



# Le rôle complexe des forêts dans les changements climatiques (puits et sources de carbone)

*Philippe Peylin  
(et de nombreux contributeurs)*



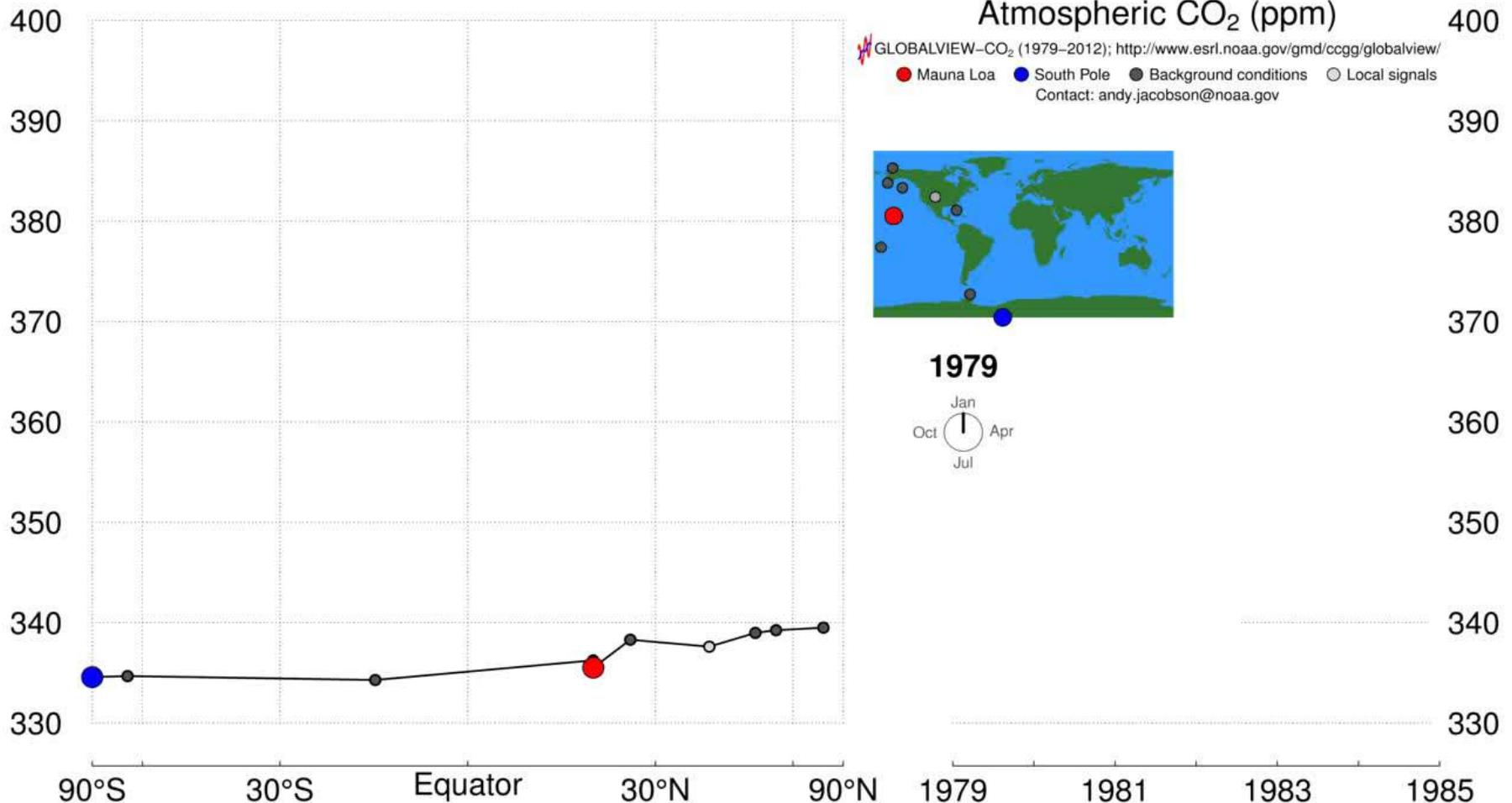
- Cycle du carbone et forêts
  - Cycle global du carbone
  - Forêts et flux de carbone naturels
- Déforestation
  - impact sur le cycle du carbone
  - Fermeture du bilan de carbone
- Réponse des forêts aux changements globaux
  - Augmentation du CO<sub>2</sub> & changement du climat
- Modélisation des écosystèmes forestiers
  - Les approches et leurs incertitudes
  - Projections futures et enjeux

# Le cycle du carbone vu de l'atmosphère

## The global carbon budget 1959–2011

C. Le Quéré<sup>1</sup>, R. J. Andres<sup>2</sup>, T. Boden<sup>2</sup>, T. Conway<sup>3</sup>, R. A. Houghton<sup>4</sup>, J. I. House<sup>5</sup>, G. Marland<sup>6</sup>, G. P. Peters<sup>7</sup>, G. R. van der Werf<sup>8</sup>, A. Ahlström<sup>9</sup>, R. M. Andrew<sup>7</sup>, L. Bopp<sup>10</sup>, J. G. Canadell<sup>11</sup>, P. Ciais<sup>10</sup>, S. C. Doney<sup>12</sup>, C. Enright<sup>1</sup>, P. Friedlingstein<sup>13</sup>, C. Huntingford<sup>14</sup>, A. K. Jain<sup>15</sup>, C. Jourdain<sup>1,8</sup>, E. Kato<sup>16</sup>, R. F. Keeling<sup>17</sup>, K. Klein Goldewijk<sup>18,19,20</sup>, S. Levis<sup>21</sup>, P. Levy<sup>14</sup>, M. Lomas<sup>22</sup>, B. Poulter<sup>10</sup>, M. R. Raupach<sup>11</sup>, J. Schwinger<sup>23,24</sup>, S. Sitch<sup>25</sup>, B. D. Stocker<sup>26,27</sup>, N. Viovy<sup>10</sup>, S. Zaehle<sup>28</sup>, and N. Zeng<sup>29</sup>

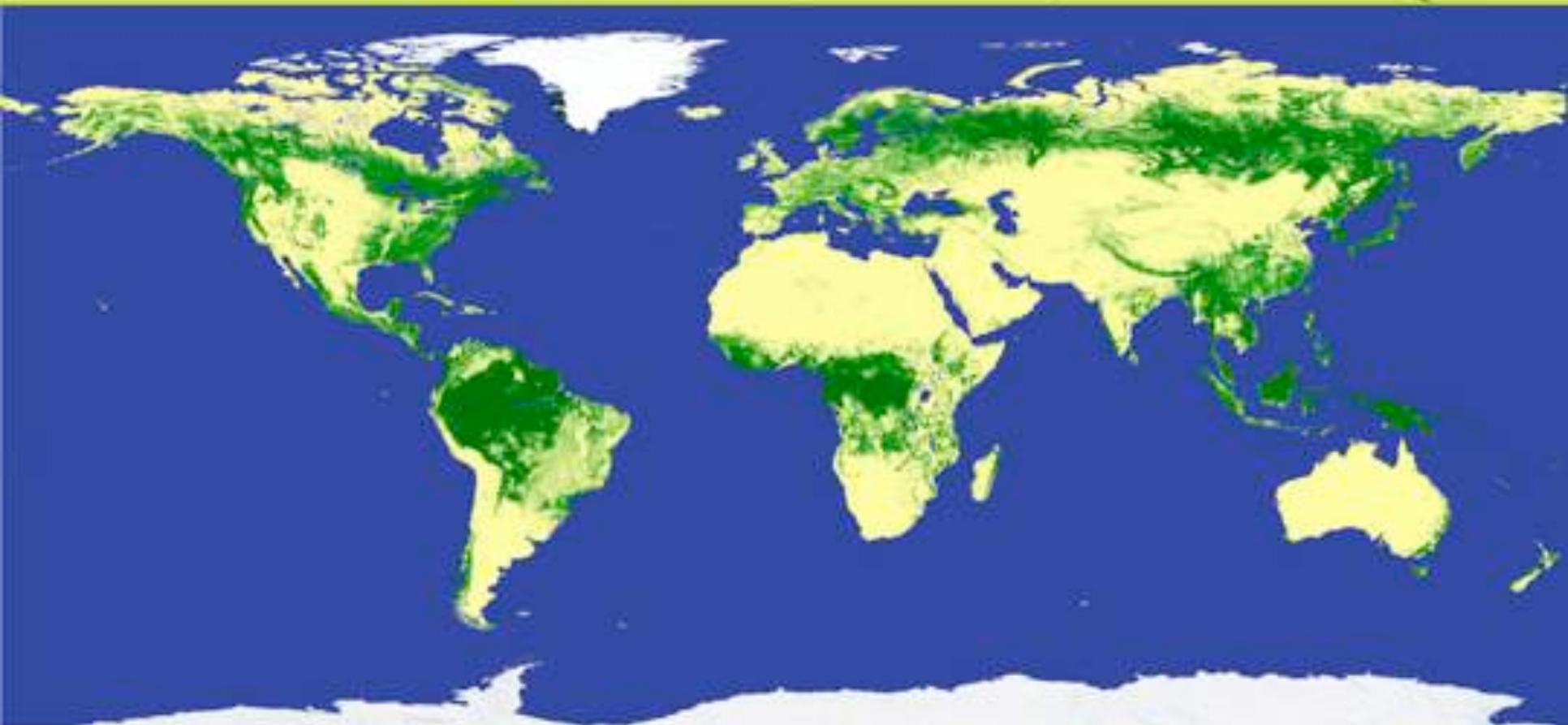
**1 PPM  $\approx$  2.12 Gt de C**  
 (1 Gigatone (Gt) =  $1 \times 10^{15}$ g  
 = 1 Petagram (Pg))



# Extension globale des forêts

- 4 milliard d'hectares  $\approx$  30 % surface émergée
- Déforestation  $\approx$  7-10 million hec entre 2000-2005

PALSAR 10m Global Forest/Non-Forest Map 2009

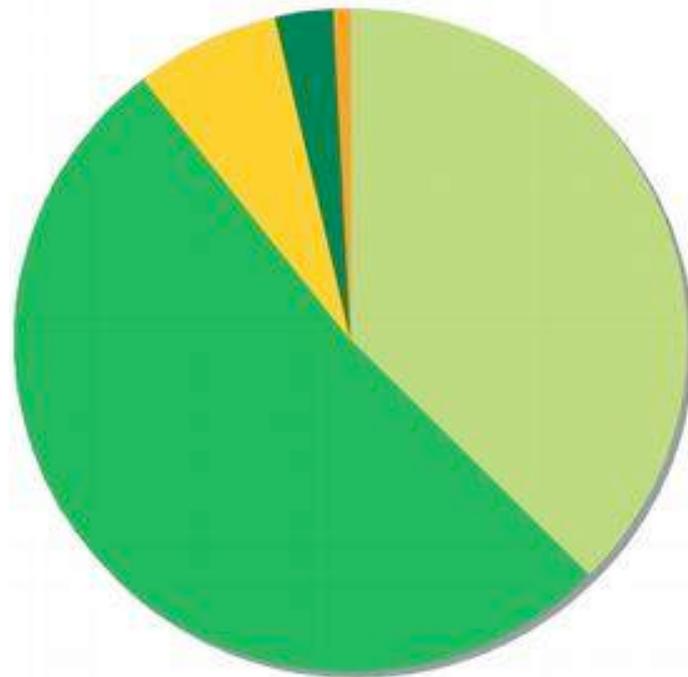


# Quelques caractéristiques globales

## Superficies

- Tropicale:  $\approx 52\%$
- Subtropicale:  $\approx 9\%$
- Tempérée:  $\approx 13\%$
- Boréale / Polaire:  $\approx 25\%$

## Types de forêt



### Caractéristiques des forêts du monde, 2005 (%)

Forêts primaires	36,4
Forêts naturelles modifiées	52,7
Forêts semi-naturelles	7,1
Plantations de production	3,0
Plantations de protection	0,8

## Mesures "in situ"



- Diamètre
- Hauteur

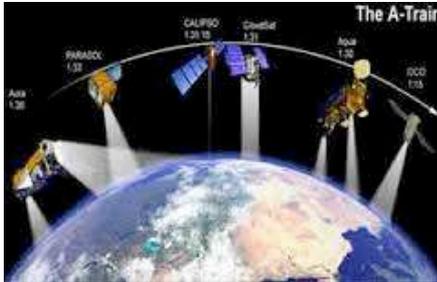
## Relations empiriques



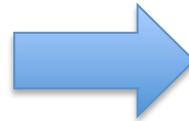
## Estimations :

- la biomasse Aérienne
- Biomasse totale

## Observations spatiales



- Hauteur
- Biomasse



- la biomasse Aérienne
- Biomasse totale

## Modèle d'écosystème

- Equation physiques
- Relation empiriques

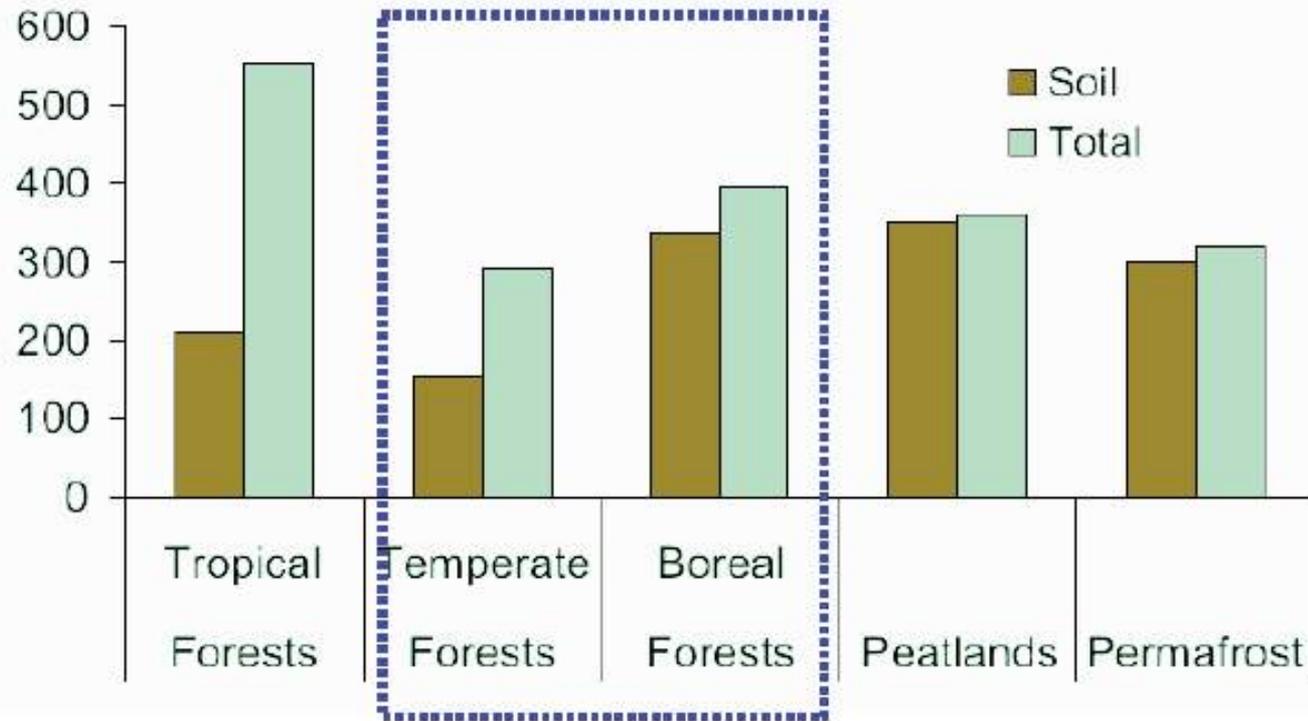
## Intégration spatiale / temporelle



- Flux de carbone
- Stocks par réservoir

# Stock de carbone global des écosystèmes

Stock  
(PgC)



after Gruber et al. 2004, Lal, 2005, Davidson & Janssens 2006

# Fortes incertitudes sur le contenu en carbone

Estimation via mesures satellites

- Importante source information (REDD+)
- **Mais fortes incertitudes!**

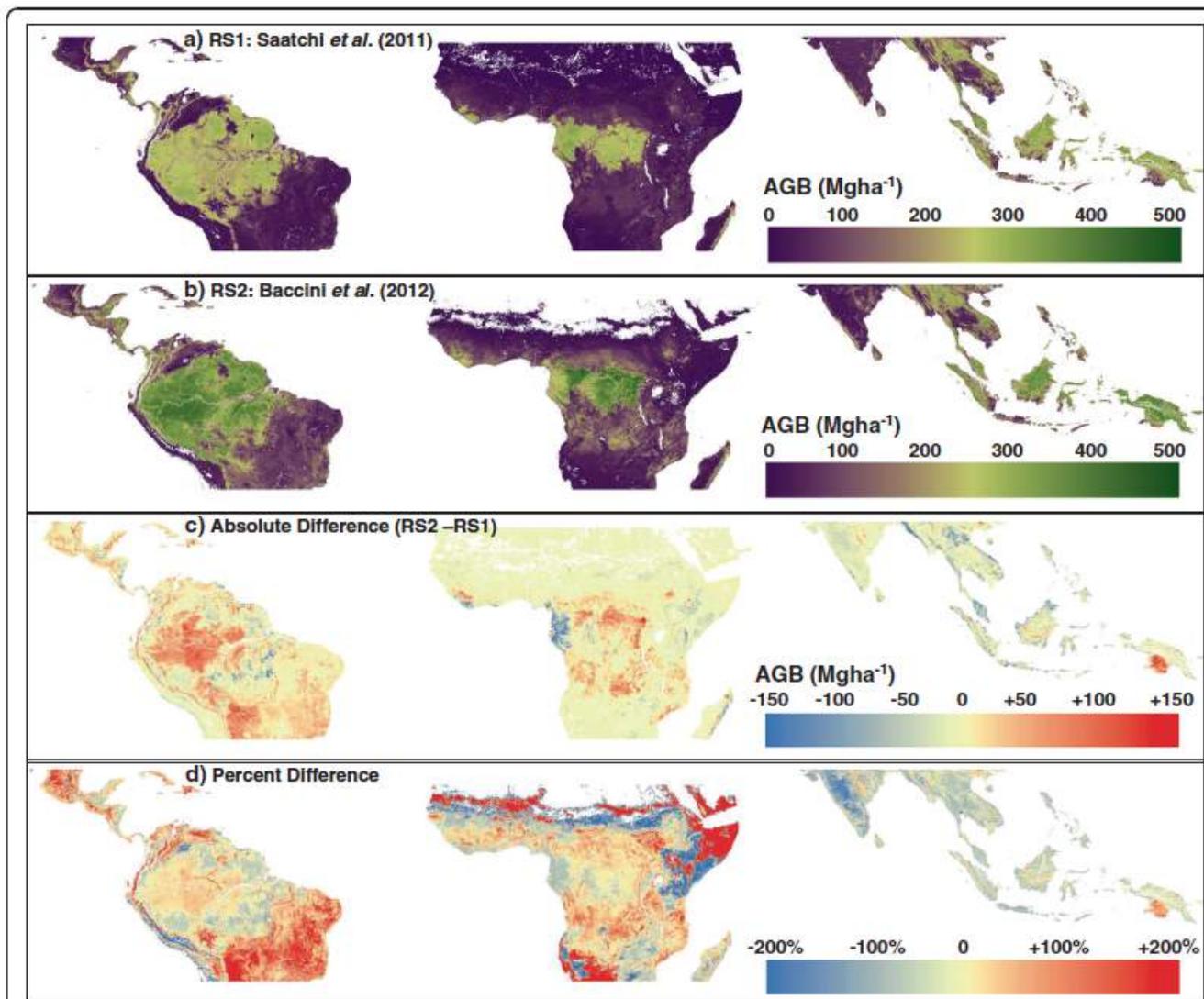
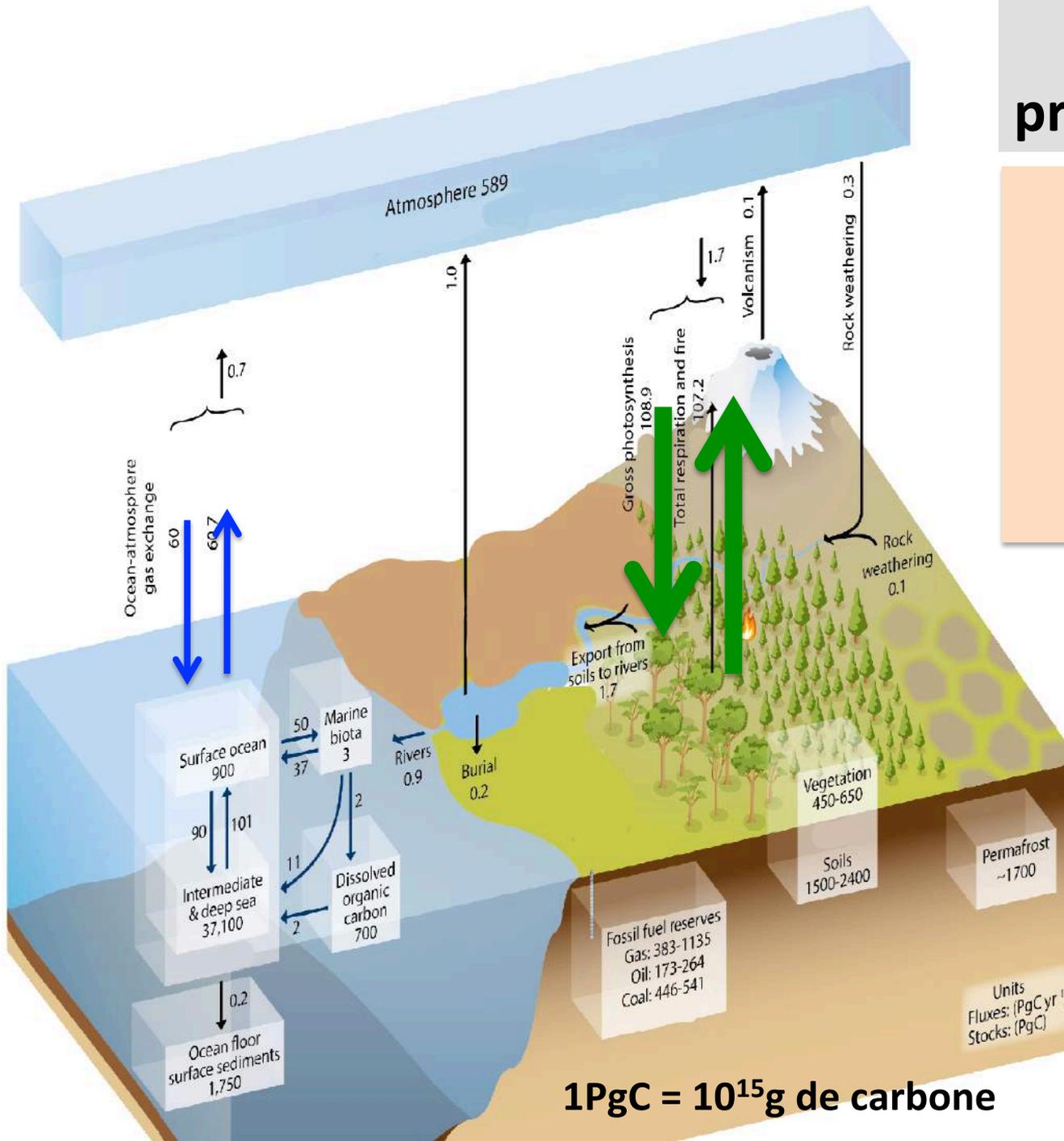


Figure 1 A comparison of two remote sensing based maps of aboveground biomass (AGB) across the tropics: a) AGB for RS1 [15]; b) AGB for RS2 [16]; c) absolute difference,  $RS2 - RS1$ ; d) the percent difference between  $RS2$  and  $RS1$ . The projection is sinusoidal, an equal area projection.

