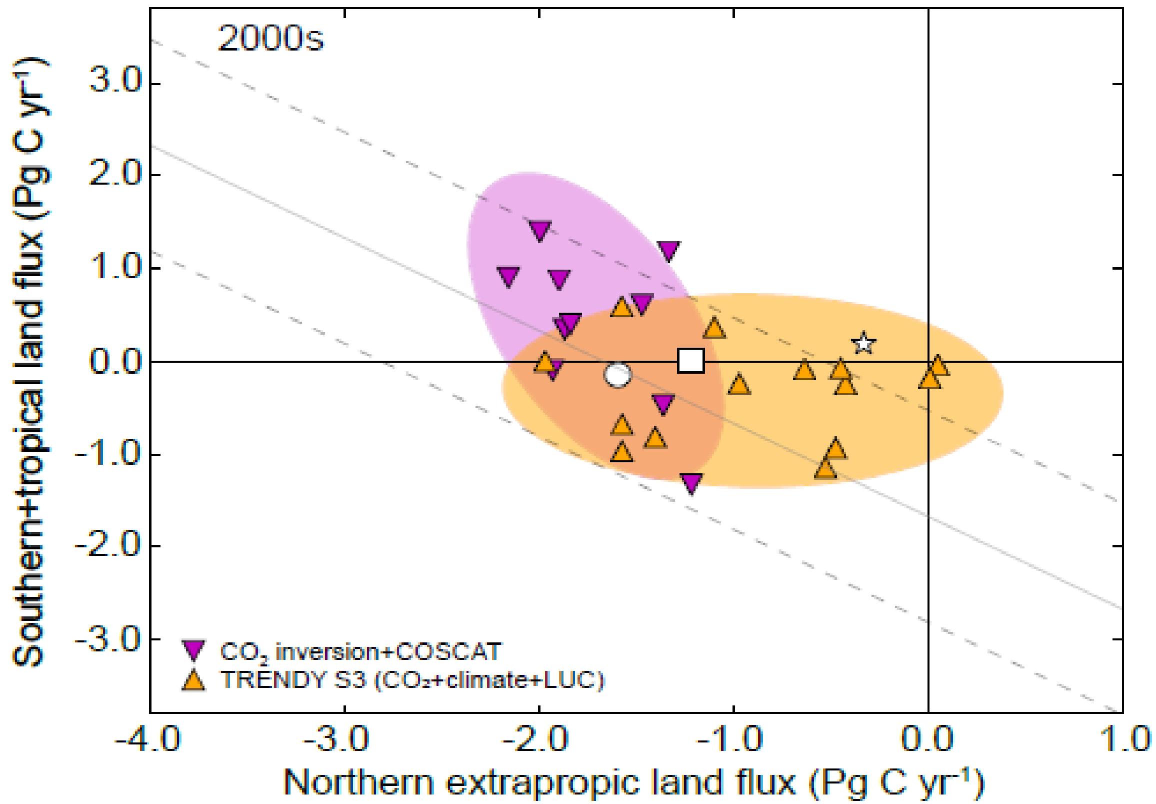
The global forest carbon balance from flux towers

P. Ciais, S. Besnard, Y. Yao, C. Yue
B. Poulter, T. Pugh, S. Saatchi, M. Jung, J. Chave, P. Stoy
M. Herold, D. Rozendaal
M. Reichstein, S. Piao, N. Carvalhais.

Motivation

Persistent and large uncertainties on the partitioning of the land carbon sink between the tropics and the northern hemisphere



M. Kondo, unpublished

Drivers of land carbon balance at global and local scale

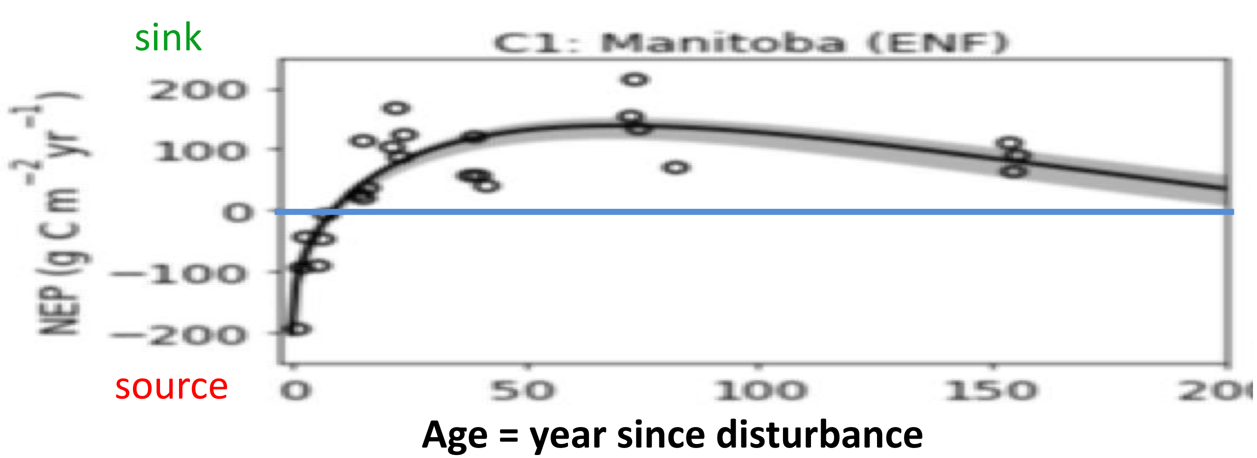
- At global scale
  - Human-caused perturbation of the carbon cycle causes global land carbon sink

