esa

# → EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

# Observations of the terrestrial carbon cycle

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CTCD Centre for Terrestrial Carbon Dynamics

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

# Lecture content

Measuring the global C balance and its components

- Atmospheric observations of $CO_2$
- Using satellite data to improve estimates of carbon fluxes from the land
- Using satellite data to improve estimates of carbon fluxes from the ocean
- New missions and challenges

# Fate of anthropogenic $CO_2$ emissions (2007–2016)

**Sources = Sinks**

34.4 ±1.8 $GtCO_2$/yr
88%

4.8 ± 2.6 $GtCO_2$/yr
12%

17.2 ±0.4 $GtCO_2$/yr
46%

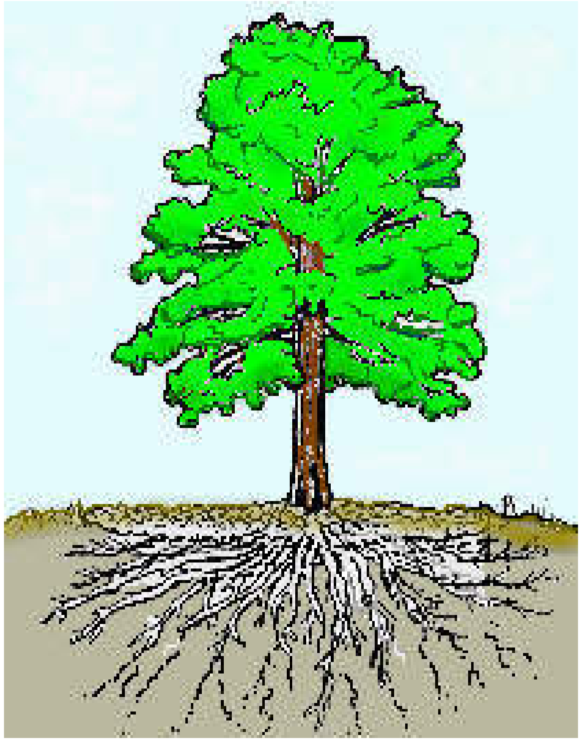
11.0 ± 2.9 $GtCO_2$/yr
30%

8.8 ± 1.8 $GtCO_2$/yr
24%

Budget Imbalance = difference between estimated sources & sinks

2.2 ± 4.3 $GtCO_2$/yr
6%

# The Role of Vegetation & Soils in the C Balance



**Terms**:

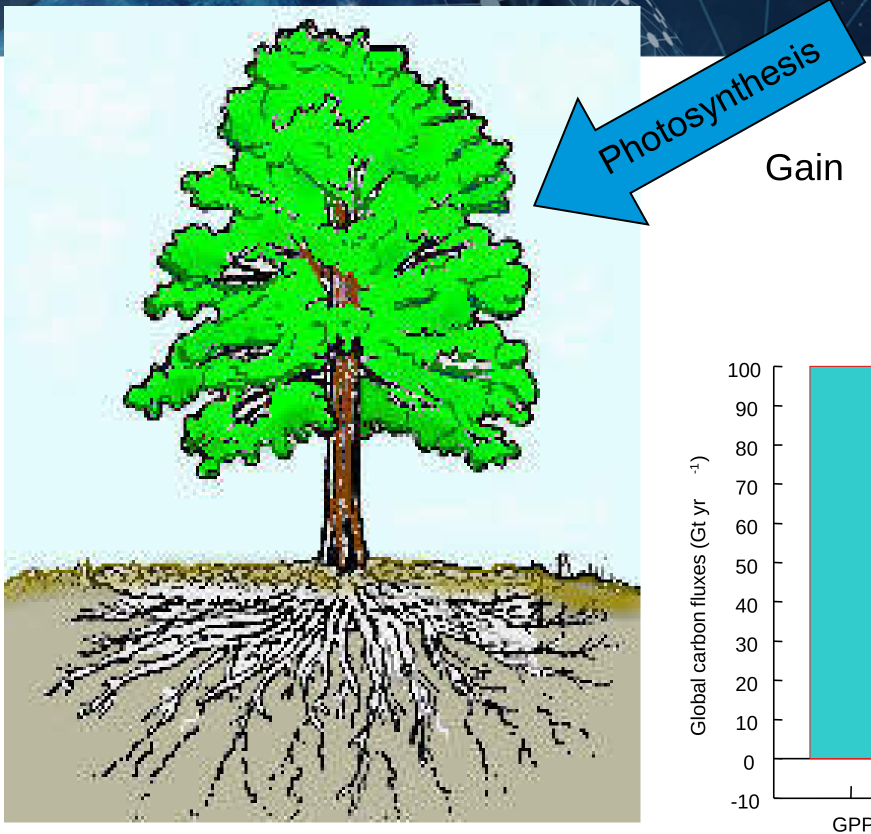
- Above Ground Biomass (AGB)
- Above Ground Biomass (BGB)
- Litter
- Soil Carbon (Organic Matter: SOM)

# Components of the Terrestrial Carbon Balance

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

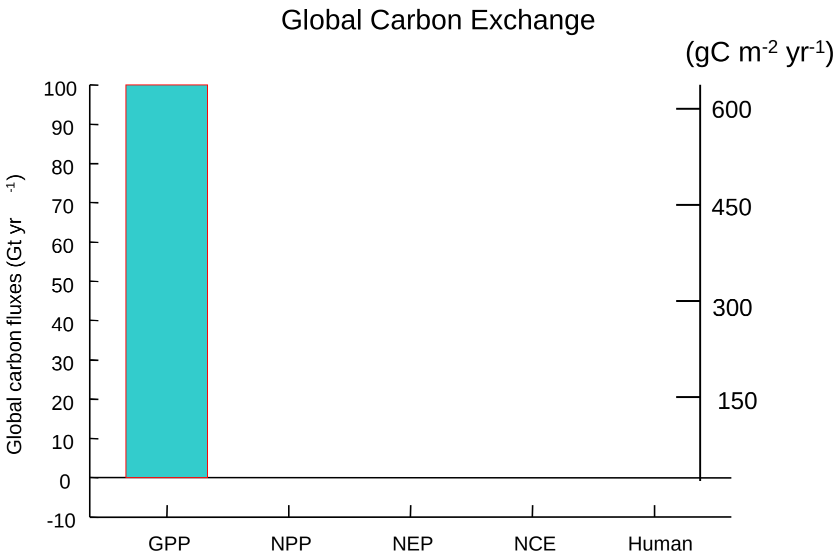
**Process equation**: $\Delta C = P - R_P - R_H - D$

| | |
|---|---|
| $\Delta C$ | carbon sequestration by vegetation and soil (+ve = carbon sink; -ve = carbon source) |
| $B$ | biomass (*A*: above and *B*: below ground), |
| $L$ | litter, |
| $S$ | soil carbon, |
| $P$ | photosynthesis, |
| $R$ | respiration (*P*: plant and *H*: heterotrophic), |
| $D$ | carbon loss by disturbance. |




Gross Primary Production

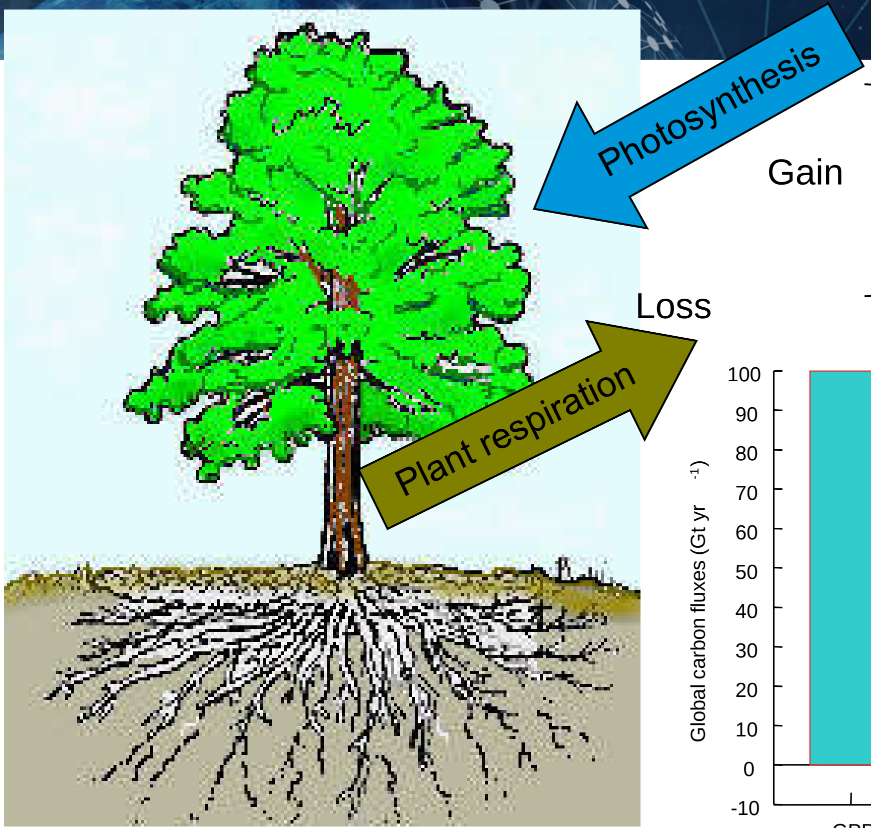
Gain



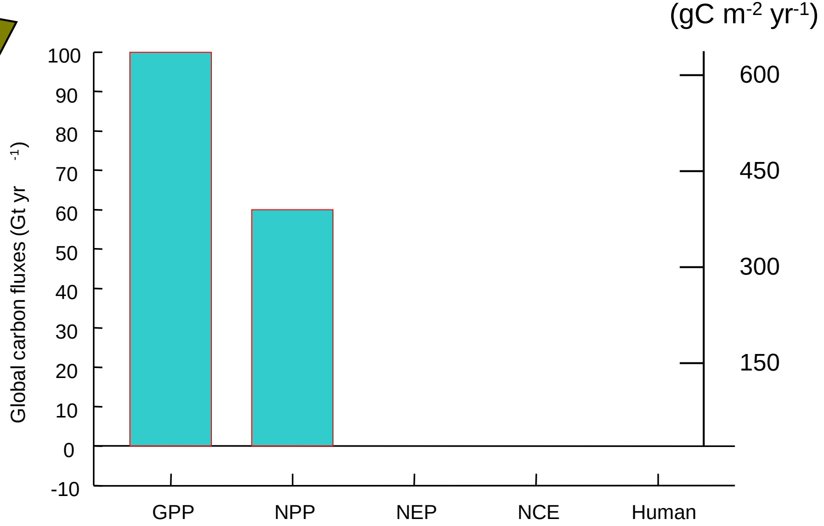
## Net Primary Production

Gain

Loss




Global Carbon Exchange

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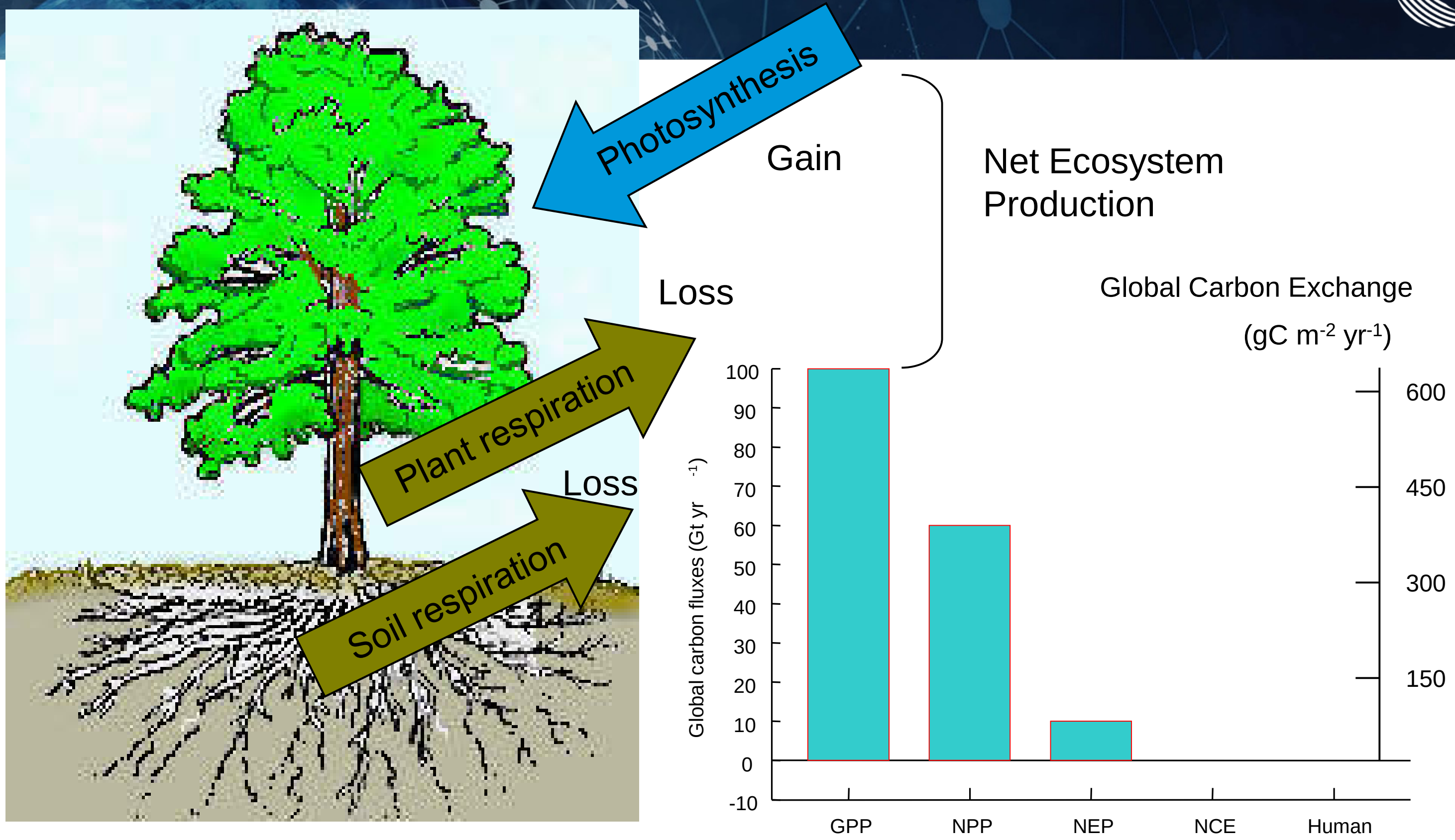


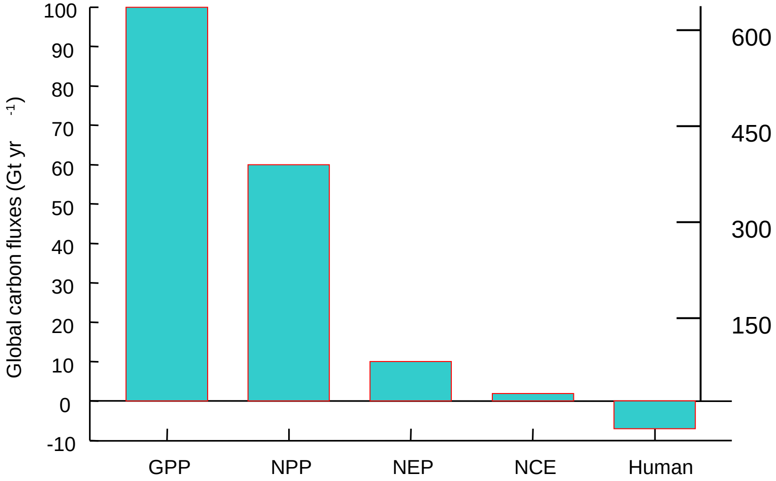
Photosynthesis
Gain
Net Ecosystem Production
Loss
Plant respiration
Loss
Soil respiration
Global Carbon Exchange
(gC m-2 yr-1)
Global carbon fluxes (Gt yr -1)
100
90
80
70
60
50
40
30
20
10
0
-10
600
450
300
150
GPP
NPP
NEP
NCE
Human

