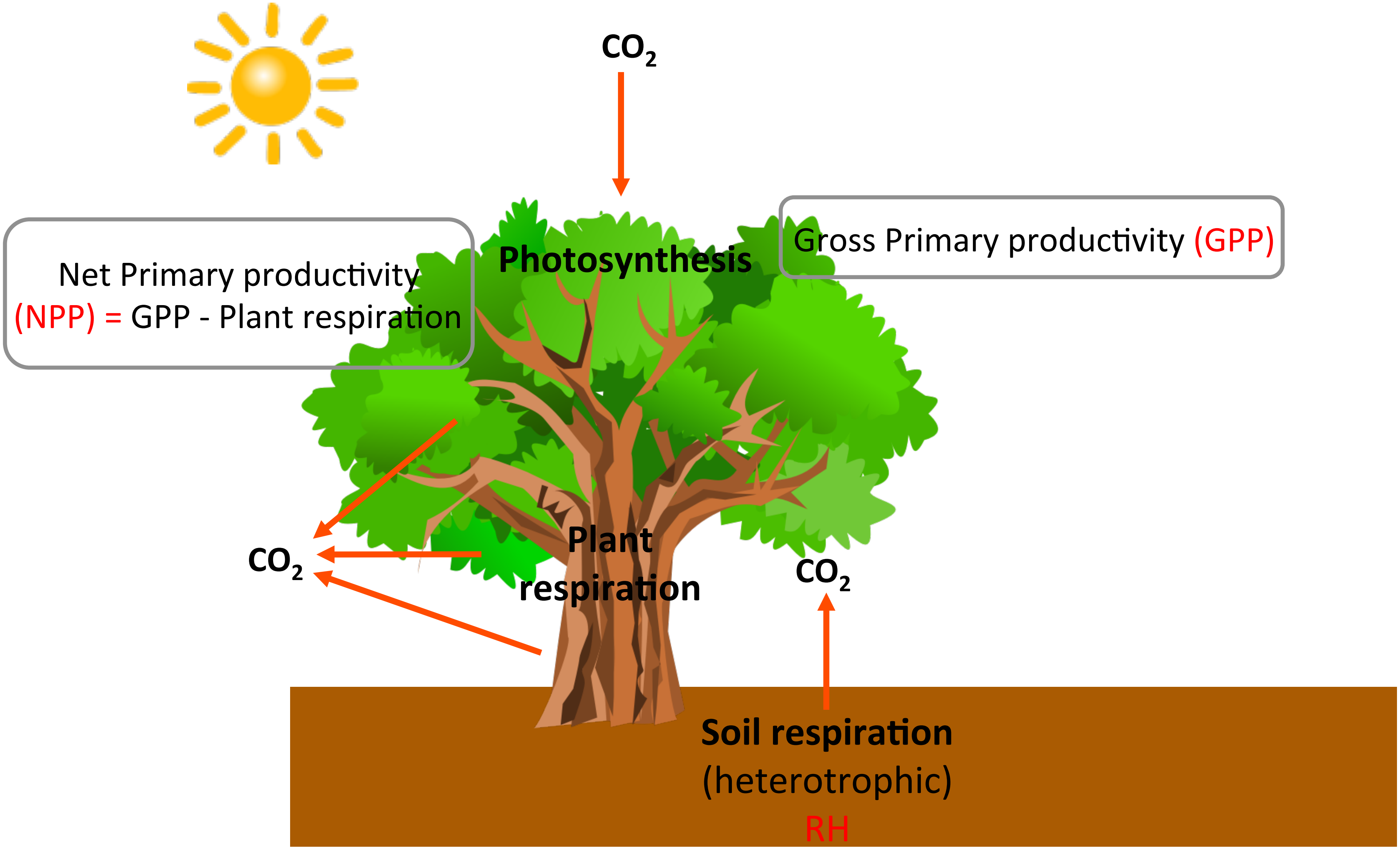
Red arrows = 2000-2009

$$d[CO_2]/dt = E_{FF} + E_{LUC} - S_O - S_L$$

Figure from Ciais et al. (2013)

Global carbon-cycle overview

Basic elements of the terrestrial carbon cycle:



CO_2

Photosynthesis

Gross Primary productivity (GPP)

Net Primary productivity
(NPP) = GPP - Plant respiration

CO_2

Plant respiration

CO_2

Soil respiration
(heterotrophic)
RH

Global carbon-cycle overview

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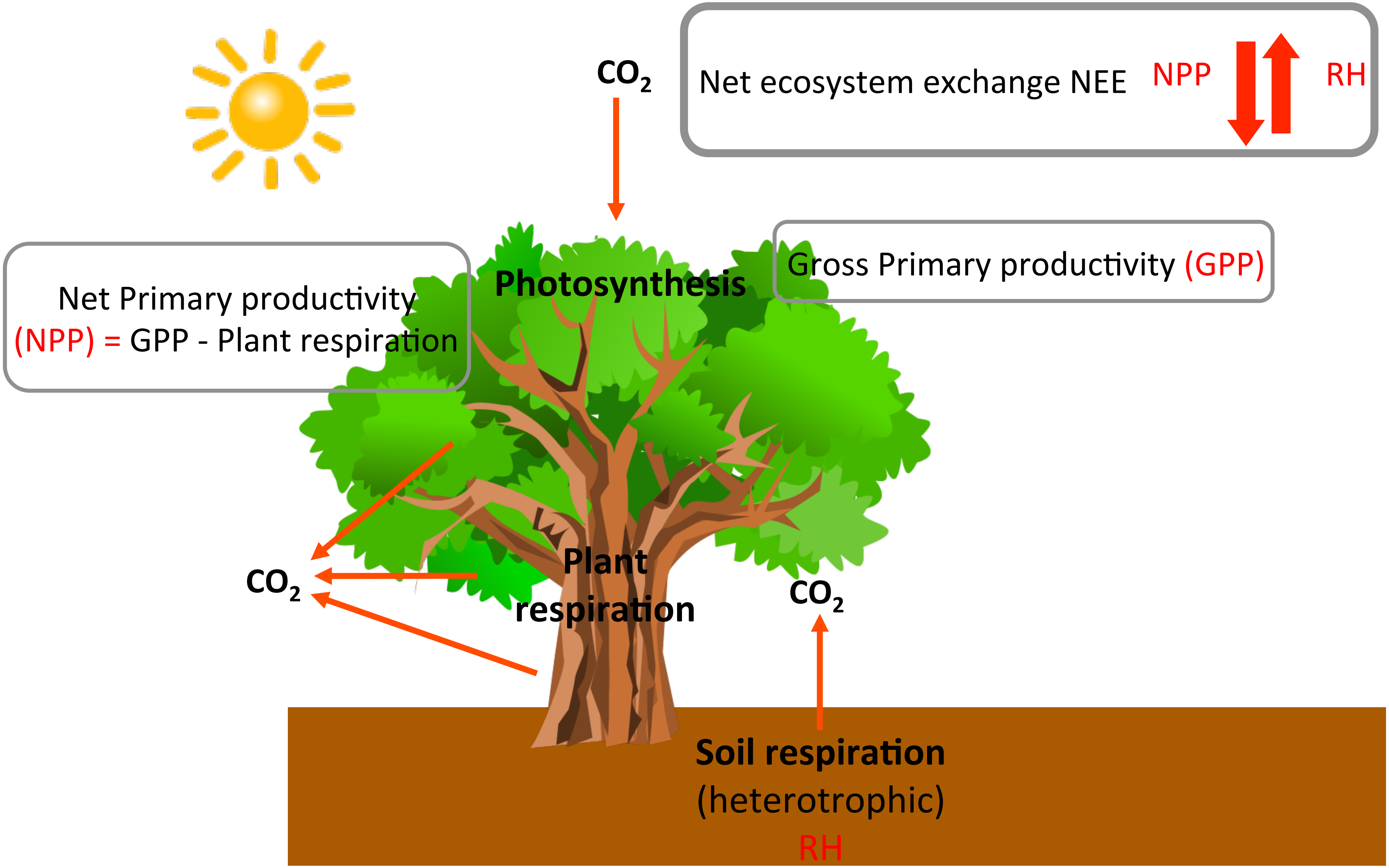


CO_2

Net ecosystem exchange NEE NPP RH

Net Primary productivity (NPP) = GPP - Plant respiration

Photosynthesis

Gross Primary productivity (GPP)

CO_2

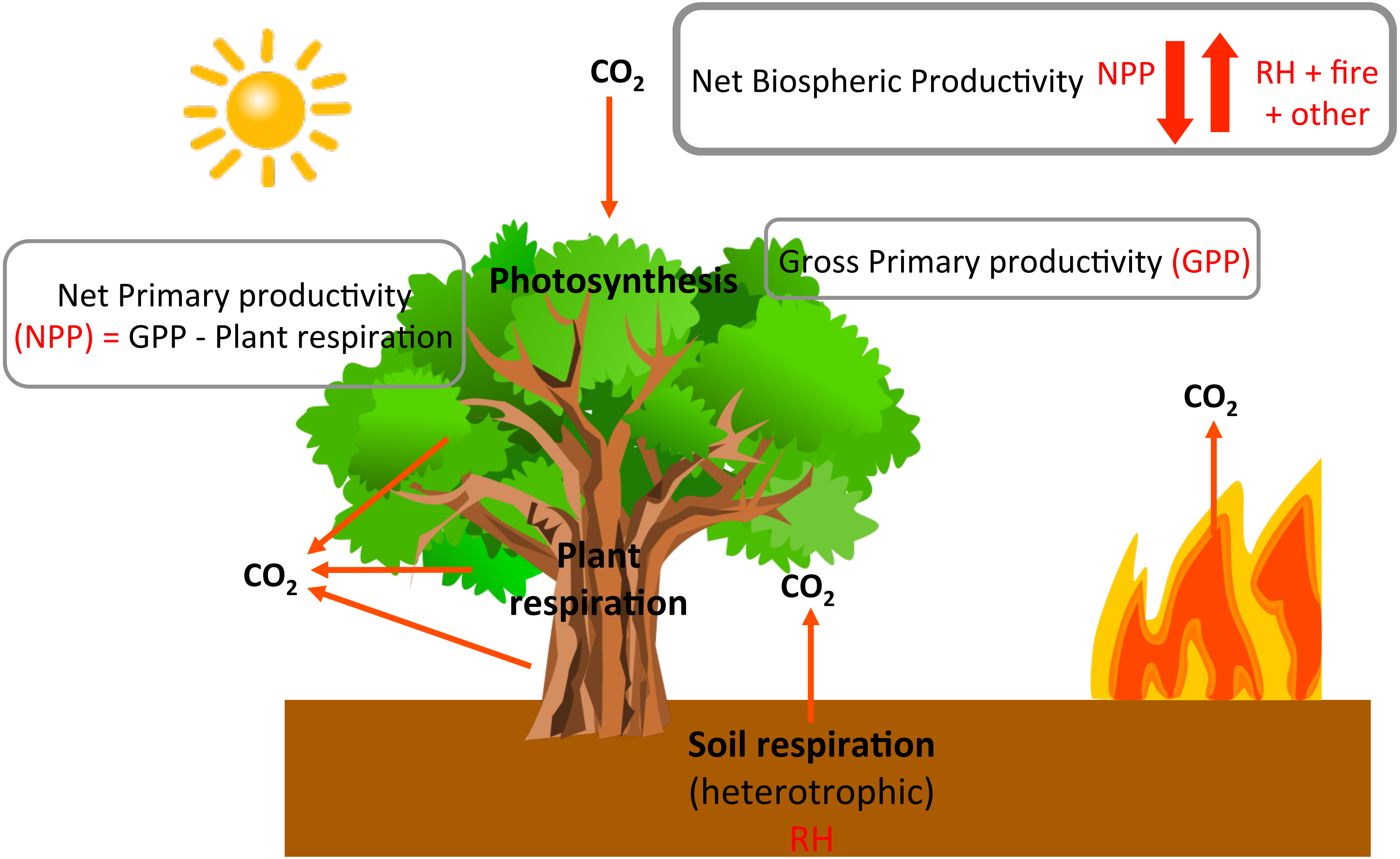
Plant respiration

CO_2

Soil respiration
(heterotrophic)
RH

Global carbon-cycle overview

Basic elements of the terrestrial carbon cycle:



CO_2

Net Biospheric Productivity NPP RH + fire + other

Net Primary productivity (NPP) = GPP - Plant respiration

Photosynthesis

Gross Primary productivity (GPP)

CO_2

CO_2

Plant respiration

CO_2

Soil respiration

(heterotrophic)

RH

Global carbon-cycle modelling tools

Non-exhaustive overview of available measurements for terrestrial carbon cycle

Flux towers

- GPP
- NEE
- Total respiration

Spatial coverage: point
Frequency: <1 sec

Satellites

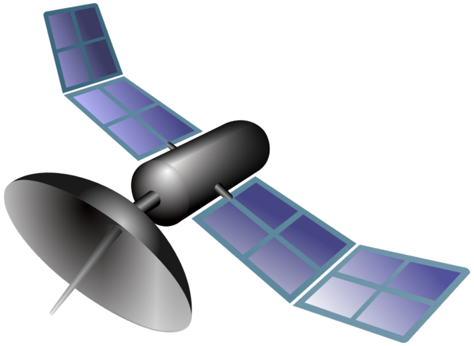
- NDVI
- Canopy height
- GPP
  (derived, e.g. from NDVI)

Spatial coverage: regional/ global
Frequency: days-weeks

Inventories

- Biomass
- Growth rates
- Allometry

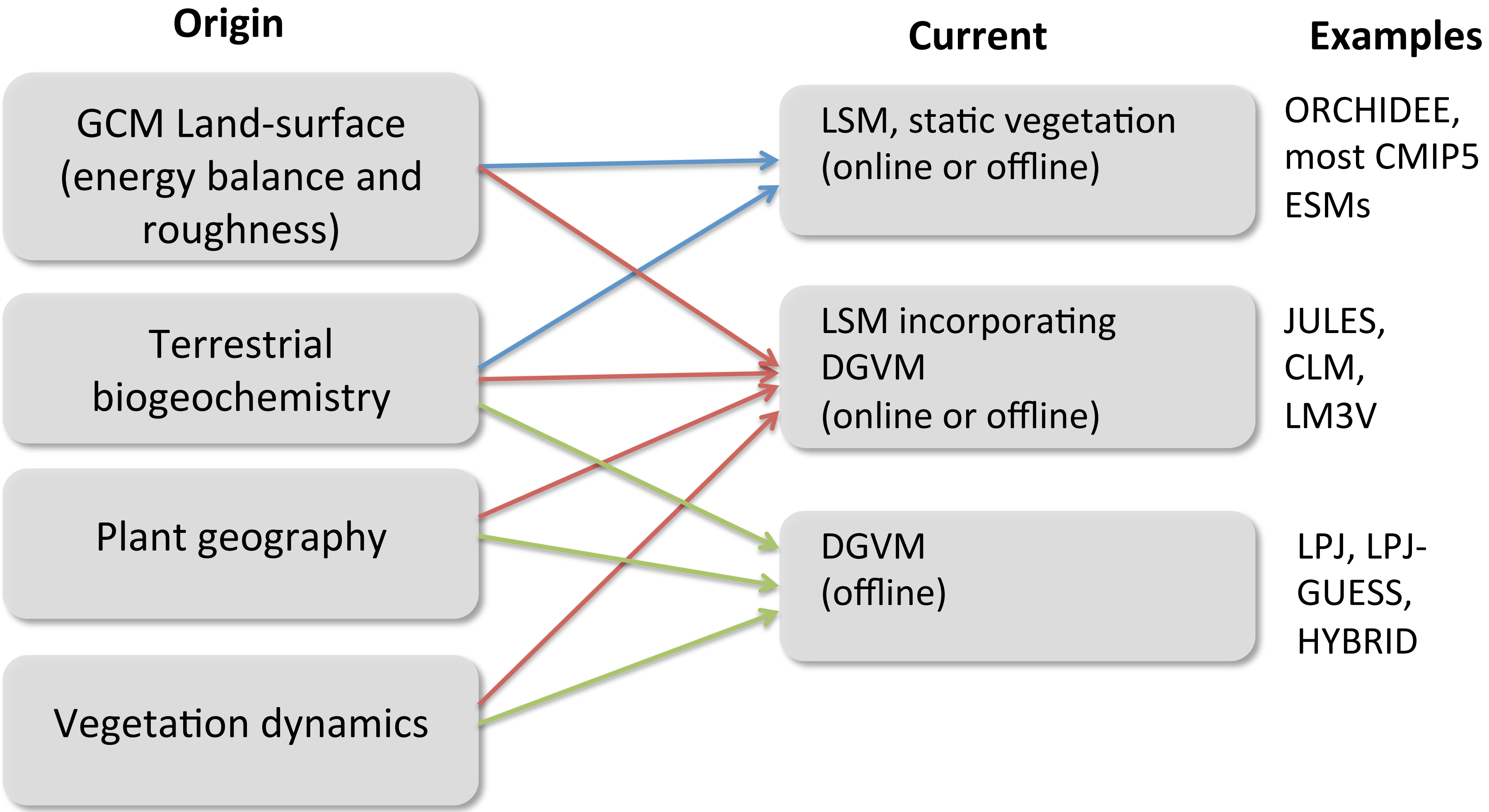
Spatial coverage: plot-landscape
Frequency: years



Global carbon-cycle modelling tools

Typically we use process-based models to study the terrestrial biosphere.

The main models in use today have evolved from a variety of backgrounds, which make each differentially suited to the study of different aspects of the biosphere.



Origin

GCM Land-surface (energy balance and roughness)

Terrestrial biogeochemistry

Plant geography

Vegetation dynamics

Current

LSM, static vegetation (online or offline)

LSM incorporating DGVM (online or offline)

DGVM (offline)

