

→ 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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Measuring the global C balance and its components

- Atmospheric observations of CO₂
- 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 CO₂ emissions (2007–2016)

Sources = Sinks



34.4 ± 1.8
GtCO₂/yr
88%



4.8 ± 2.6
GtCO₂/yr
12%

17.2 ± 0.4
GtCO₂/yr
46%



11.0 ± 2.9
GtCO₂/yr
30%

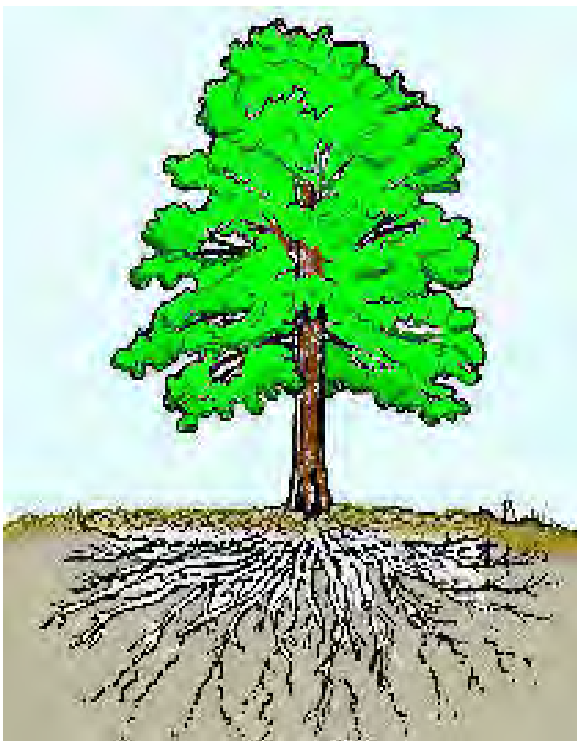


8.8 ± 1.8
GtCO₂/yr
24%



Budget Imbalance = difference between estimated sources & sinks

2.2 ± 4.3 GtCO₂/yr
6%



Terms:

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

Mass balance:

$$\Delta C = \Delta B_A + \Delta B_B + \Delta L + \Delta S$$

Process equation:

$$\Delta C = P - R_P - R_H - D$$

ΔC 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.

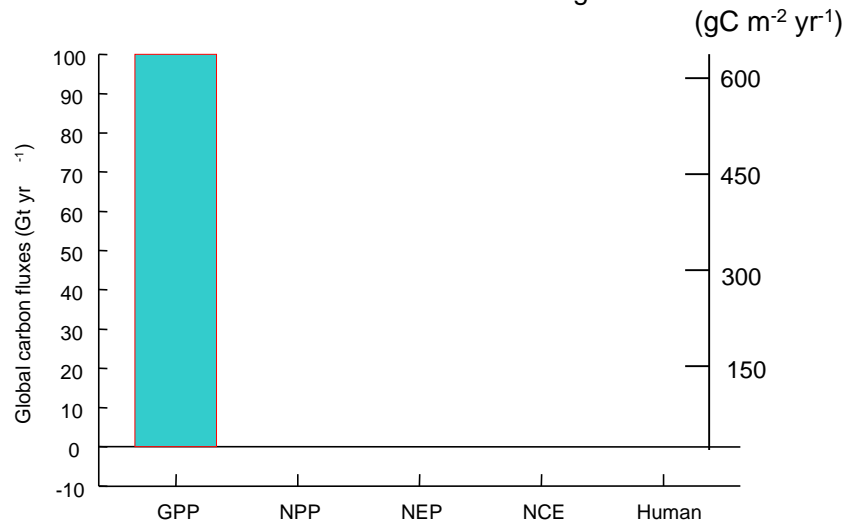


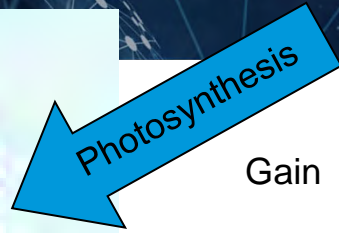
Photosynthesis

Gain

Gross Primary Production

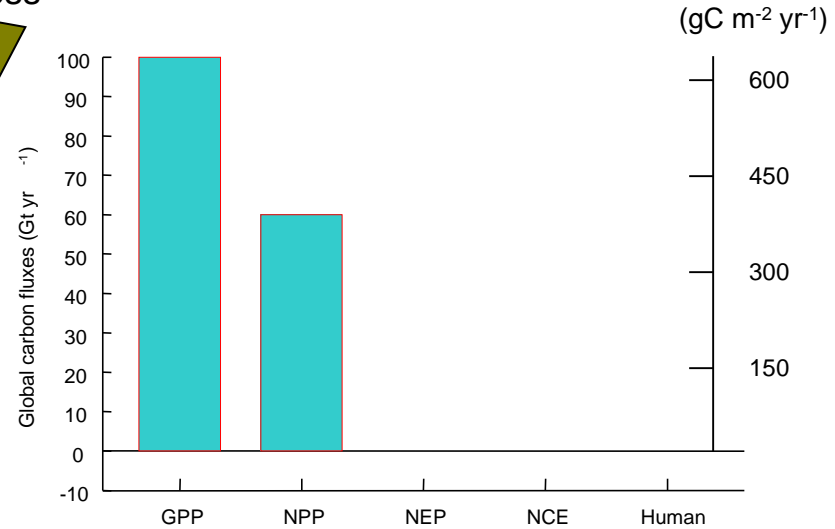
Global Carbon Exchange

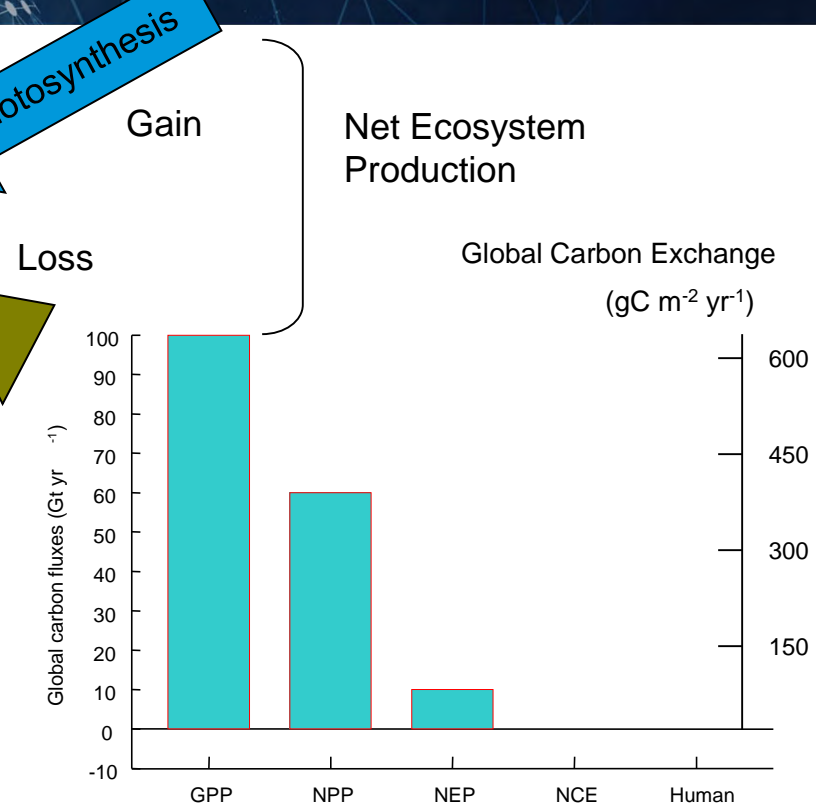
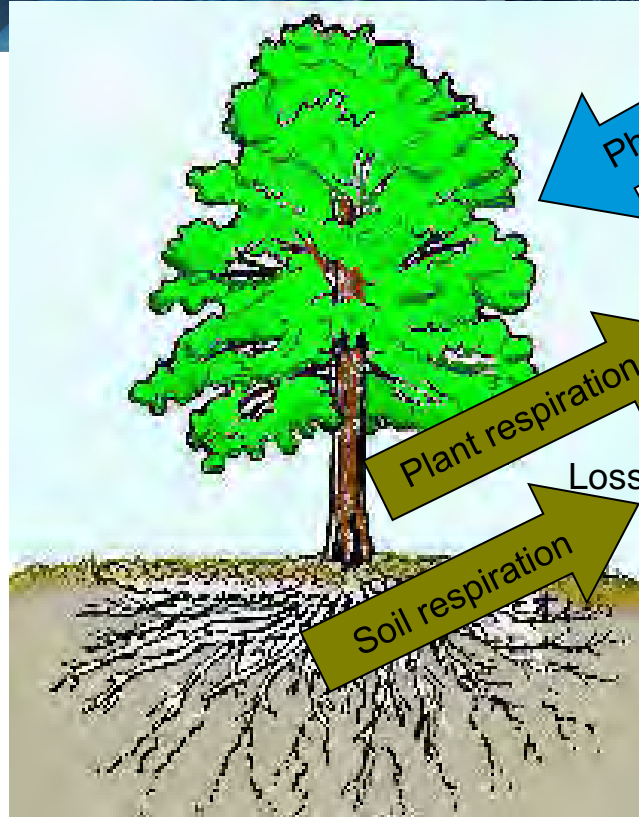




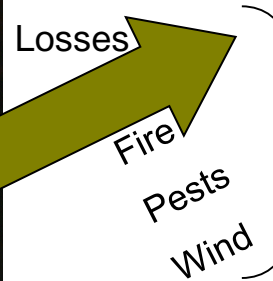
Net Primary Production

Global Carbon Exchange

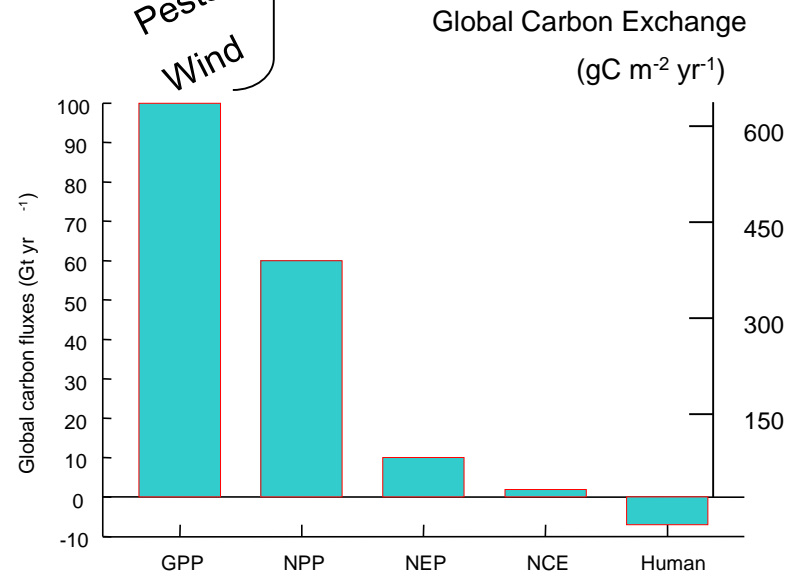




Disturbance Flux



Net Carbon Exchange
OR
Net Biome Production



Mass balance:

$$\Delta C = \Delta B_A + \Delta B_B + \Delta L + \Delta S$$

Process equation:

$$\Delta C = P - R_P - R_H - D$$

ΔC 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,

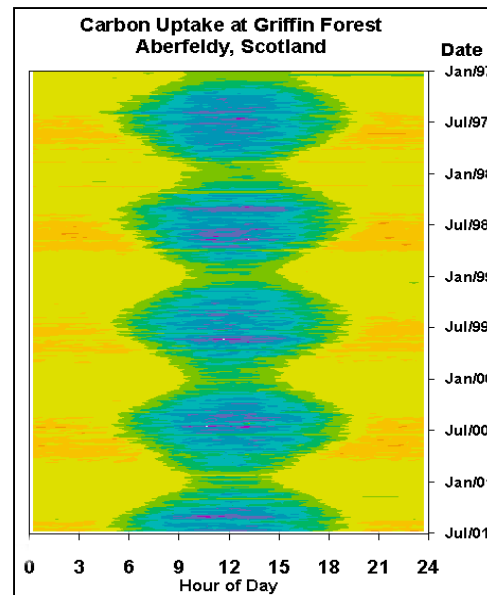
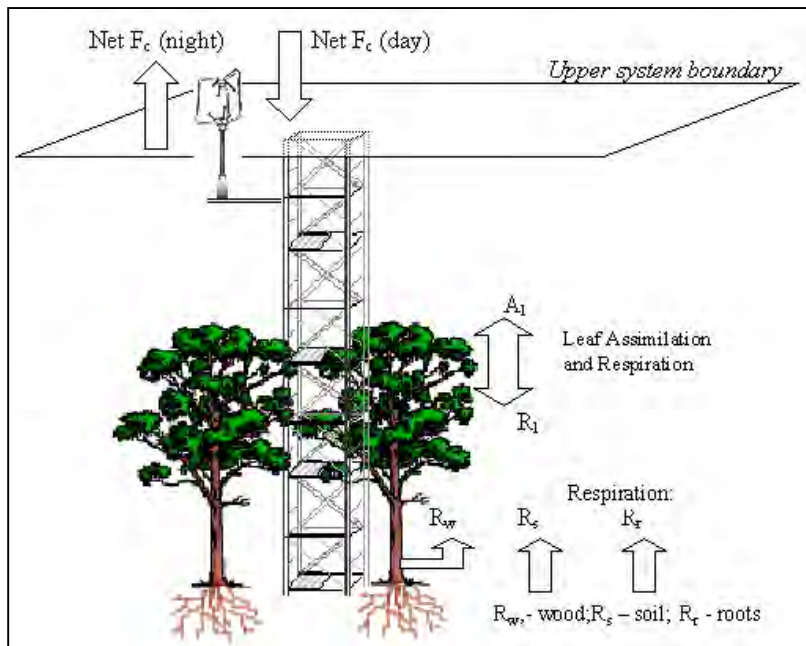
P photosynthesis,

R respiration (P : plant and H : heterotrophic),

D carbon loss by disturbance.

