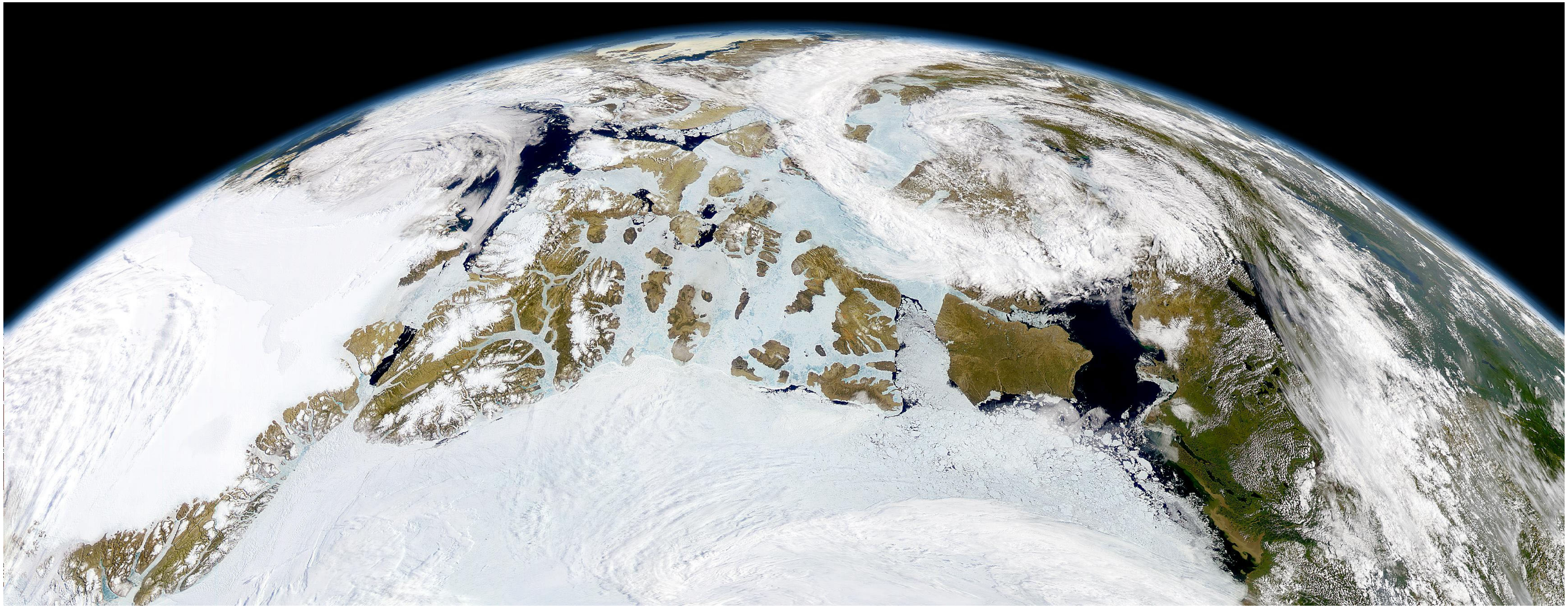
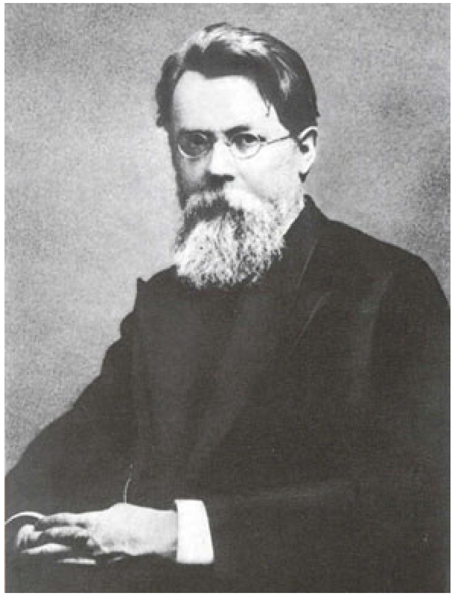


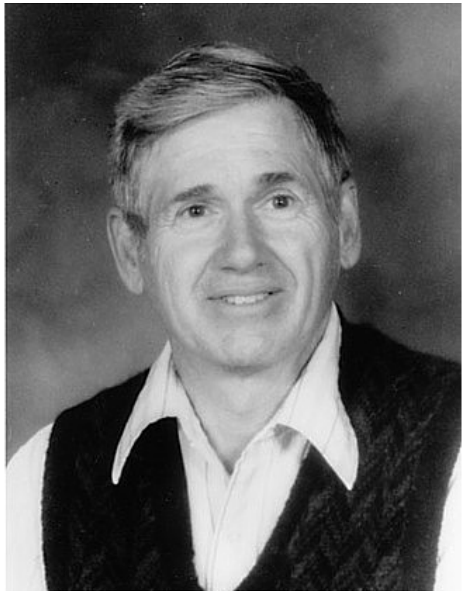
# Carbon cycle and global vulnerability

*Wolfgang Lucht* Potsdam Institute for Climate Impact Research

Our guides will be 3 innovators in biogeochemistry (of course there are more!)



Vladimir I. Vernadski
1863 – 1945



Charles D. Keeling
1928 – 2005

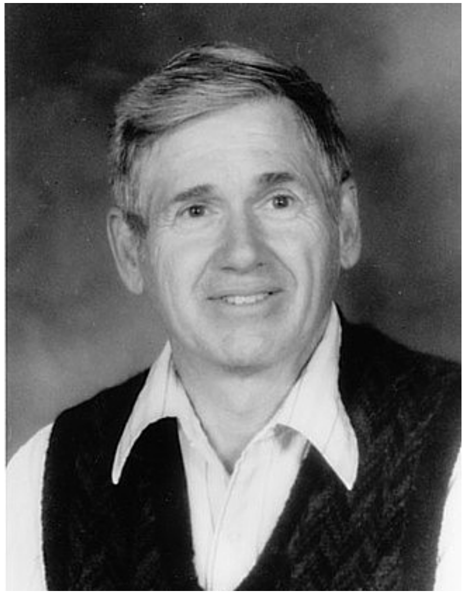
I. Colin Prentice
*1952

Biogeochemistry

Greenhouse Gas Increase

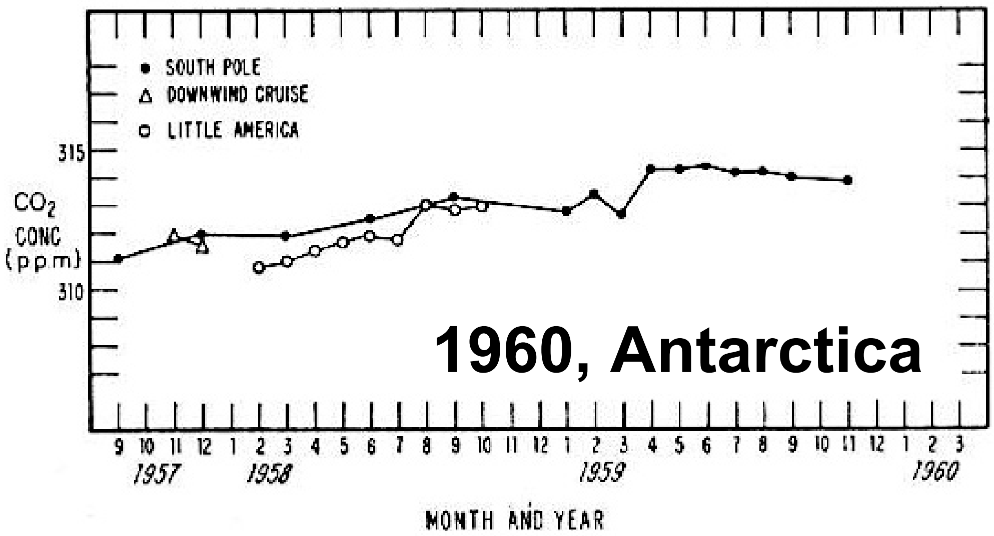
Biosphere Modelling

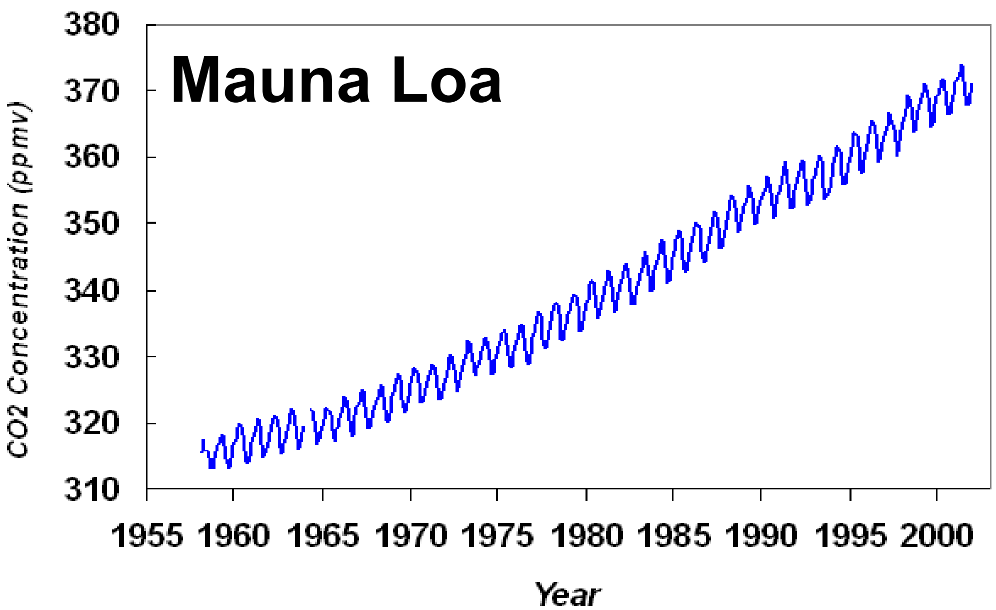
(And let there be no mistake: a lot of people were/are behind these guys.
But they did have some pretty good ideas.)

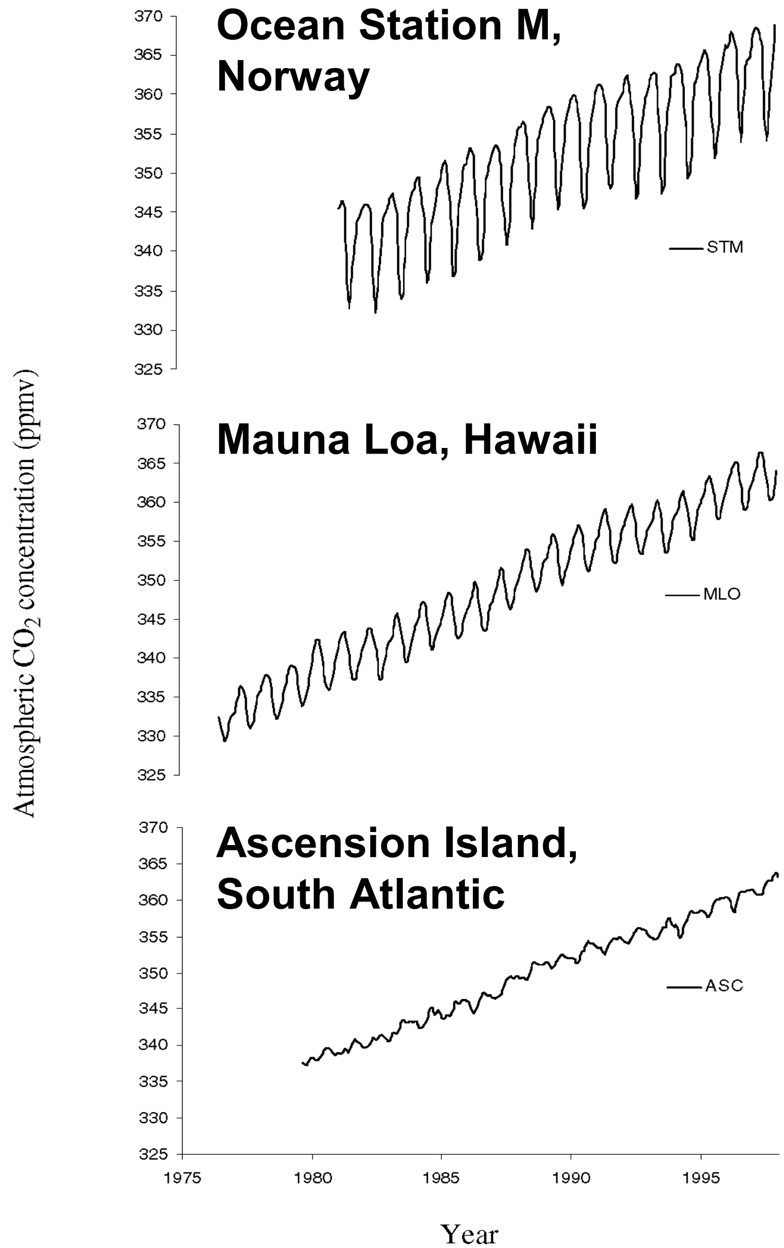


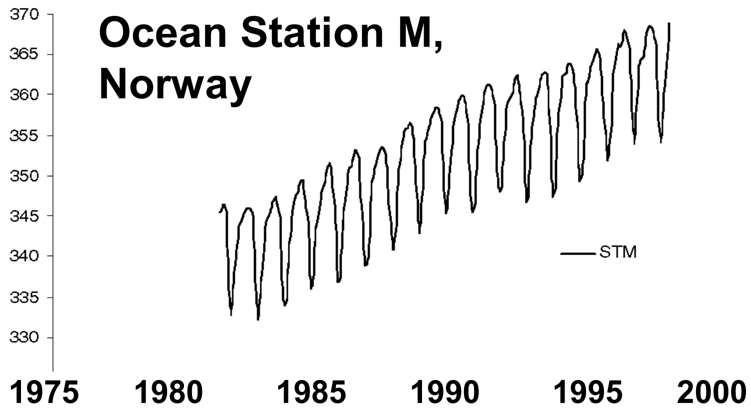
Guiding Spirit for this section:
Charles D. Keeling
1928 – 2005

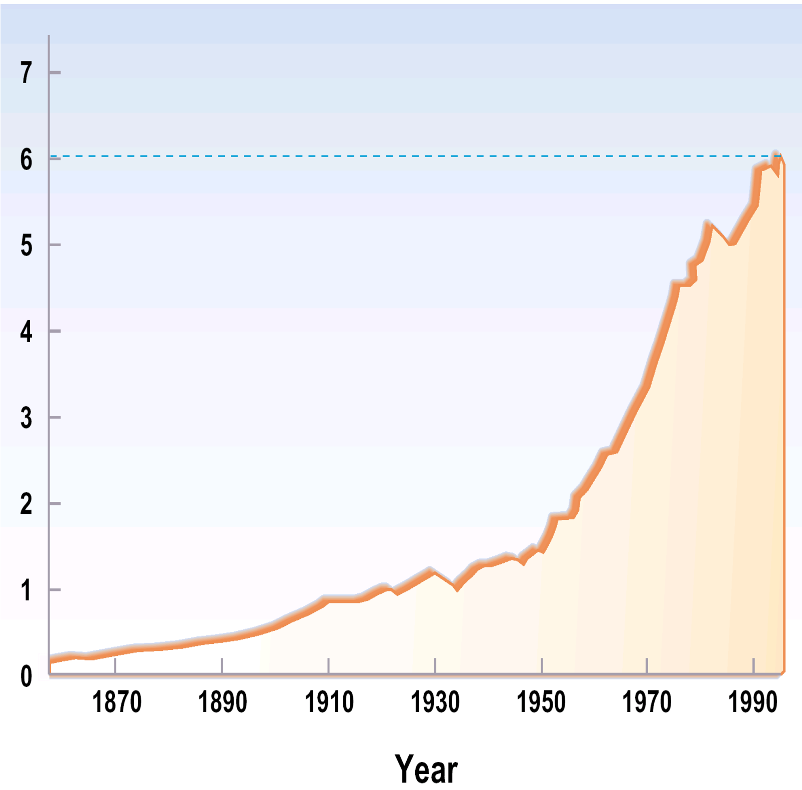
# - 1- Atmospheric Greenhouse Gas Increases and Global Climate Change


1960, Antarctica
SOUTH POLE
DOWNWIND CRUISE
LITTLE AMERICA
CO2 CONC (ppm)
315
310
9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3
1957 1958 1959 1960
MONTH AND YEAR


Mauna Loa
CO2 Concentration (ppmv)
380
370
360
350
340
330
320
310
1955 1960 1965 1970 1975 1980 1985 1990 1995 2000
Year


Atmospheric CO2 concentration (ppmv)
Ocean Station M, Norway
STM
Mauna Loa, Hawaii
MLO
Ascension Island, South Atlantic
ASC
370
365
360
355
350
345
340
335
330
325
1975 1980 1985 1990 1995
Year




# Rising Values of Atmospheric $CO_2$ Concentration

## Increase of atmospheric $CO_2$

1980-1989: 3.3 ± 0.1 GtC/yr

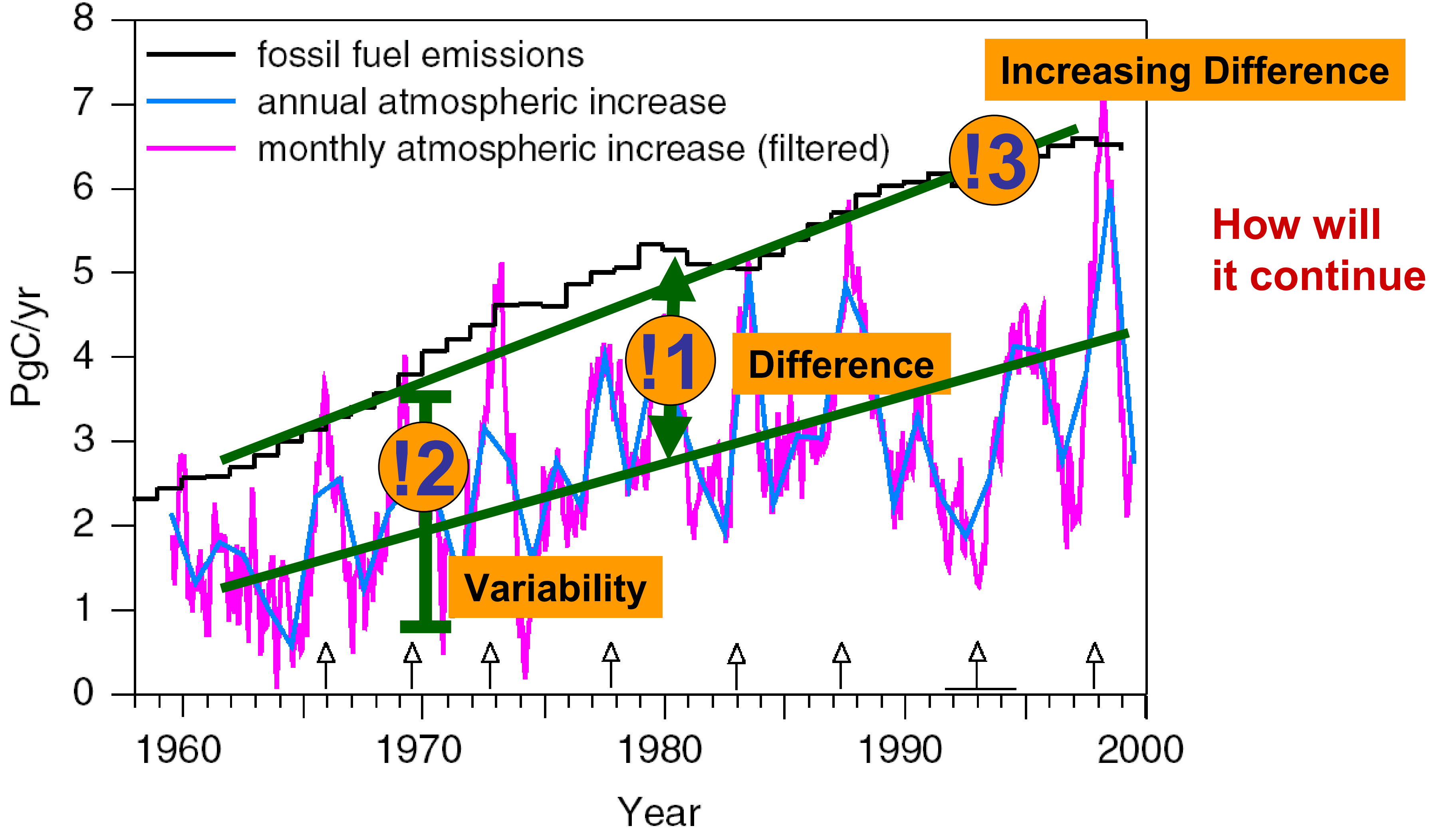
1990-1999: 3.2 ± 0.1 GtC/yr

## Fossil fuel emissions

1980-1989: 5.4 ± 0.3 GtC/yr

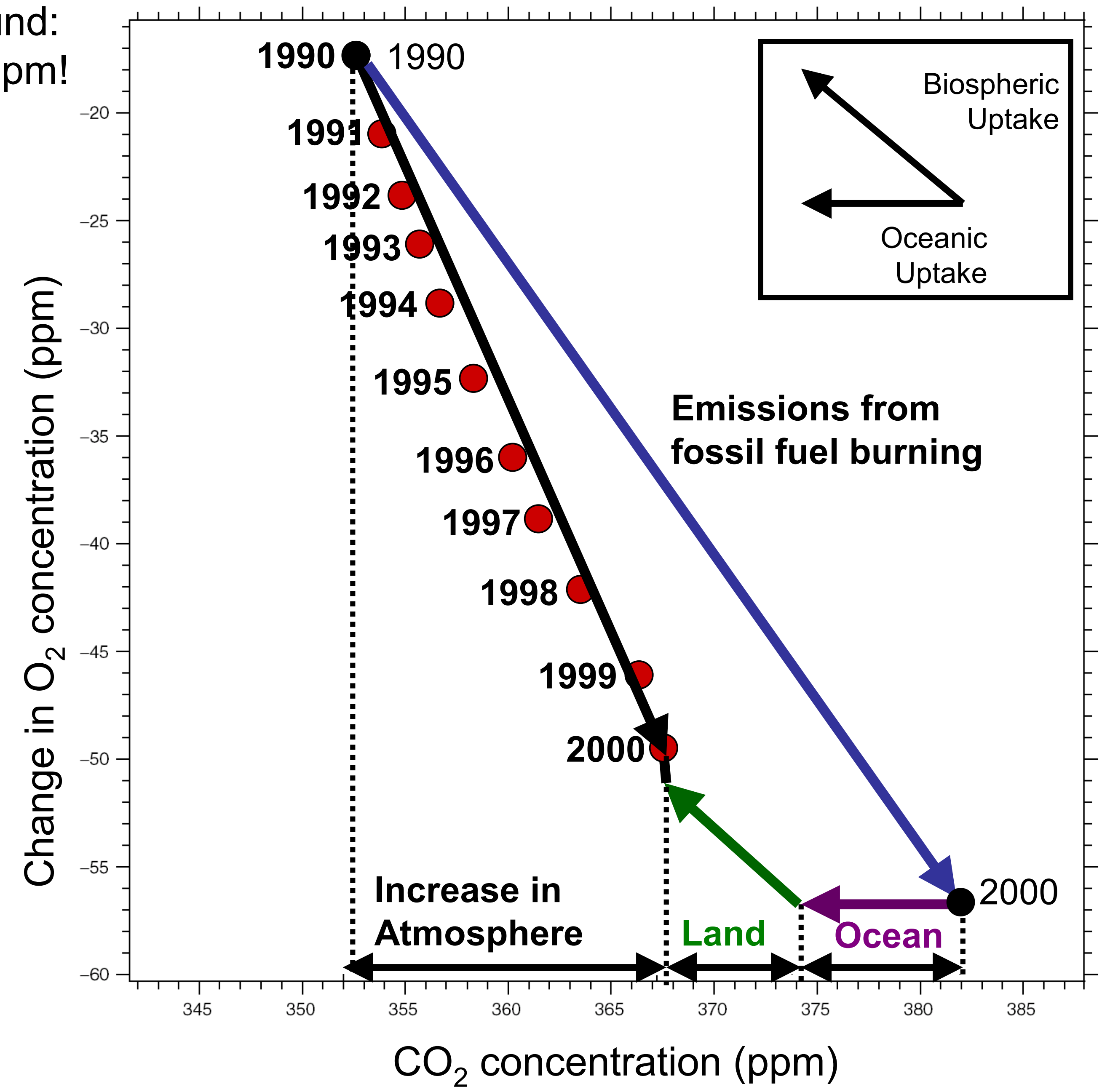
1990-1999: 6.4 ± 0.4 GtC/yr

# Yearly increase of atmospheric $CO_2$ concentration




How will it continue?

Background:
209000 ppm!