# Cycle naturel pré-industriel du CO<sub>2</sub>



↓ Photosynthèse brute  
108.9 PgC/an

↑ Respiration et feux  
107.2 PgC/an

↓ Absorption océans  
60 Pg/an

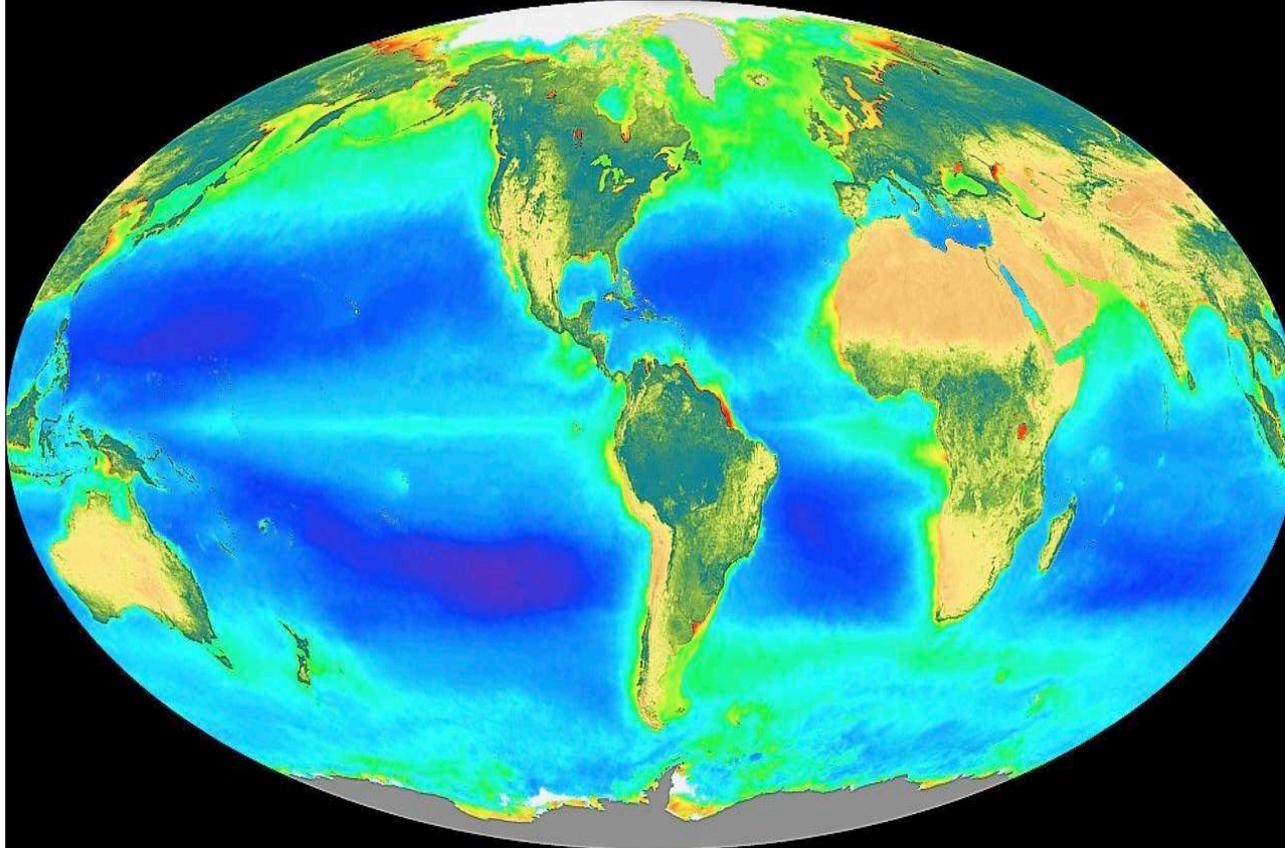
↑ Dégazage océans  
60.7 Pg/an

↕ Erosions, rivières, volcans,  
sédimentation, ...  
2 PgC/an

1PgC = 10<sup>15</sup>g de carbone

# Productivité Primaire nette continentale et océanique

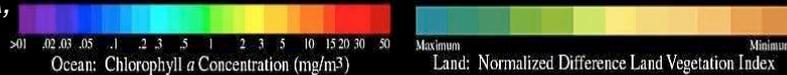
## Indicateurs approximatifs de la productivité primaire



Source :  
SeaWiFS NASA,  
ORBIMAGE

Océans

Continents



Chlorophylle

Indice de végétation

## CONTINENTS

~ 60 PgC/an

Assurée par les  
Plantes vasculaires

Limitée par:

Lumière

Température

Eau

Nutriments (C, N, P,...)

→ **Role crucial  
des forêts**

**Productivité Primaire Nette = Photosynthèse brute - Respiration végétale**

# Perturbation “anthropique”...

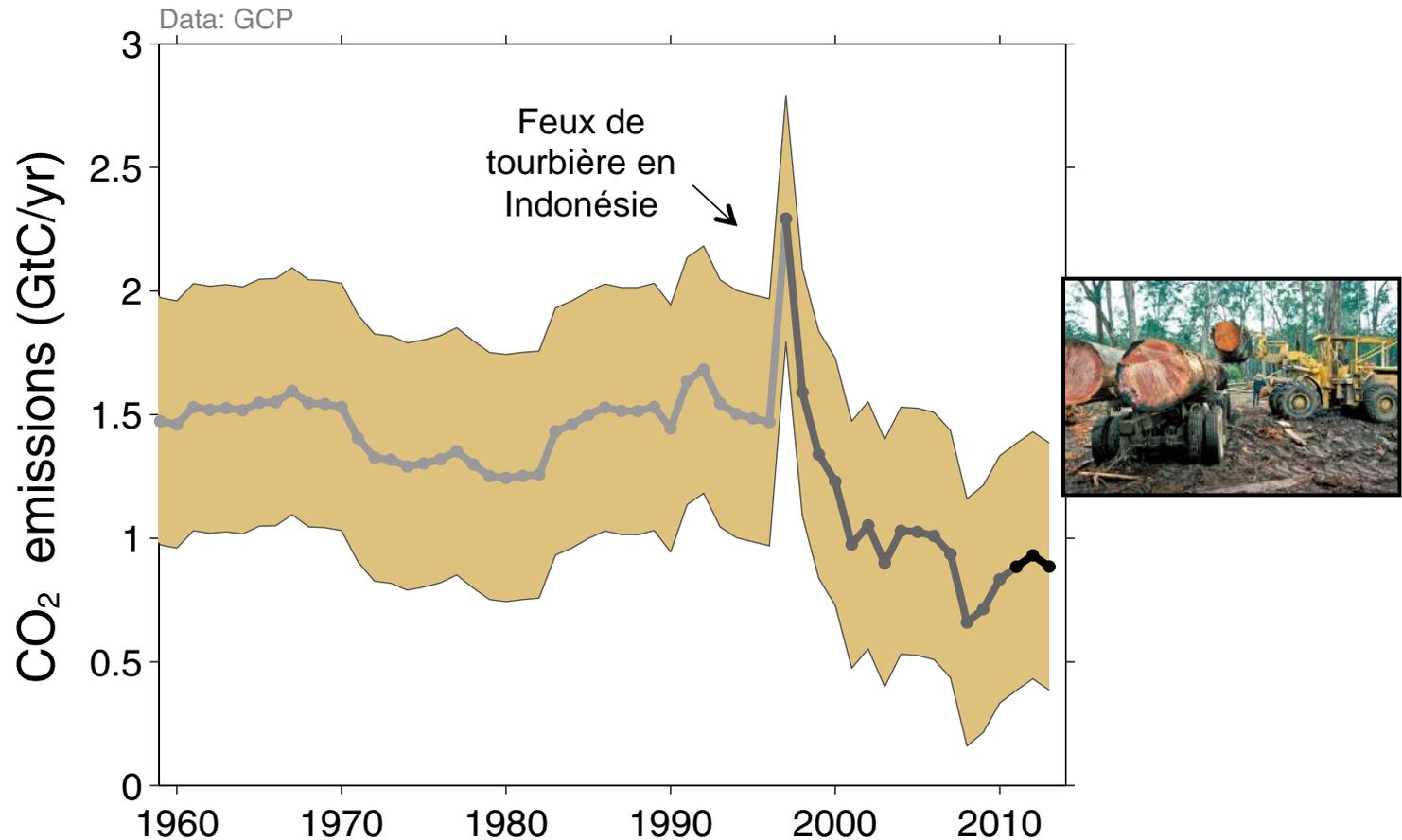
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## Emissions de carbon Liées à la déforestation



# Emissions liées aux changements d'utilisation des terres

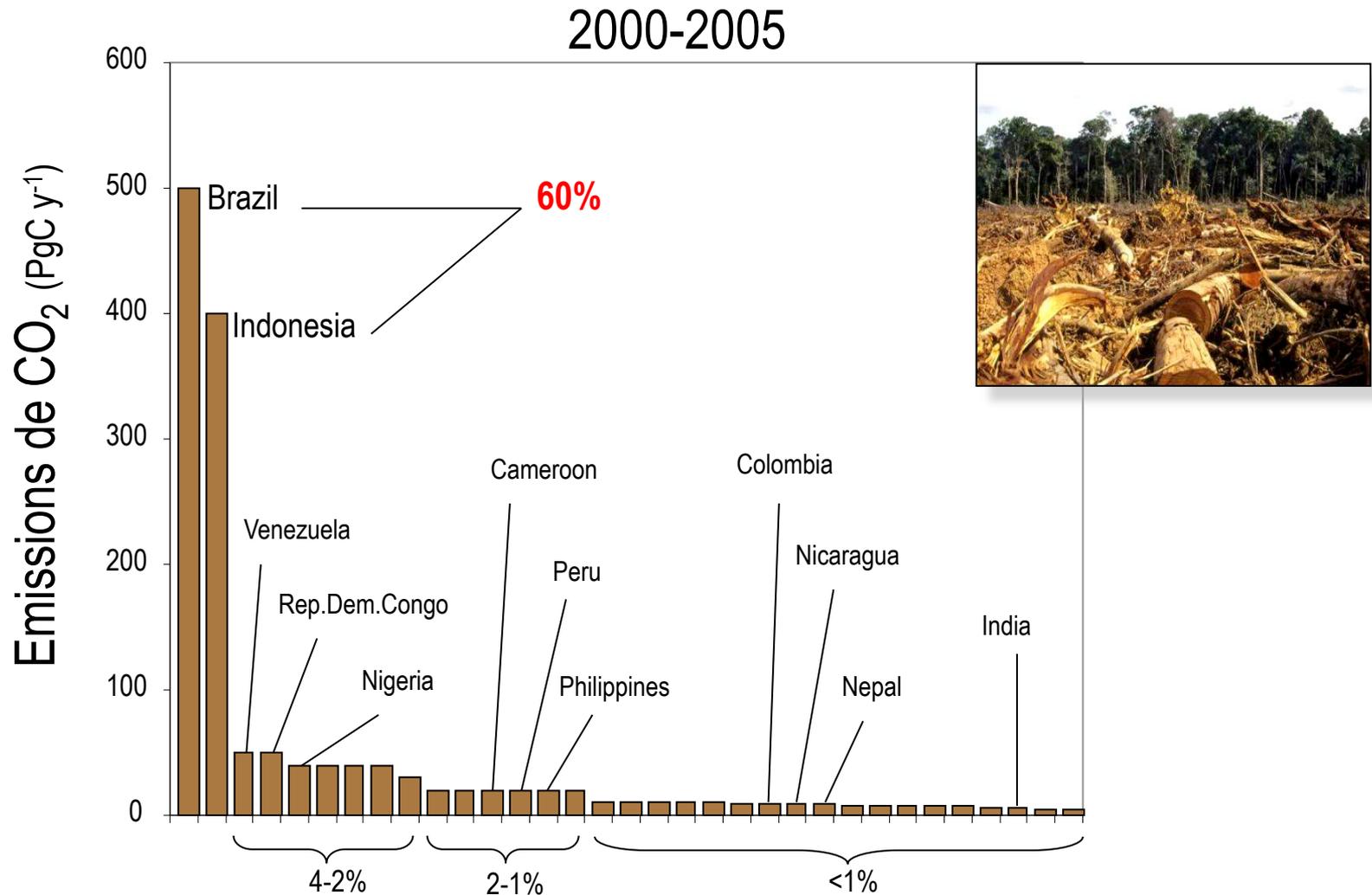
Emissions globales estimées:  $0.9 \pm 0.5$  GtC/an pour période 2004–2013



- Three different estimation methods have been used, indicated here by different shades of grey  
Land-use change also emits CH<sub>4</sub> and N<sub>2</sub>O which are not shown here

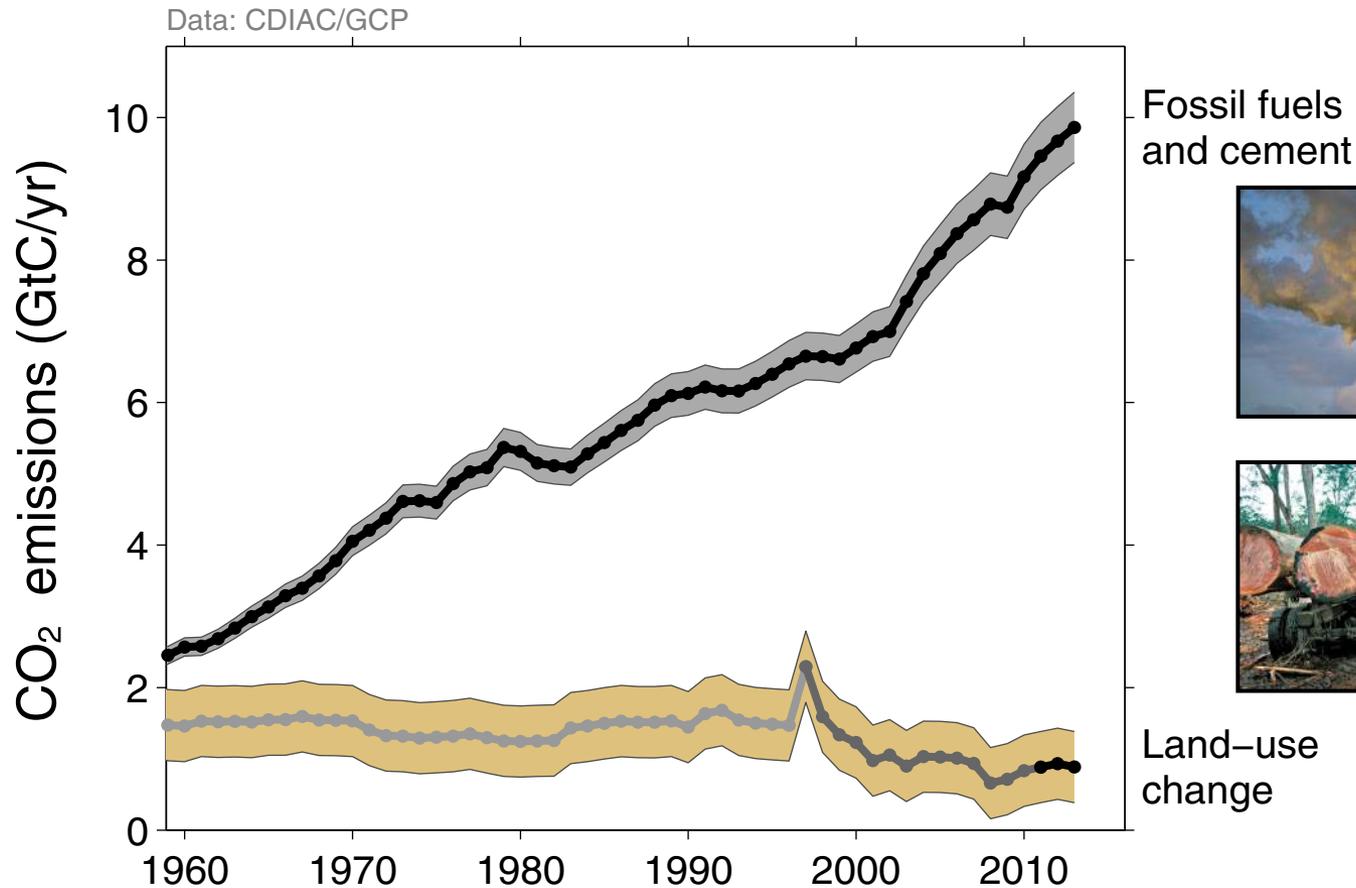
Source: [Houghton et al 2012](#); [Giglio et al 2013](#); [Le Quéré et al 2014](#); [Global Carbon Budget 2014](#)

# Emissions de CO<sub>2</sub> dues à la déforestation



# Emissions totales globales

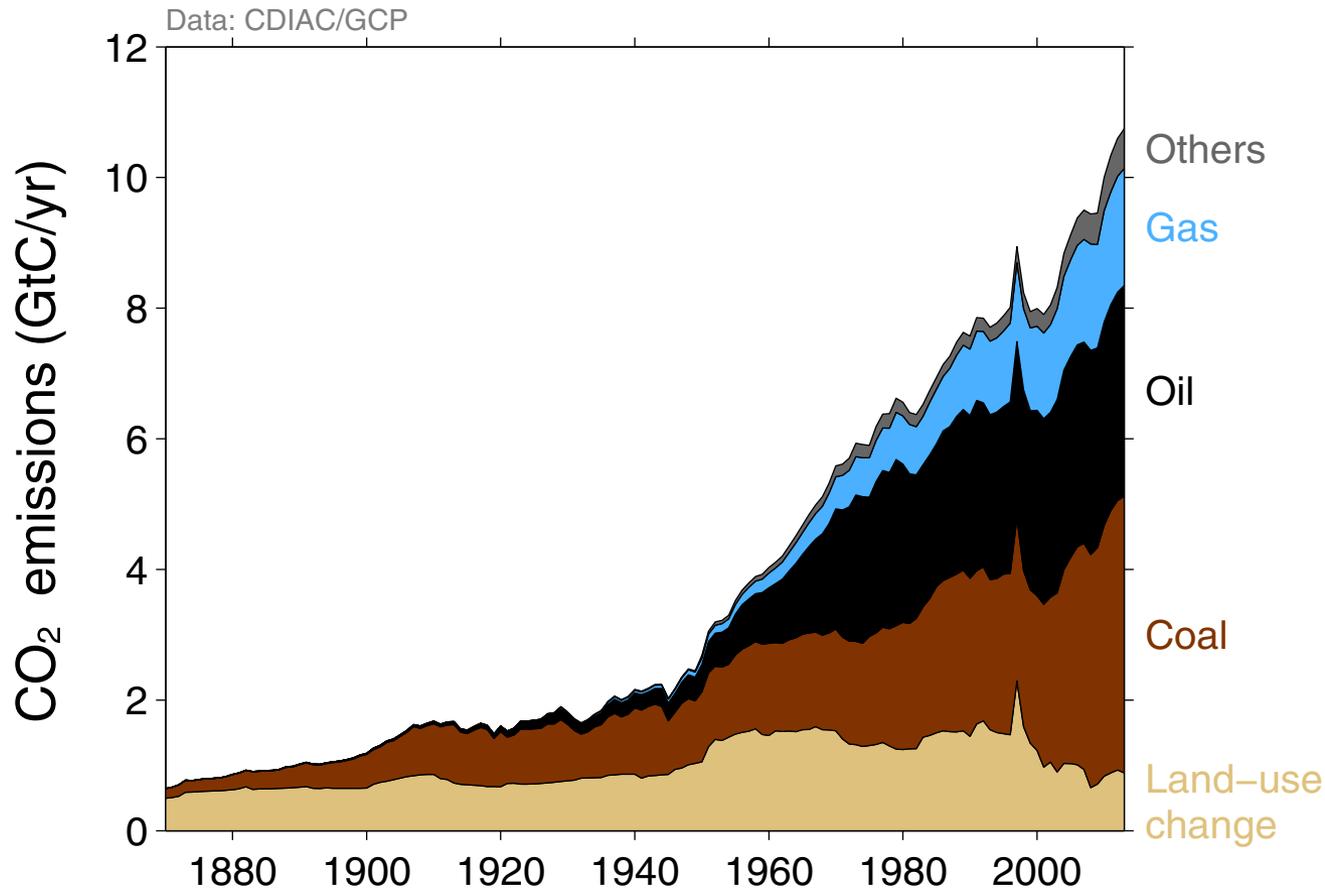
Total global emissions:  $10.7 \pm 0.9$  GtC in 2013, 42% over 1990  
Percentage land-use change: 36% in 1960, 19% in 1990, 8% in 2013