ΔC : The atmosphere (the integrator)

Eddy covariance: CO₂ and H₂O fluxes



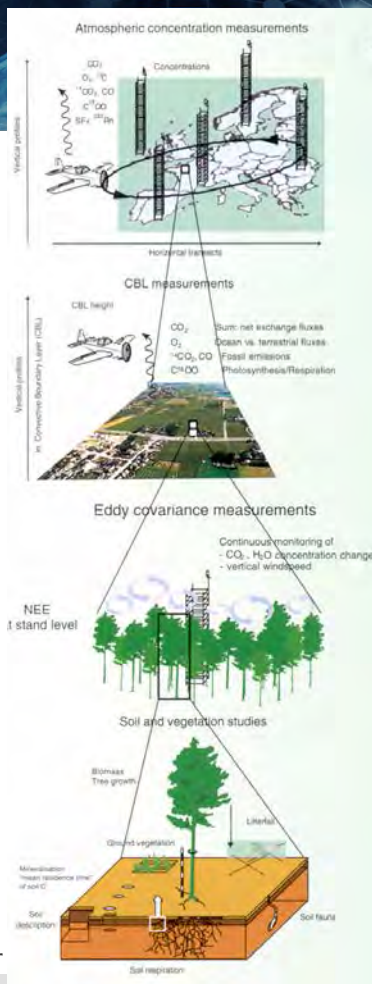
Losses	Gains
g C m ⁻² hour ⁻¹	
	0.64 – 0.80
	0.48 – 0.64
-0.48 – -0.32	0.32 – 0.48
-0.32 – -0.16	0.16 – 0.32
-0.16 – 0.0	0.0 – 0.16

Top down vs bottom up

Atmospheric signal,
tall towers (minus
fossil fuels)

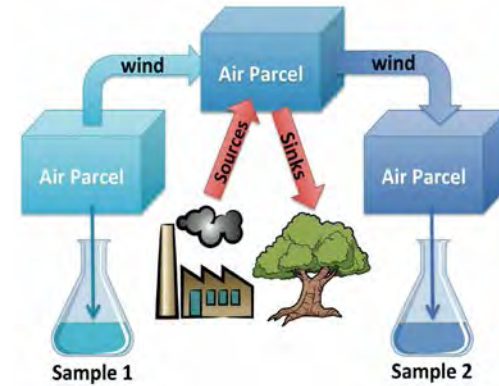
The same result ?

Terrestrial signal, eddy
covariance, upscale

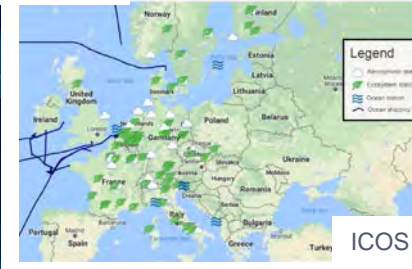


Role of Atmospheric Measurements

- 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

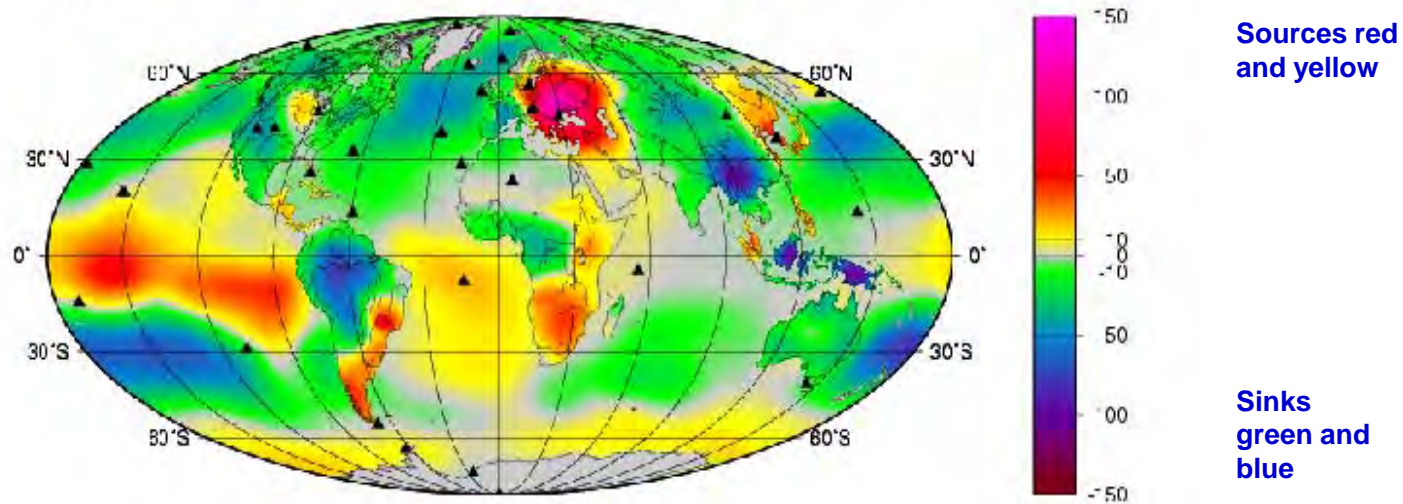


Surface Networks



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

A Posteriori Fluxes, Average July 1995 - June 2000 [$\text{gC}/\text{m}^2/\text{yr}$]



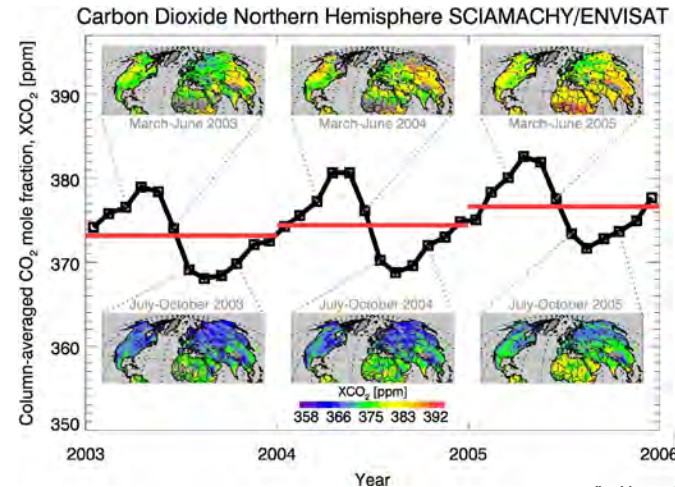
Fossil fuels not included

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

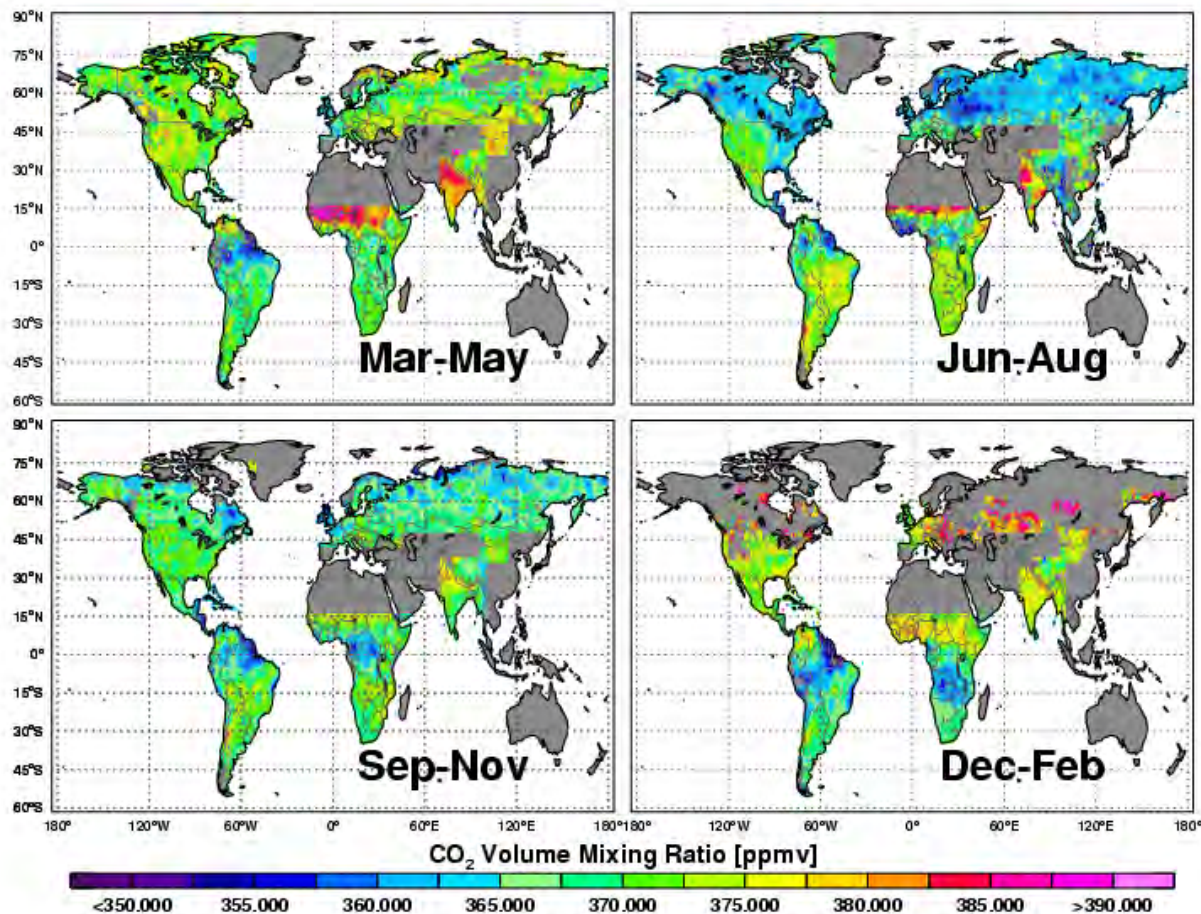


First global satellite observations of total atmospheric CO₂ (SCIAMACHY/ENVISAT)