# Disturbance Flux


Net Carbon Exchange
OR
Net Biome Production

Global Carbon Exchange

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



# Components of the Terrestrial Carbon Balance

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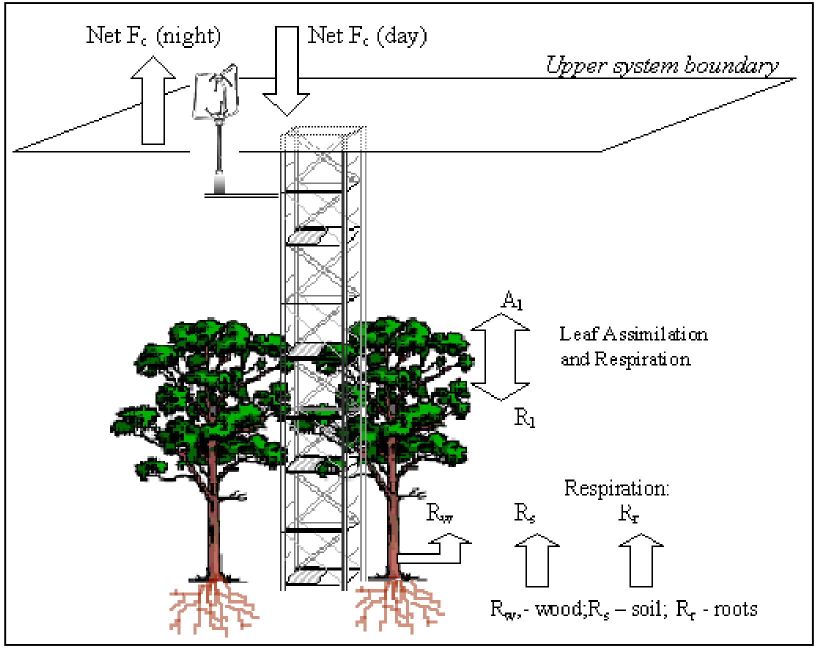
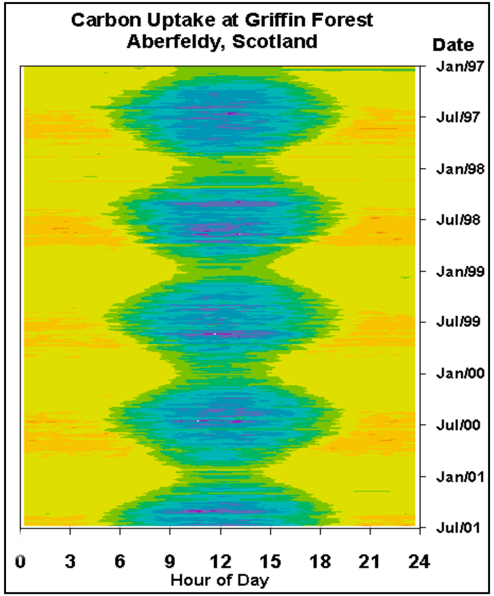
# Decomposing the carbon balance

$\Delta C$: The atmosphere (the integrator)

# Eddy covariance: $CO_2$ and $H_2O$ fluxes

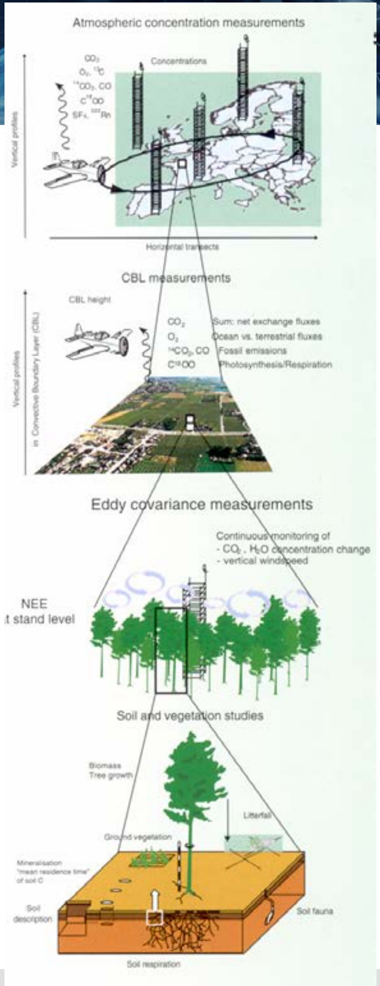



| Losses | Gains |
|---|---|
| g C $m^{-2}$ | $hour^{-1}$ |
| | 0.64 – 0.80 |
| | 0.48 – 0.64 |
| -0.48 – -0.32 | 0.32 – 0.48 |
| -0.32 – -0.16 | 0.16 – 0.32 |
| -0.16 – 0.0 | 0.0 – 0.16 |

CTCD Centre *for* Terrestrial Carbon Dynamics

# Top down vs bottom up



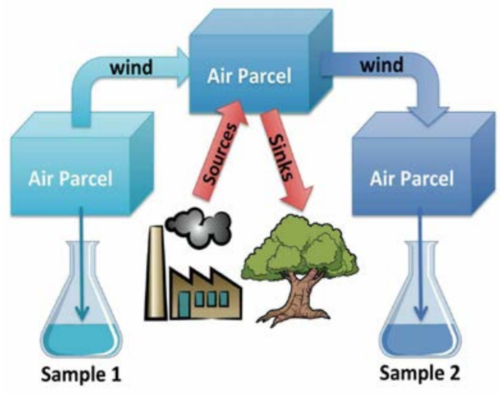

Atmospheric signal, tall towers (minus fossil fuels)

The same result ?

Terrestrial signal, eddy covariance, upscale

# Role of Atmospheric Measurements

- Atmosphere is a powerful integrator of surface fluxes
- Measurement of concentrations (gradients) provides strong constraint on regional carbon exchange between surface and atmosphere
- Well tested approach using in situ networks but global coverage too sparse

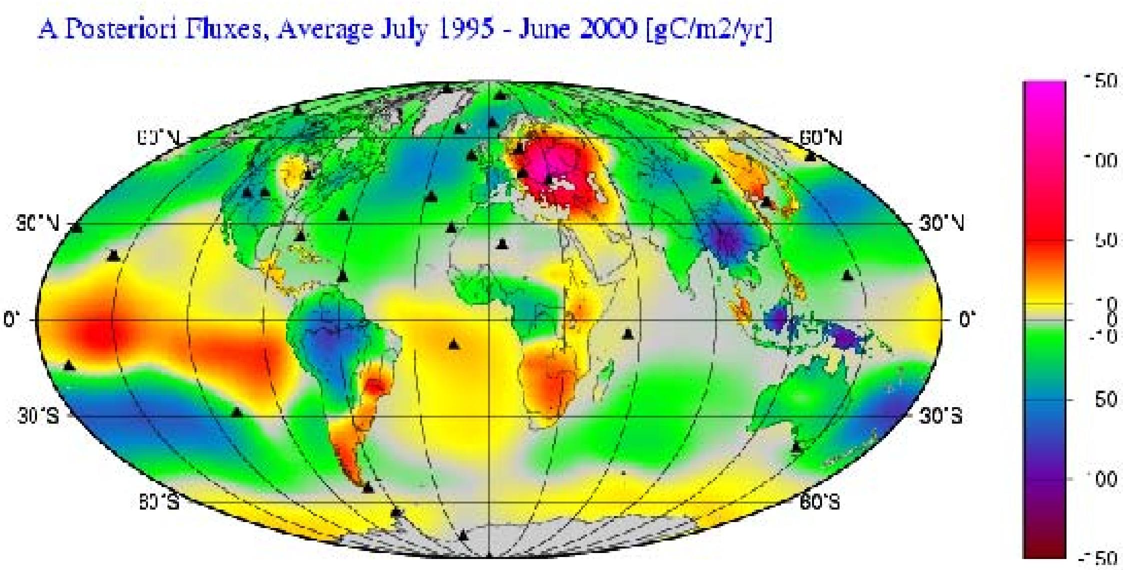



**Surface Networks**

NOAA


ICOS

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




**Sources red and yellow**

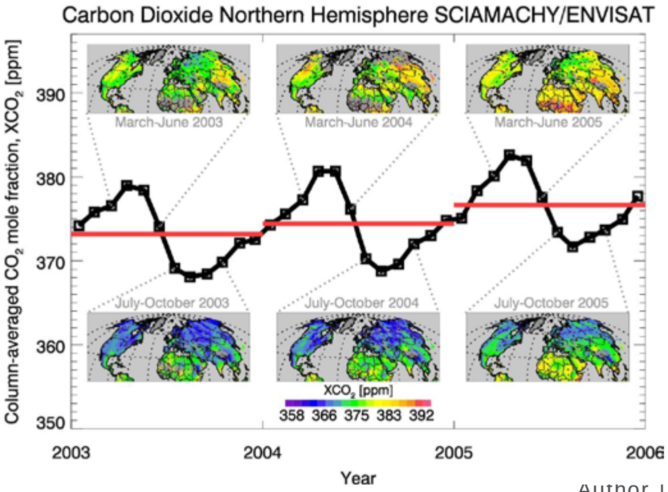
**Sinks green and blue**

**Fossil fuels not included**

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

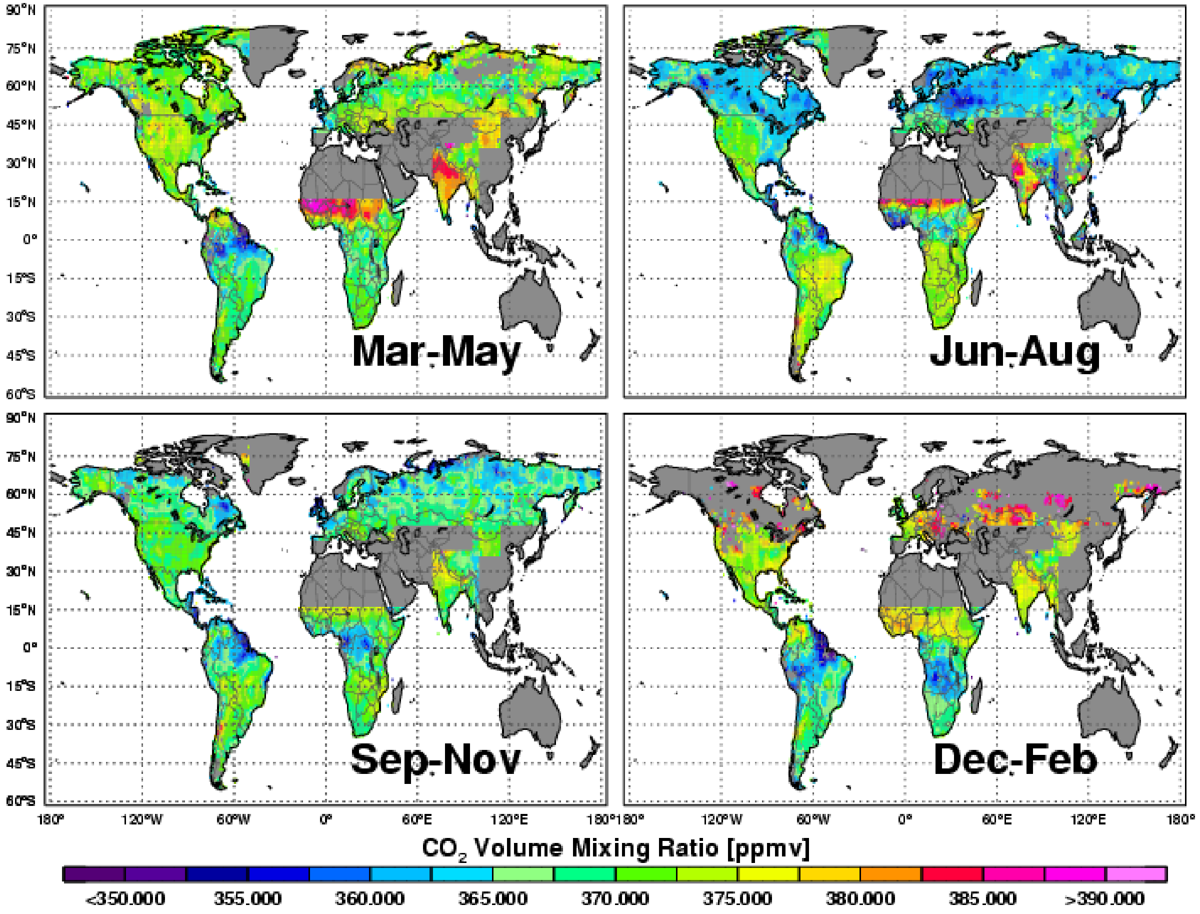
# Atmospheric carbon dioxide from space

**First global satellite observations of total atmospheric $CO_2$ (SCIAMACHY/ ENVISAT)**

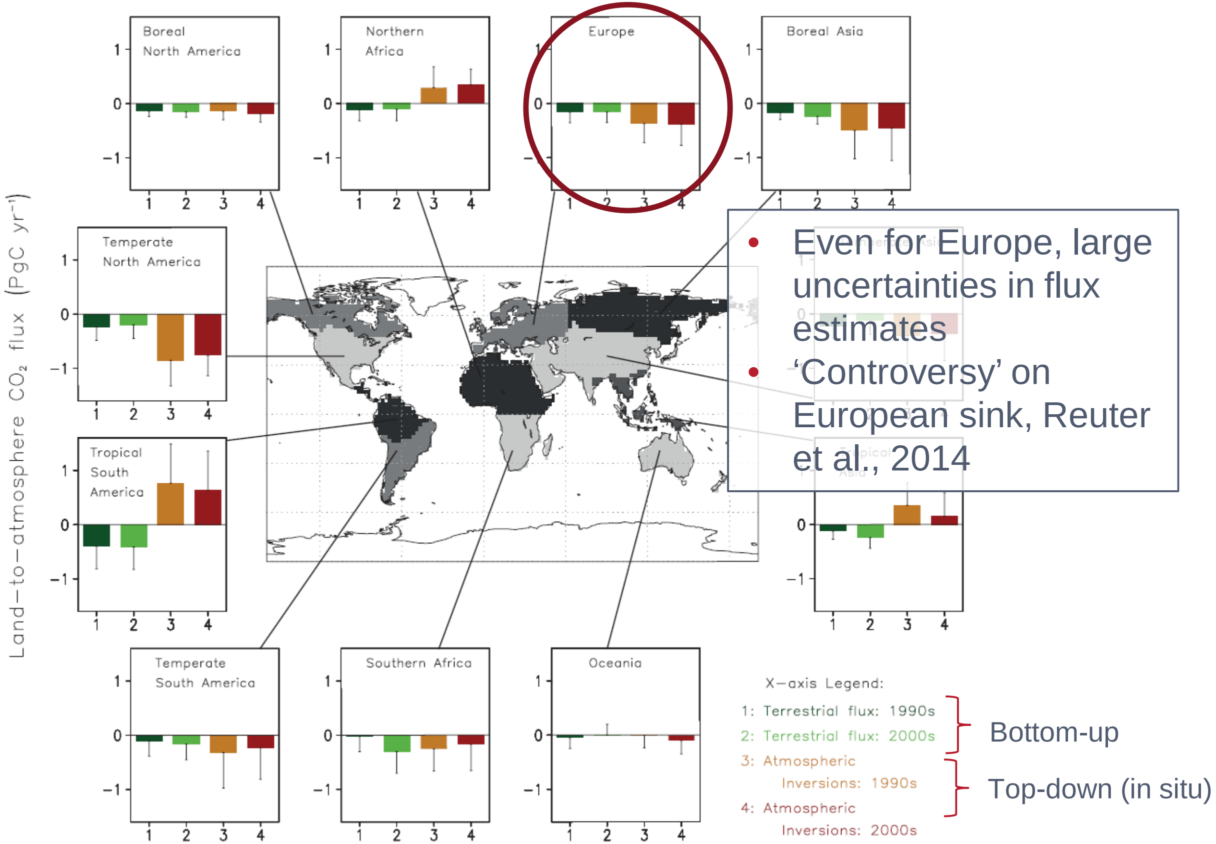



Buchwitz et al, 2007

# Seasonal variability in atmospheric $CO_2$



# Better Understanding of Regional Fluxes is Needed




- Even for Europe, large uncertainties in flux estimates
- ‘Controversy’ on European sink, Reuter et al., 2014