# Emissions totales globales par catégorie

Land-use change was the dominant source of annual CO<sub>2</sub> emissions until around 1950

Coal consumption continues to grow strongly

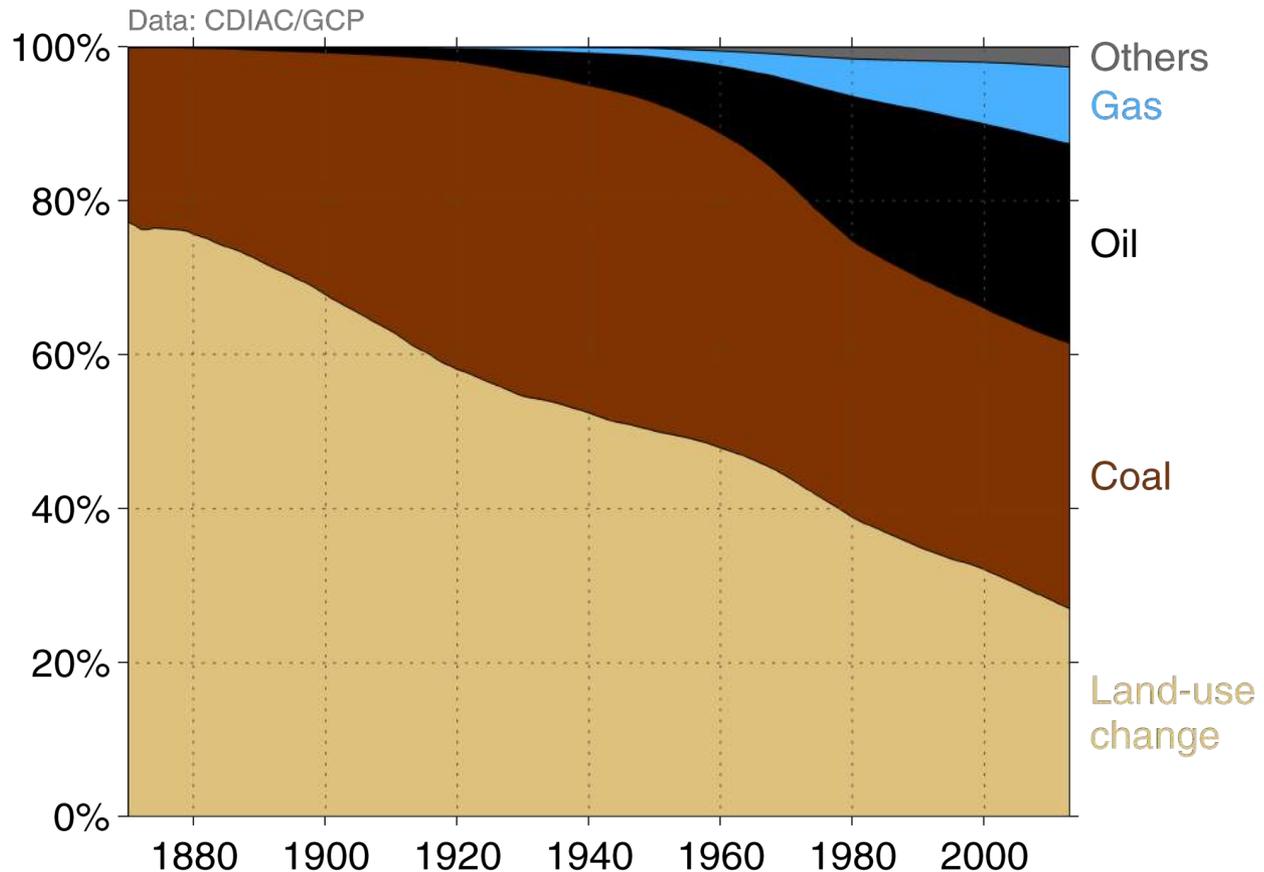


Others: Emissions from cement production and gas flaring

Source: [CDIAC](#); [Houghton et al 2012](#); [Giglio et al 2013](#); [Le Quéré et al 2014](#); [Global Carbon Budget 2014](#)

# Emissions cumulées depuis 1800 par catégorie

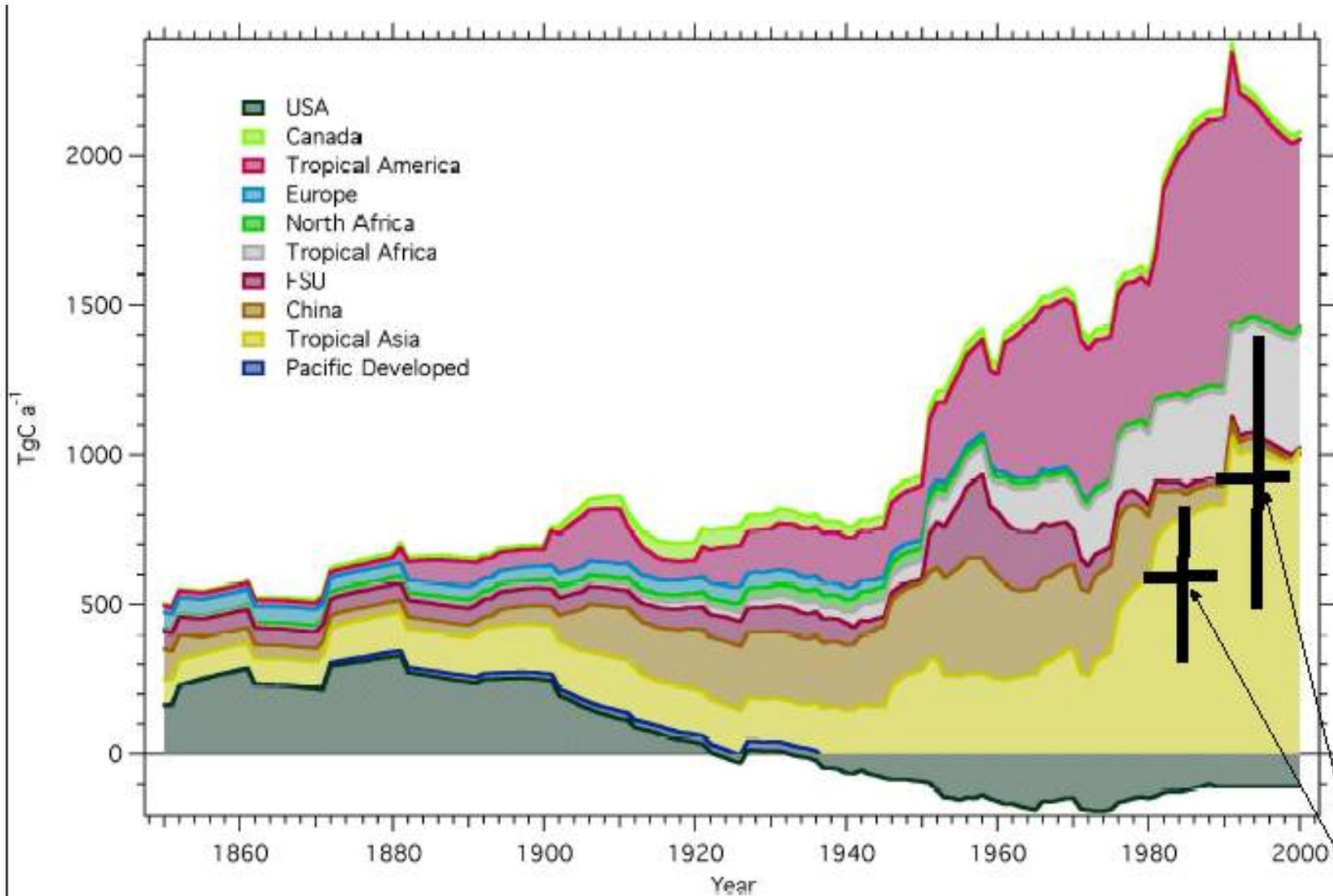
It represents about 27% of cumulative emissions in 2013  
Coal represents about 35%, oil 26%, gas 10%, and others 3%



Others: Emissions from cement production and gas flaring

Source: [CDIAC](#); [Houghton et al 2012](#); [Giglio et al 2013](#); [Le Quéré et al 2014](#); [Global Carbon Budget 2014](#)

# Historique des émissions de C par région

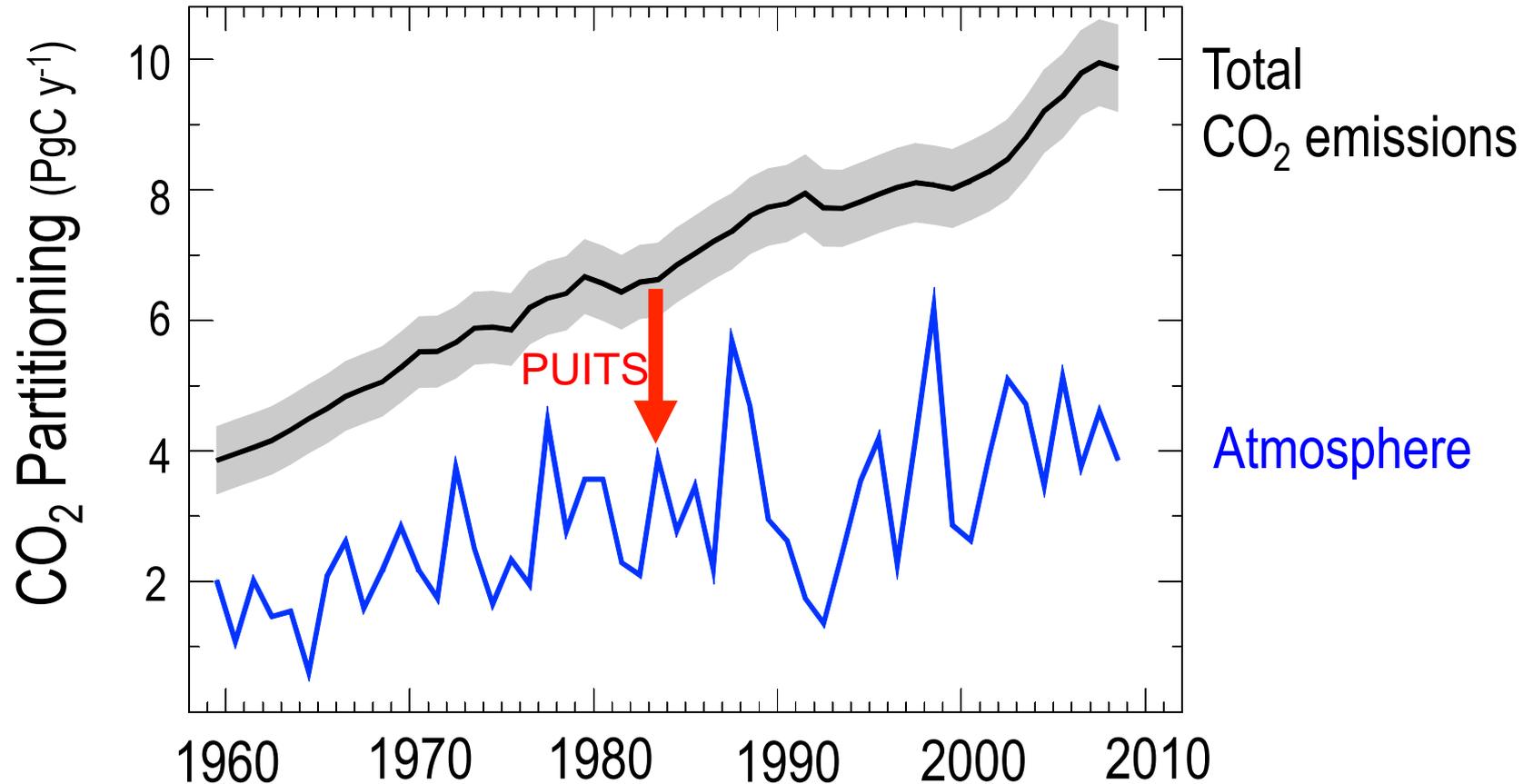


New estimates based on remote sensing data [de Fries et al., 2002]

# Fermeture du bilan de carbone

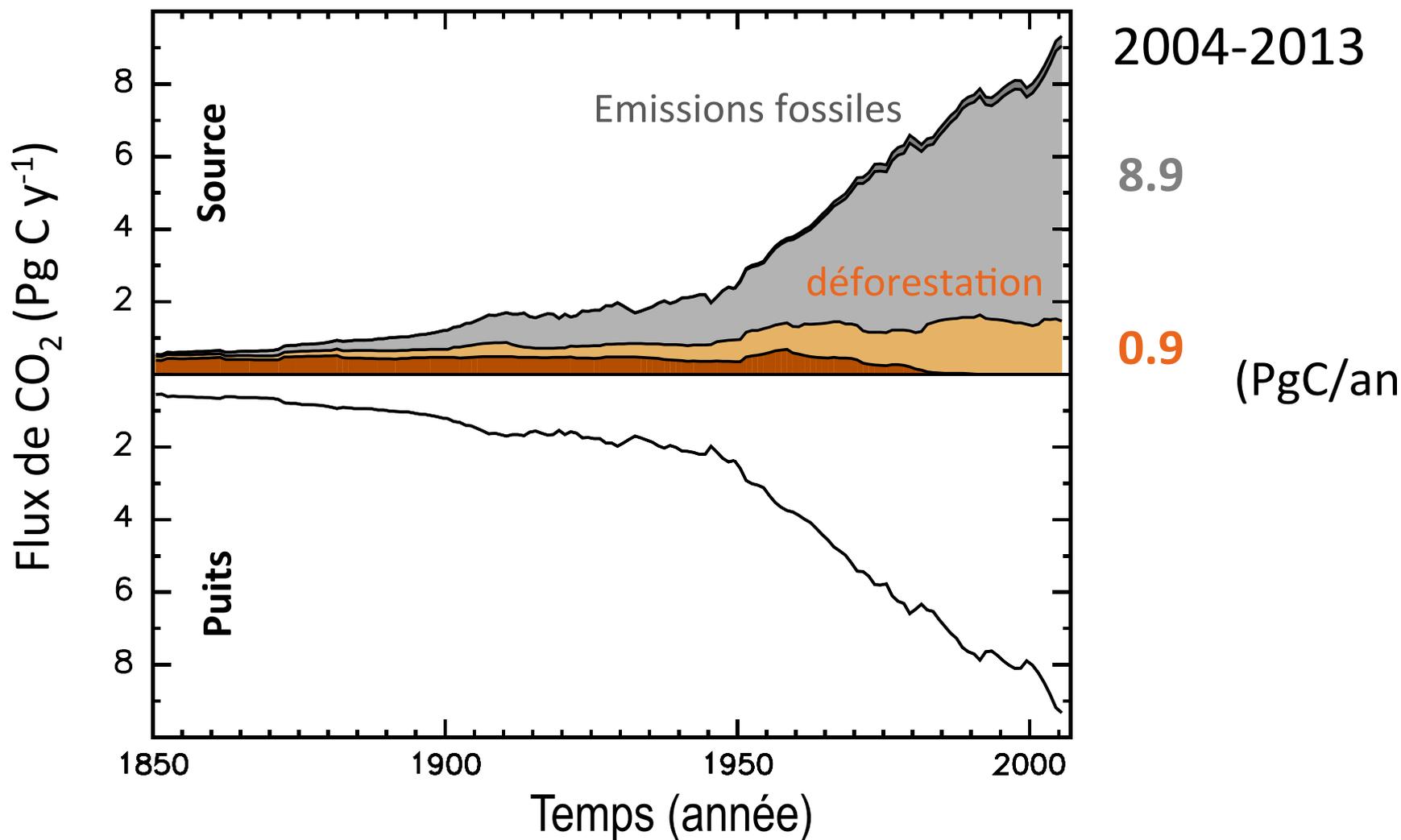
Role des écosystèmes terrestres  
et des forêts en particulier ?

# Où vont les 55% de CO<sub>2</sub> restants ?

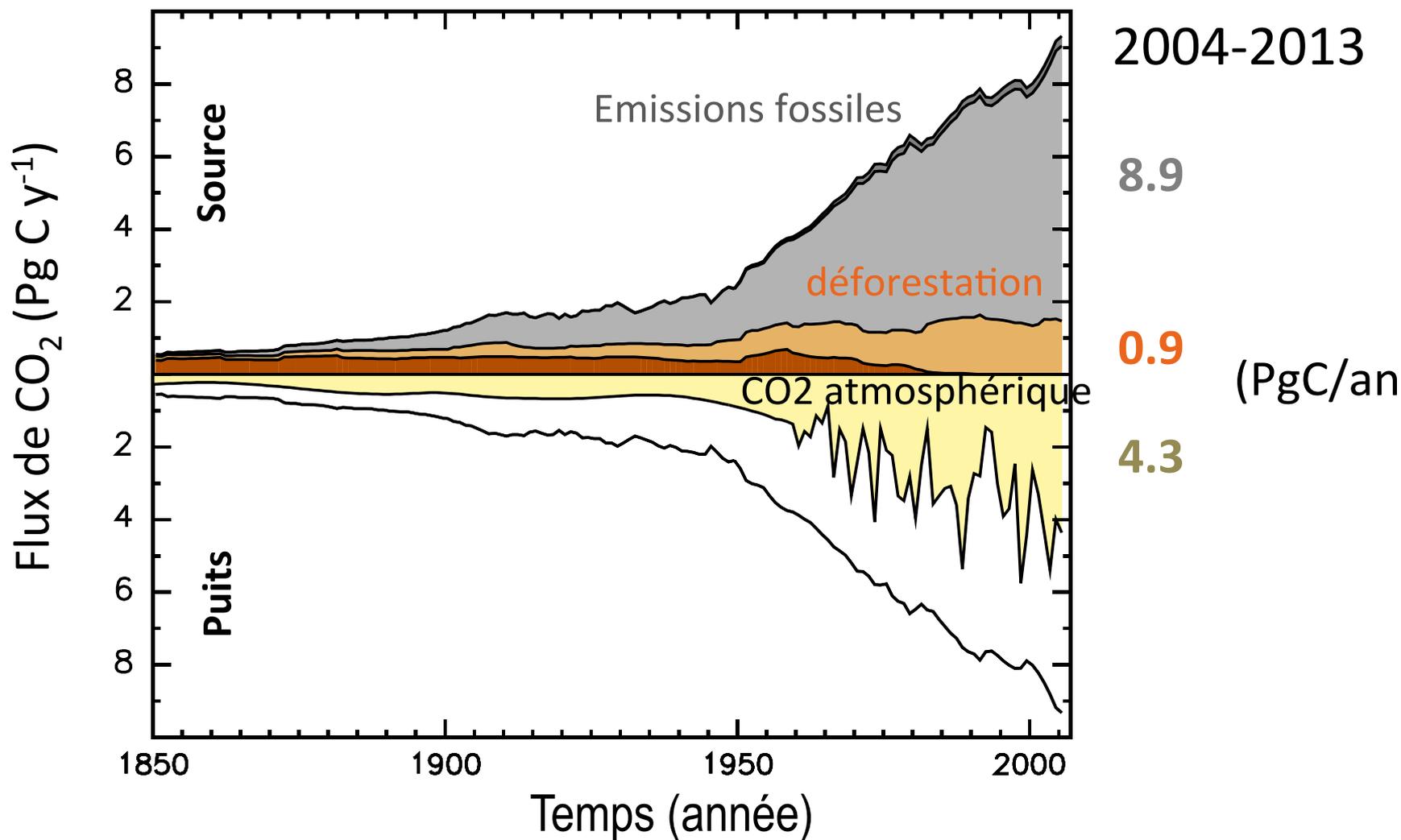


*Les puits de CO<sub>2</sub> océaniques et continentaux correspondent à la différence entre les émissions anthropogéniques et l'accumulation de CO<sub>2</sub> dans l'atmosphère.*