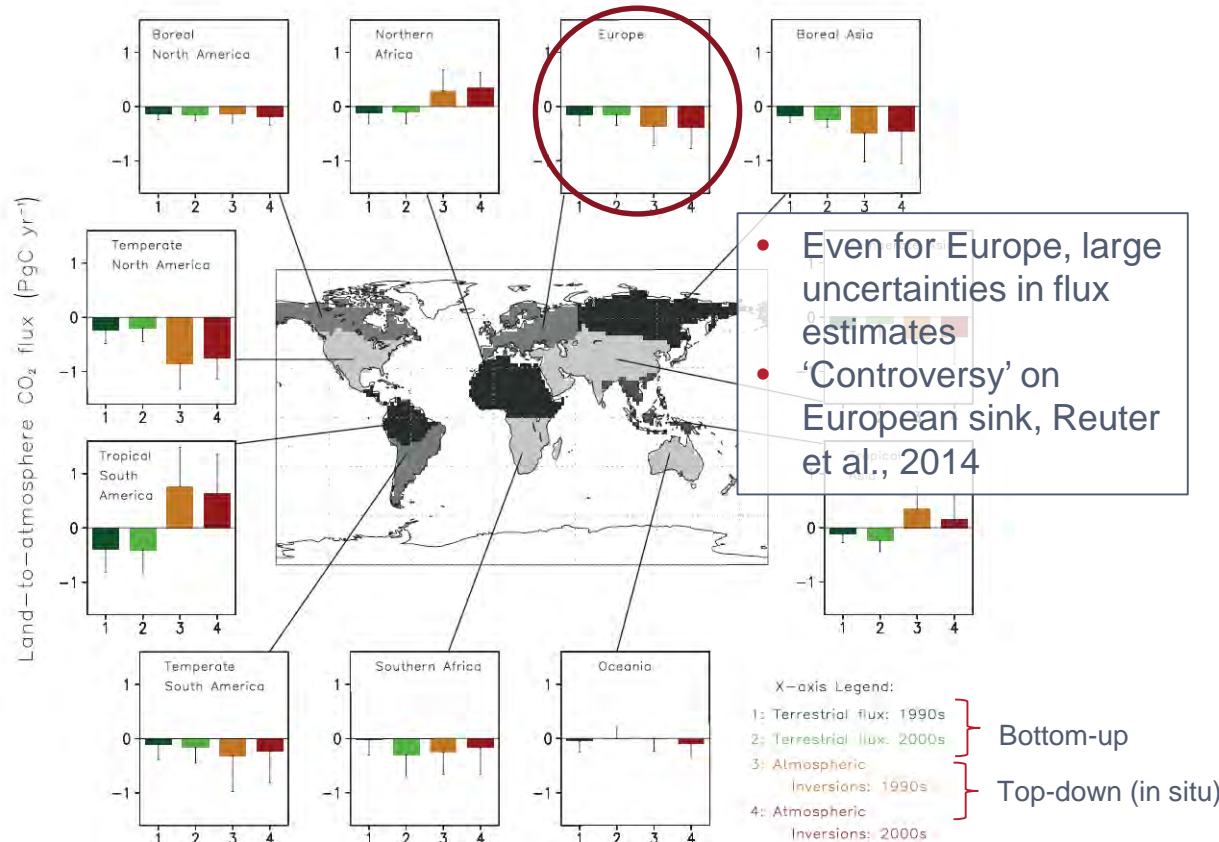
Buchwitz et al,
2007



Seasonal variability in atmospheric CO₂



Better Understanding of Regional Fluxes is Needed



ΔB : The mass balance equation

P & D: The process equation

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

C_{em} = Carbon emission from deforestation

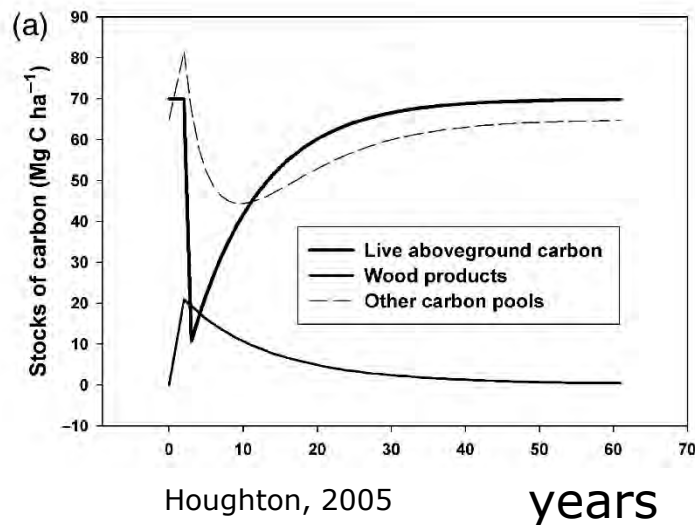
A_i = Area of deforestation

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.



1975

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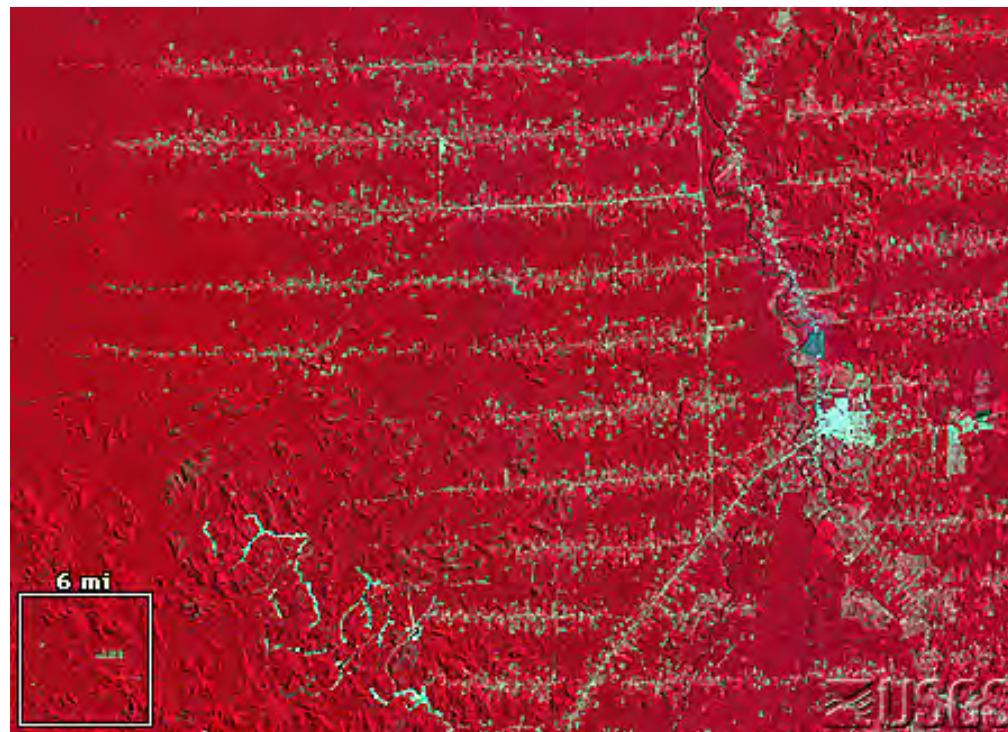
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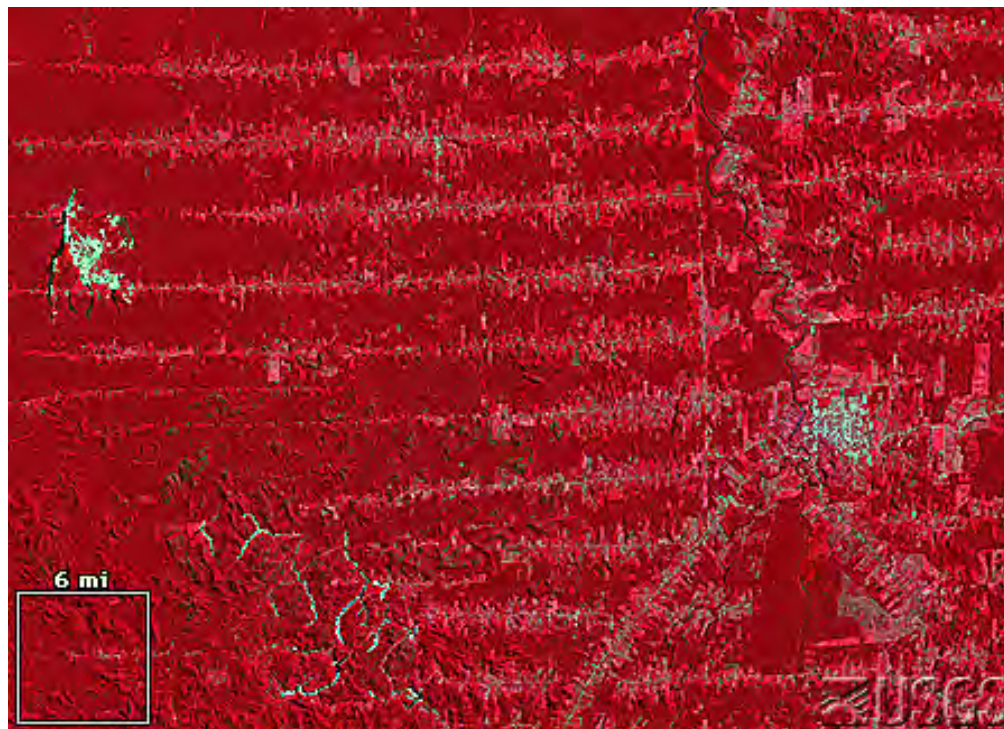
1986



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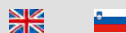


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1992



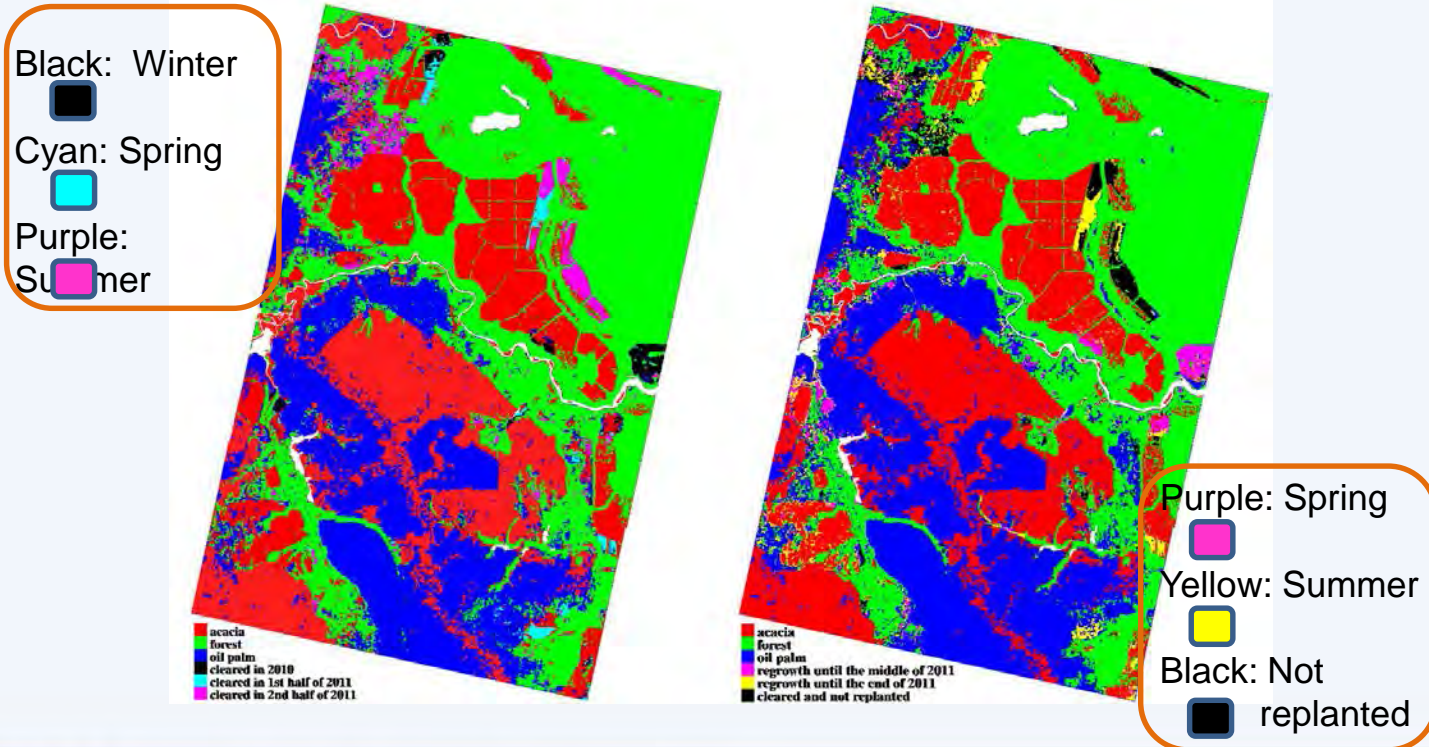
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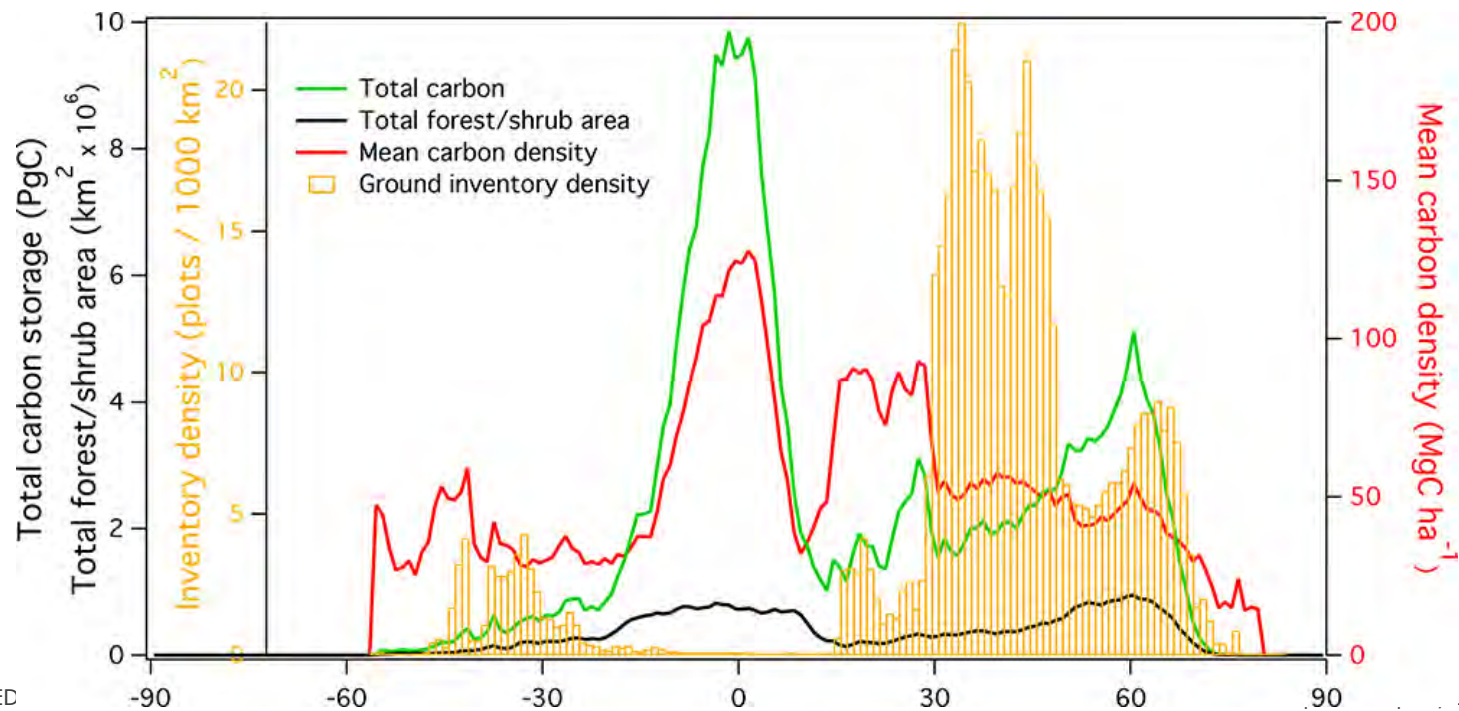
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Clearance