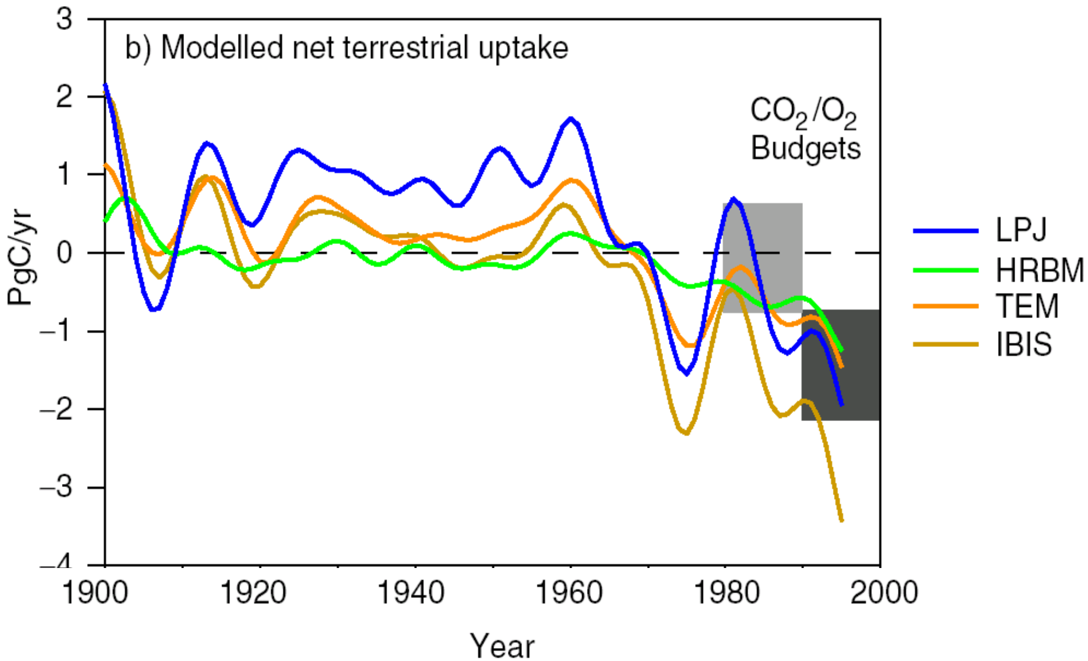

***A key question:***

**Where does the missing carbon go?**

**Onto the land or into the ocean?**

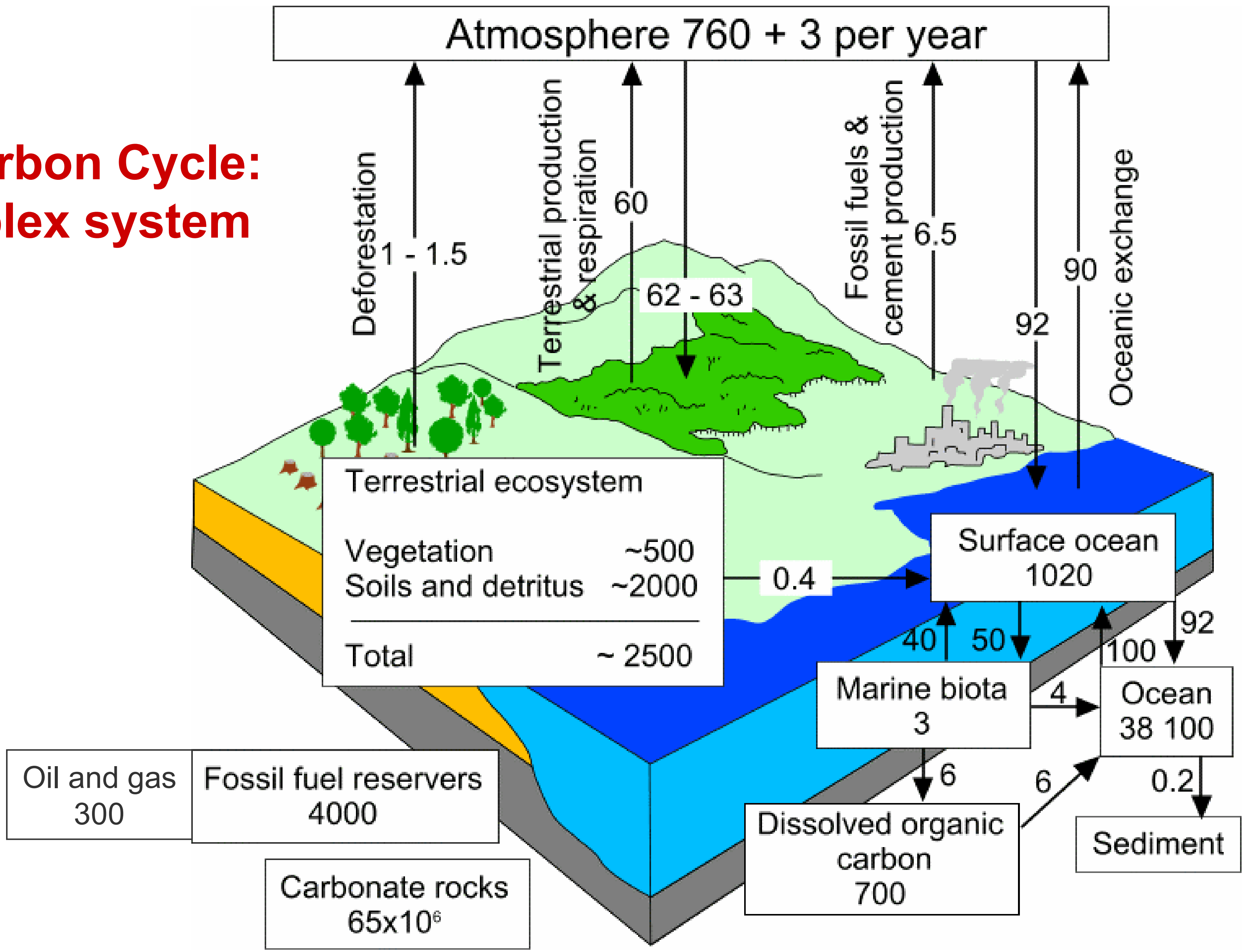
# Global Carbon Balance of the 1990ies (GtC/yr)

| Increase Atmosphere | = | Fossil Fuel Emissions | - | Land Uptake | - | Ocean Uptake |
|---|---|---|---|---|---|---|
| **3.2** | | **6.3** | | **1.4** | | **1.7** |

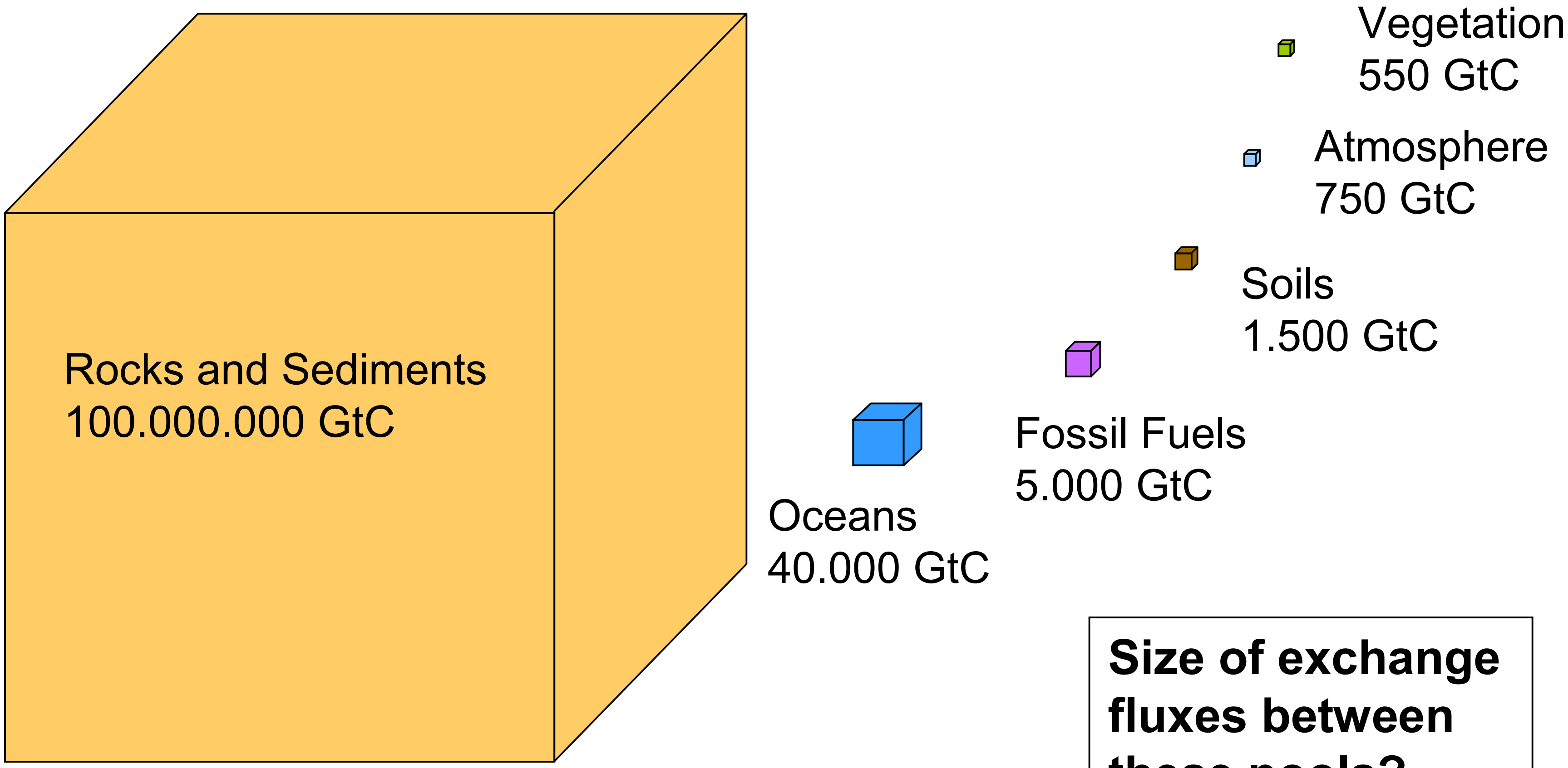



| Deforestation | | Inferred C Sink |
|---|---|---|
| **-1.6** | + | **3.0** |

# The Carbon Cycle: a complex system

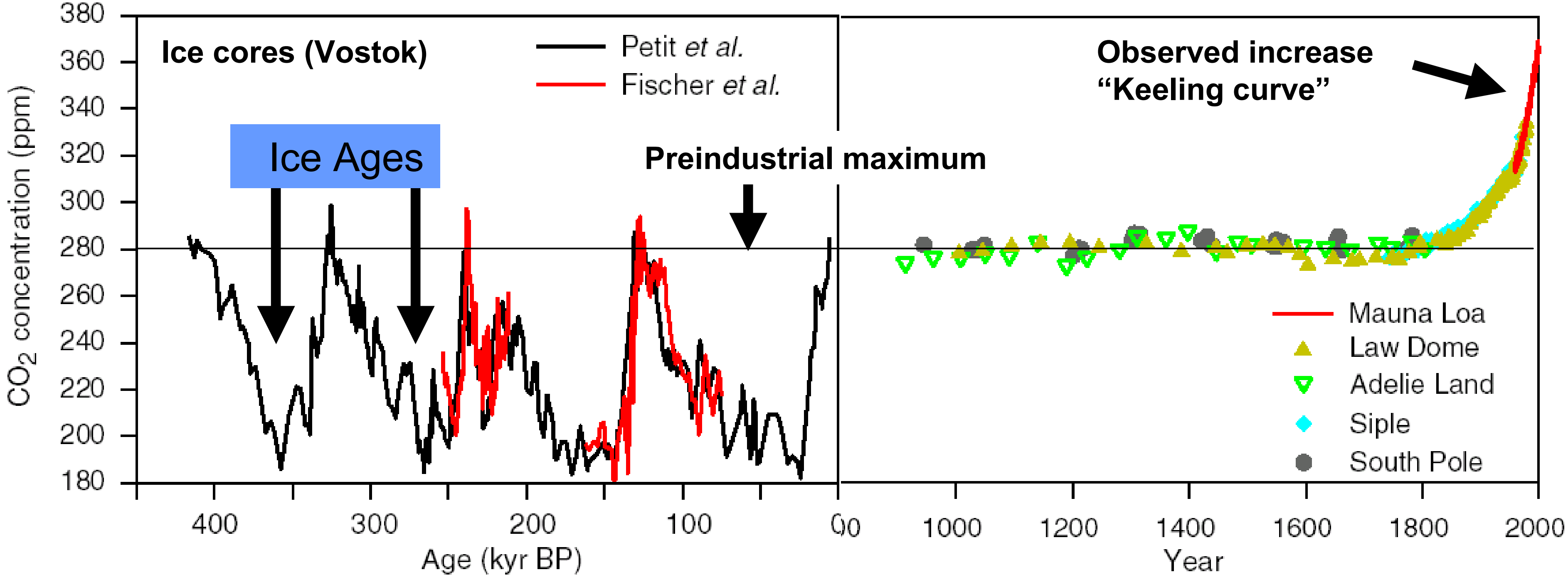


# Where is the Carbon? Sizes of Pools




**Size of exchange fluxes between these pools?**

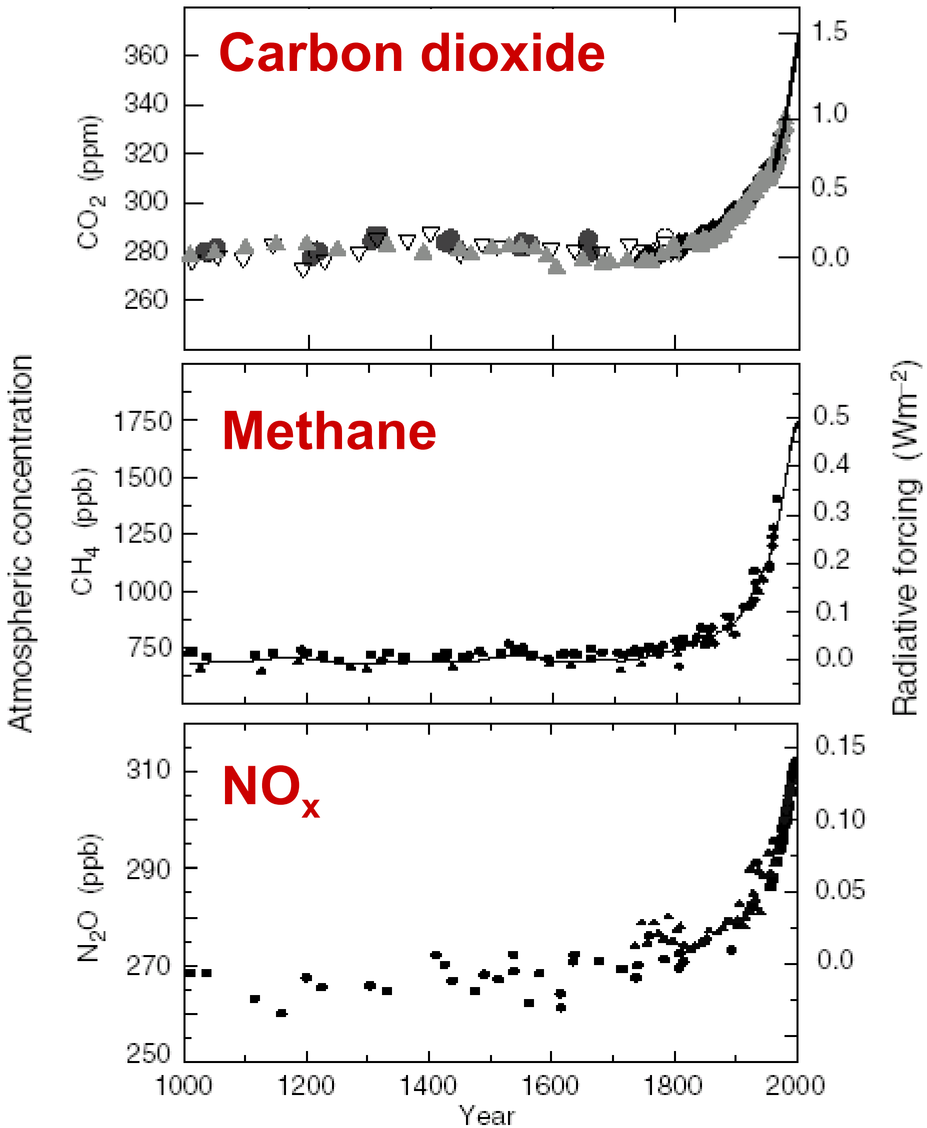
# Variations of atmospheric $CO_2$ concentration in Earth history

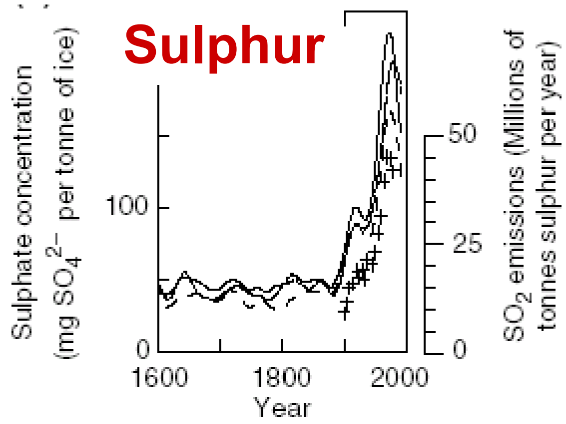


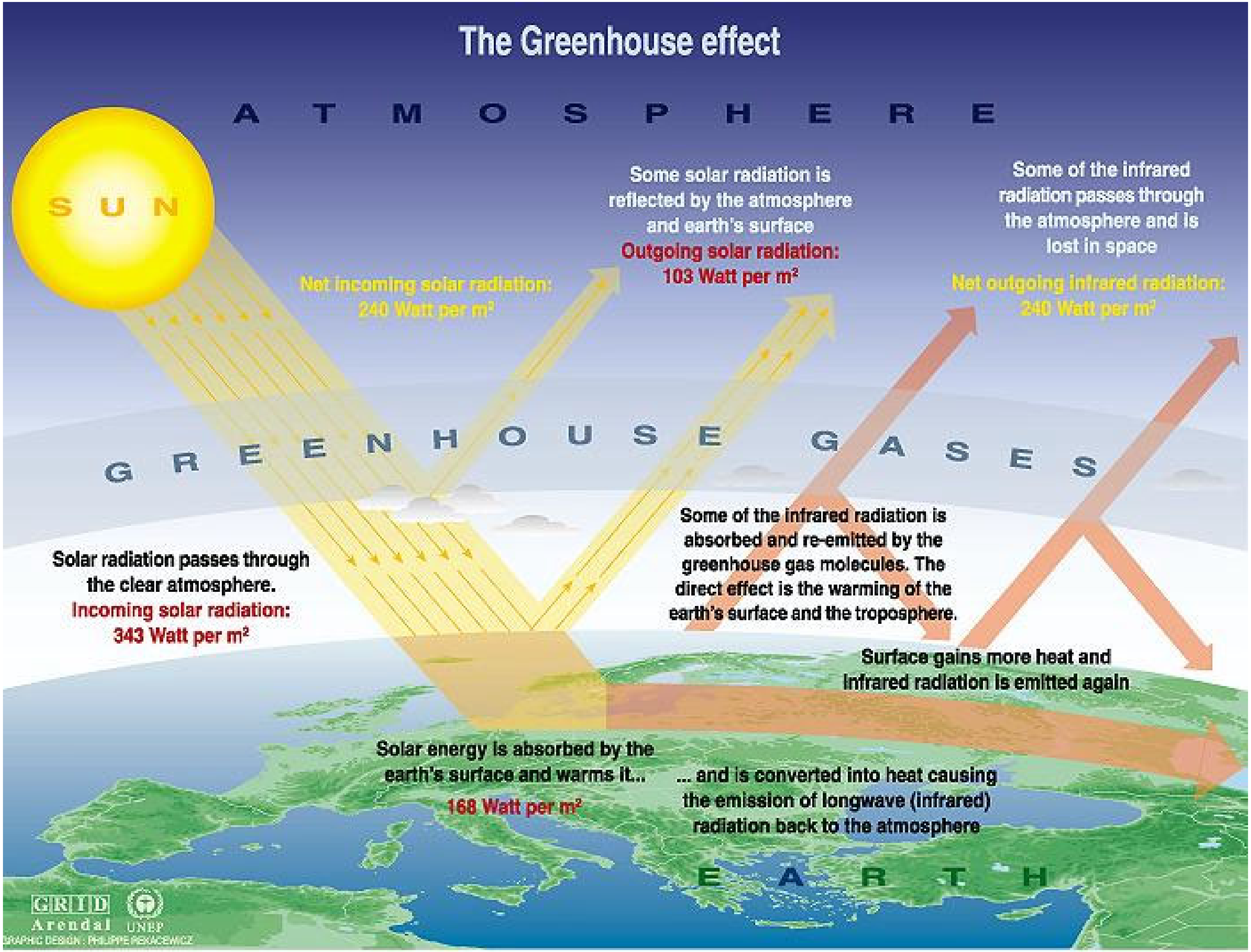

**Current $CO_2$ levels are without example in the last 20 000 000 years**

**Until ca. 1850: 280 ppmv**
**Today: 370 ppmv**
**Future: 550 … 800 … 1000 ppmv?**

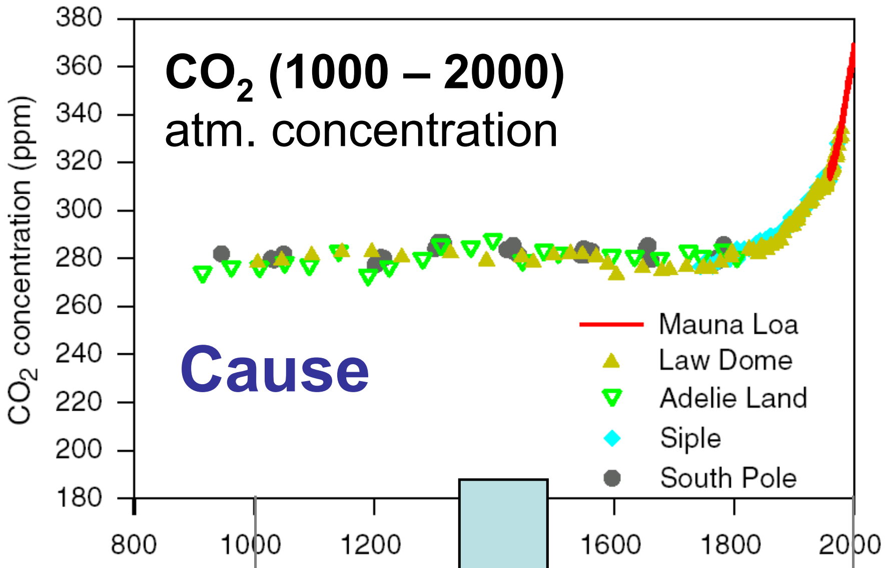
IPCC WG I, Ch. 3, 2001


Carbon dioxide
Methane
NOx
Atmospheric concentration
CO2 (ppm)
CH4 (ppb)
N2O (ppb)
Radiative forcing (Wm-2)
Year

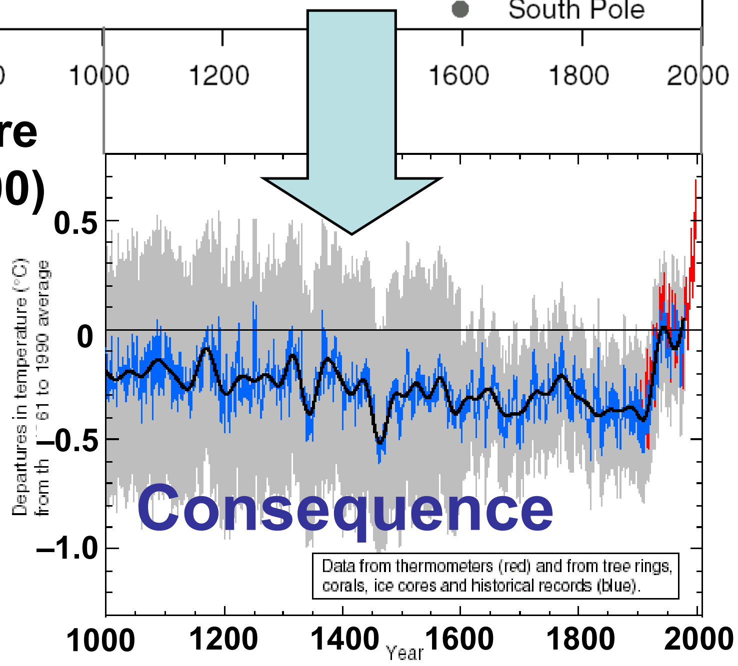

Sulphur
Sulphate concentration (mg SO42- per tonne of ice)
SO2 emissions (Millions of tonnes sulphur per year)
Year

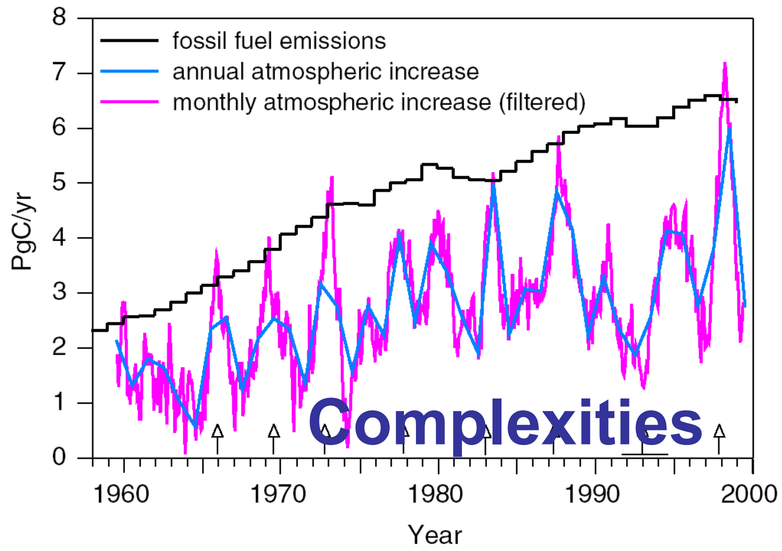

The Greenhouse effect
ATMOSPHERE
SUN
Some solar radiation is reflected by the atmosphere and earth's surface
Outgoing solar radiation: 103 Watt per m²
Some of the infrared radiation passes through the atmosphere and is lost in space
Net incoming solar radiation: 240 Watt per m²
Net outgoing infrared radiation: 240 Watt per m²
GREENHOUSE GASES
Some of the infrared radiation is absorbed and re-emitted by the greenhouse gas molecules. The direct effect is the warming of the earth's surface and the troposphere.
Solar radiation passes through the clear atmosphere.
Incoming solar radiation: 343 Watt per m²
Surface gains more heat and infrared radiation is emitted again
Solar energy is absorbed by the earth's surface and warms it...
168 Watt per m²
... and is converted into heat causing the emission of longwave (infrared) radiation back to the atmosphere
EARTH
GRID Arendal
UNEP
GRAPHIC DESIGN : PHILIPPE REKACEWICZ

# Climate Change – Interactions in the Earth System



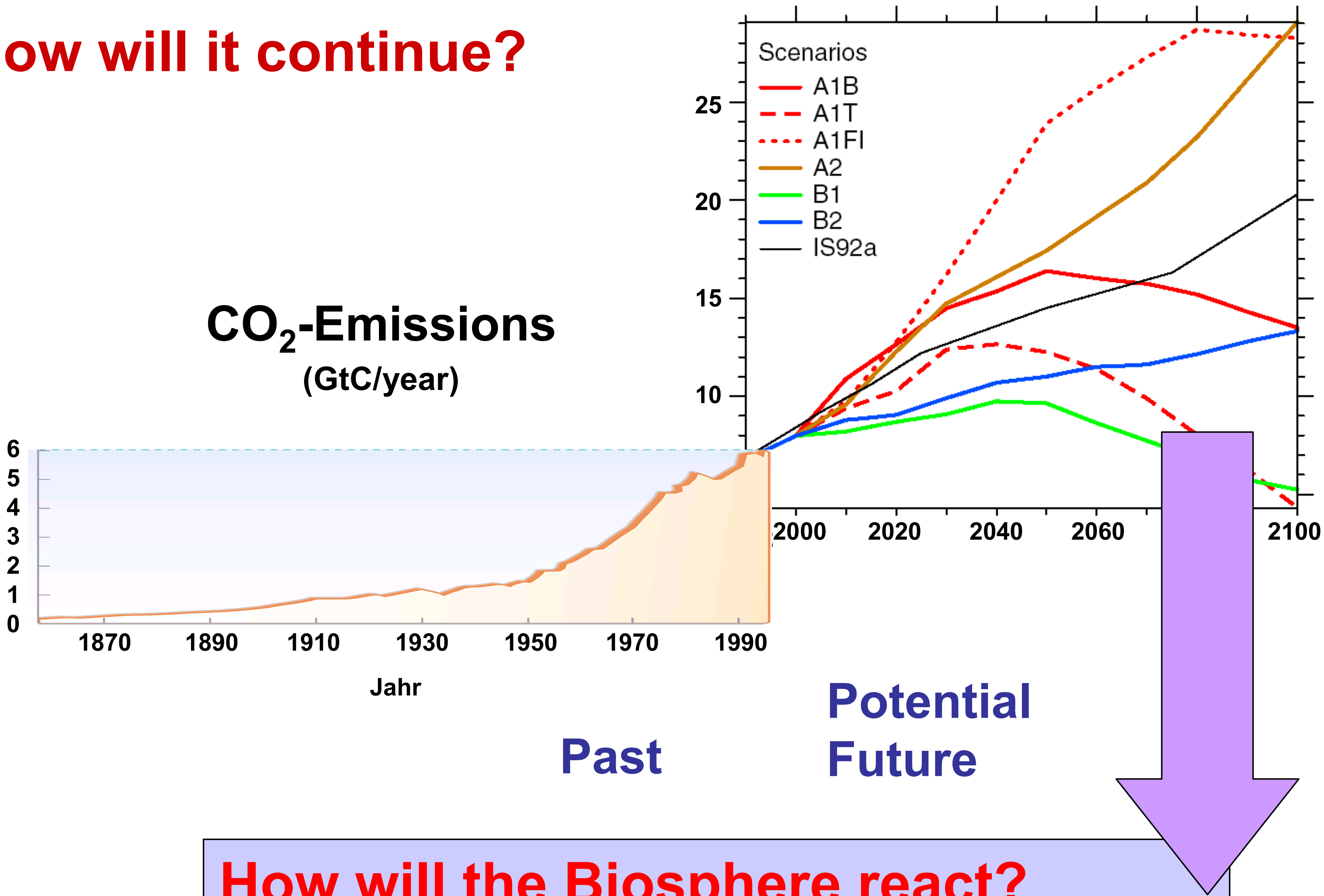

**Temperature (1000 – 2000)**
anomalies of the northern hemisphere



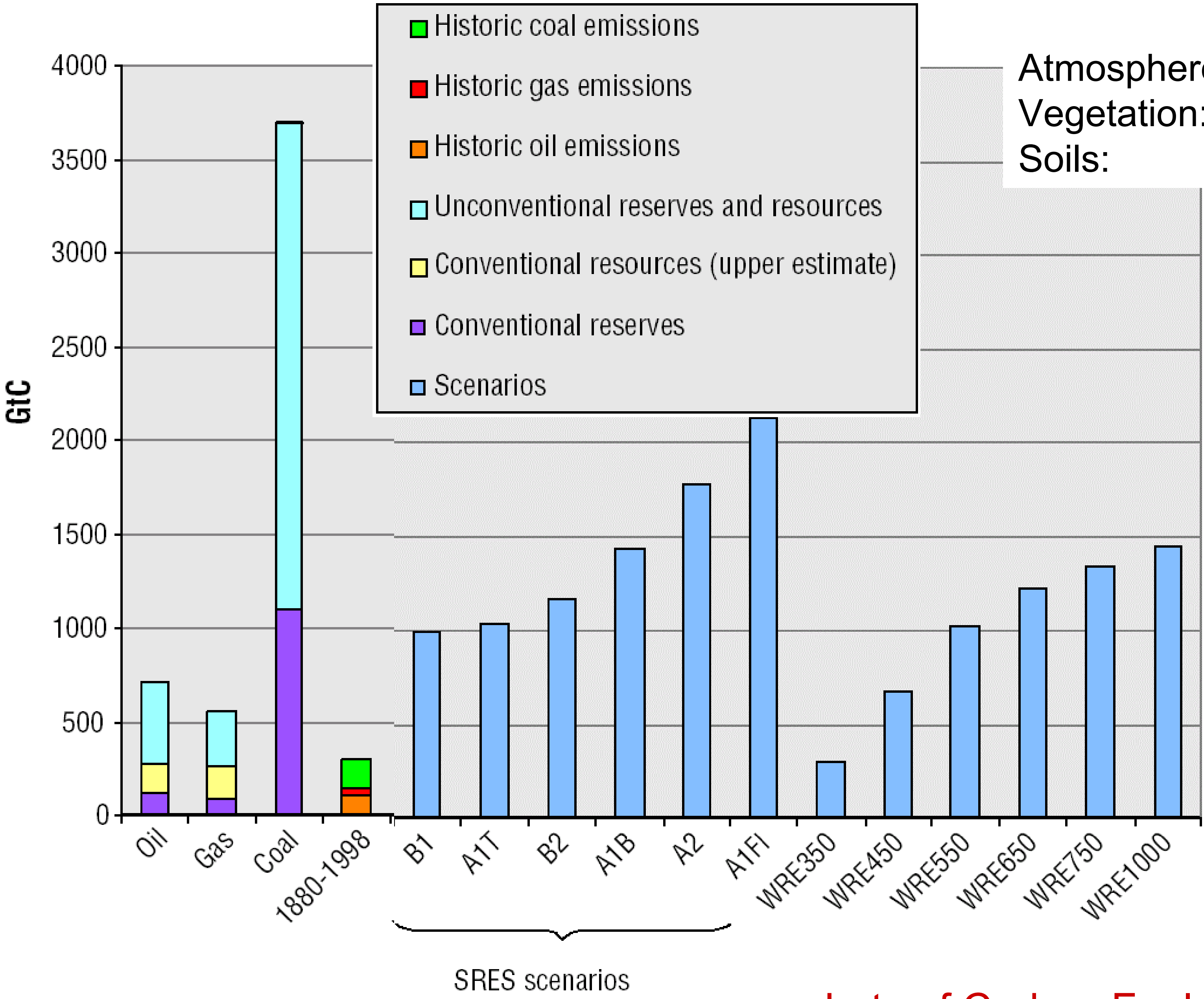




**$\Delta CO_2$ (1958 – 2000)**
Increase in the Atmosphere

# How will it continue?




How will the Biosphere react?
Will it continue to be sink of carbon?