Examples

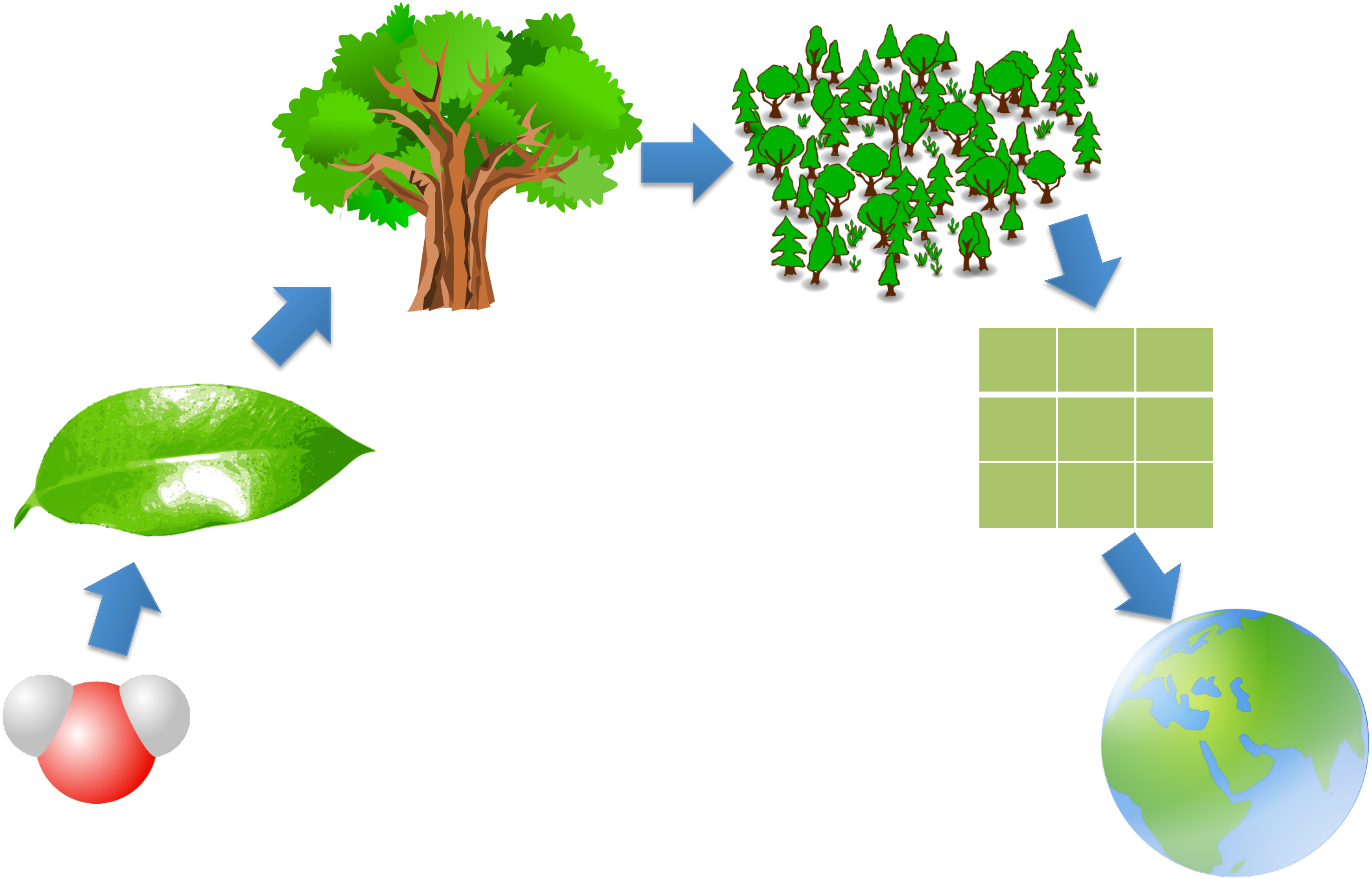
ORCHIDEE, most CMIP5 ESMs

JULES, CLM, LM3V

LPJ, LPJ-GUESS, HYBRID

Global carbon-cycle modelling tools

Terrestrial biosphere models must span a range of spatial scales…



Global carbon-cycle modelling tools

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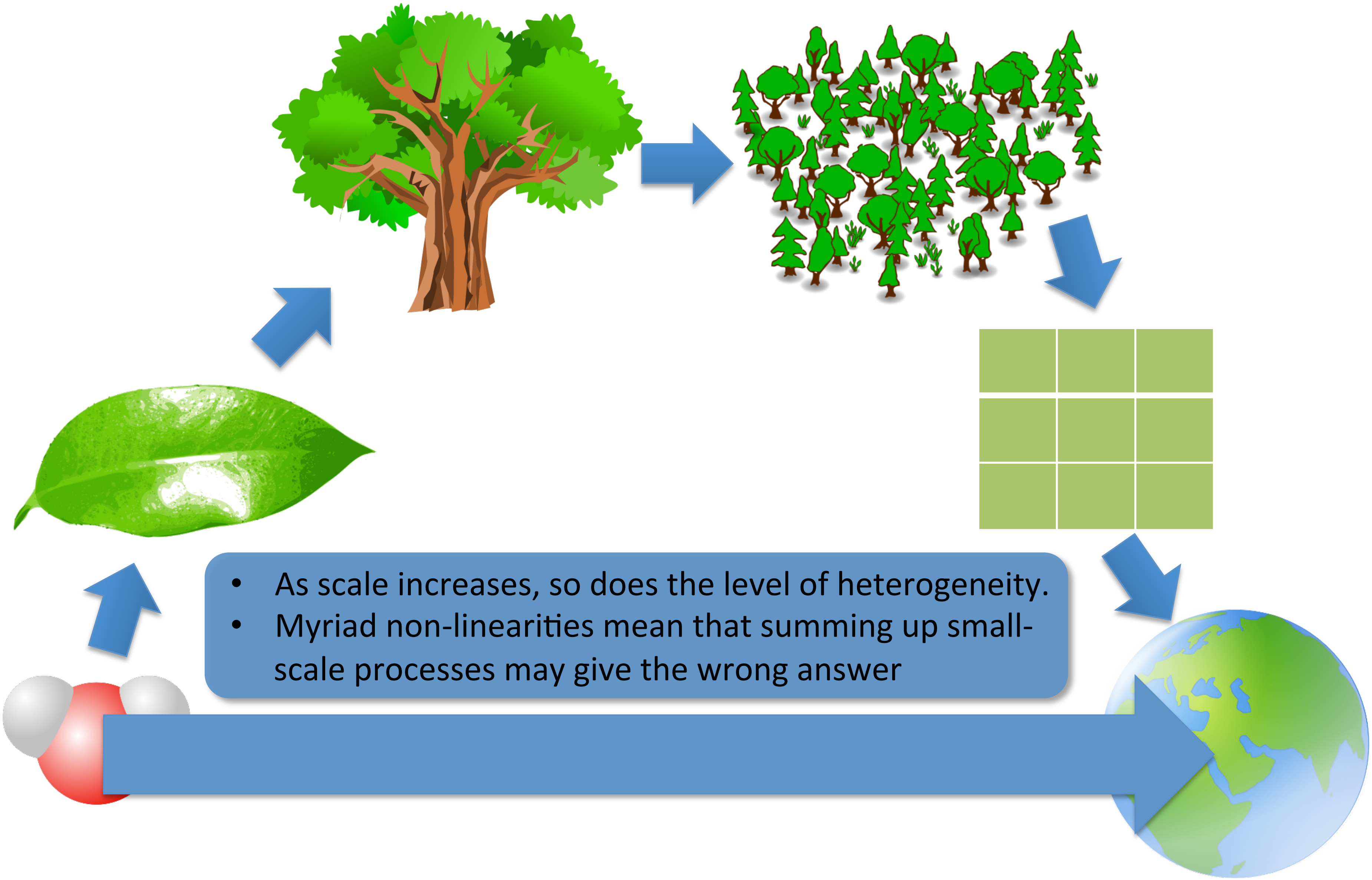
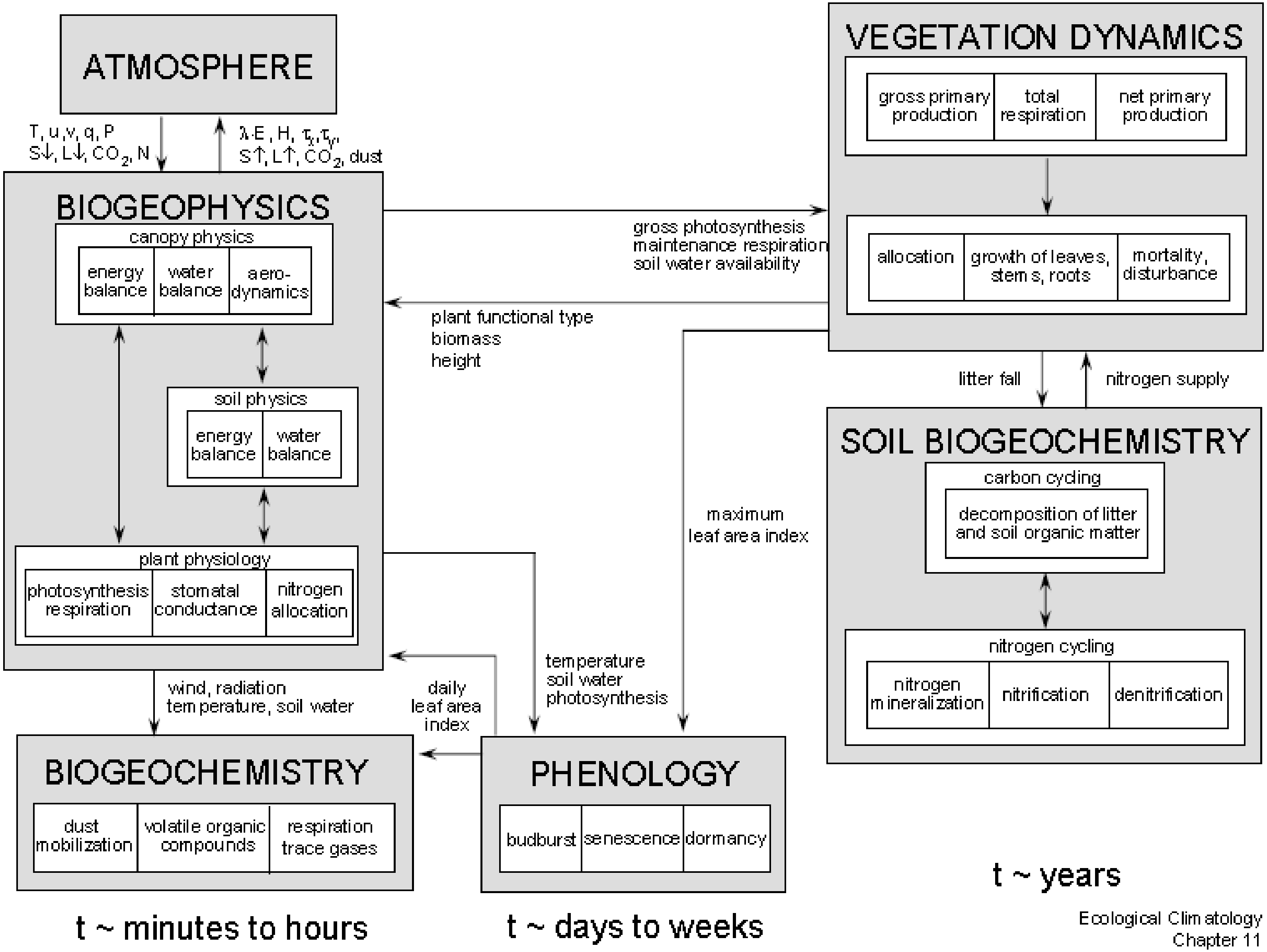


- As scale increases, so does the level of heterogeneity.
- Myriad non-linearities mean that summing up small-scale processes may give the wrong answer

Global carbon-cycle modelling tools

… and also timescales



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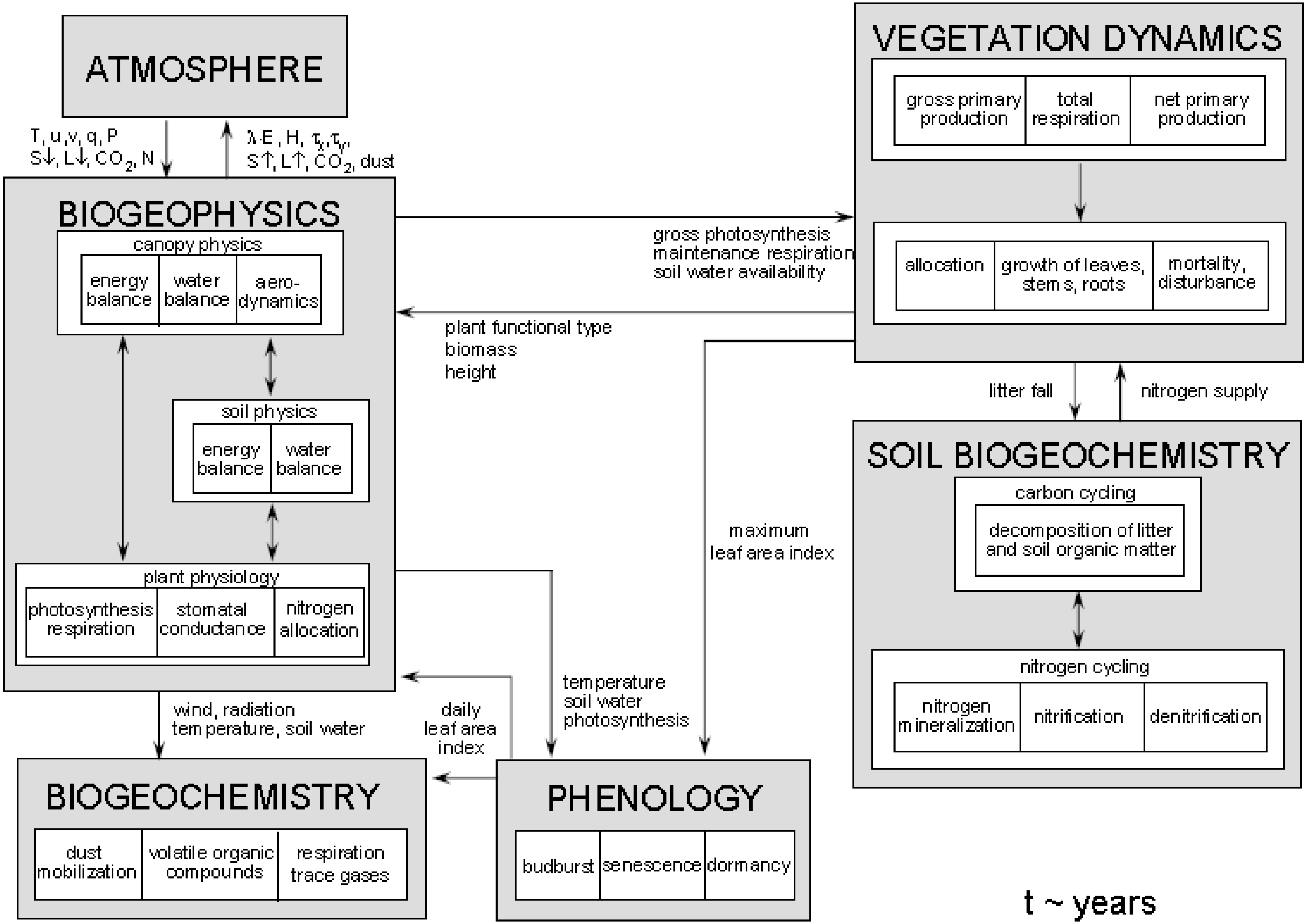
Global carbon-cycle modelling tools

… and also timescales



Often daily in DGVMs

t ~ days to weeks

t ~ years

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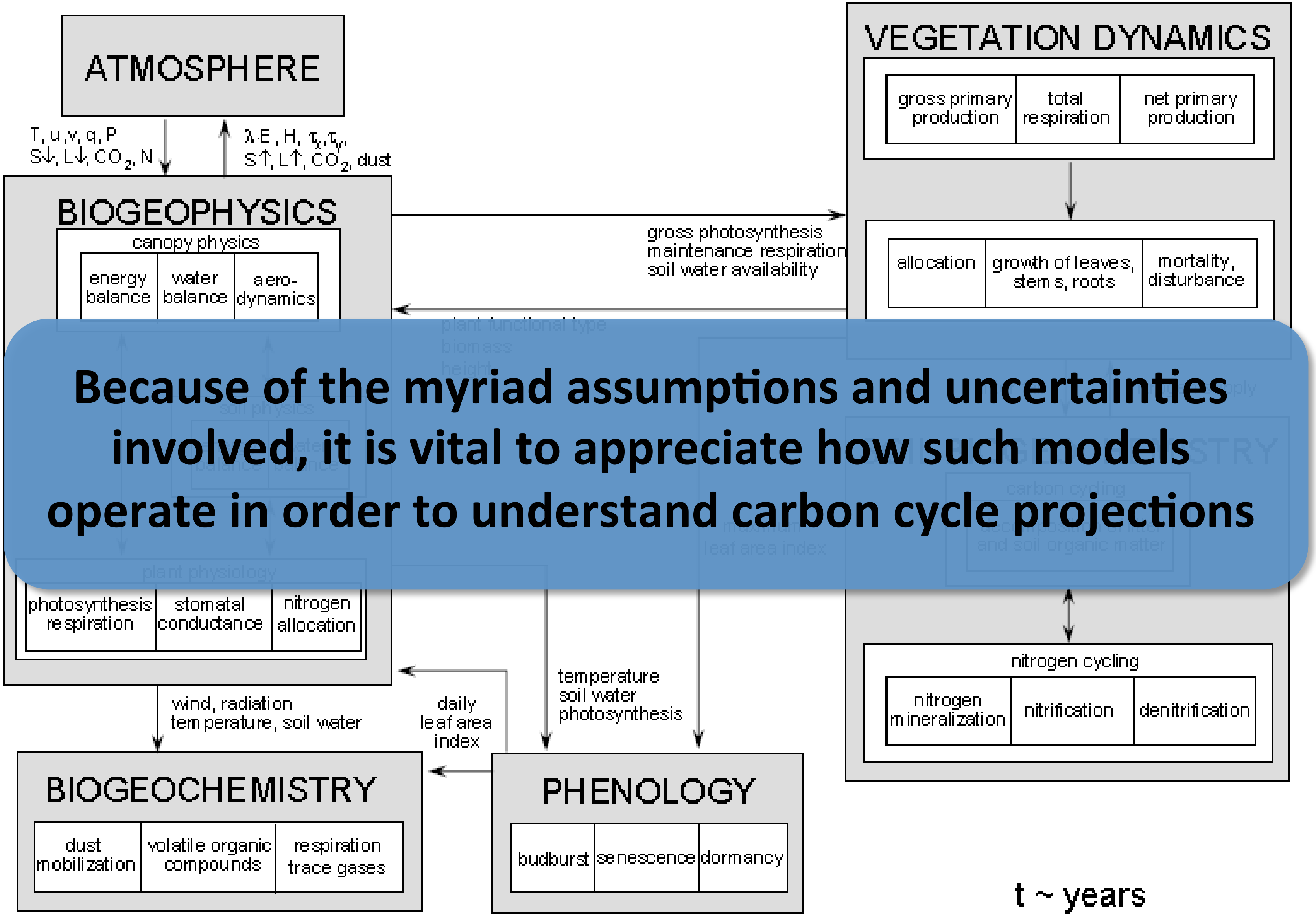
Global carbon-cycle modelling tools

… and also timescales



Because of the myriad assumptions and uncertainties involved, it is vital to appreciate how such models operate in order to understand carbon cycle projections

Often daily in DGVMs

t ~ days to weeks

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Overview of the remainder of this talk

Representations of key ecosystem processes in global terrestrial models

- Boundary conditions
- Primary production
- Respiration
- Structures and pools
- Species and vegetation dynamics
- Managed landcovers

Projecting the global carbon cycle - examples

Boundary conditions

The key boundary conditions for terrestrial biosphere models are usually atmospheric:

- Incoming short-wave radiation
- Surface/Air temperature (sometimes surface temp. is calculated explicitly from other variables)
- Precipitation
- Atmospheric CO_2 mixing ratio
- Incoming long-wave radiation
- Humidity
- Wind-speed
- Nitrogen/Phosphorus deposition

Others are:

- Soil parameters
- Vegetation type maps (not in DGVMs)
- Landcover/land-use/management variables

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Come from either historical reconstructions, or based on future scenarios (based on assumed human trajectories of e.g. emissions, management)

Others are:

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Primary production: Farquhar model

$$6CO_2 + 6H_20 + hv \rightarrow C_6H_{12}O_6 + 6O_2$$

λ = 400-700 nm

Photosynthesis is modelled as minimum of two limiting rates:

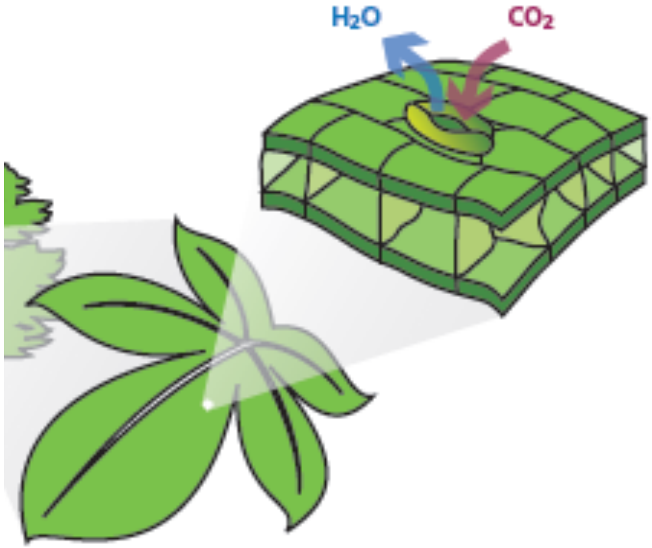
Carboxylation capacity (Rubisco-limited rate)

RuBP Regeneration (electron transport limited rate)

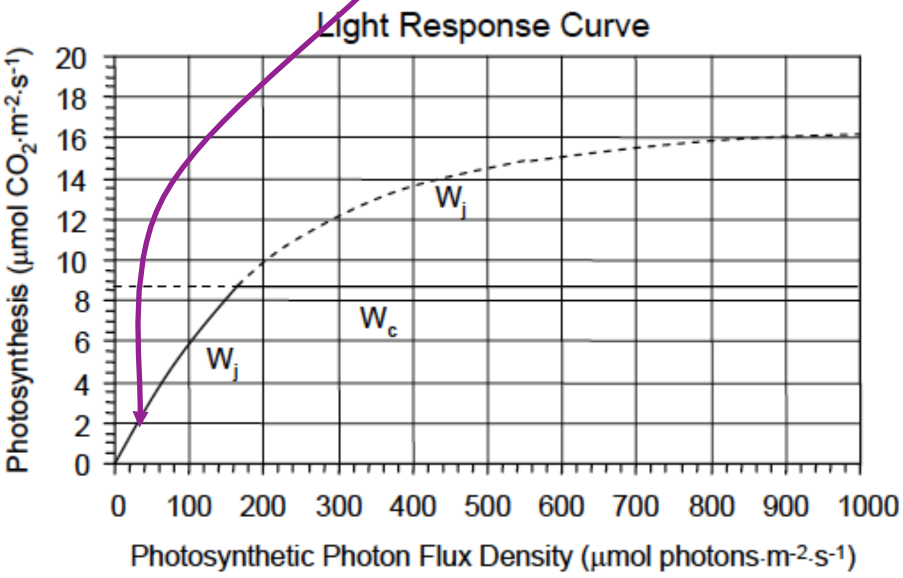
$$A = \min\left\{ \frac{V_{\max}\left(C_i - \Gamma^*\right)}{C_i + K_c\left(1 + O_i / K_o\right)}; \frac{J\left(C_i - \Gamma^*\right)}{4\left(C_i + 2\Gamma^*\right)} \right\}$$