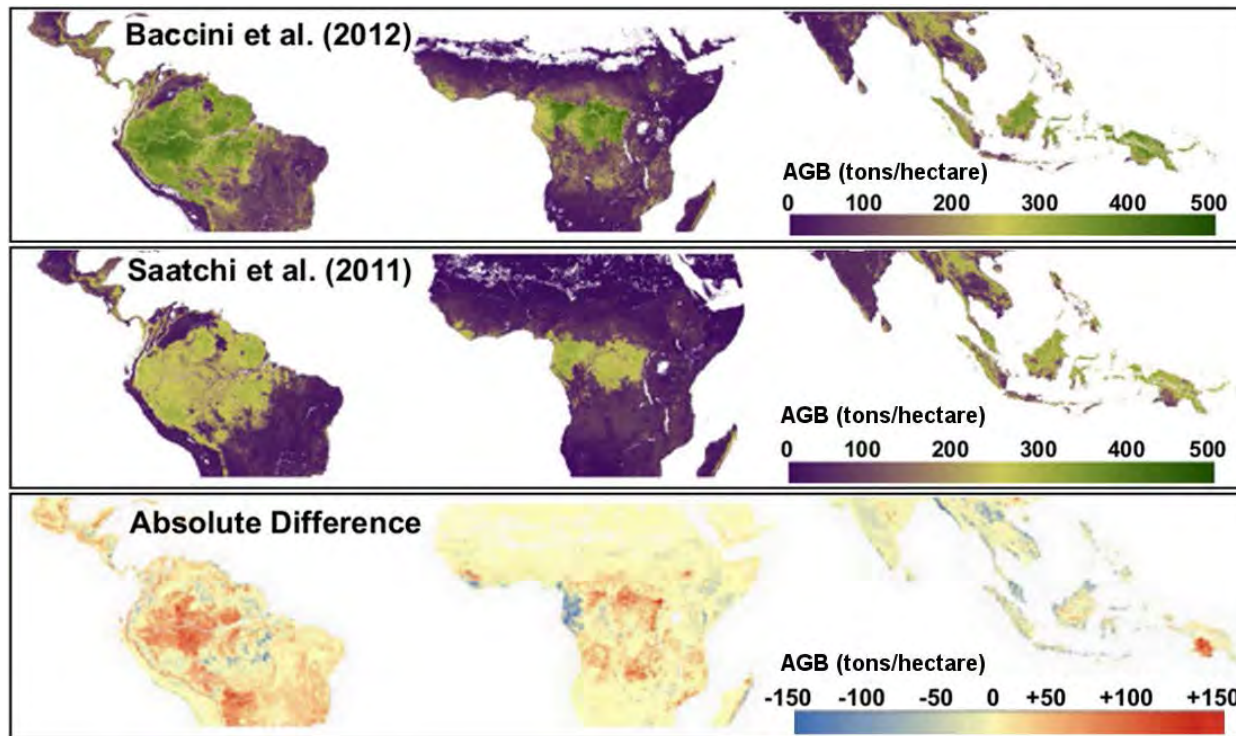
Regrowth



State of Carbon and Inventory of Global Forests

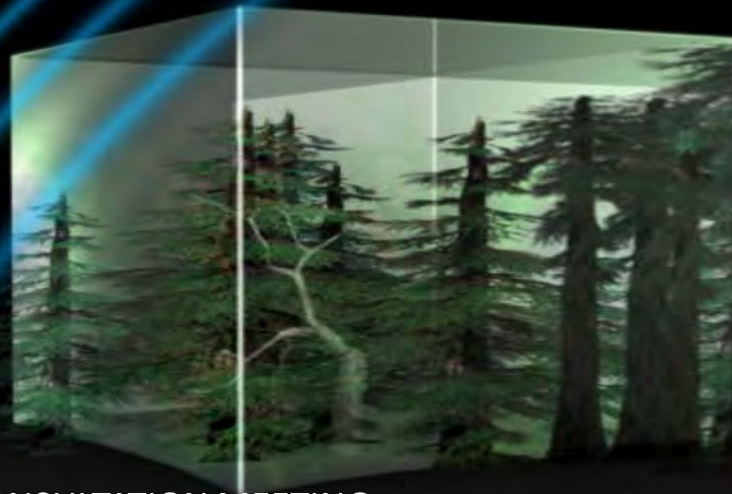


Latest tropical biomass maps use height data from satellite lidar but have large biases



biomass

ESA's 7th Earth
Explorer
mission



EARTH EXPLORER 7 USER CONSULTATION MEETING

An Earth Explorer to observe forest biomass

Carbon emission estimates from deforestation and degradation are uncertain

Gross
carbon
emission
s



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

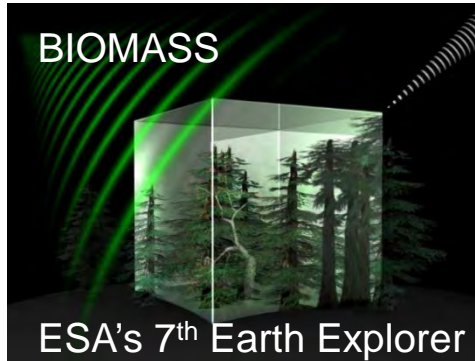
where A is the area of forest type, with biomass B and an emission efficiency factor E

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

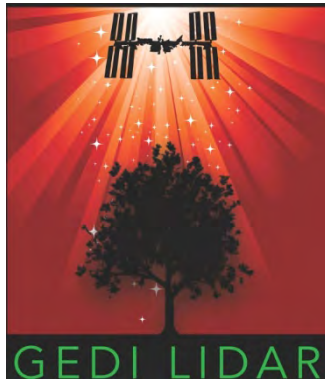


Forest
biomass &
height



Forest
structure &
lower level
biomass

Forest
structure
& biomass



The “4th
mission”;
in situ
networks

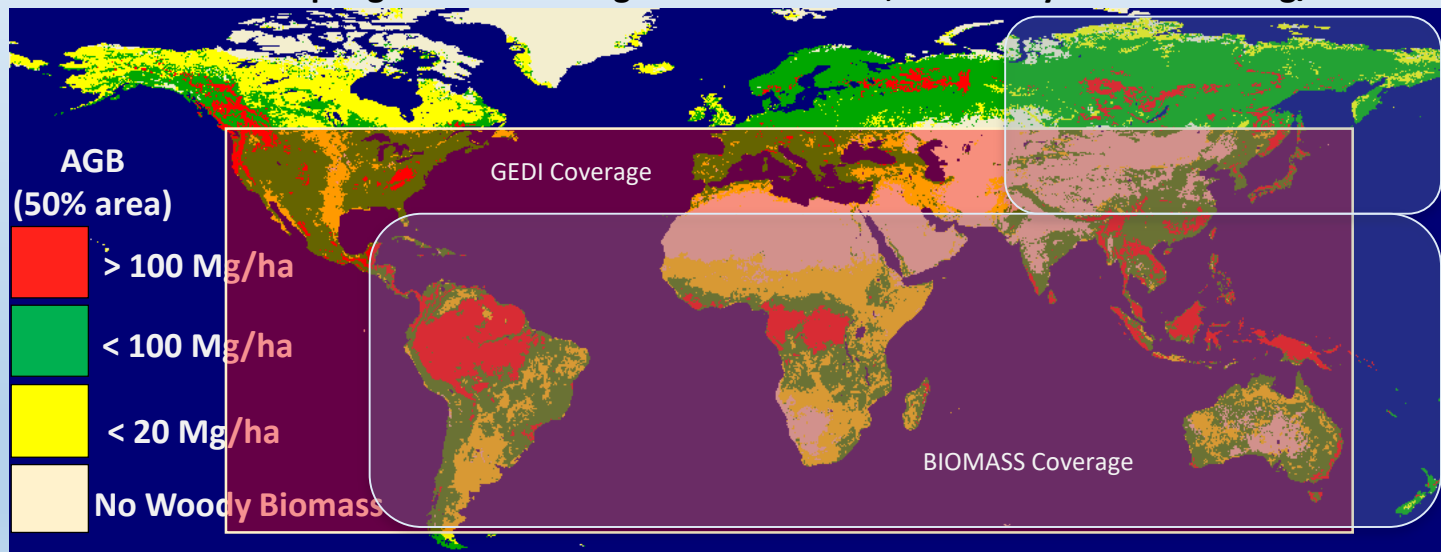


Synergistic Forest Observations

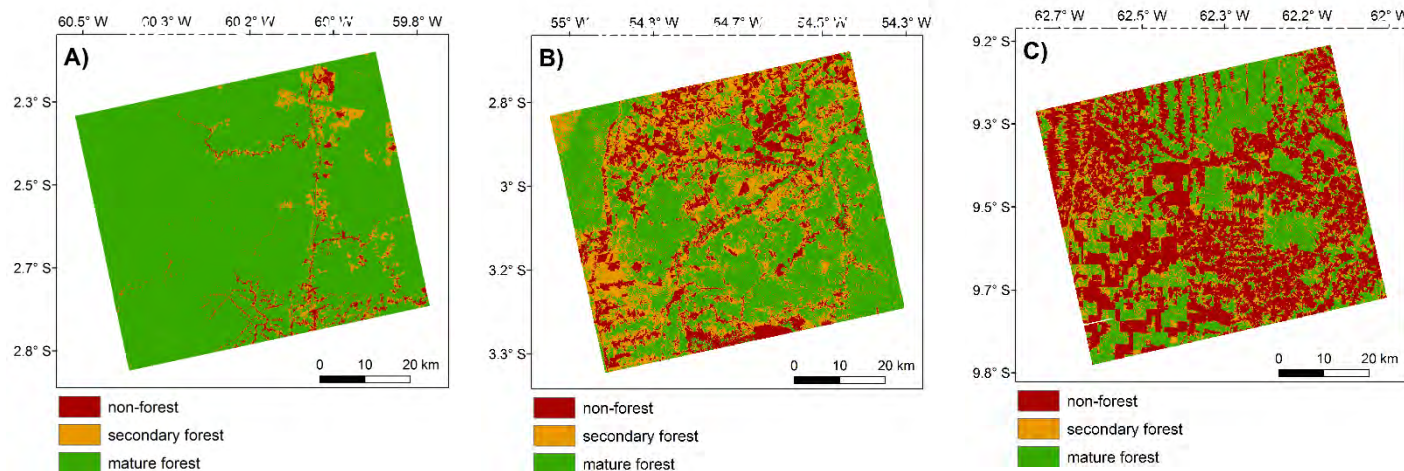
NISAR: Global Coverage, sensitivity to AGB < 100 Mg/ha

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

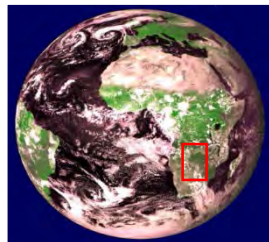


- high overall accuracy (95–96%)
- highest errors in the secondary forest class (omission and commission errors in the range 4–6% and 12–20% respectively)

Space Measurements of Carbon Emissions from Biomass Burning



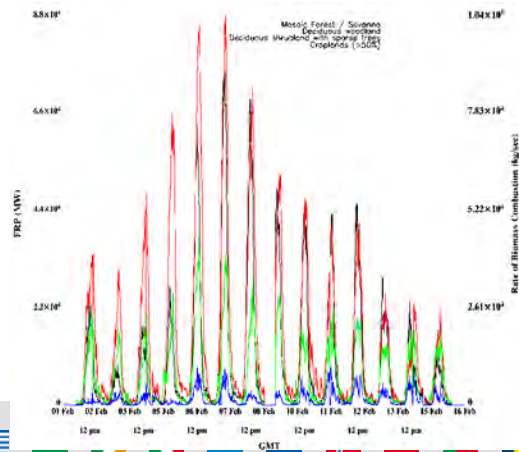
MSG SEVIRI



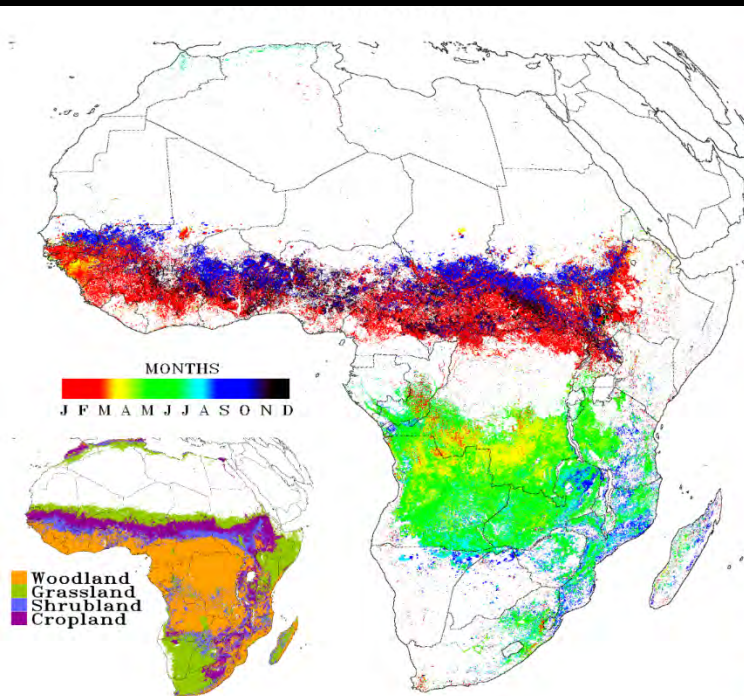
Vegetation releases fixed amount of energy when burned
A proportion emitted as radiation – detectable by satellite