    Photosynthesis - Respiration - Disturbance losses = 2.7 ± 0.7 PgC y^{-1}

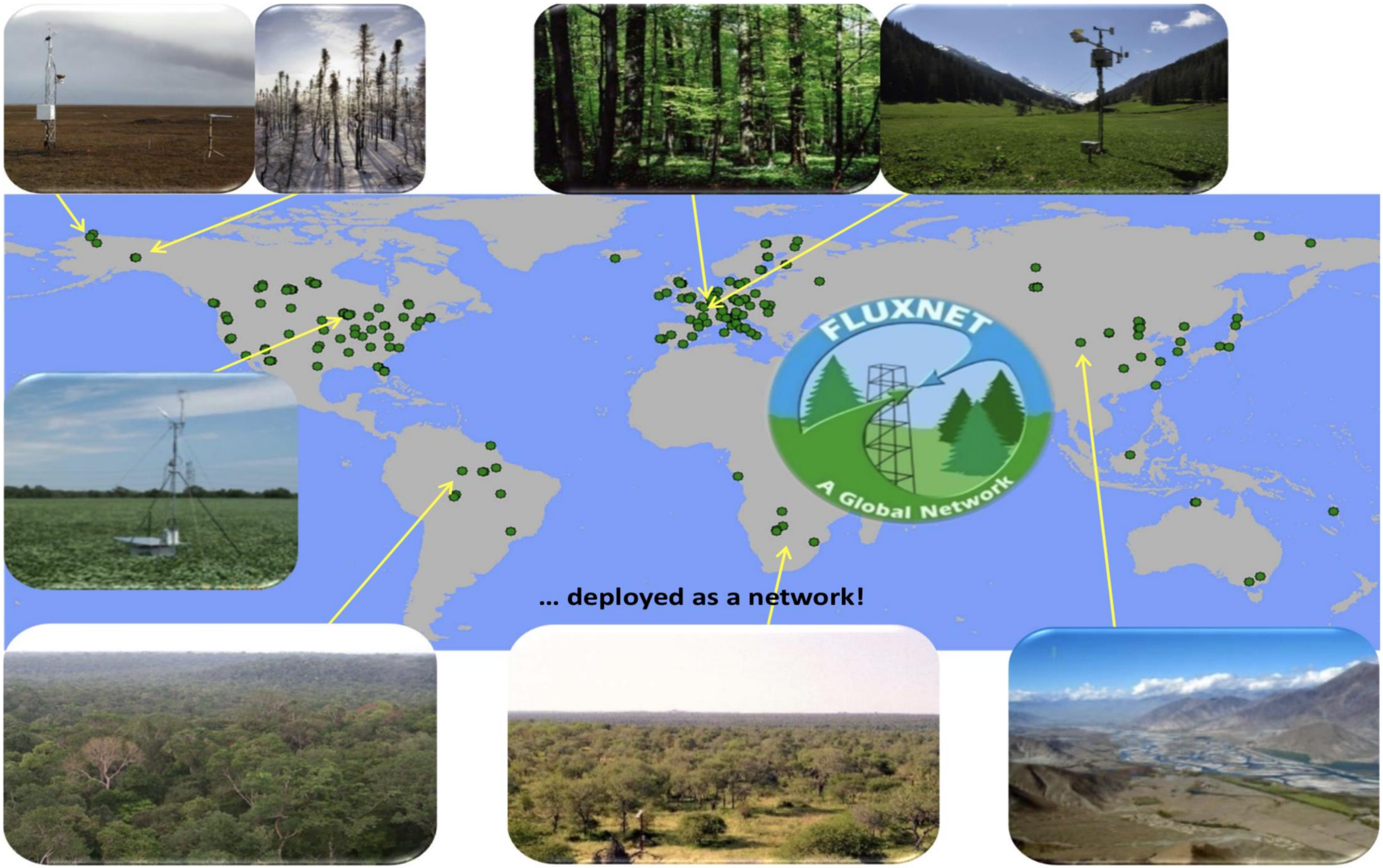
  - Pre-industrial Era, land carbon cycle in quasi-equilibrium

    Photosynthesis - Respiration - Disturbance losses = river export = 0.7 PgC y^{-1}

- At local scale
  - A system is a sink or a source depending on <u>age since last disturbance</u>
  - C-balance = f(age) is modified by climate change, CO_2, N deposition …



NEP up-scaled from flux towers using climate and remote sensing is a too large sink