Photorespiration compensation point

Leaf-internal [CO_2] **[O_2]** **Constants**



Arneth et al., 2014, Slide A. Arneth



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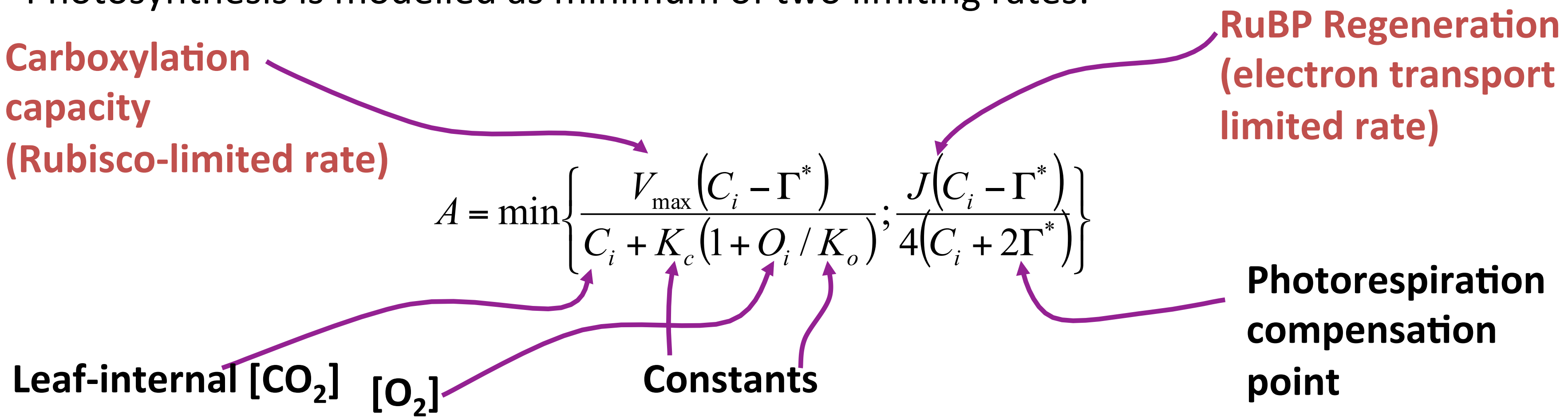

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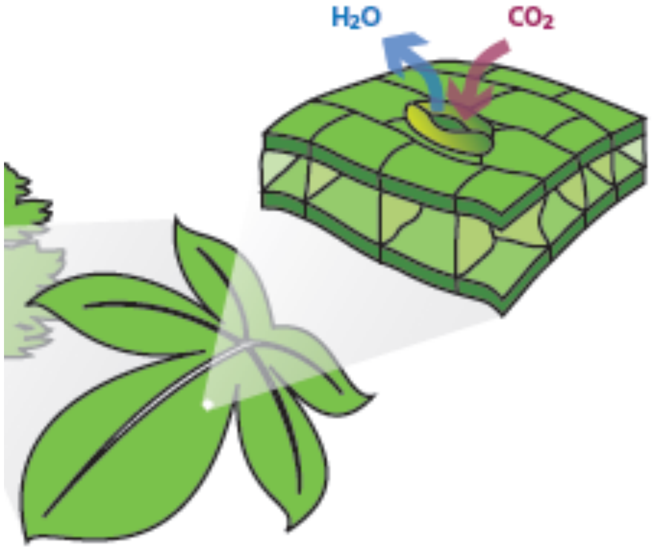

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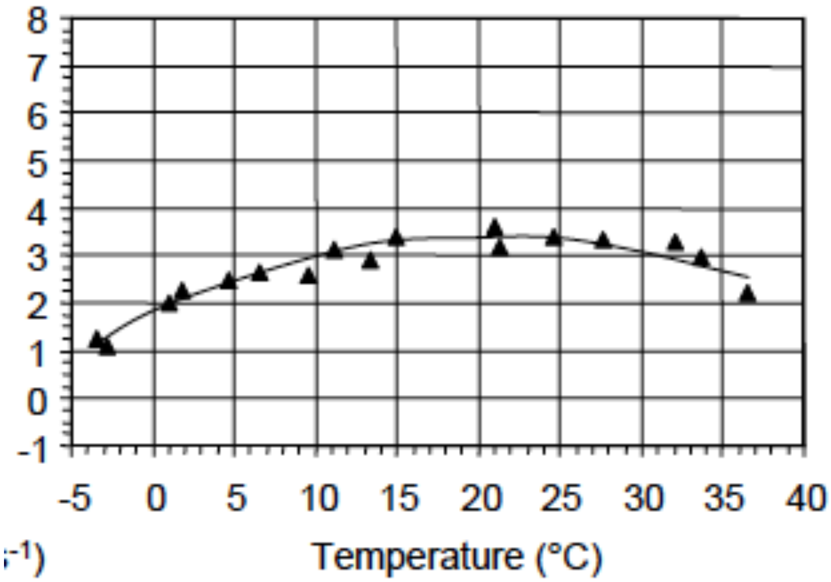

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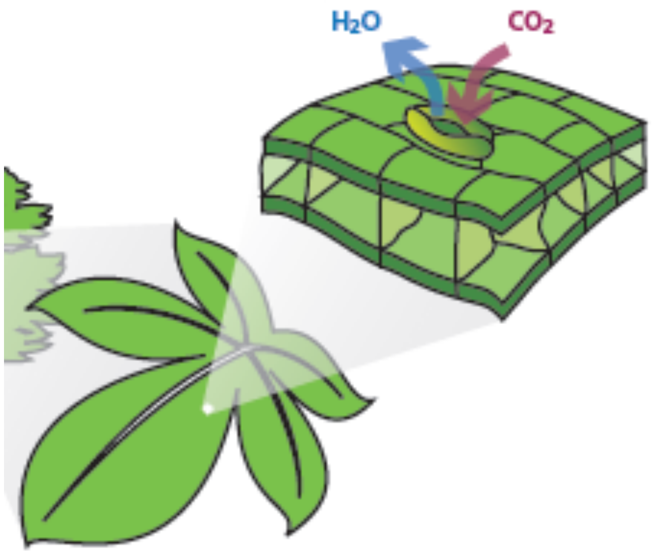
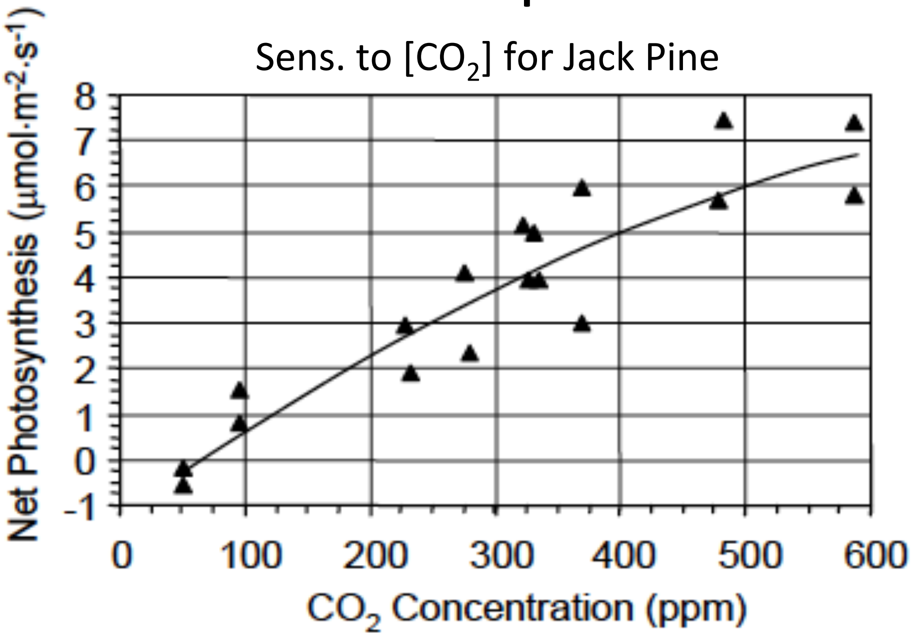


Arneth et al., 2014

Sens. to [CO_2] for Jack Pine



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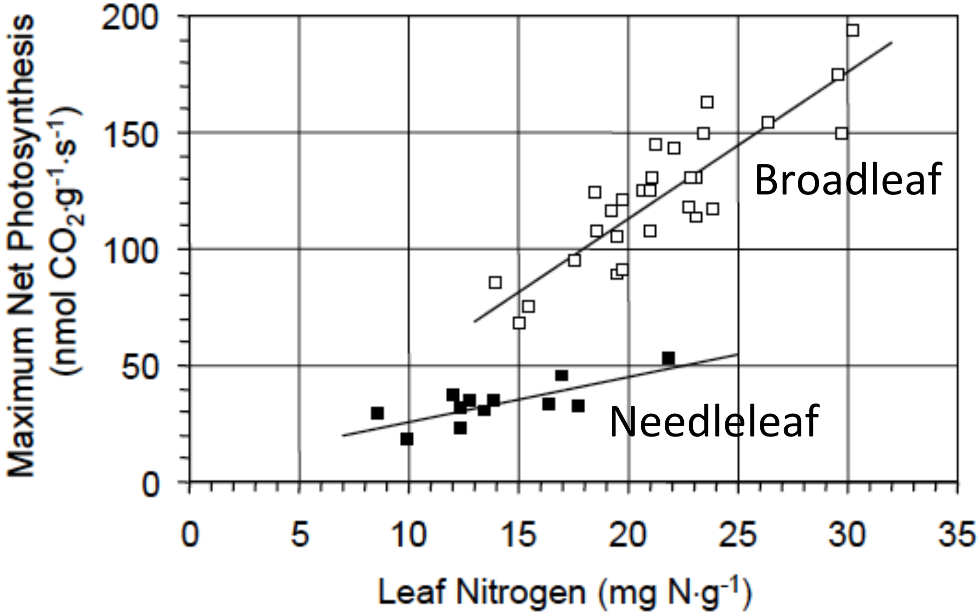
Leaf-internal [CO_2] **[O_2]**

Nitrogen is a fundamental control on photosynthesis. Key component of proteins, including Rubisco



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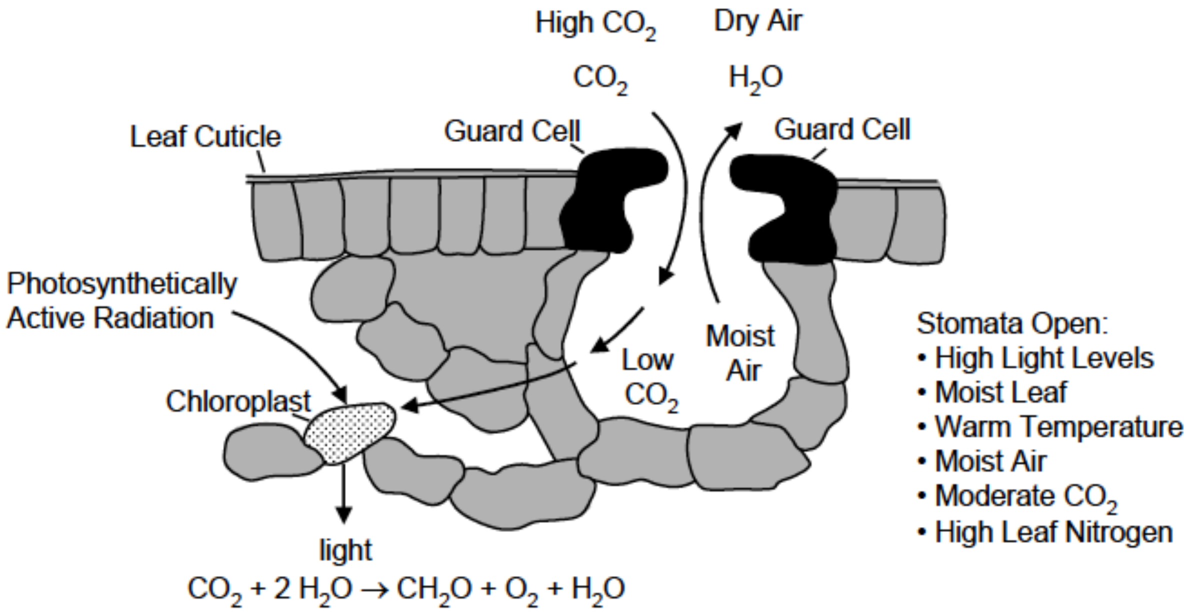
Leaf-internal [CO_2] **[O_2]**

Amount of CO_2 available for photosynthesis is controlled by stomatal pores, but the trade-off is moisture loss



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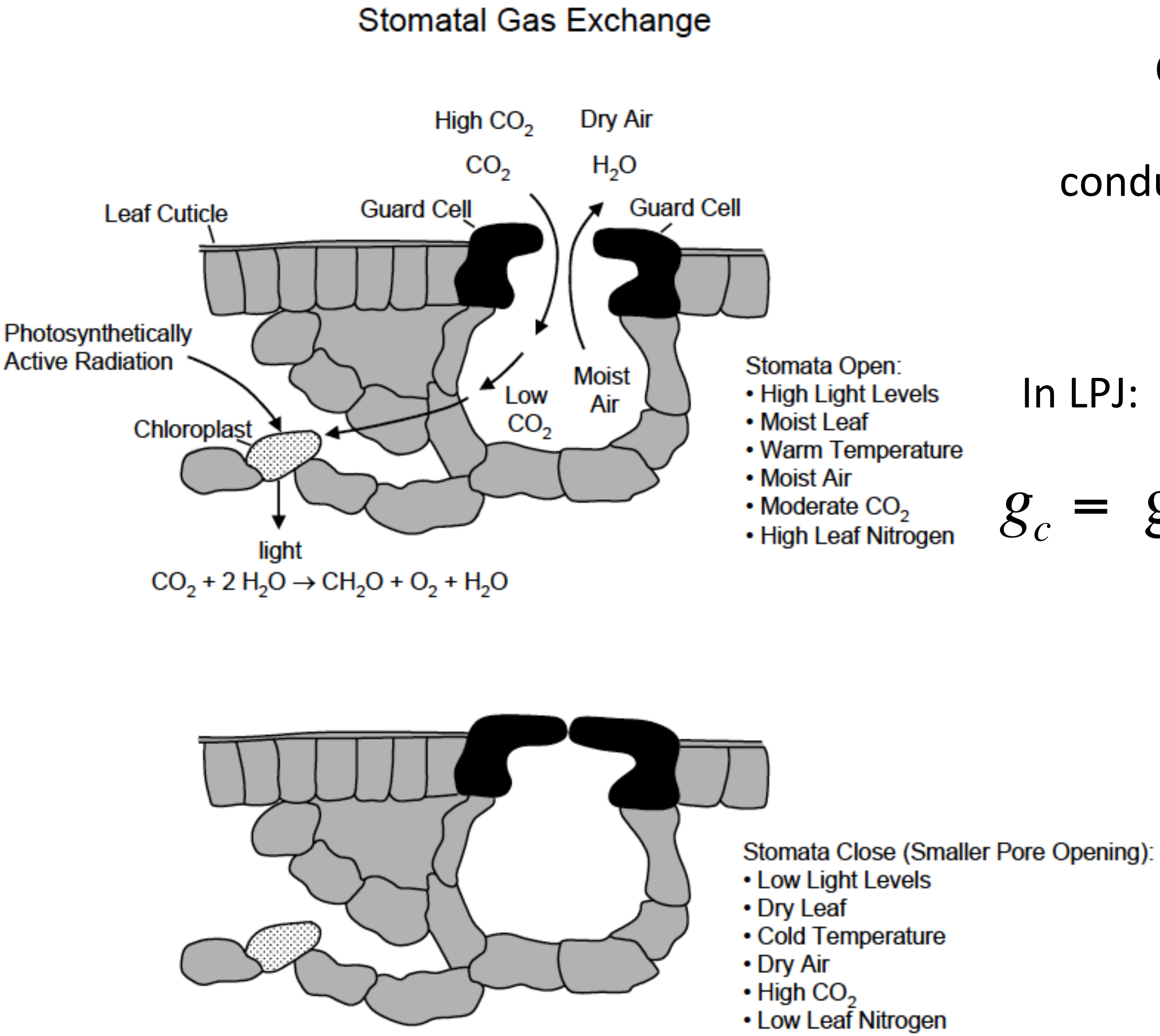

Stomata Open:
- High Light Levels
- Moist Leaf
- Warm Temperature
- Moist Air
- Moderate CO_2
- High Leaf Nitrogen

Stomata Close (Smaller Pore Opening):
- Low Light Levels
- Dry Leaf
- Cold Temperature
- Dry Air
- High CO_2
- Low Leaf Nitrogen

Optimality assumption:
Plants adjust stomatal conductance to optimise CO_2 intake vs water loss.

In LPJ:

$$g_c = g_{\min} + \frac{1.6A}{C_a\ (1-\alpha)}$$

α is reduced under water stress

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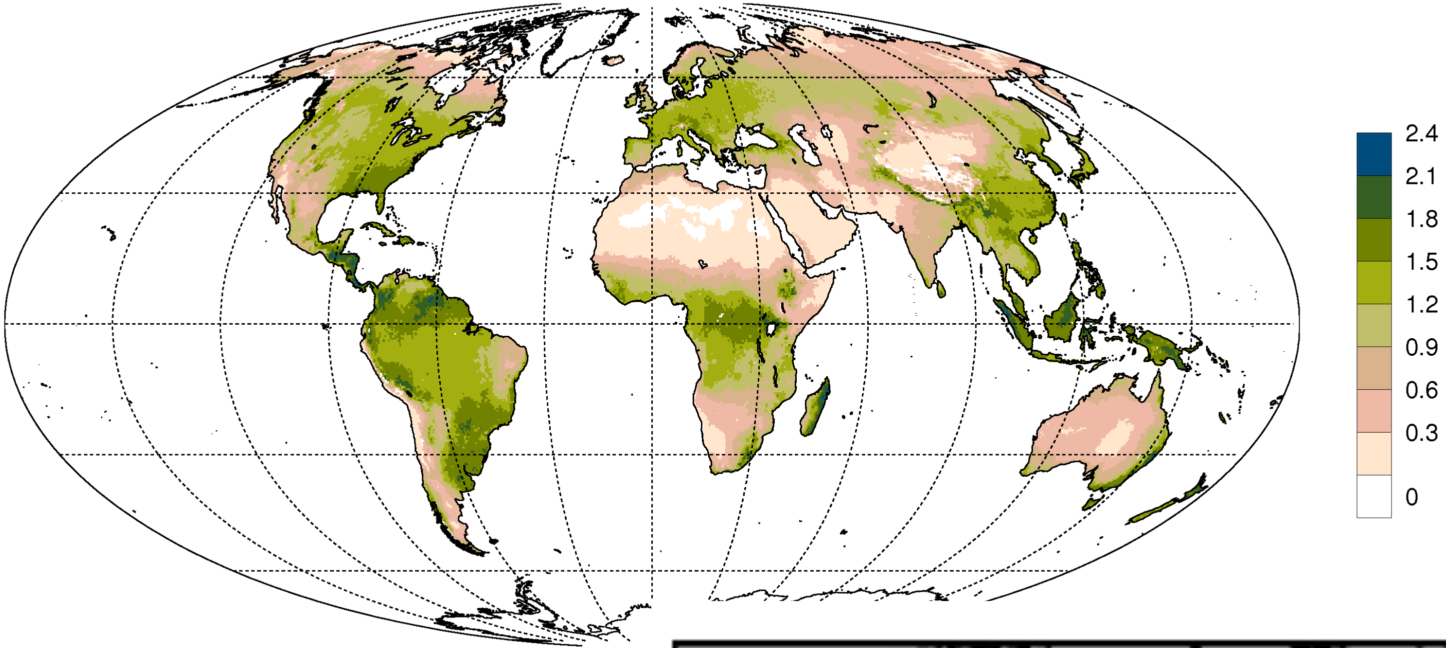
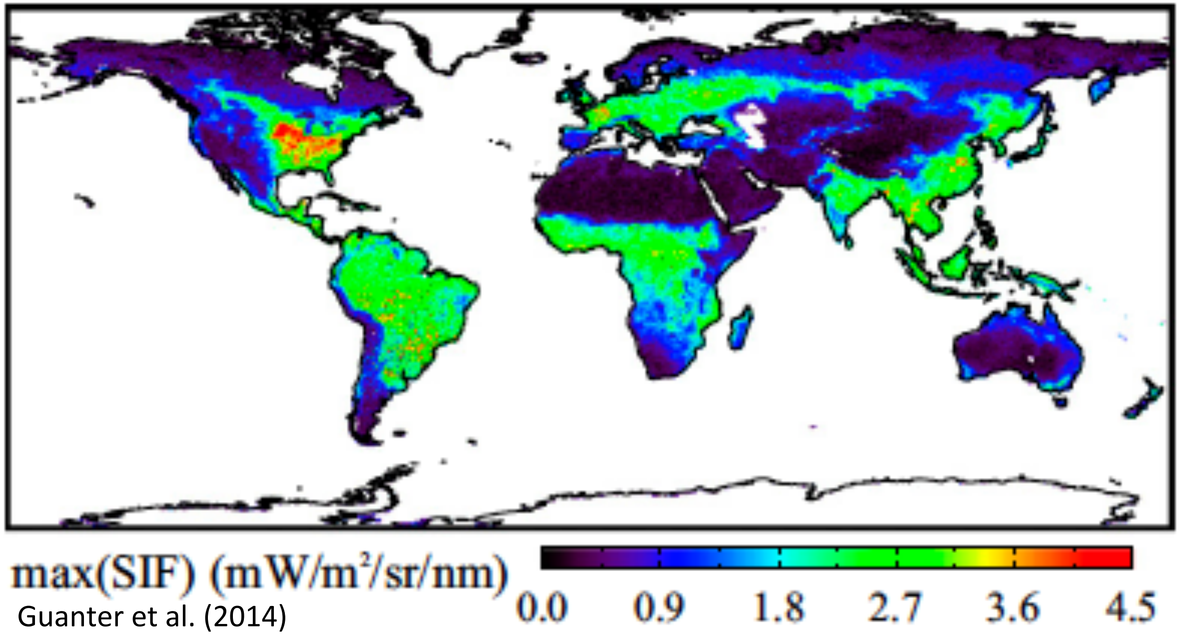
Primary production