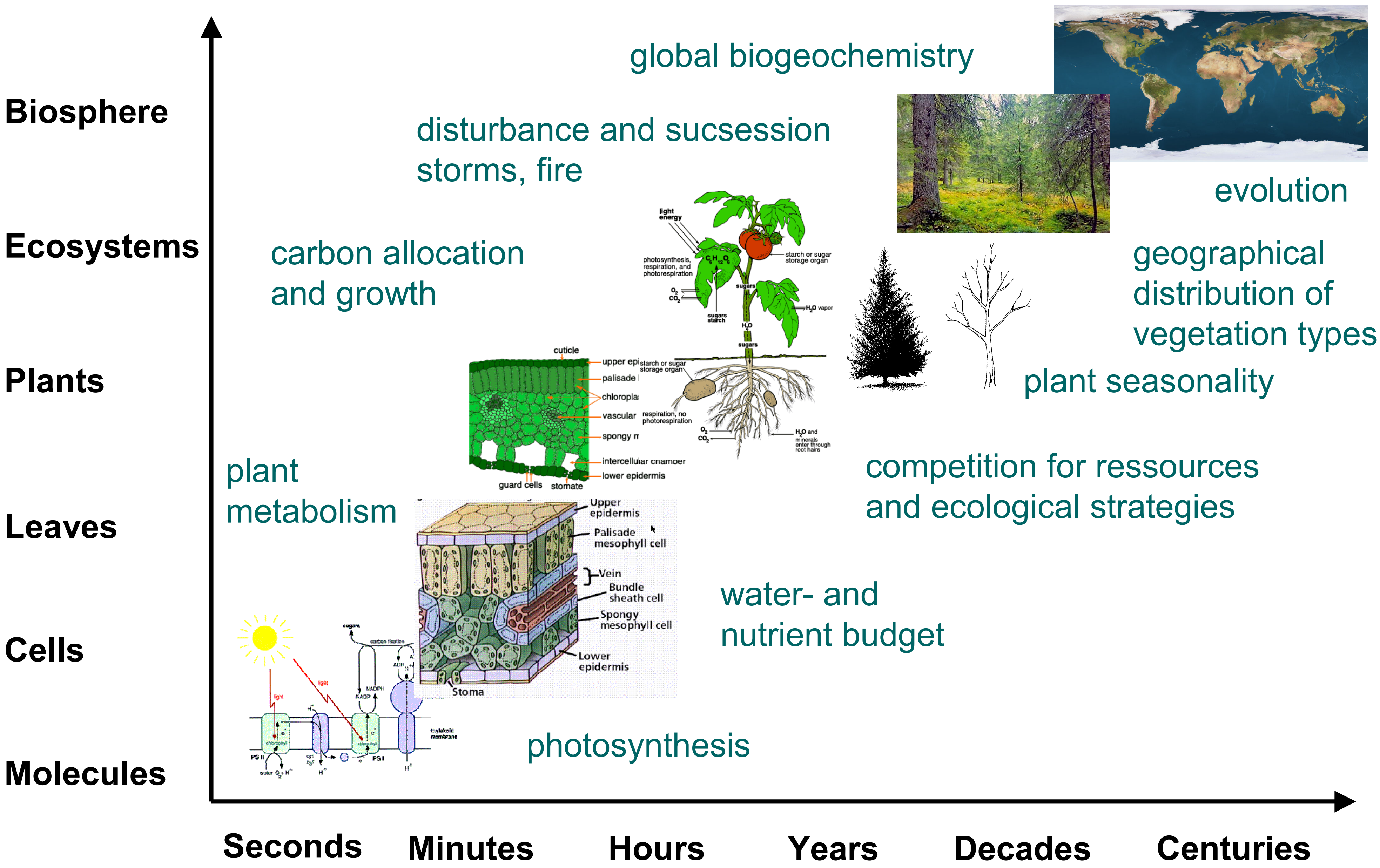

Atmosphere today: 760 GtC
Vegetation: 500 GtC
Soils: 1500 GtC

Lots of Carbon Fuel Reserves

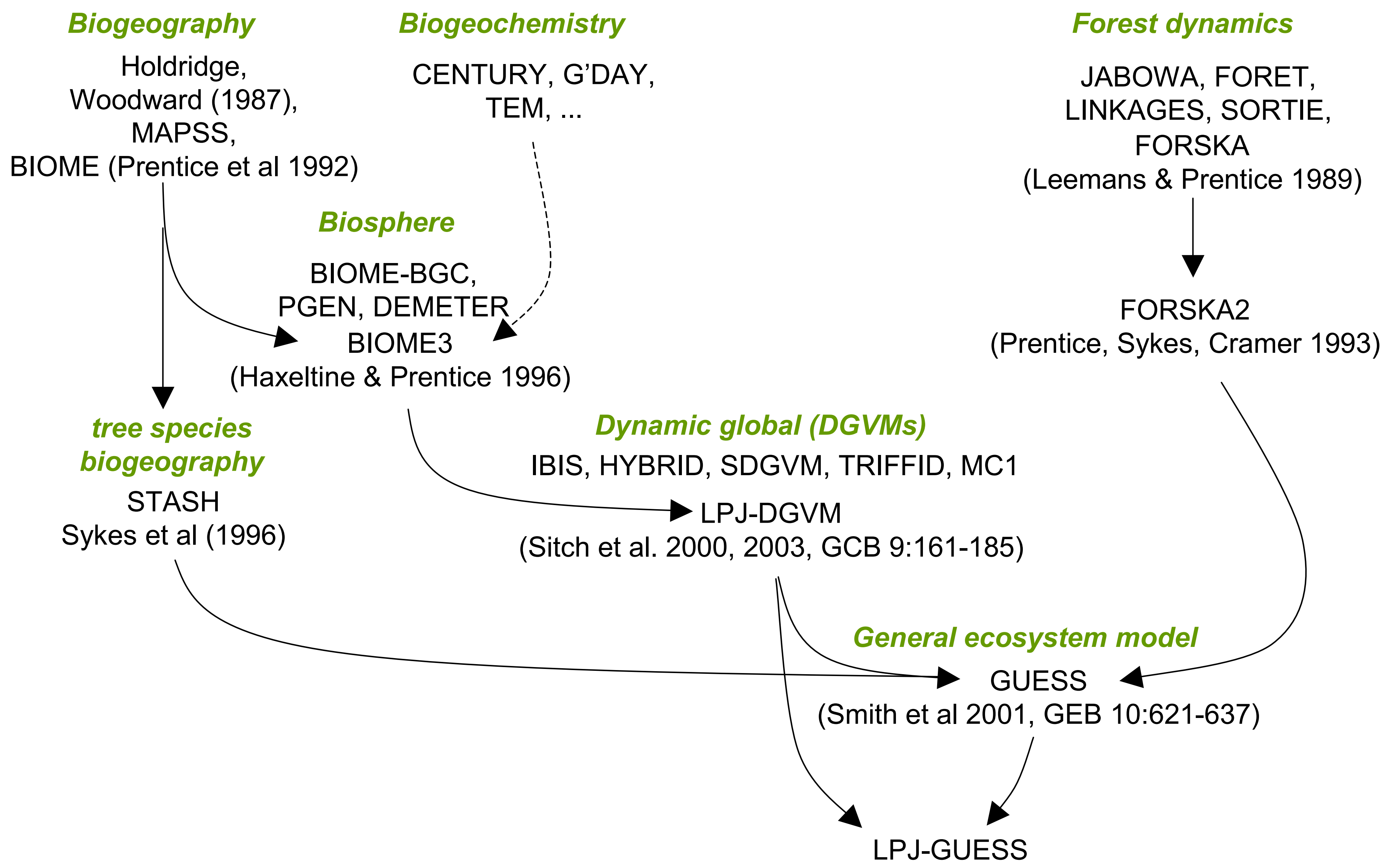
Guiding Spirit for this section:
I. Colin Prentice
*1952

# - 2 - Understanding the Terrestrial Carbon Cycle through Global Vegetation/Soil Modelling

# Interacting Scales in Biogeochemistry



# Historical Decendence of Some Ecosystem/Biosphere Models



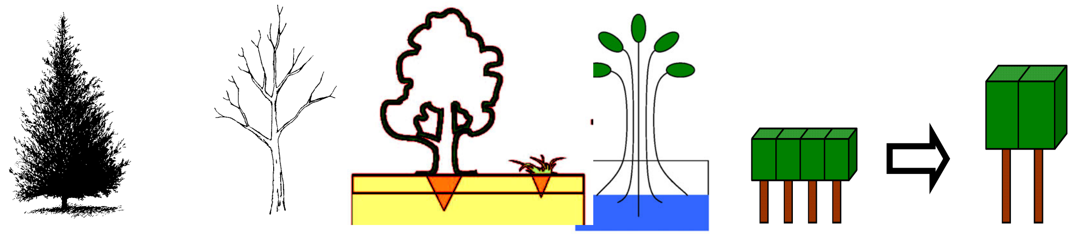
# LPJ

## Dynamic Global Vegetation Model LPJ-DGVM (Sitch et al., 2003)

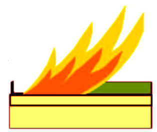
**Climate, Soil, $CO_2$**

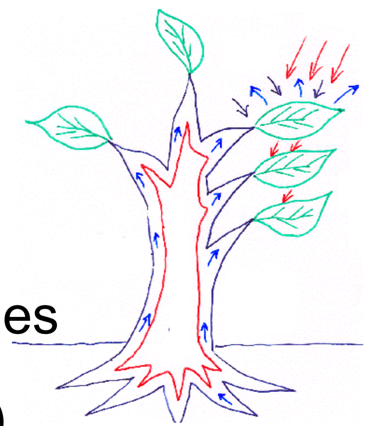
Space & Time Loops

**Transformed by process modules into**

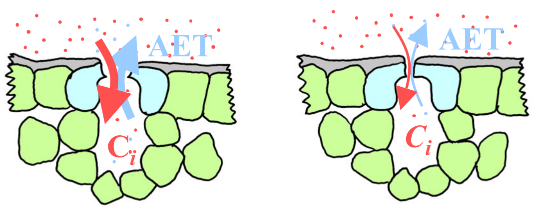


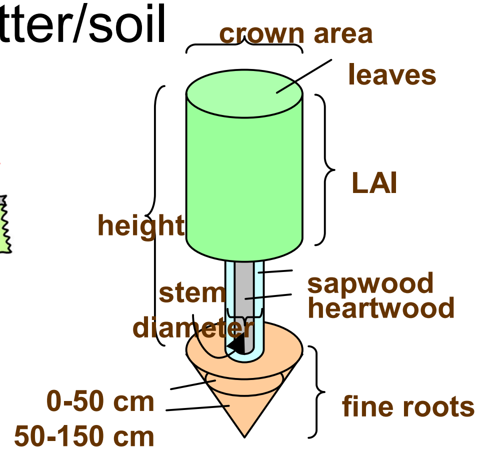
- 10 plant functional types
- competition, mortality, establishment
- fire, permafrost



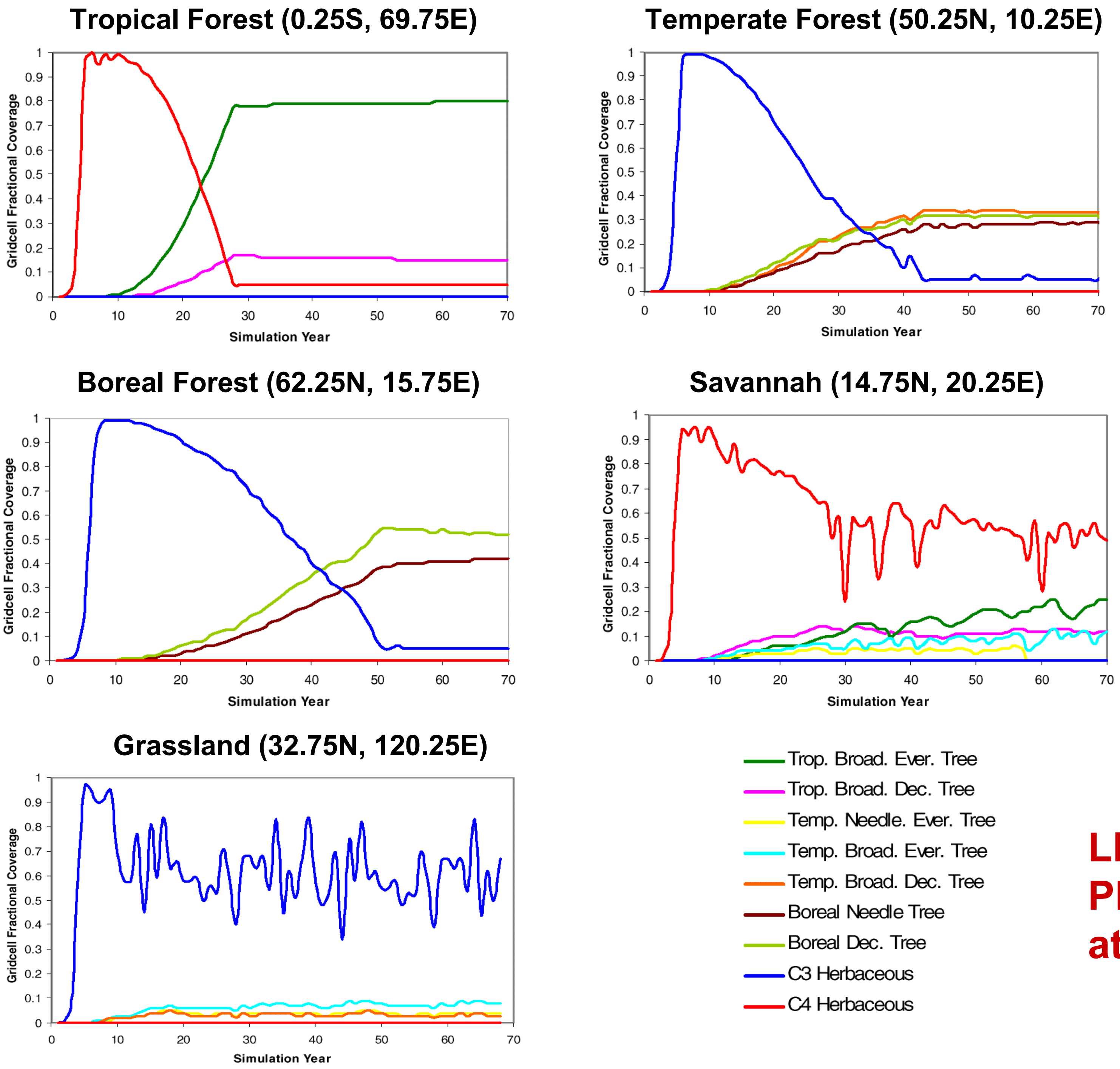


- photosynthesis: coupled C and $H_2O$ cycles
- C allocation (funct. and struct. relations)
- Carbon pools: 4 in vegetation, 4 in litter/soil
- Full hydrology