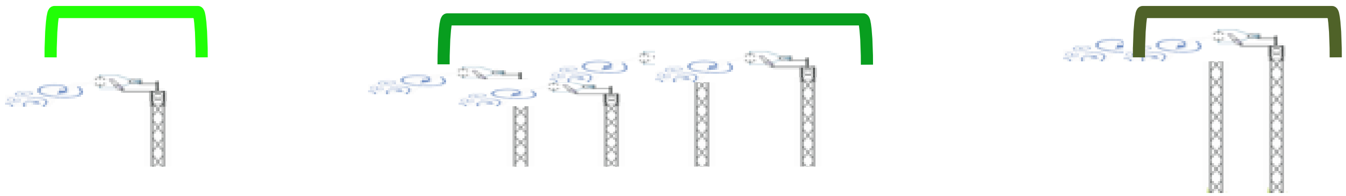


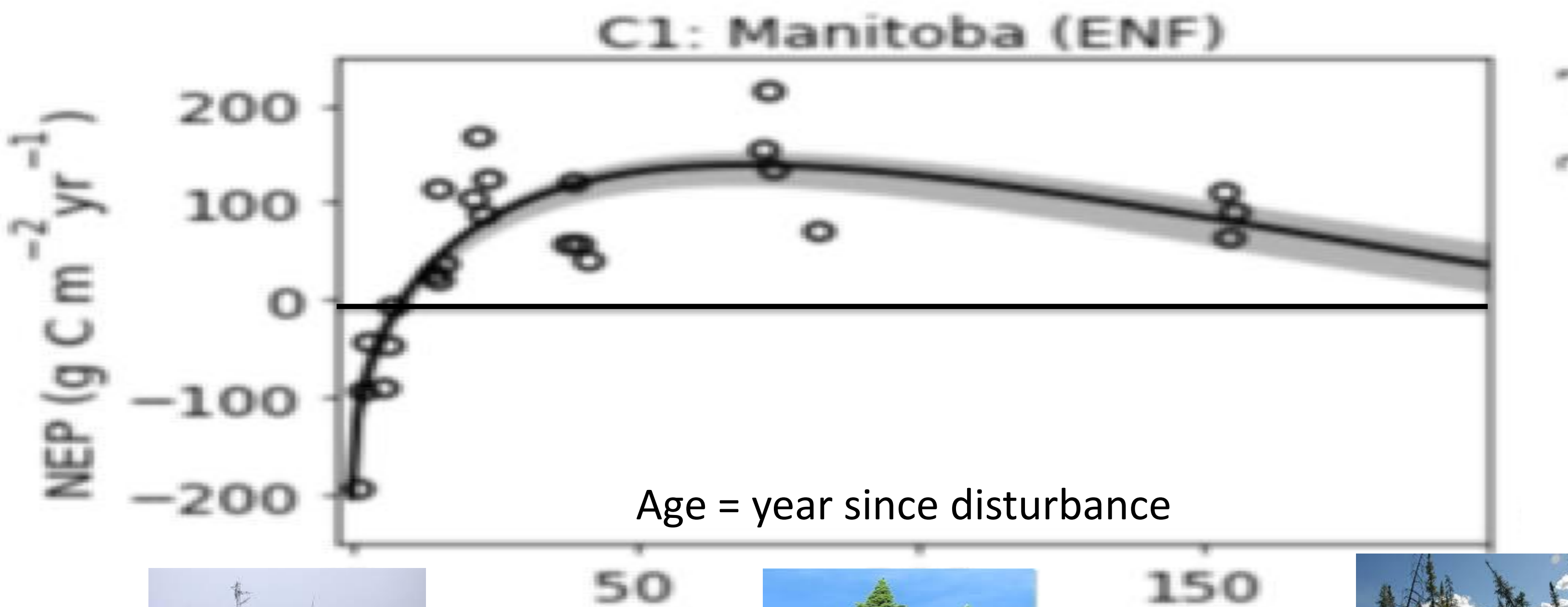
Age drives NEP

Very few flux towers

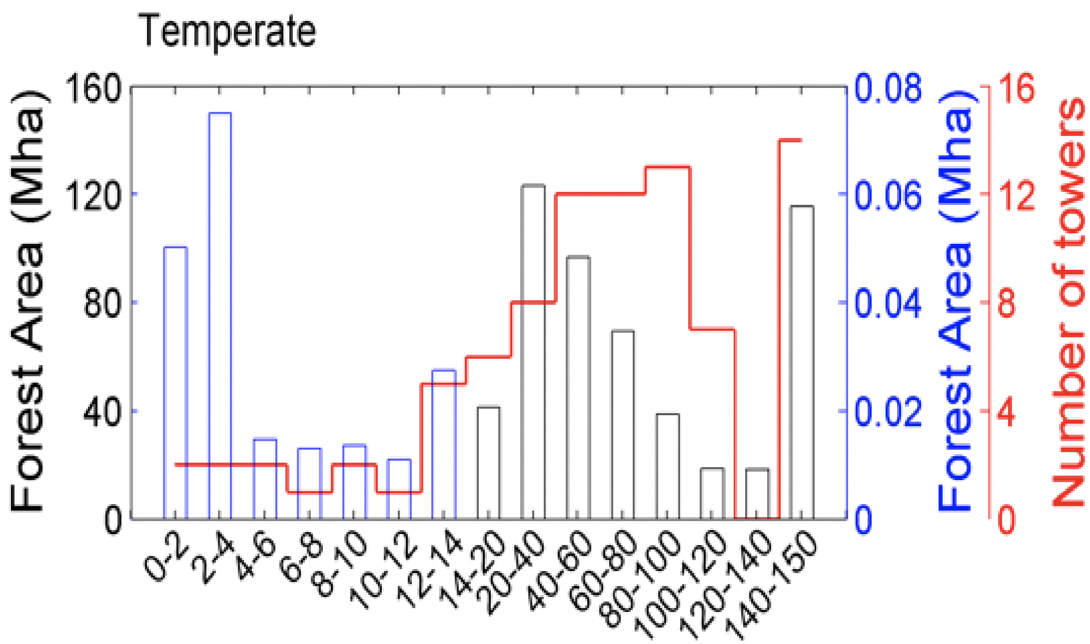
A lot of flux towers

Few flux towers



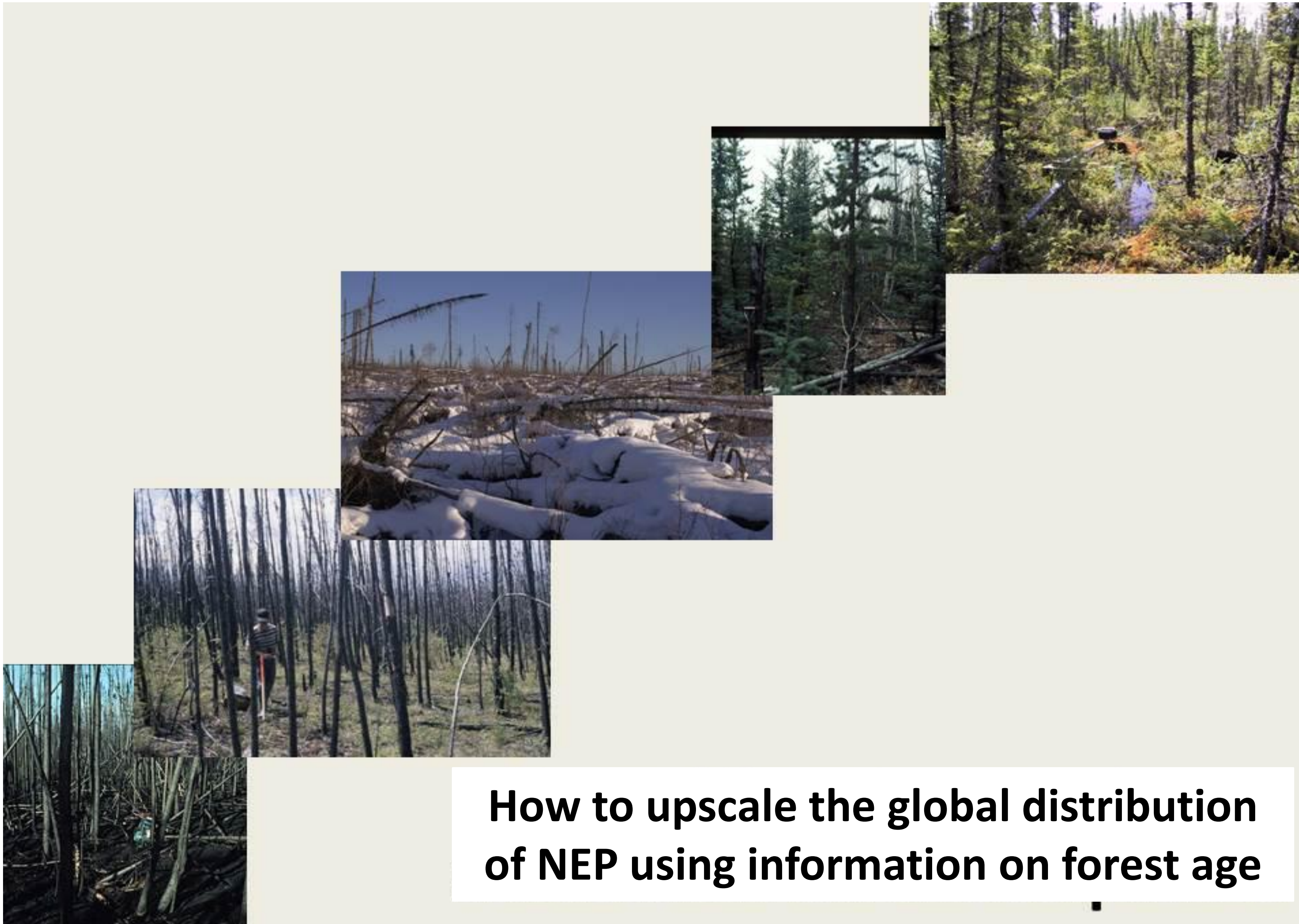


Detection of age-effects on NEP impaired by FLUXNET sampling



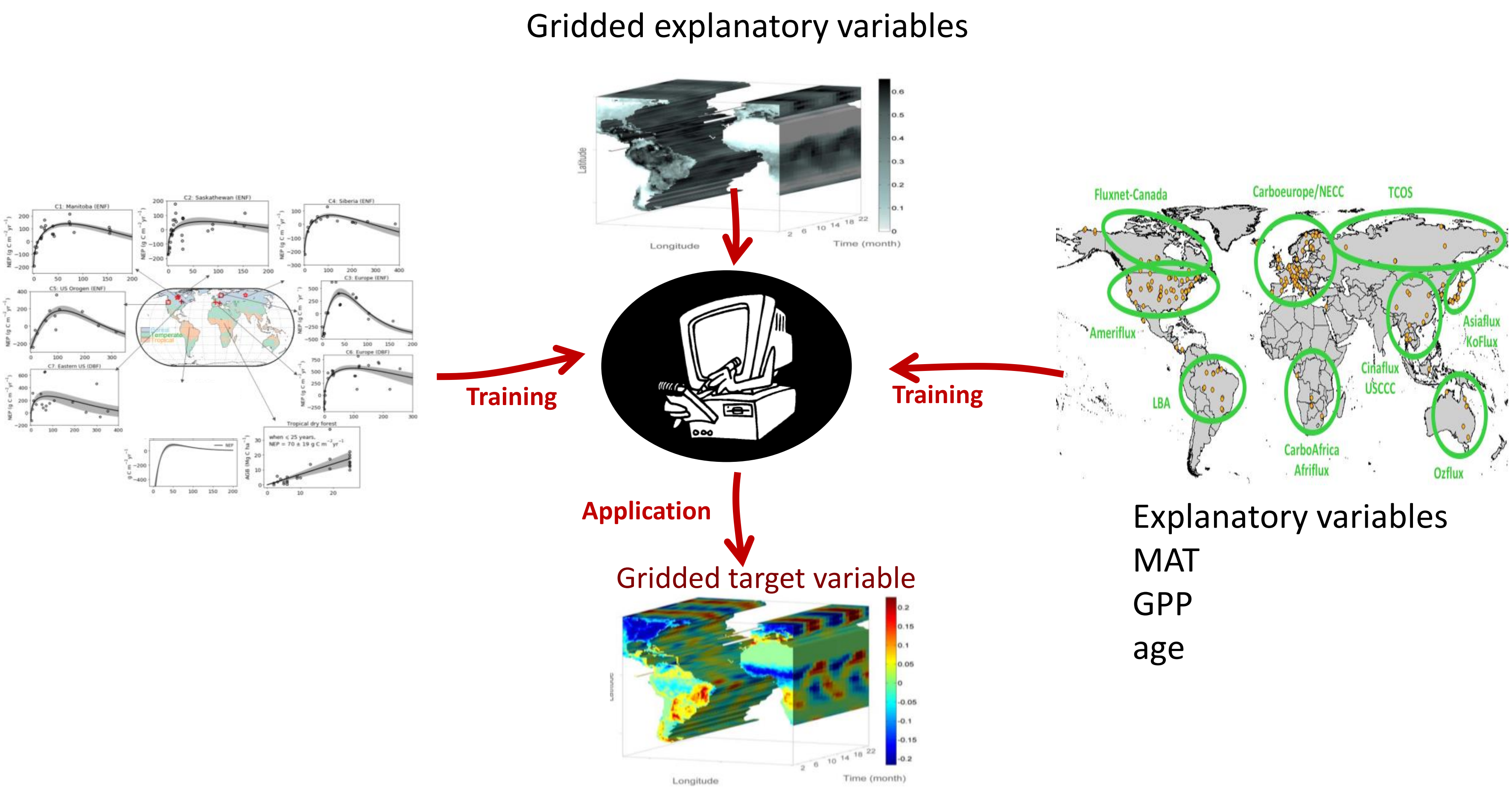
Blue Bars = Forest age distribution (see later)

Red curve = Sampling by flux towers



How to upscale the global distribution of NEP using information on forest age

NEP upscaling



Training : local tower NEP residuals + NEP(age) models with local age, GPP, MAT

Up-scaling ensemble : Random forest with 1 MAT map x 36 GPP maps x 36 age maps members