GPP
from LPJ-GUESS
1981-2000
(kg C m^{-2} a^{-1})

Chlorophyll fluorescence –
can be detected by satellite. Indicator for GPP



Guanter et al. (2014)

Autotrophic respiration

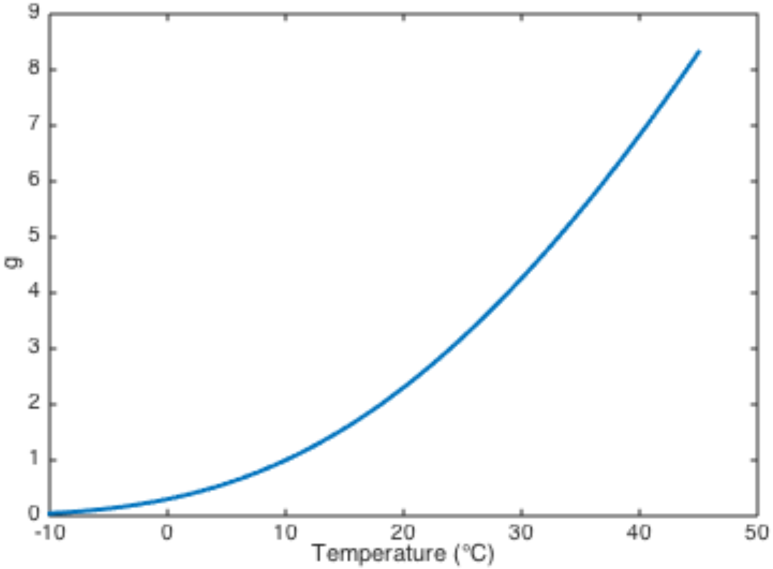
Plant respiration usually divided into growth and maintenance respiration

Example functions from LPJ/LPJ-GUESS:

$$R_{\text{leaf}} = r \cdot \frac{C_{\text{leaf}}}{\text{cn}_{\text{leaf}}} \phi \cdot g(T)$$

$$R_{\text{sapwood}} = r \cdot \frac{C_{\text{sapwood}}}{\text{cn}_{\text{sapwood}}} g(T)$$

$$R_{\text{root}} = r \cdot \frac{C_{\text{root}}}{\text{cn}_{\text{fineroot}}} \phi \cdot g(T_{\text{soil}})$$



Rate is tissue dependent – related to nitrogen content

$$g(T) = \exp\left[308.56 \cdot \left(\frac{1}{56.02} - \frac{1}{(T + 46.02)}\right)\right]$$

Strong dependence on temperature

Growth:

$R_g = 0.25 \times (GPP - R_{\text{leaf}} + R_{sapwood} + R_{root})$

Further reading: Thornley and Cannell (2000), Annals of Botany

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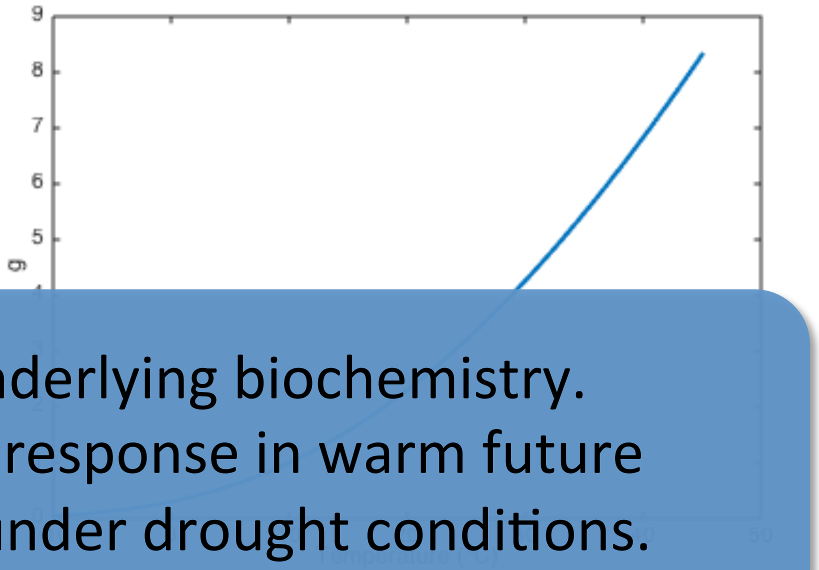

BUT: Hugh simplification of underlying biochemistry. Acclimatisation could moderate response in warm future climates. Model appears to fail under drought conditions.

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$R_g = 0.25 \text{ X } (GPP - R_{\text{leaf}} + R_{sapwood} + R_{root})$

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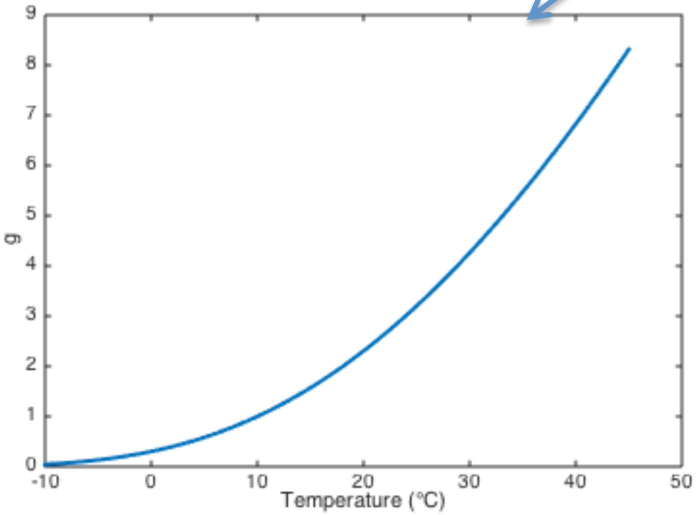
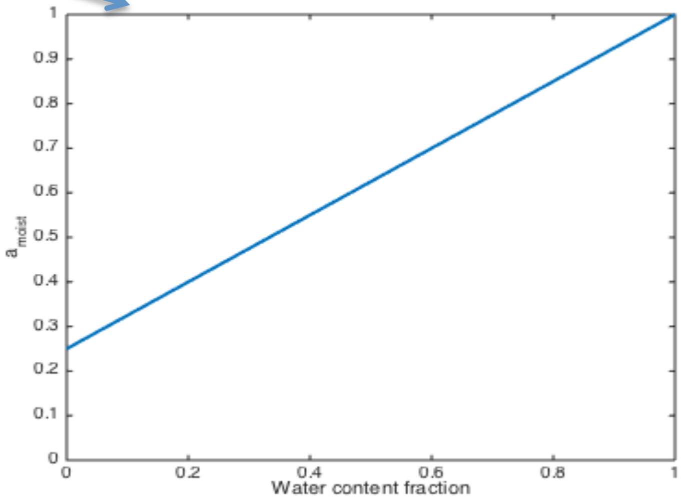
Heterotrophic respiration

Respiration by decomposers in the soil.

Typically global models use simple lifetime functions modified by temperature and moisture:

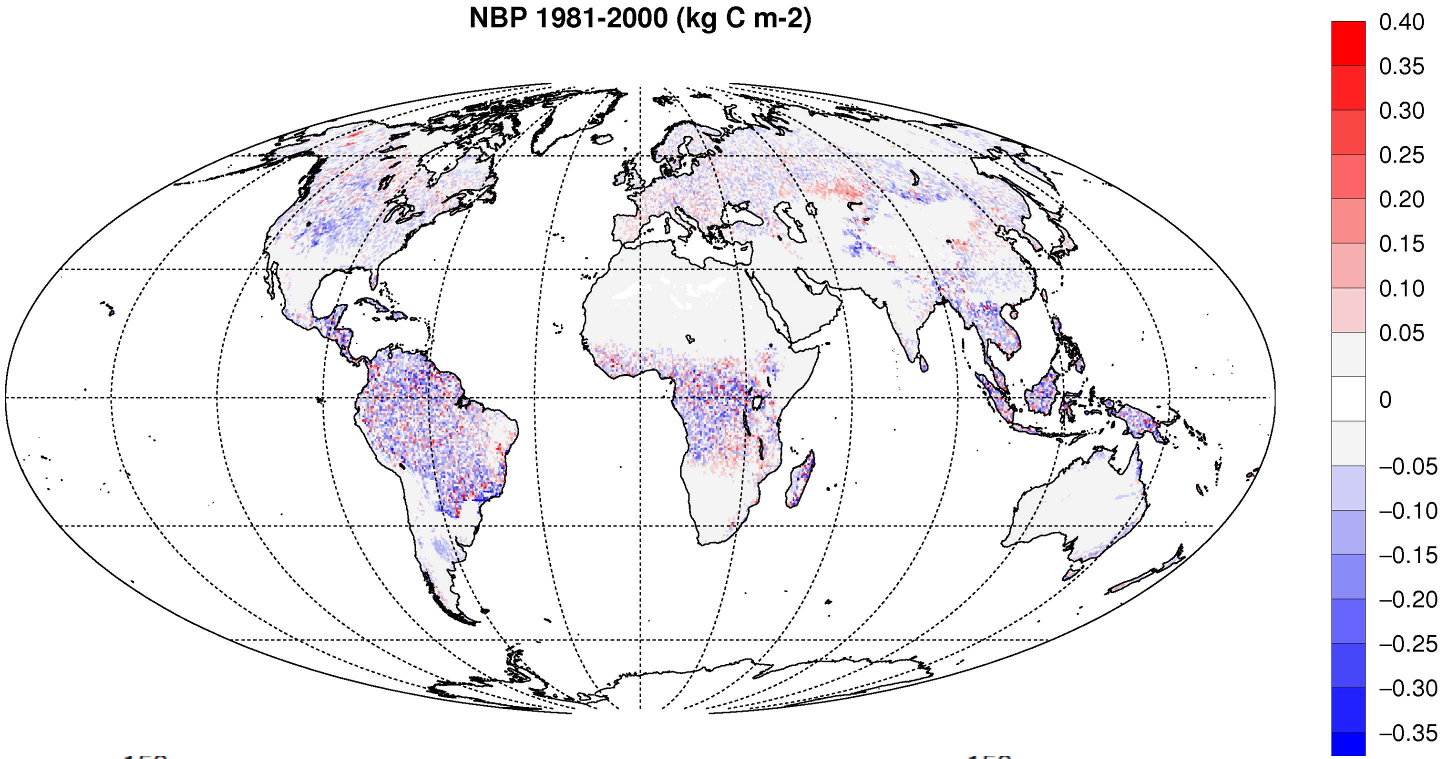
$$R_H = \exp(\,(1/\tau).\, g_T \,.\, g_{moist}\,) \qquad \tau \approx 2\text{-}1000 \text{ years}$$





Heavily over-simplified in most global models. Is actually a function of a whole range of factors – bacteria, substrate, moisture, N, temperature. See, e.g. Koven et al. (2013)

Net ecosystem flux balance



NBP
LPJ-GUESS
1981-2000
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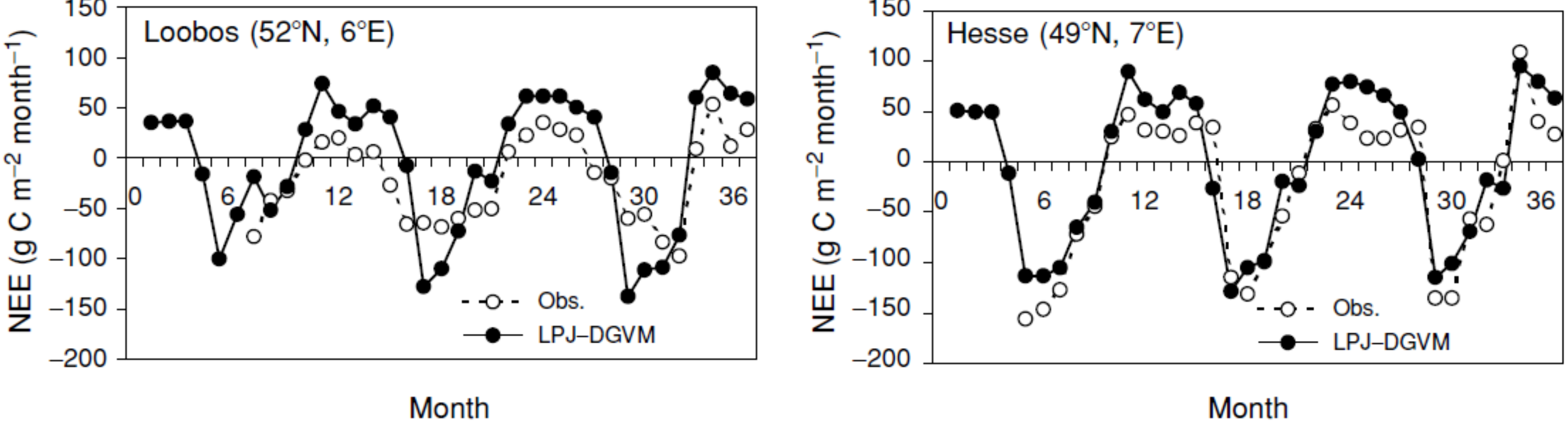
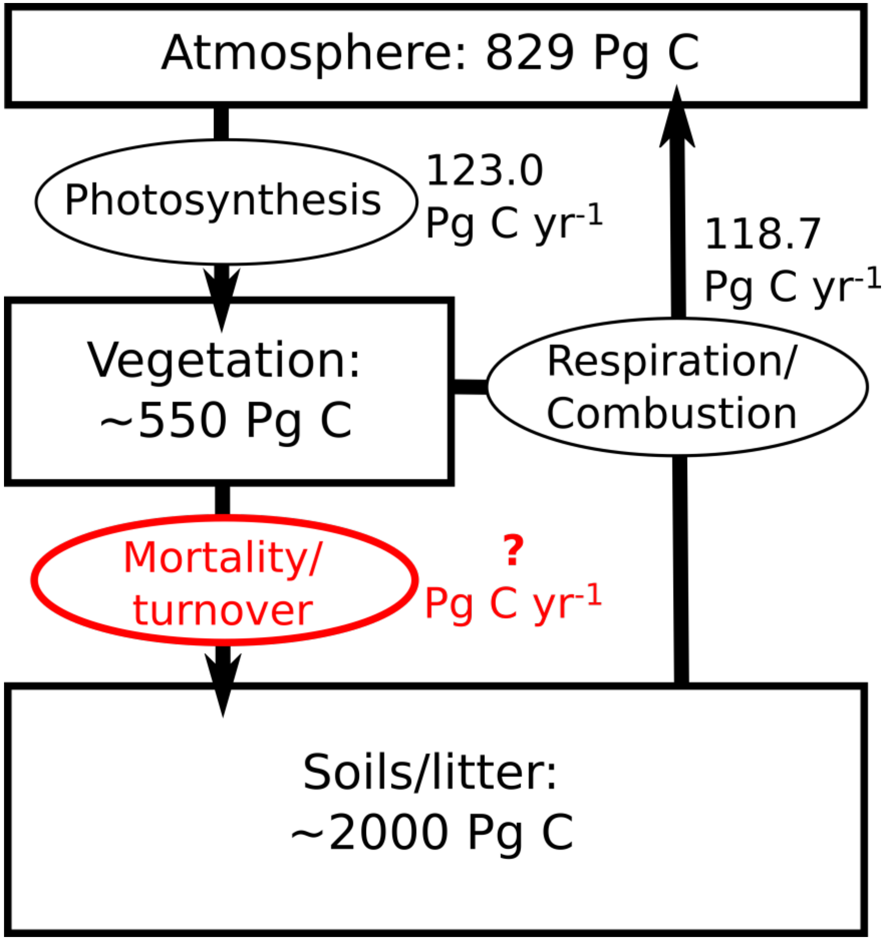


Bottom figure Sitch et al. (2003)

Model structure

We model the effect of these fluxes on terrestrial carbon storage using the concept of pools.



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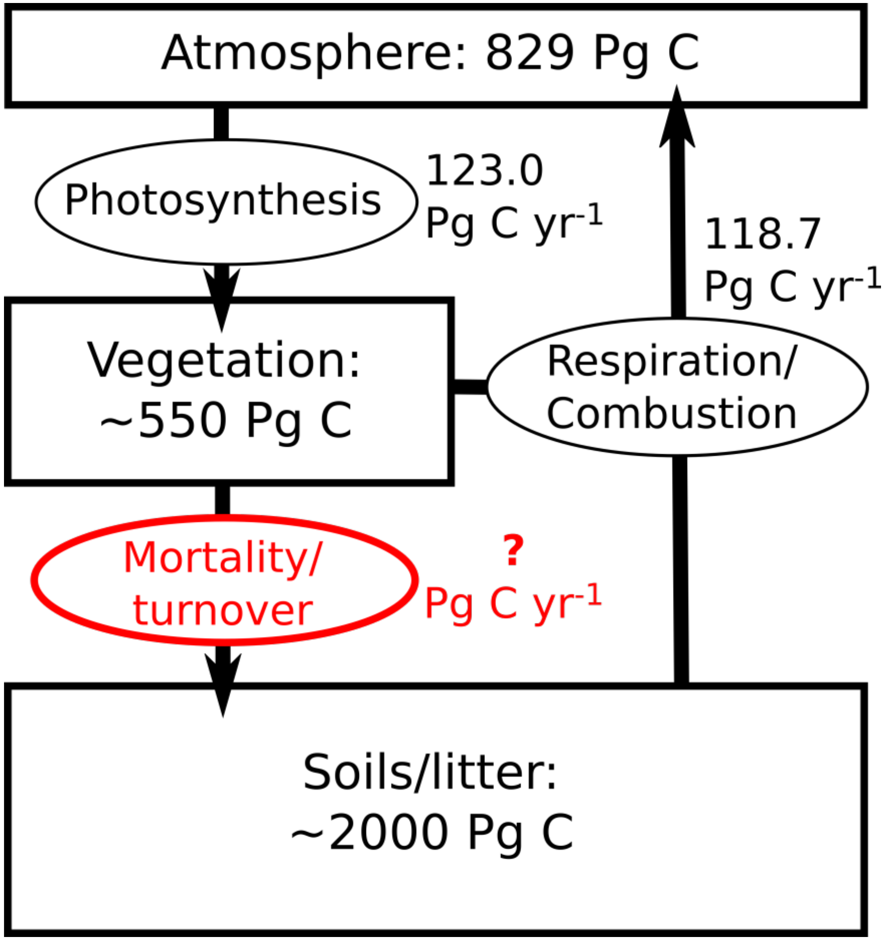

Soils and litter are often split into several different sub-pools depending on their basic decomposition rates. Typical pool turnover times are a few years for litter, and 10-1000 years for soil pools

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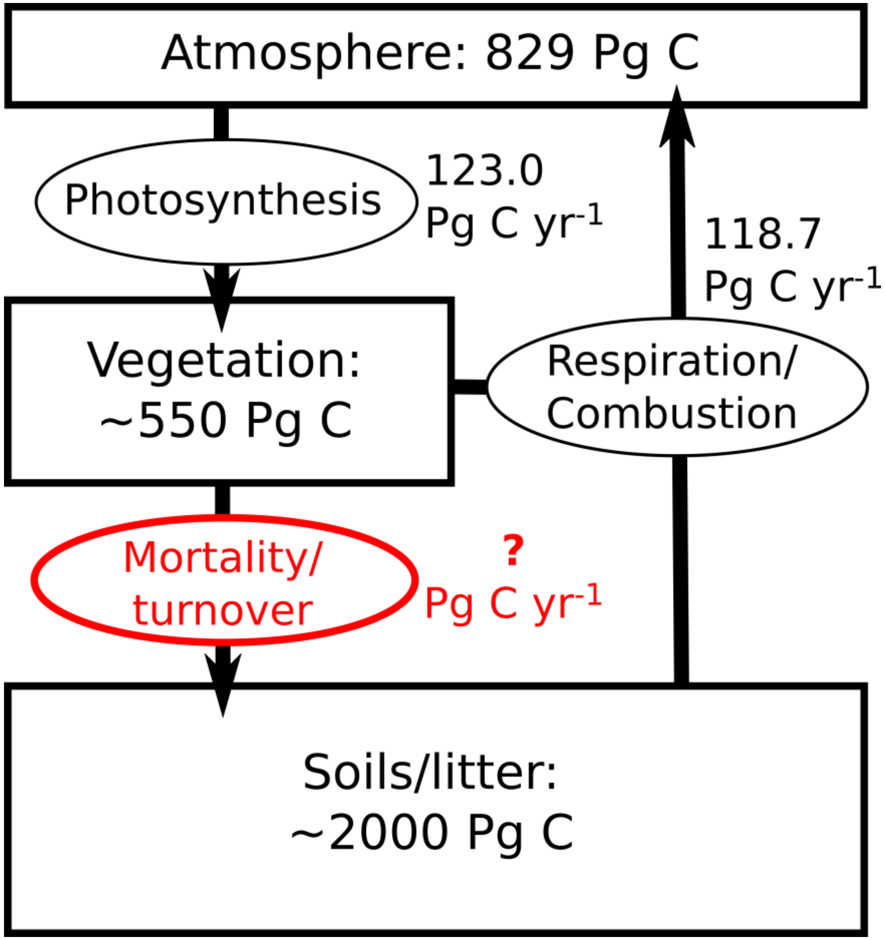