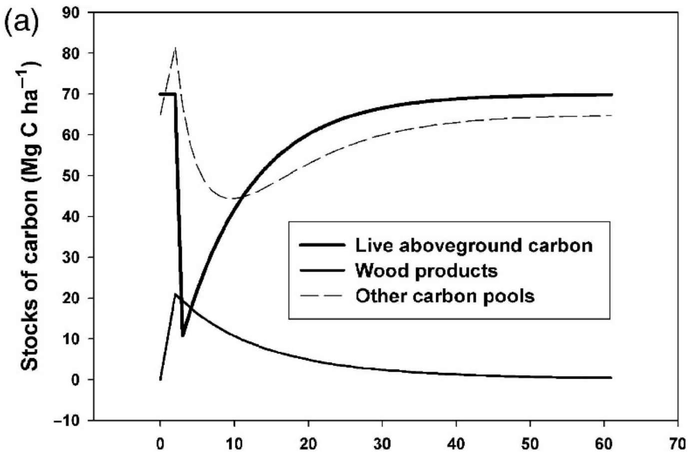
# Decomposing the carbon balance

$\Delta B$: The mass balance equation

P & D: The process equation

# Calculating carbon emissions from land use change

$$C_{em} = \sum_{i=1}^{m} A_i \cdot B_i \cdot E_i$$




Houghton, 2005 years

$C_{em}$ = Carbon emission from deforestation
$A_i$ = Area of deforestation
$B_i$ = Biomass
$E_i$ = Efficiency factor
m = number of forest types
(UNFCCC Good Practice Guide 2003)

The book-keeping approach: each land use change event launches a sequence of carbon processes.
Requires:

- mapping of change at scale of disturbance through time.
- a known value of biomass in disturbed area.

# Rondônia, Brazil


1975



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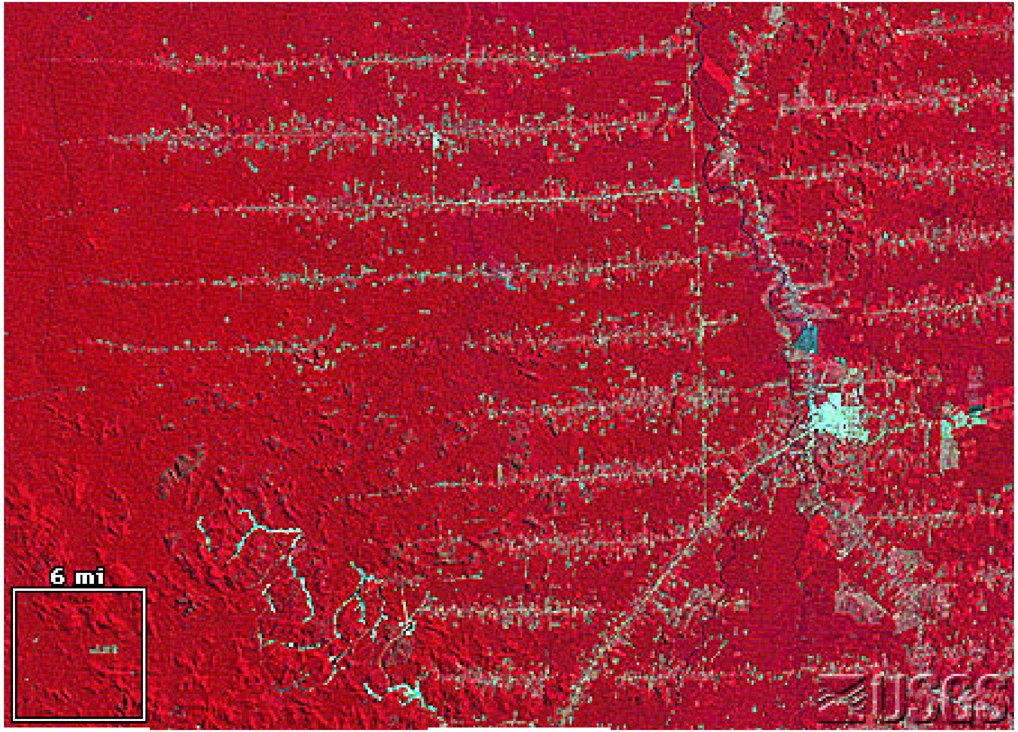
# Rondônia, Brazil




1986



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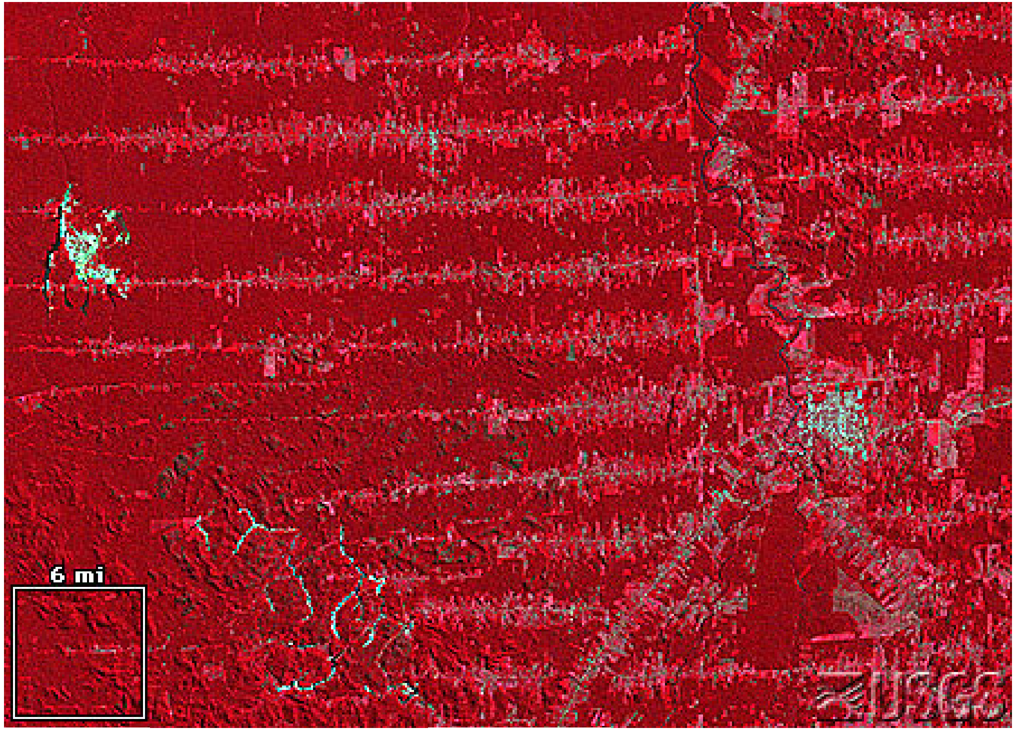
# Rondônia, Brazil