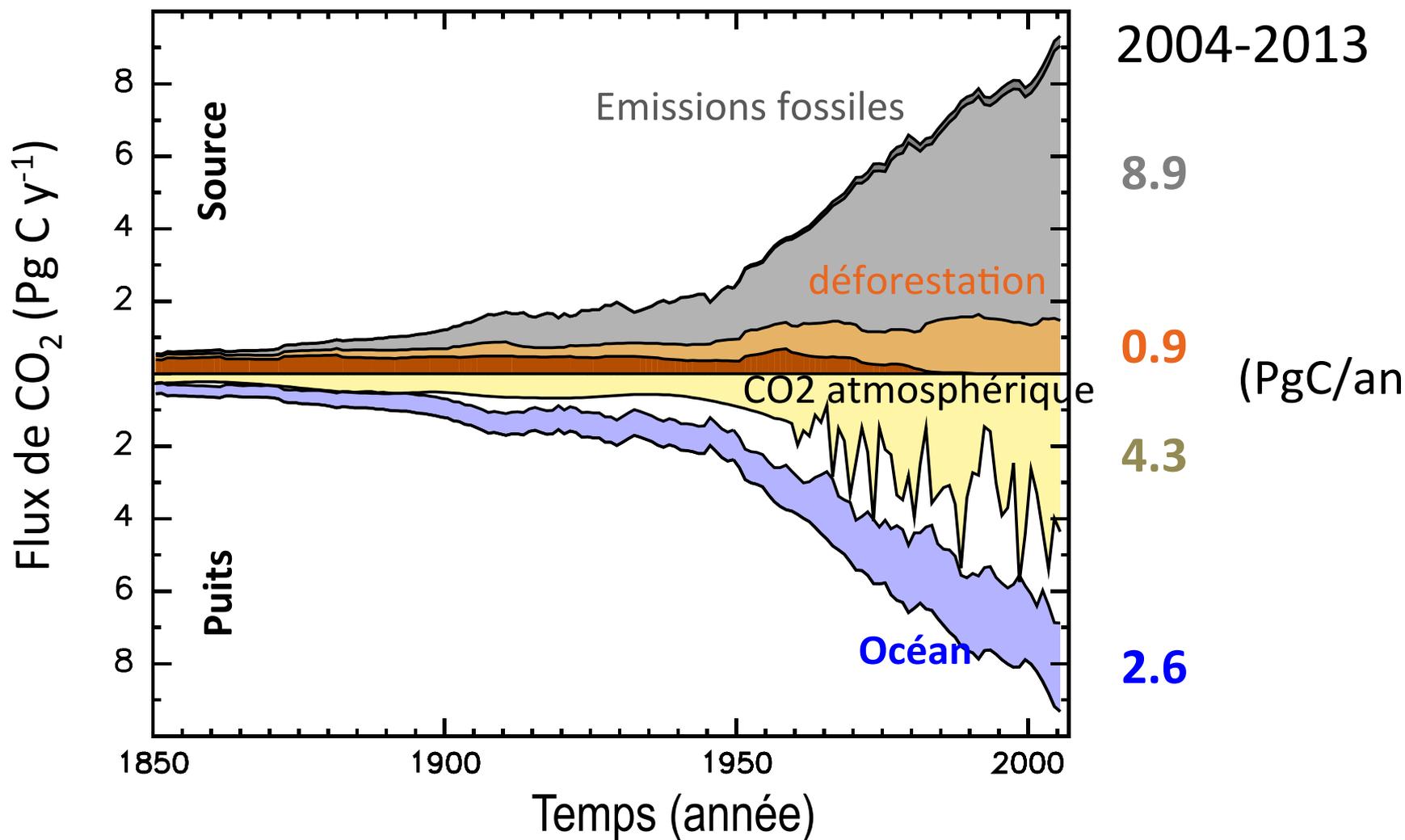
# Bilan: perturbation du cycle global du Carbone



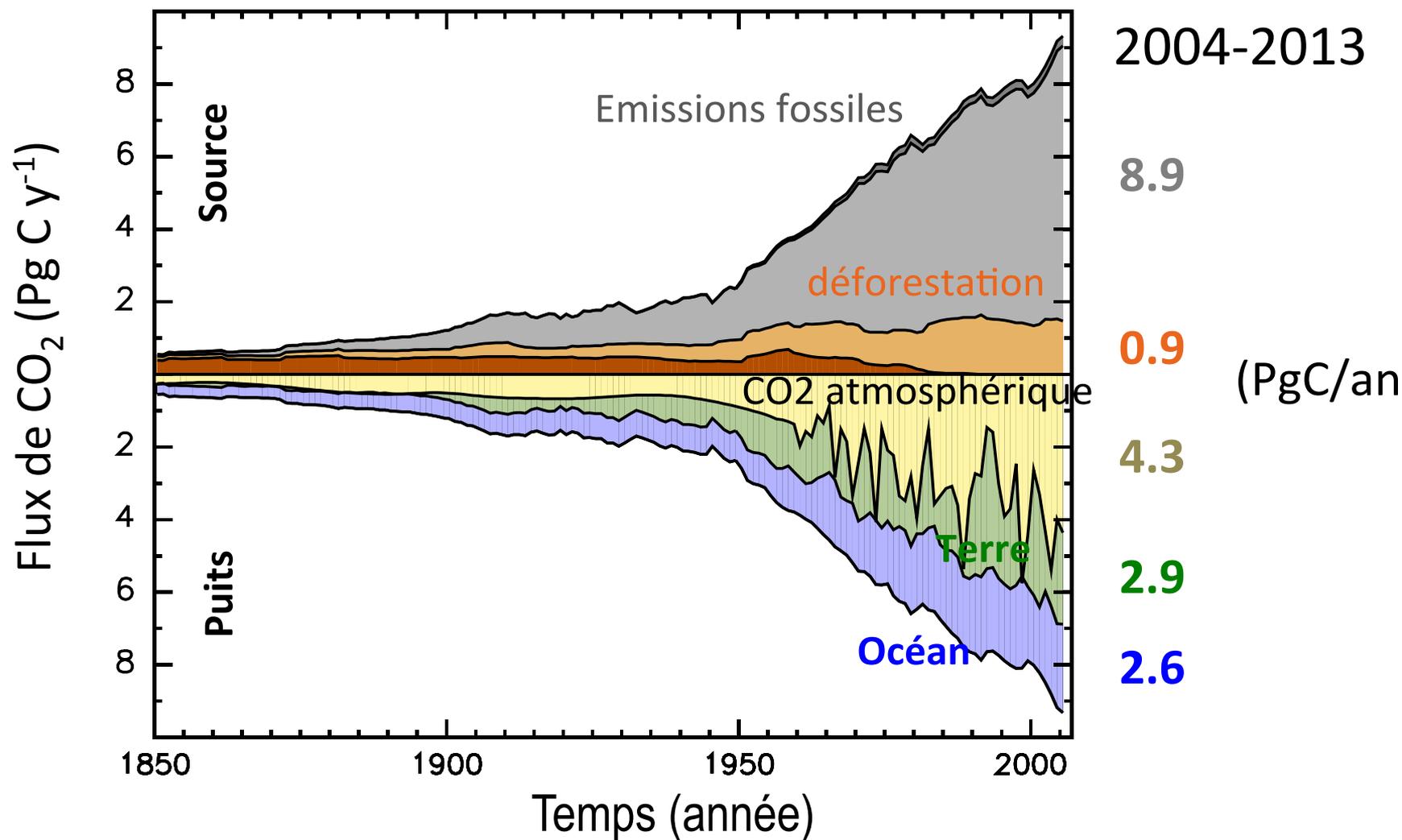
# Bilan: perturbation du cycle global du Carbone



# Bilan: perturbation du cycle global du Carbone

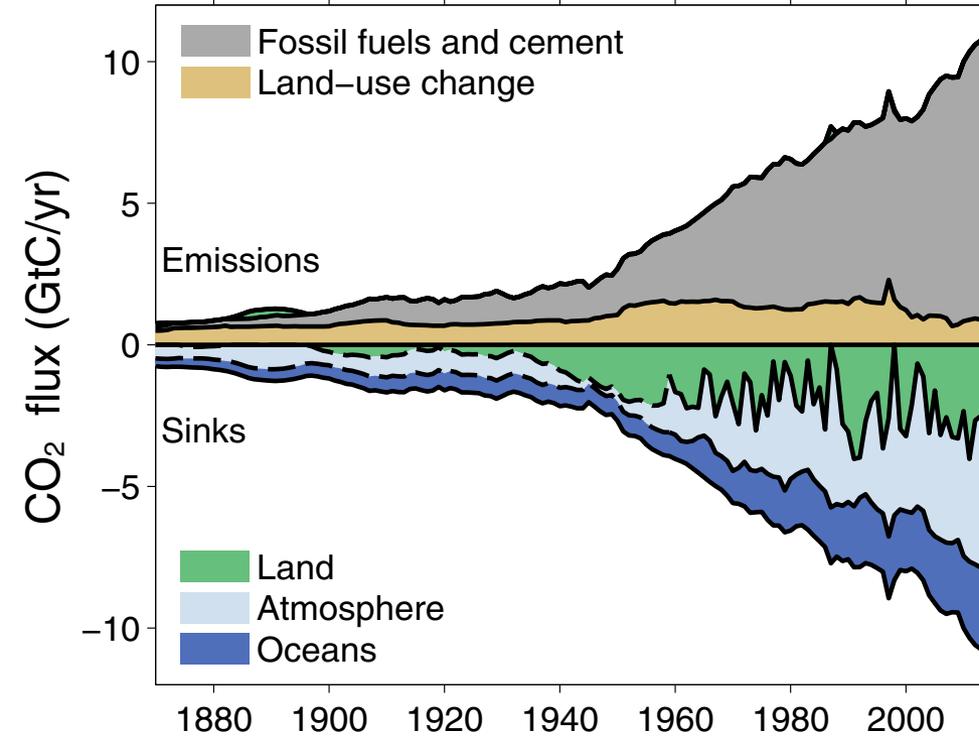


# Bilan: perturbation du cycle global du Carbone



# Retro-actions du cycle du carbone

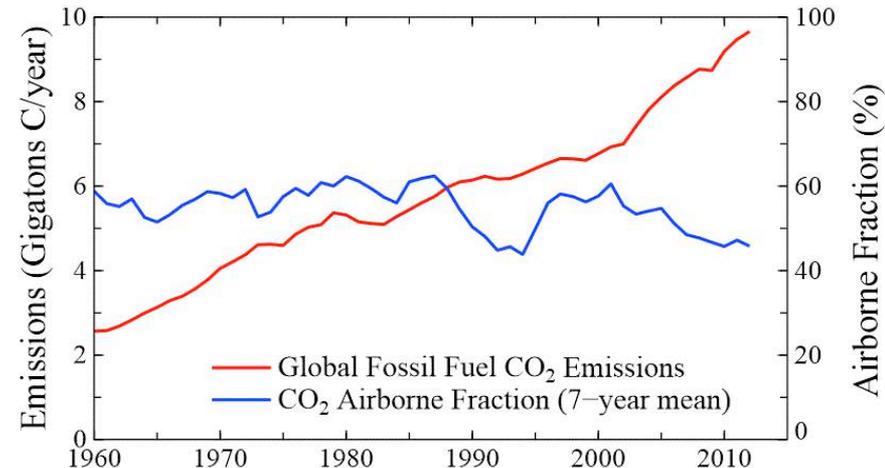
Data: CDIAC/NOAA-ESRL/GCP/Joos et al 2013/Khatiwala et al 2013



- Fraction atmosphérique (AF)

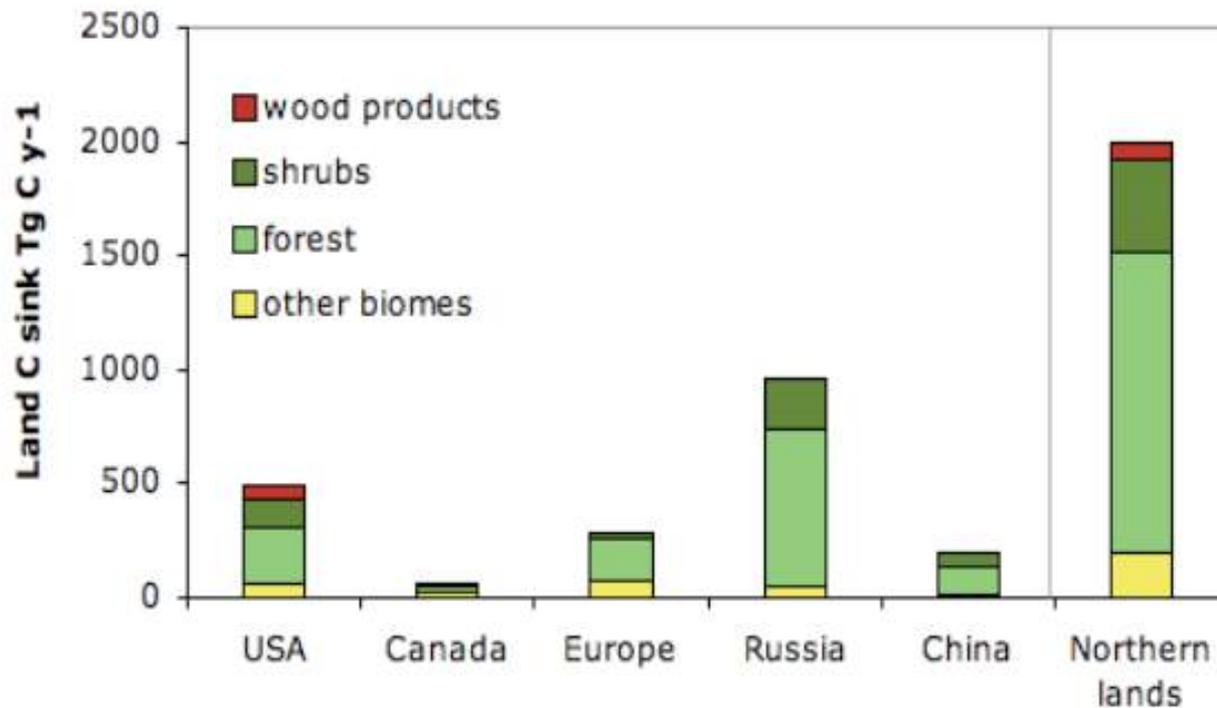
$$AF = \frac{S_{ATM}}{(E_{FF} + E_{LUC})}$$

- AF constant et contrôlée par:
  - Changement climat
  - Fertilization CO<sub>2</sub>
  - Dépot N
  - Utilisation des terres



# Contribution des forêts au puits de C

➔ Plus de 70 % du puits de C du “Nord” est dans les forêts



Unmanaged forest appear to be significant C sinks

# Absorption du CO<sub>2</sub> anthropique par les forêts

Mécanismes  
et incertitudes



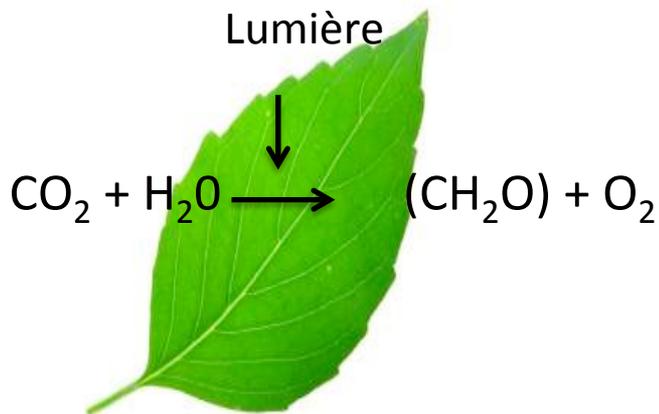
# Absorption par la biosphère terrestre

→ Effet fertilisant du CO<sub>2</sub> atmosphérique

## Photosynthèse (principe)

CO<sub>2</sub> atmos : substrat limitant

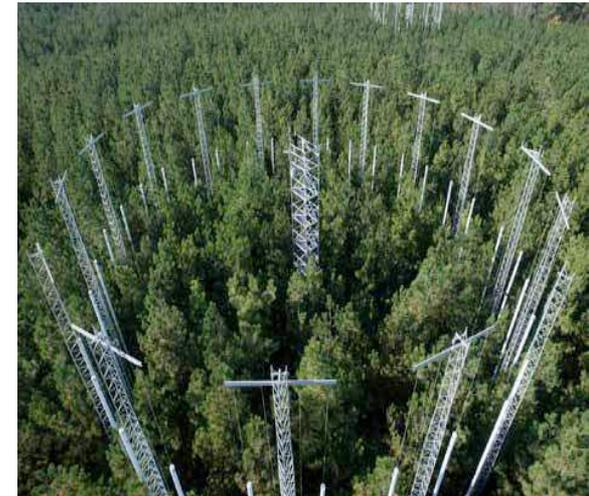
[CO<sub>2</sub>]<sub>atm</sub> ↑ → Assimilation C ↑



Plante chlorophyllienne

## Mise en évidence expérimentale

Expérience FACE (doublement CO<sub>2</sub>)



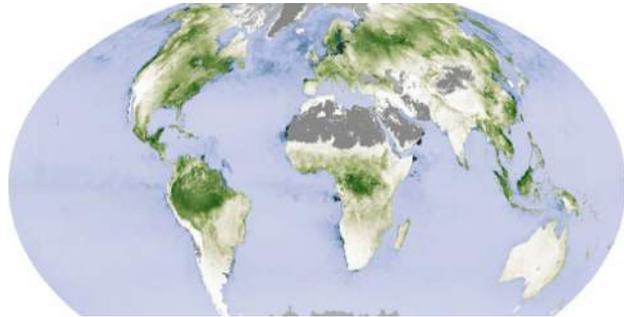
→ Augmentation de la productivité  
primaire nette ≈ 20-40%  
(Norby et al. 2010)



# Absorption par la biosphère terrestre

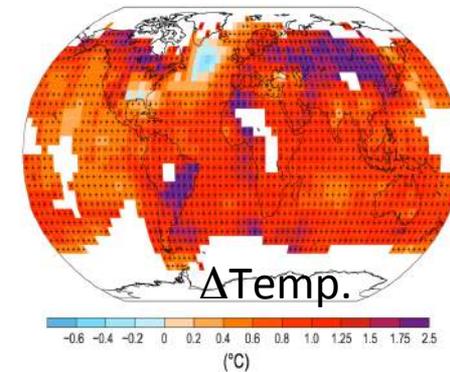
➤ Effet fertilisant du CO<sub>2</sub>

➤ Impact du changement climatique



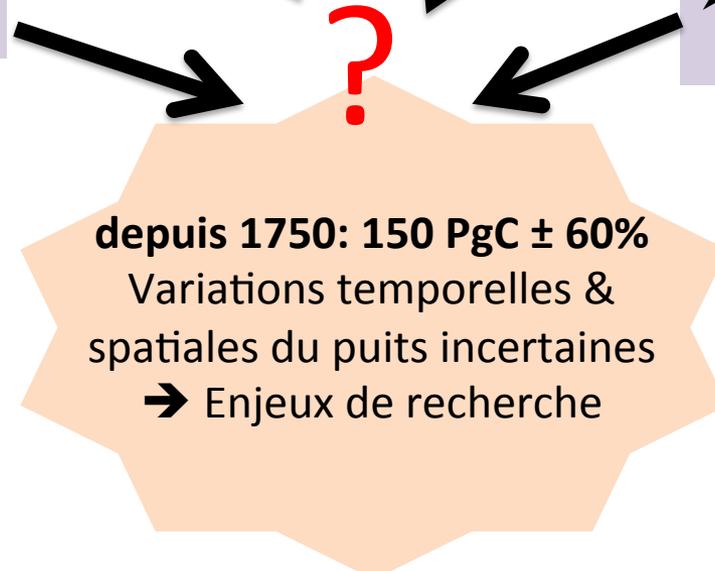
➔ Lié à la productivité primaire

- ✧ sur la photosynthèse
- ✧ sur la dégradation du C organique des sols



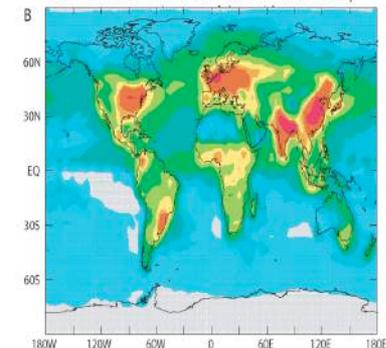
➤ Gestion des écosystèmes

➤ Disponibilité en nutriments (dépôts d'azote)



**depuis 1750: 150 PgC ± 60%**  
Variations temporelles & spatiales du puits incertaines  
➔ Enjeux de recherche

Dépôt de N inorganique (mg m<sup>-2</sup> an<sup>-1</sup>)



Extensif vs Intensif

# Bilans nets variables selon les écosystèmes

## Importance des sols:



- Dynamique du C sol
- Impactée par CC ?
- effet « priming » ?

→ Temps de résidence moyen du « carbone aérien » très variable

Forêts tempérées



Forêts boréales



Forêts tropicales



# Modèle du fonctionnement des écosystèmes

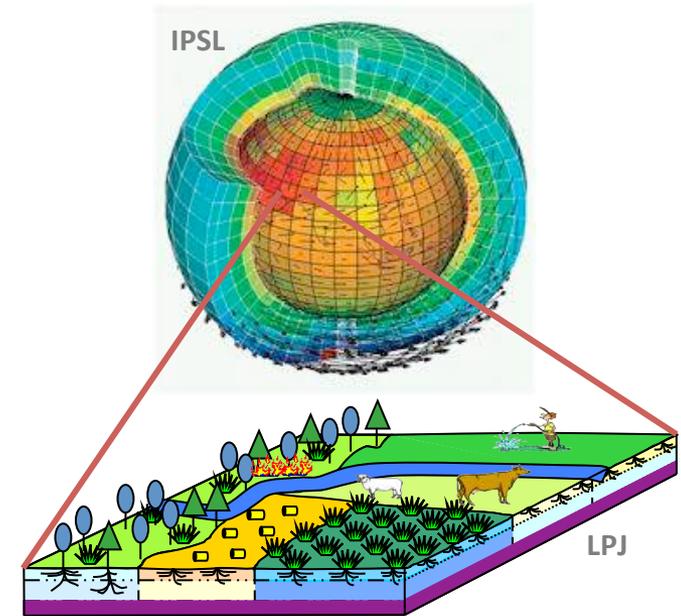
→ Extrapolation dans le temps & l'espace utilisant des lois physiques...

- From **diagnostic** to fully **prognostic** models  
(*ex: TURC*) (ORCHIDEE, ISBA-AGs)
- **Local** scale to **global** scales  
(Castanea, Musica) (ORCHIDEE, ISBA-Ags)  
(PASIM, STICS, ...)