*Diurnal cycle
in emissions*

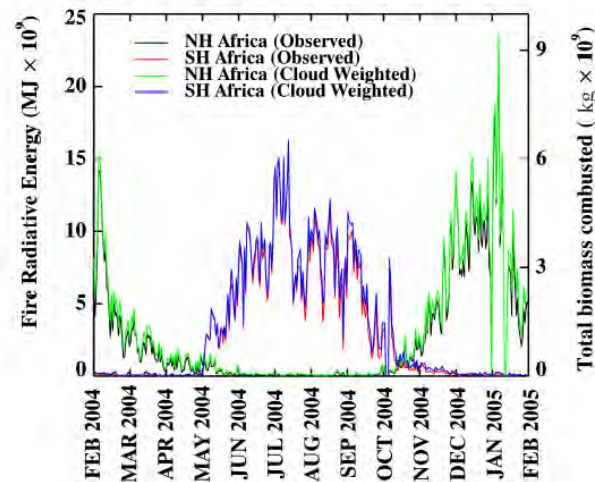


Fire Seasonality and Location Variation



[Very strong seasonal cycle]

Temporal Emissions



→ NH Africa 362 - 414 Tg

→ SH Africa 402 - 440 Tg

0.0 0.5 1.0 1.5 2.0 2.5
Fire Radiative Energy ($\text{MJ} \times 10^{10}$)

Short-Term Emissions Estimation as Model Drivers

Observed Geostationary FRP [W/m²] (red)
Modelled (blue)

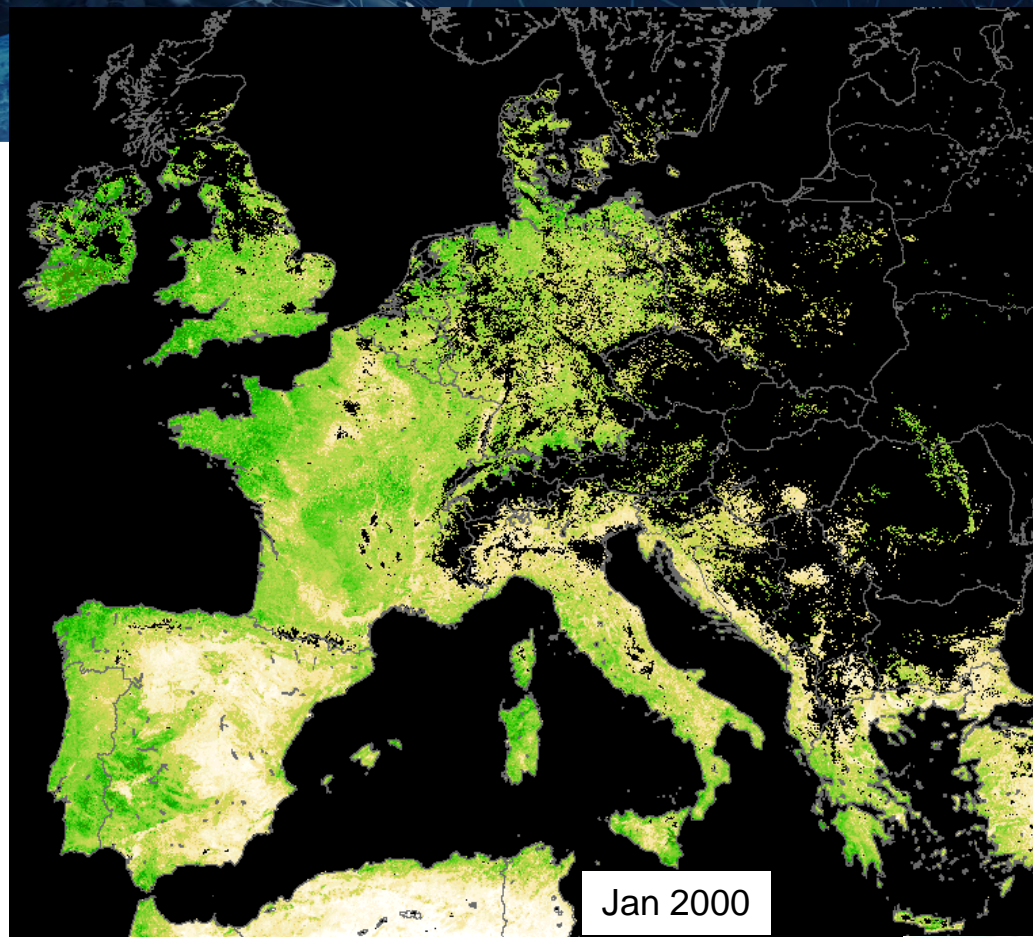


Light Use Efficiency:

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

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

Phenology: seasonal patterns of vegetation



Jan 2000

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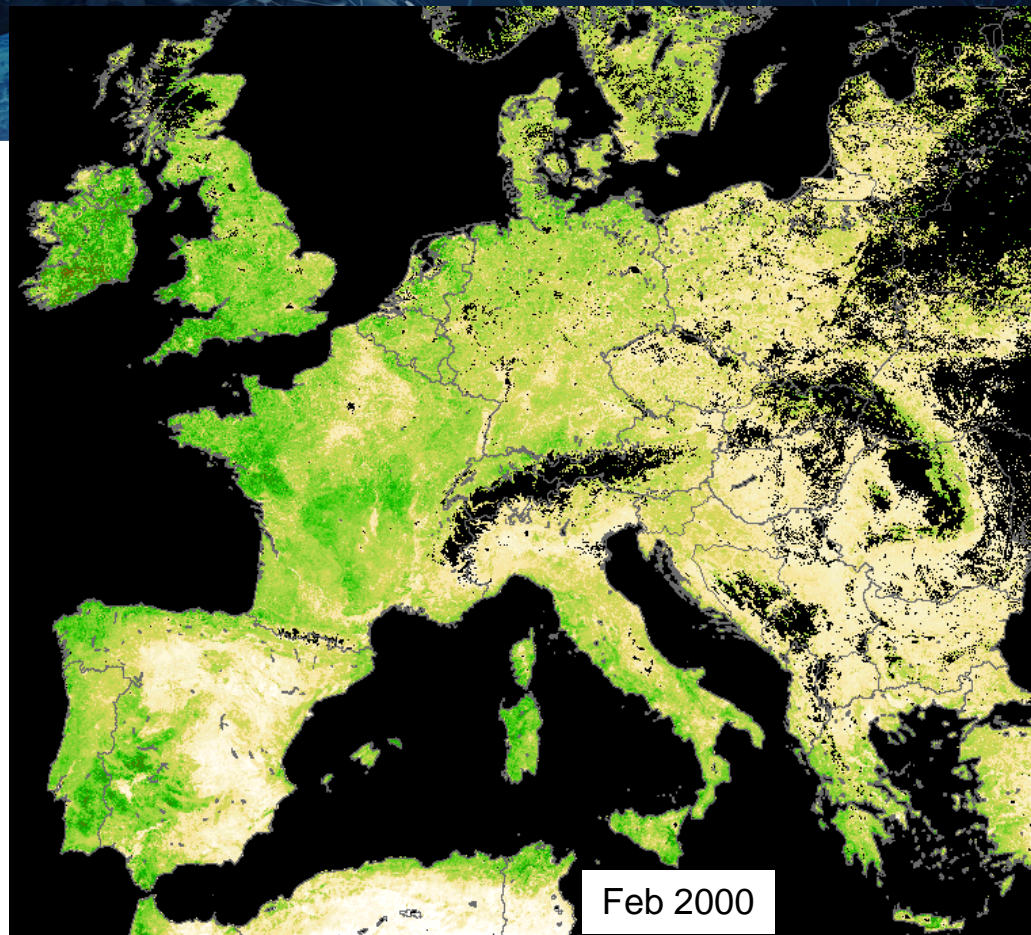


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Feb 2000

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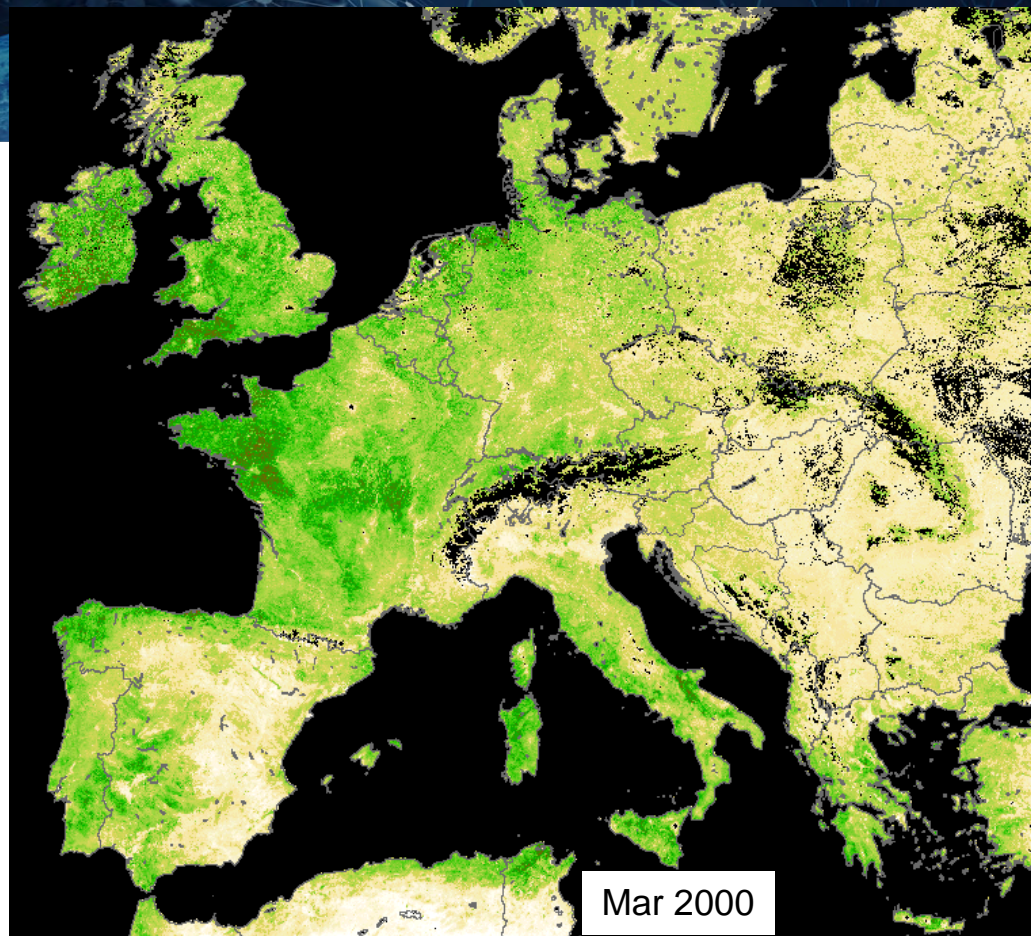