GPP : Fluxcom
Age maps : Poulter et al. + MODIS

BAC Method : up-scaling NEP from Biome specific NEP(age) data + Age + Climate (GPP)

1

Biome specific
NEP(age,biome) models
From chronosequences

↓

Up-scaling
with forest age + biome maps
$NEP_b(x)$

→

2

Residuals $NEP_b(x,age)$
at 140 towers
[688 site . Years]

↓

Upscale residuals using
machine learning
$NEP_{res}(x) = ML(MAT, GPP, age)$

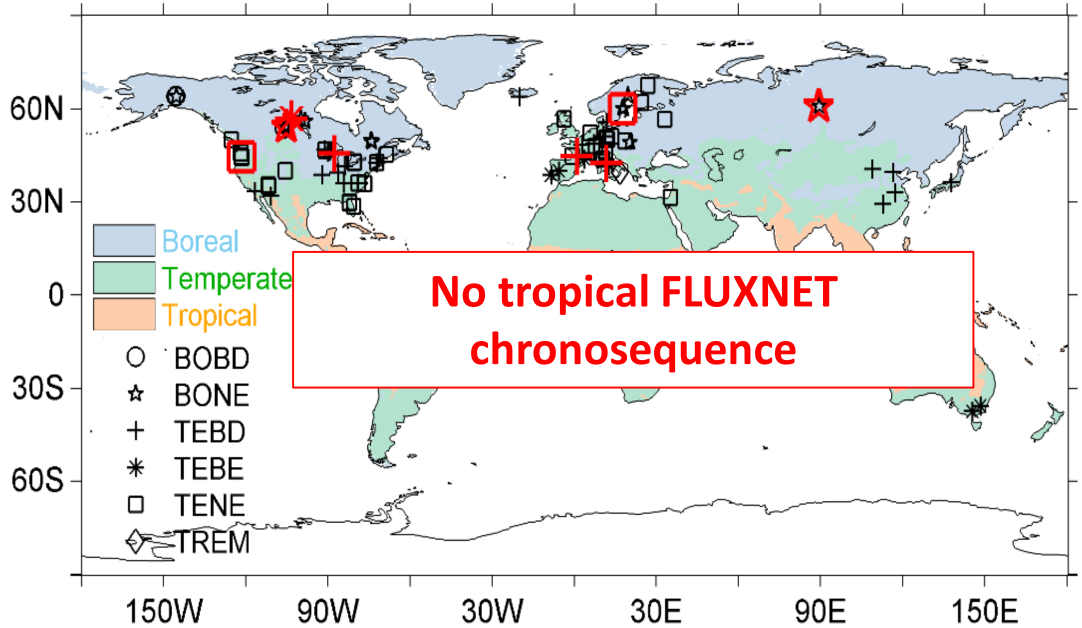
$$NEP(x) = NEP_b(x) + NEP_{res}(x)$$

Gives : a map of global forest NEP based on <u>age</u> maps, climate and remote sensing datasets

1

Biome specific NEP-age curves

- Regional chronosequence data were collected to construct <u>NEP = f(age) models in different biomes</u>