Atmosphere: 829 Pg C

Photosynthesis

123.0 Pg C yr^{-1}

Vegetation: ~550 Pg C

Respiration/ Combustion

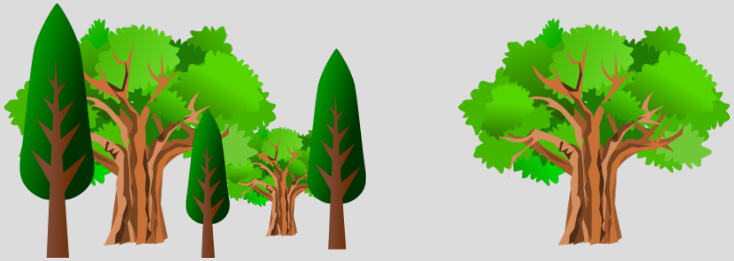
118.7 Pg C yr^{-1}

Mortality/ turnover

? Pg C yr^{-1}

Soils/litter: ~2000 Pg C

Vegetation pool may be one average individual, or a range of different individuals of different age and species, depending on the model



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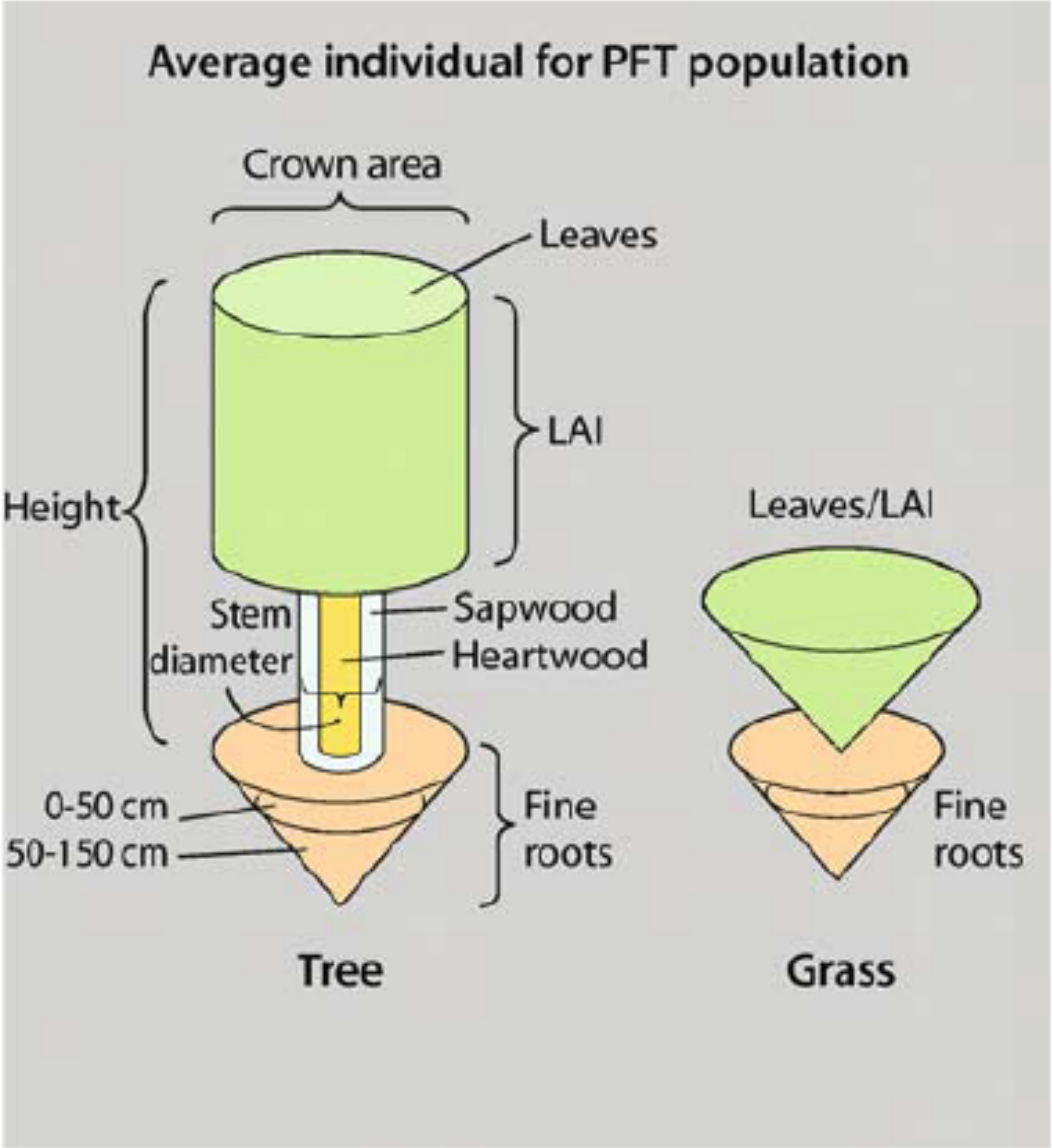
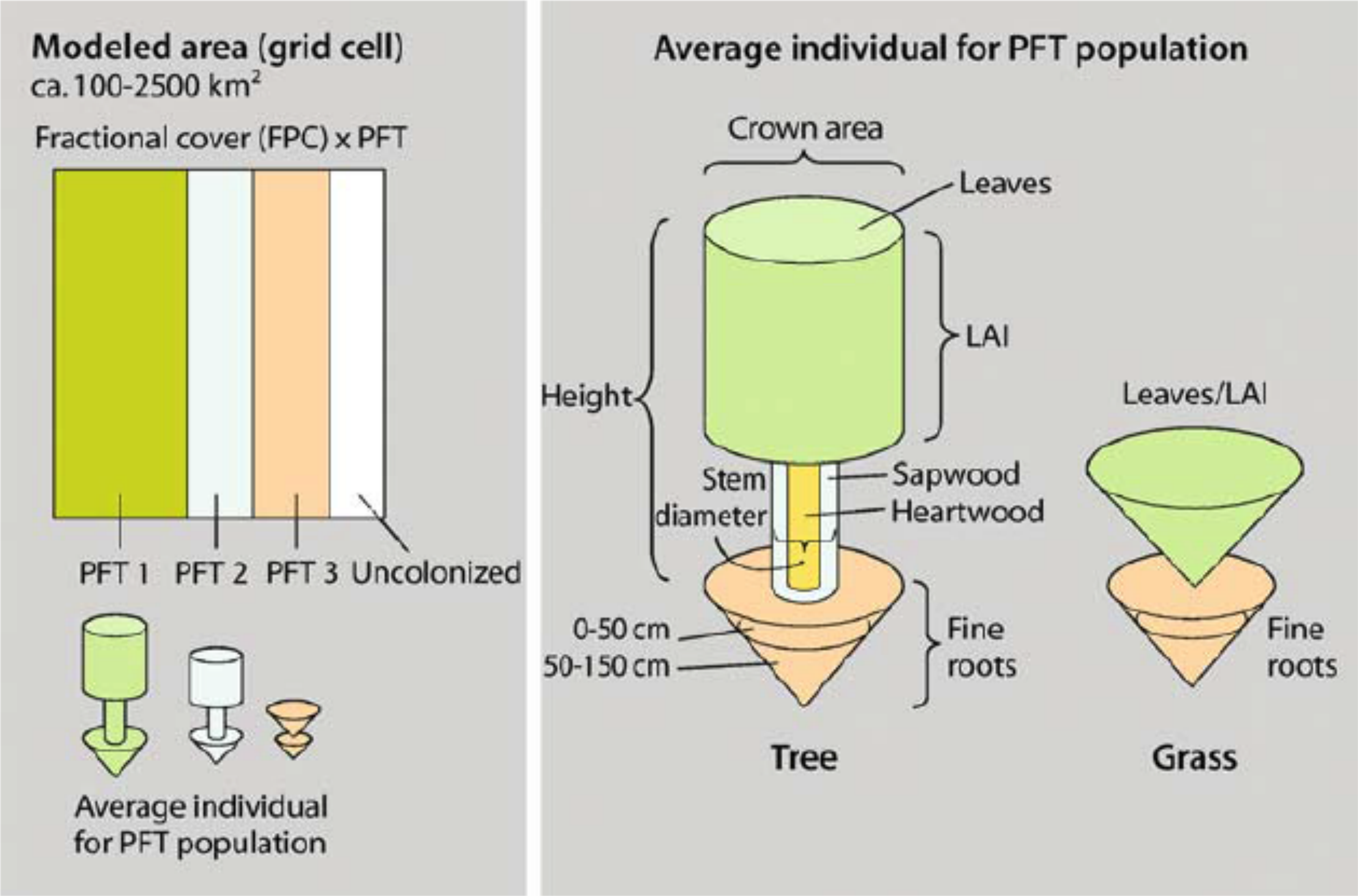
Model structure and vegetation dynamics



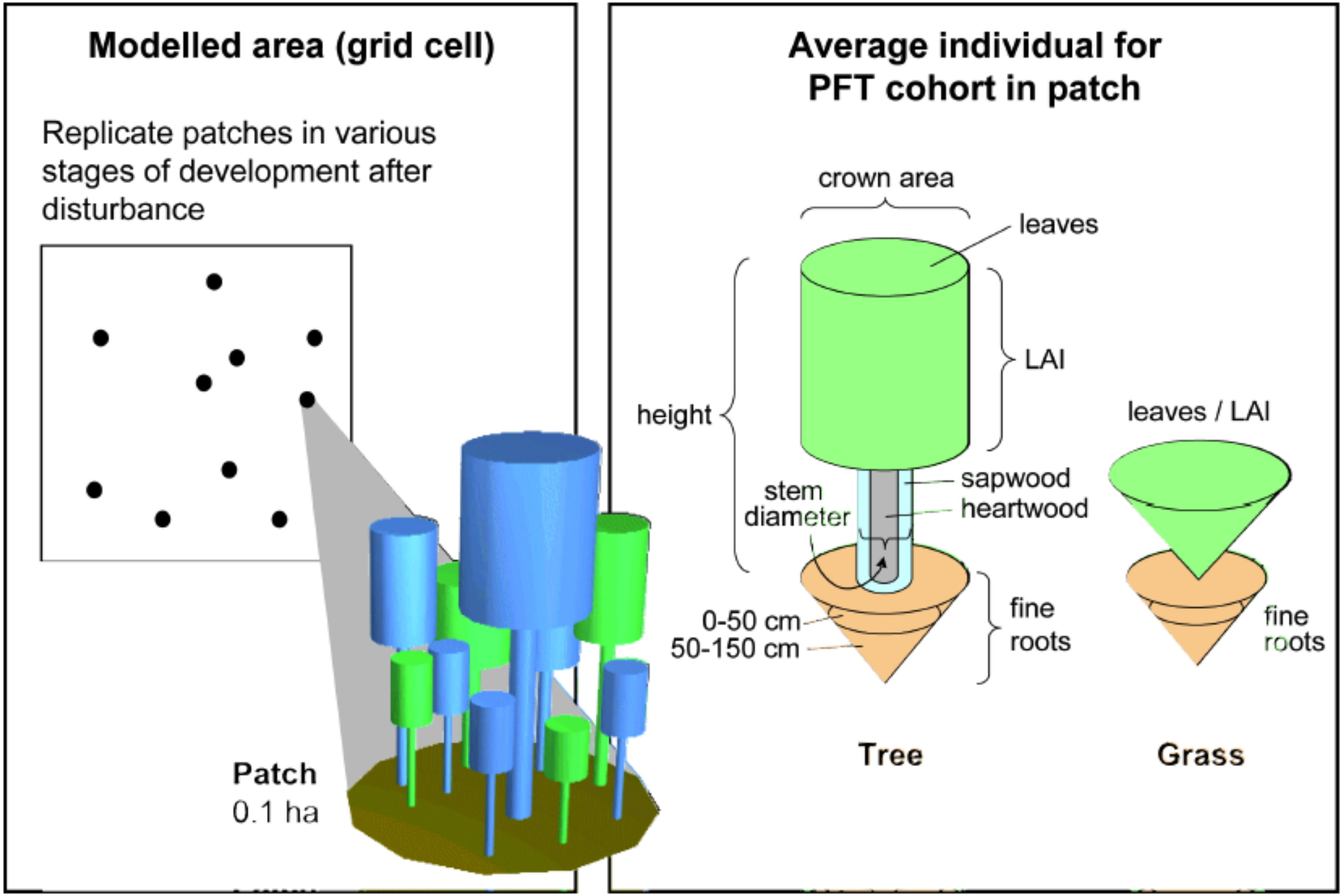
Prentice et al. (2007)

Model structure and vegetation dynamics



Prentice et al. (2007)

Model structure and vegetation dynamics



Smith et al. (2014)

Model structure and vegetation dynamics

Plants can also die. Typical death mechanisms related to resource availability or physiological limits include:

- Bioclimatic limits
- Negative productivity
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- Insect attack

This is a major uncertainty in the understanding of ecosystem response to future environments. A doubling of mortality rates leads to a large drop in vegetation carbon stocks.

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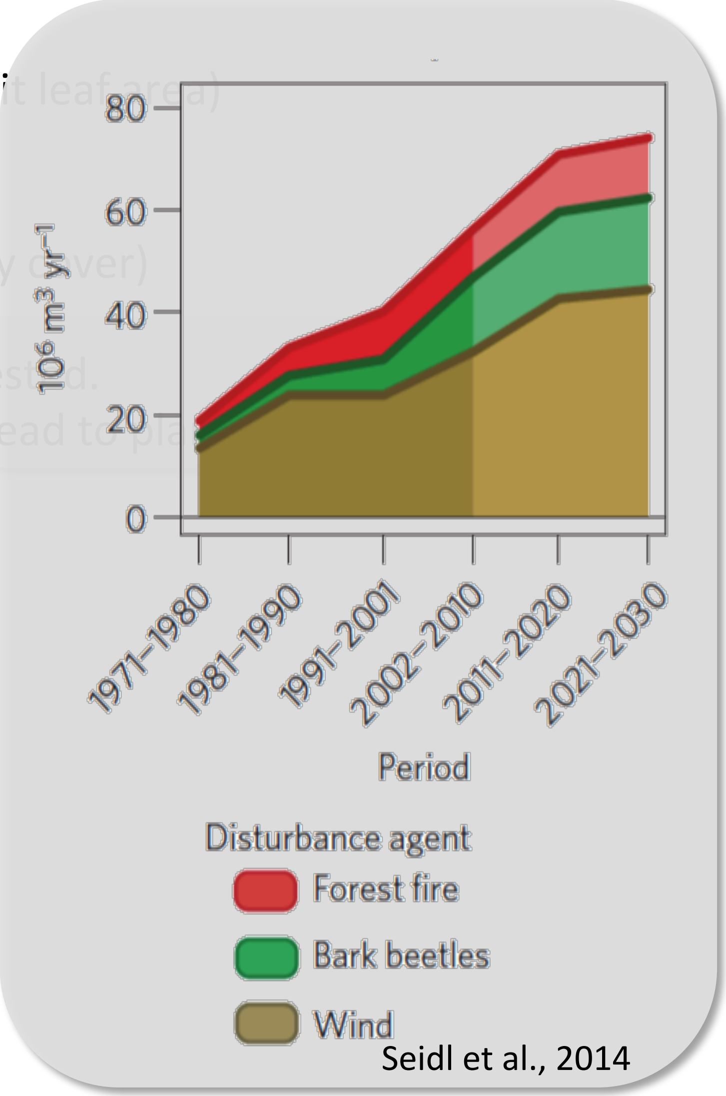

Seidl et al., 2014

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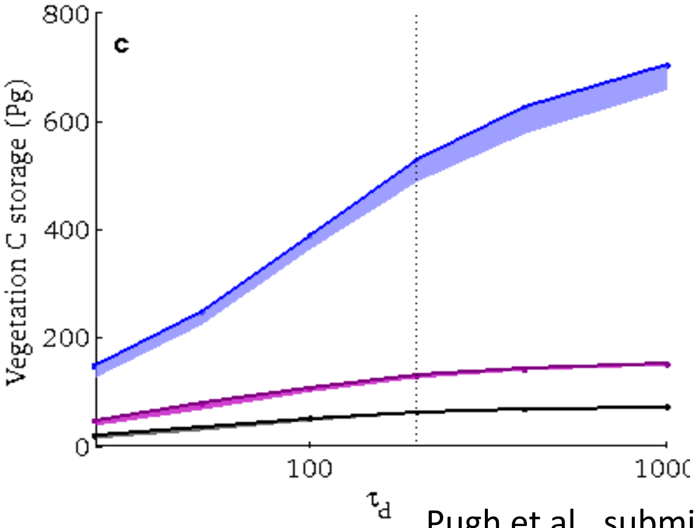


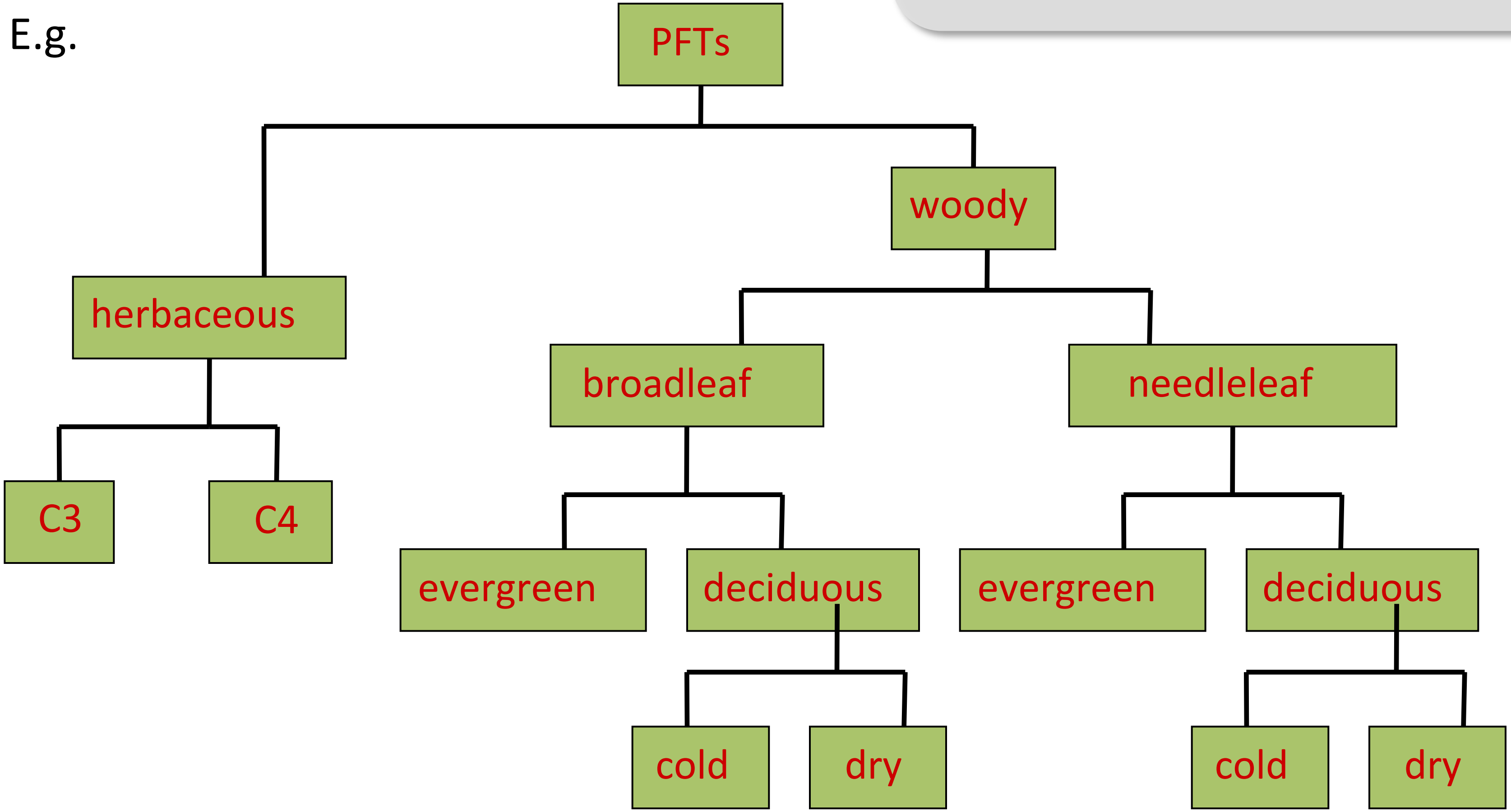
Pugh et al., submitted

Species composition

Huge range of species in reality. We have neither computational capacity or data to capture these in large-scale models. Typical approach is to classify species into PFTs.

E.g.