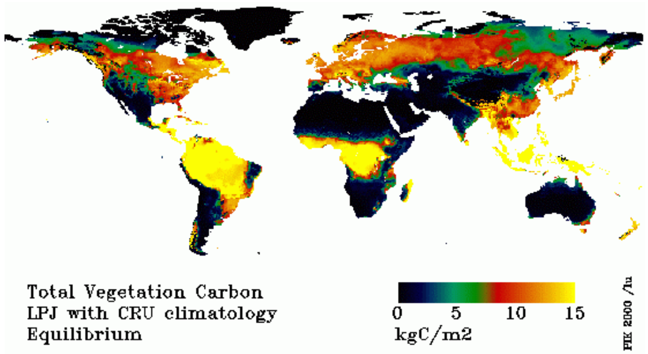




**C budget, $H_20$ Budget, Vegetation Composition**




# LPJ-DGVM: PFT Competition at Spin-Up

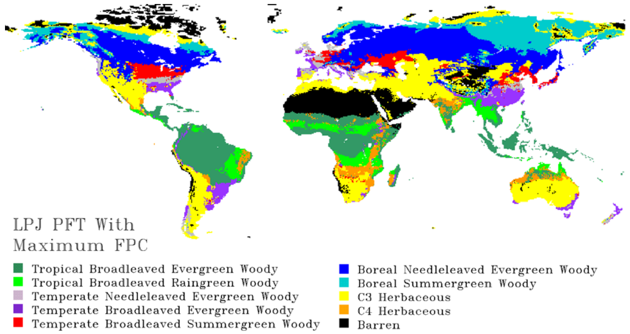
# LPJ Simulation Results

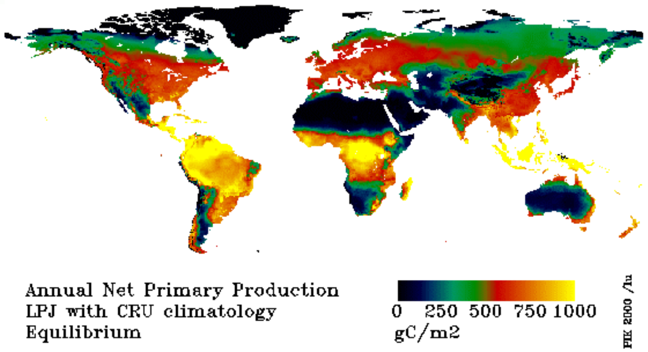



## Biomass

## Distribution of Vegetation Types

Sitch et al., GCB, 2003

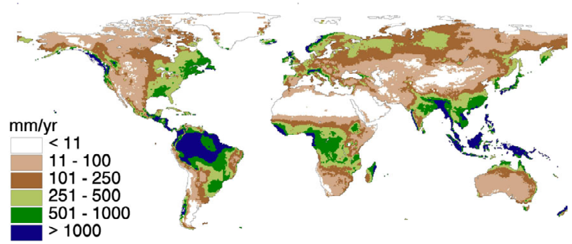


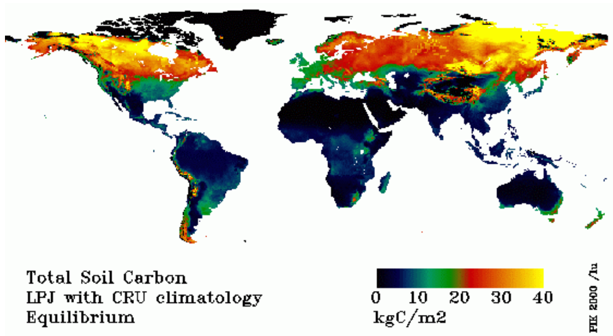




## Net Primary Production

## Runoff

Gerten et al., J. Hydrol., 2004

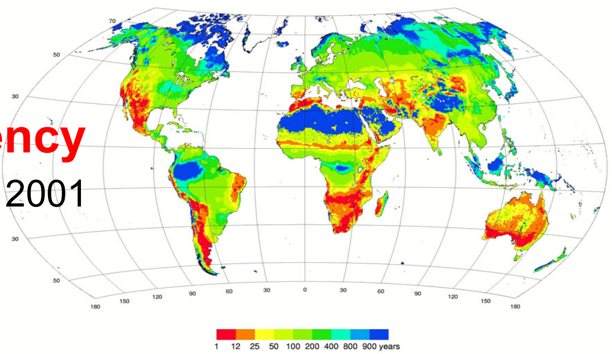


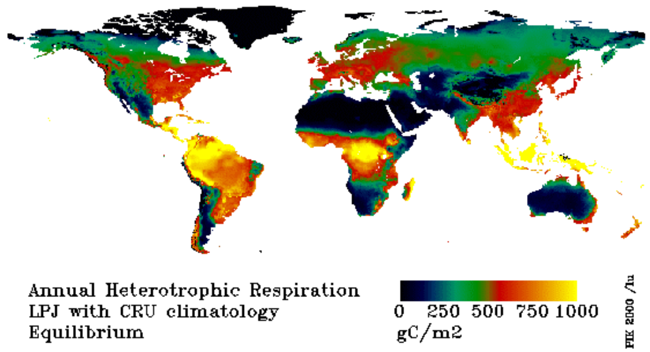




## Soil Carbon

## Fire Frequency

Thonicke et al., GCB, 2001

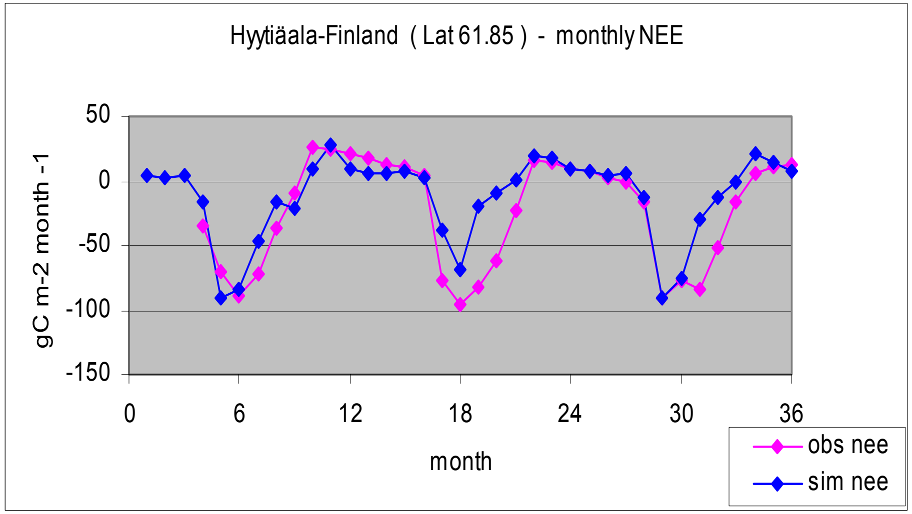


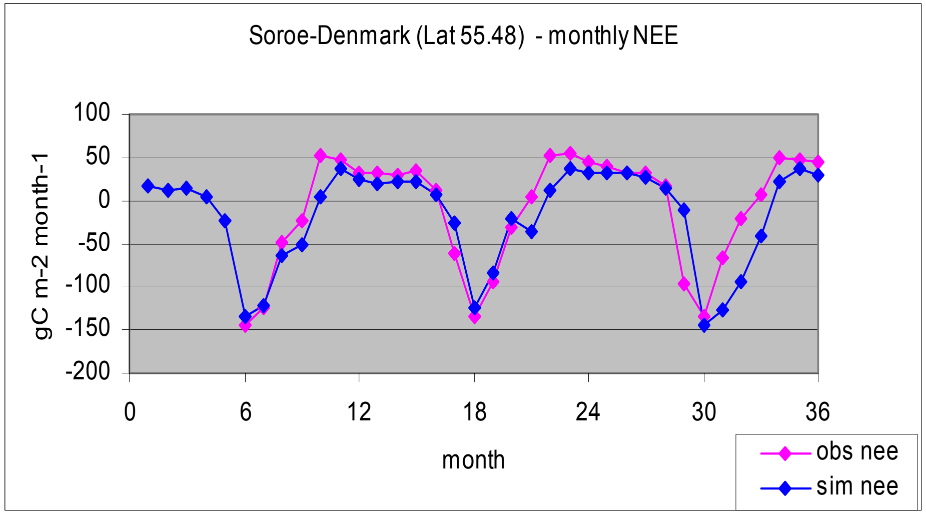



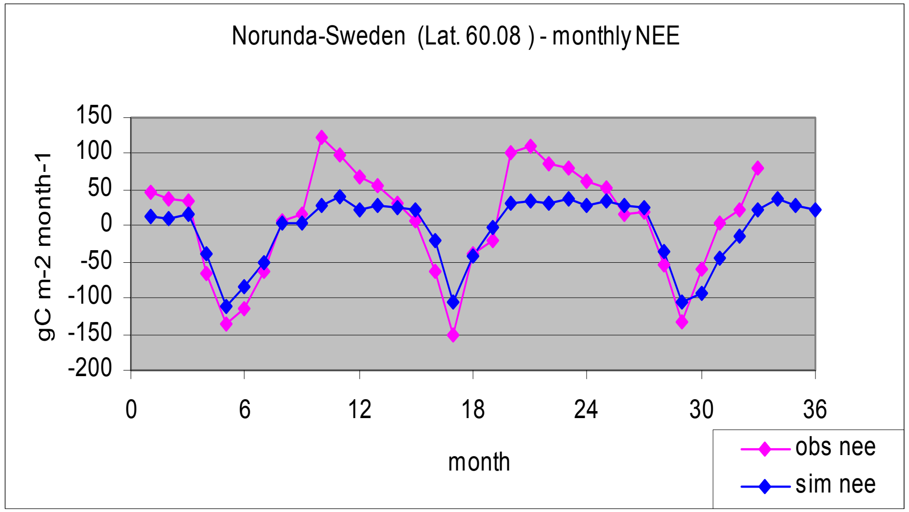

## Soil Carbon Change

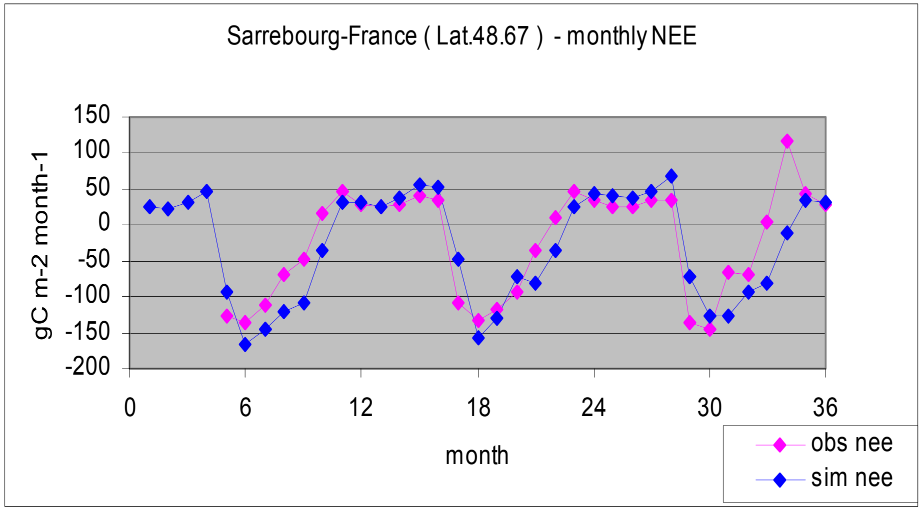
Sitch et al., GCB, 2003

# Validating net ecosystem C exchange (GUESS)
# Comparison to ecosystem C flux measurements from EUROFLUX

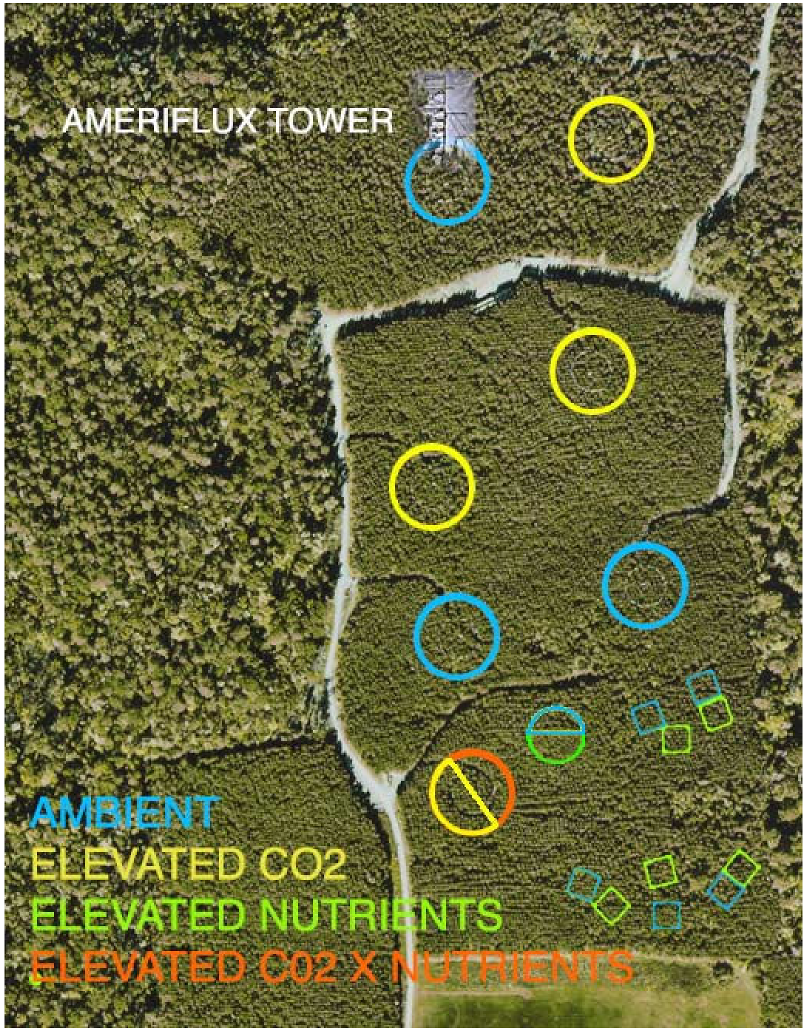


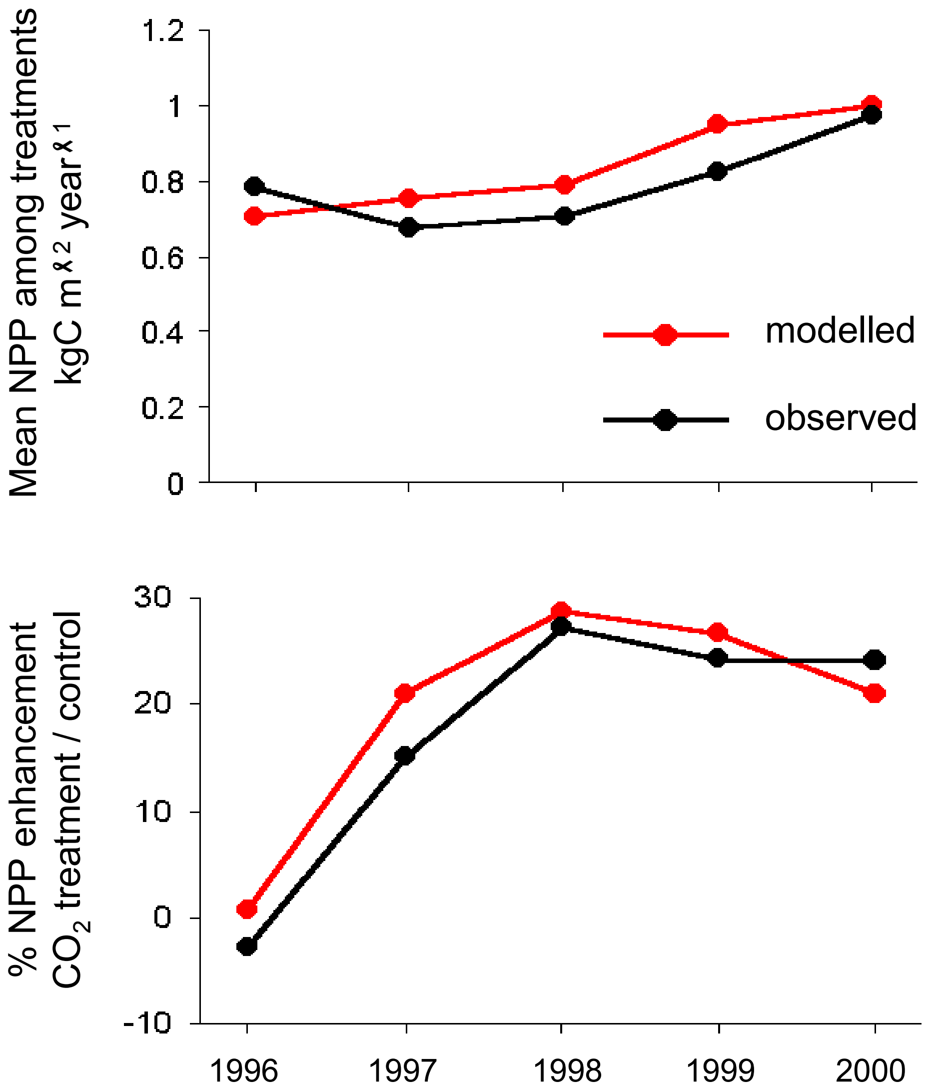



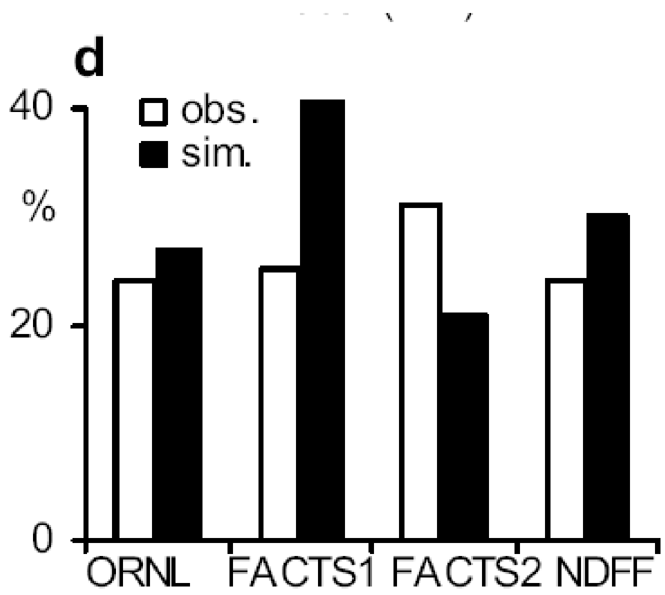

Work by Pablo Morales




Duke Forest, North Carolina

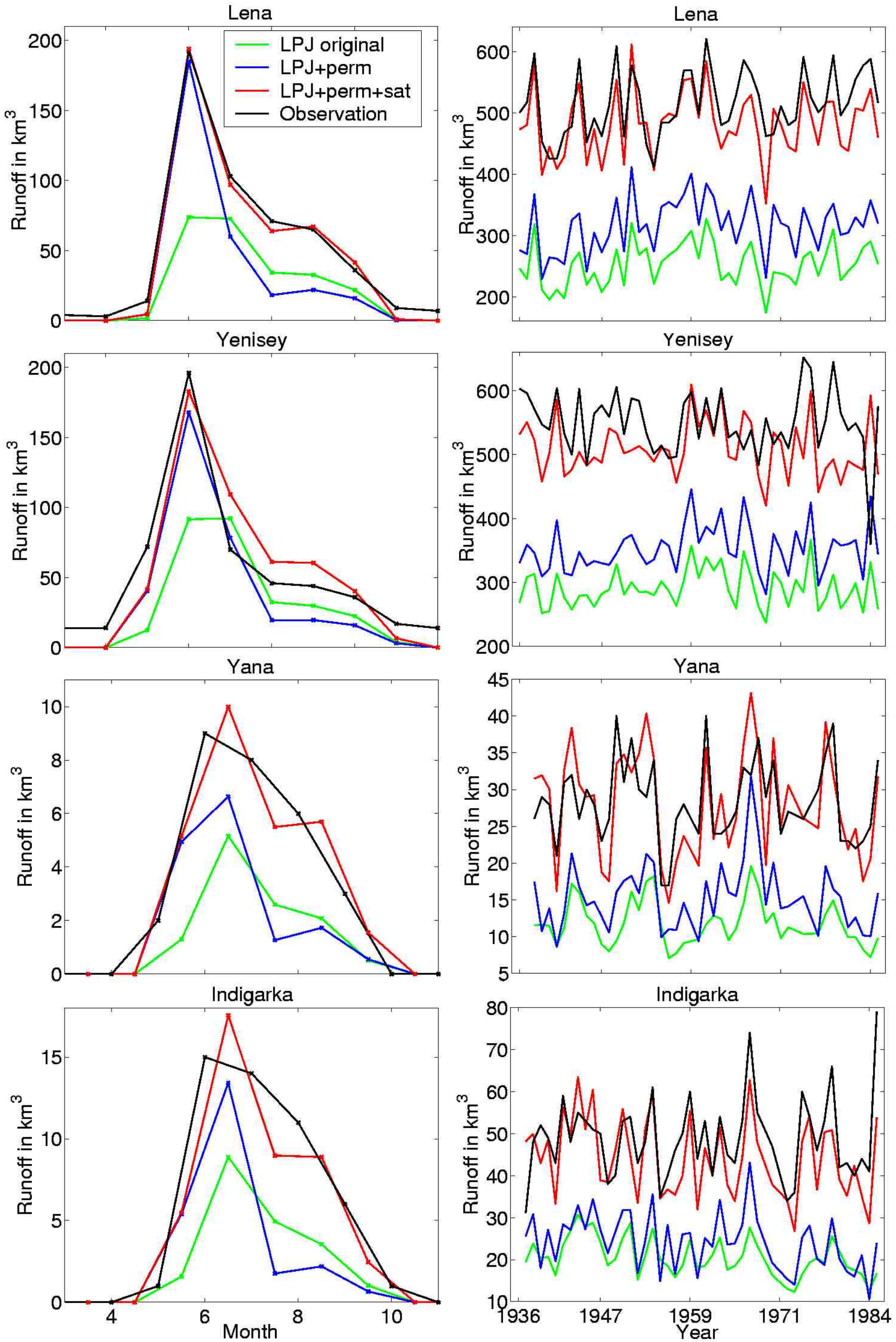
# Validatierung der $CO_2$-Reaktion der Nettoprimärproduktion im Modell GUESS
# Vergleich Modell vs. Duke Forest FACE (Thomas Hickler)




Annual NPP enhancement (%) under 200 ppm CO2 increase, multiyear averages (Gerten et al., subm.)

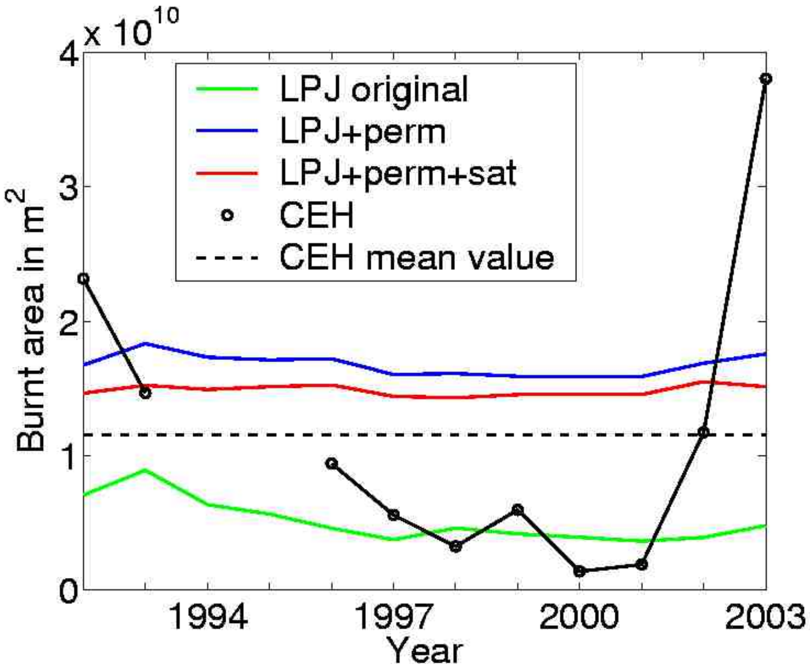
NPP-Beobachtungen:
DeLucia *et al.* 1999, Hamilton *et al.* 2002, Schäfer *et al.* (in review)

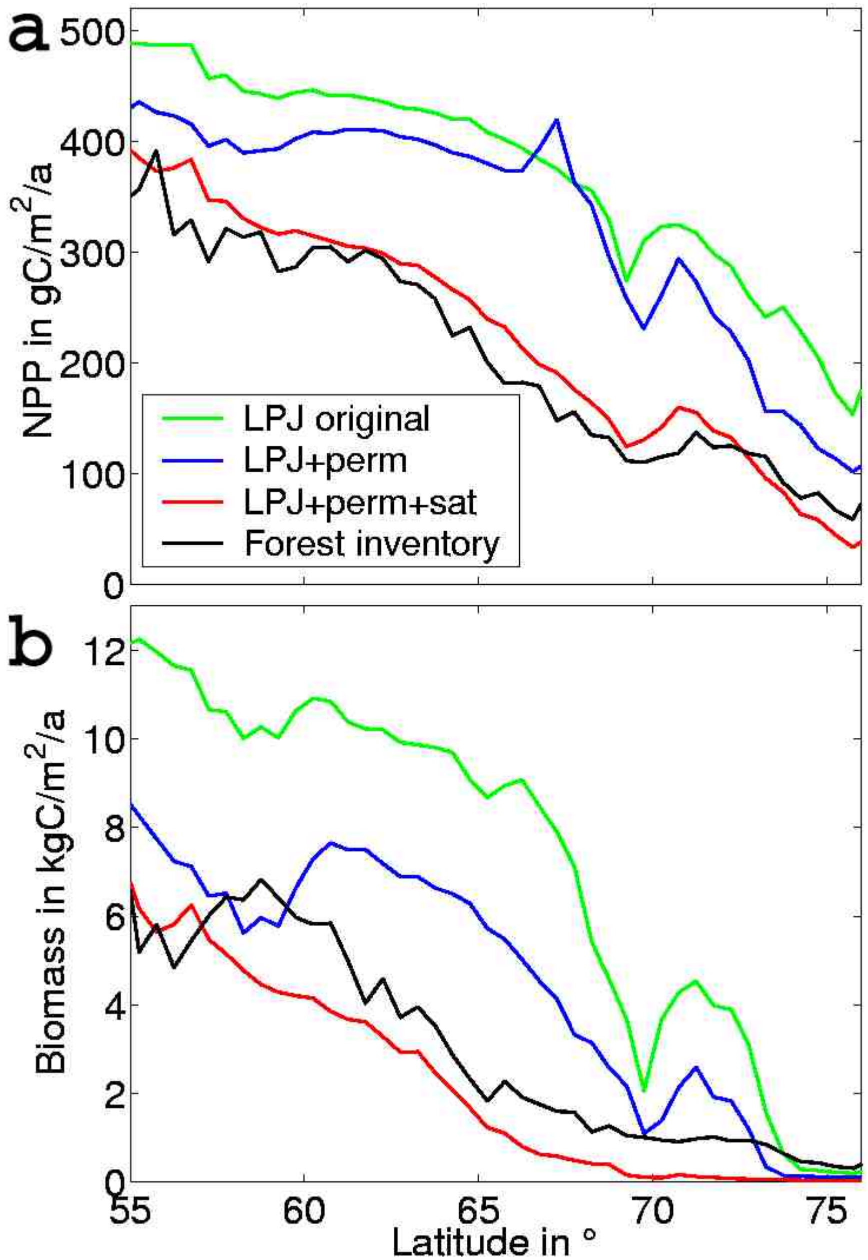



# Processes are important!
# Example 1:

Siberian Biomass, Fire, Runoff, NEP: Influence of Permafrost and Vegetation Density

Beer et al., submitted






Biomass Increase 80ies+90ies:
74 TgC/yr from LPJ
76 TgC/yr from Inventories
(satellites: 284 TgC/yr)

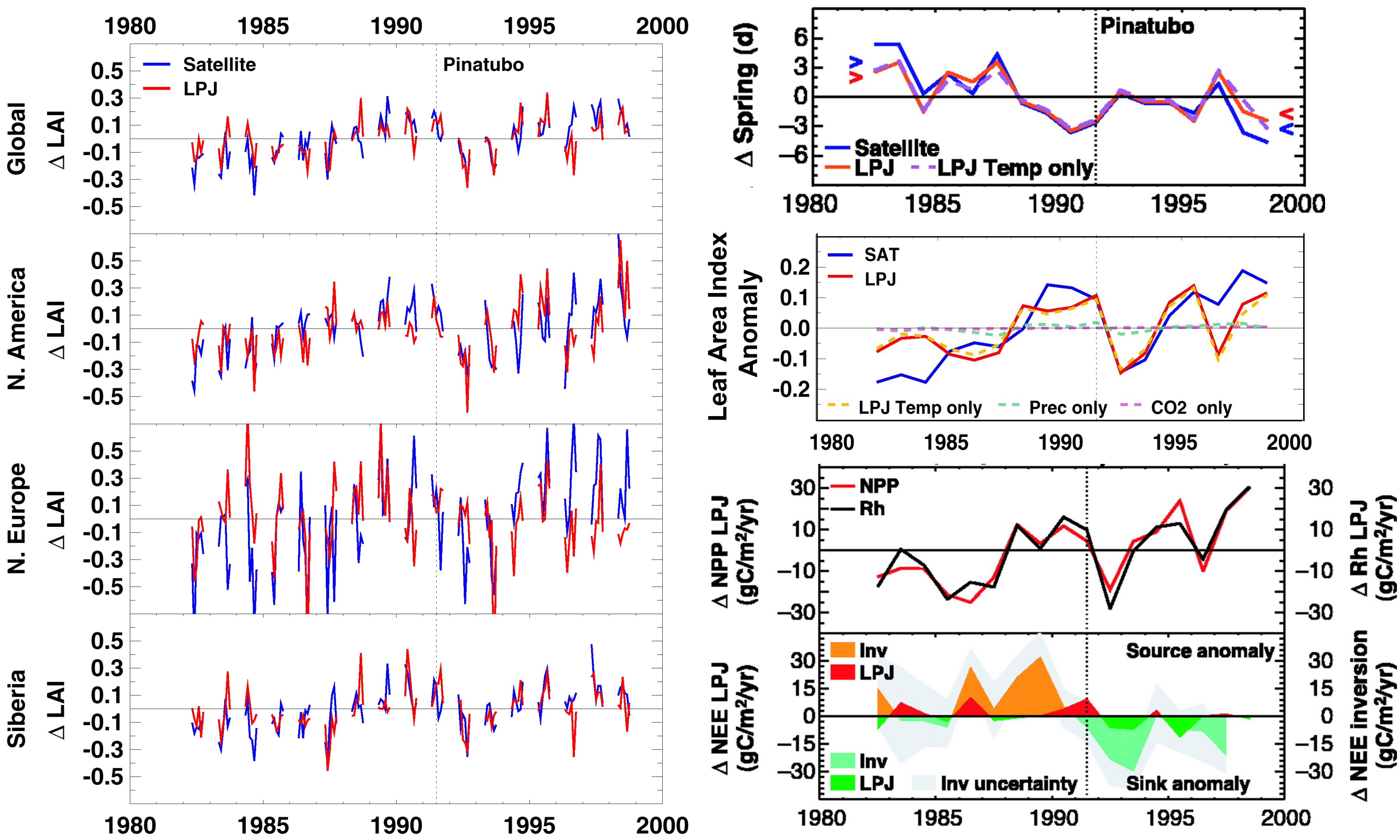
NEP from LPJ:
0.13 Gt/yr (80ies+90ies)

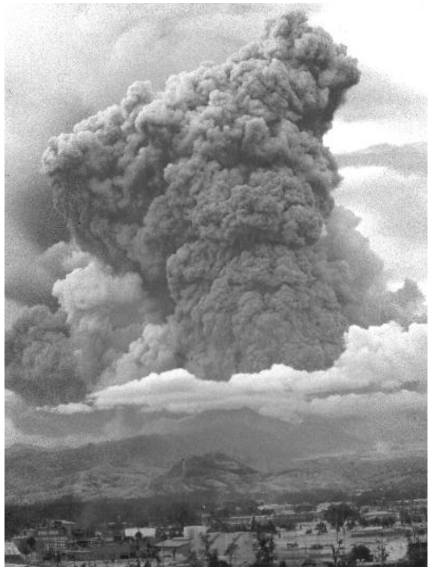
→ 7% of Eurasian C emissions

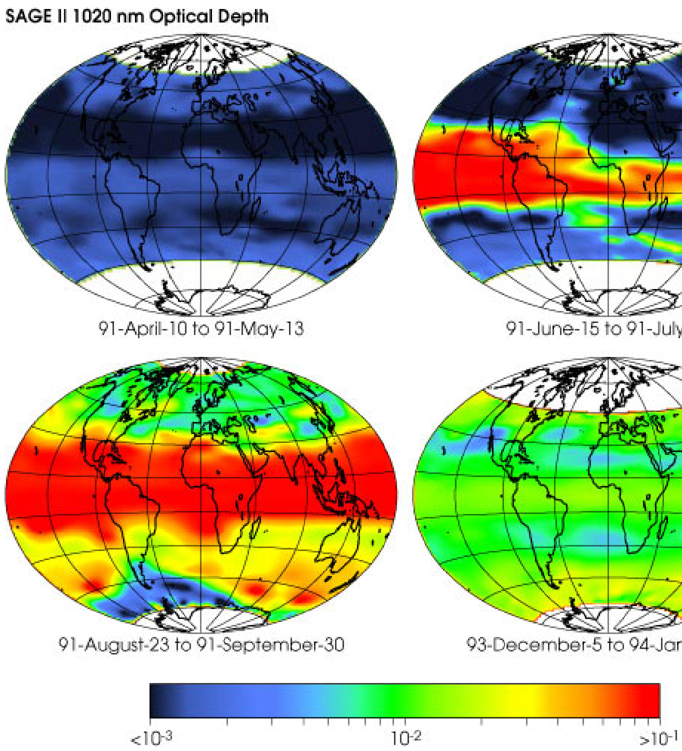
Conclusions:
1) Where is the biosphere sink?
2) Biosphere sinks are not a Kyoto solution!

Beer et al., submitted

## **Processes are important! – Example 2:** Vegetation trends in the boreal zone (Lucht et al., 2002)







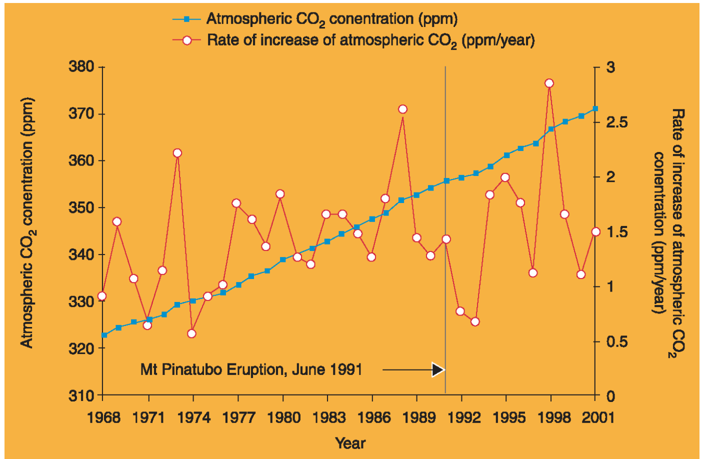
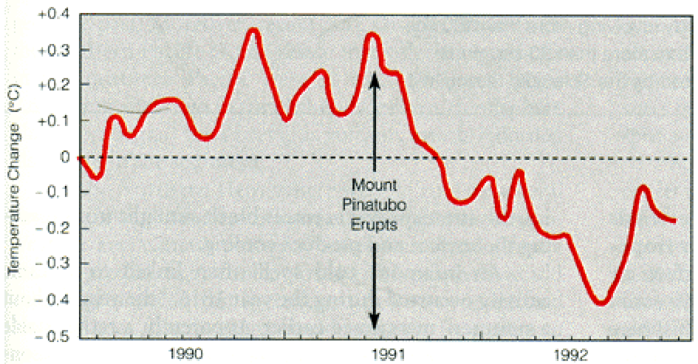



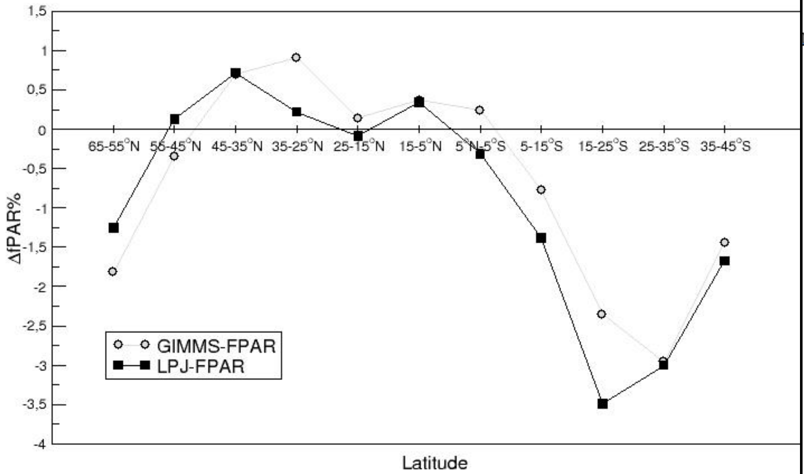

Figure 1. Atmospheric $CO_2$ concentration (ppm) from Mauna Loa (Keeling et al., 1995) and its rate of increase (ppm/year) for the 1968-2001 duration. The average rate of increase of atmospheric $CO_2$ concentration from 1968-2001 is ~1.43 ppm/year. The rate of $CO_2$ increase in the atmosphere dropped to ~0.72 ppm/year for two years following the Mt. Pinatubo eruption.

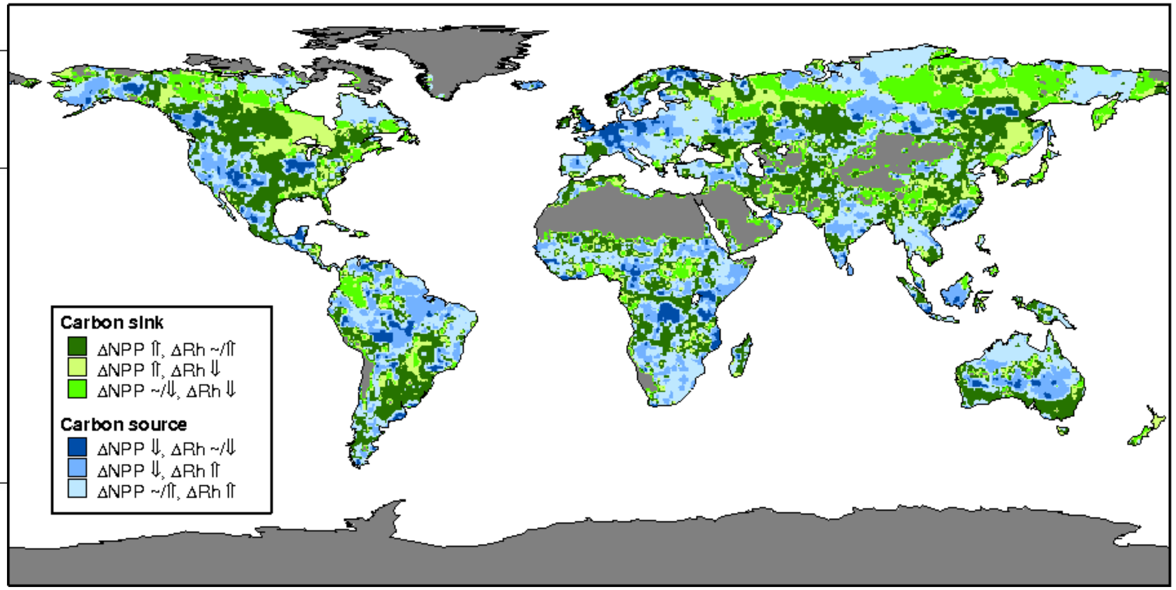



## „Processes are important" – Example 2:

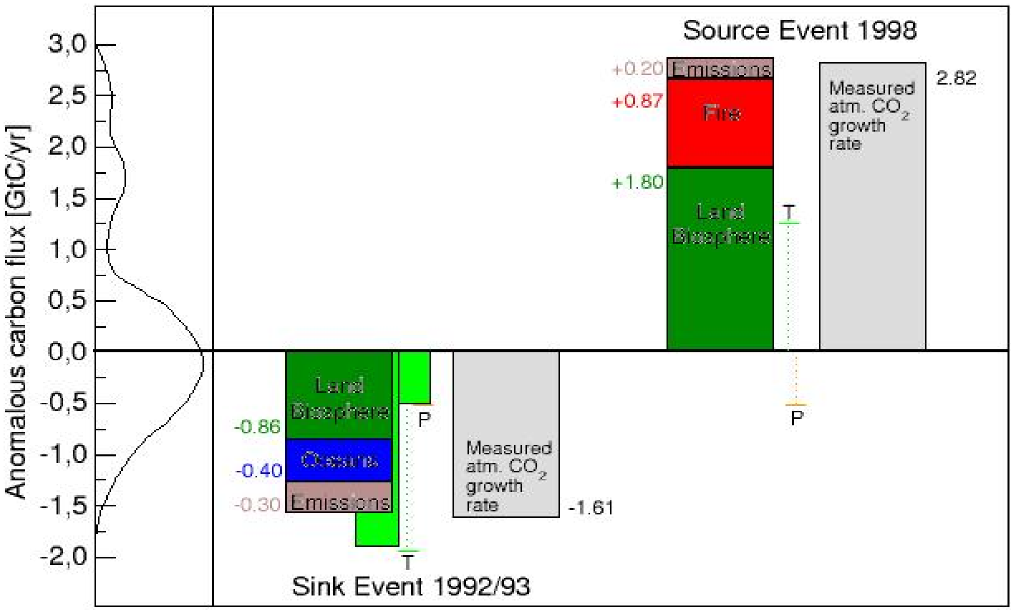
Effects of the Pinatubo Eruption, June 1991

Lucht et al., Science, 2002
Erbrecht and Lucht, in prep.