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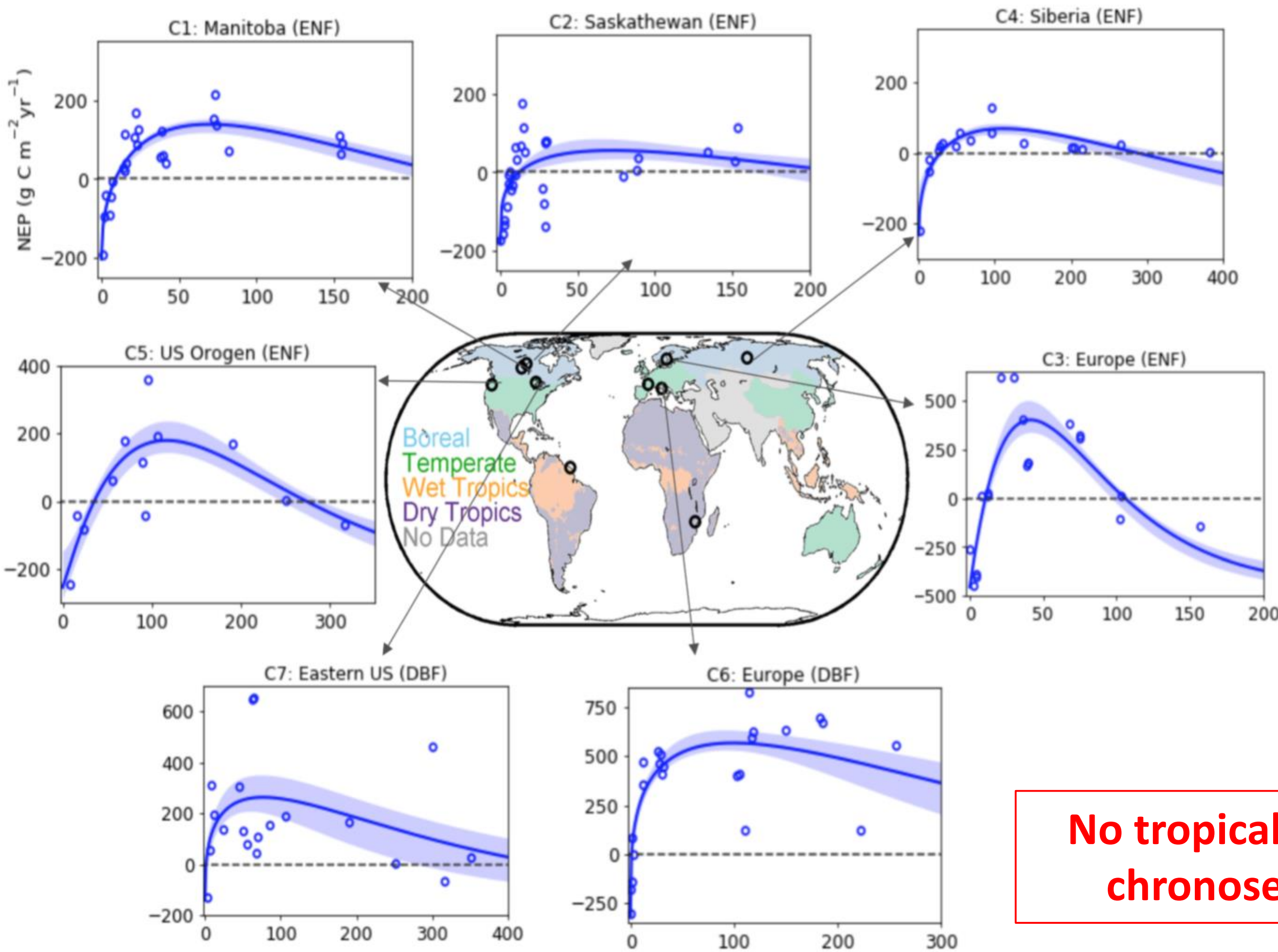
NEP-age models
for temperate and boreal forests

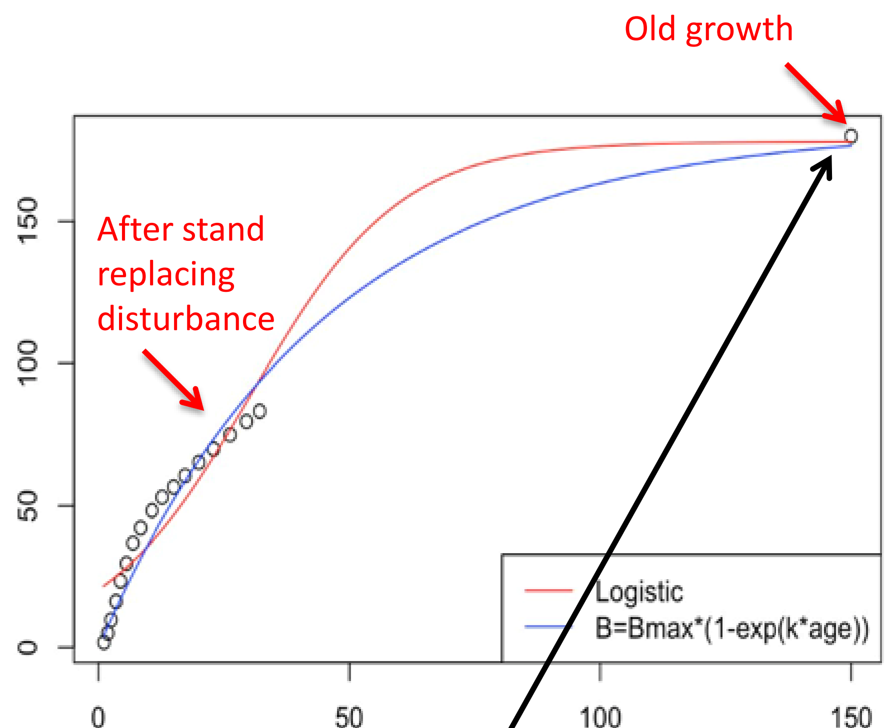
- Regional chronosequence data were collected to construct
  <u>NEP = f(age) models in different biomes</u>



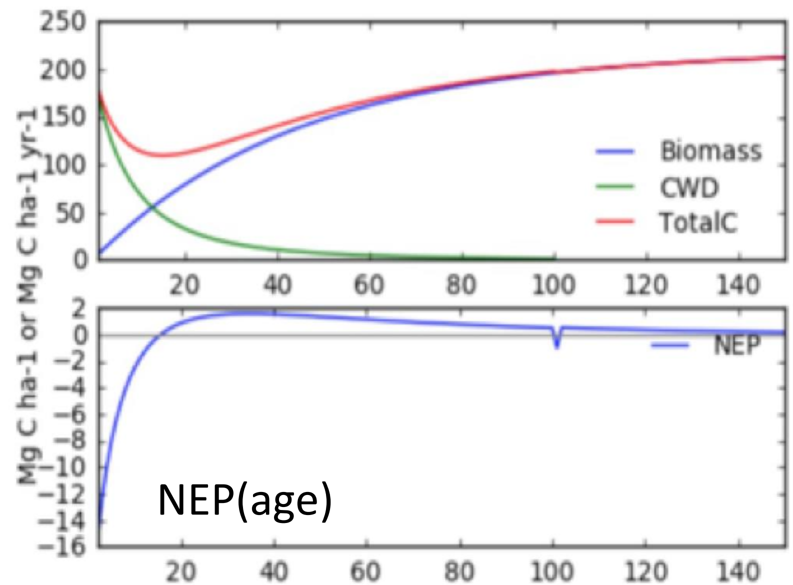
No tropical FLUXNET chronosequence

1

NEP –age models in the tropics ?
No flux towers chronosequences
=> Use biometric measurements