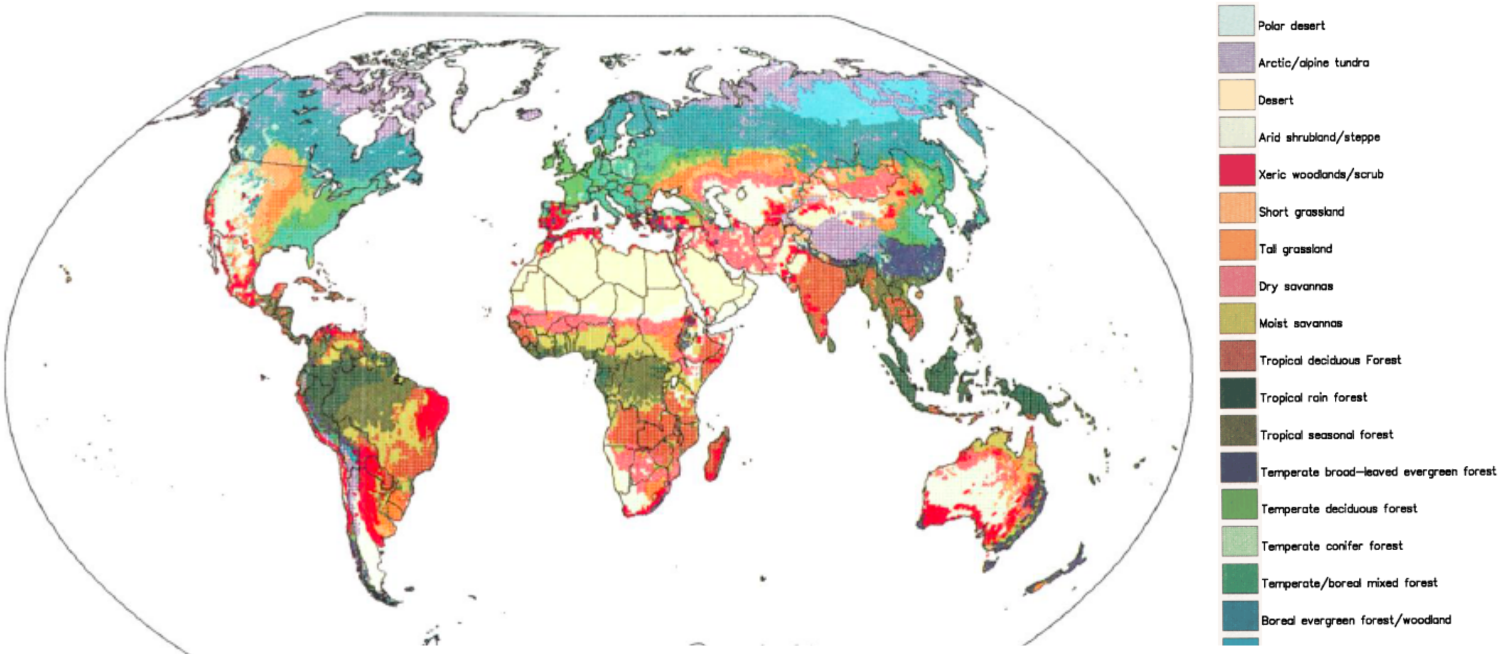
Distinguished by, e.g.
Plant physiology (C3/C4 photosynthesis)
Phenology (Evergreen/Deciduous)
Physiognomy (Woody/Herbaceous)
Bioclimatic limits (Cold/Heat tolerance)



- PFTs
  - herbaceous
    - C3
    - C4
  - woody
    - broadleaf
      - evergreen
      - deciduous
        - cold
        - dry
    - needleleaf
      - evergreen
      - deciduous
        - cold
        - dry

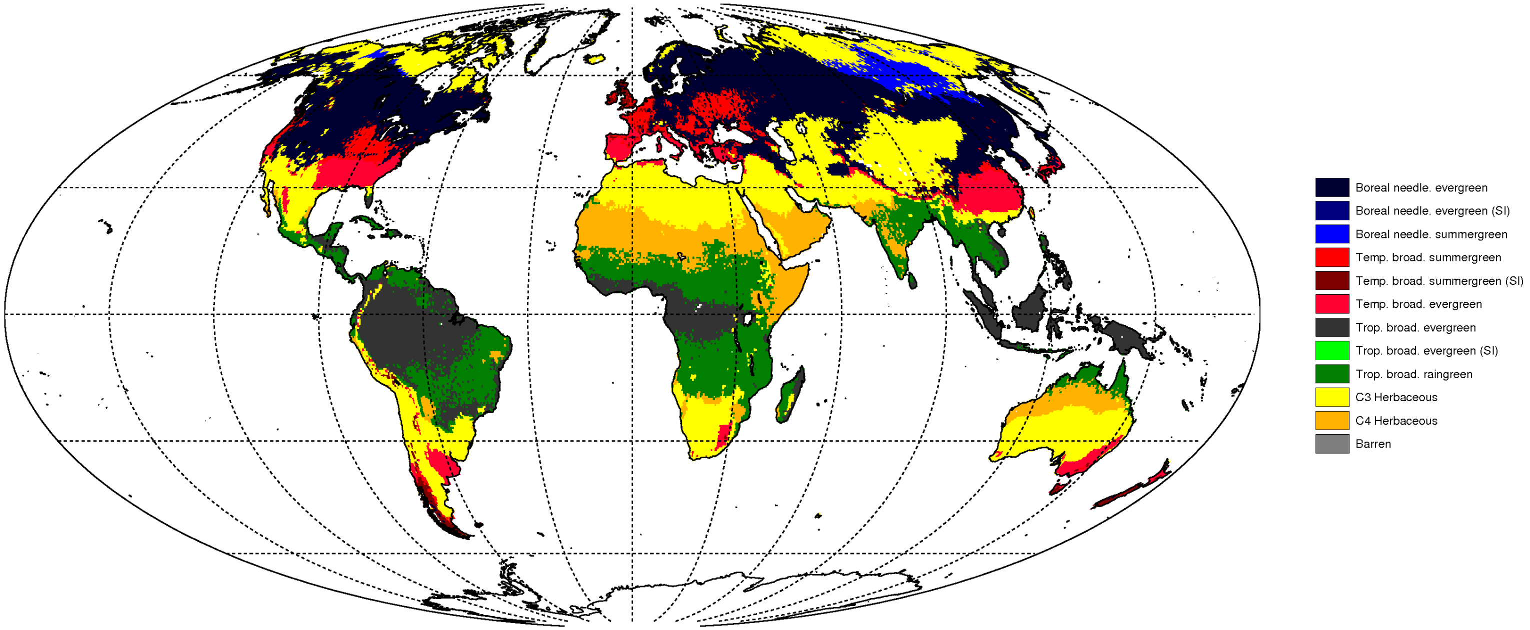
Slide: S. Sitch

Species composition



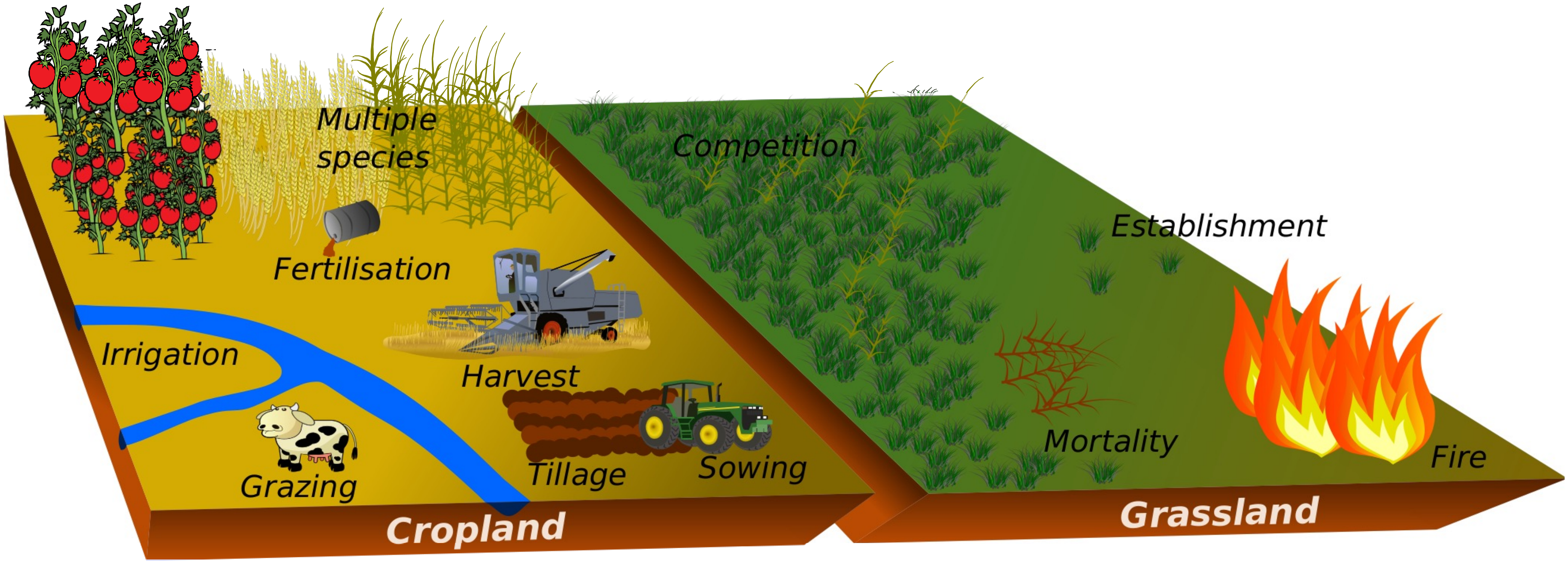
Data-based map of potential natural vegetation (Haxeltine and Prentice, 1996)

LPJ-GUESS dominant potential vegetation type 1981-2000



Managed land: Agriculture

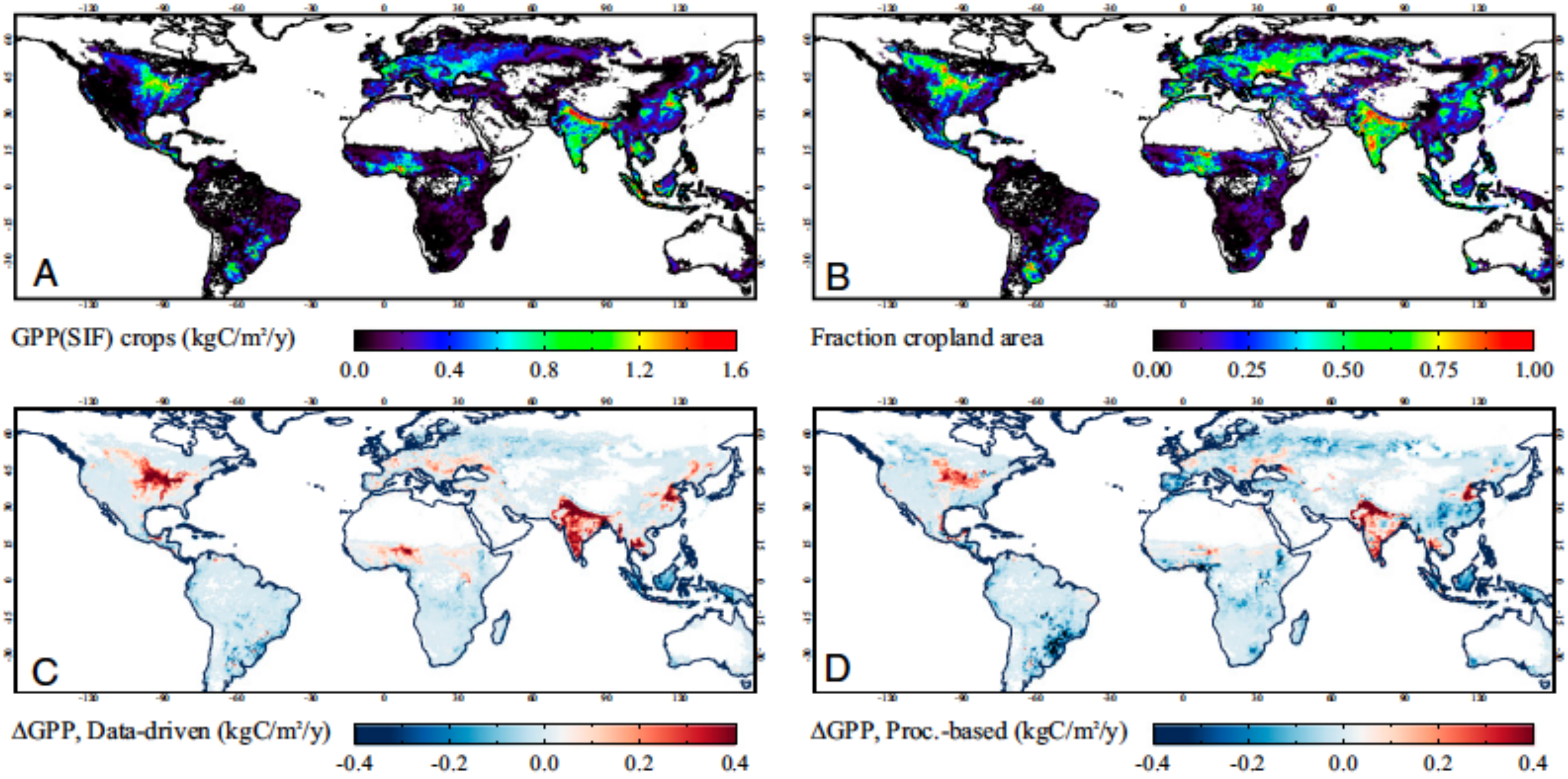
Until recently, ESMs and DGVMs concentrated on PNV.
But managed system differ fundamentally in many respects:



Models are now being expanded to account for the range of processes existing in managed systems, e.g. agriculture.

Managed land: Agriculture

Productivity of croplands can be very different

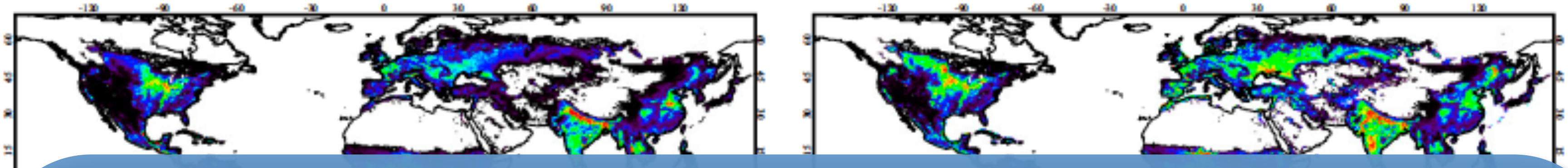


Guanter et al. (2014)

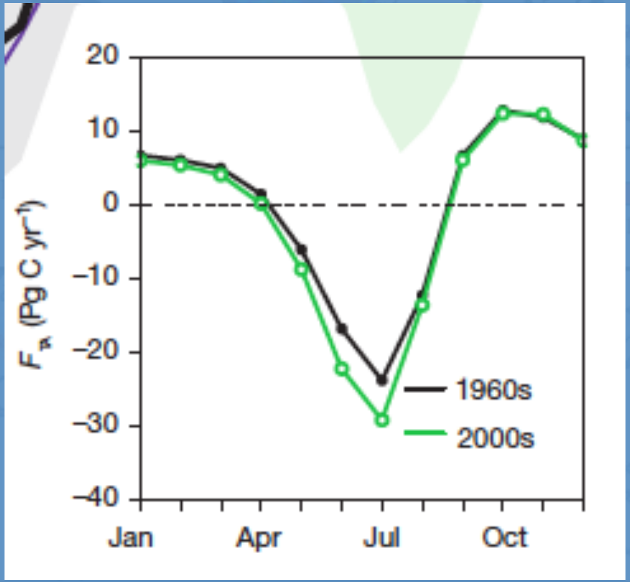
Extraction of global croplands from chlorophyll fluoresence data shows that GPP can be much higher than indicated by models which do not account for management (Guanter et al., 2014)

Managed land: Agriculture

Productivity of croplands can be very different



Recent work has shown that croplands substantially modify the seasonal cycle of atmospheric [CO_2] (Zeng et al., 2014; Gray et al., 2014)



Zeng et al. (2014)

Guanter et al. (2014)

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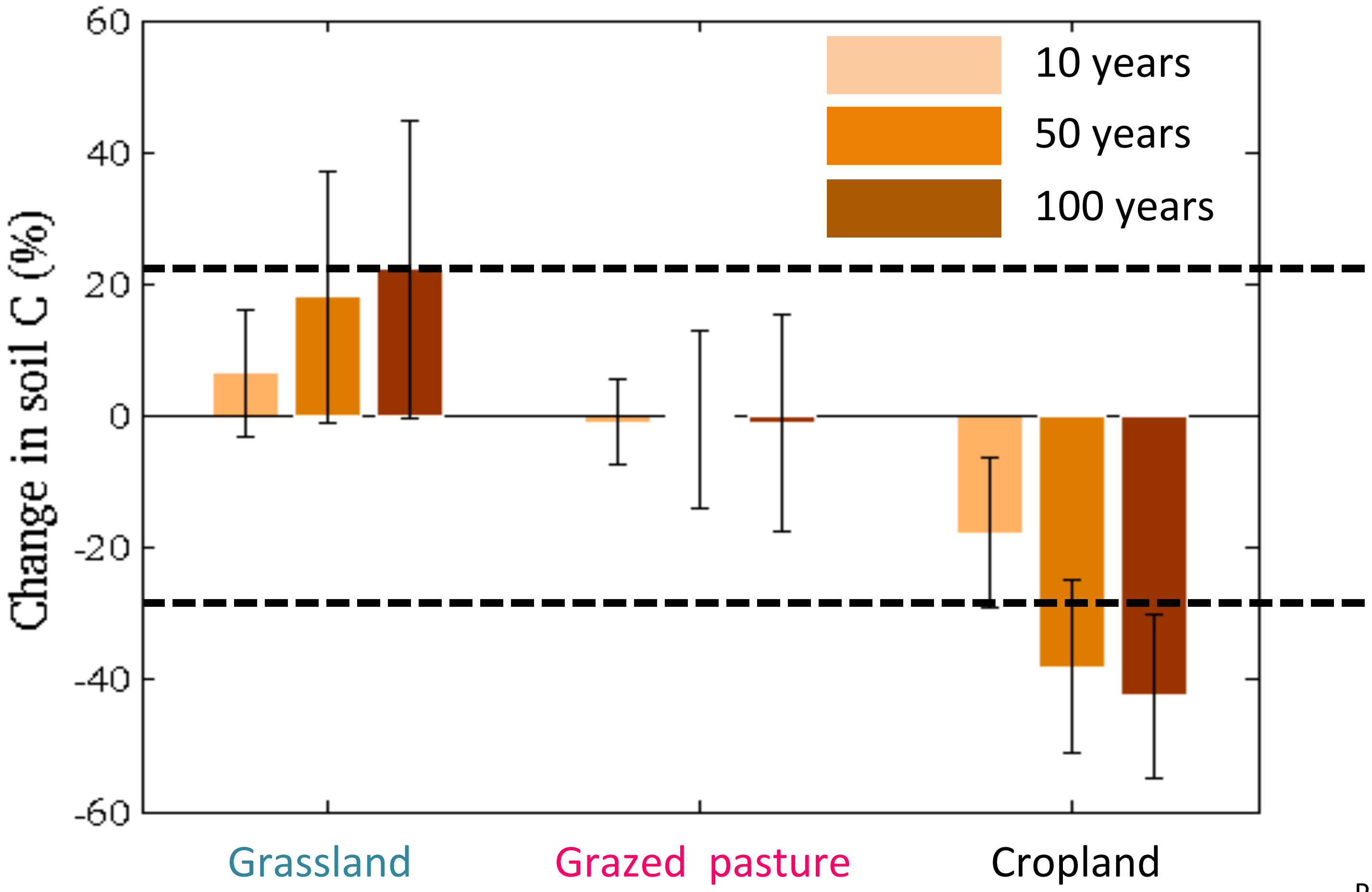
Managed land: Agriculture

However, these productivity increases may not propagate to increases in terrestrial carbon stocks because of processes such as harvest and tillage

Change in soil carbon stocks after complete conversion from natural vegetation (global mean values):