Extremes in atmospheric $CO_2$ growth rate anomalies




**Processes are important:**

Very large heterogeneity

- in space
- in time
- in balance of processes

# Temperature Increase **2100 vs. 2000, 5 Climate Models** (30yr av.)

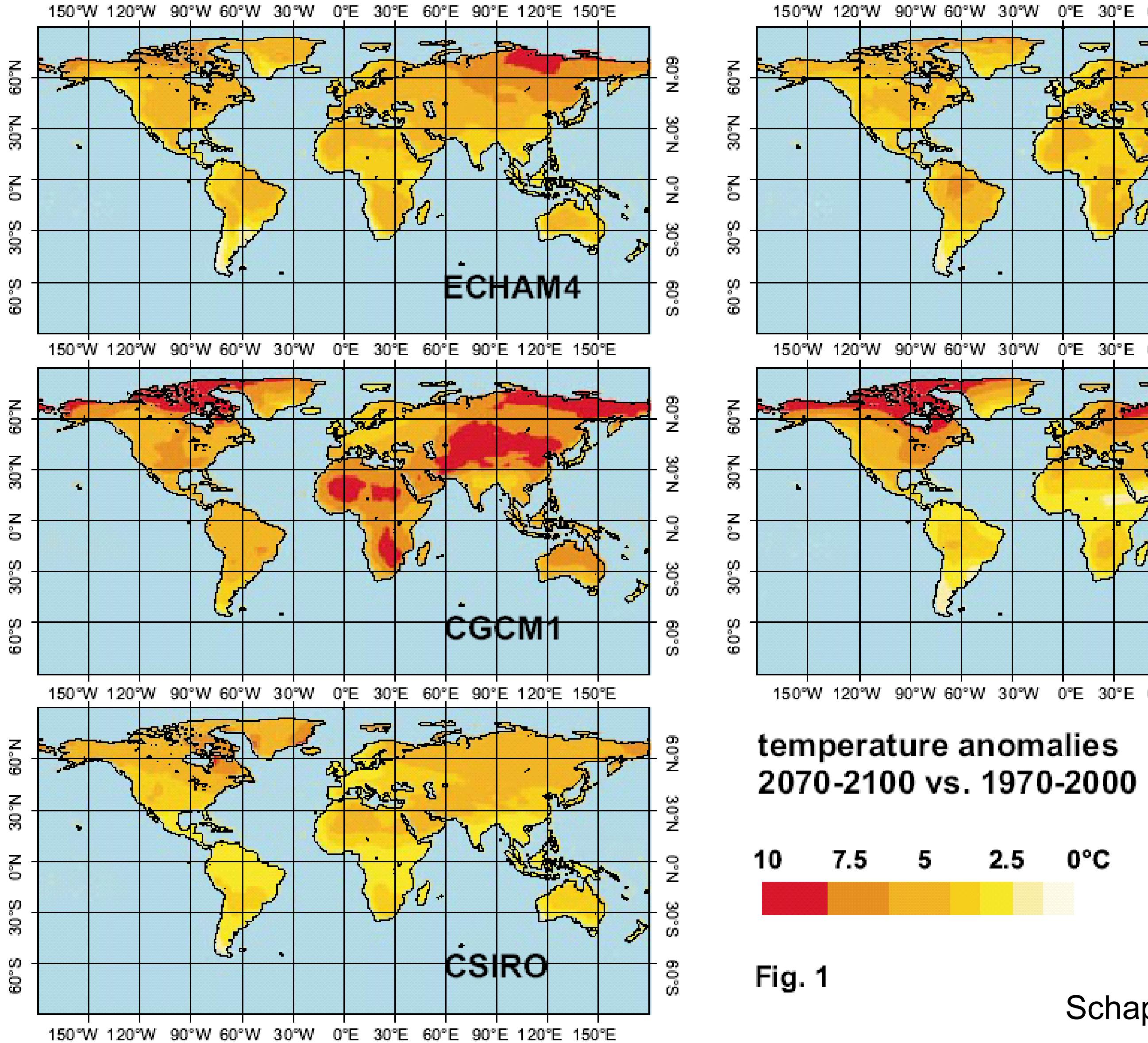
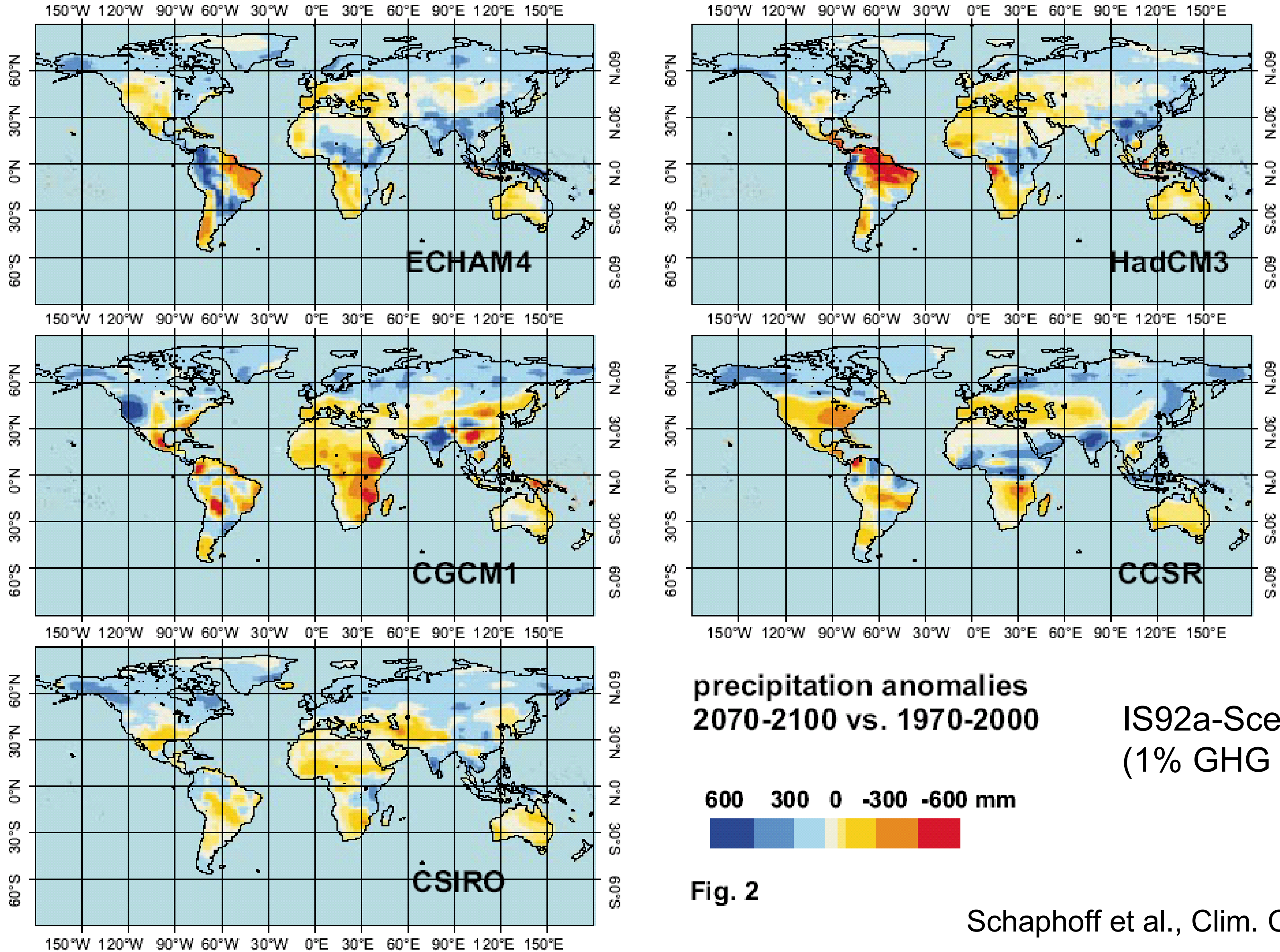



Fig. 1

IS92a-Scenario
(1% GHG Increase)

Schaphoff et al., Clim. Change, in press

# Precipitation Change 2100 vs. 2000, 5 Climate Models (30yr av.)

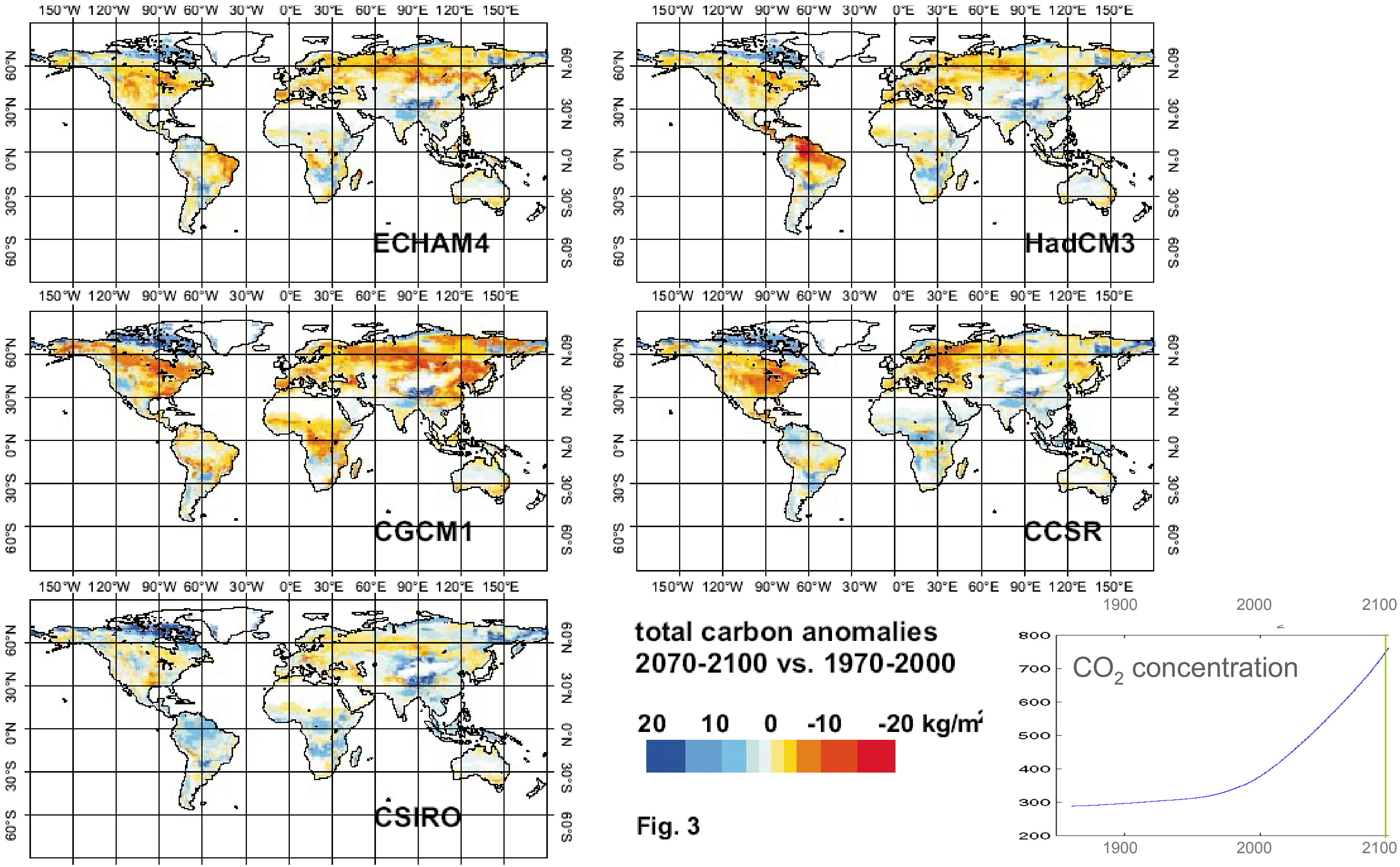



IS92a-Scenario
(1% GHG Increase)

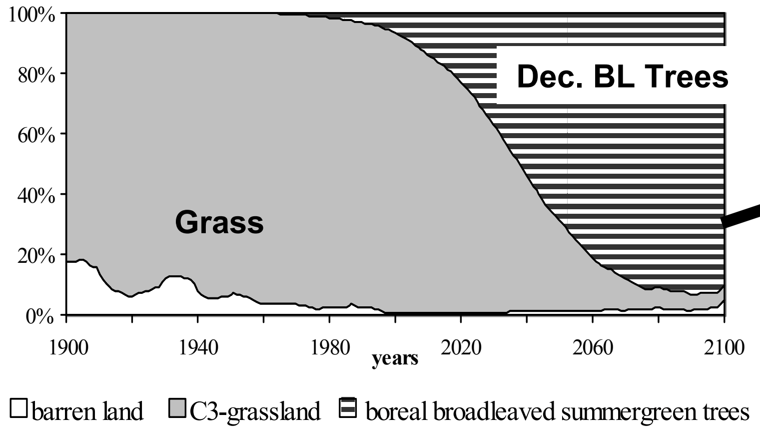
Schaphoff et al., Clim. Change, in press

# Changes in Land Carbon Storage (Vegetation, Litter and Soils)

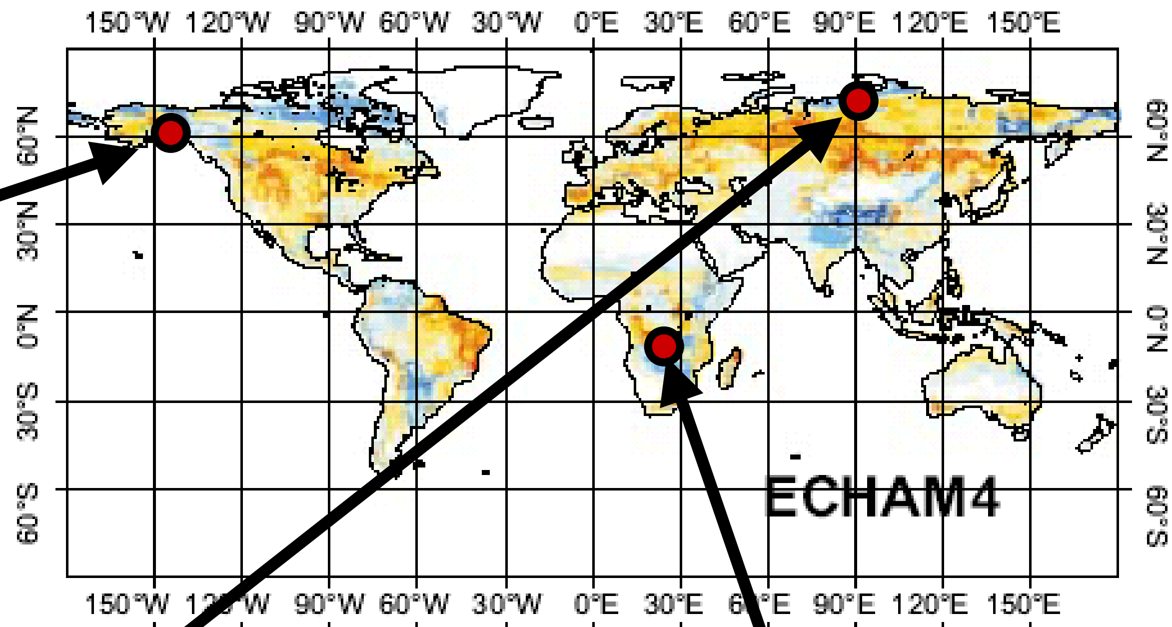
**2100 vs. 2000, 5 Climate Models** (30yr av.)




Schaphoff et al., Clim. Change, in press

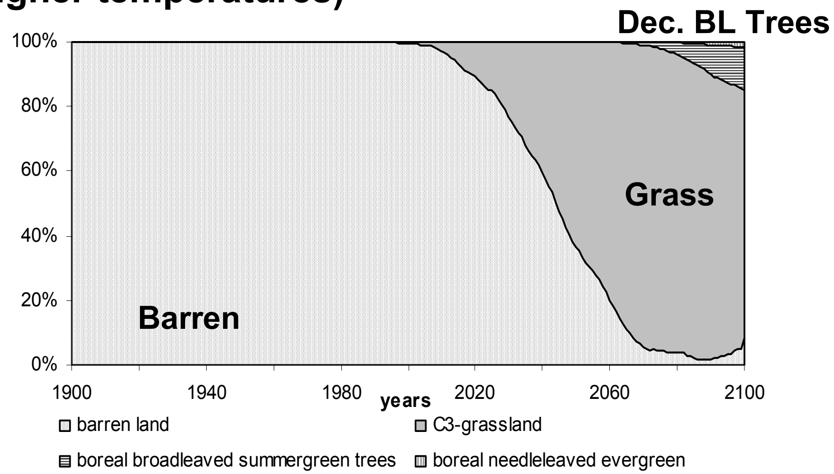



**Northward movement of the tree line**
**(higher temperatures)**

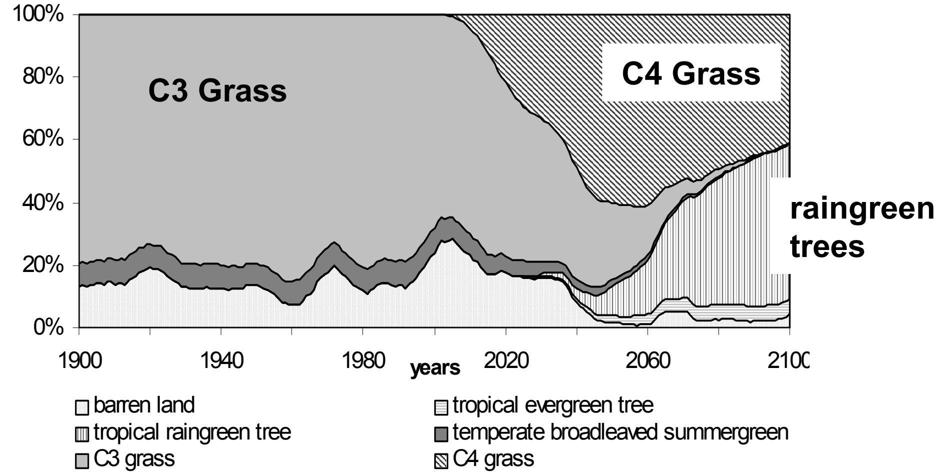



# Shifts in Vegetation Composition

**Increased growth in the Arctic North**
**(higher temperatures)**

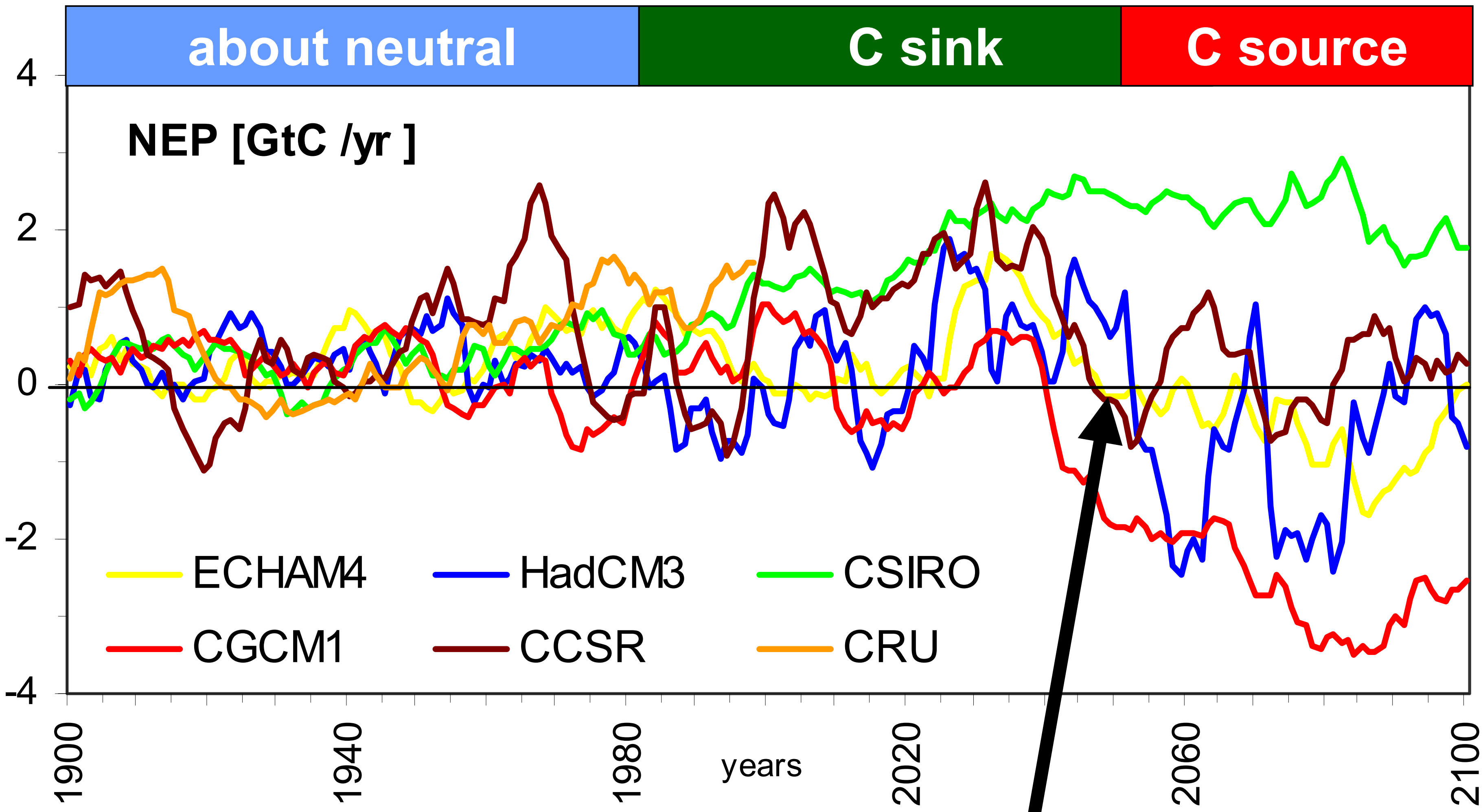



**Woody invasion of savannahs**
**(increased water use efficiencies)**



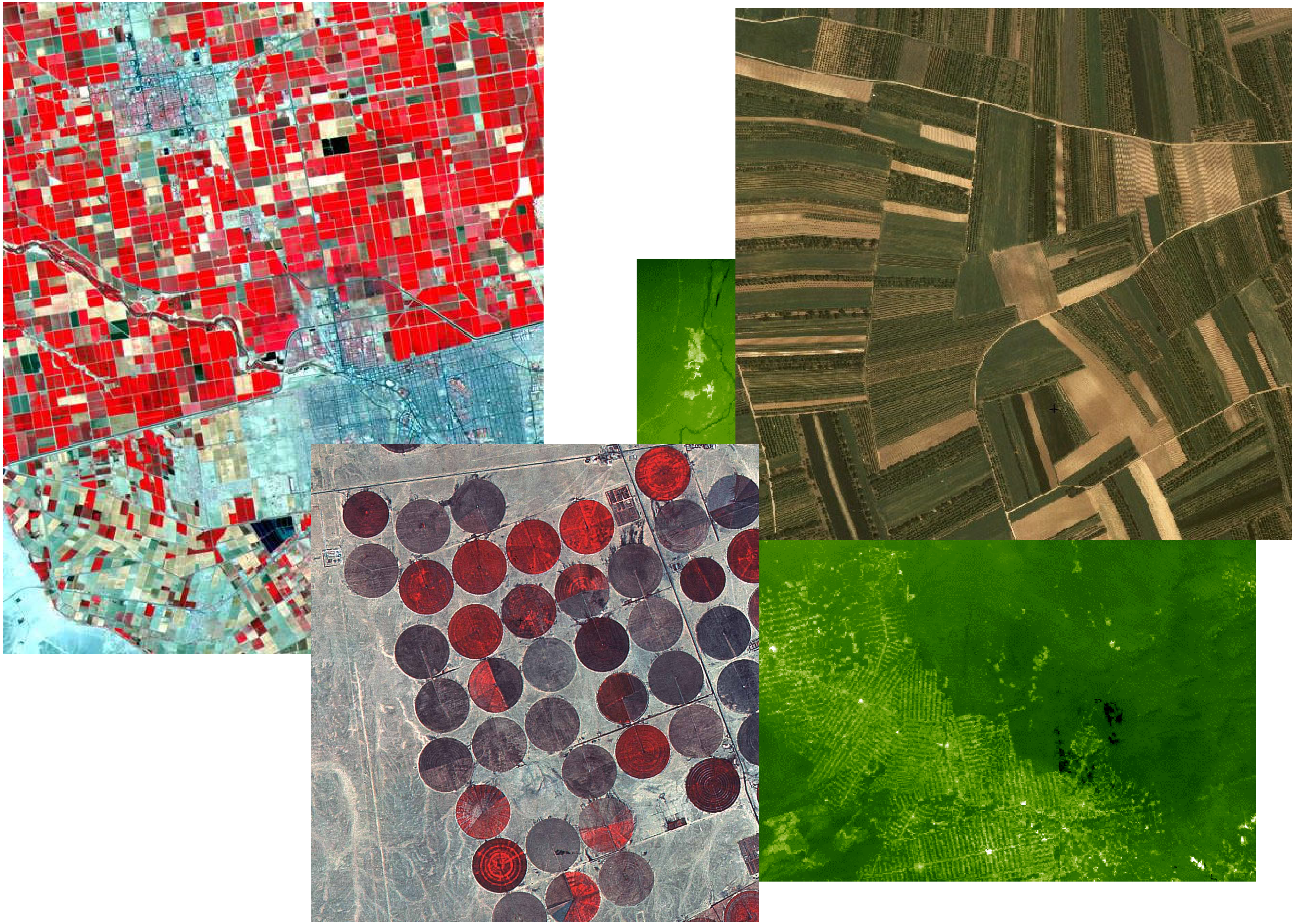

Schaphoff et al., Clim. Change, in press

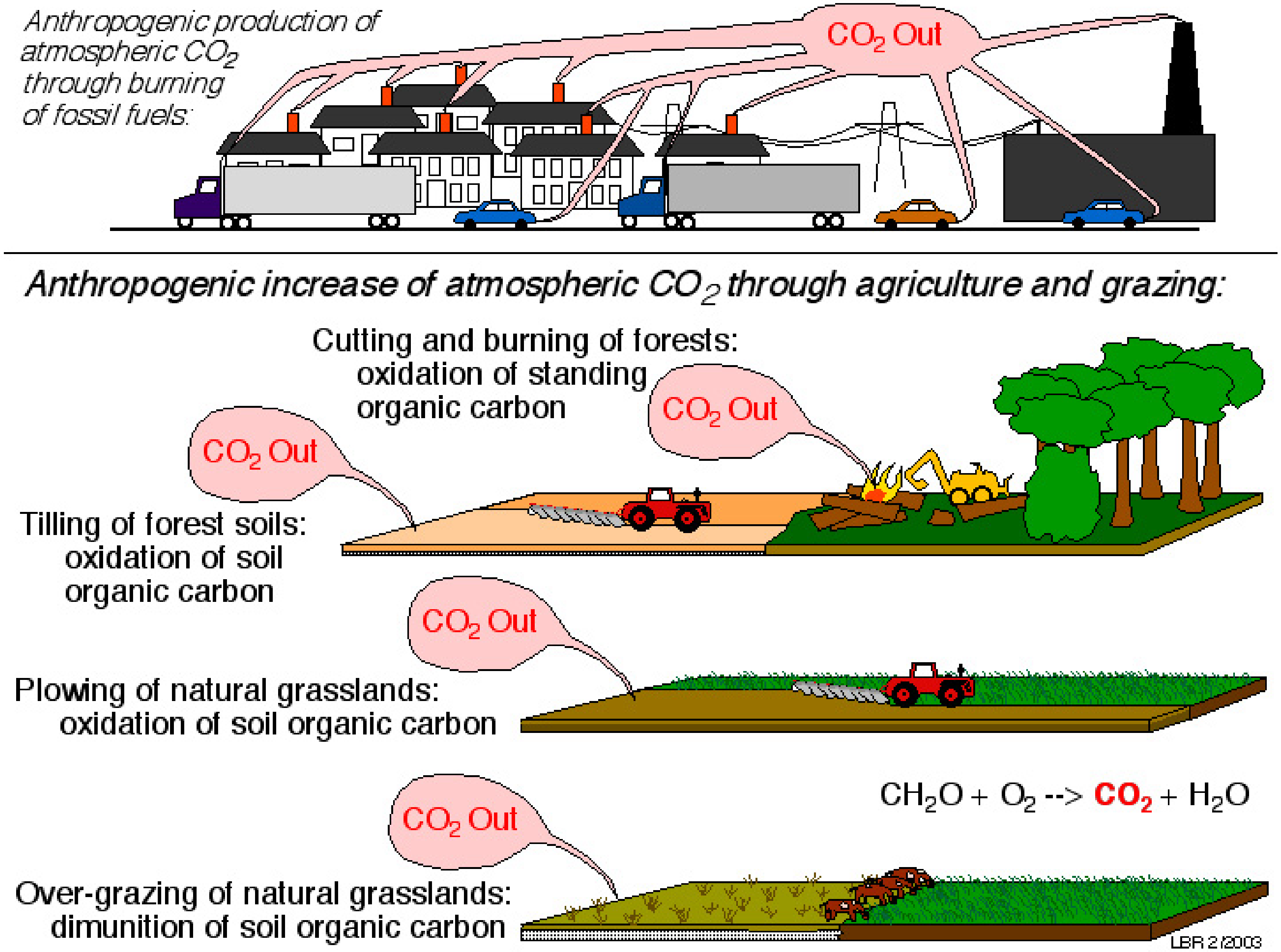
# Change in the terrestrial carbon exchange flux (IS92a)