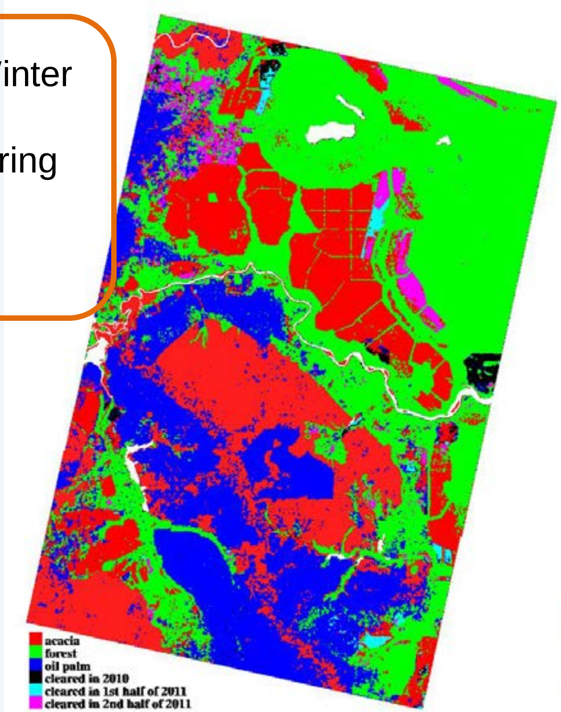



1992

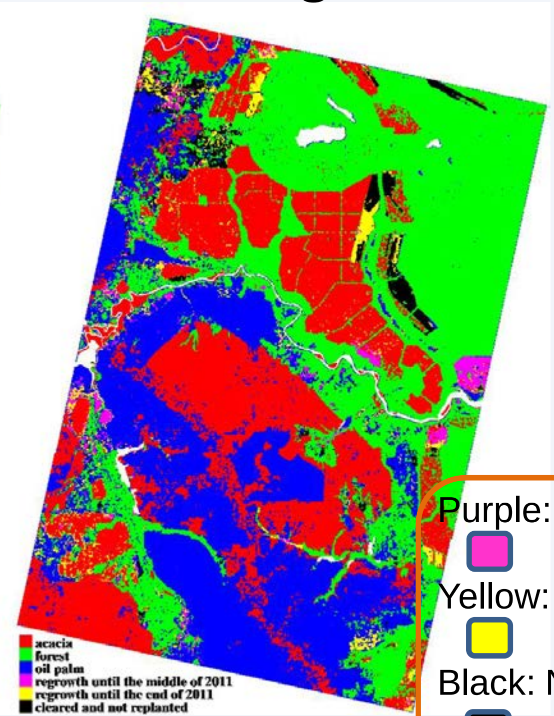
# Plantation Management

Black: Winter
Cyan: Spring
Purple: Summer

## Clearance

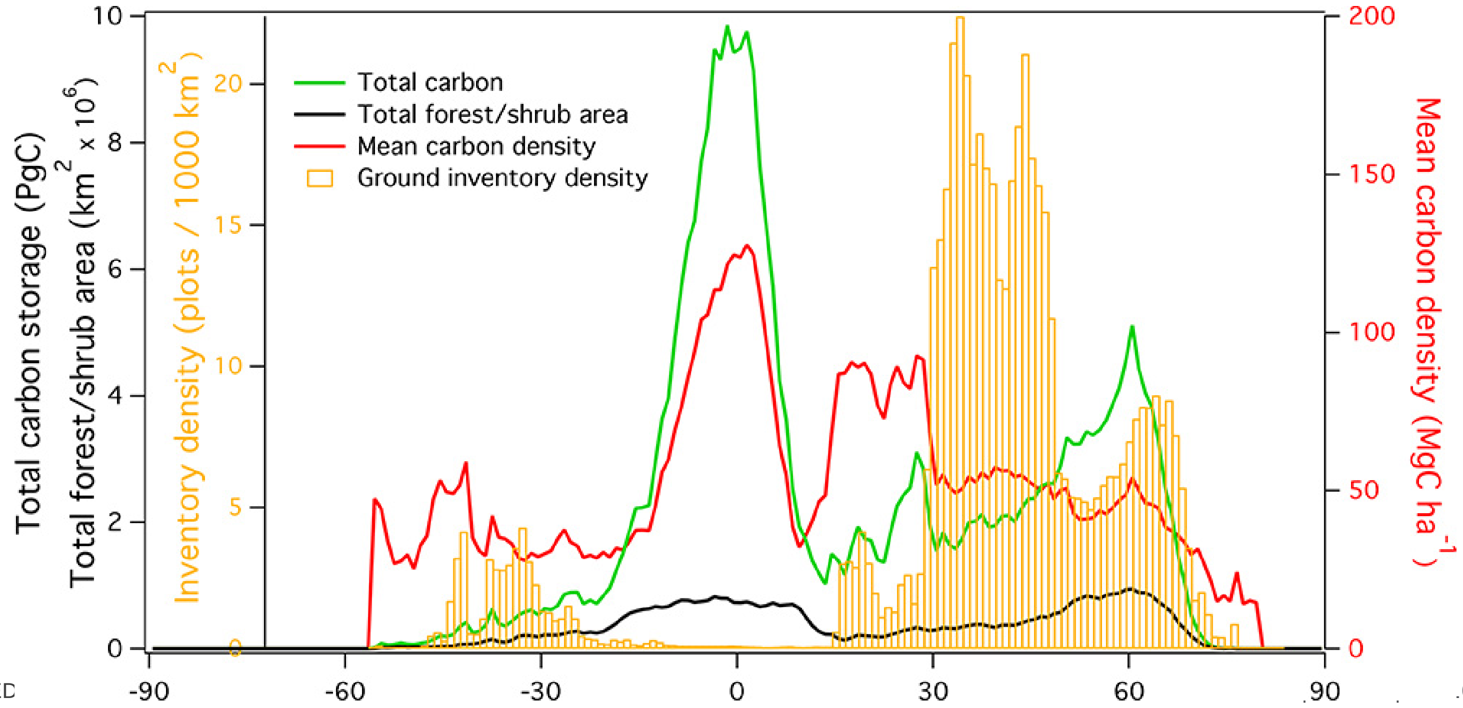



## Regrowth

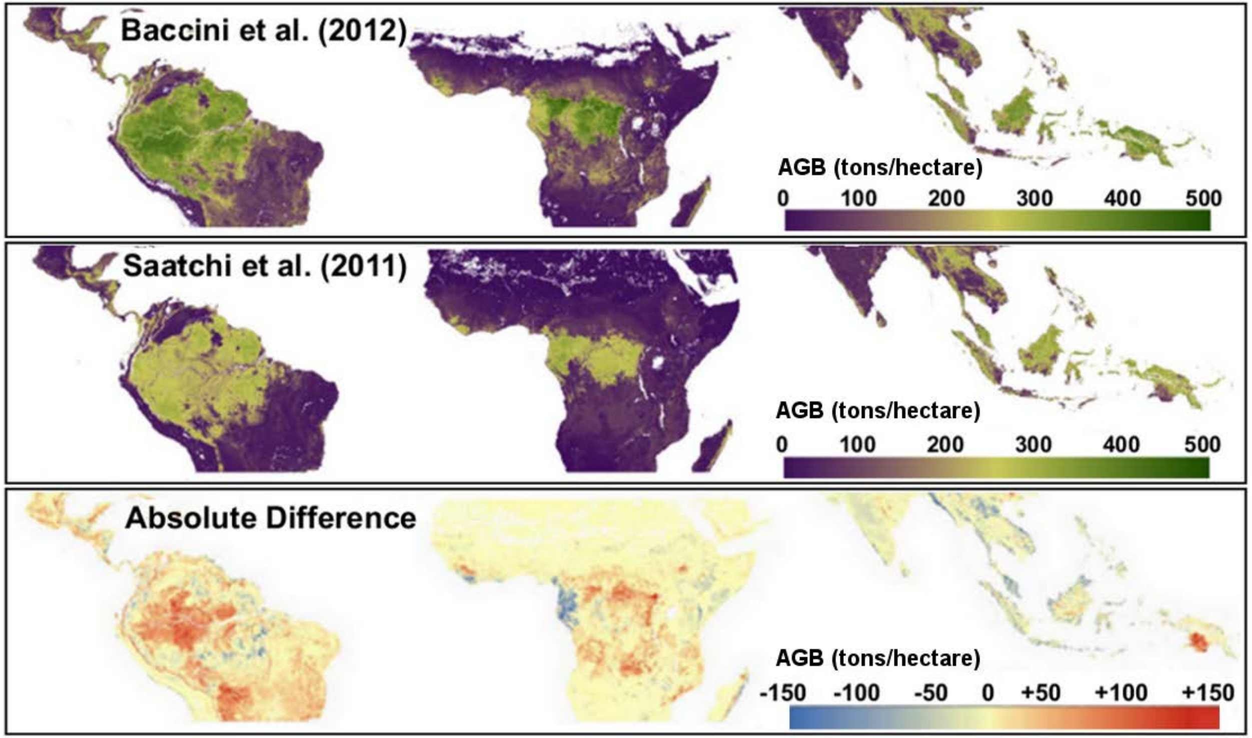



Purple: Spring
Yellow: Summer
Black: Not replanted

# State of Carbon and Inventory of Global Forests



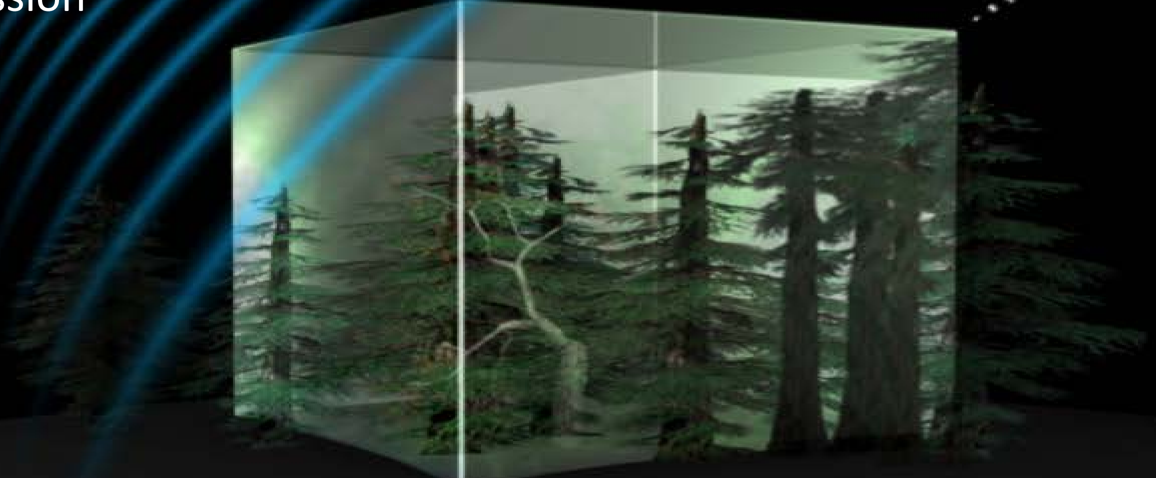
# Latest tropical biomass maps use height data from satellite lidar but have large biases




Largely based on ICEsat – failed in 2009 esa

# biomass

ESA's 7th Earth Explorer mission



EARTH EXPLORER 7 USER CONSULTATION MEETING

An Earth Explorer to observe forest biomass

European Space Agency

# Carbon emission estimates from deforestation and degradation are uncertain

Gross carbon emissions



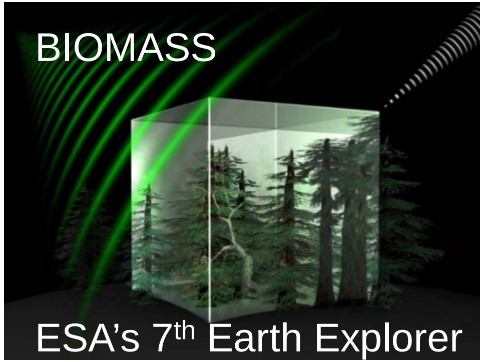
$$\Delta C = \sum \Delta A \cdot B \cdot E + \sum A \cdot \Delta B \cdot E$$

*where A is the area of forest type, with biomass B and an emission efficiency factor E*

BIOMASS will provide a direct measurement of biomass change exactly where deforestation and degradation occur

# Forest structure and biomass missions: where we'll be in 4 year's time

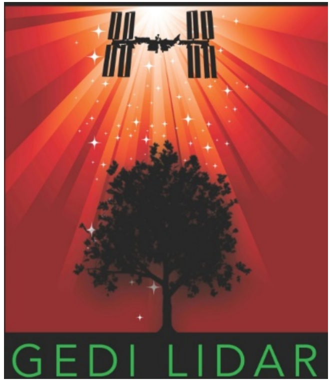
Forest biomass & height




NISAR
NASA - ISRO SAR Mission

Forest structure & lower level biomass

Forest structure & biomass

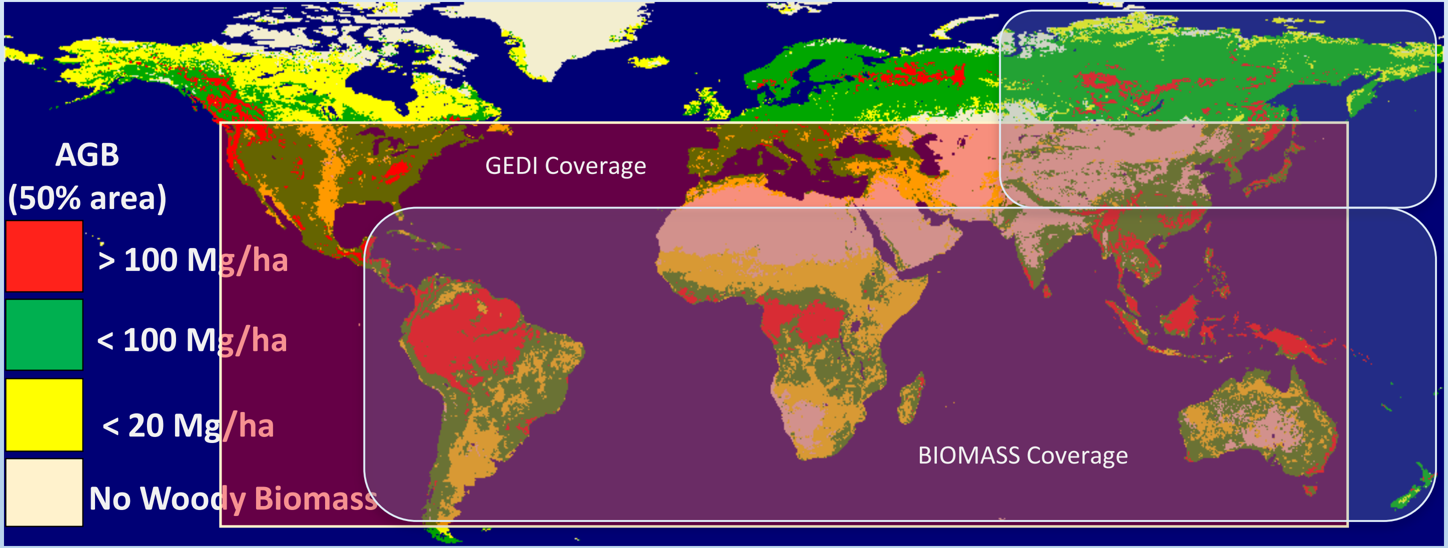




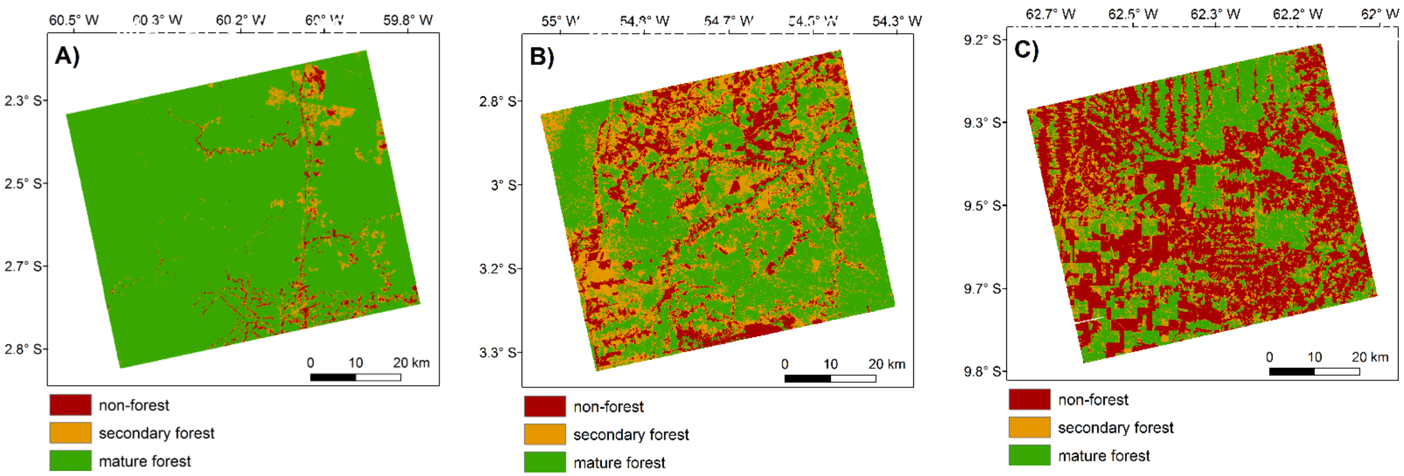
The "4th mission"; in situ networks

# Synergistic Forest Observations

**NISAR: Global Coverage, sensitivity to AGB < 100 Mg/ha**
**BIOMASS: Tropical and East Eurasia Coverage, Sensitivity to AGB > 50 Mg/ha**
**GEDI: Sampling between 50 deg North and South, Sensitivity to AGB > 20 Mg/ha**



# 1: mapping mature forest (MF), non-forest (NF) and secondary forest (SF) by year in the 2007-2010 period



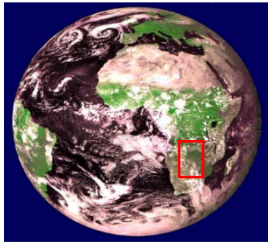

- high overall accuracy (95–96%)
- highest errors in the secondary forest class (omission and commission errors in the range 4–6% and 12–20% respectively)

# Space Measurements of Carbon Emissions from Biomass Burning

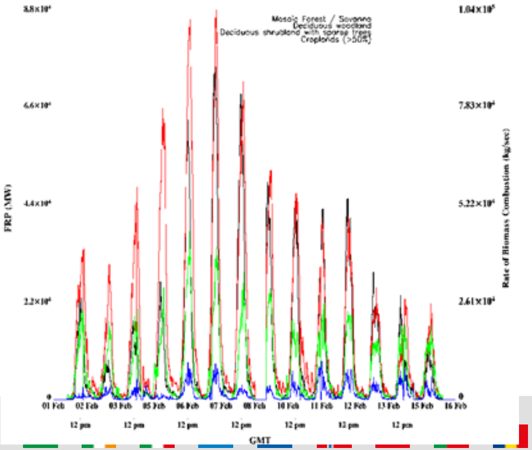
Vegetation releases fixed amount of energy when burned

A proportion emitted as radiation – detectable by satellite


*MSG SEVIRI*

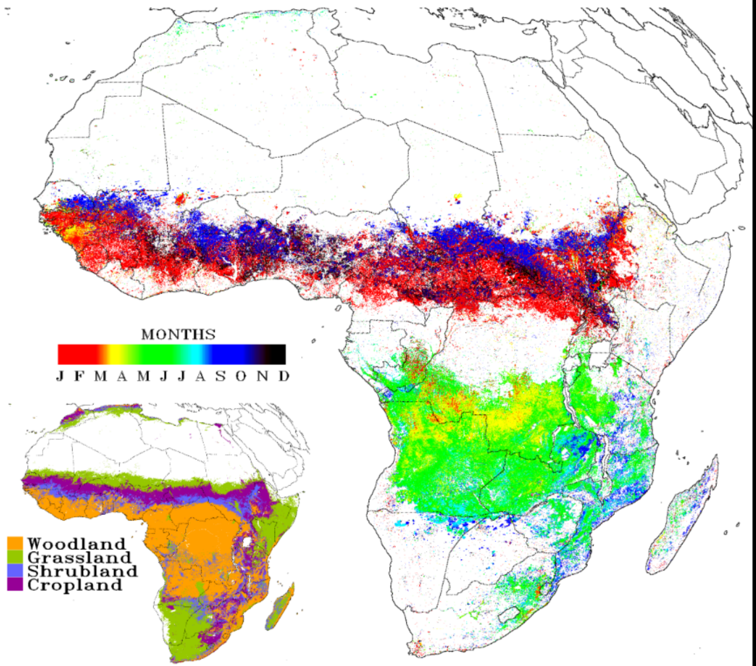



*Diurnal cycle in emissions*



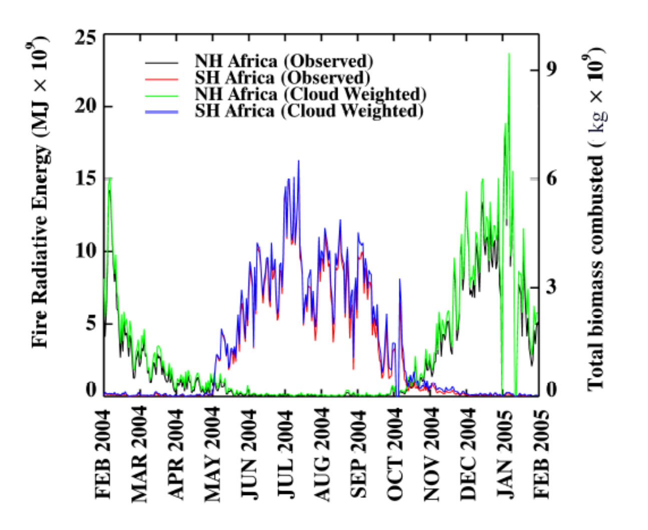
# Estimating C Emissions from Radiative Energy