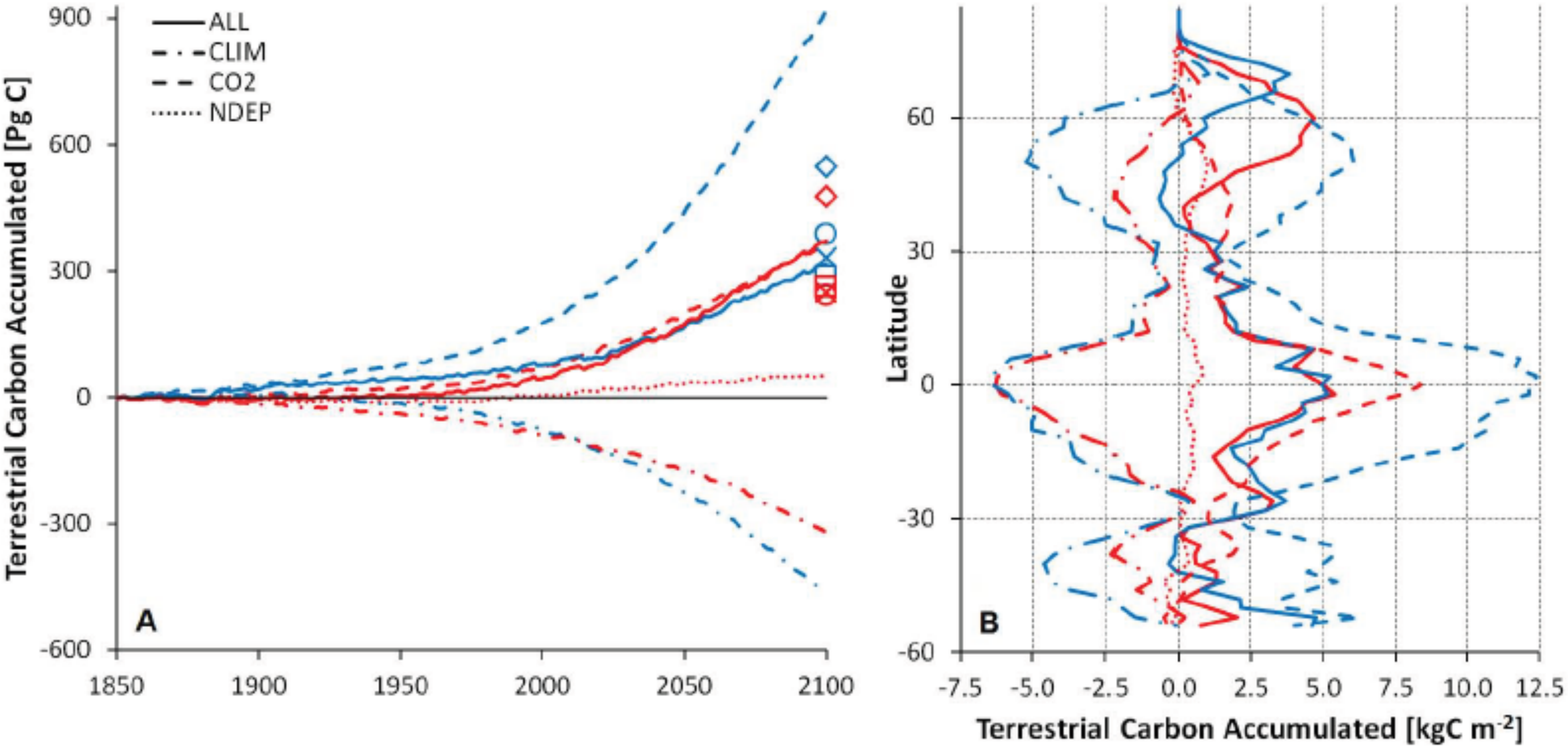
Forest to pasture conversion (meta analysis, Guo and Gifford, 2002)

Forest to crop conversion (Guo and Gifford, 2002)

Pugh, Arneth et al., submitted

Projecting the global carbon cycle

Change in terrestrial C accumulation:
(LPJ-GUESS, forced by MPI-ESM-LR following RCP 8.5)



Wårlind et al. (2014)

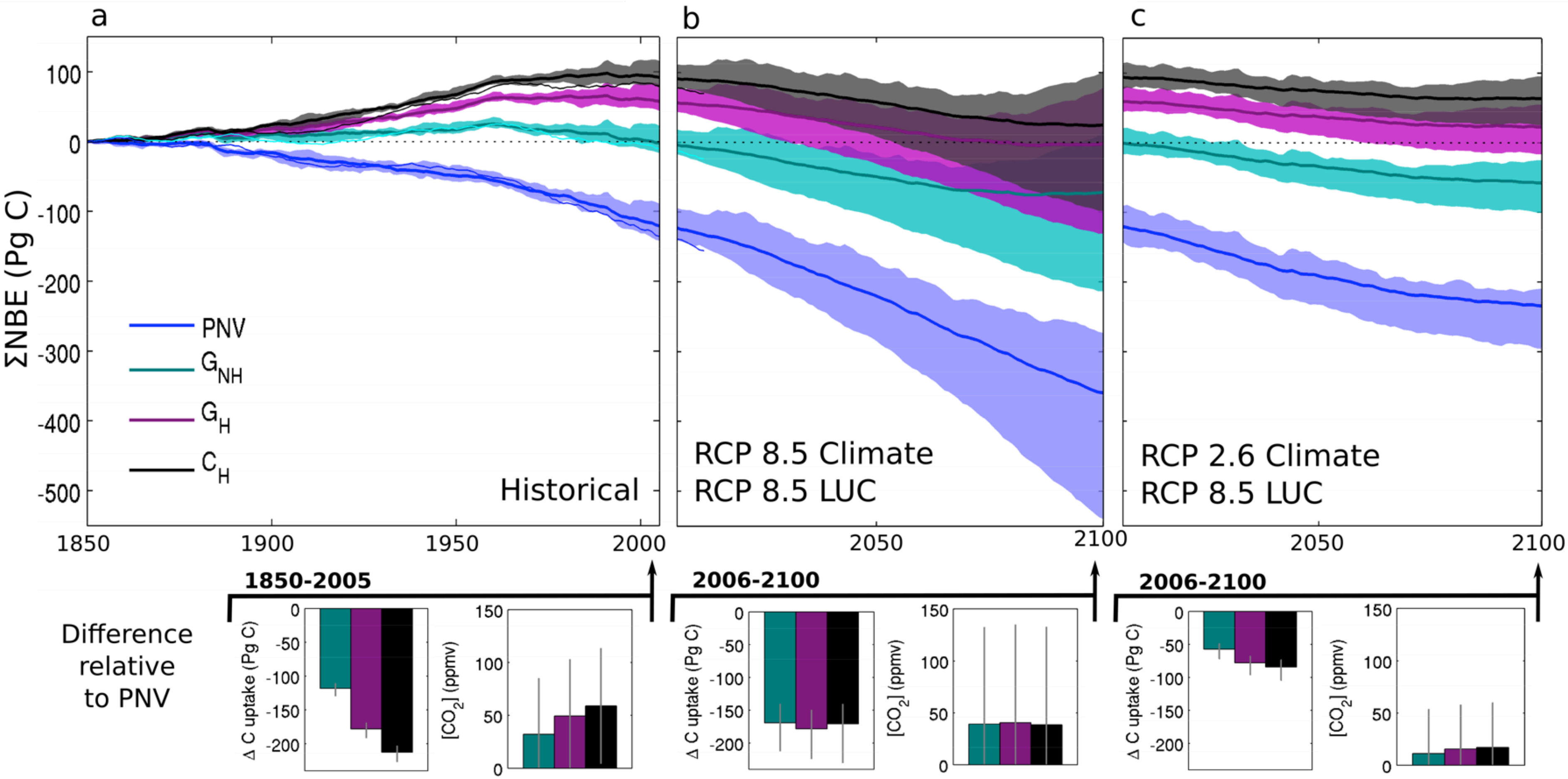
🟦 C-only version

🟥 C-N version

Symbols show other models (note opposite response)

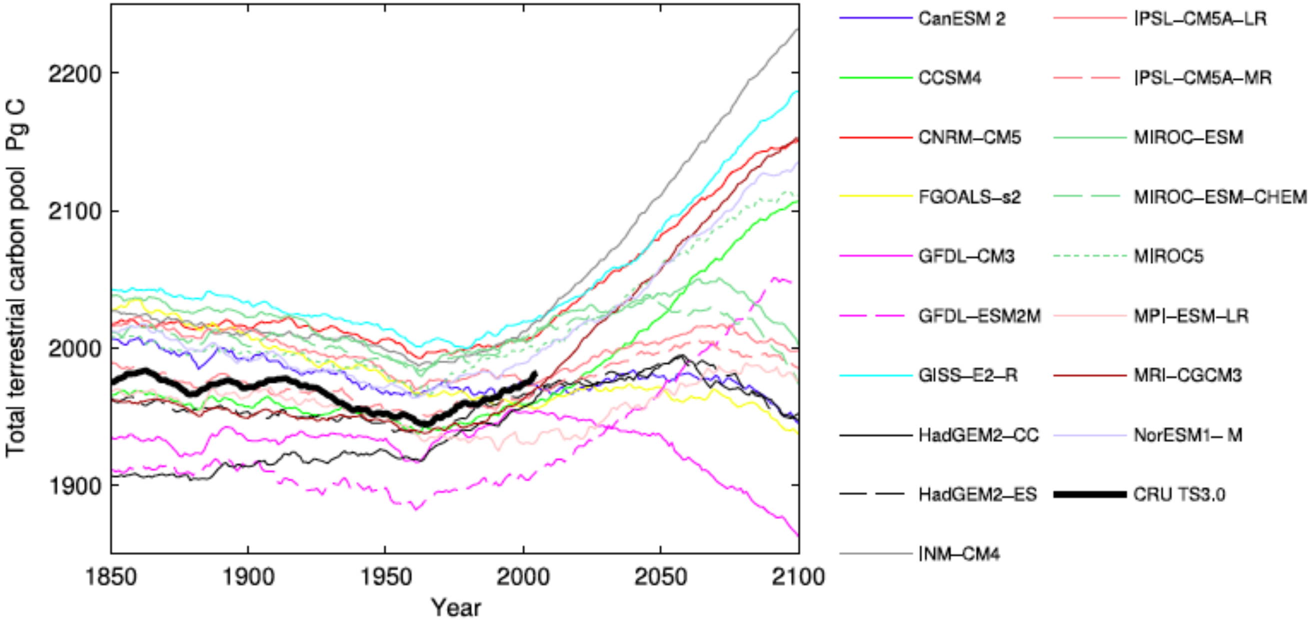
Projecting the global carbon cycle

Together agricultural processes can make a huge difference to projections of global carbon uptake



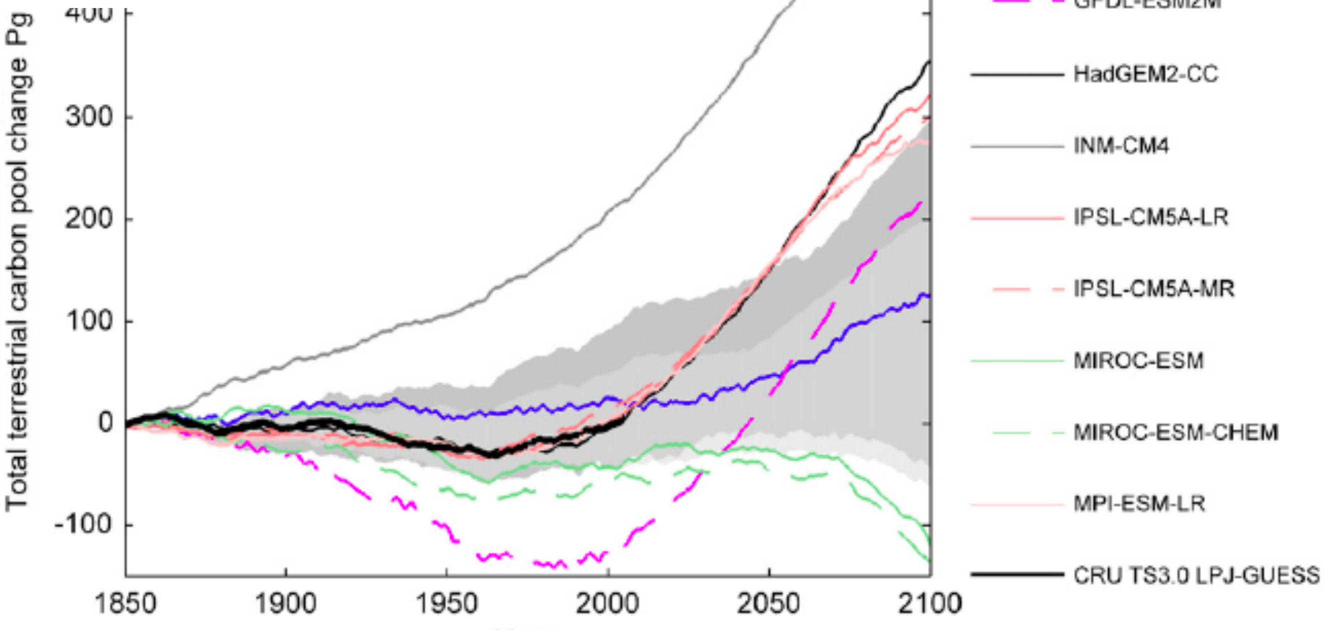
Pugh, Arneth et al., submitted

Projecting the global carbon cycle



Total terrestrial carbon uptake, as calculated by LPJ-GUESS forced by a range of GCM climates (RCP 8.5)

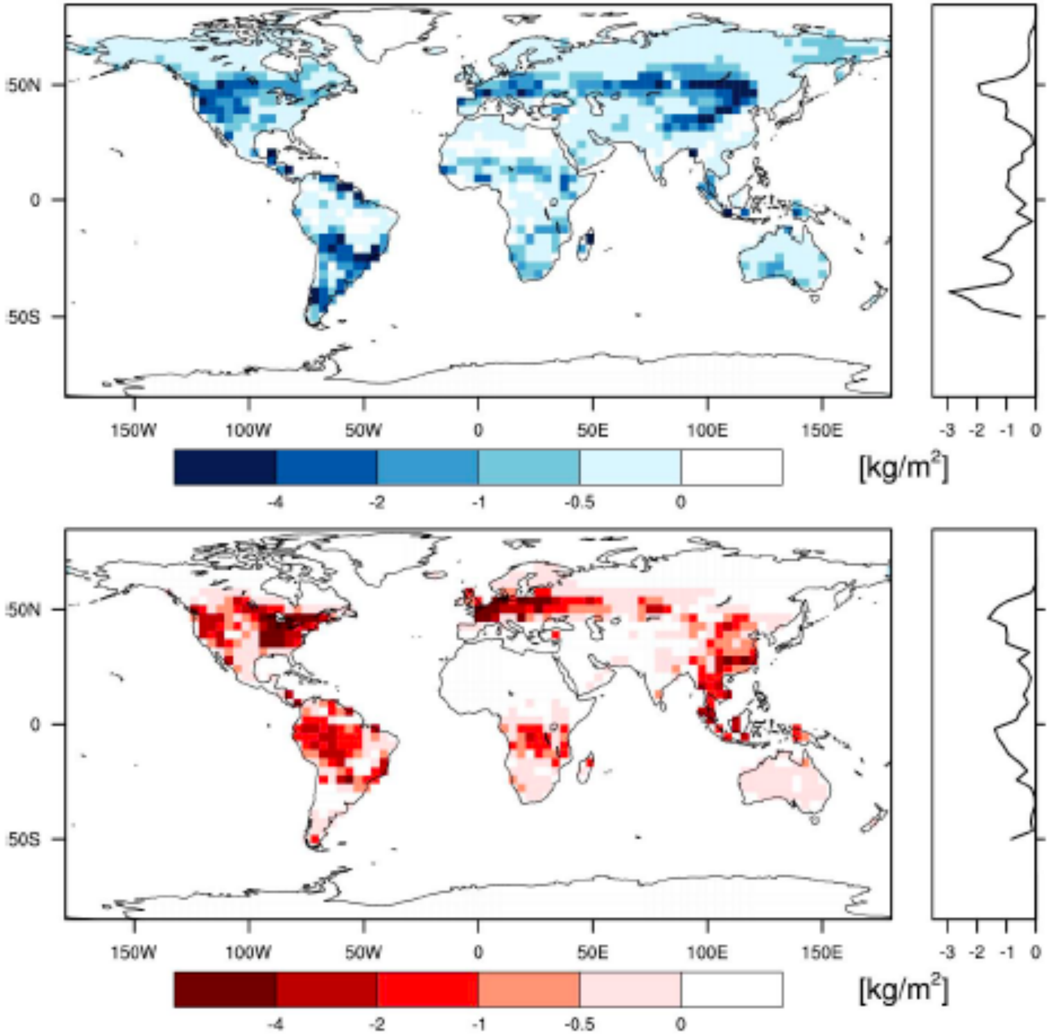
Total terrestrial carbon uptake, as calculated by several different CMIP5 ESMs (RCP 8.5)



Both figures Ahlström et al. (2012)

Projecting the global carbon cycle: Nutrient limitation

Nutrients other than nitrogen may also be important.



Reduction in 2070-2099 carbon storage due to nitrogen limitation in JSBACH (Goll et al., 2012)

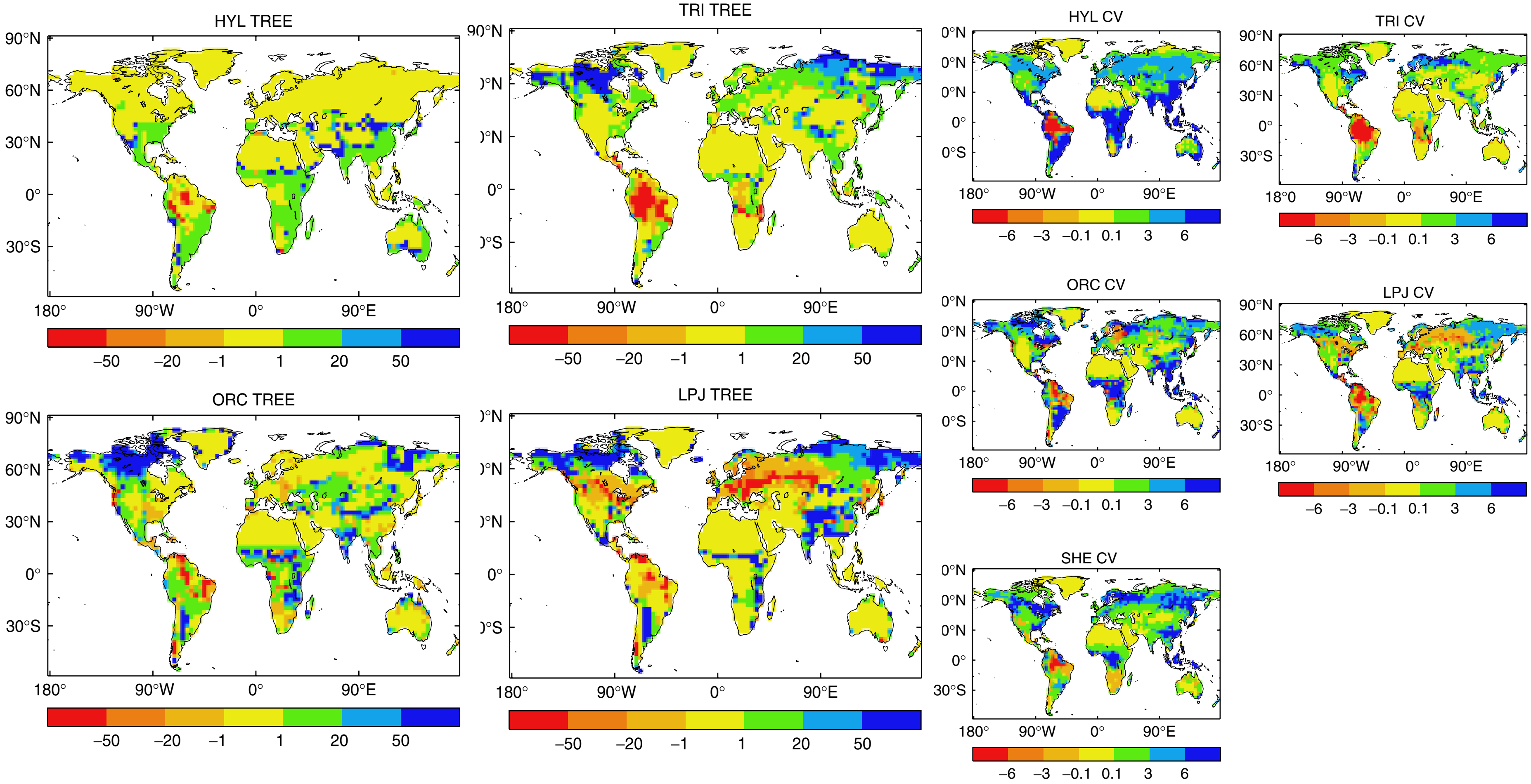
And due to phosphorus limitation (Goll et al., 2012)

Phosphorus may be the main limiting nutrient in tropical forests. Almost totally neglected in model projections, yet tropics drive expected C uptake

Goll et al. (2012)

Projecting the global carbon cycle

Spatial projections very different between models

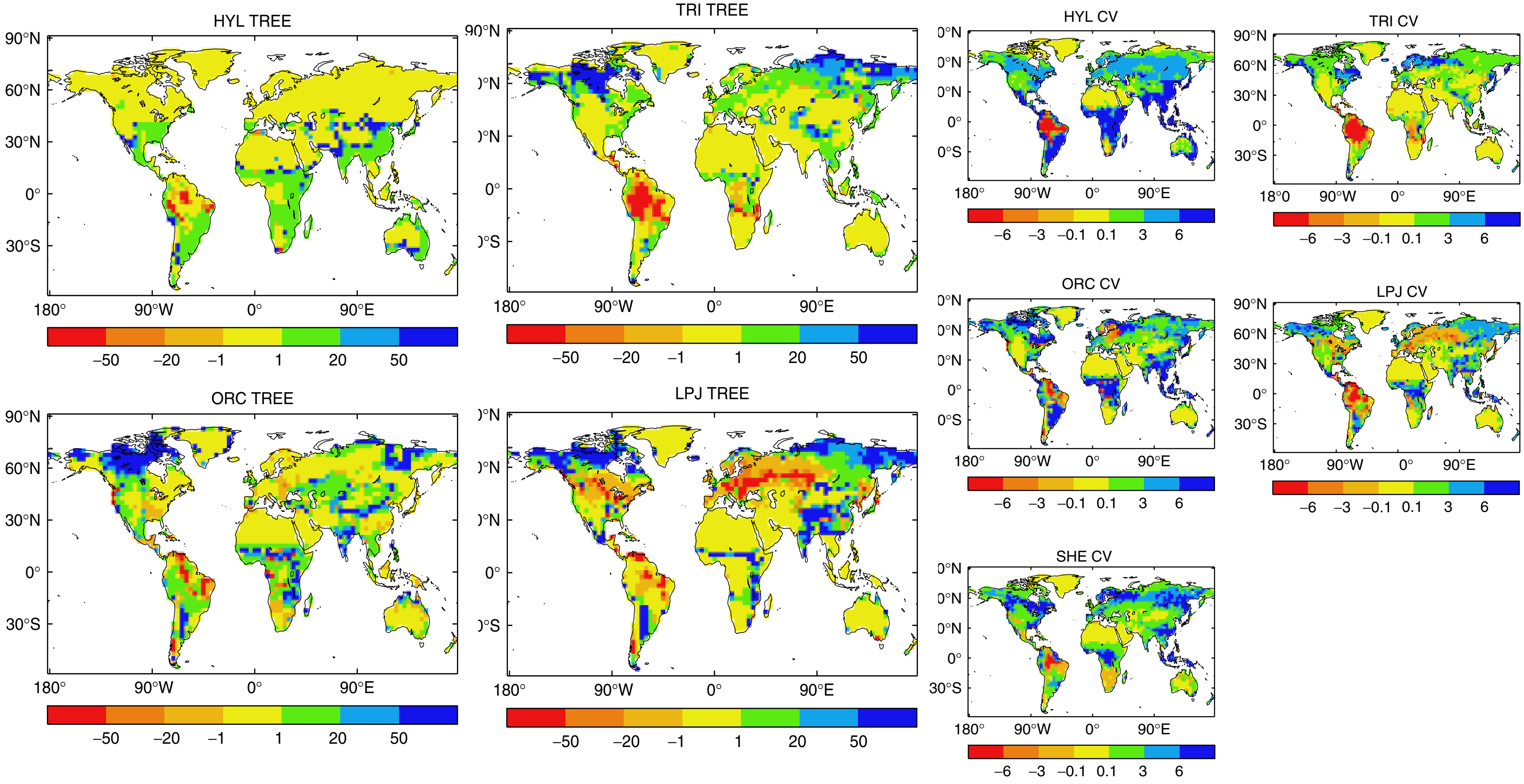


Difference 1860 to 2099. Driven with climate-carbon-cycle coupling.