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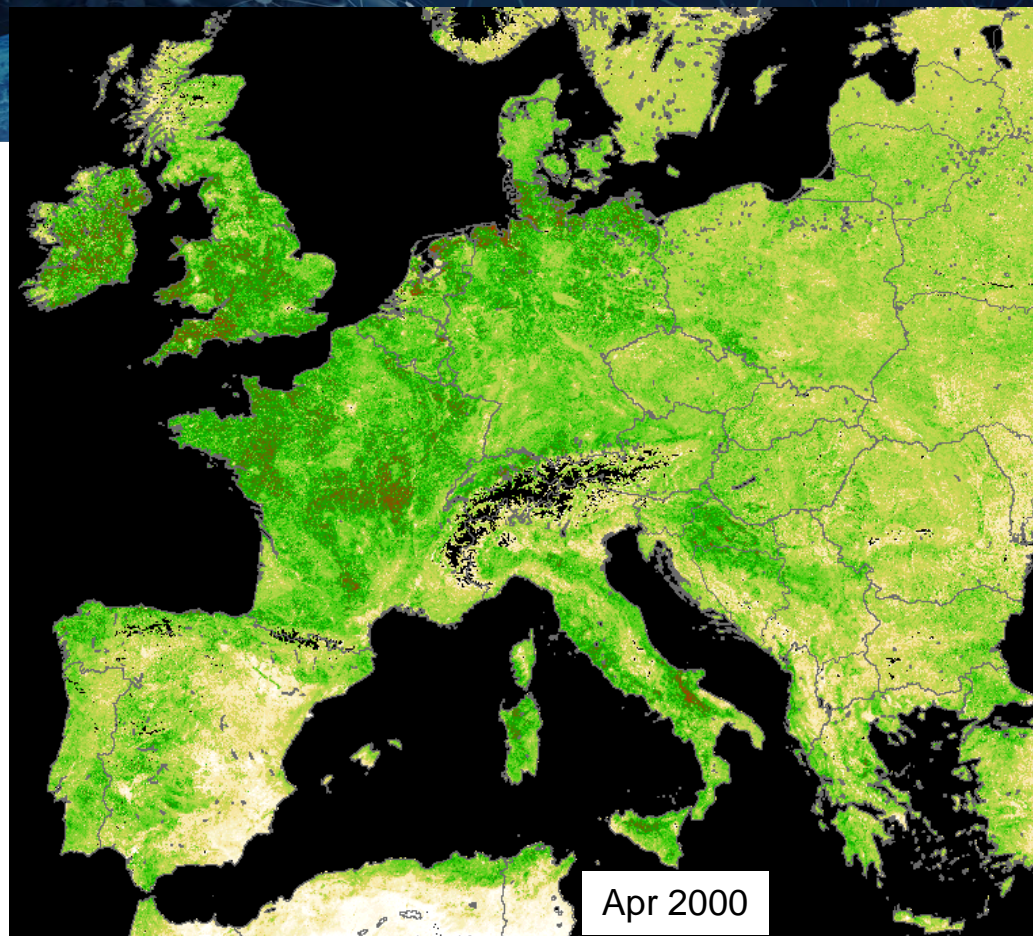


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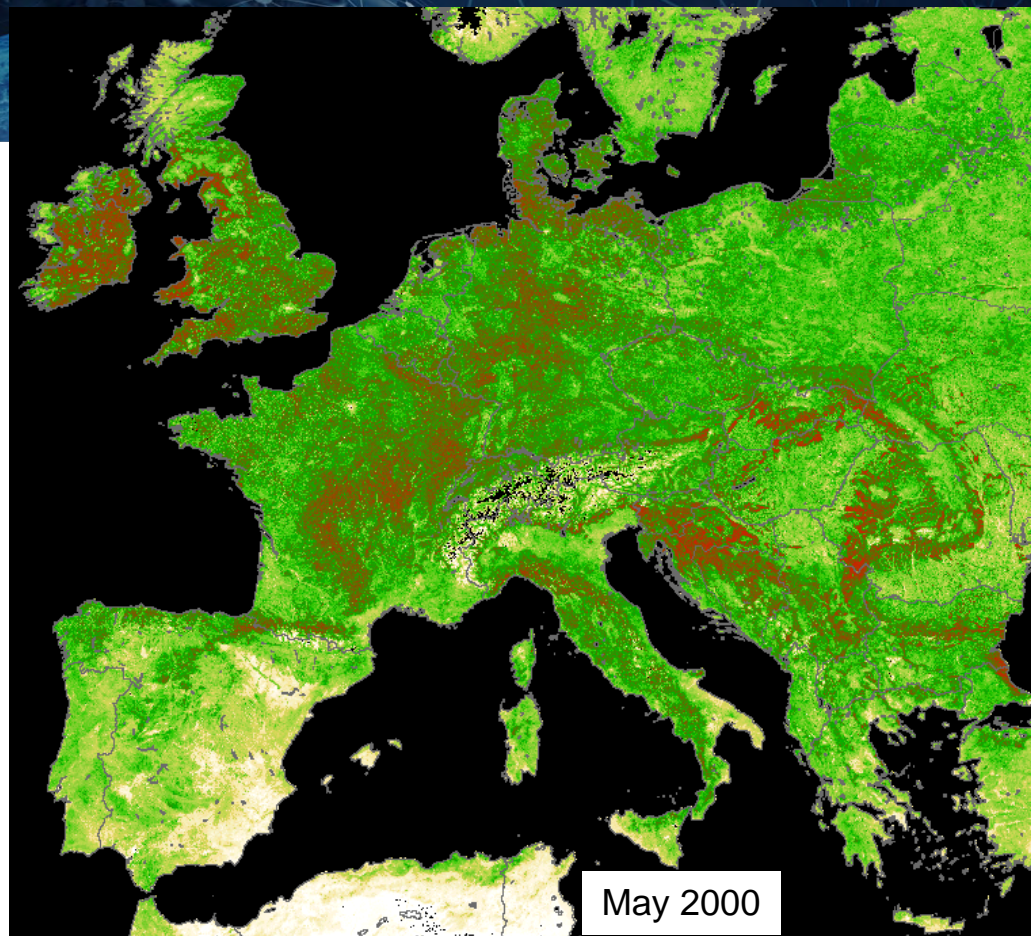


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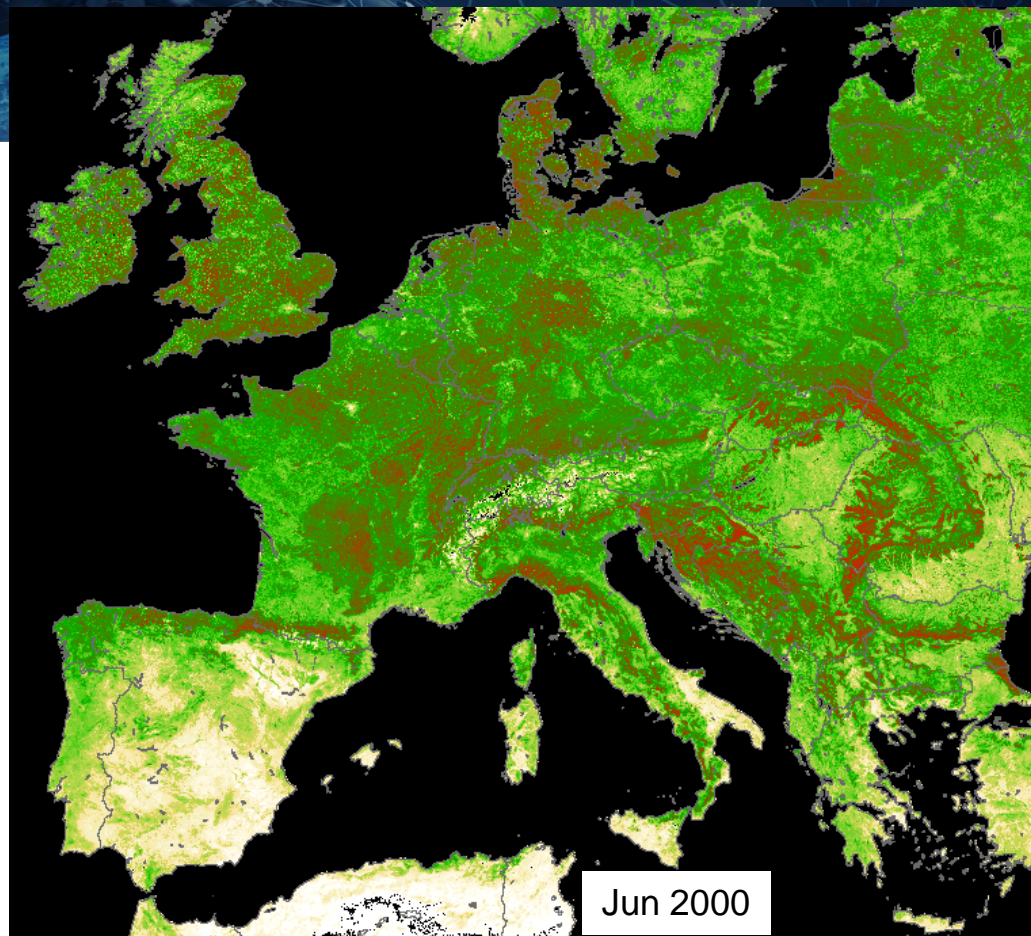


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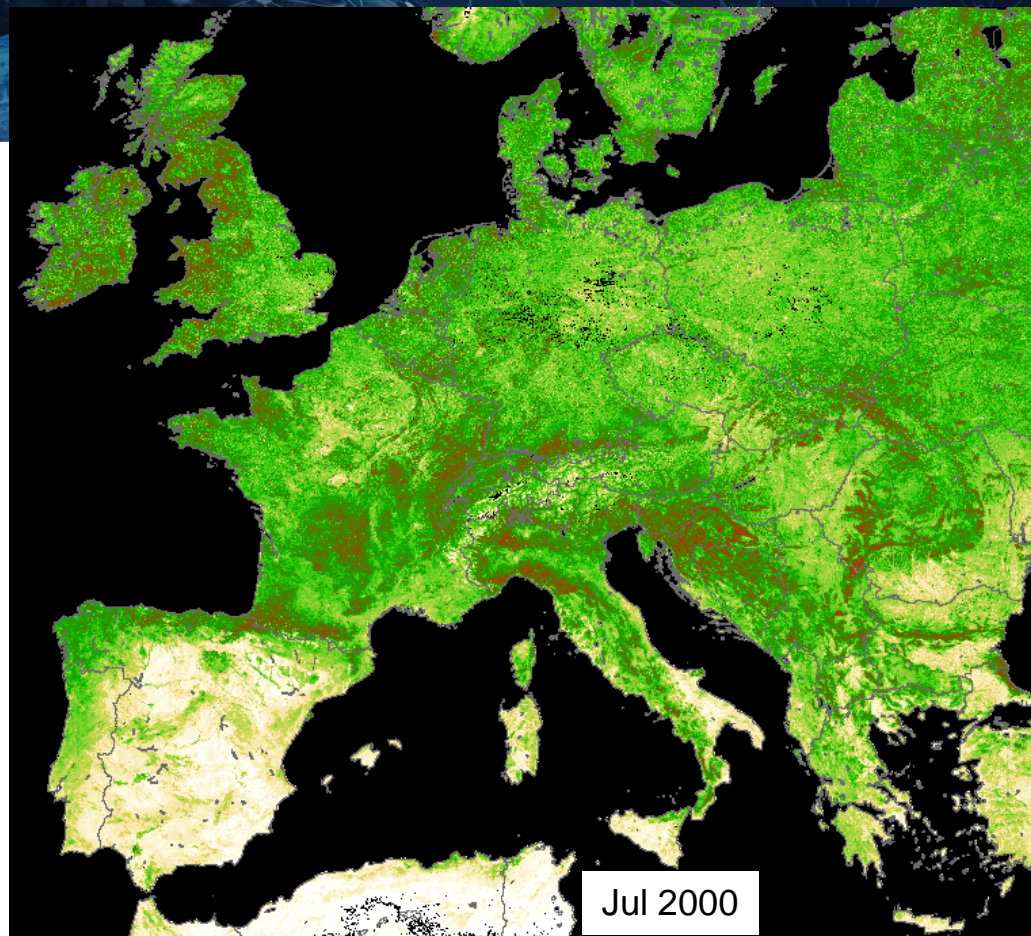


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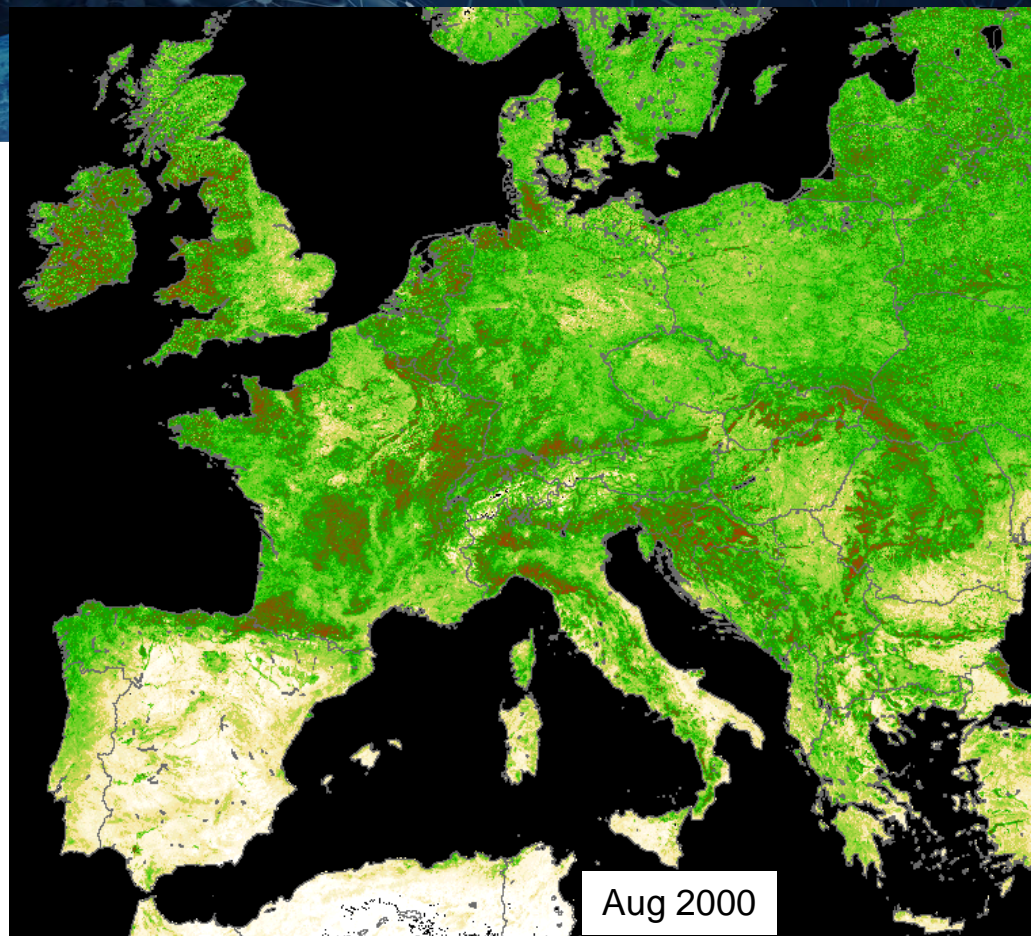