## Fire Seasonality and Location Variation



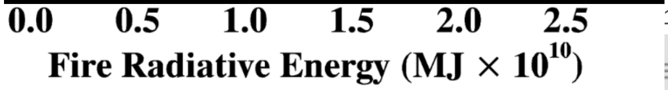

[Very strong seasonal cycle]

## Temporal Emissions




→ *NH Africa 362 - 414 Tg*

→ *SH Africa 402 - 440 Tg*



# Short-Term Emissions Estimation as Model Drivers

Observed Geostationary FRP [W/m$^2$] (red)

Modelled (blue)

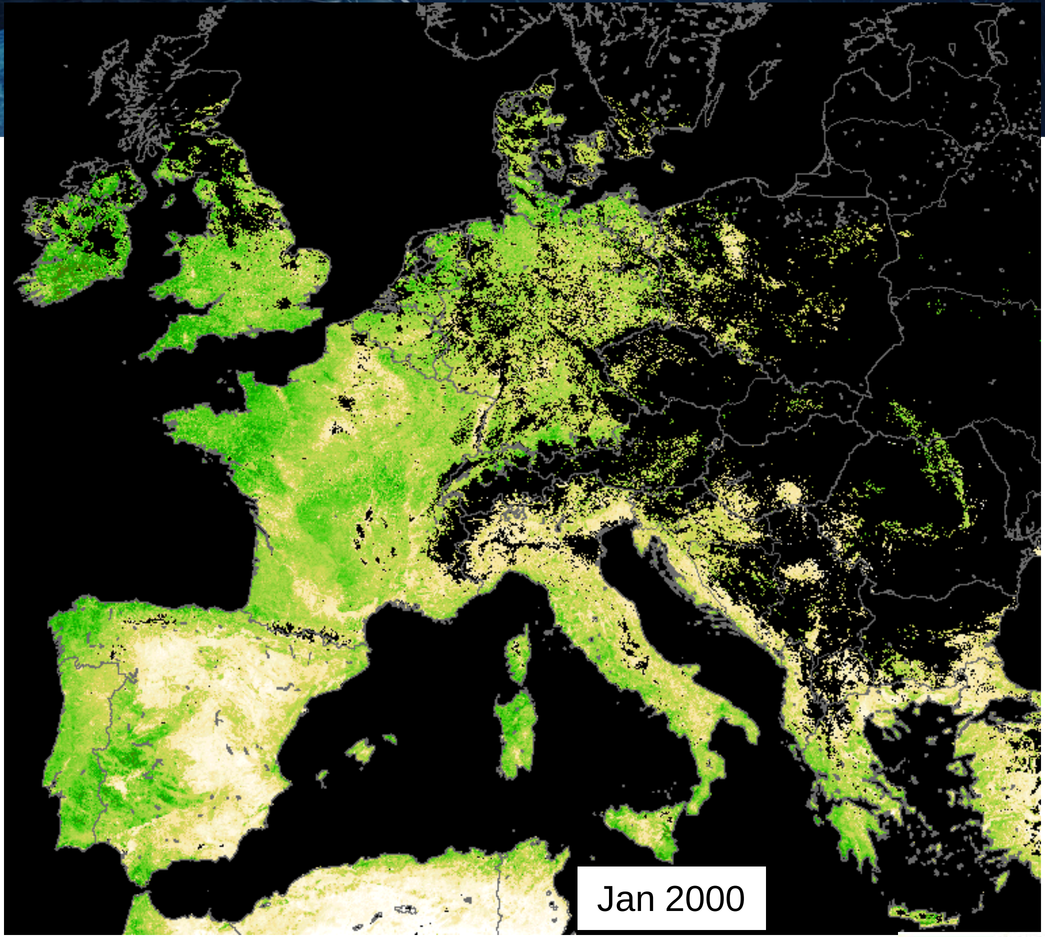
# Photosynthesis : Gross primary productivity

Light Use Efficiency:

$$GPP = \varepsilon \times PAR \times fAPAR$$

$$\varepsilon = \varepsilon_{max} \times f_t \times f_w$$

Phenology: seasonal patterns of vegetation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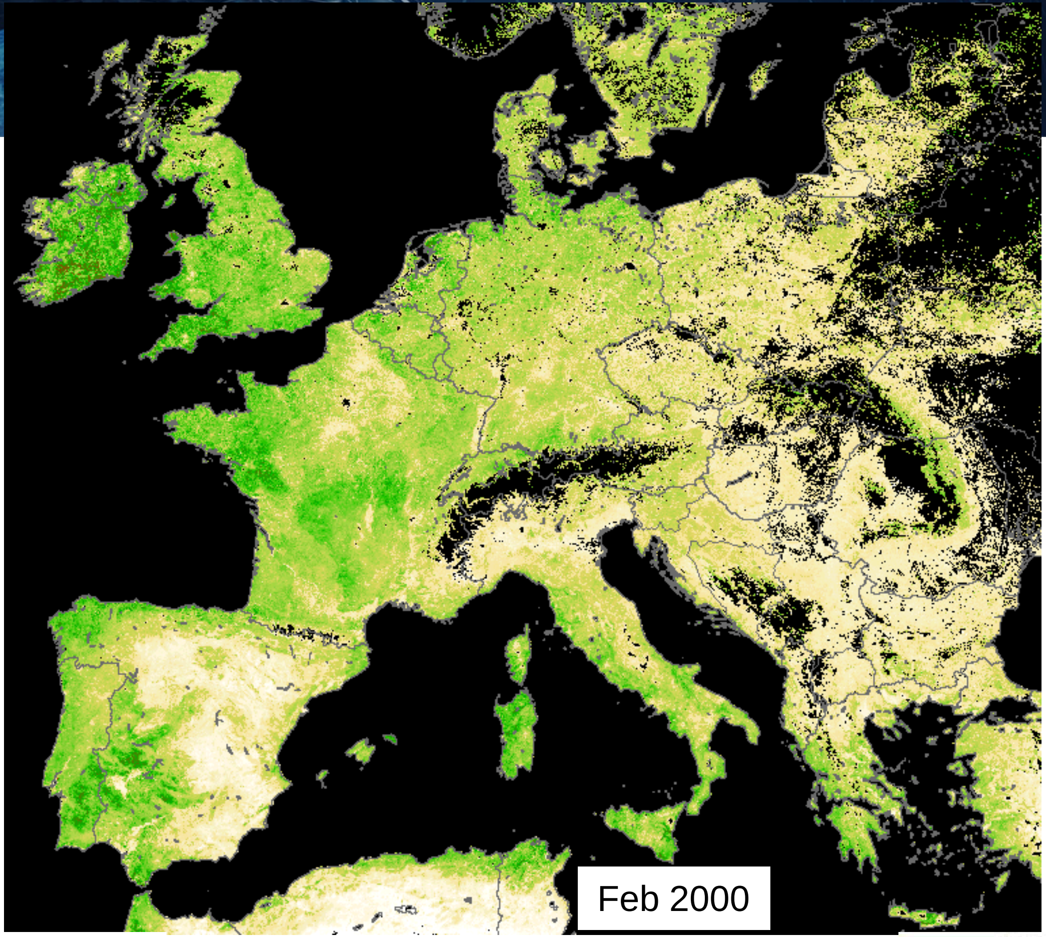
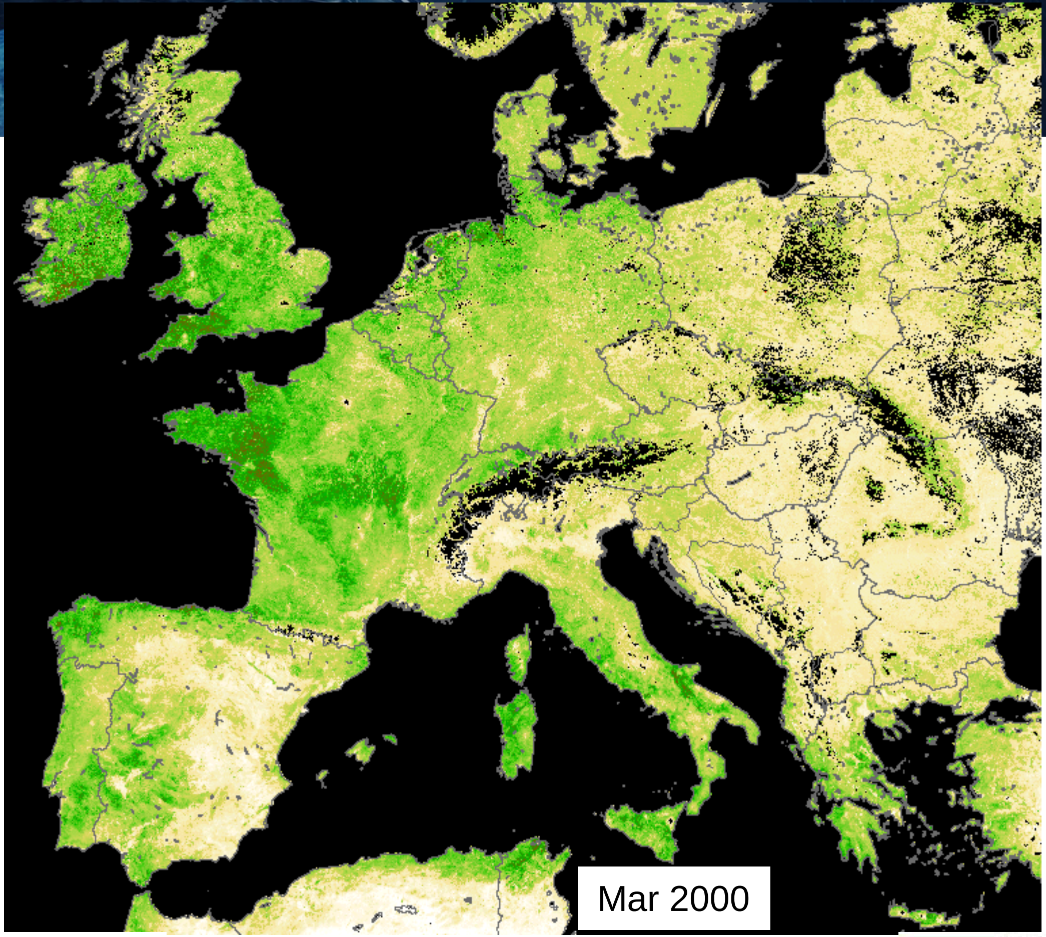
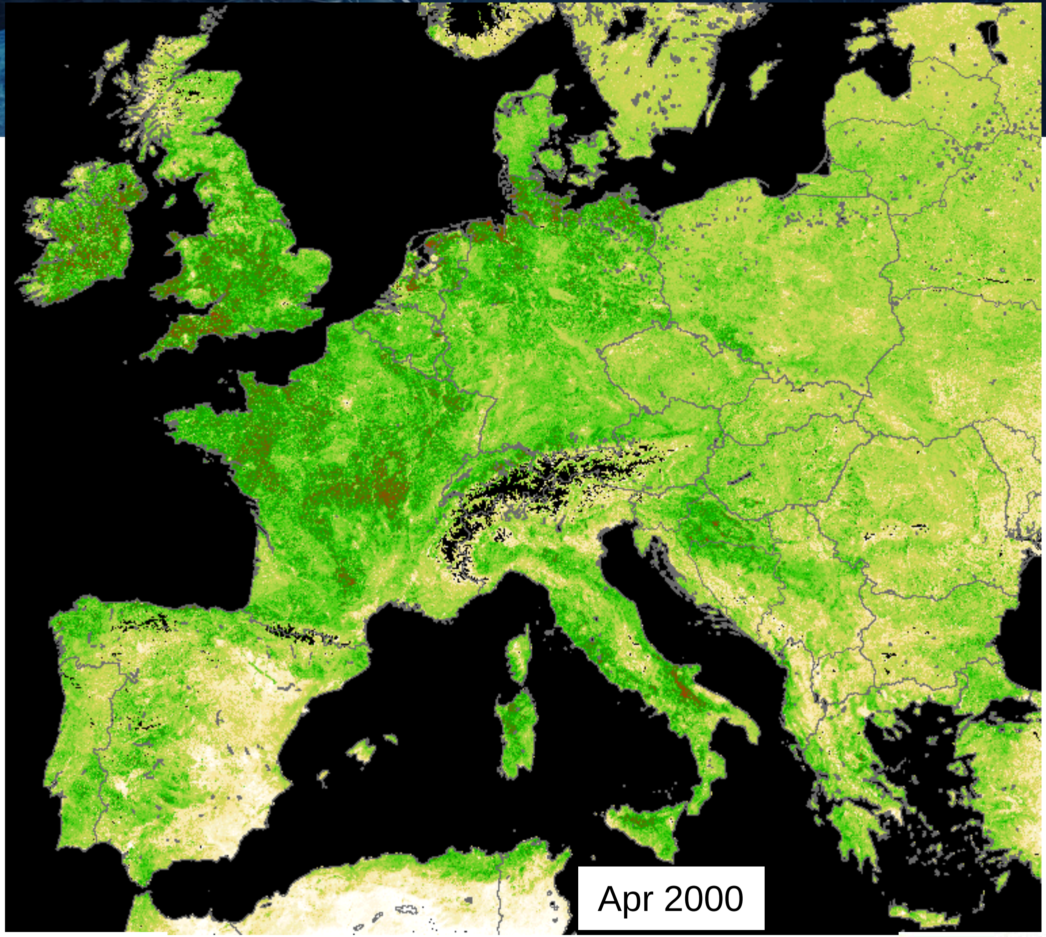

Feb 2000


Mar 2000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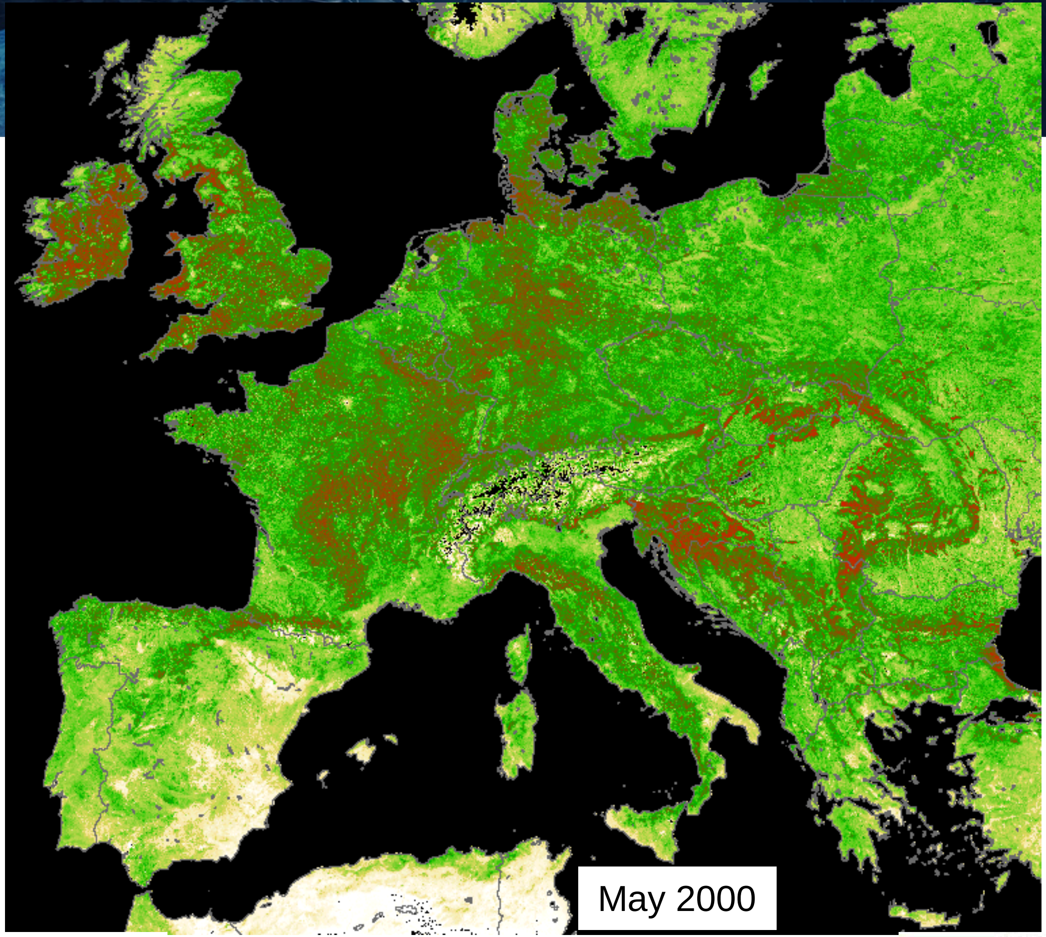