Figures from Sitch et al. (2008)

Projecting the global carbon cycle: Mortality

Amazon dieback?



HYL TREE

TRI TREE

HYL CV

TRI CV

ORC CV

LPJ CV

ORC TREE

LPJ TREE

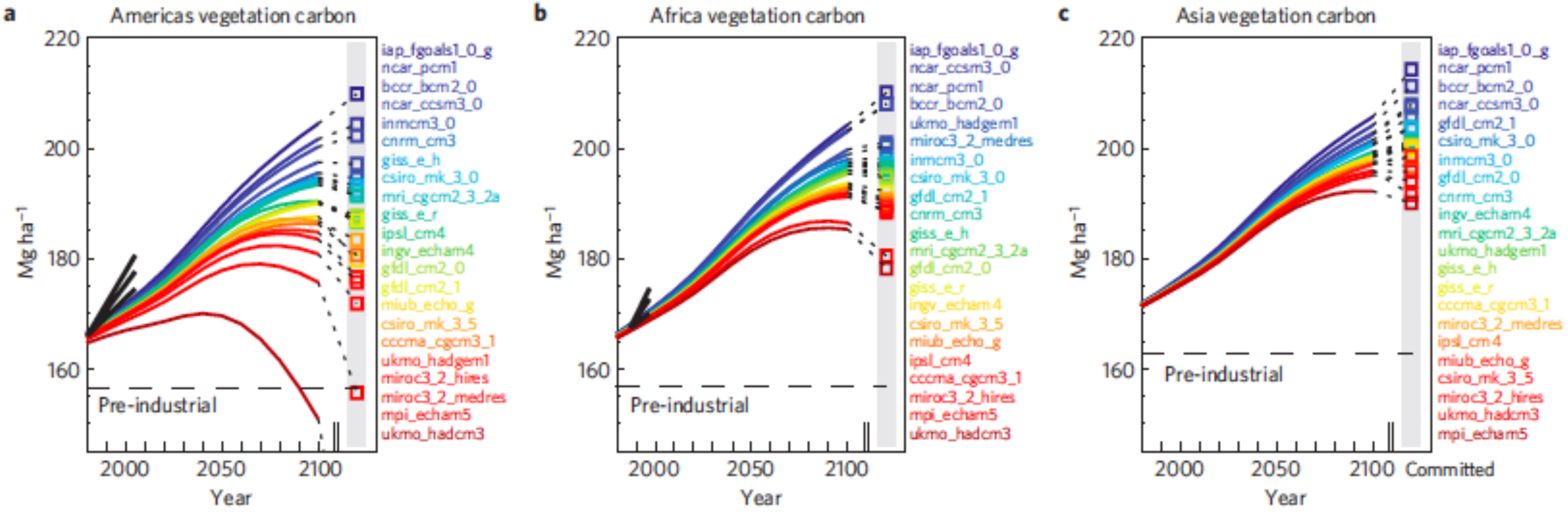
SHE CV

Difference 1860 to 2099. Driven with climate-carbon-cycle coupling.

Figures from Sitch et al. (2008)

Projecting the global carbon cycle: Mortality

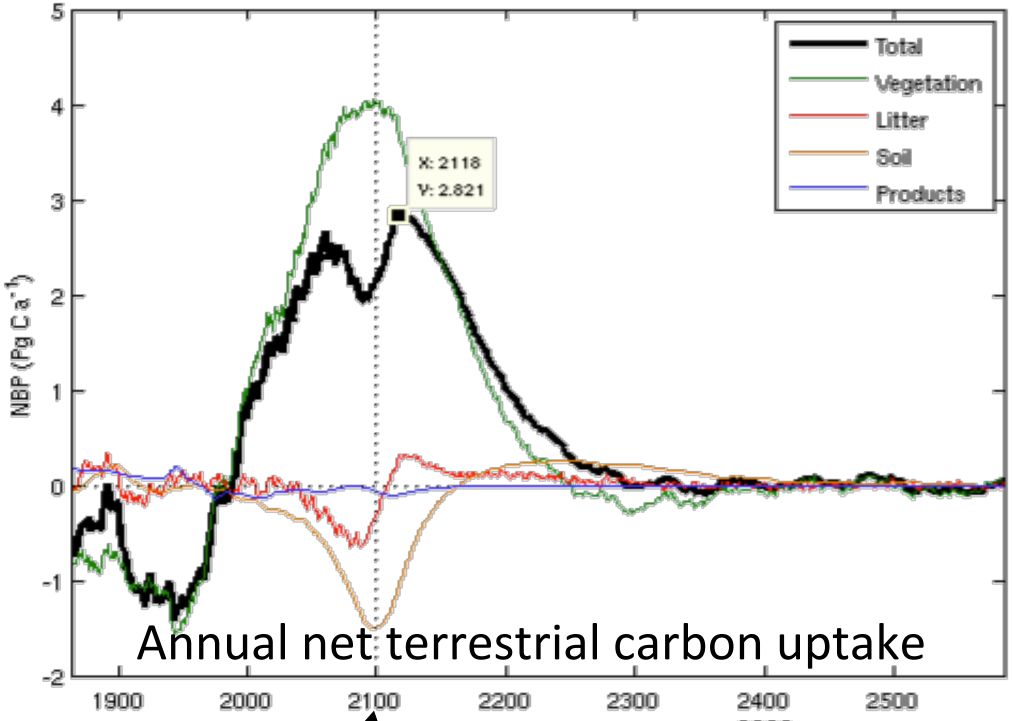
Or robust tropical forests?



TRIFFID model forced with climates from a range of GCMs. Only one climate realisation resulted in a loss of carbon.

Figures from Huntingford et al. (2013)

Projecting the global carbon cycle: Lags



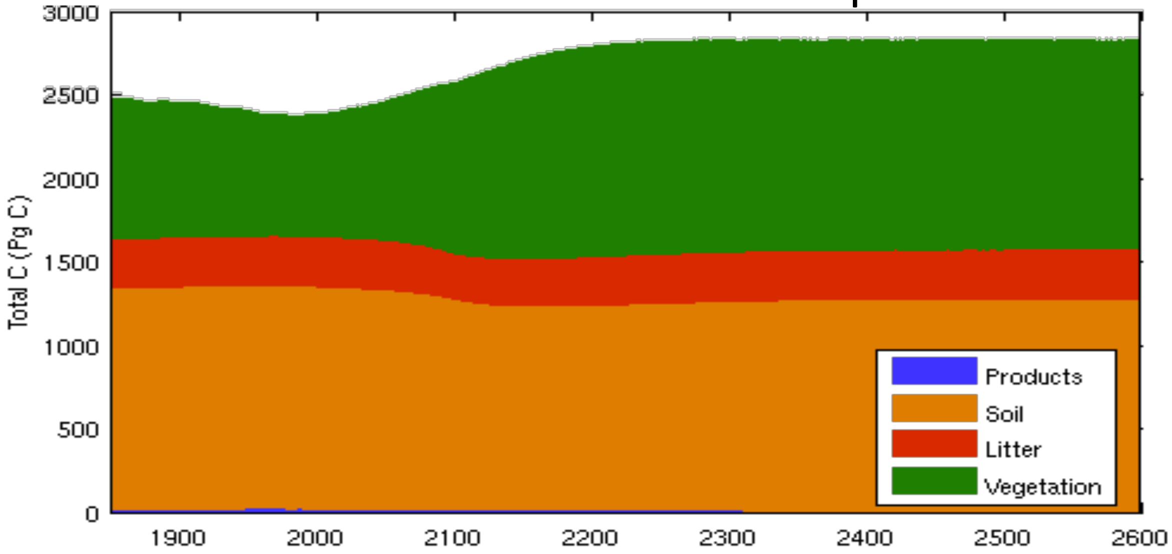
Annual net terrestrial carbon uptake

Changes in many aspects of the terrestrial biosphere are not quasi-instantaneous.
They show significant lags.
Whilst photosynthesis and respiration rates may respond rapidly, vegetation dynamics and soil carbon pools adjust over much longer timescales.

Climate fixed at 2100

LPJ-GUESS run with EC-Earth
RCP 8.5 climate and [CO_2]

Total terrestrial biospheric carbon



Summary and implications

- A lack of appropriate observations means that we must rely on models to understand the overall role of the land biosphere in the carbon cycle.
- These models attempt to capture the key processes, but in order to be applied at the global scale they adopt highly simplified process representations
- Models generally project a strong take up of carbon by the terrestrial biosphere under environmental change. However, they don't universally agree on this, and there are many uncertainties, relating to both explicitly resolved processes and to missing processes (e.g. peatlands).
- As you will see in the coming talks, these changes in natural vegetation properties under environmental change mean that calculations of human impacts based on the current land system may not hold in the future.
  - E.g. The tropical forest may be a much large C store in the future, making it even more important than it is now for keeping C out of the atmosphere. Or it may dieback anyway, meaning that todays deforestation emissions would occur naturally in the future anyway.

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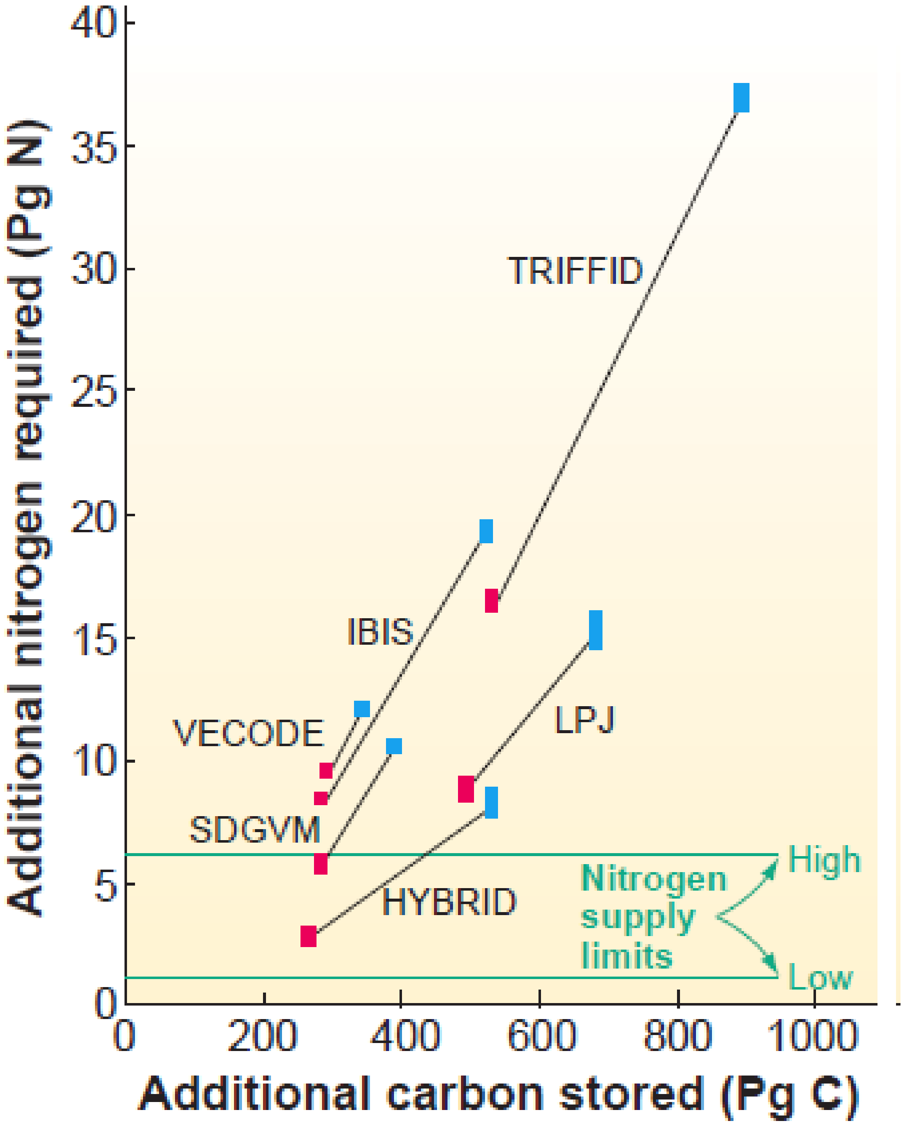
Projecting the global carbon cycle: Nutrient limitation



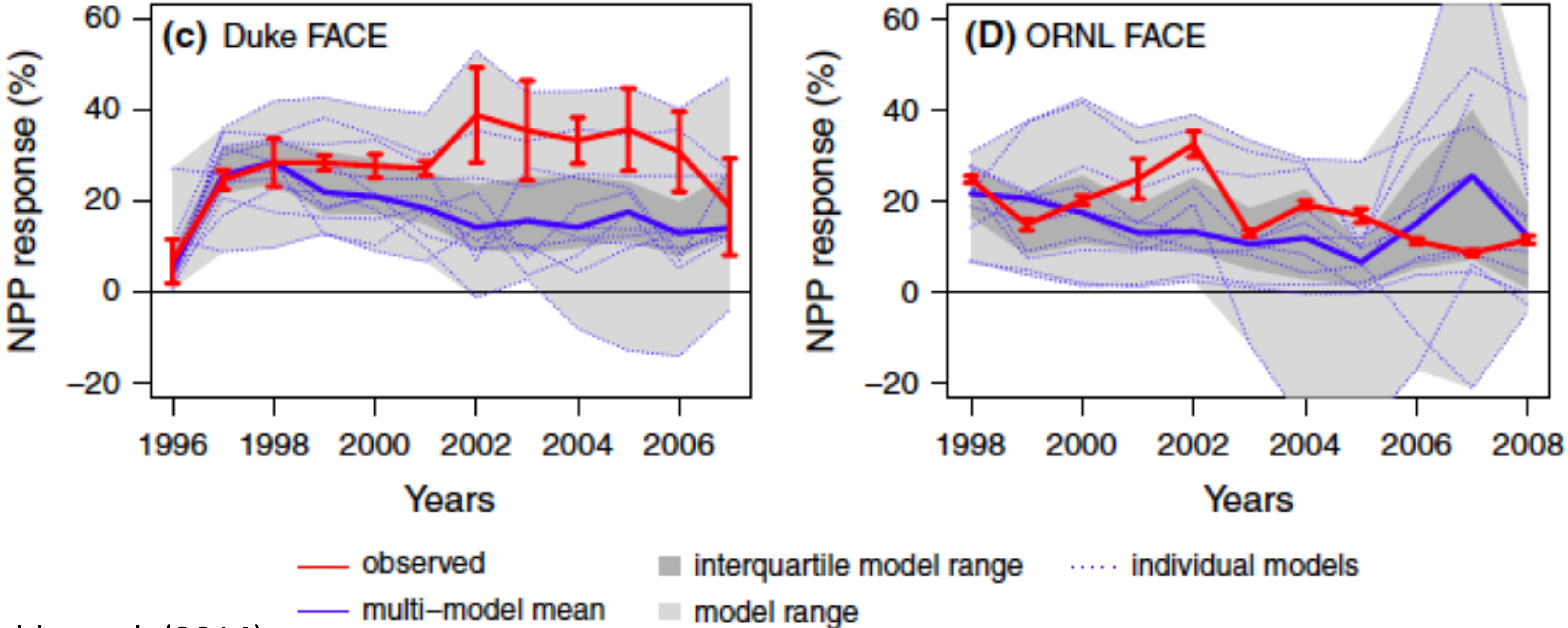
Must take results from models without nutrient constraints with a pinch of salt...

Hungate et al. (Science, 2003)

Projecting the global carbon cycle: Nutrient limitation

FACE experiments differ their long-term response to elevated [CO_2]

Must take results from models without nutrient constraints with a pinch of salt...



Zaehle et al. (2014)

Projecting the global carbon cycle: Feedbacks

Biogeochemical feedbacks

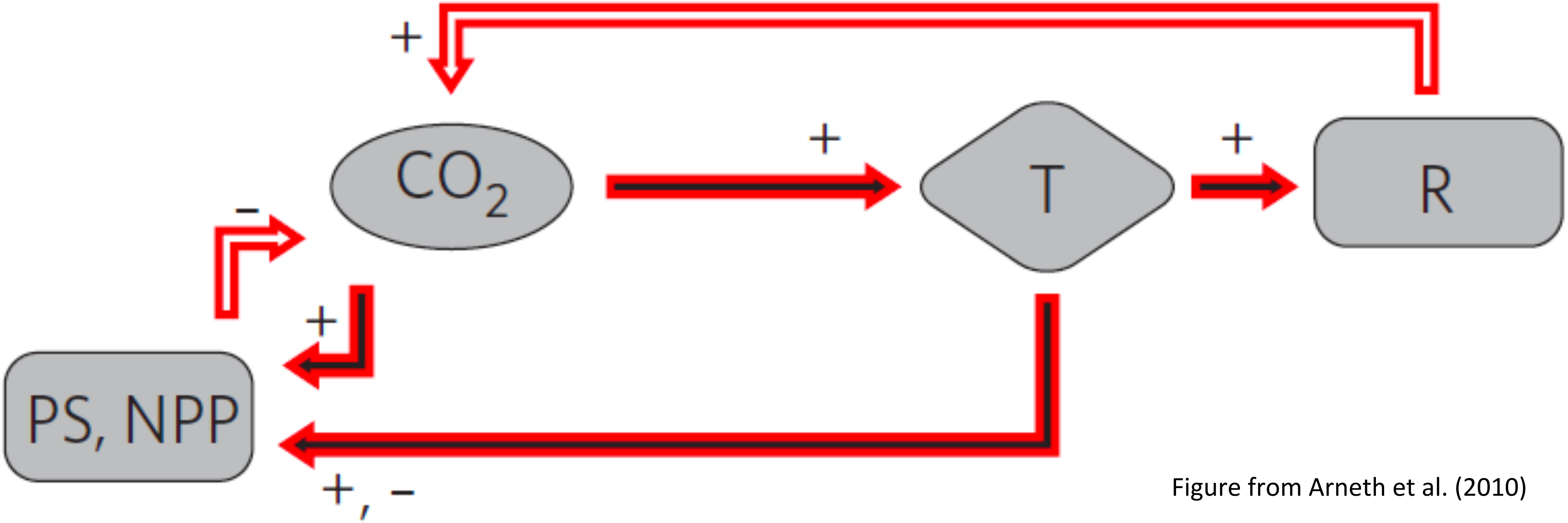


Figure from Arneth et al. (2010)

Many other feedbacks exist
Further reading: Arneth et al. (2010)