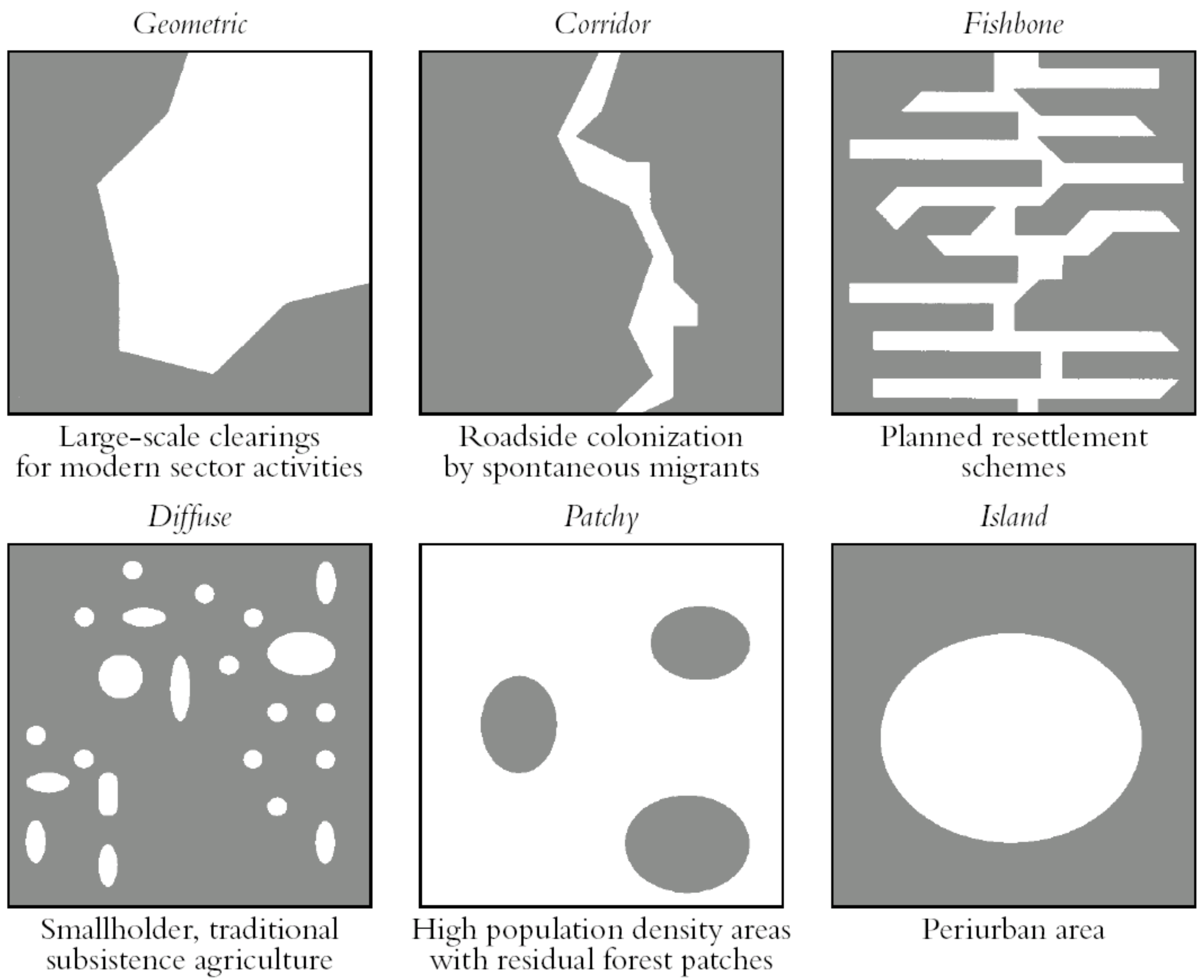

**The land biospheric sink of $CO_2$ may turn into a source**

Schaphoff et al., Clim. Change, in press






Source: Bruce Railsback, U. Georgia



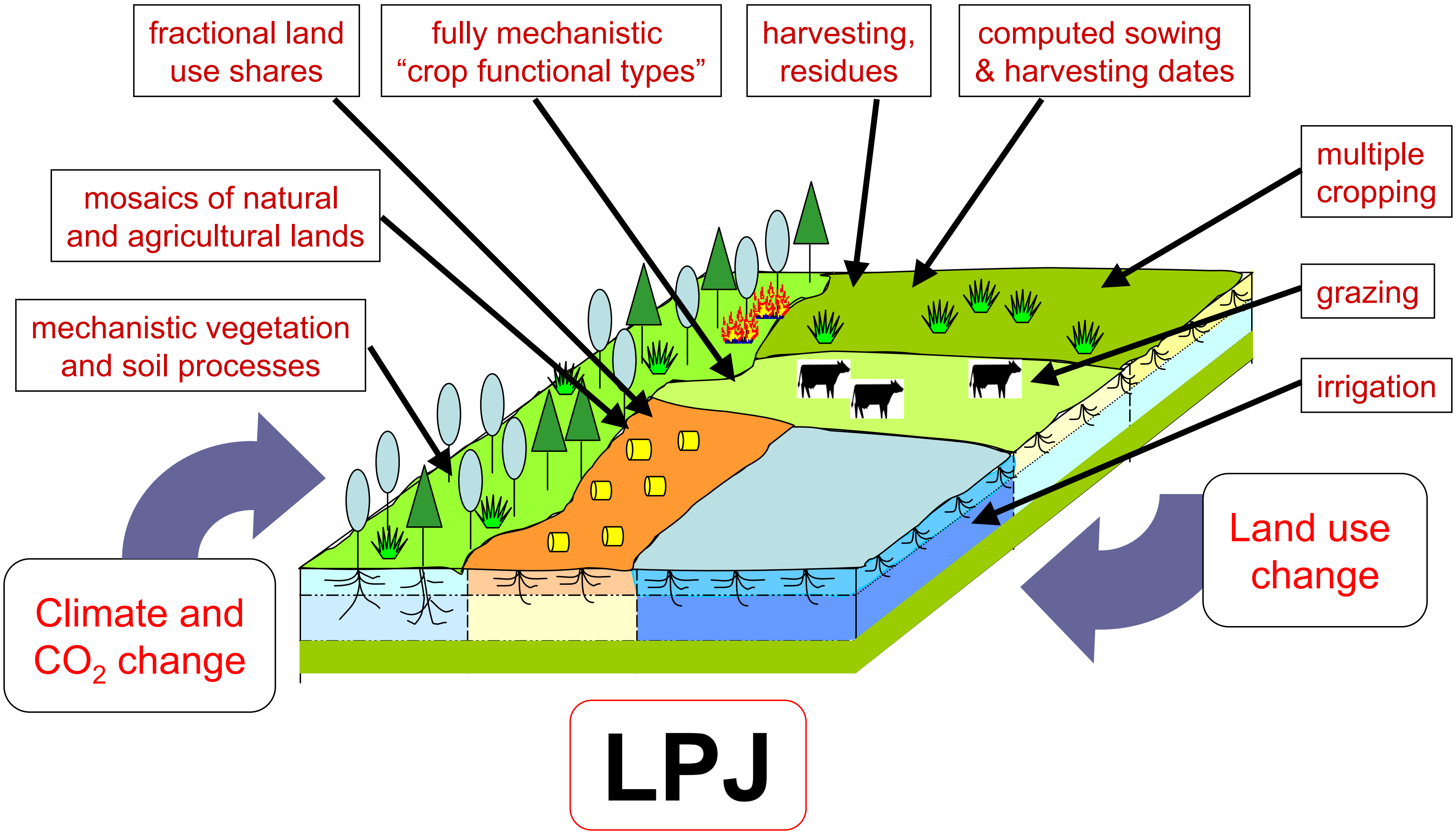

*Source: Mertens and Lambin (1997), Spatial modelling of deforestation, p. 149.*

# Some Processes relevant to Land Use

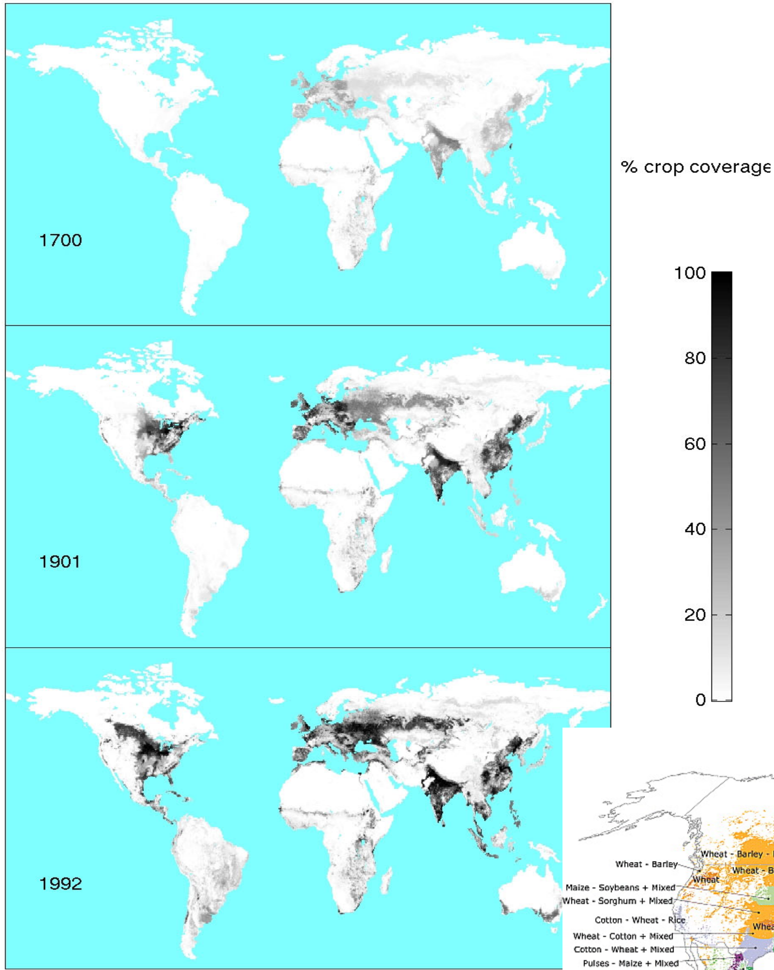
- How many people are there?
- How many of them are vegetarians?
- How much biomass is being used?
- Which agricultural technology is being used?
- How extensive is global trade?
- How rich are the different regions of the globe?

LPJ

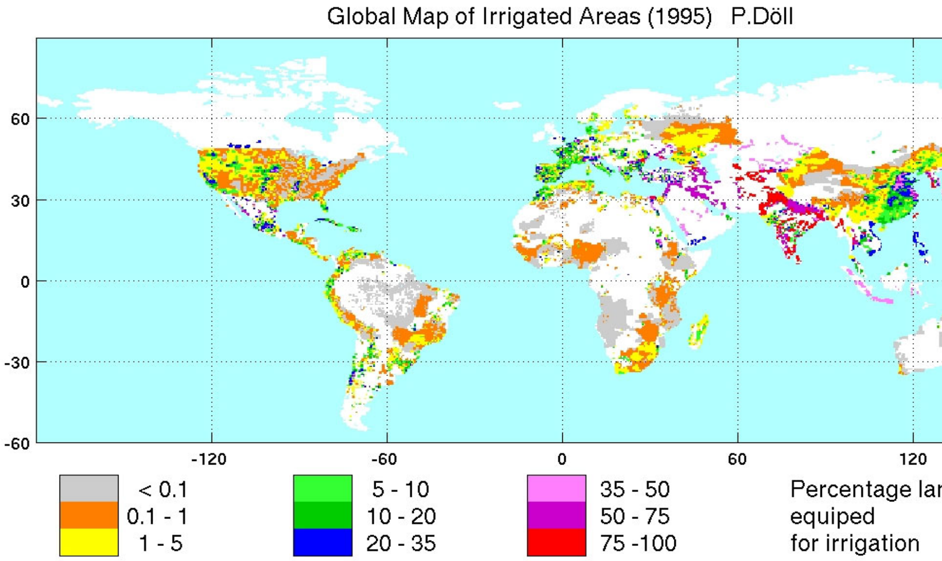
# LPJ expanded to include mechanistic agriculture



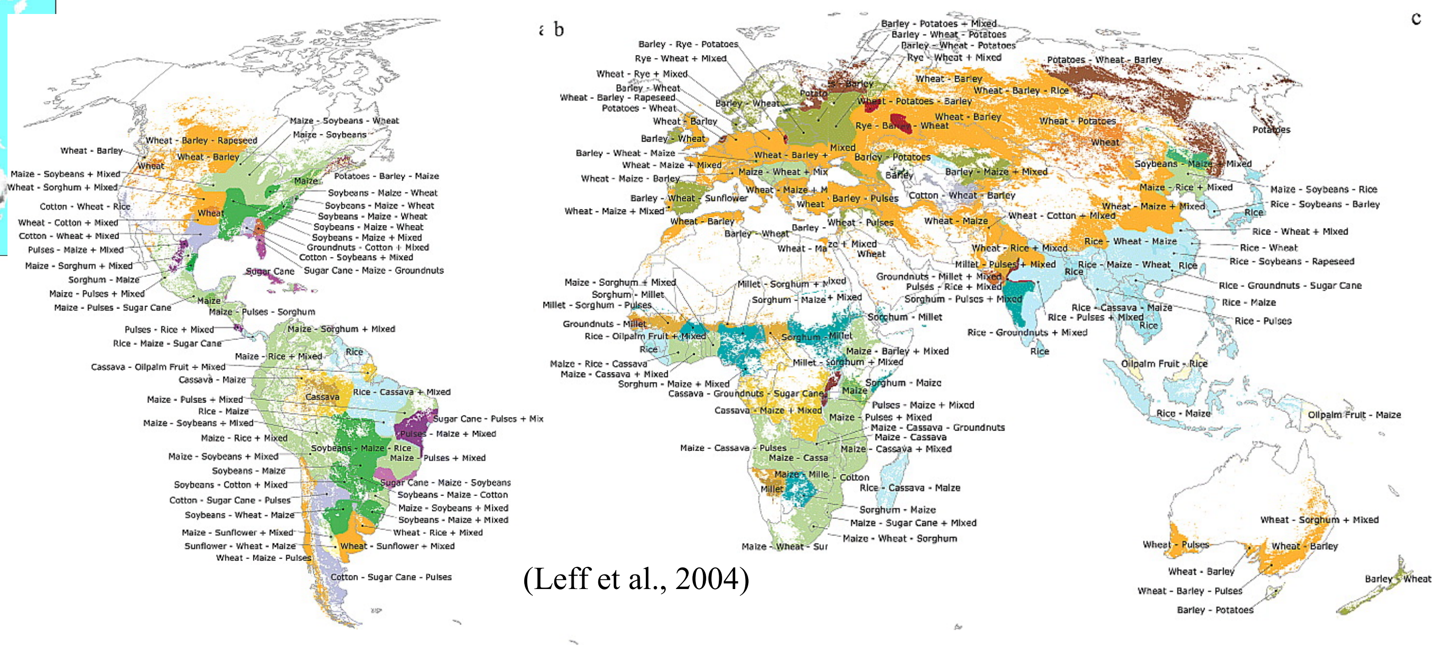
# Inputs: land use + irrigation + spatial distribution of crop types




(Ramankutty et al. 2002)



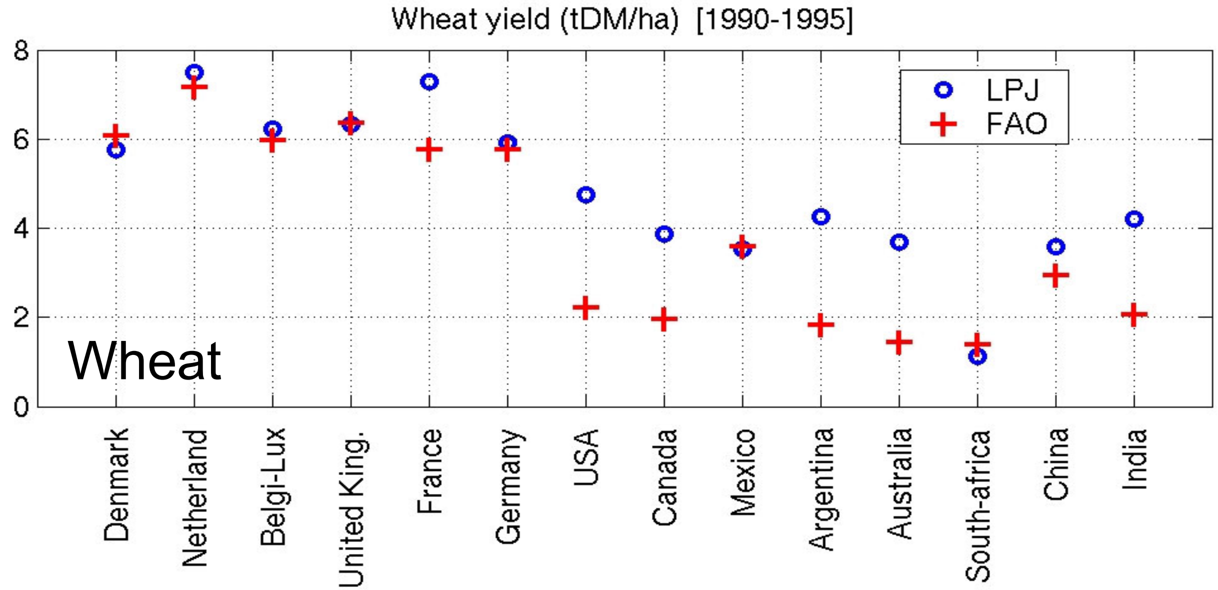

(Döll, 1999)




(Leff et al., 2004)

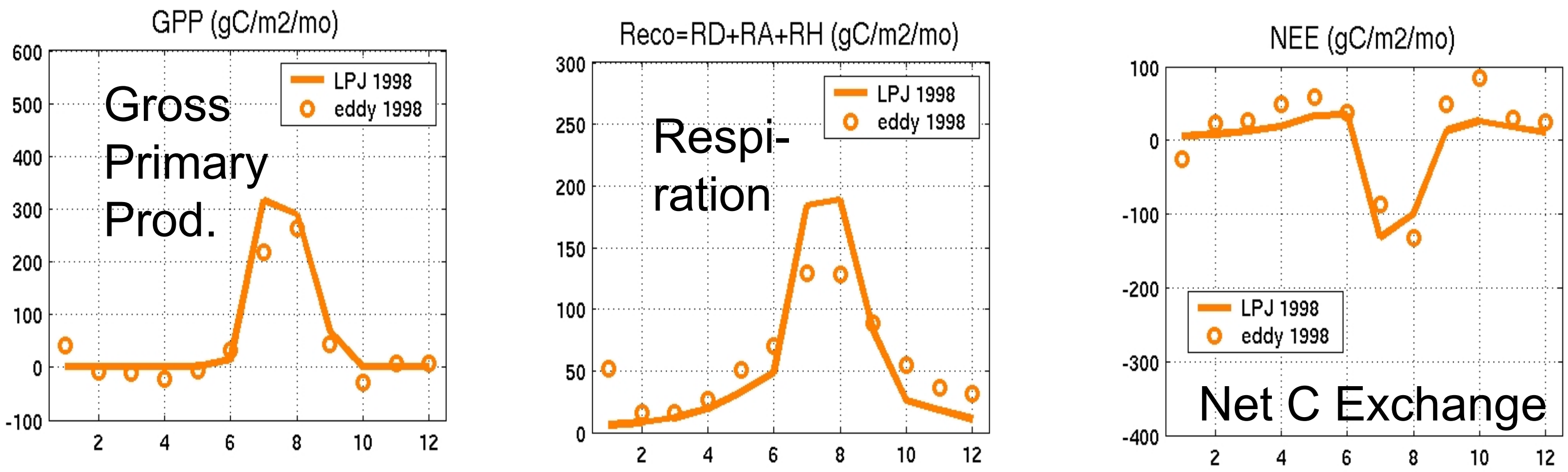
LPJ

# Examples for validation of LPJ agriculture




Test of LPJ-simulated crop yields 1990-95 vs FAO statistics

Test of LPJ-simulated seasonal C fluxes vs. eddy flux measurements

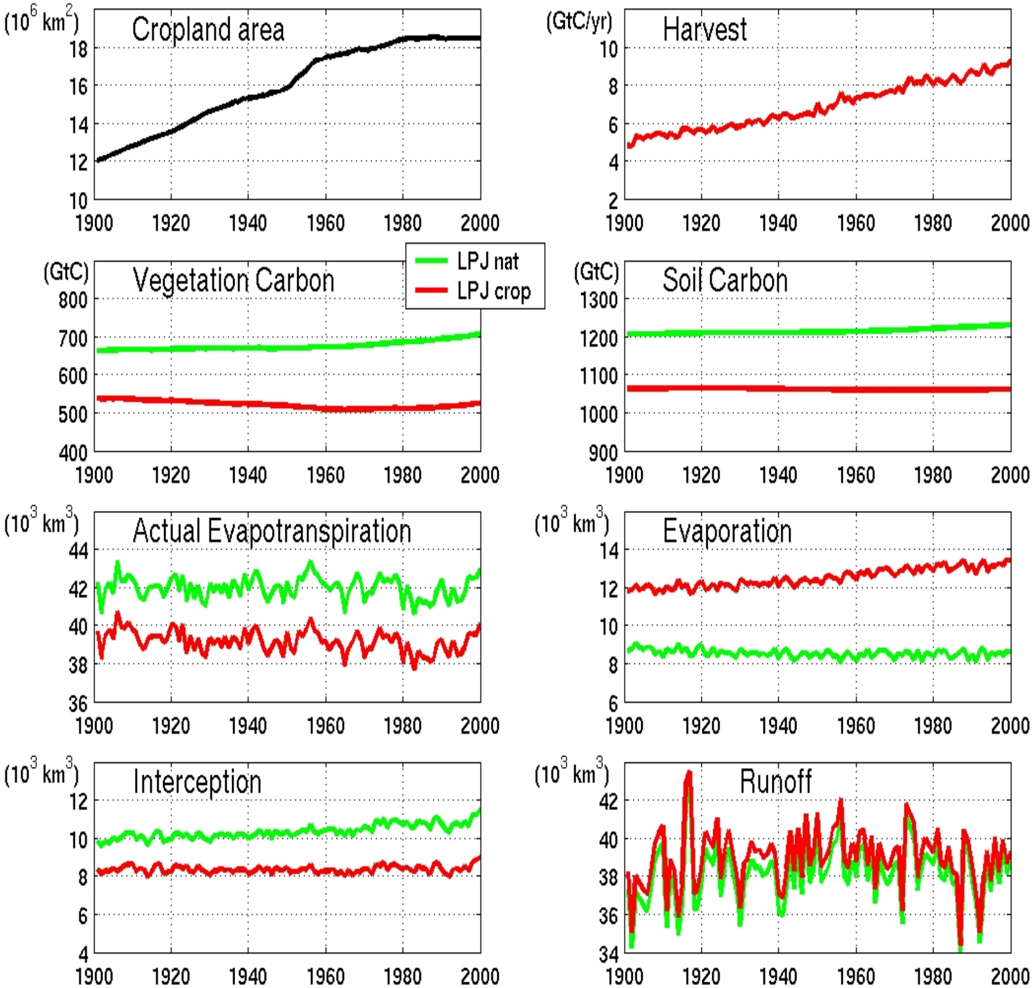



A. Bondeau et al., in prep.

# LPJ

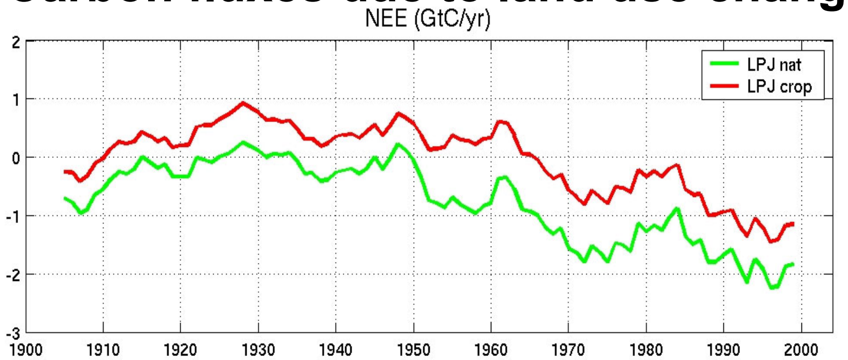
# Studies of 20th Century Land Use Effects

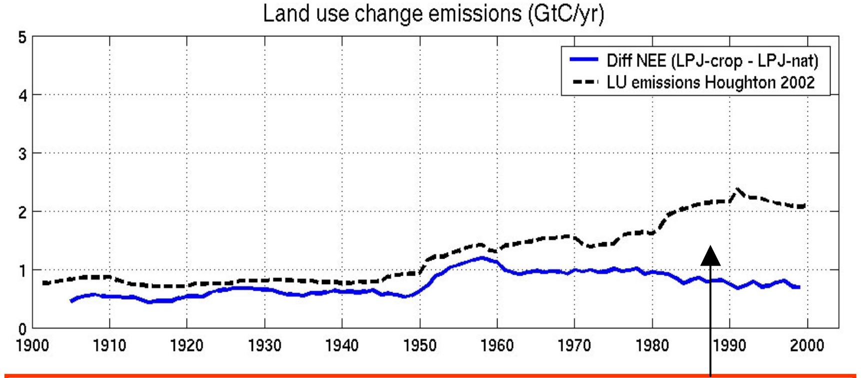
## Carbon stocks & water fluxes




Effect of agriculture: green water: -7%, blue water: +2% *(Gerten et al., 2004)*

## Carbon fluxes due to land use change




Very different estimates on the areas deforest-ated in the tropics at the end of the 20th century

Tropical forest areas 1990 ($10^3$ km$^2$):

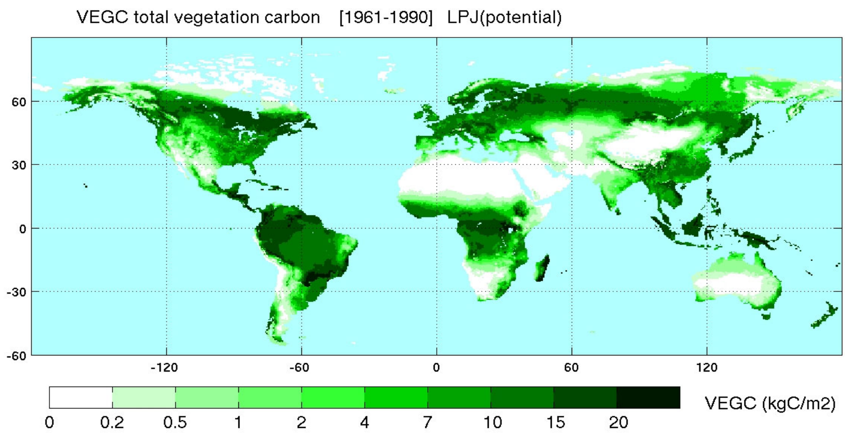
| | |
|---|---|
| Fearnside (2000) | 18620 |
| Malhi & Grace (2000) | 15099 |
| Achard et al. (2002) | 11500 |
| FAO (2003) | 20261 |
| HYDE data base (1997) | 14790 |