This asymptote depends on regional max biomass values

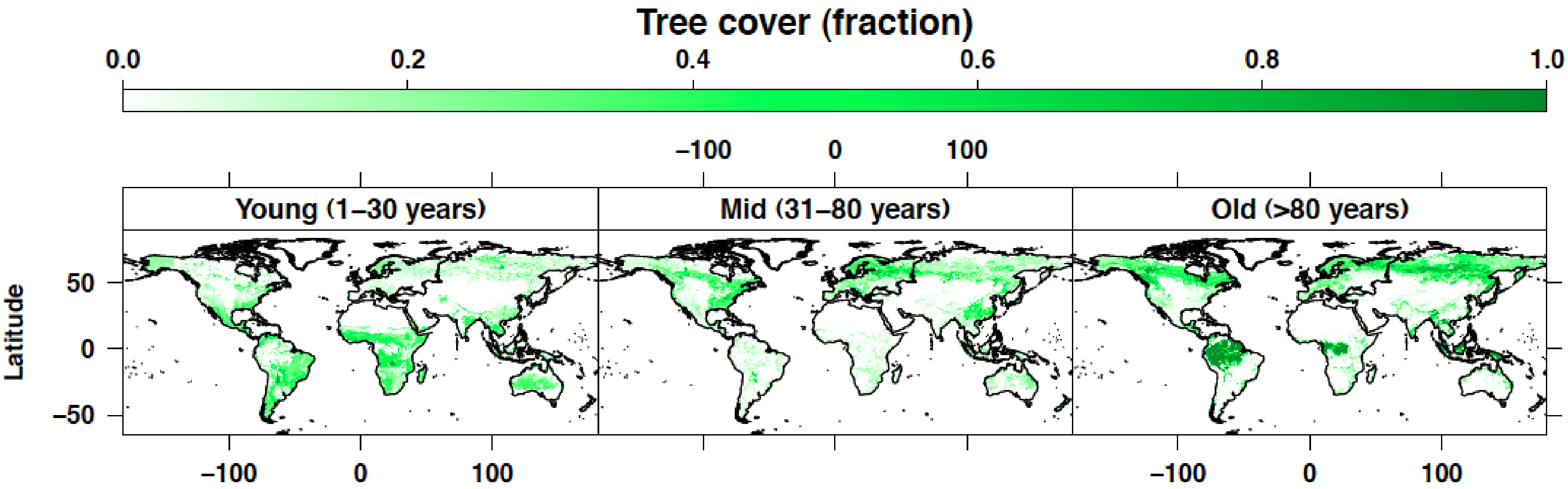


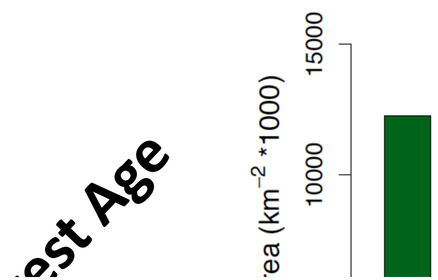
Forest age-maps

Age-maps

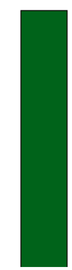
- In the young ages 0-15 years, where NEP changes rapidly, we build a 2 - years resolution global forest age map from time since disturbance (MODIS)
- In the middle and old ages, B Poulter NASA GSFC constructed a global age map from species maps, forest inventories data and MODIS NDVI. This global map has a resolution of 10 years
- Age maps (forest area of the same age class) with fine step of two years until 15 years old, and coarse steps of ten years after 15 years.

Age maps





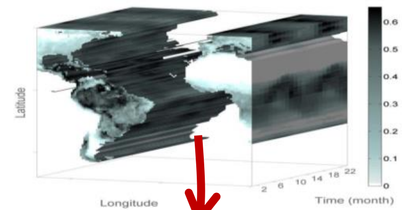
50 Mkm² forest area
- 32 Mkm² < 150 yr
- 22 Mkm² < 50 yr
- 16 Mkm² < 25 yr