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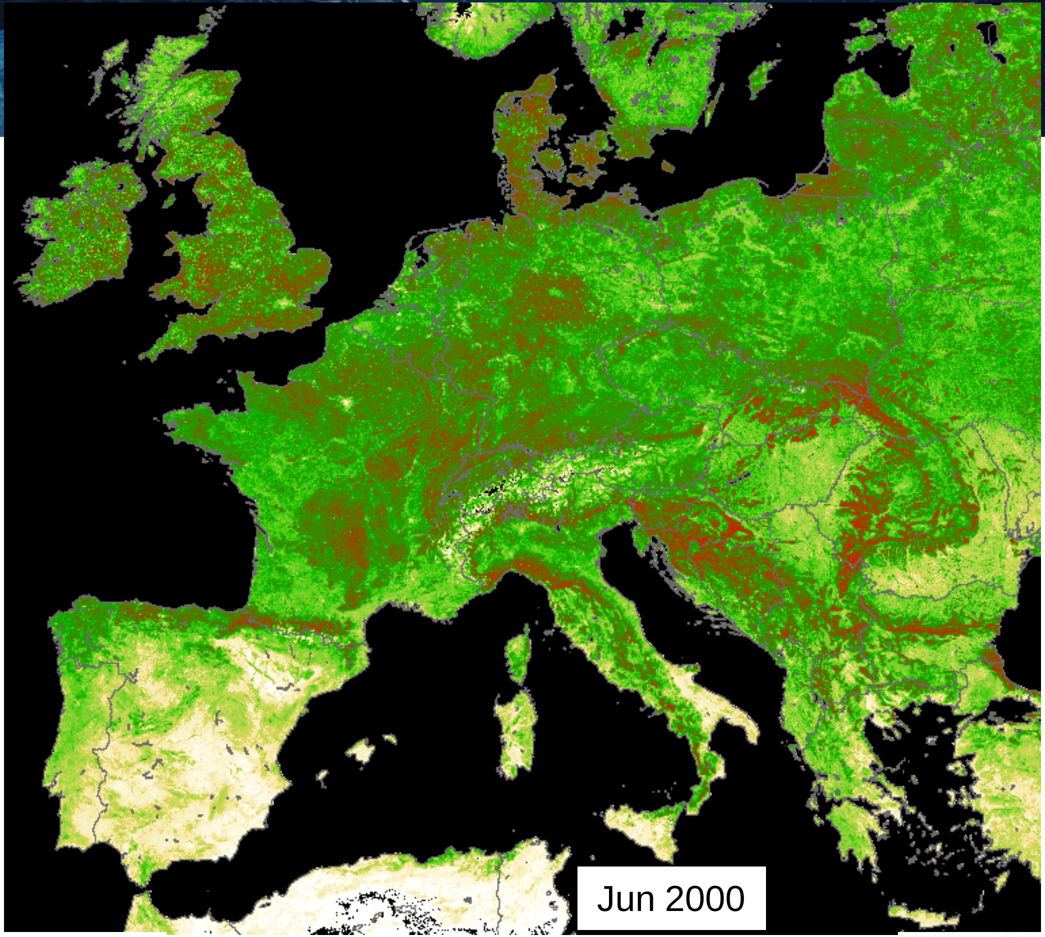
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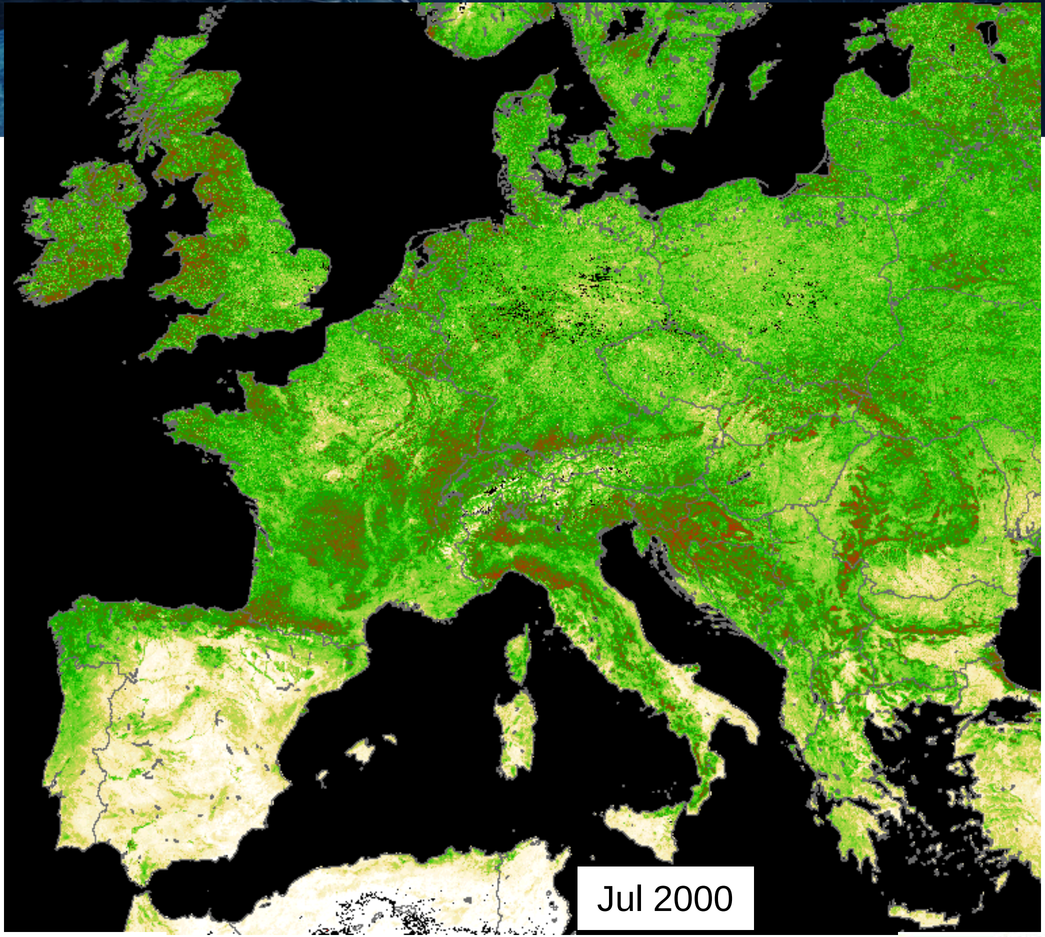
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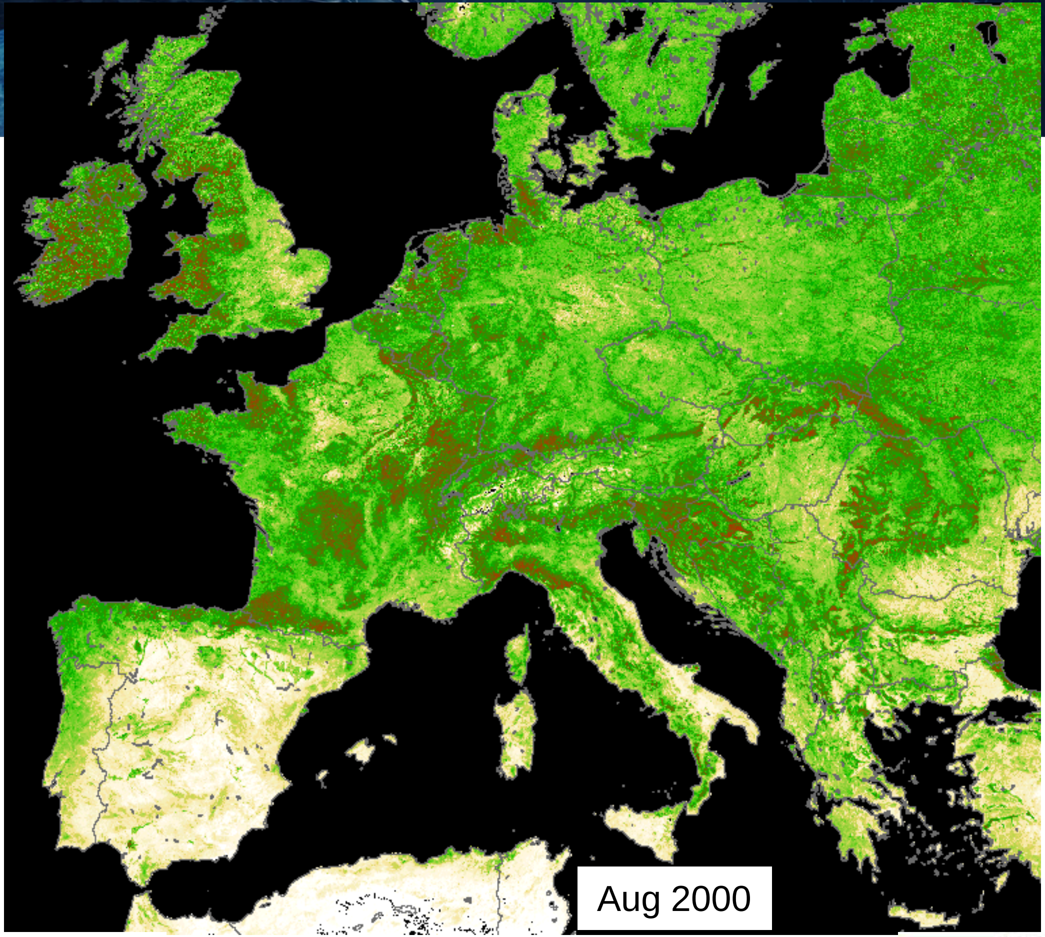
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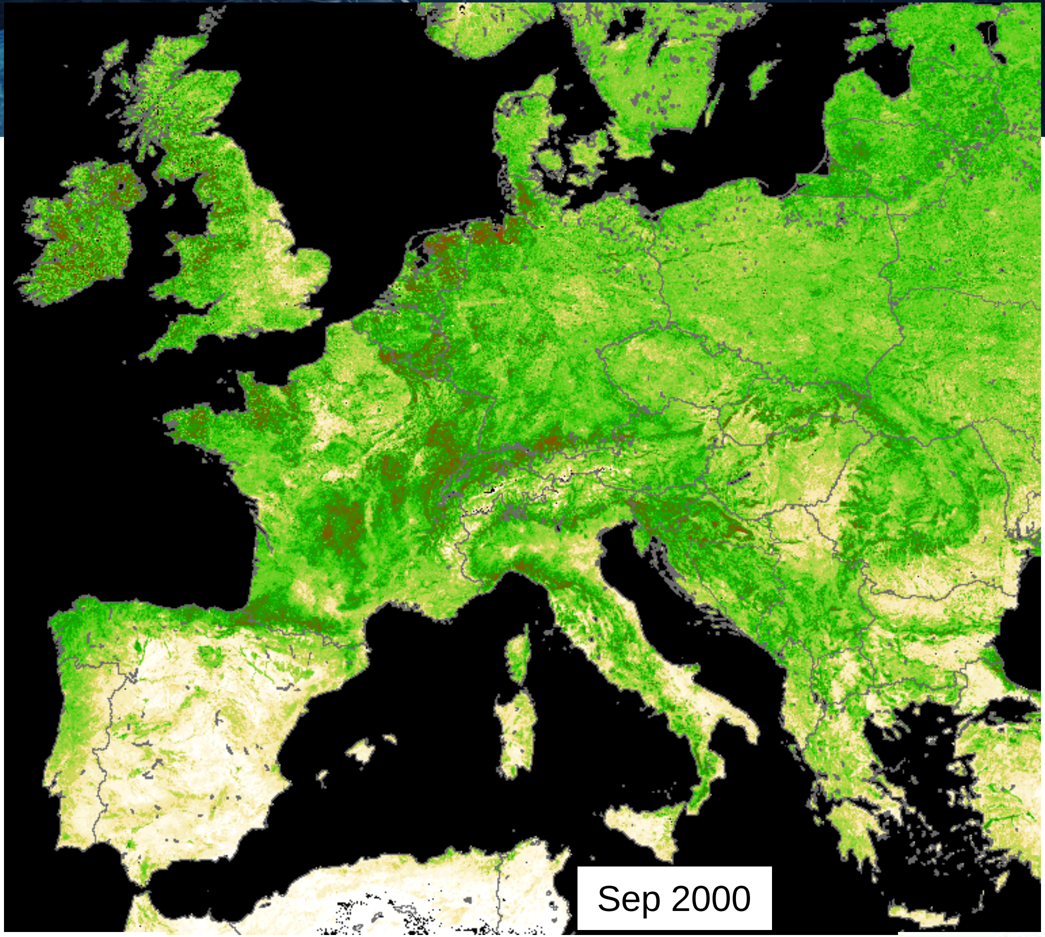