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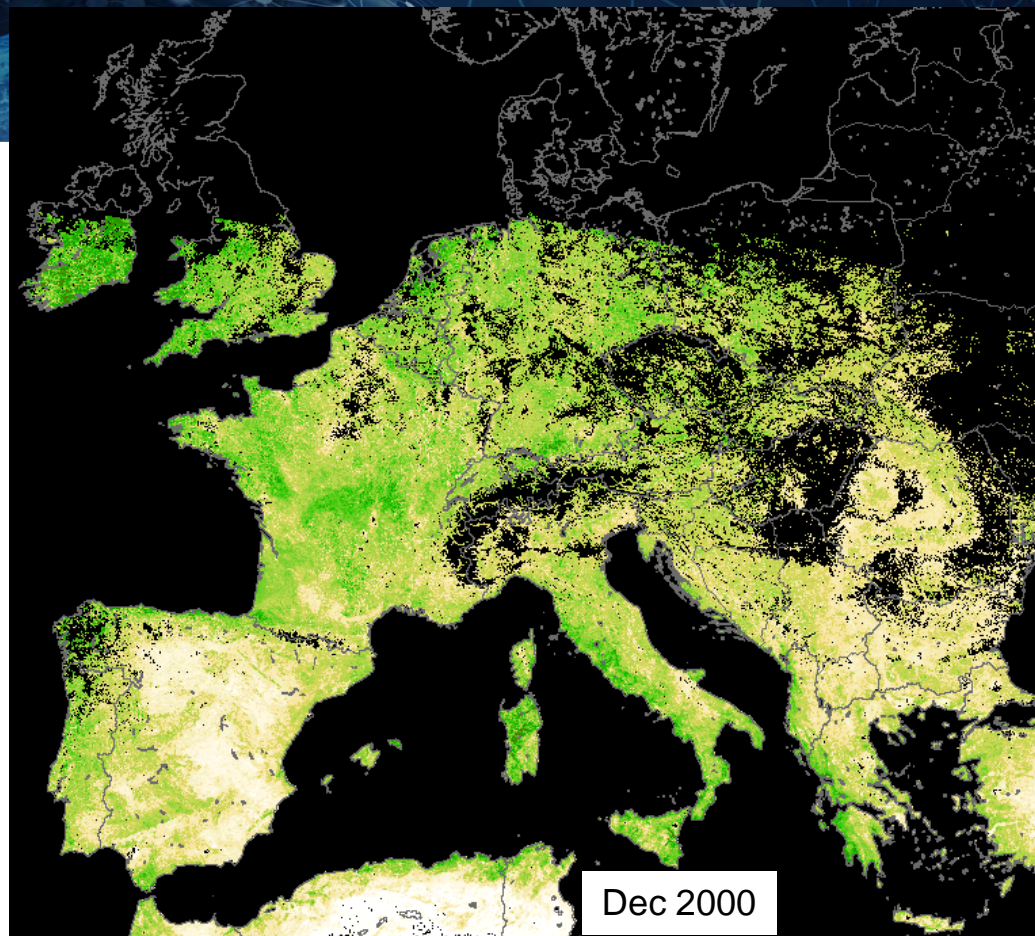


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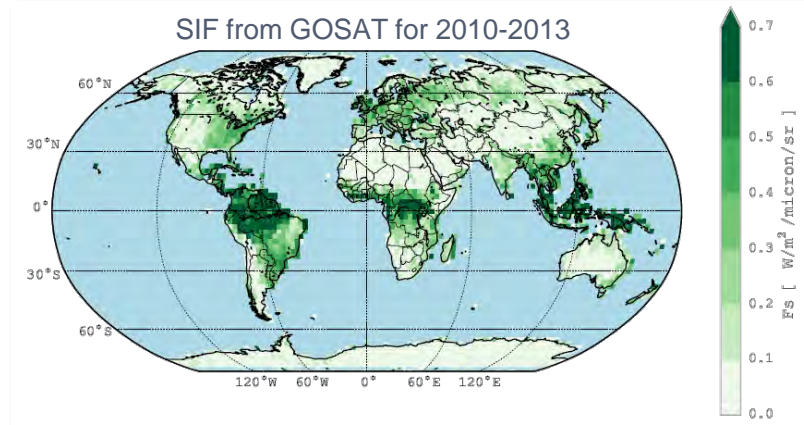
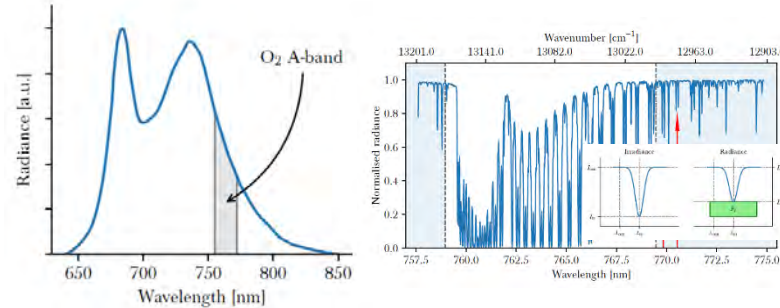
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Solar Induced Fluorescence

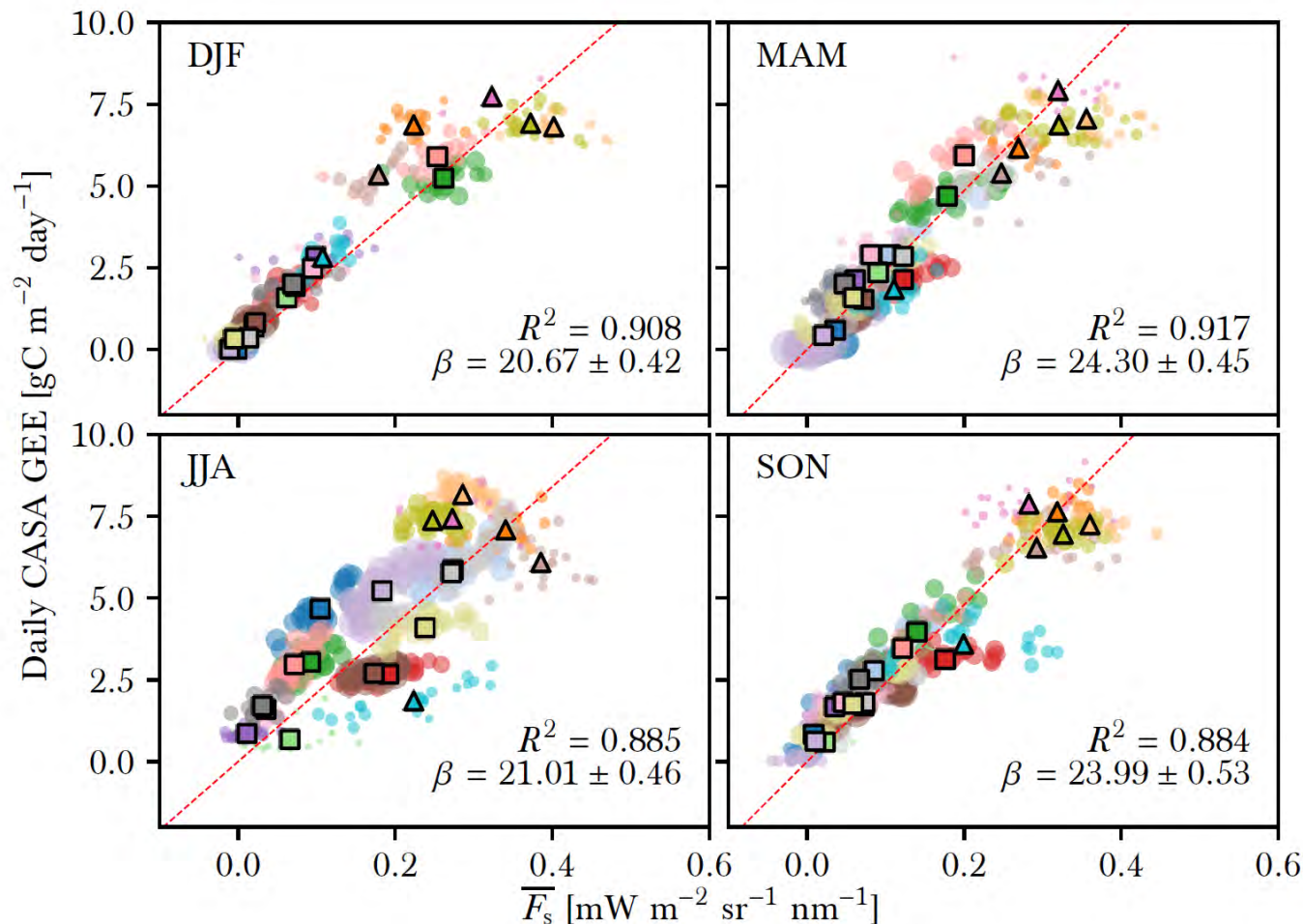
- Solar-induced fluorescence SIF is related to plant productivity and water stress
- SIF is observable from satellites through filling-in of solar lines (Frankenberg et al., 2011)
- (Macroscopic) Relationship between SIF and GPP:

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



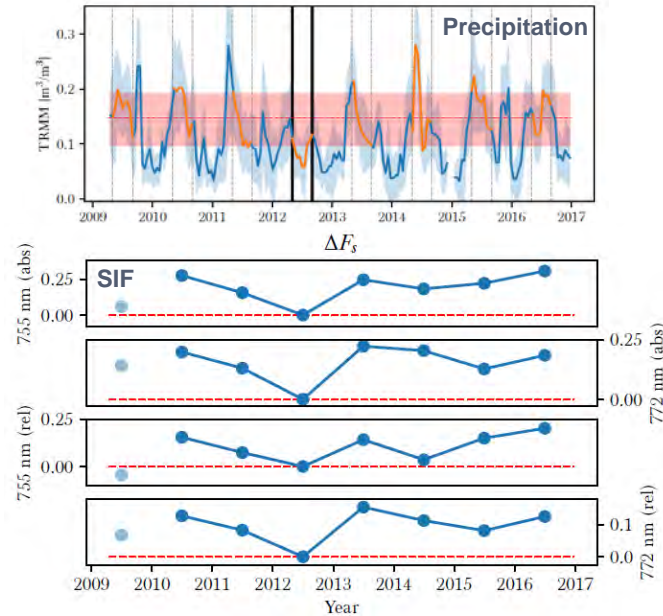
SIF vs GPP

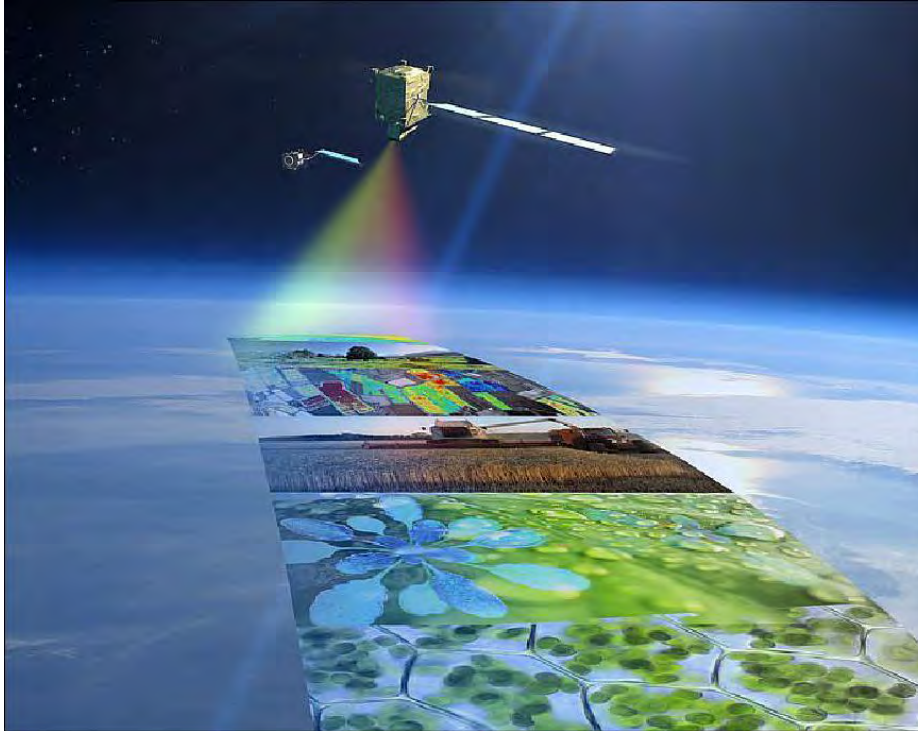
- North American Boreal
- North American Temperate
- ▲ Northern Tropical South America
- ▲ Southern Tropical South America
- South American Temperate
- Temperate Northern (north extratropical) Africa
- Northern Tropical Africa
- Southern Tropical Africa
- Temperate Southern (south extratropical) Africa
- Eurasia Boreal
- Eurasia Temperate
- ▲ Northern Tropical Asia
- ▲ Southern Tropical Asia
- Tropical Australia
- Temperate Australia
- Europe
- ▲ Amazonia
- East Asia
- ▲ South Asia