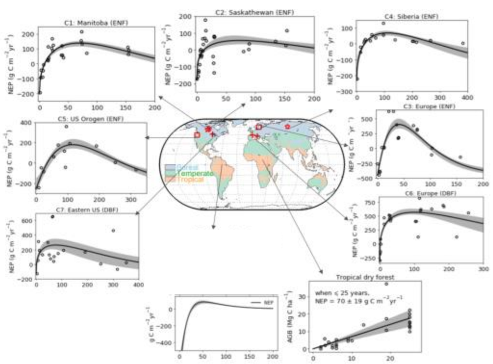


Now a new map at 1 km has been produced from in situ and RS biomass

NEP upscaling

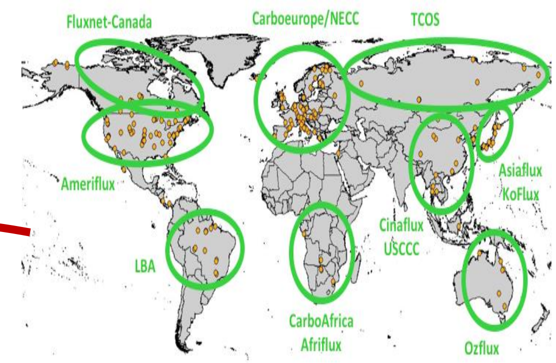
Gridded explanatory variables





Training

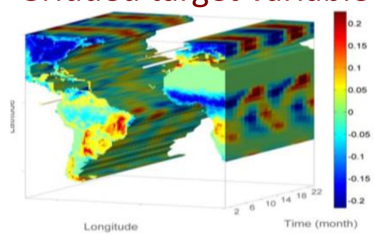
Training



Explanatory variables
MAT
GPP
age

Application

Gridded target variable



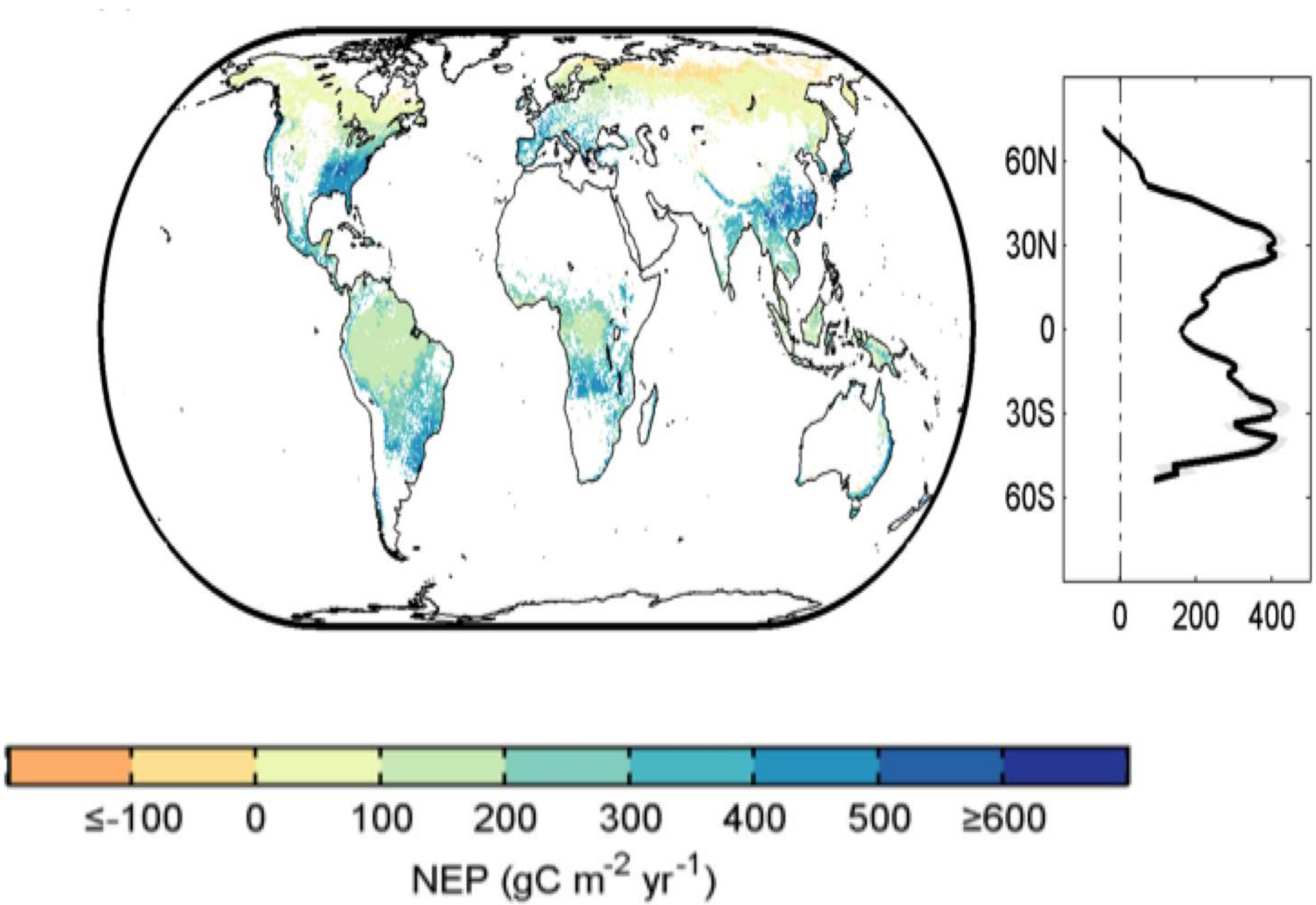
Training : local tower NEP residuals + NEP(age) models with local age, GPP, MAT

Up-scaling ensemble : Random forest with 1 MAT map x 36 GPP maps x 36 age maps members

GPP : Fluxcom

Age maps : Poulter et al. + MODIS

Global NEP distribution (BAC)



AC Method : Up-scaling NEP with : Age + Climate

Local NEP(x,age)
at 140 towers

↓

Upscale local residuals using
machine learning algorithm

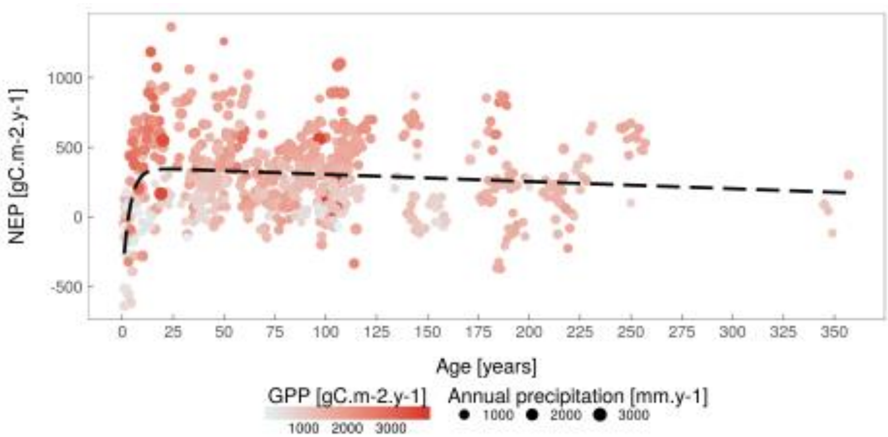
NEP(x) = ML(MAT, GPP, age)

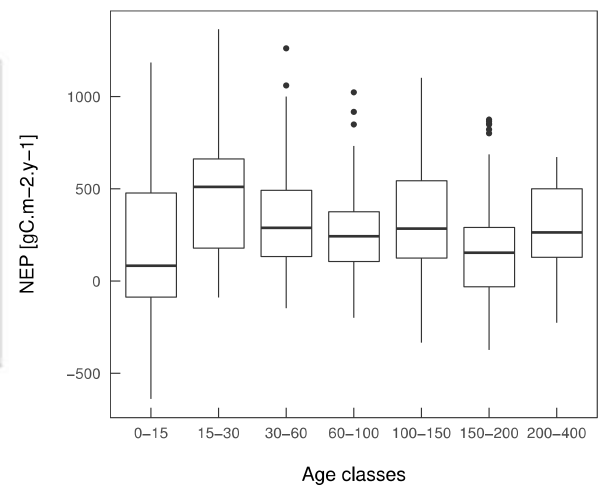
Single step approach
But relies only on a single NEP(age) relationship ‘hidden’ in the FLUXNET data

Non linear models fitted to FLUXNET sites to derive a global 'universal' NEP = f(age) model