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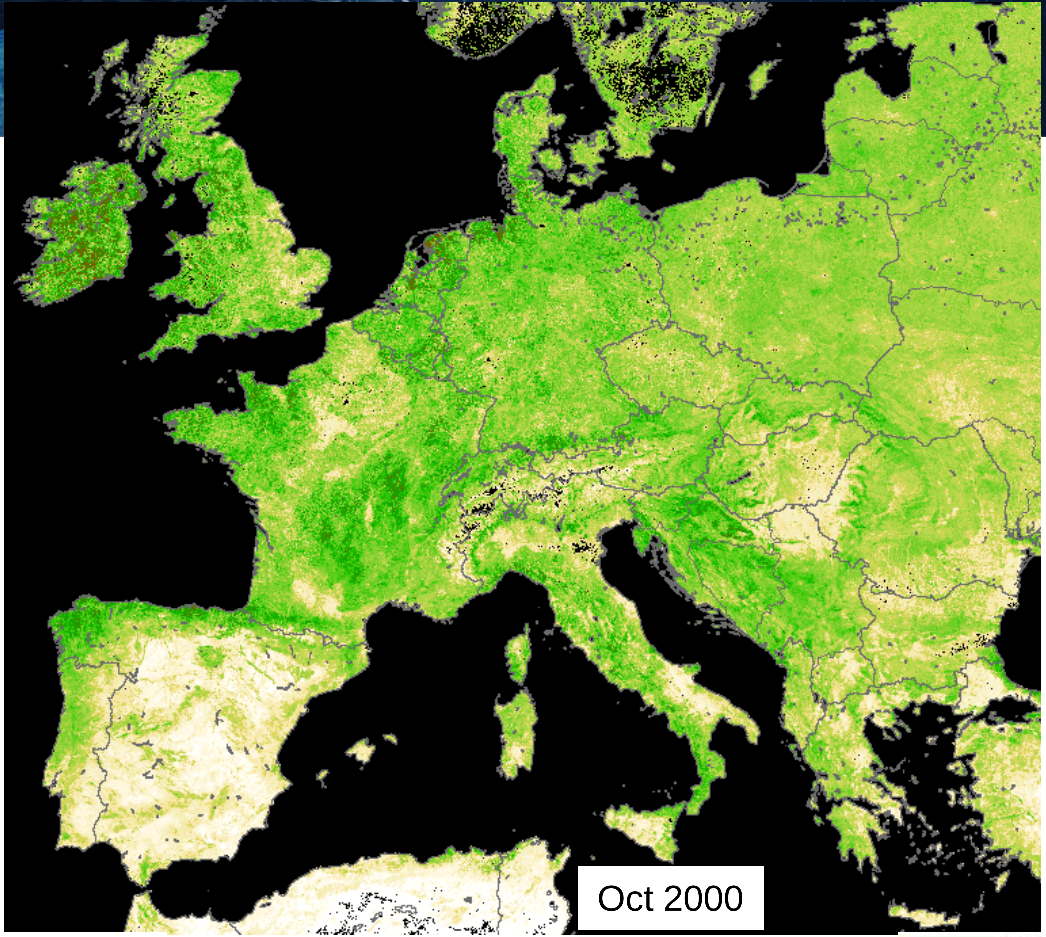
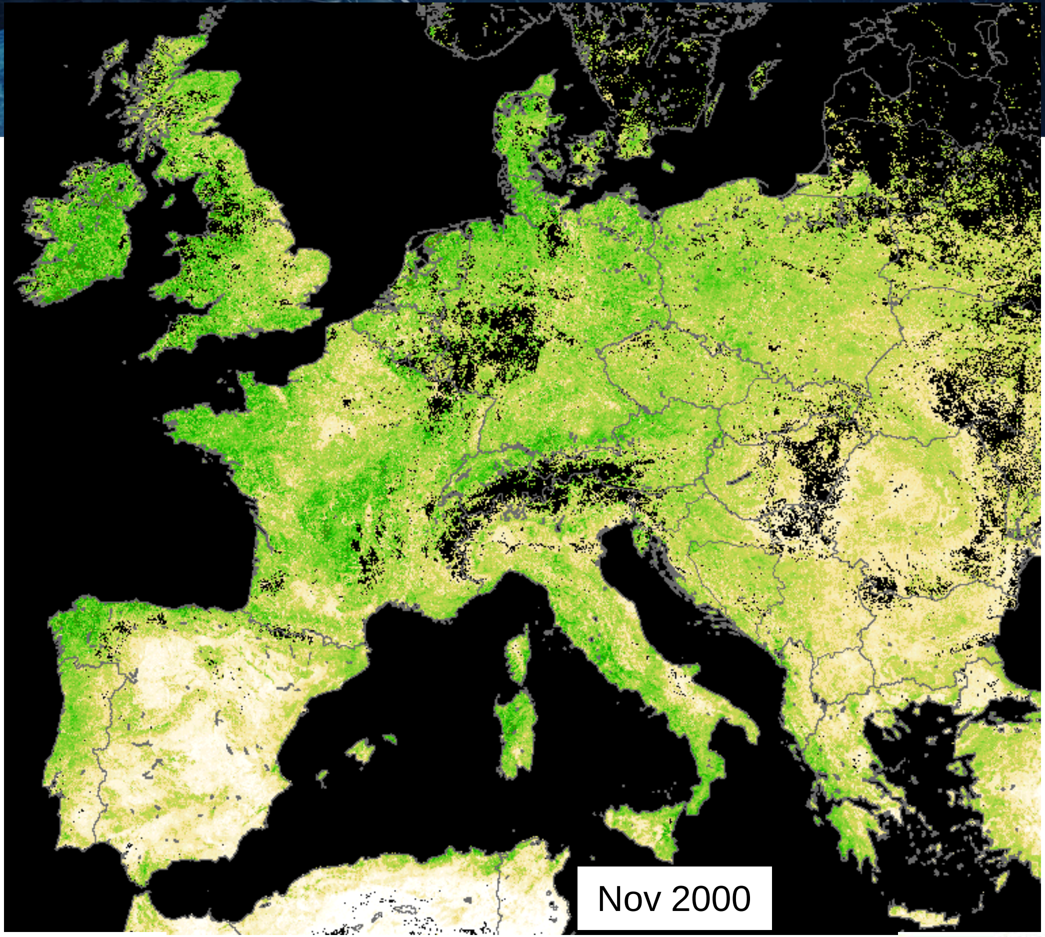

Oct 2000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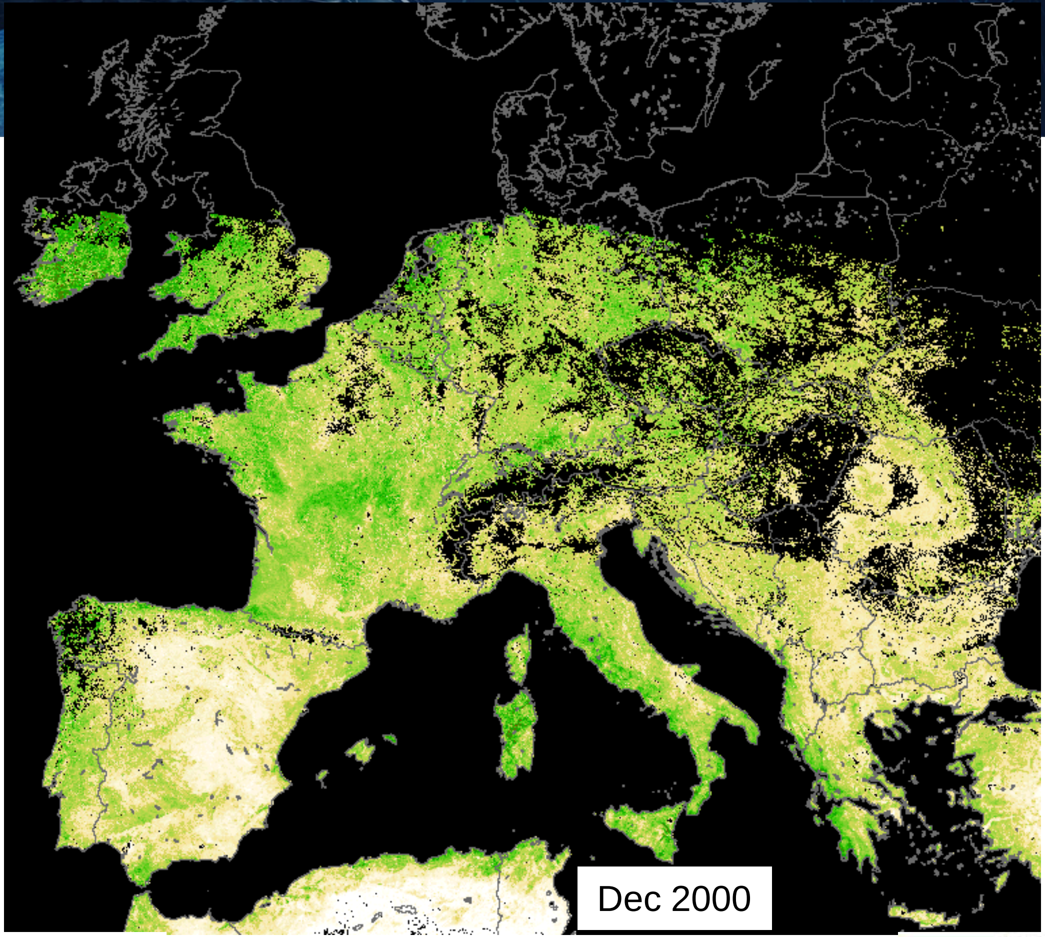




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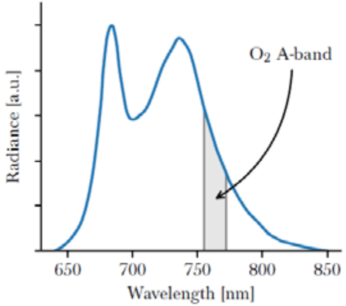
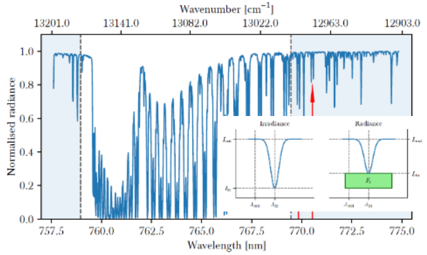
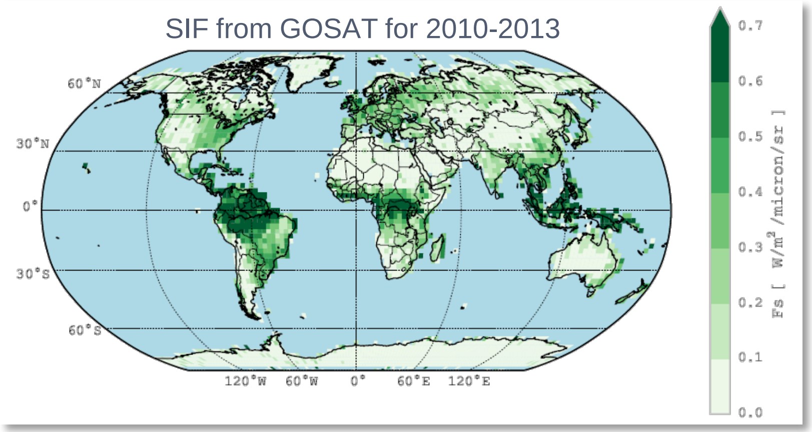
# Solar Induced Fluorescence

- Solar-induced fluorescence SIF is related to plant productivity and water stress
- SIF is observable from satellites through filling-in of solar lines (Frankenberg et al., 2011)
- (Macroscopic) Relationship between SIF and GPP:

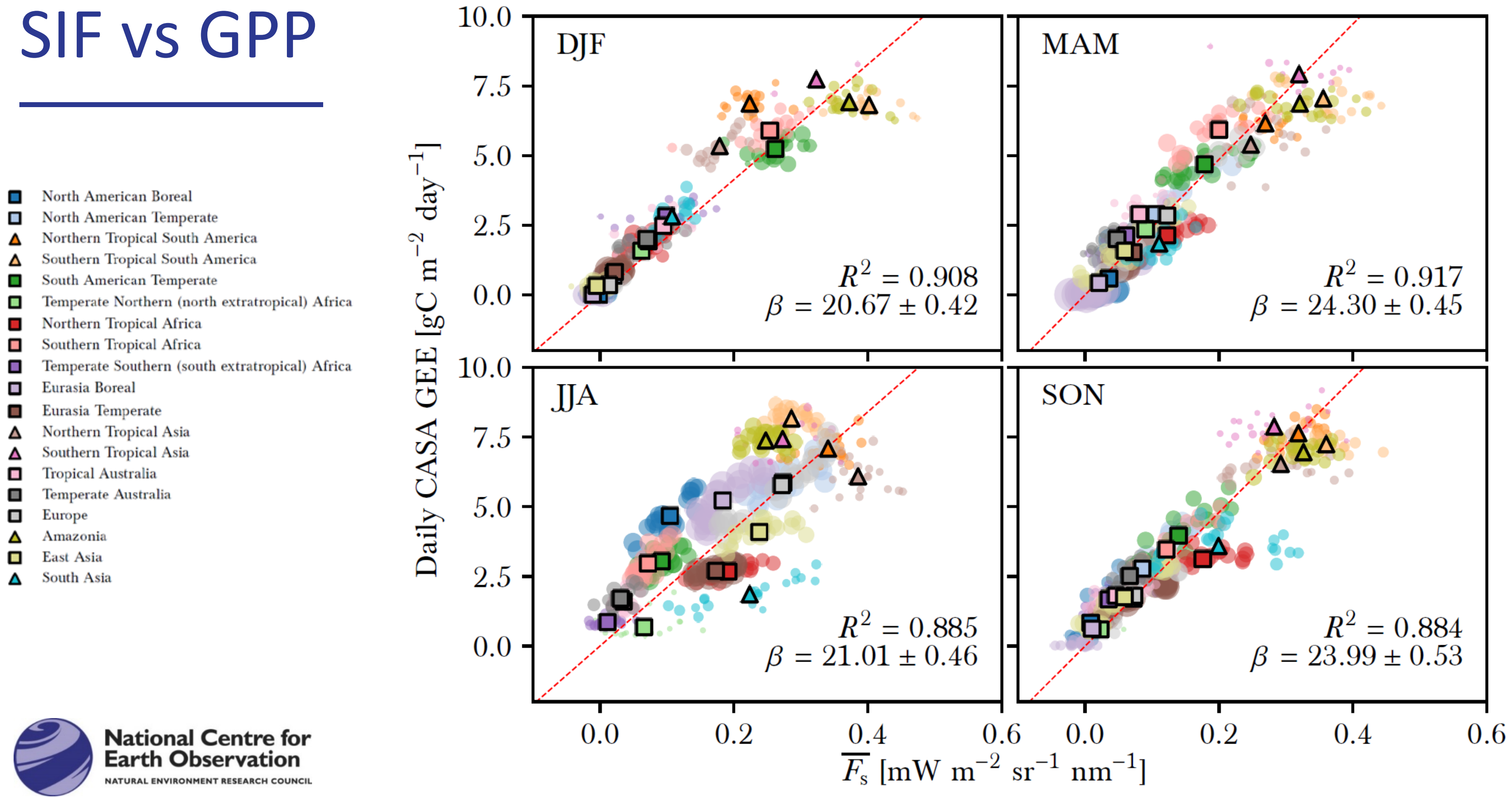
$$GPP = \frac{\epsilon_P}{\epsilon_F}\mathrm{SIF}$$