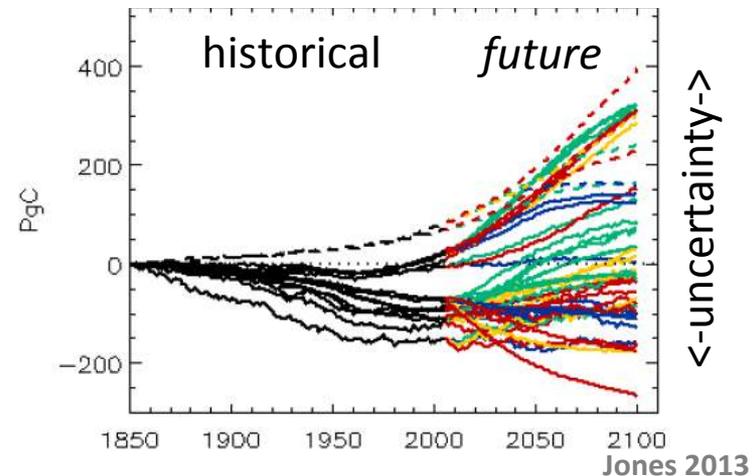
# Role des modèles de surface

Modèles de surface et de dynamique de la végétation permettent de :

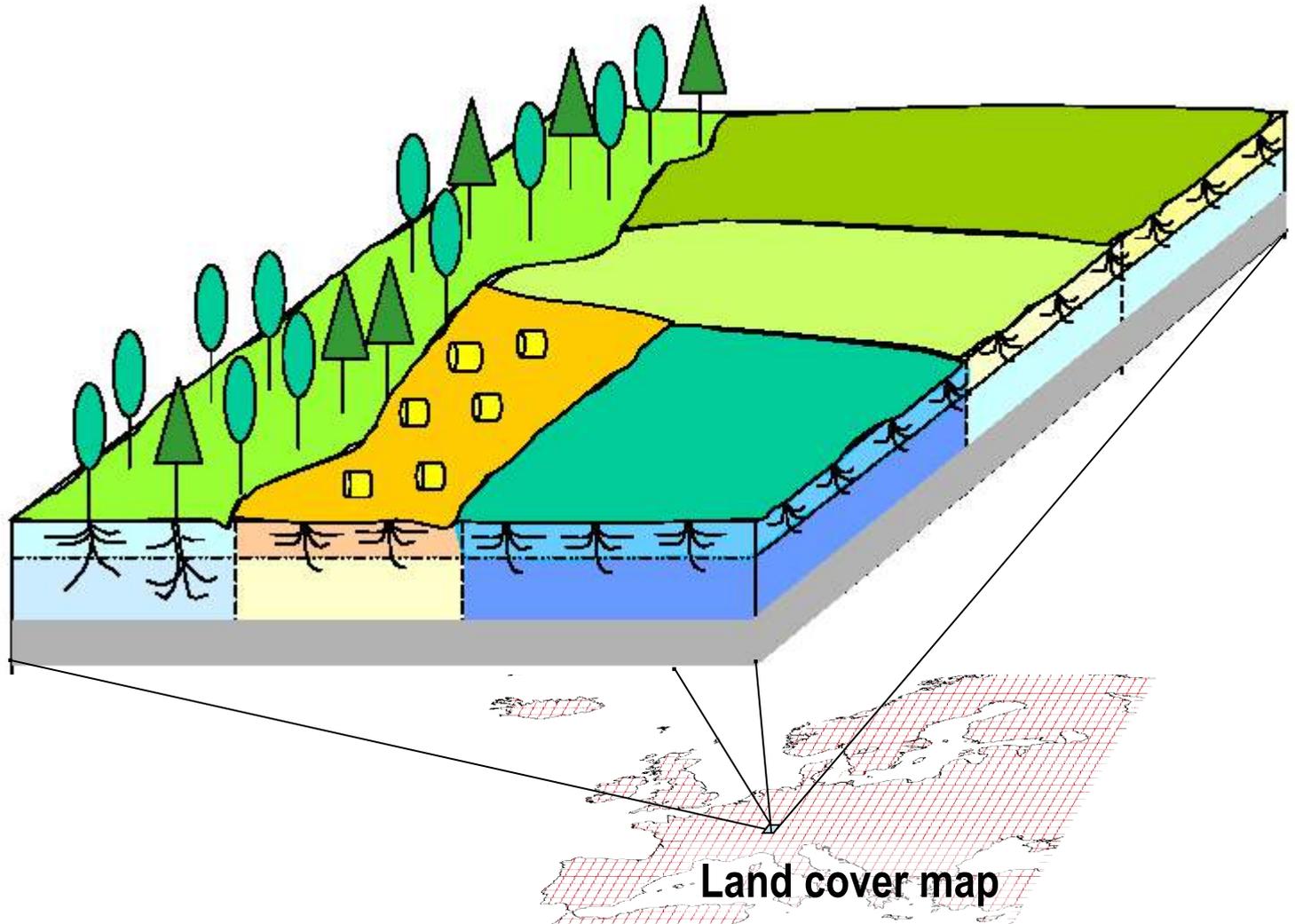
- **SUIVRE** les tendances à long terme des bilan de Carbone, Eau, Energie
- **ATTRIBUER** les causes des tendances et de la variabilité observées
- **PREDIRE** les changements futurs sous l'impact des changements globaux



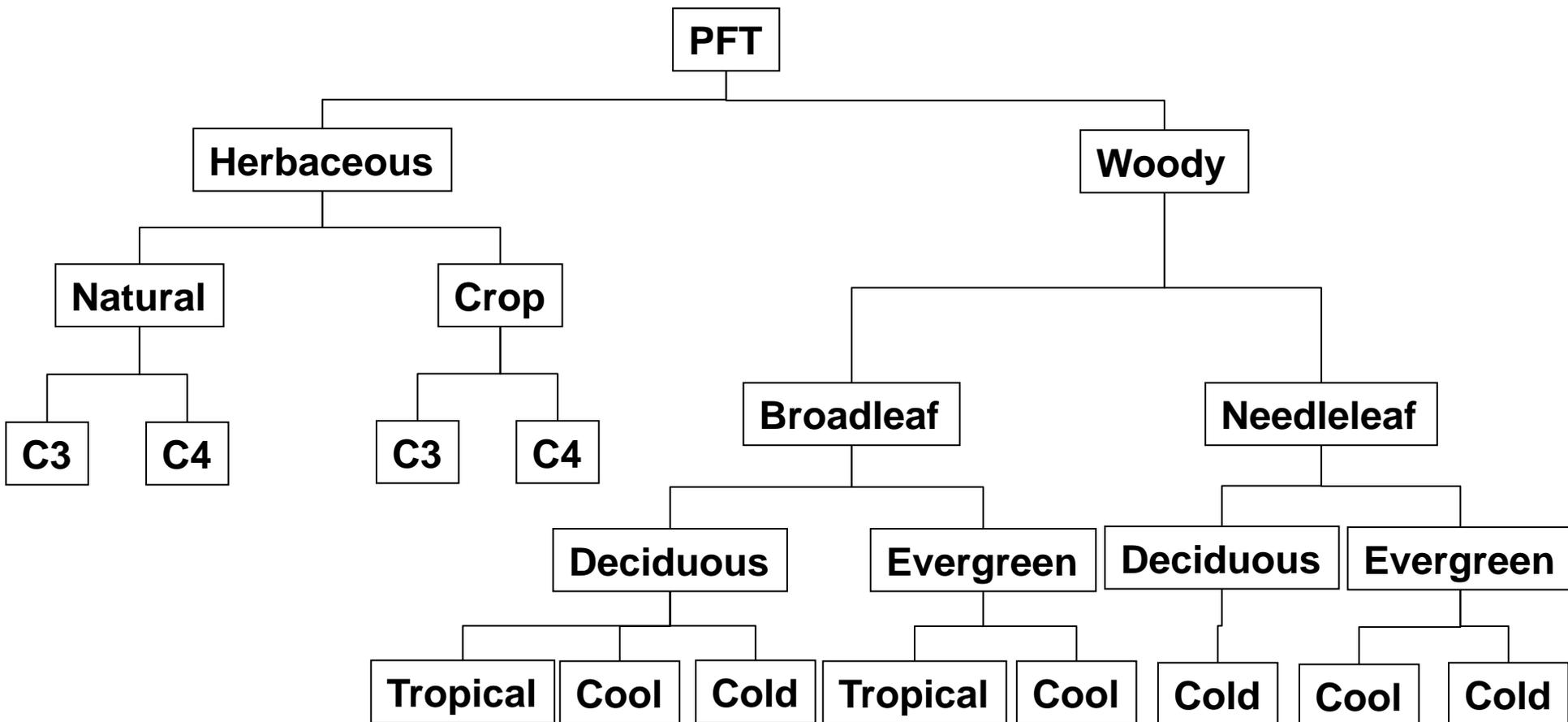
Change in global biomass



- A mosaic of vegetation



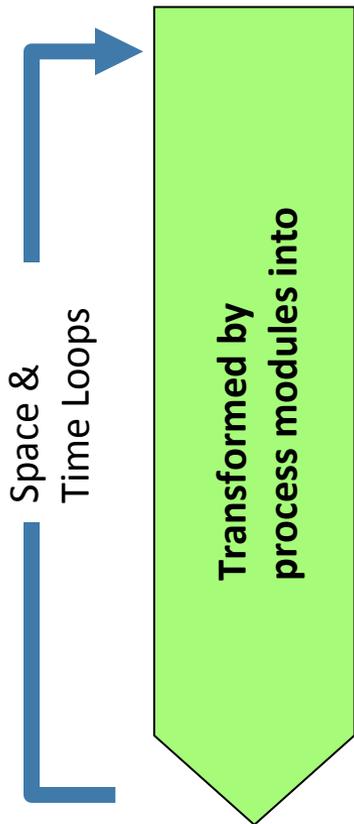
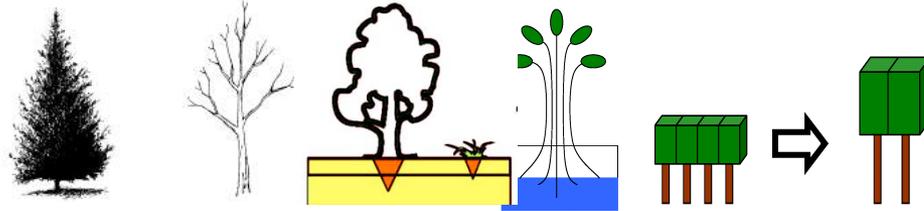
- Concept de 'Type fonctionnel de plante' (PFT)
- Définit selon des critères systématiques, physiologiques, phénologiques, climatiques



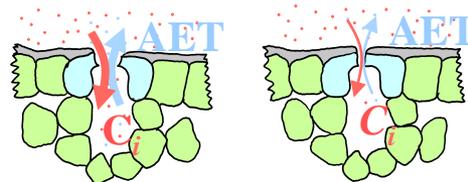
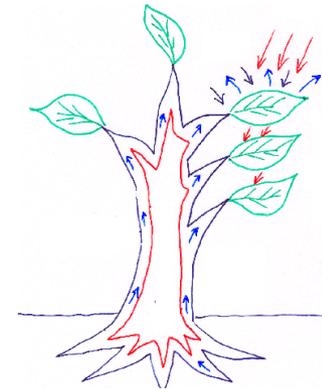
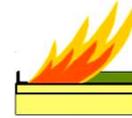
# Intégration de nombreux processus

Fournit par B. Poulter (basé sur modèle LPJ)

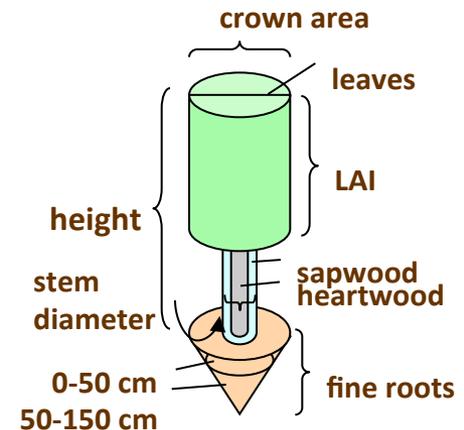
Climate, Soil, CO<sub>2</sub>

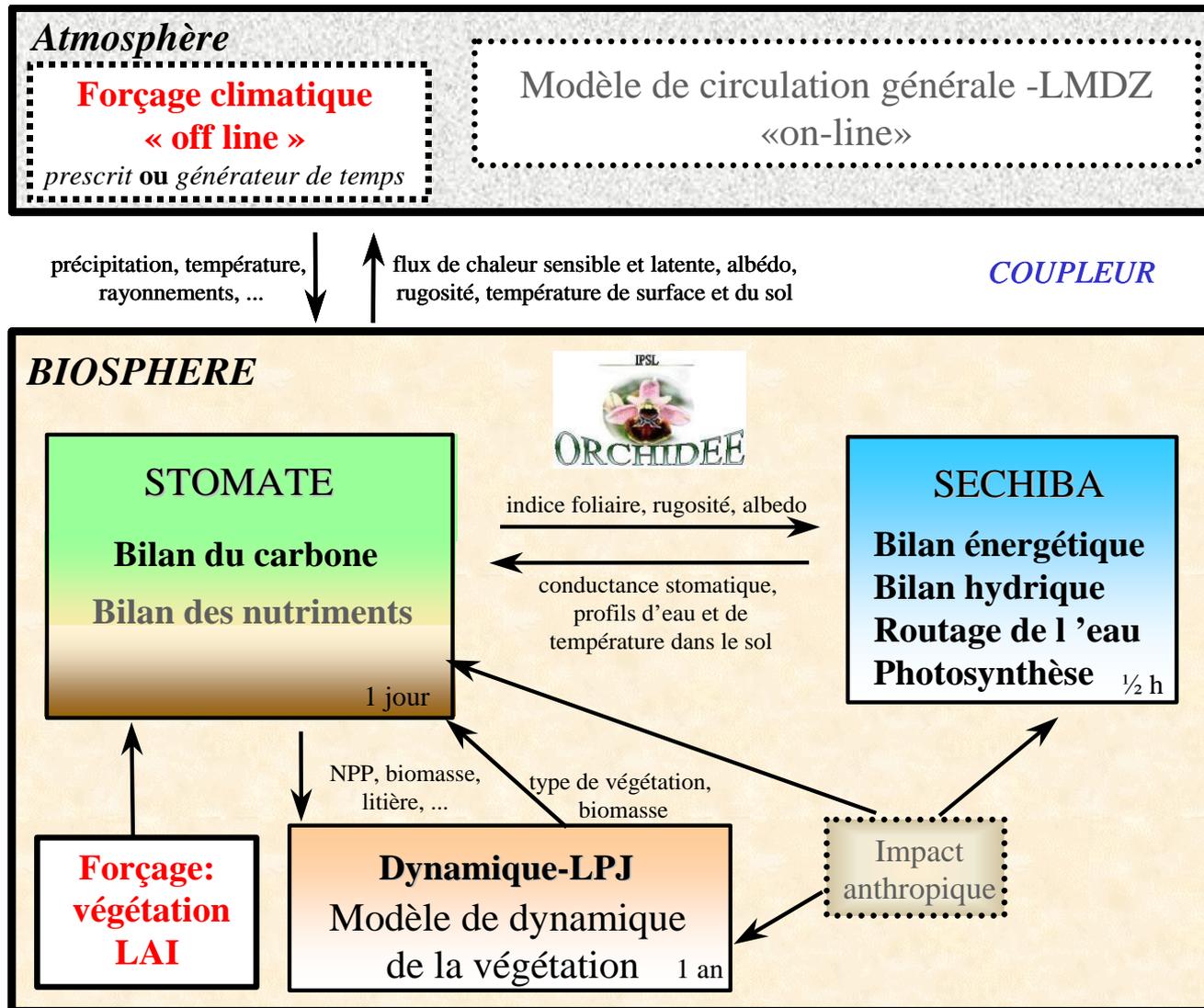


- 10 plant functional types
- competition, mortality, establishment
- fire (globfirm)
- photosynthesis: coupled C and H<sub>2</sub>O cycles
- C allocation (funct. and struct. relations)
- Carbon pools: 4 in vegetation, 4 in litter/soil
- Full hydrology



C budget, H<sub>2</sub>O Budget, Vegetation Composition





## ➤ Allocation du carbone dans la plante

- Répartition racine / partie aérienne
- Dépendance de l'allocation aux nutriments

## ➤ Mortalité naturelle des arbres

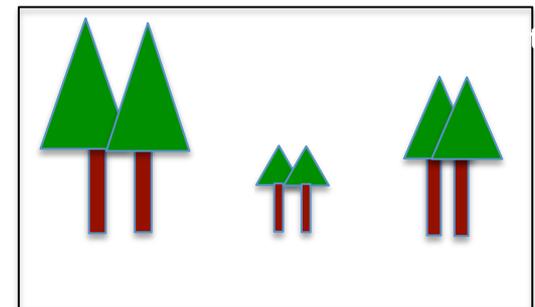
- Mécanismes peu connus ?
- Dépendent de la structure du peuplement (“densité”)

## ➤ Déforestation / feux / Insectes / Coup de vent

- Processus difficile à modéliser (stochastique)

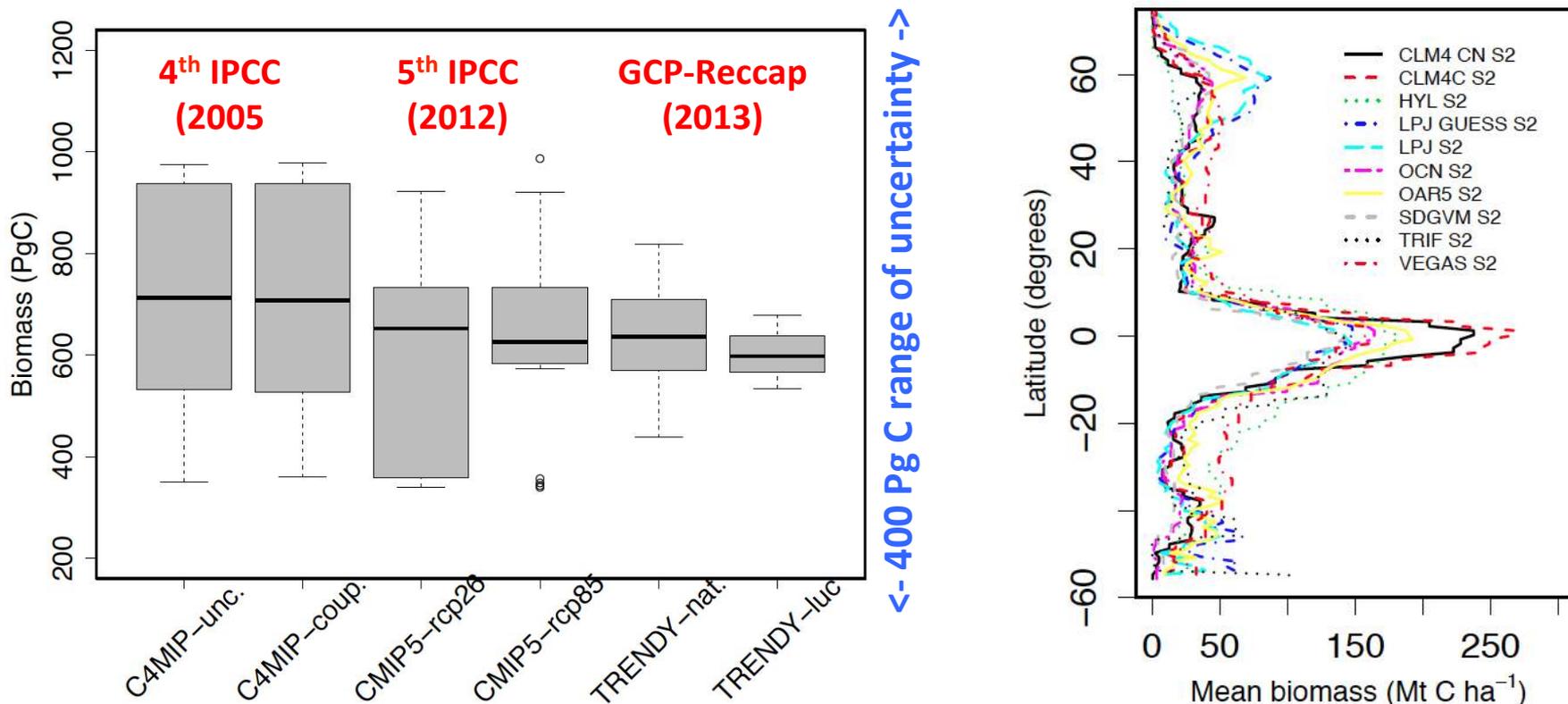
## ➤ GESTION des forêts

- Incluant repousse de la forêt



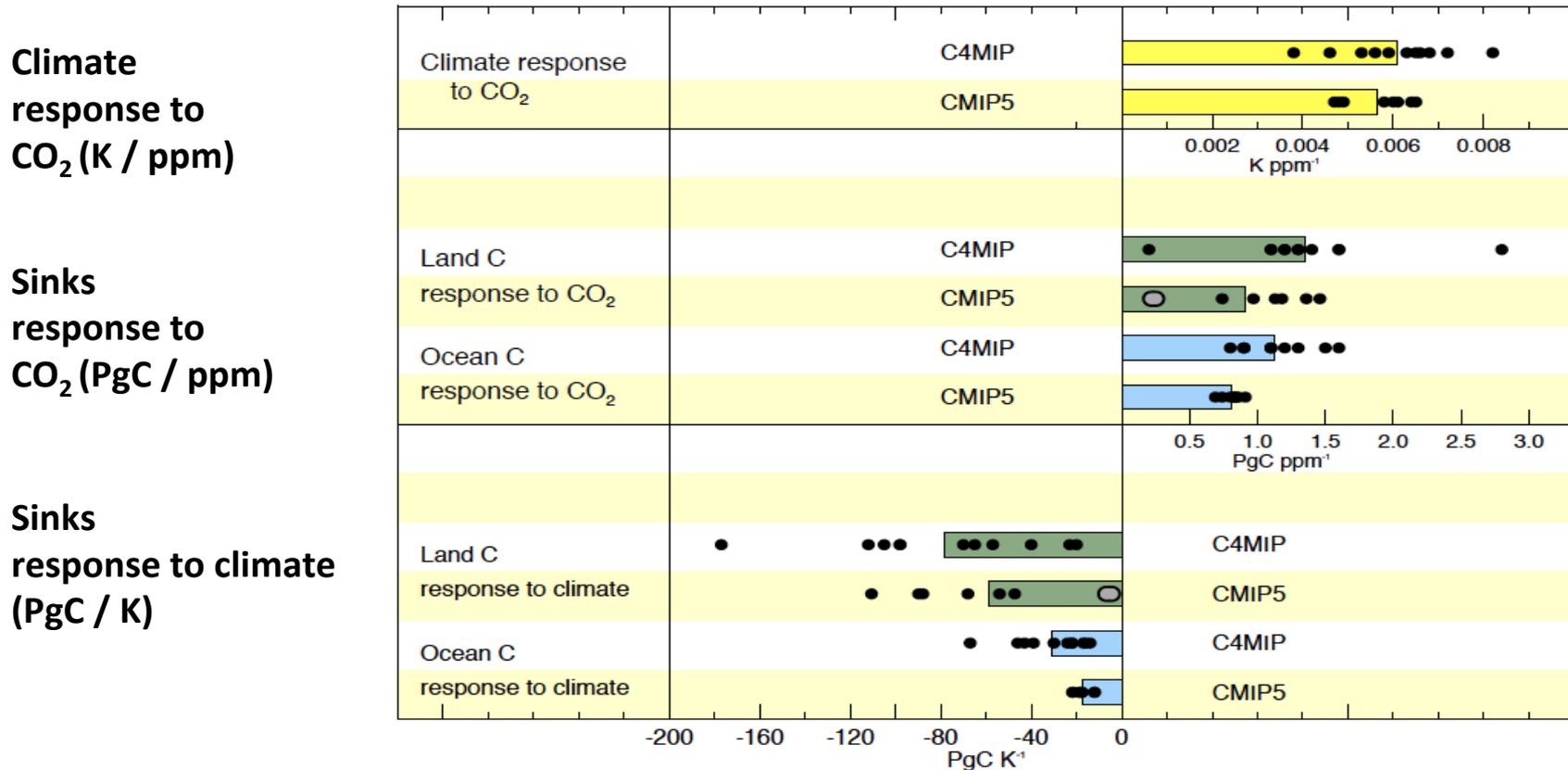
# Besoin crucial de mesurer la biomasse forestière

- Incertitude des modèles IPCC ne diminue pas...