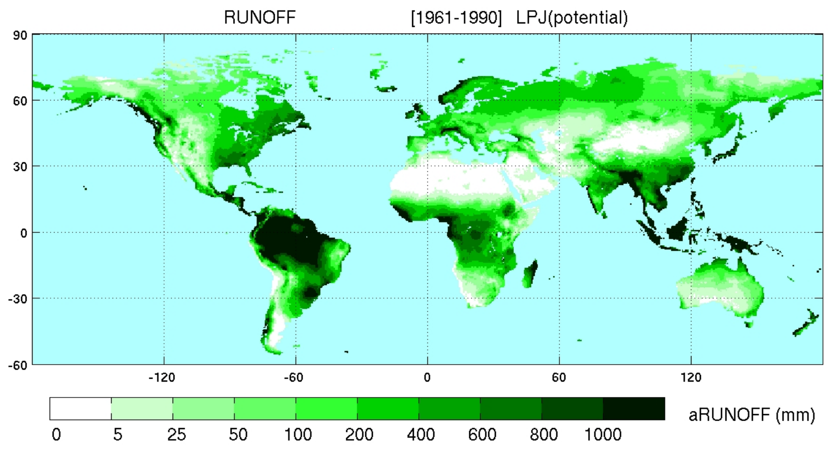
# LPJ+Crop Model

## Example: Biomass

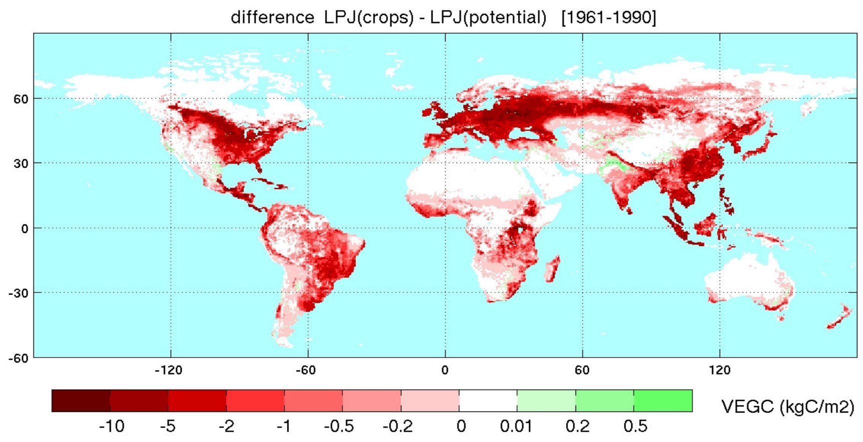
## Example: Runoff

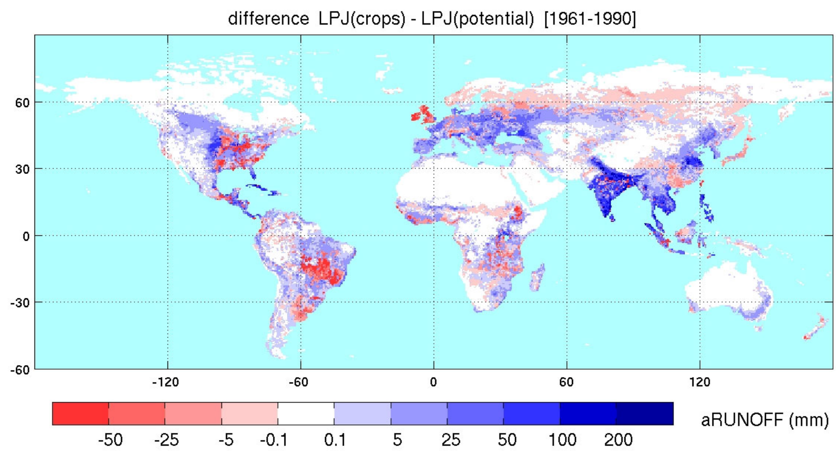
### Today's distribution



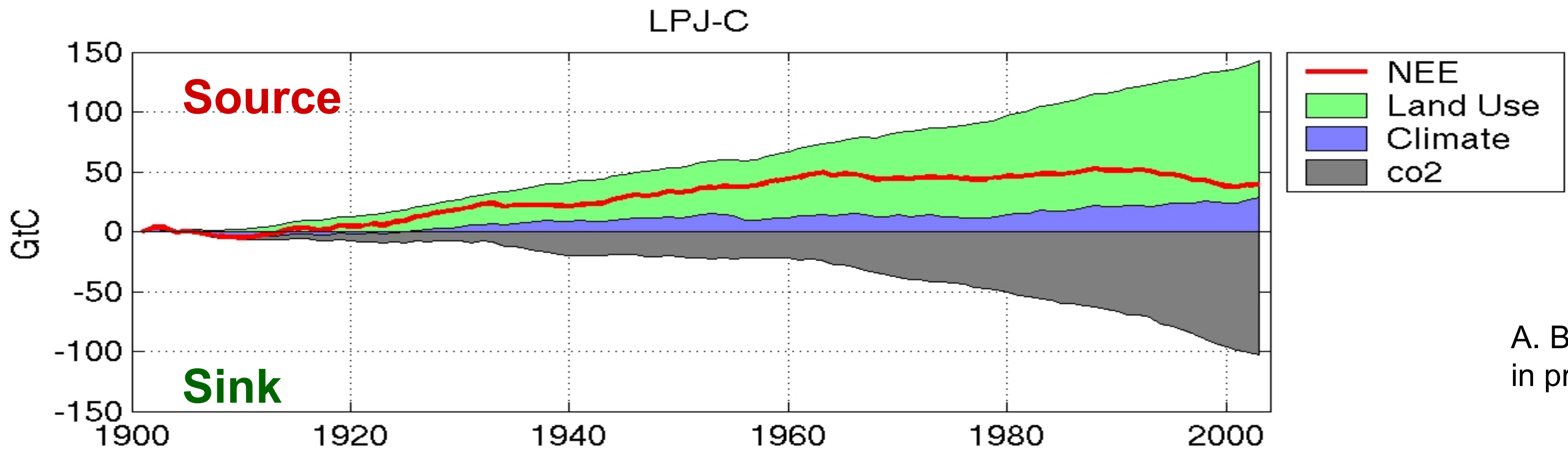

### Change due to human influence



# LPJ

## Cumulative change in net carbon storage




A. Bondeau et al.,
in prep.

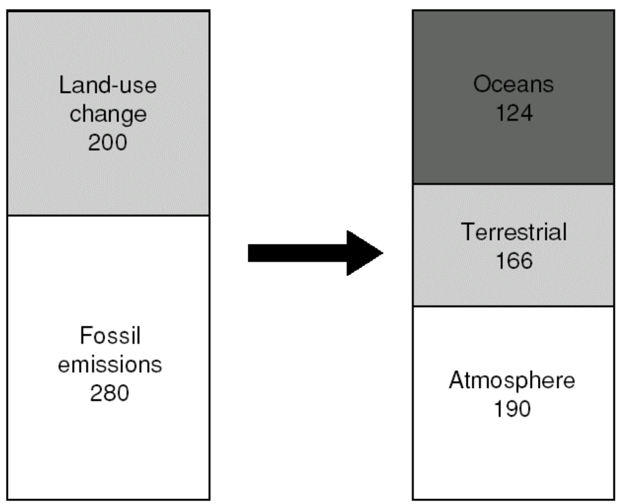



**Fig. 1** Carbon sources and sinks over the last two centuries (PgC).

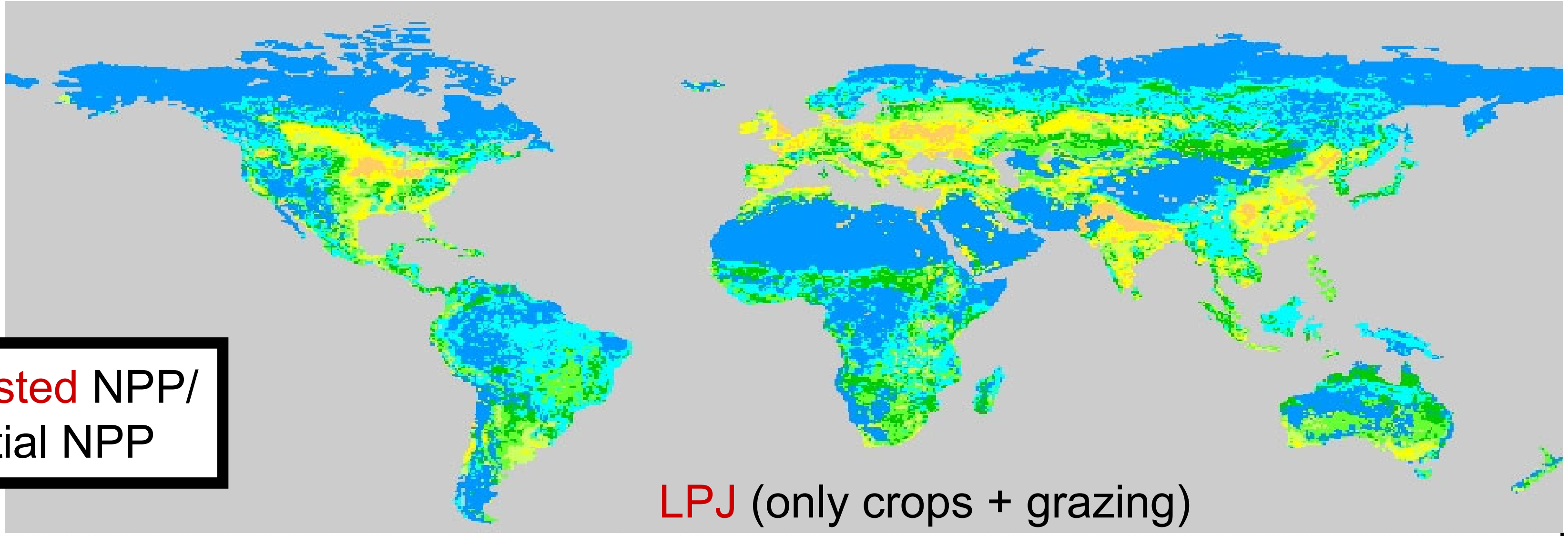
The Expansion of Land Use is an Effect of the First Order on the Carbon Cycle!

House et al., Tellus, 2003

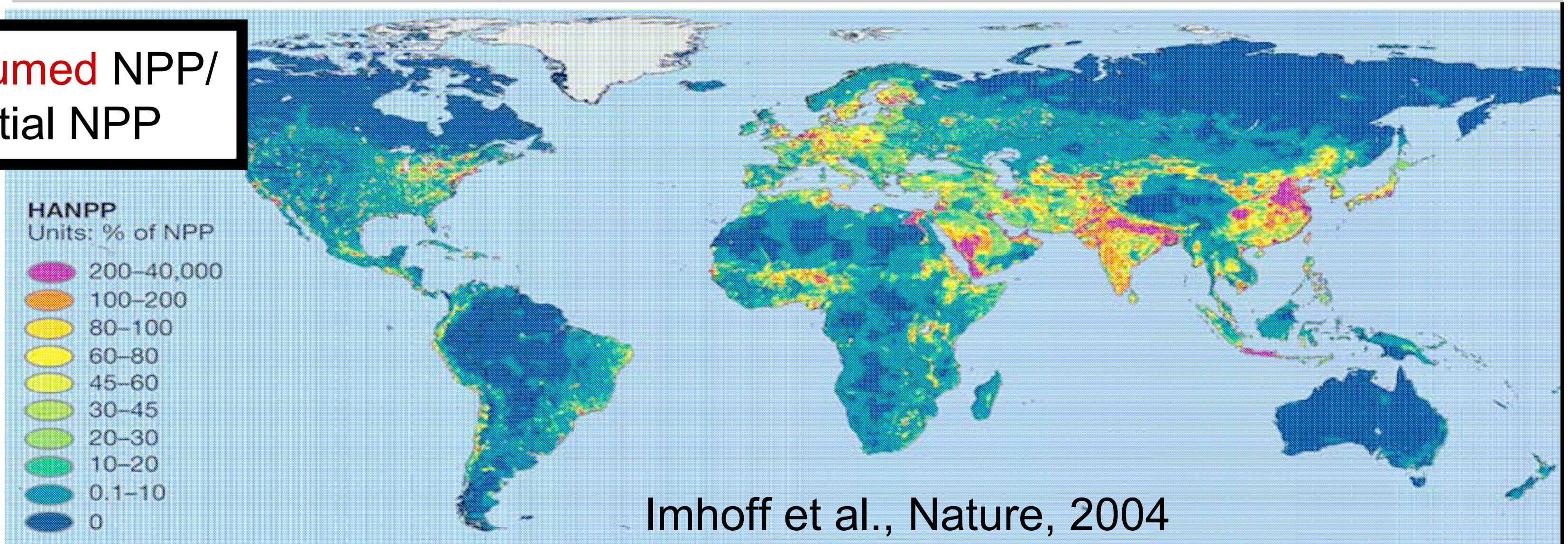
# LPJ

## Human Appropriation of Global Net Primary Production

Harvested NPP/
Potential NPP




Consumed NPP/
Potential NPP




A. Bondeau et al., in prep.

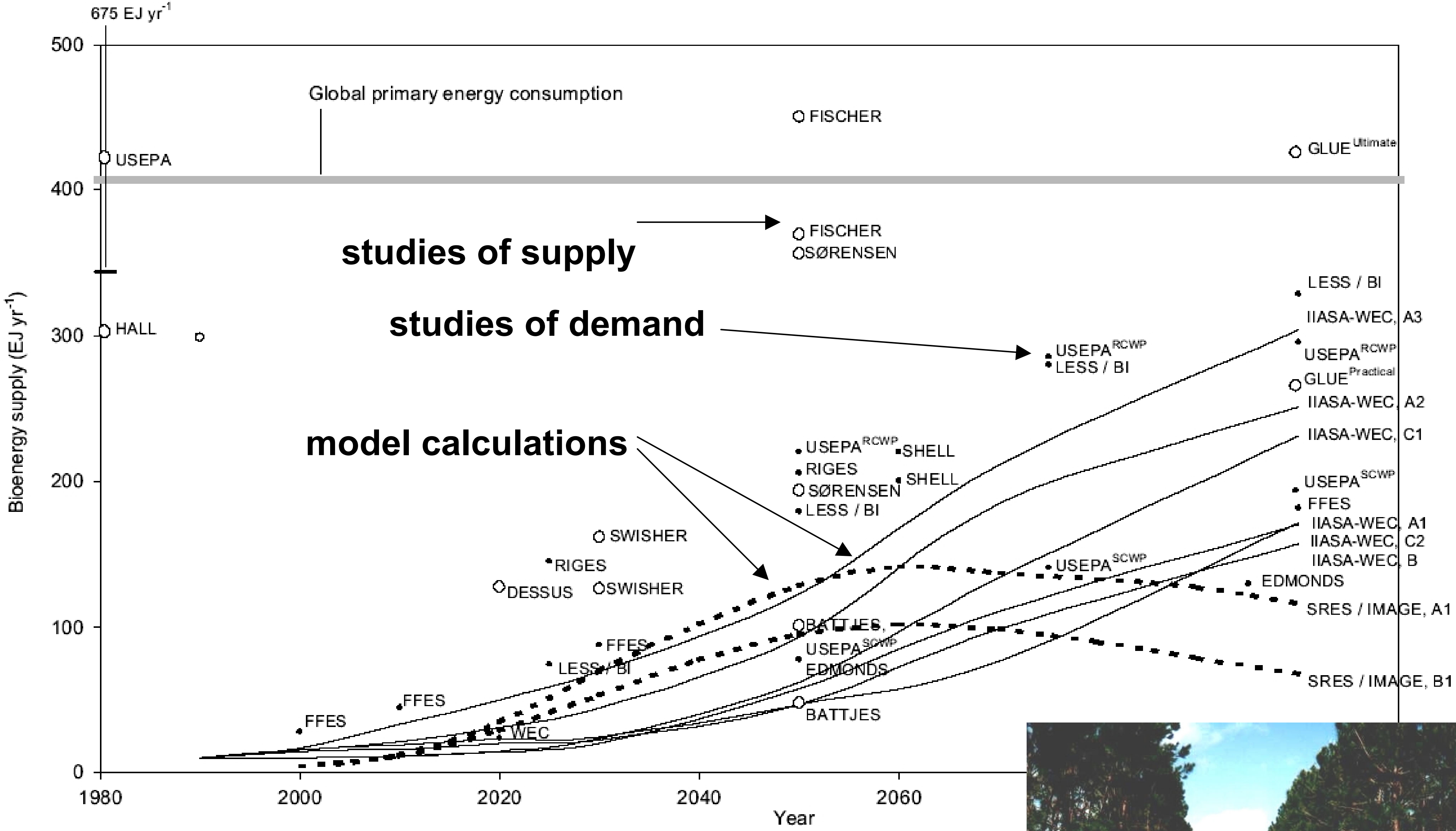
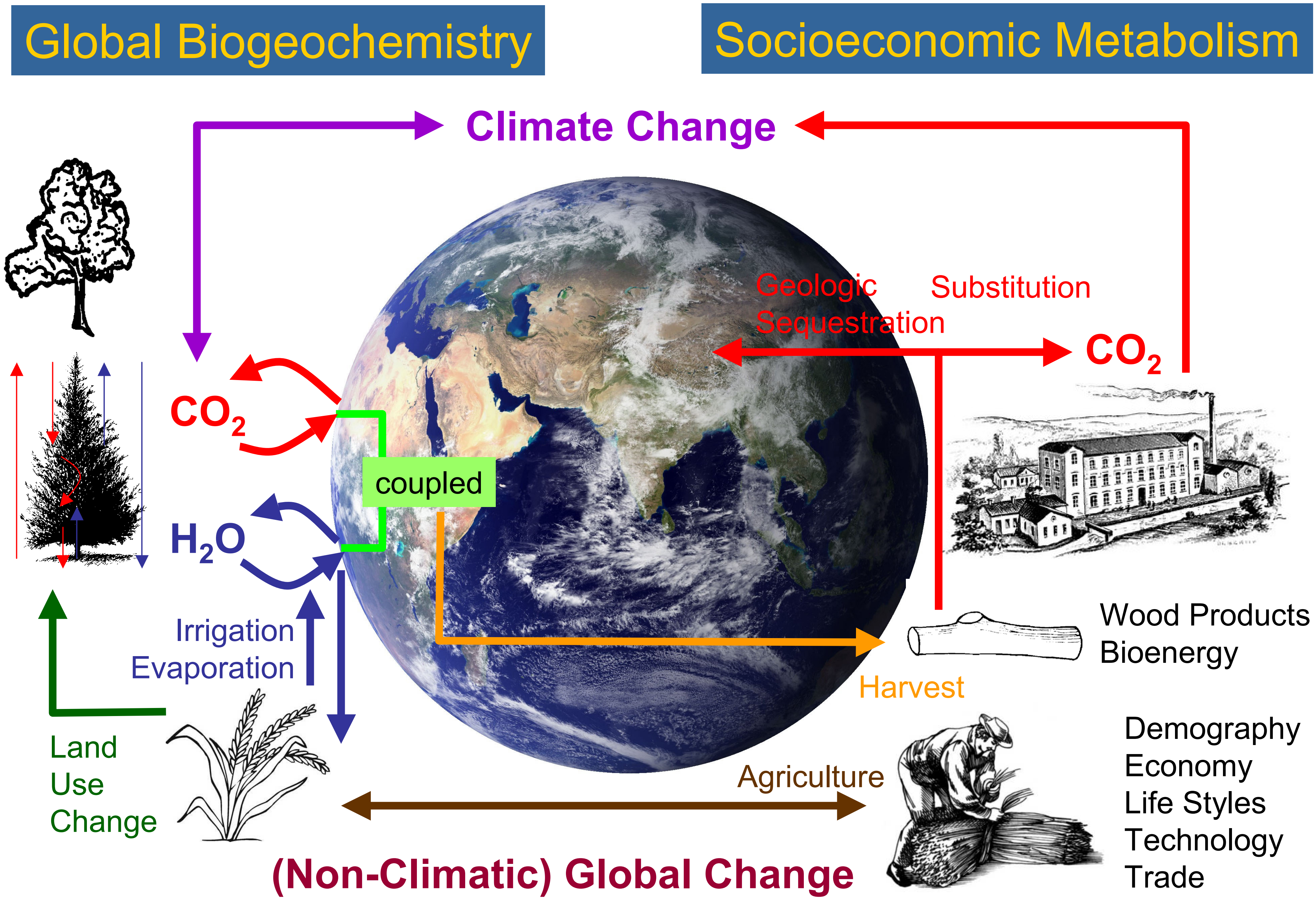
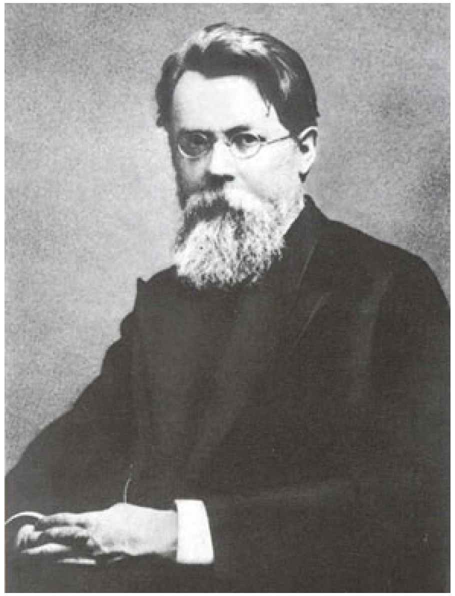



Fig. 2. Potential biomass supply for energy over time. Resource-focused studies are represented by hollow circles and circles. USEPA and HALL, who do not refer to any specific time, are placed at the left side of the diagram. IIASA-WE dashed lines respectively, with scenario variant names given without brackets at the right end of each line. The present a included for comparison. (The global consumption of oil, natural gas, coal, nuclear energy and hydro electricity 1999–2 consumption for energy is estimated at 35–55 EJ yr$^{-1}$ [44–46].)

Berndes et al., 2003



Global Biogeochemistry
Socioeconomic Metabolism
Climate Change
Geologic Sequestration
Substitution
$CO_2$
$CO_2$
coupled
$H_2O$
Irrigation
Evaporation
Land
Use
Change
Harvest
Wood Products
Bioenergy
Demography
Economy
Life Styles
Technology
Trade
Agriculture
(Non-Climatic) Global Change



Guiding Spirit for this section:
Vladimir I. Vernadski
1863 – 1945

# - 3 - Biogeochemistry, the Earth as a System and the human quest to understand it

**Vernadsky, in his 1926 book „The Biosphere“, was an early pioneer of many things still discussed today**

„There is no substantial chemical equilibrium on the crust [of Earth] in which the influence of life is not evident, and in which chemistry does not display life‘s work.“ (sec. 21)

Emergence of biogeochemistry as a discipline.

„Life is not an external or accidental phenomenon of the Earth‘s crust. It is closely bound to the structure of the crust, forms part of its mechanism, and fulfills functions of prime importance to the existence of this mechanism.“ (sec. 21)

Gaia hypothesis, since 1960ies

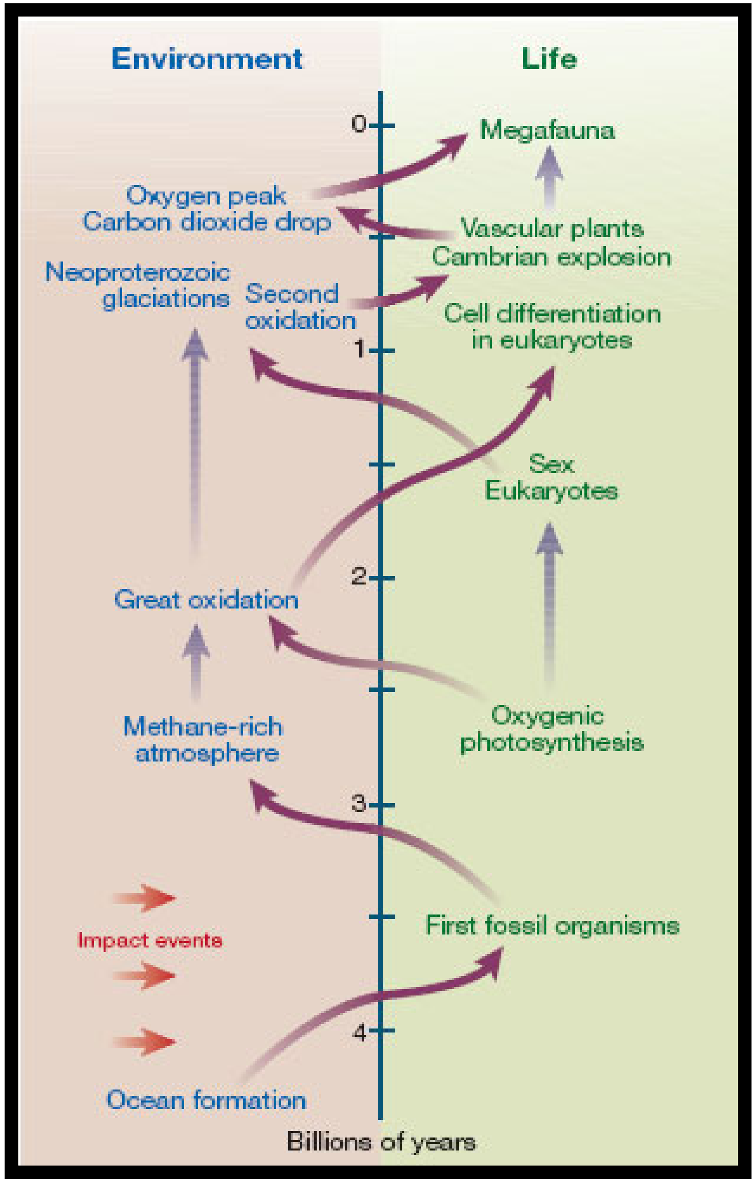
„Civilized humanity has intorduced changes into the structure of the film [of life] on land […] These changes are a new phenomenon in geological history, and have chemical effects yet to be determined. One of the principal changes is the systematic destruction during human history of forest […].“ (sec. 150)

The „Anthropocene“, since 1990ies

# The Earth as a System: Co-Evolution

Lenton et al., 2004

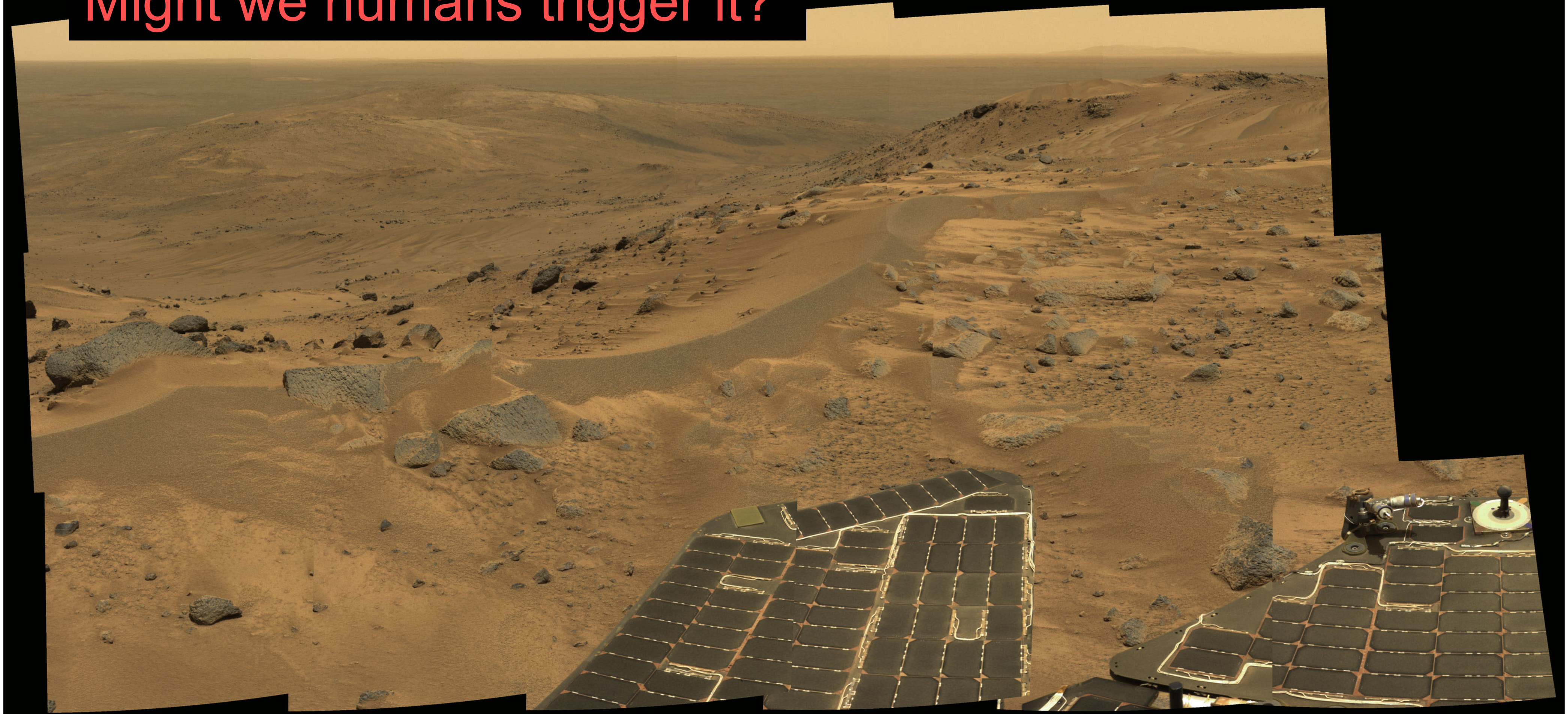
Since the oceans began to exist and extraterrestrial disturbences decreased in frequency
life has evolved closely interlinked with its environment.