# SIF vs GPP

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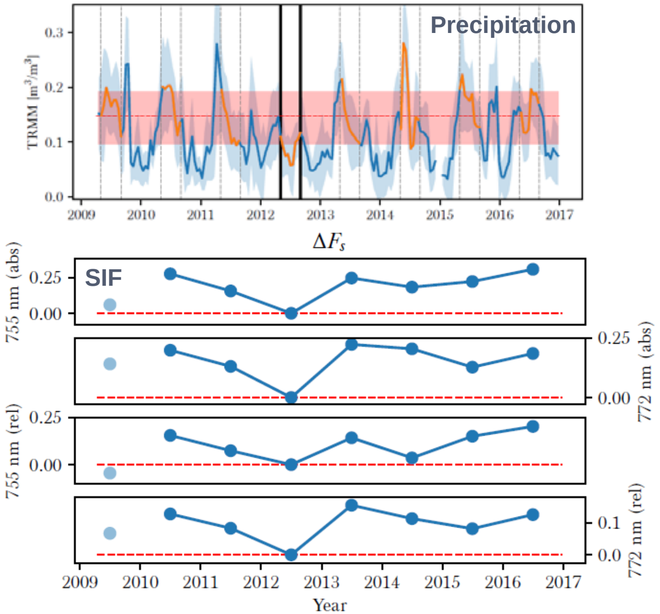
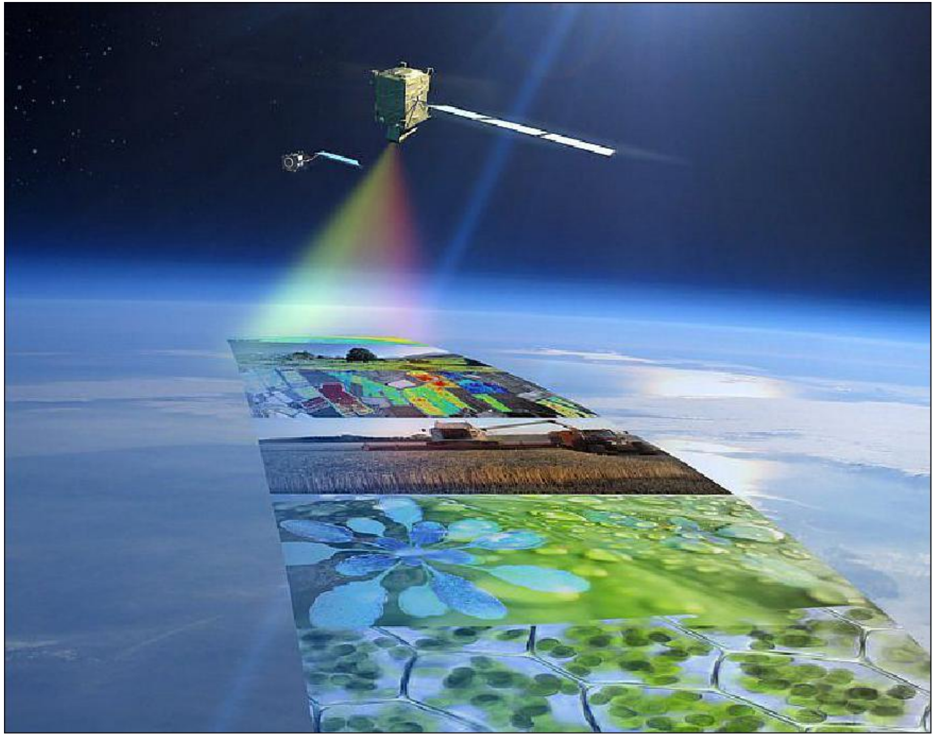
# Case Study: 2012 North American Drought

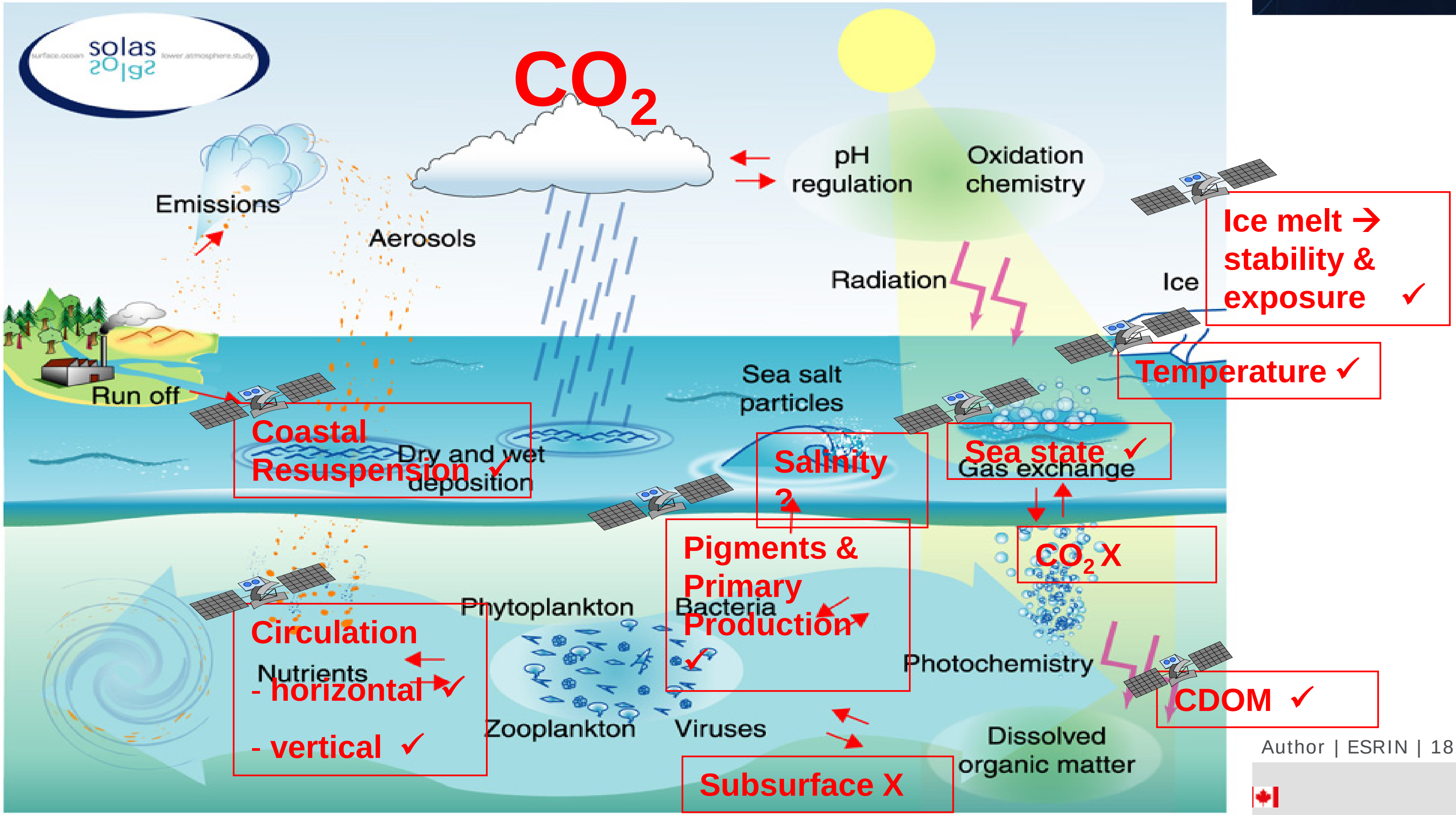
- USA experienced severe drought in 2012
- Climate anomaly with significant impact on productive corn belt region
- Large drop in SIF is observed (SIF as proxy for drought stress)





**FLEX:**
**Fluorescence Explorer** aims to provide global maps of vegetation fluorescence that can reflect photosynthetic activity and plant health and stress.

# Processes influencing air-sea fluxes of CO2



# How can we measure $CO_2$ exchange with the ocean?

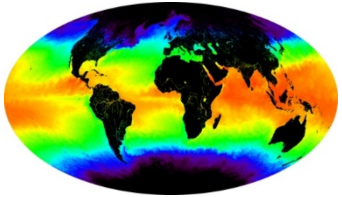
Directly by satellites?

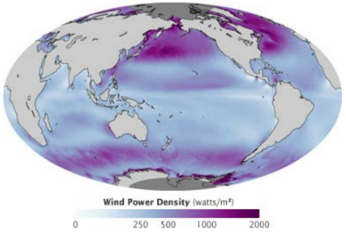
Not yet

Indirectly by satellites?

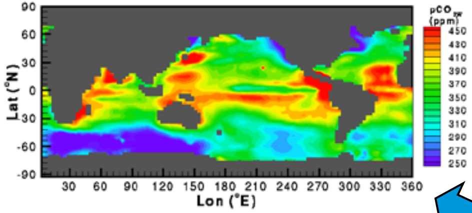
- Temperature ✓
- Sea state/winds ✓
- Algal biomass ✓

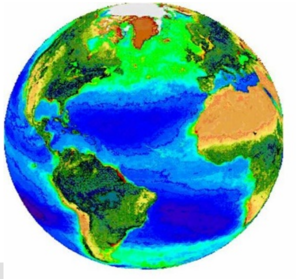
**Also need direct measurements – only available in situ**



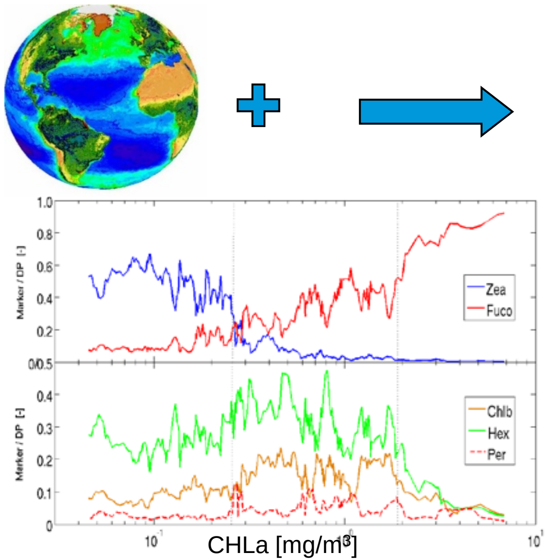


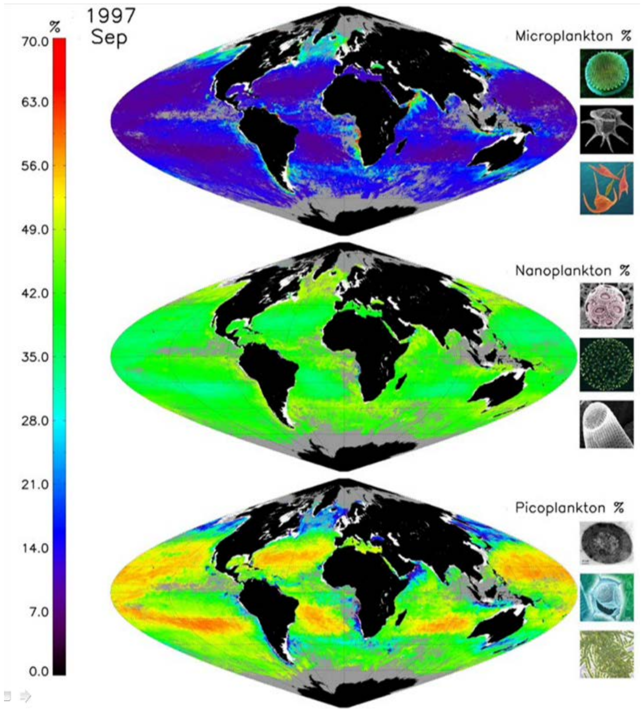

**Models**



# Biological carbon reservoir & Primary Production




**Bigger cells (>20µm)**

**Medium cells (2-20 µm)**

**Smaller cells (<2 µm)**

**Size of algal cells regulates ecosystem processes:**

- Primary production
- Length of food web
- Whole ecosystem production & respiration
- Carbon dioxide drawdown

Hirata et al., 2008 RSE;
Brewin et al., 2010 Eco Mod

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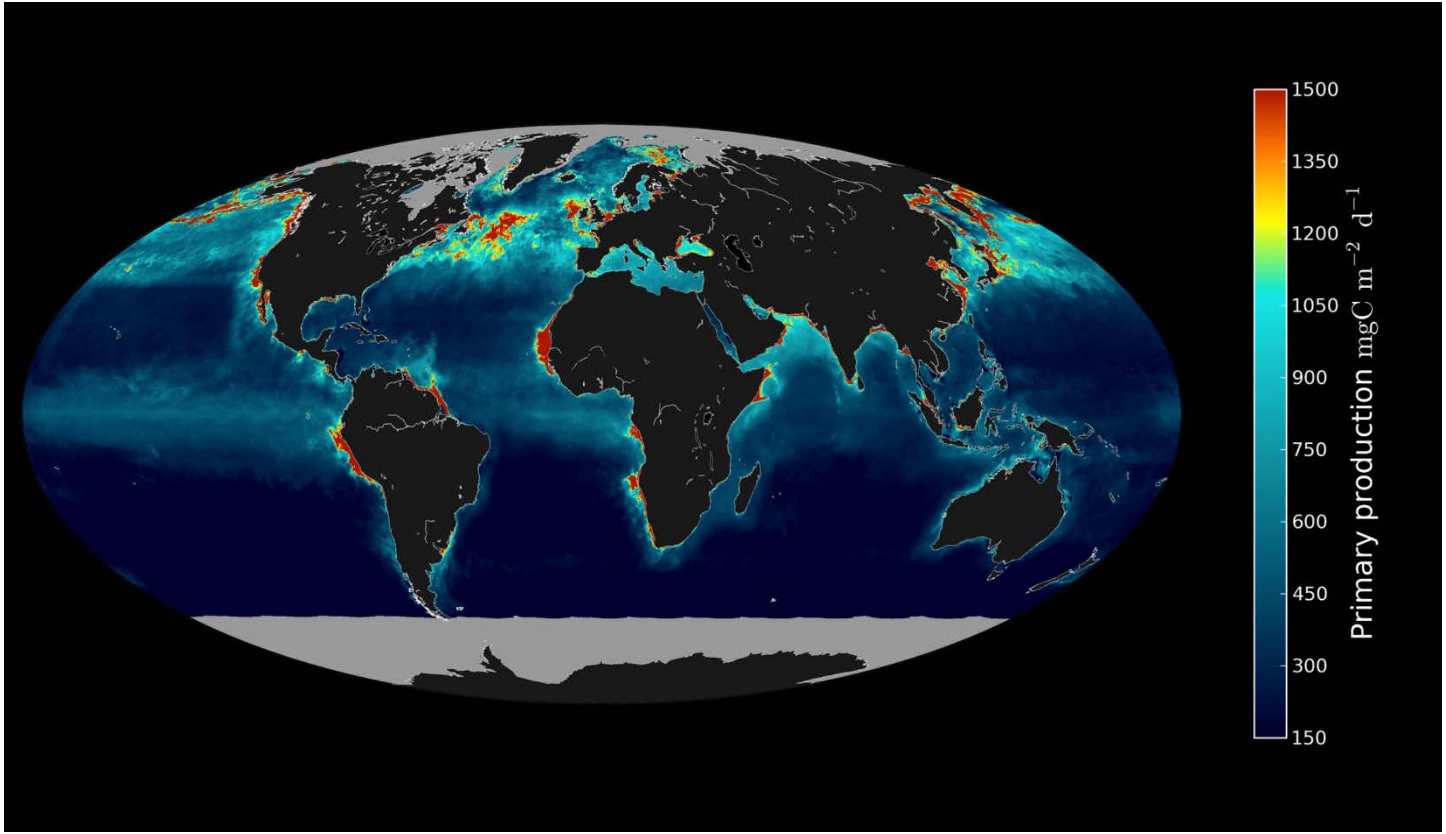
# Computed Global Primary Production




Sathyendranath et al. May 2004, using OC-CCI data, TWAP Project

# Summary & Challenges

- Quantifying the land and ocean carbon cycle requires knowledge about a wide range of processes.
- At local and maybe regional scale, we can use in situ measurements.
- At global scale we need satellite measurements: certain key processes are accessible from satellites (but others are not).
- In particular, direct measurements of $CO_2$ **fluxes** are not available from space.

# Summary & Challenges

- New sensors bring major new opportunities for carbon cycle monitoring.
  - Atmospheric greenhouse gases
  - Biomass
  - Photosynthesis
- Many sensors bring valuable ancillary information: soil moisture, land surface temperature, etc.
- Crucial in combining data and filling gaps is the use of models.
- We need an integrated approach to using satellite EO with in situ observations and modelling systems.