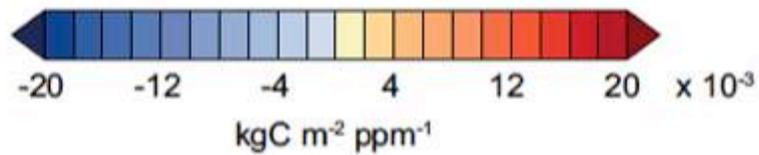
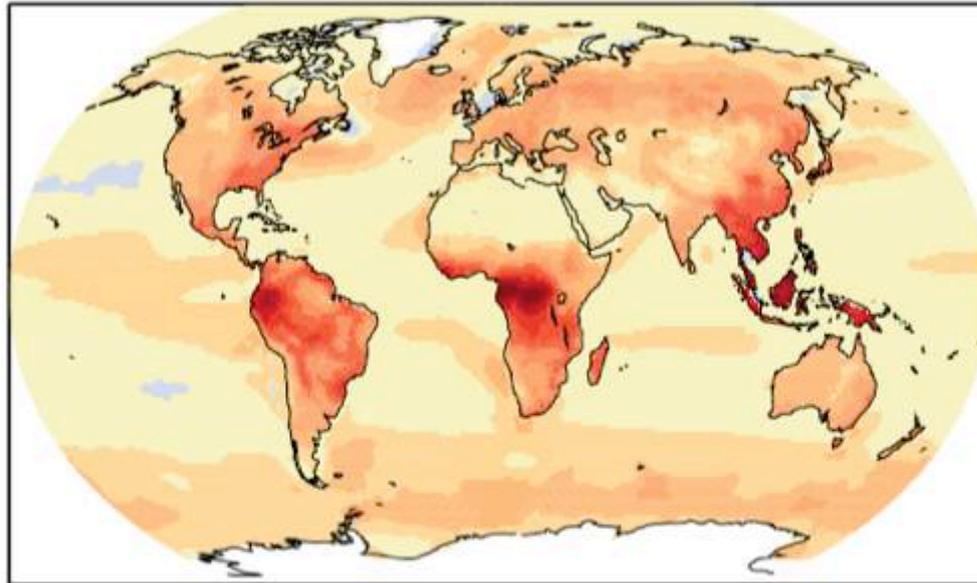
- ➔ Need Biomass data to validate global model simulations
- ➔ Current estimates from Remote Sensing still need to be improved !

# Rétroactions positives Climat - Carbone



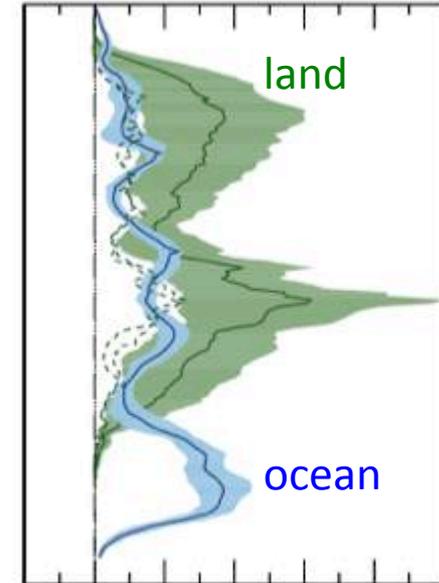
Climate change will affect carbon cycle processes in a way that will exacerbate the increase of  $\text{CO}_2$  in the atmosphere (*high confidence*)

# Réponse au CO<sub>2</sub> atmosphérique seul



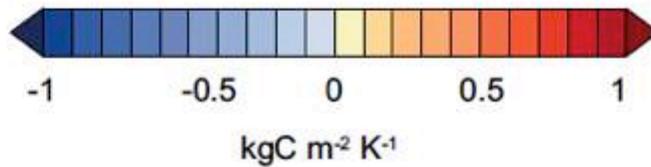
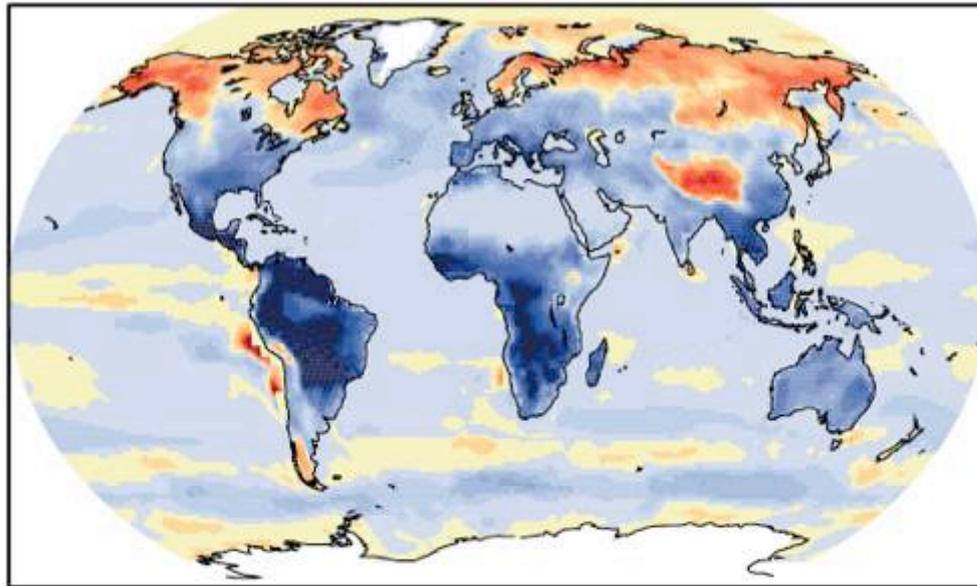
decreasing  
sink

increasing sink



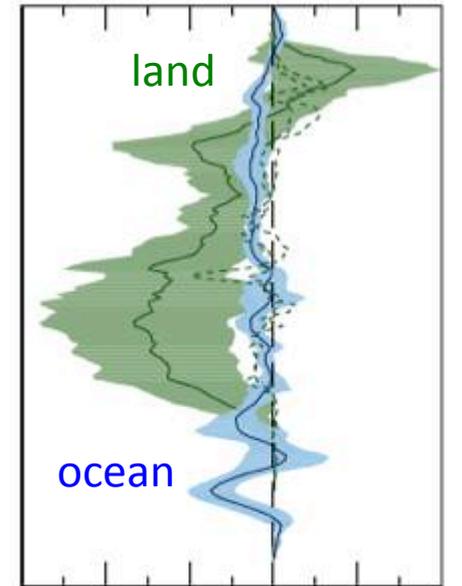
0 0.10 0.20  
 $10^8$  kgC m<sup>-1</sup> ppm<sup>-1</sup>

# Réponse au changement du climat seul



decreasing  
sink

increasing sink

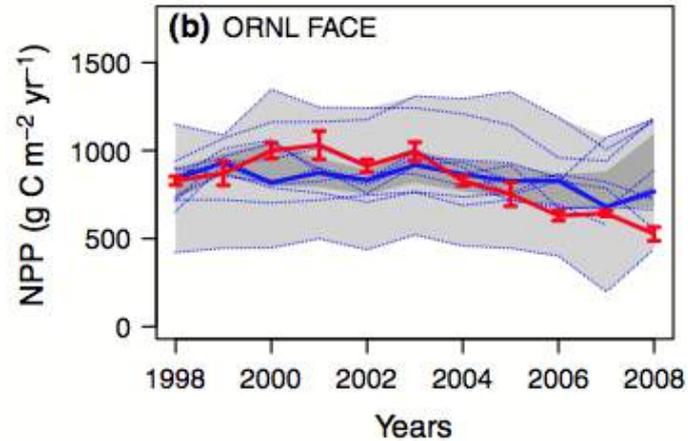
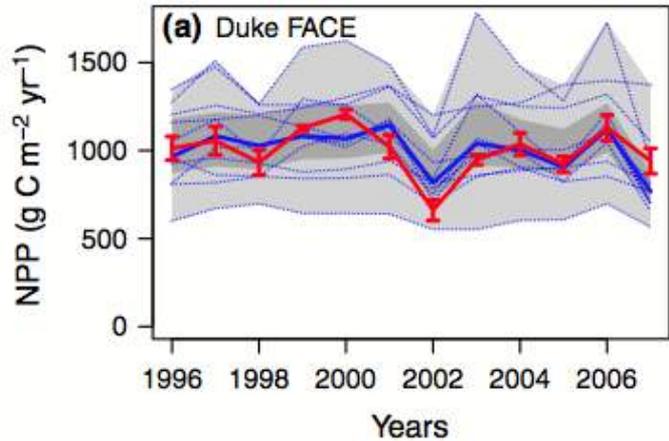


models do not include the release  
of permafrost C

# Evaluation de la réponse des modèles au CO2

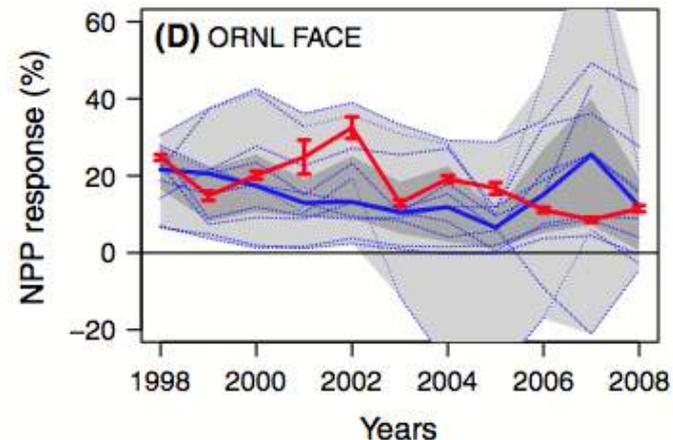
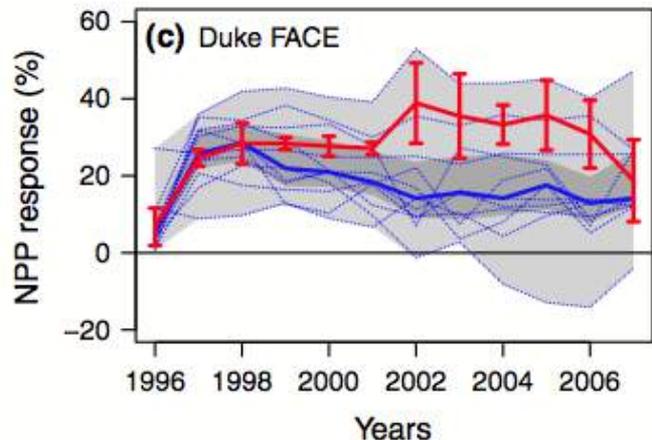
Expérience d'enrichissement en CO2 : réponse simulée de la Productivité Primaire Nette (NPP) de modèle incluant cycles C/N

NPP  
(control  
CO2)



Observed  
Models

NPP  
(double  
CO2)



— observed      ■ interquartile model range      ··· individual models  
— multi-model mean      ■ model range

# Productivité limitée par les nutriments

nature  
geoscience

LETTERS

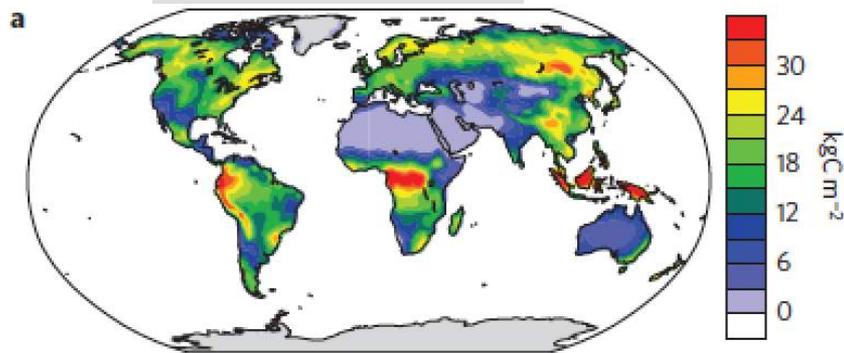
PUBLISHED ONLINE: 20 APRIL 2015 | DOI: 10.1038/NGEO2413

## Future productivity and carbon storage limited by terrestrial nutrient availability

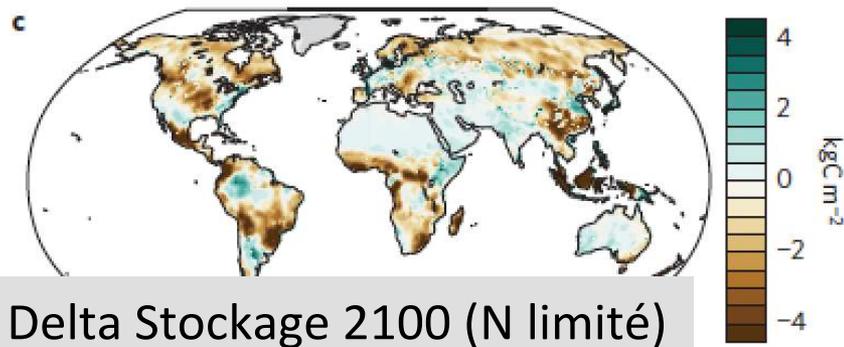
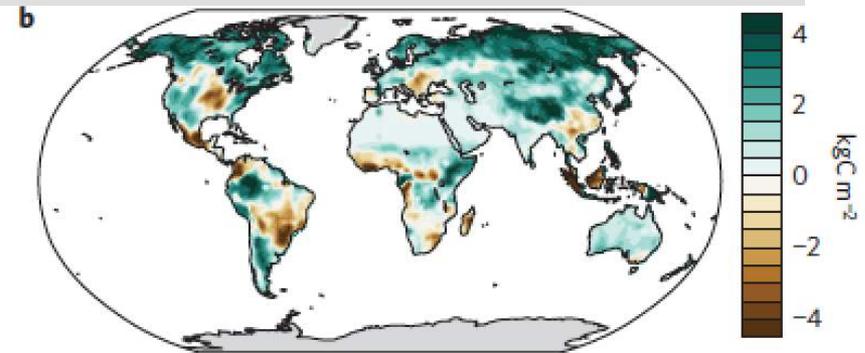
William R. Wieder<sup>1,2\*</sup>, Cory C. Cleveland<sup>3</sup>, W. Kolby Smith<sup>3,4</sup> and Katherine Todd-Brown<sup>5,6</sup>

Wieder et al., Nature 2015

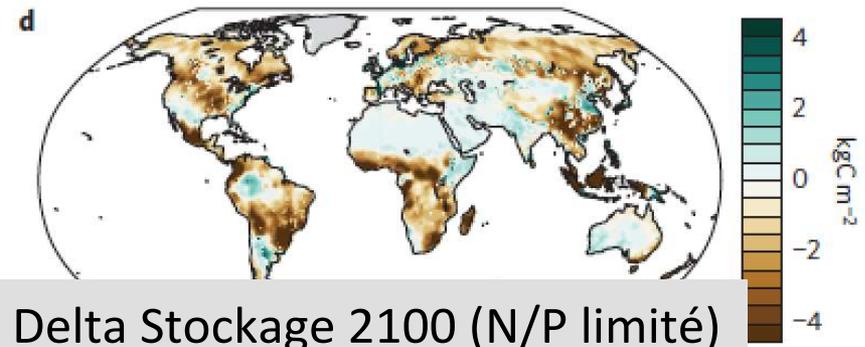
### Stockage initial



### Delta Stockage 2100 (Pas de limite)



### Delta Stockage 2100 (N limité)



### Delta Stockage 2100 (N/P limité)

**Figure 2 | Multi-model mean terrestrial C storage and changes in C storage with different assumptions about nutrient limitation. a**, Mean initial terrestrial C storage for all CMIP5 models (1860-1869). **b-d**, Multi-model mean changes in terrestrial C storage at the end of the twenty-first century under RCP 8.5 assuming that increases in NPP are limited by nothing (as in the CMIP5 archive; **b**), new N inputs (**c**), and new N and P (**d**). Individual model results for data summarized are shown in Supplementary Figs 8-10.