Case Study: 2012 North American Drought

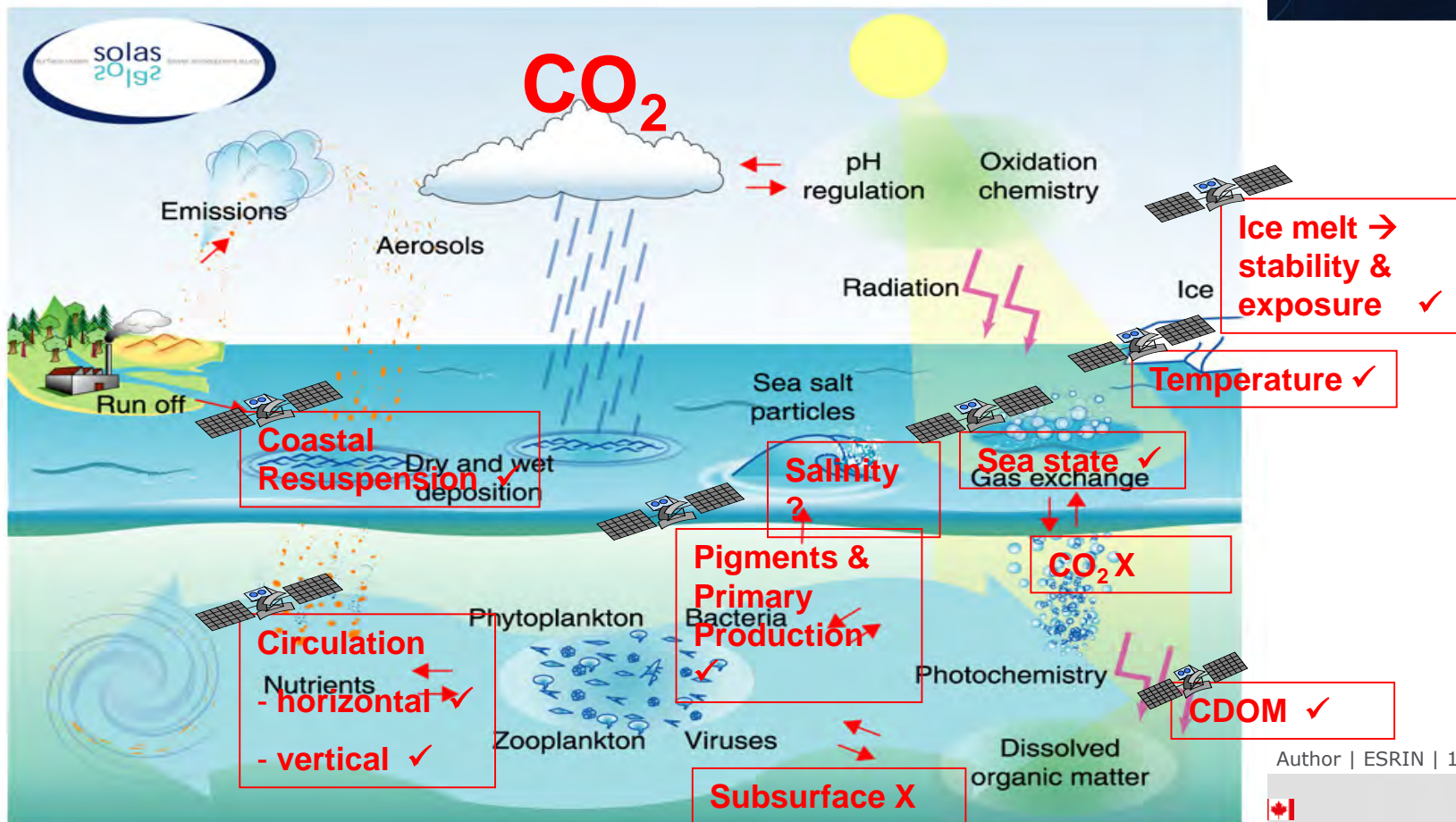
- USA experienced severe drought in 2012
- Climate anomaly with significant impact on productive corn belt region
- Large drop in SIF is observed (SIF as proxy for drought stress)





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 CO₂ exchange with the ocean?

Directly by satellites?

Not yet

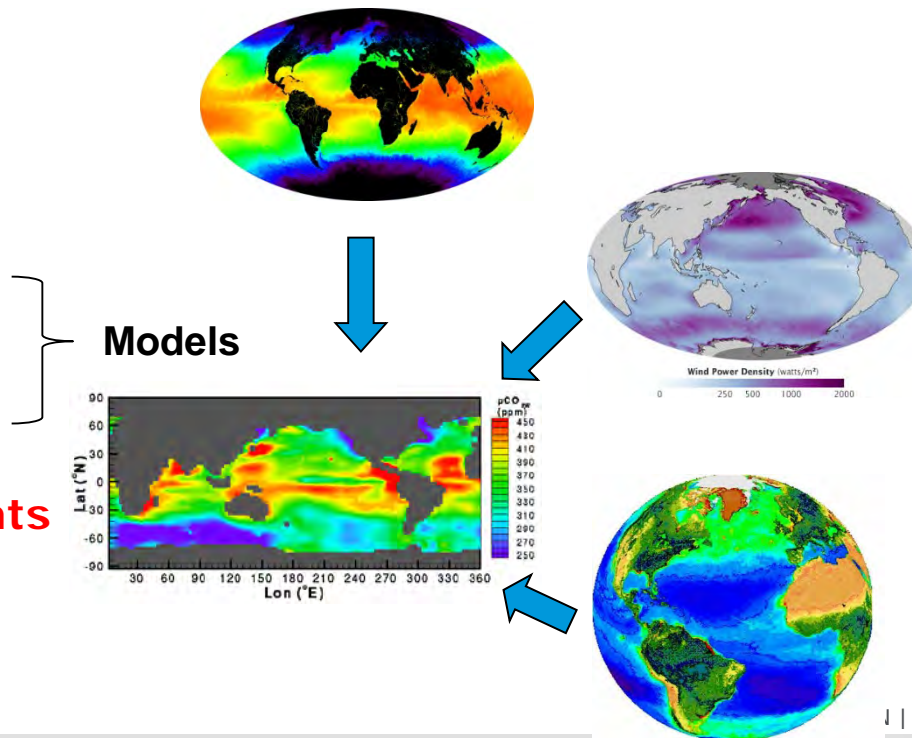
Indirectly by satellites?

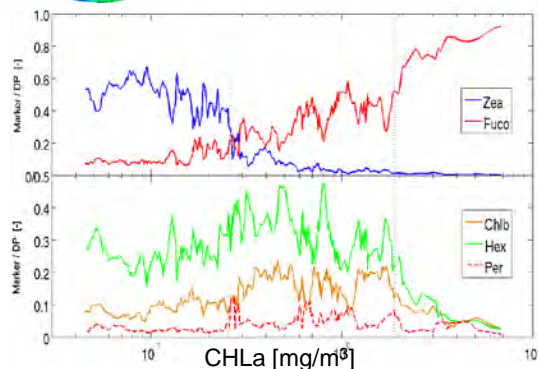
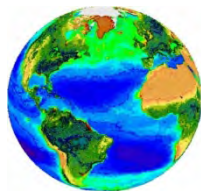
Temperature ✓

Sea state/winds ✓

Algal biomass ✓

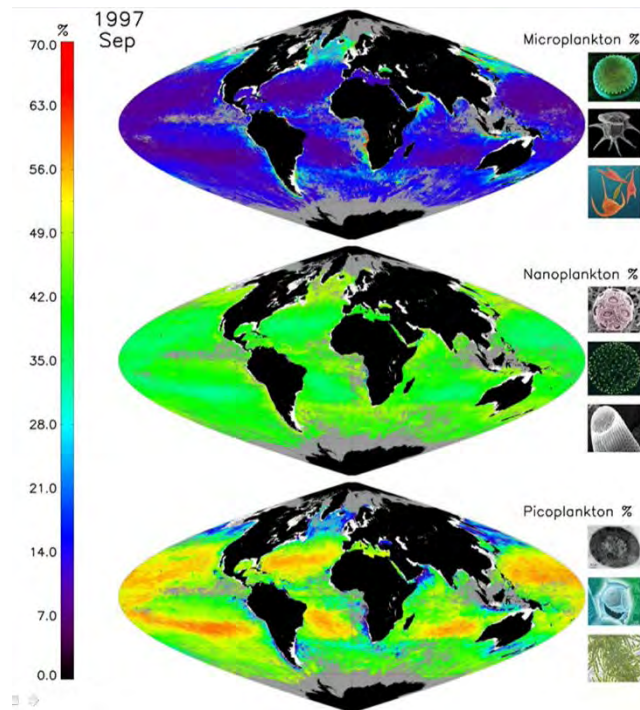
**Also need direct measurements
– only available in situ**



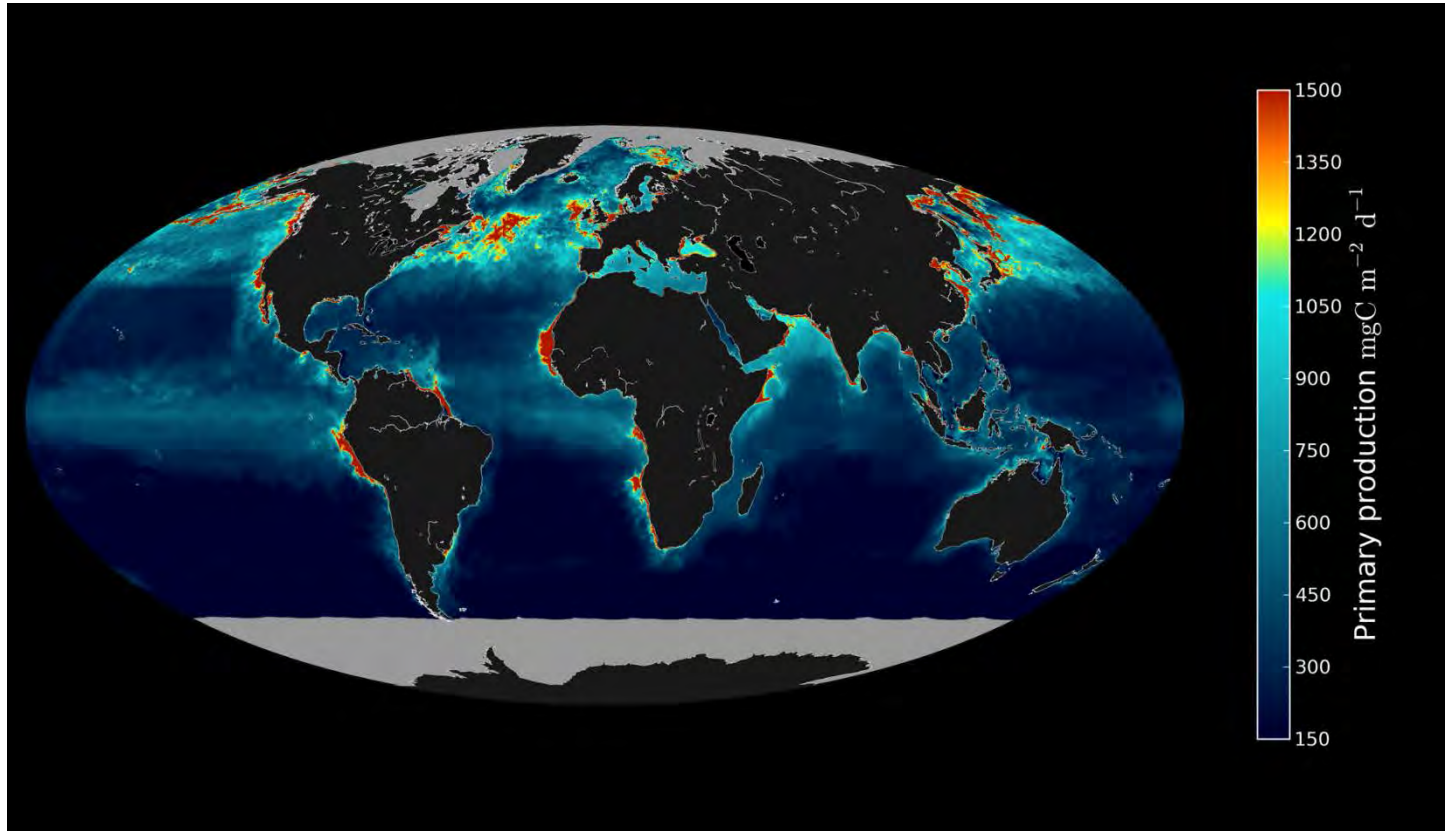


Size of algal cells regulates ecosystem processes:

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



Computed Global Primary Production



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

- 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 CO2 **fluxes** are not available from space.

- 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.