**Gaia hypothesis:** Earth as a biochemically and biophysically self-regulating and self-sustaining „super-organism“:

„Organisms and their abiotic environment evolve as a single coupled system, from which self-sustaining autoregulation emerges that maintains climate and the chemical composition of the environment in a state that of habitability.“
(J. Lovelock, 1972)

What happened on Mars?
Can it happen on Earth?
Might we humans trigger it?

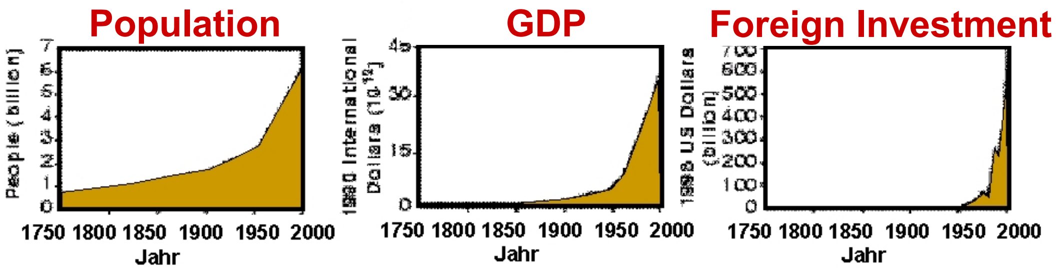


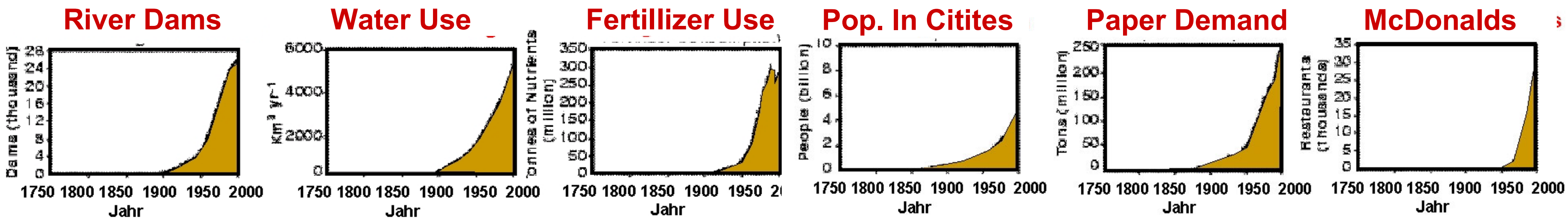
Is a planetary biosphere the exception or the rule?
Is the persistence of the Earth‘s biosphere an exception or the rule?

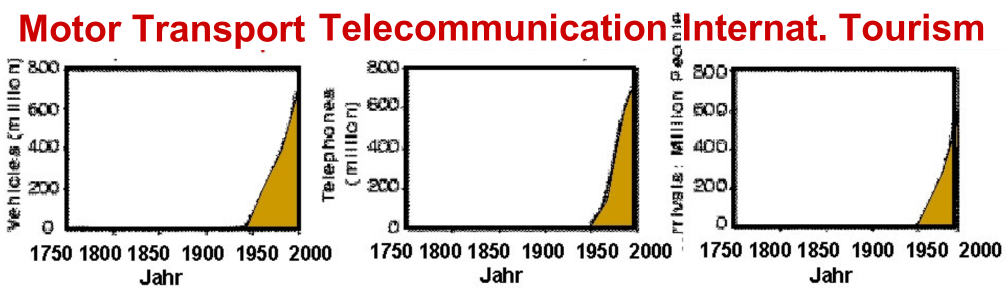
# Enter: Humans

**„The Anthropocene“**

(Crutzen and Störmer, 2000)



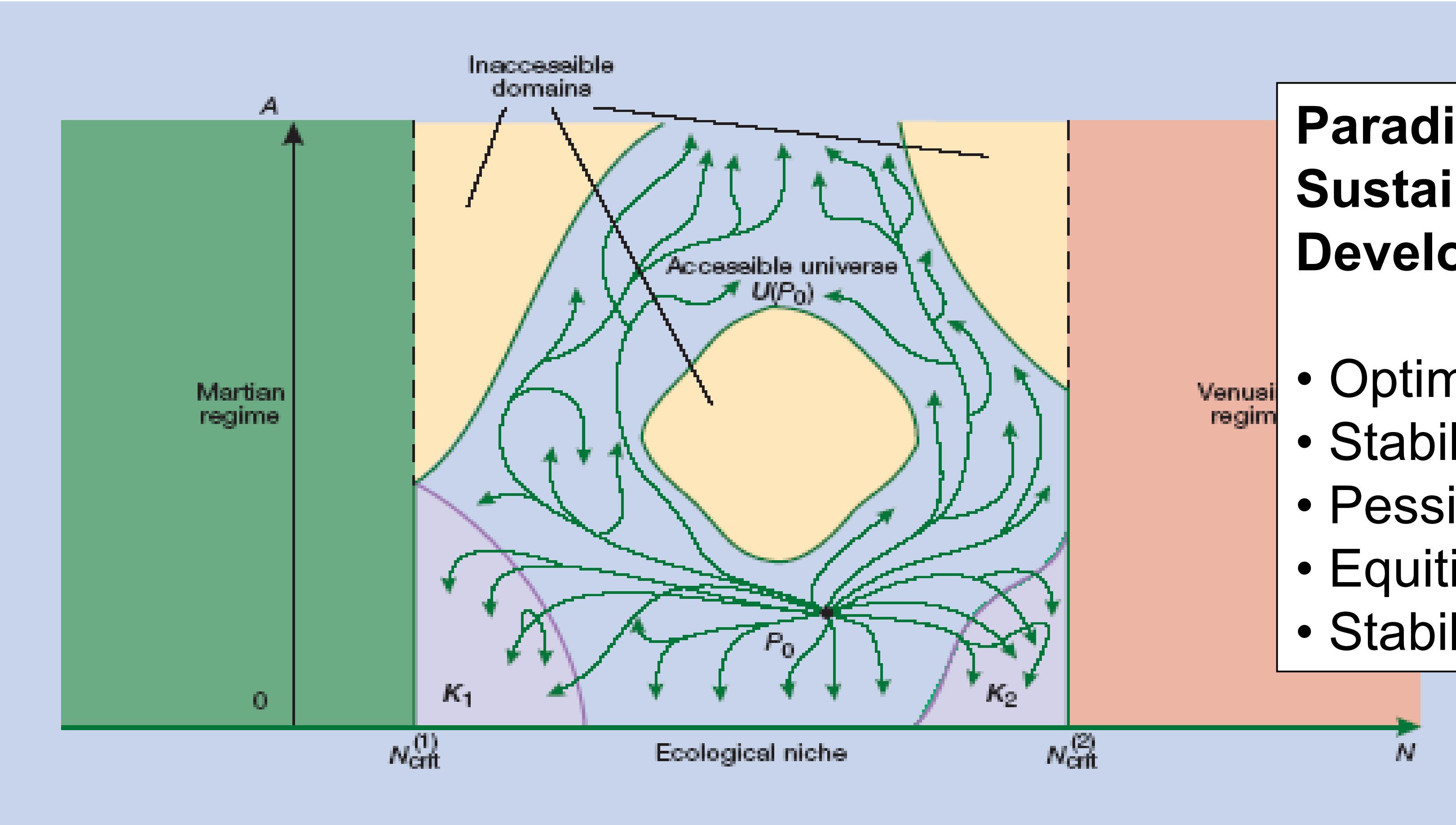




## What are the biogeochemical consequences?

## What are the consequences for Earth system evolution?

Crutzen and Steffen, 2004

## Can we understand this system?
## Can we understand the influence of human interventions?
## Can we consciously manage the system?



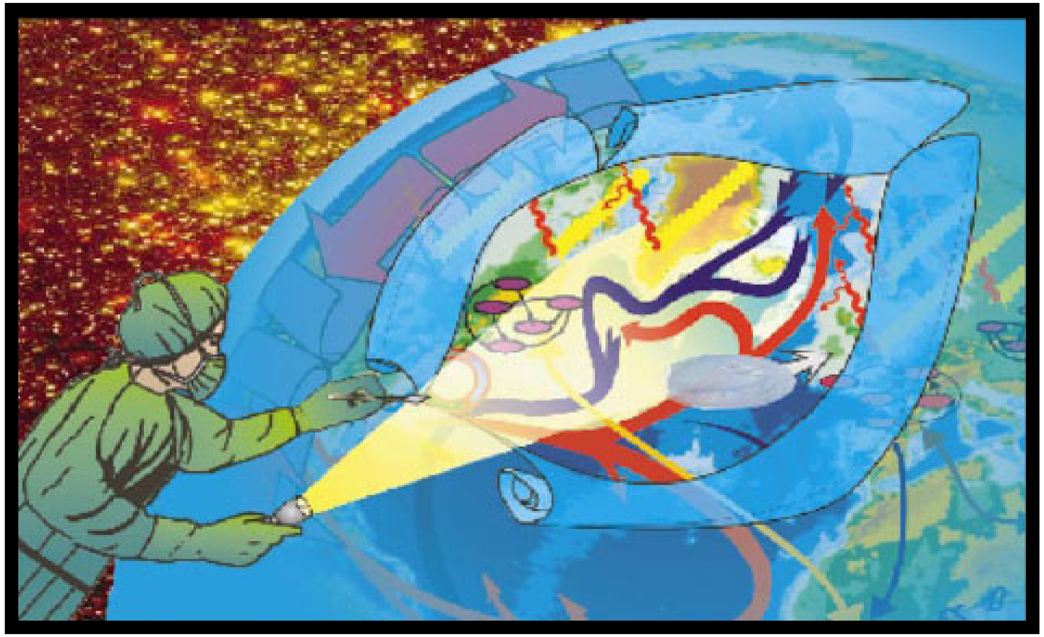

**Paradigms for Sustainable Development**

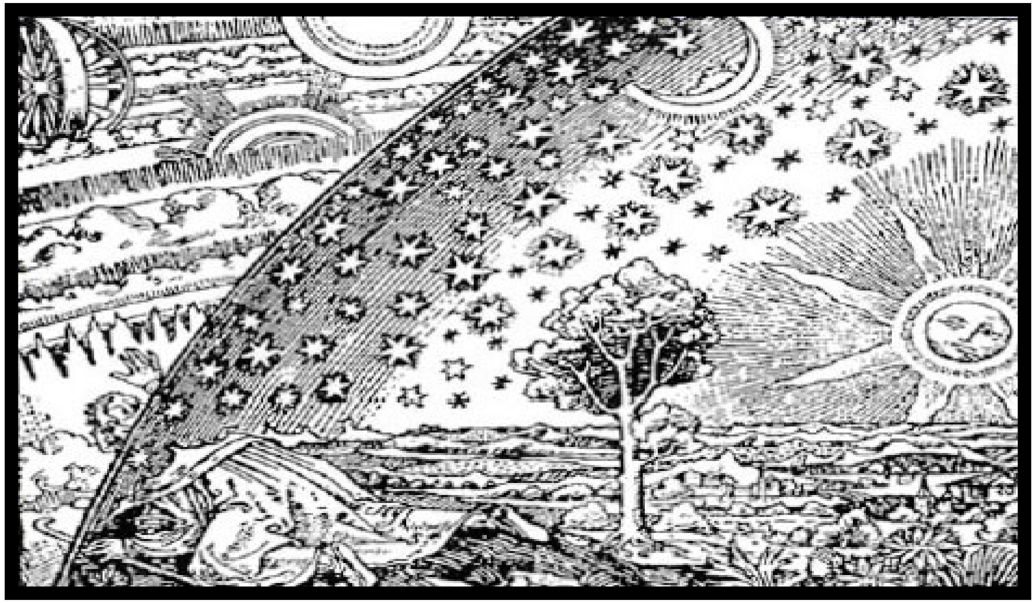
- Optimization
- Stabilization
- Pessimization
- Equitization
- Stabilization

**dN/dt = f(N)** **dN/dt = f(N,A)** **dN/dt=f(N,A,S) „Global Subject(s)“**

# Perceiving the Earth as a System

Scientific and technological advances permit for the first time to gain a ‚holistic‘ view of our planet.



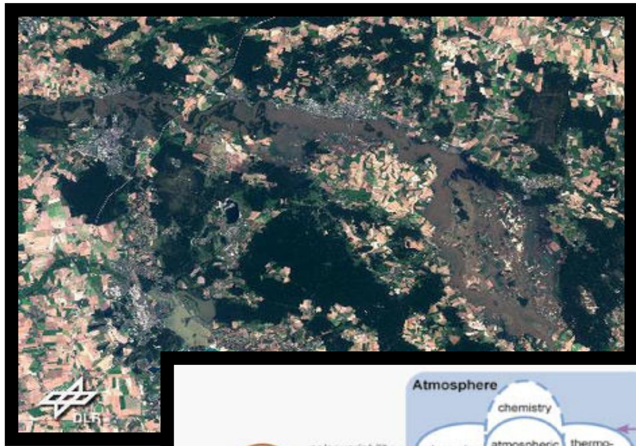


„…it will enable us to look back on our planet to perceive one single, complex, dissipative, dynamic entity,far from thermodynamic equilibrium — the‘Earth system’

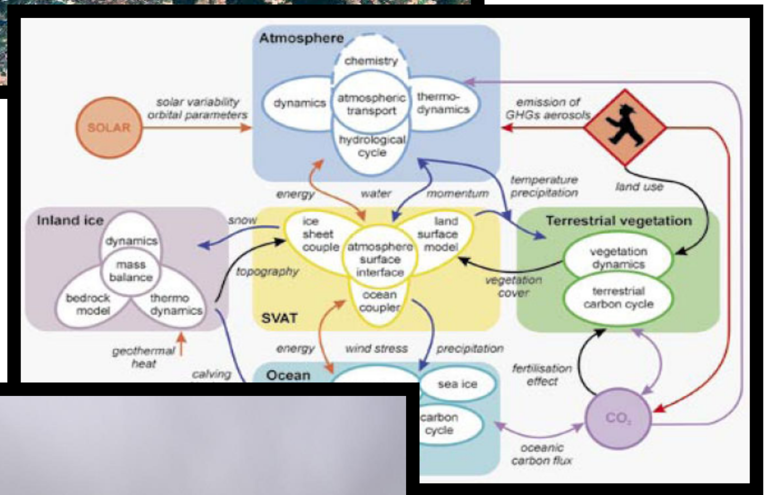
**„2nd Copernican Revolution“**
(Schellnhuber, 1999)

# The new „Macroscopes“:

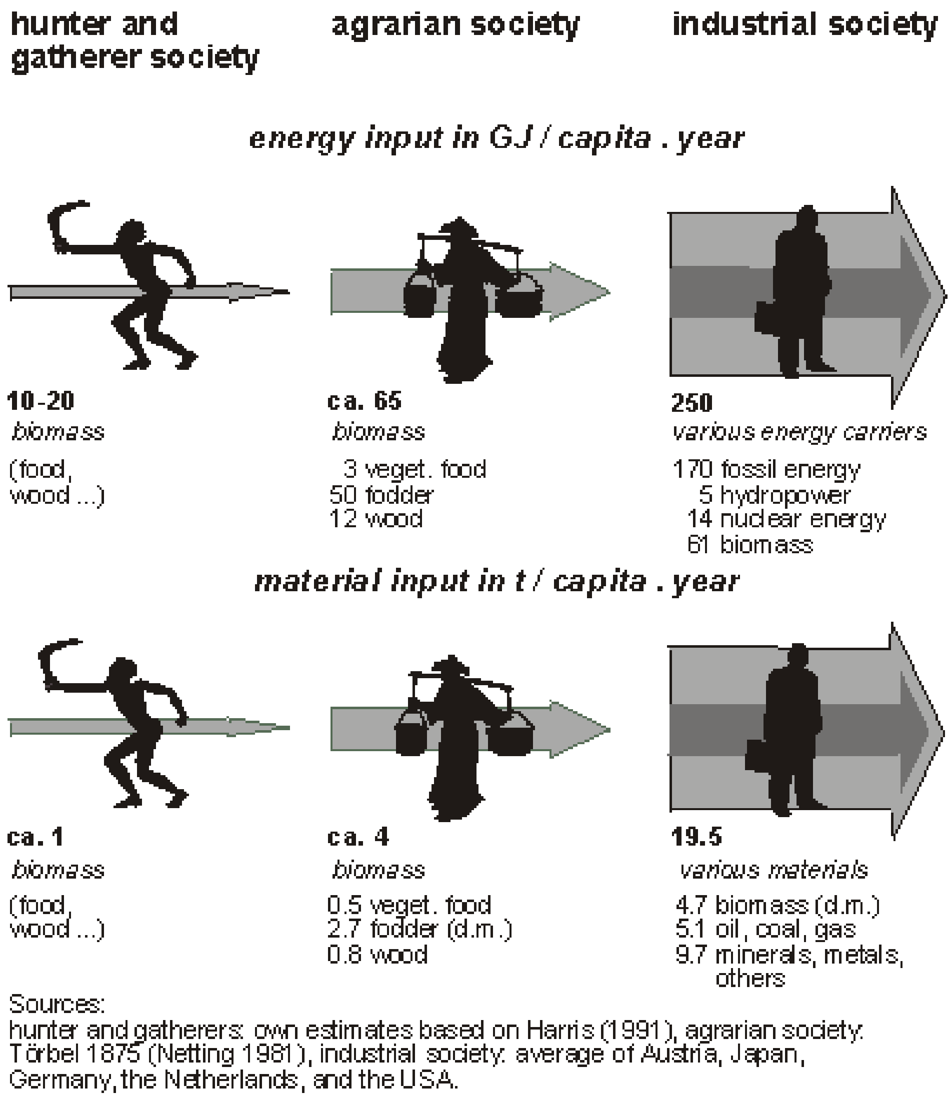
1. **‚Bird’s-eye’ principle**
   (Remote sensing)



2. **‚Digital-mimicry‘ principle**
   (Intermediate complexity modelling)




3. **‚Lilliput‘ principle**
   (Bio-spheres, field manipulation studies)




## One possible goal is certain and is biogeochemical:

## Constraining Societal Metabolism

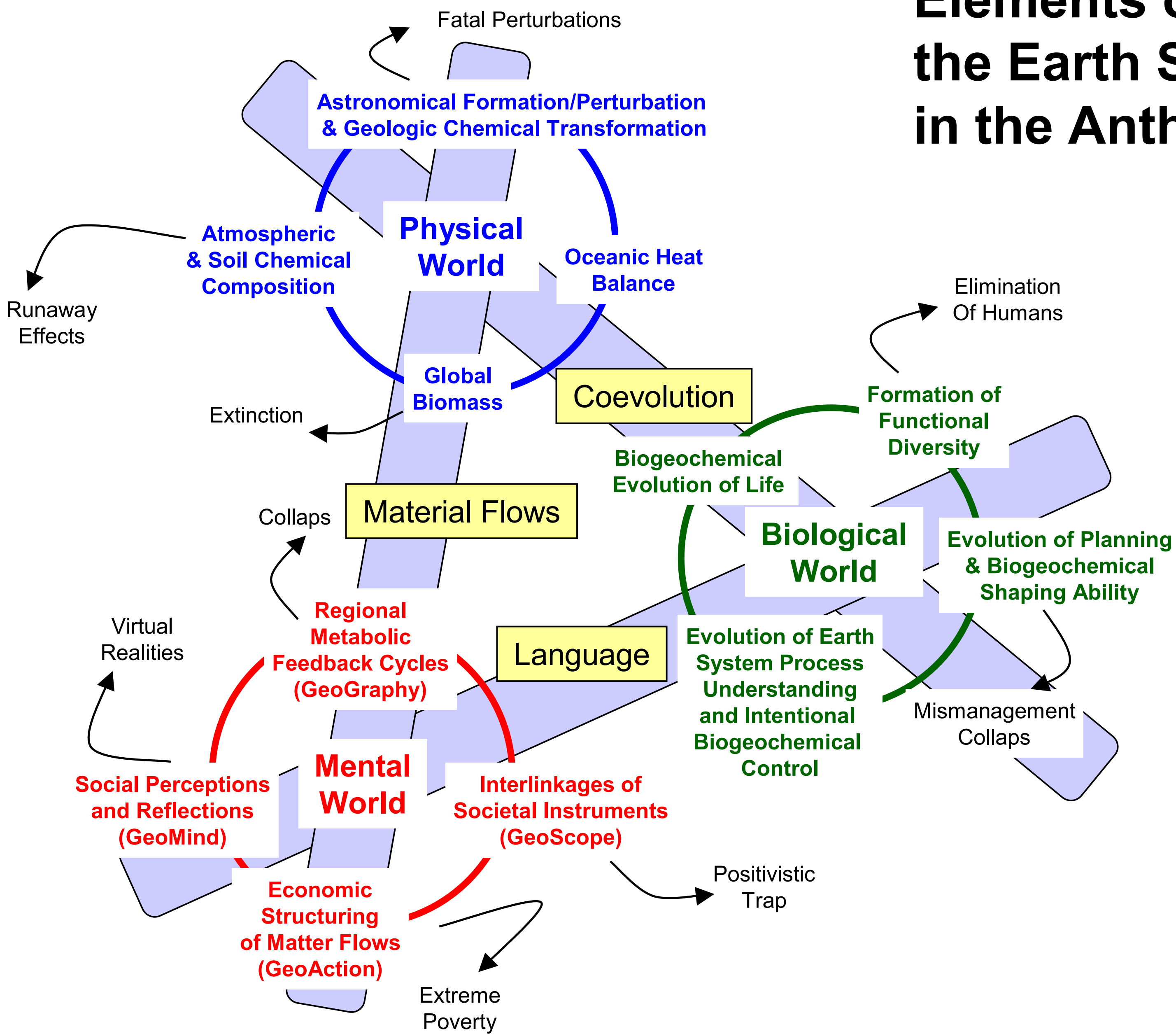
**Can we, for the first time, achieve a transition to smaller material intensity as we move forward?**

- **Dematerialization**
- **Decarbonization**

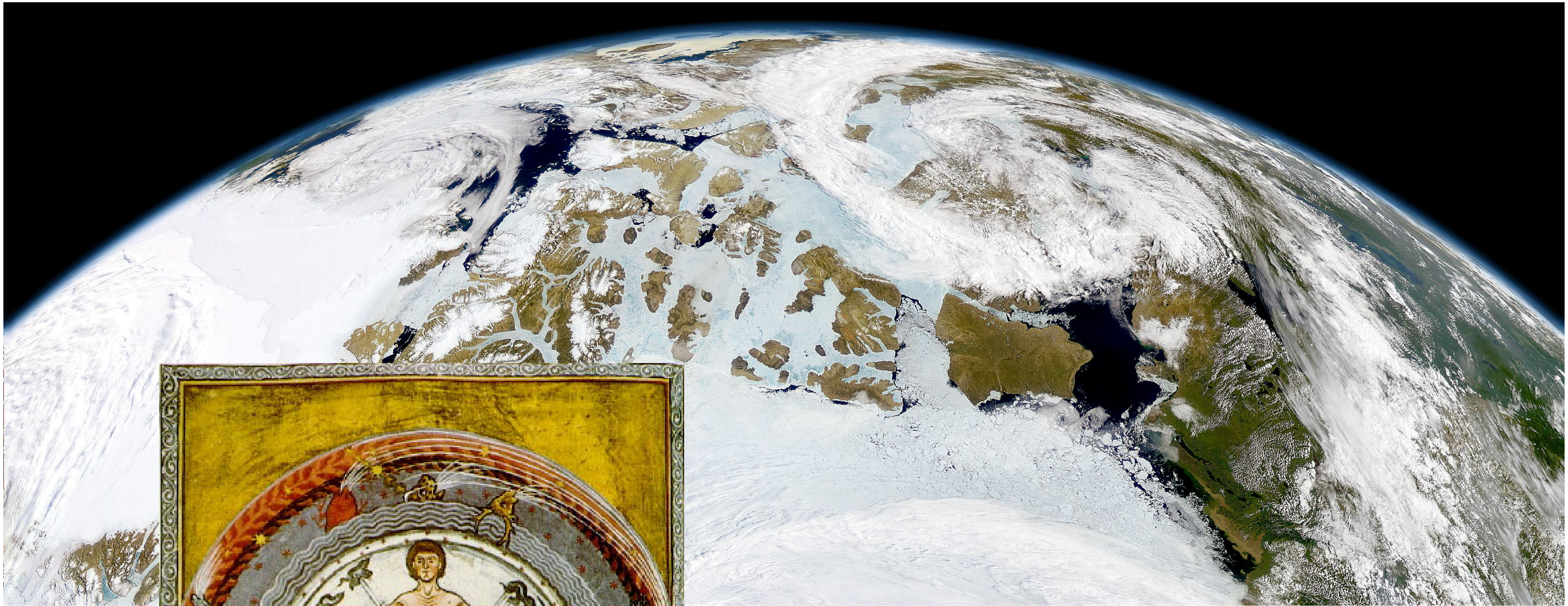
**Under limited resources:**

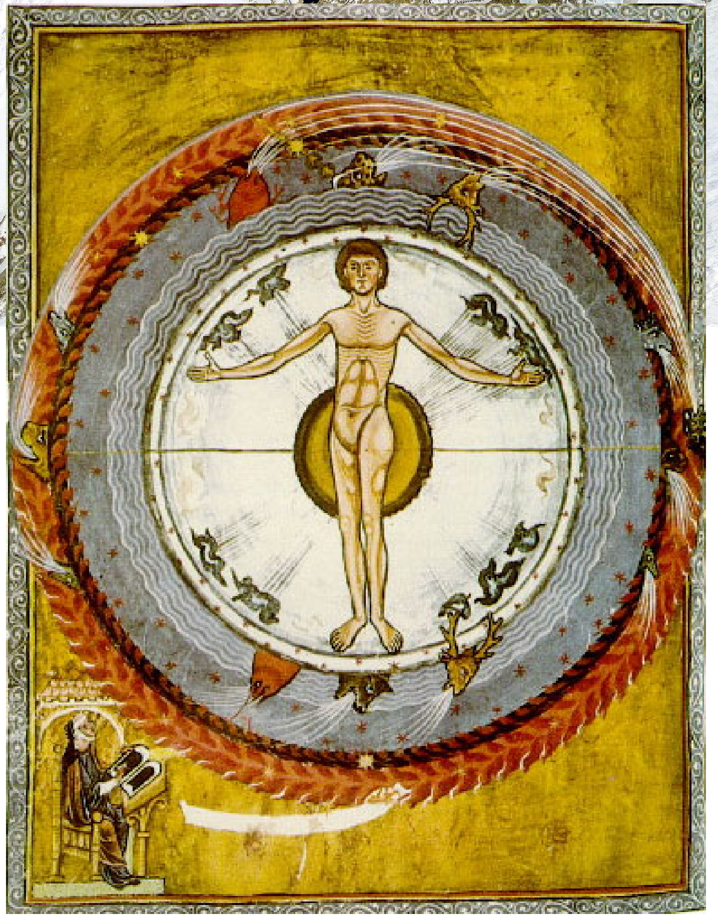
- **Adapt to nature**
- **Adapt nature to us**
- **Separate from nature**

# Elements of the Earth System in the Anthropocene




Lucht and Pachauri, 2004





**What we need is:**

**A comprehensive view of the planet and of human existence.**

Thanks to Dieter Gerten, Sibyll Schaphoff, Alberte Bondeau, Stephen Sitch, Wolfgang Cramer, Birgit Schröder, Christoph Müller, Christian Beer, Tim Erbrecht, Werner von Bloh