# Impact biophysique de la déforestation

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- Changement de l'albédo de la surface
  - ➔ Augmentation de l'albédo (prairie vs forêts)
  
- Changement de l'évapotranspiration
  - ➔ Diminution de la transpiration
  
- Changement de la couverture nuageuse et de la circulation atmosphérique

# Effet combiné climat - carbone

## Combined climate and carbon-cycle effects of large-scale deforestation

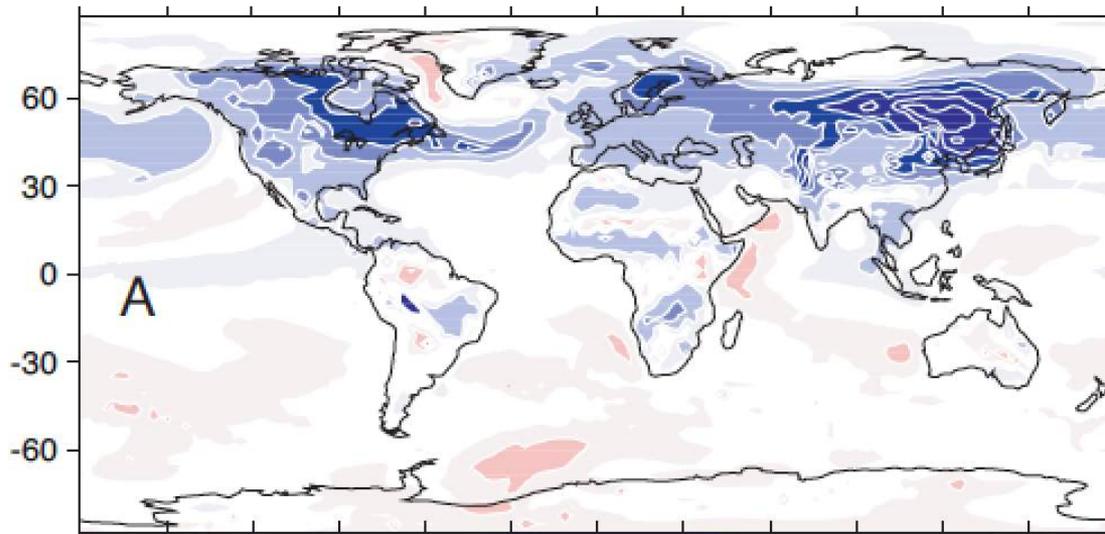
*Bala et al., PNAS, 2007*

G. Bala<sup>\*†</sup>, K. Caldeira<sup>‡</sup>, M. Wickett<sup>\*</sup>, T. J. Phillips<sup>\*</sup>, D. B. Lobell<sup>\*</sup>, C. Delire<sup>§</sup>, and A. Mirin<sup>\*</sup>

<sup>\*</sup>Energy and Environment Directorate, Lawrence Livermore National Laboratory, Livermore, CA 94550; <sup>†</sup>Department of Global Ecology, Carnegie Institution, Stanford, CA 94305; and <sup>‡</sup>Université Montpellier II, 34095 Montpellier cedex 5, France

Edited by Peter Vitousek, Stanford University, Stanford, CA, and approved February 24, 2007 (received for review October 11, 2006)

Simulation du Delta Température en 2100:  
Avec déforestation – Reference (sans déforestation)



➔ Effet biophysique  
refroidissant  
sur-compense  
effet réchauffant du CO<sub>2</sub>

# Forêts boréales et climat..

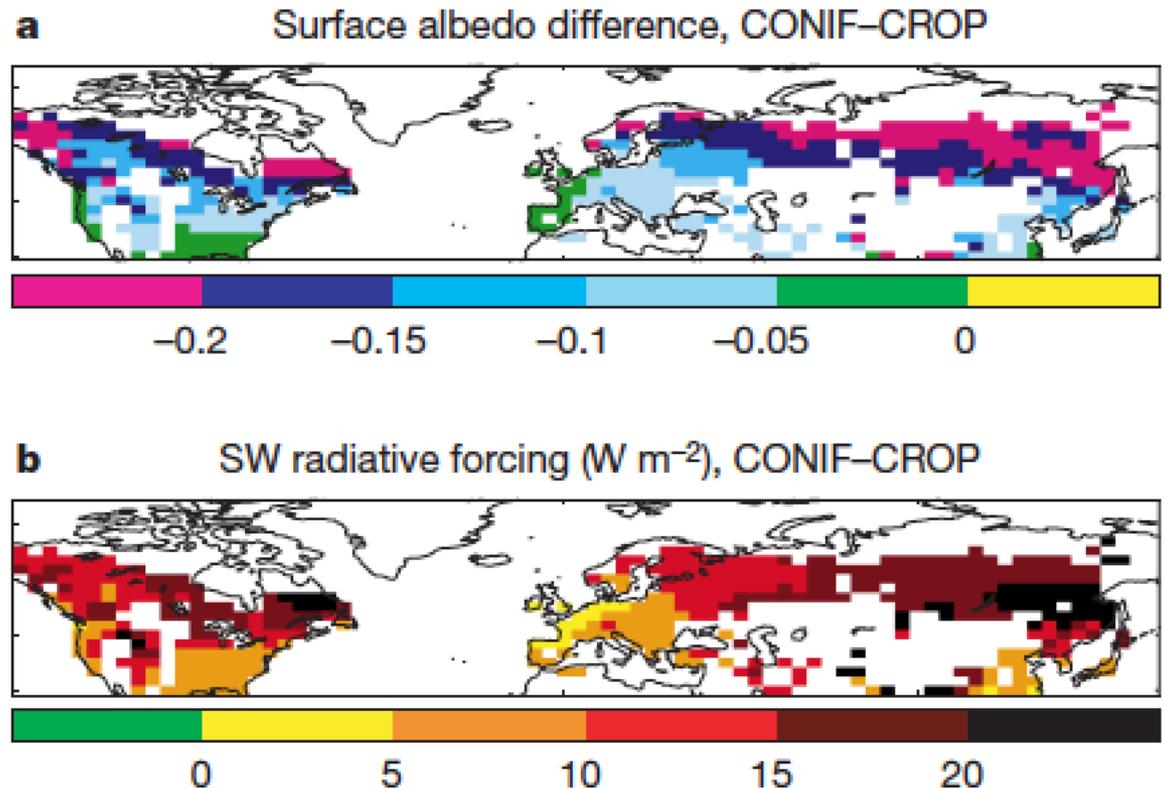
**Offset of the potential carbon sink from boreal forestation by decreases in surface albedo**

Richard A. Betts

Hadley Centre for Climate Prediction and Research, The Met Office, Bracknell, Berkshire RG12 2SY, UK

→ Augmentation des forêts boréales compense en partie l'effet de stockage du CO<sub>2</sub> sur le climat (température)  
Via une diminution de l'albédo

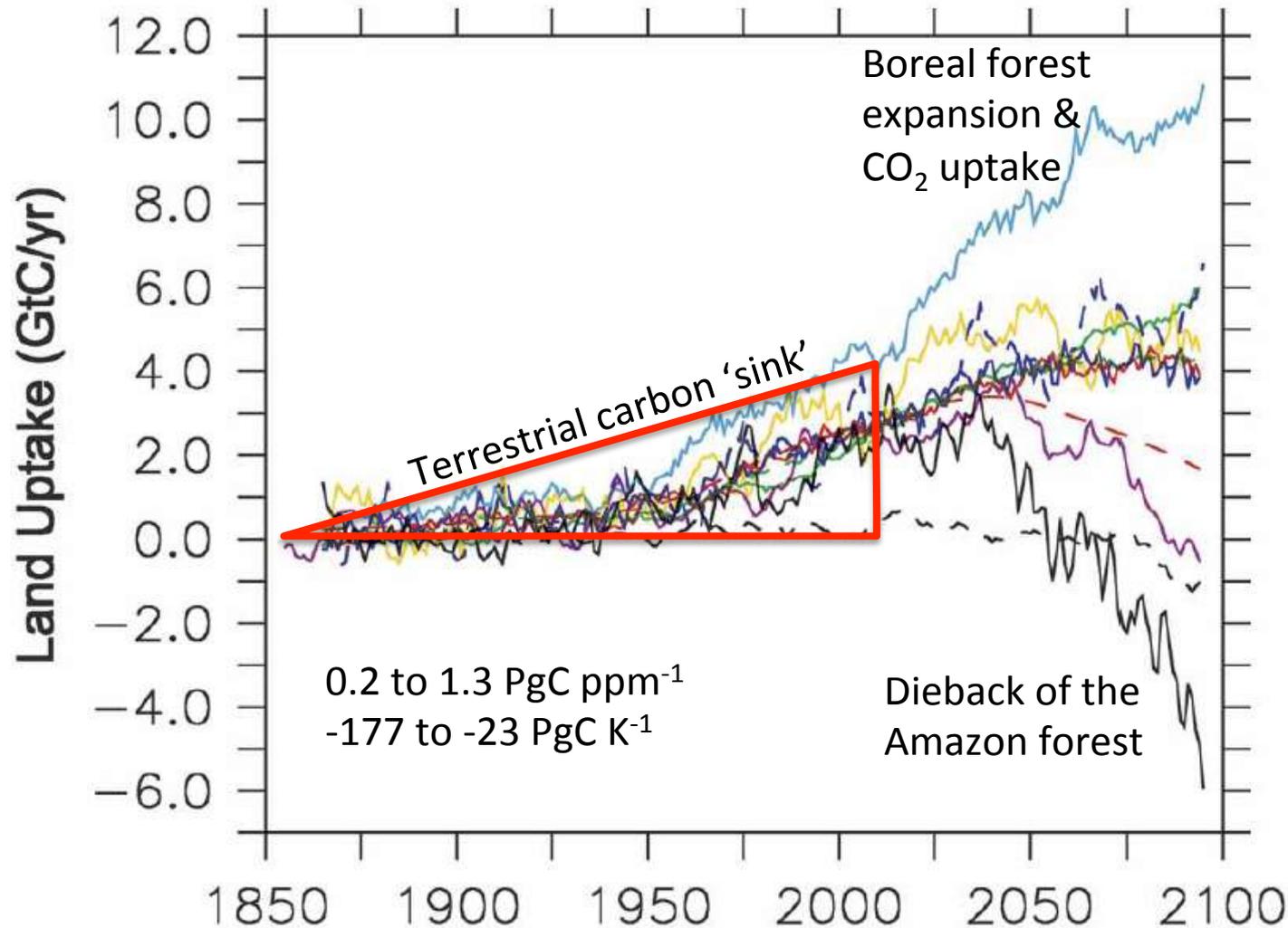
*Betts et al., Nature, 2000*



**Figure 1** Effects of forestation on the solar radiation budget. **a**, Difference in annual-mean surface albedo  $\alpha$  simulated by CONIF and CROP. **b**, Local instantaneous shortwave (SW) radiative forcing at the tropopause due to surface albedo change. At uncoloured gridpoints, vegetation was identical in CONIF and CROP.

Quelques enjeux actuels  
&  
perspectives

# Rétroactions climat - carbone



Friedlingstein et al 2006

# Cartographie globale de l'âge des forêts

Tree cover (fraction)



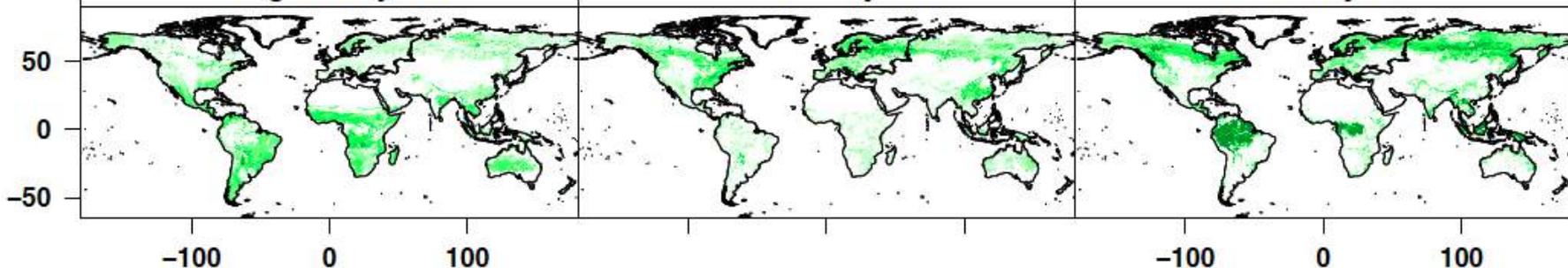
-100 0 100

Young (1–30 years)

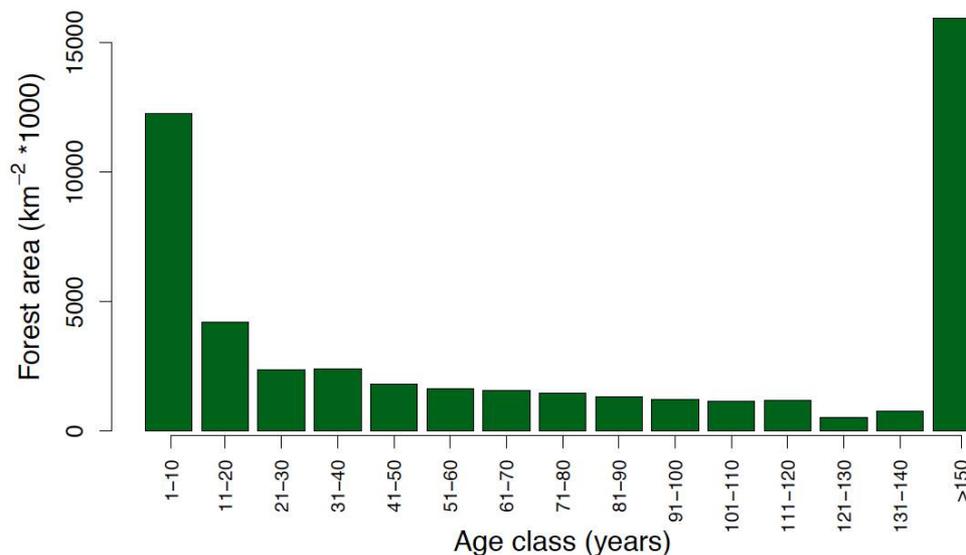
Mid (31–80 years)

Old (>80 years)

Latitude



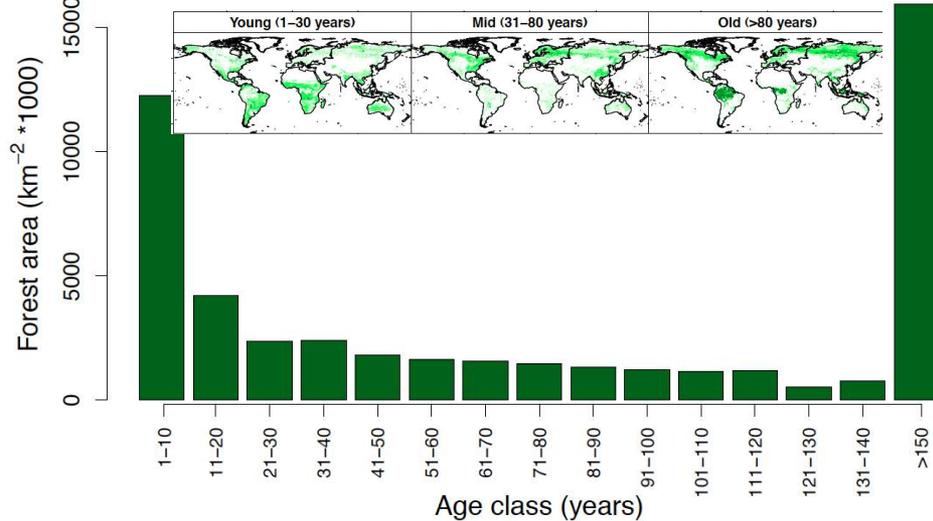
Global Forest Age



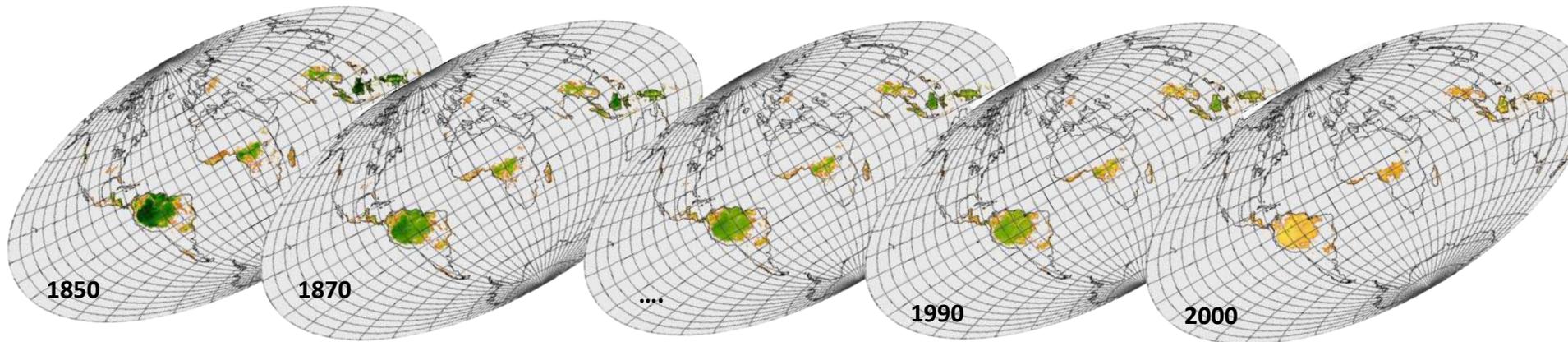
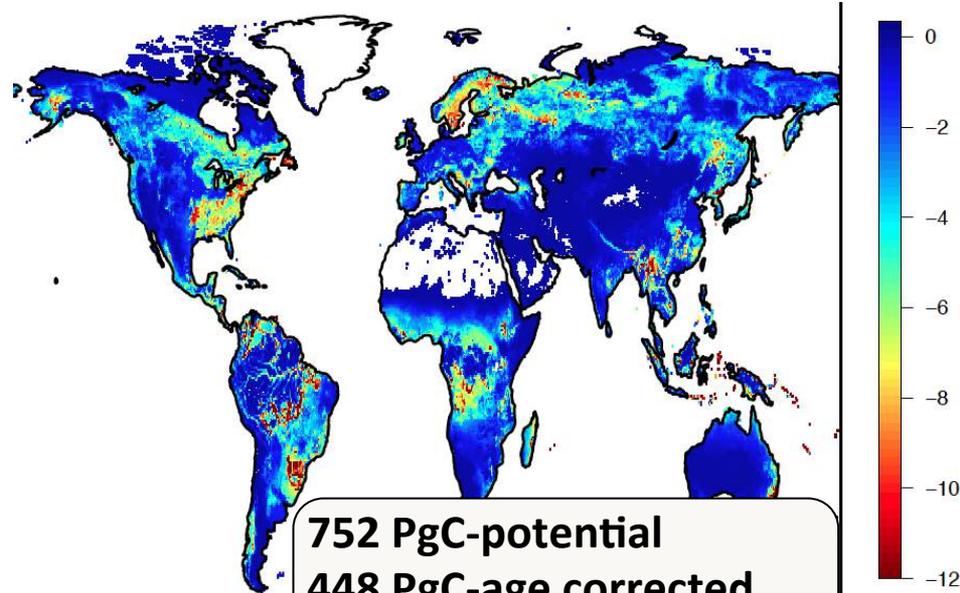
# Effet retard de la gestion des forêts

## Global forest age distribution

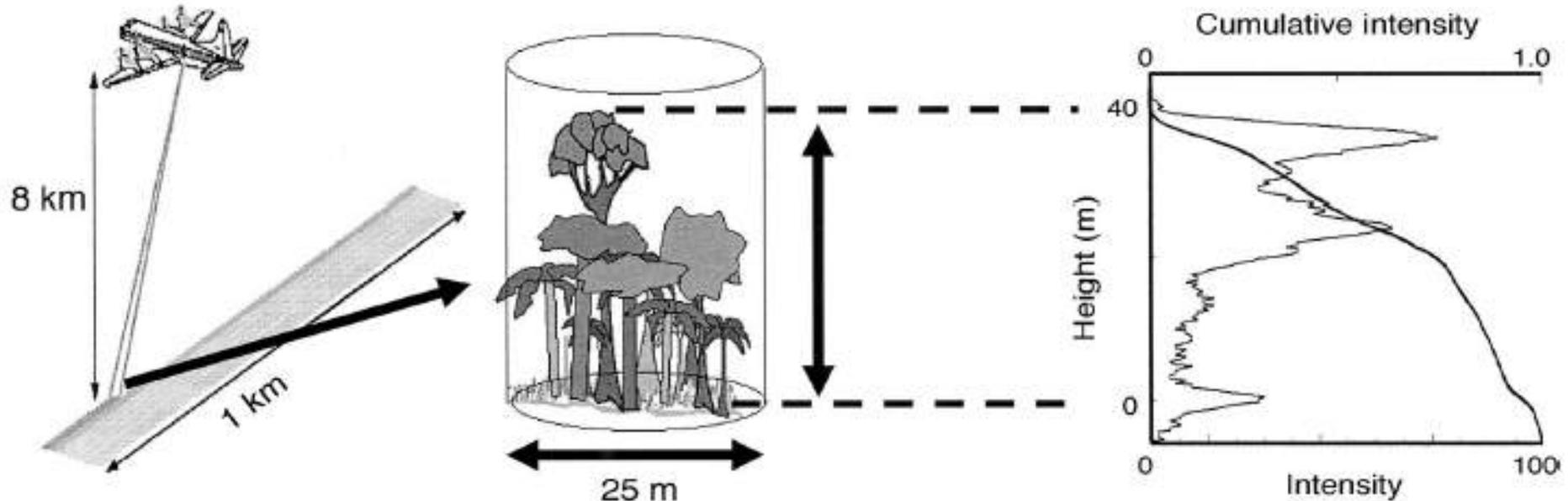
- half of worlds forest <50 years age



## Biomass reduction with age (KgC m<sup>-2</sup>)

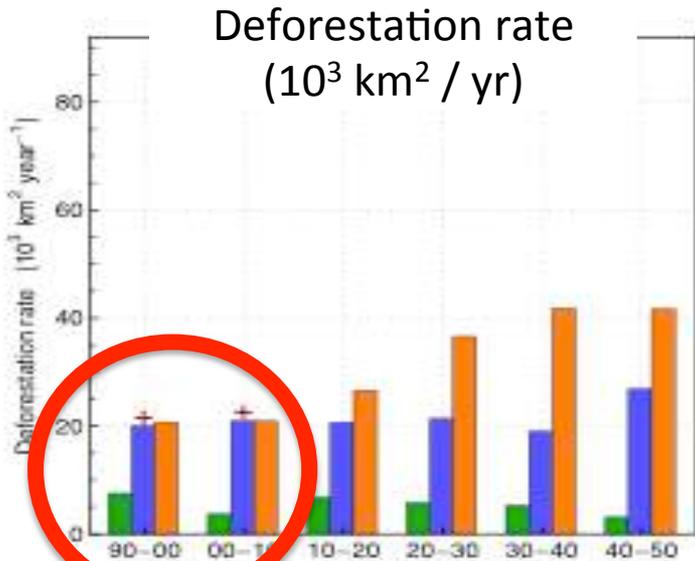


# Fusion modèle –données cruciale

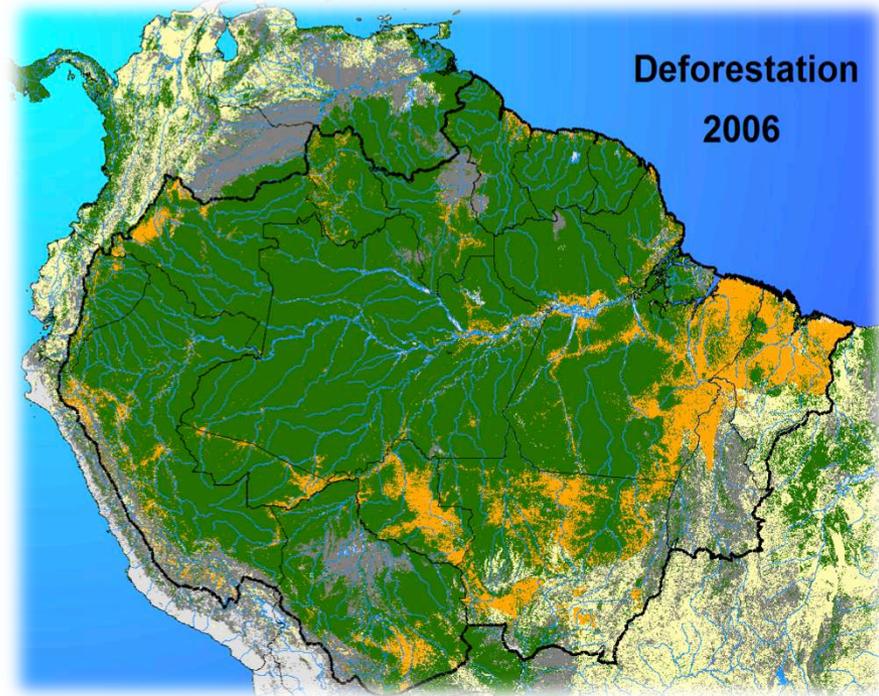


- Models estimate potential growth
- Thus the initial conditions for forest growth are not what is in reality
- Matching reality requires assimilating remote sensing data

# Incertitudes sur la déforestation ?



**Green** : RCP8.5 scenario over Amazon **Blue** & **Orange** : Brazilian projections (**LUCME** in blue and **SIMAMAZONIA**)



*Soares Filho et al., 2006*

## Research needs:

- Understand differences between global and regional land use scenarios
- Reconcile food security scenarios (MA, FAO) with climate scenarios (IPCC)

# Quelques enjeux...

nature  
climate change

LETTERS

PUBLISHED ONLINE: 29 JANUARY 2012 | DOI: 10.1038/NCLIMATE1354

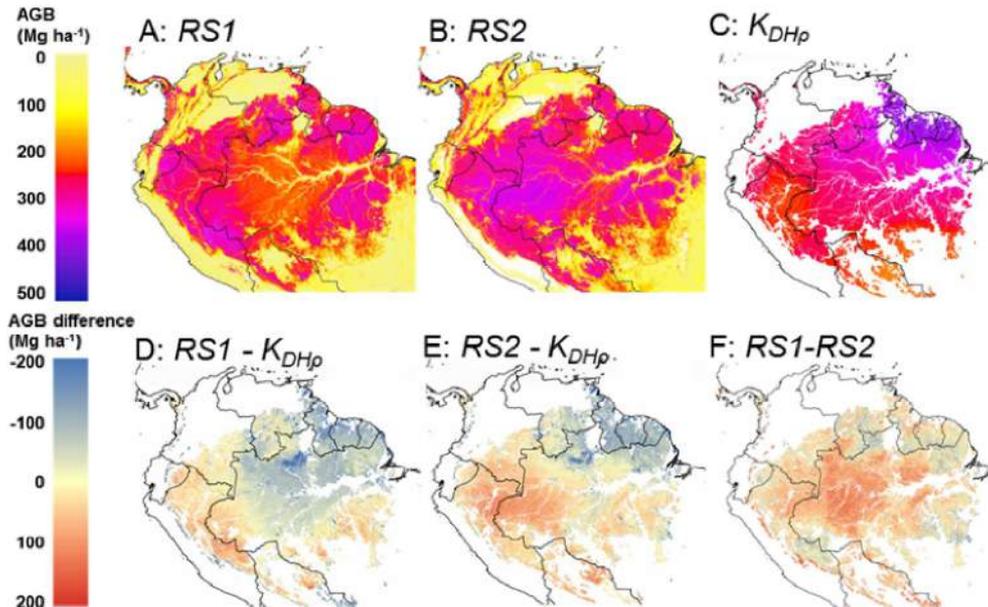
## Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps

A. Baccini<sup>1\*</sup>, S. J. Goetz<sup>1</sup>, W. S. Walker<sup>1</sup>, N. T. Laporte<sup>1</sup>, M. Sun<sup>1</sup>, D. Sulla-Menashe<sup>2</sup>, J. Hackler<sup>1</sup>, P. S. A. Beck<sup>1</sup>, R. Dubayah<sup>3</sup>, M. A. Friedl<sup>2</sup>, S. Samanta<sup>1</sup> and R. A. Houghton<sup>1</sup>

→ Densité du bois des Forêts tropicales variable et incertaine

## Markedly divergent estimates of Amazon forest carbon density from ground plots and satellites

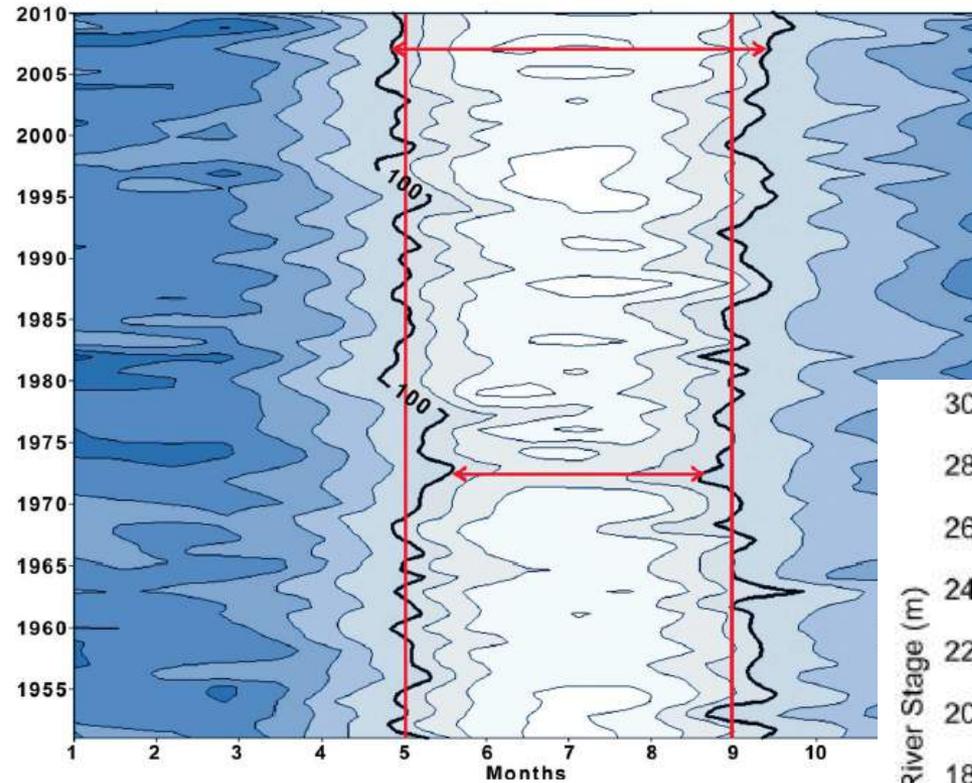
*Mitchard et al. GEB 2015*



→ Différences de densité du bois expliquent en partie les différences de stock estimées

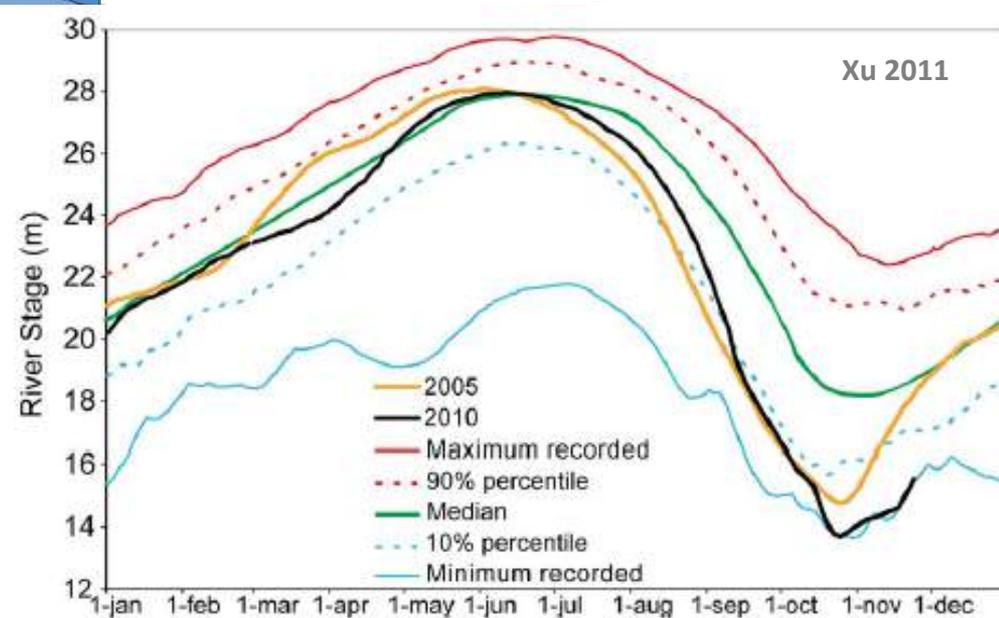
# Dépérissement de la forêt Amazonienne ?

Dry season length has increased in 20<sup>th</sup> century



Marengo 2011

Two consecutive droughts 2005 & 2010



# Dépérissement de la forêt Amazonienne ?

Drought as analog for future climate response

- Role of optical remote sensing (MODIS)
  - High temporal frequency
  - Moderate resolution
  - Blue band to address aerosol
  - Algorithm that avoids saturation effects
    - Enhanced vegetation index (EVI)

$$EVI = 2.5 \frac{\rho_N - \rho_R}{L + \rho_N + C_1 \rho_R - C_2 \rho_B}$$

Satellite remote sensing of tropical forest canopies and their seasonal dynamics

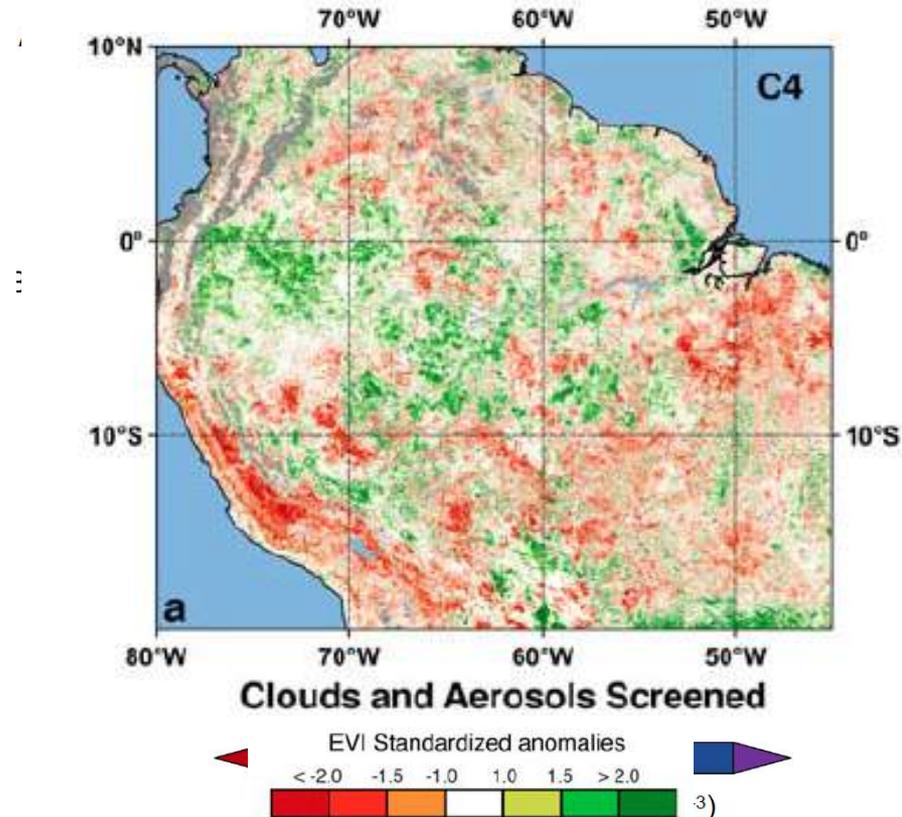
BENJAMIN POULTER†‡\*\* and WOLFGANG CRAMER†

## Amazon Forests Green-Up During 2005 Drought

Scott R. Saleska,<sup>1†</sup> Kamel Didan,<sup>2\*</sup> Alfredo R. Huete,<sup>2</sup> Humberto R. da Rocha<sup>3</sup>

## Amazon forests did not green-up during the 2005 drought

Arindam Samanta,<sup>1</sup> Sangram Ganguly,<sup>2</sup> Hirofumi Hashimoto,<sup>3</sup> Sadashiva Devadiga,<sup>4</sup> Eric Vermote,<sup>5</sup> Yuri Knyazikhin,<sup>1</sup> Ramakrishna R. Nemani,<sup>6</sup> and Ranga B. Myneni<sup>1</sup>

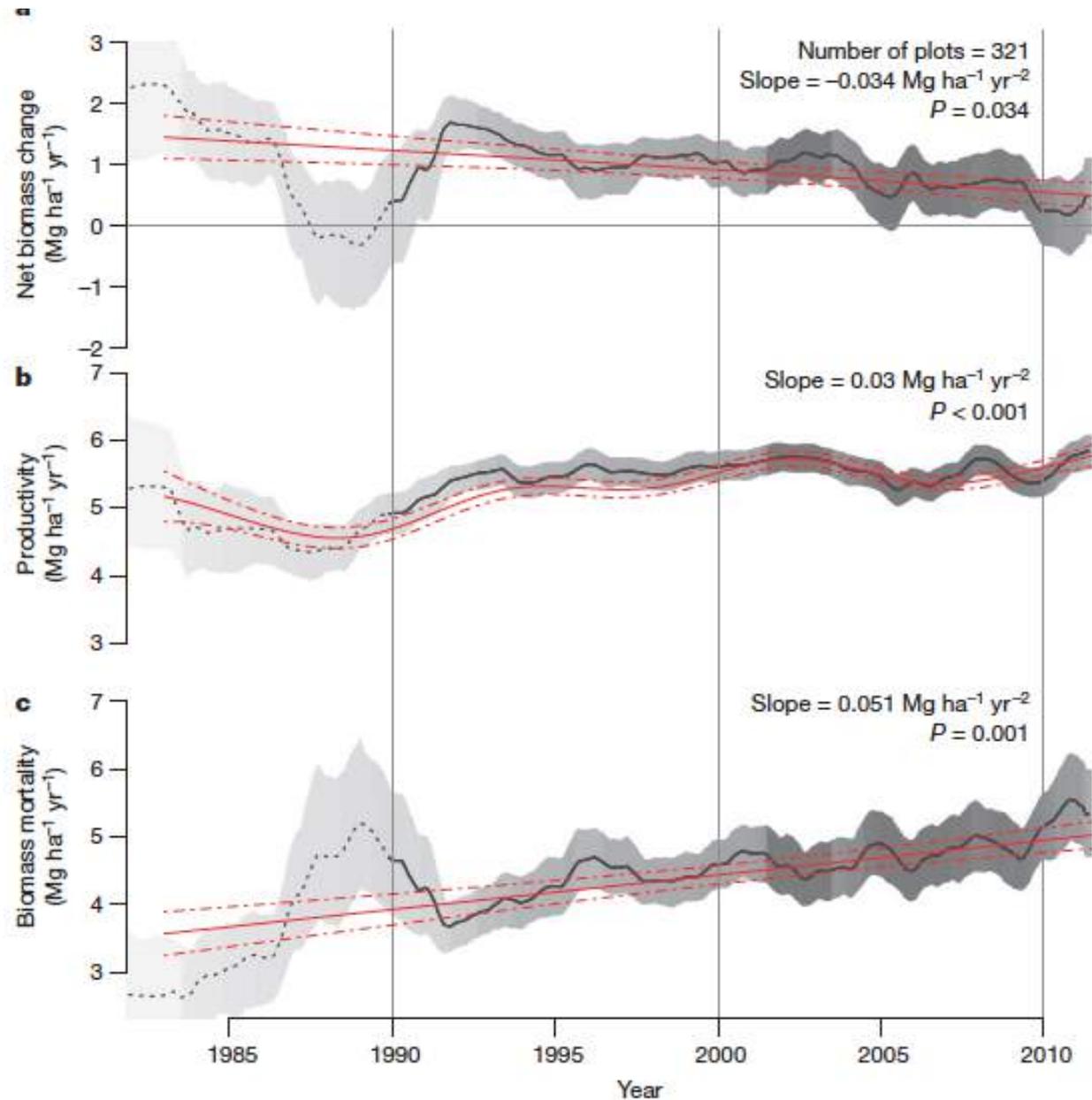
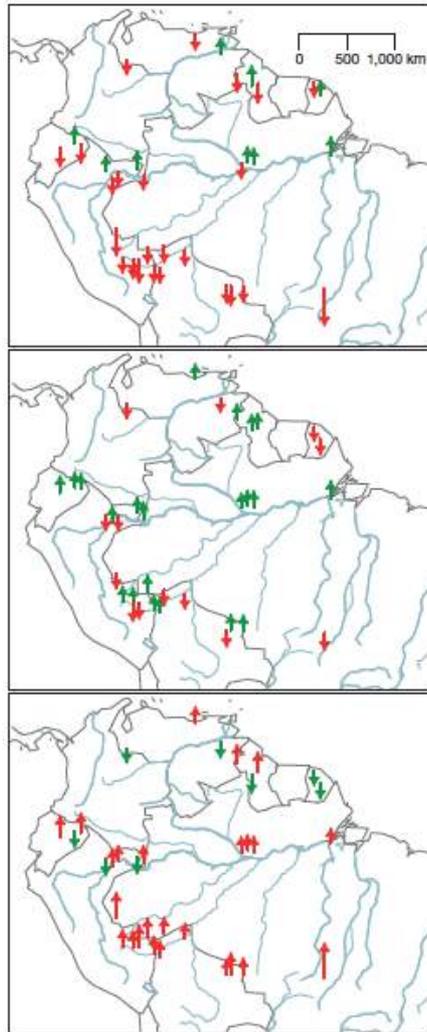


Saleska 2007

Poulter 2009

Samanta 2011

# Récentes observations pour l'Amazonie

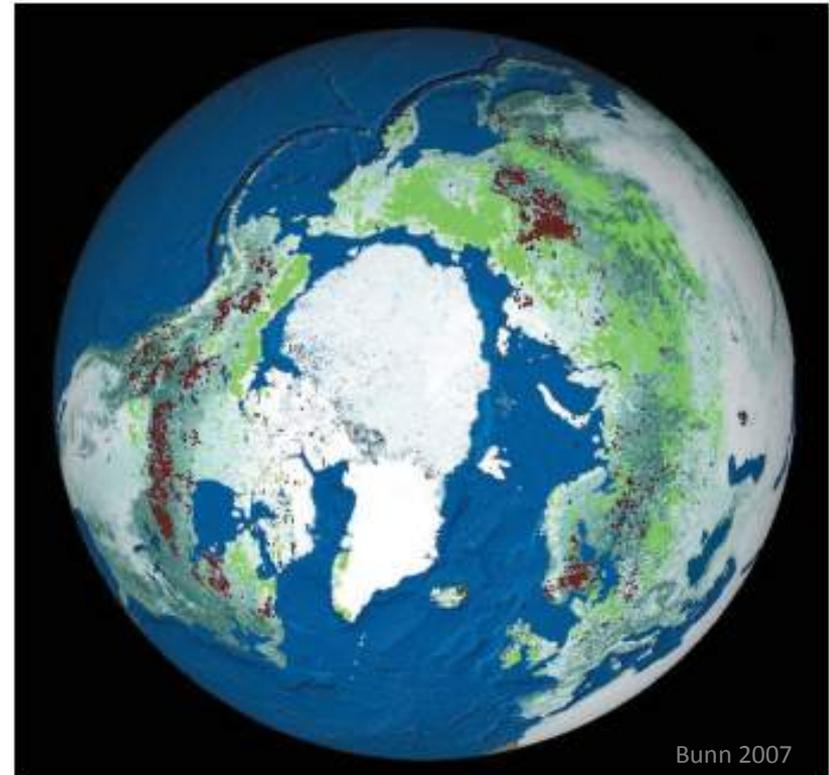


Déclin du puits de C  
de l'amazonie

*Brienen et al. 2015*

# Augmentation des forêts boréales ?

- 5-13 day increase in onset of boreal growing season
- Boreal forest browning detected in satellite and plot measurements
- DGVM models agree with satellite trends in growing season length
- **But high disagreement in LAI dynamics**



<i>Vegetation Type</i>	<i>Declining</i>	<i>Increasing</i>
All	86.1 (3%)	266.2 (9%)
Needle-leaved Evergreen Forest	37.8 (6%)	25.9 (4%)
Sparse Deciduous Forest (mostly Larch)	18.1 (4%)	64.4 (15%)
Herbaceous or Shrub	4.8 (1%)	31.9 (6%)



**Merci pour  
votre attention !**

## GLOBAL CARBON ATLAS

The Global Carbon Atlas is a platform to explore and visualize the most up-to-date data on carbon fluxes resulting from human activities and natural processes. Human impacts on the carbon cycle are the most important cause of climate change.

### OUTREACH

Take a journey through the history and future of human development and carbon

GO



### EMISSIONS

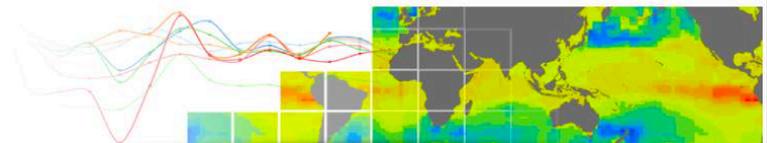
Explore and download global and country level carbon emissions from human activity.

GO

### RESEARCH

Explore and visualize research carbon data, and get access through data providers

GO



[www.globalcarbonatlas.org](http://www.globalcarbonatlas.org)