Age-dependent forest C dynamics

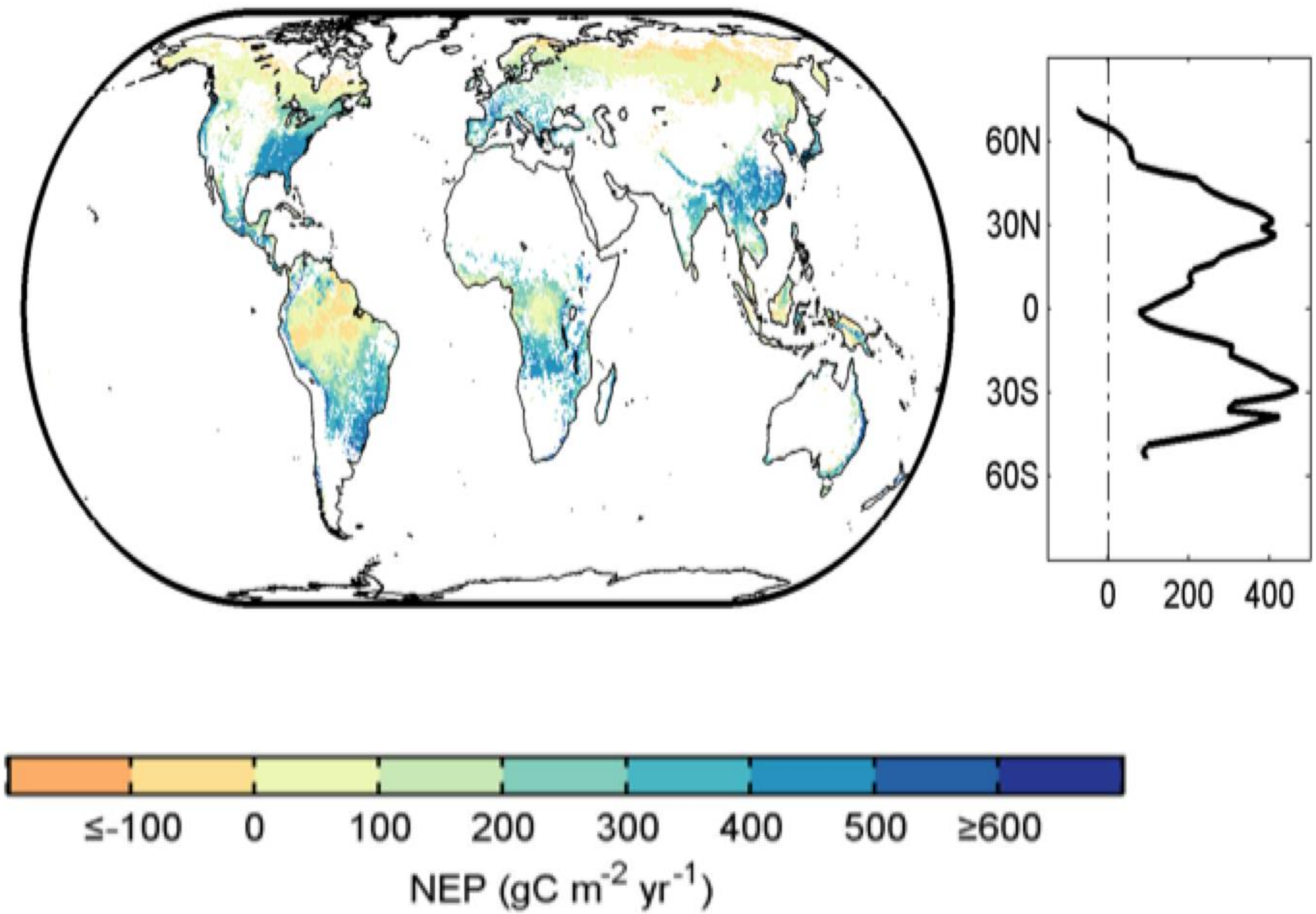
- 140 FLUXNET sites in forest ecosystems
- Sites with forest age information
- Tested several stand age model (e.g. Amiro et al. 2010, Coursolle et al. 2012, etc.)





Besnard et al.

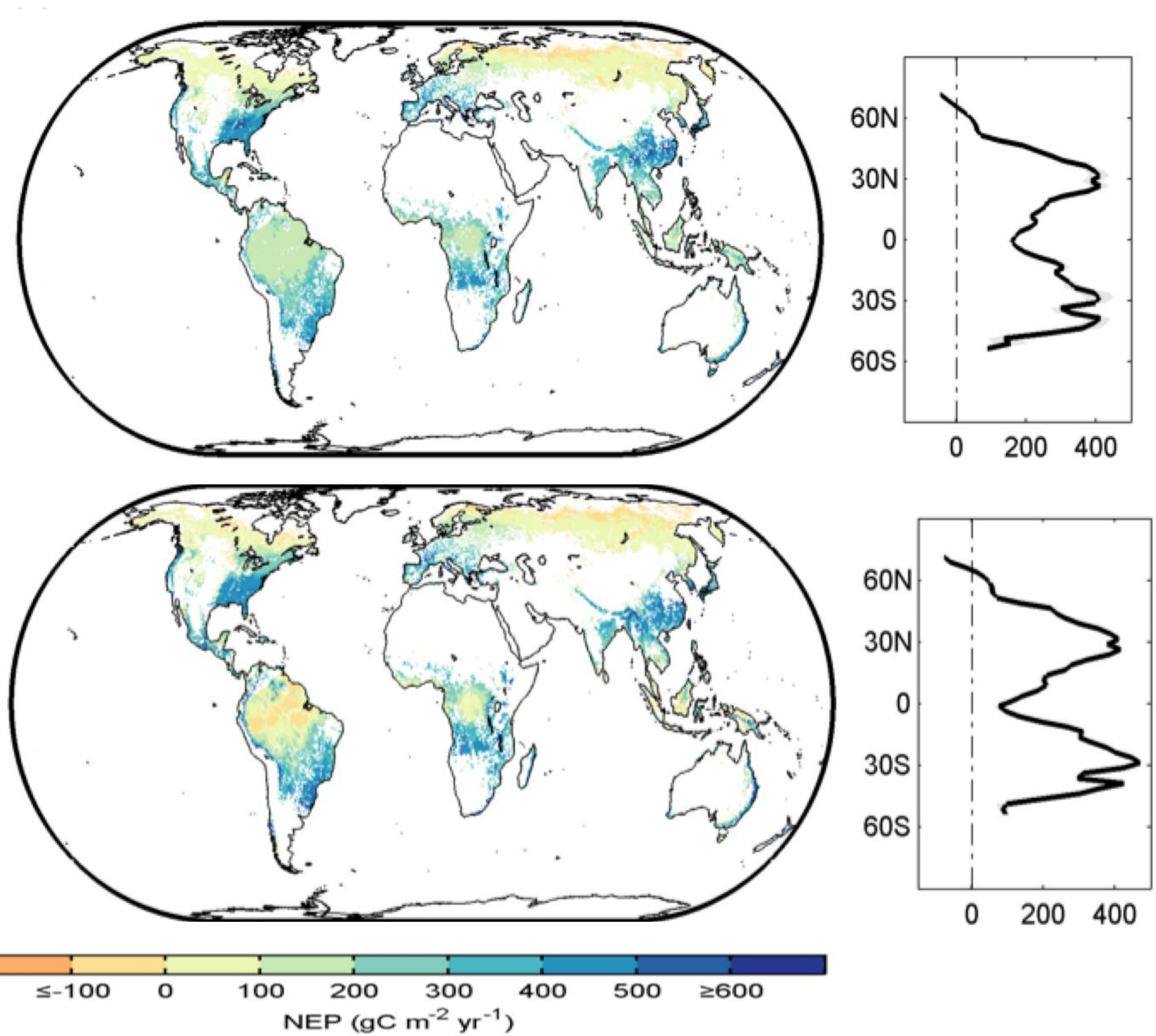
Global NEP distribution (AC)



Comparison of both approaches

BAC

AC

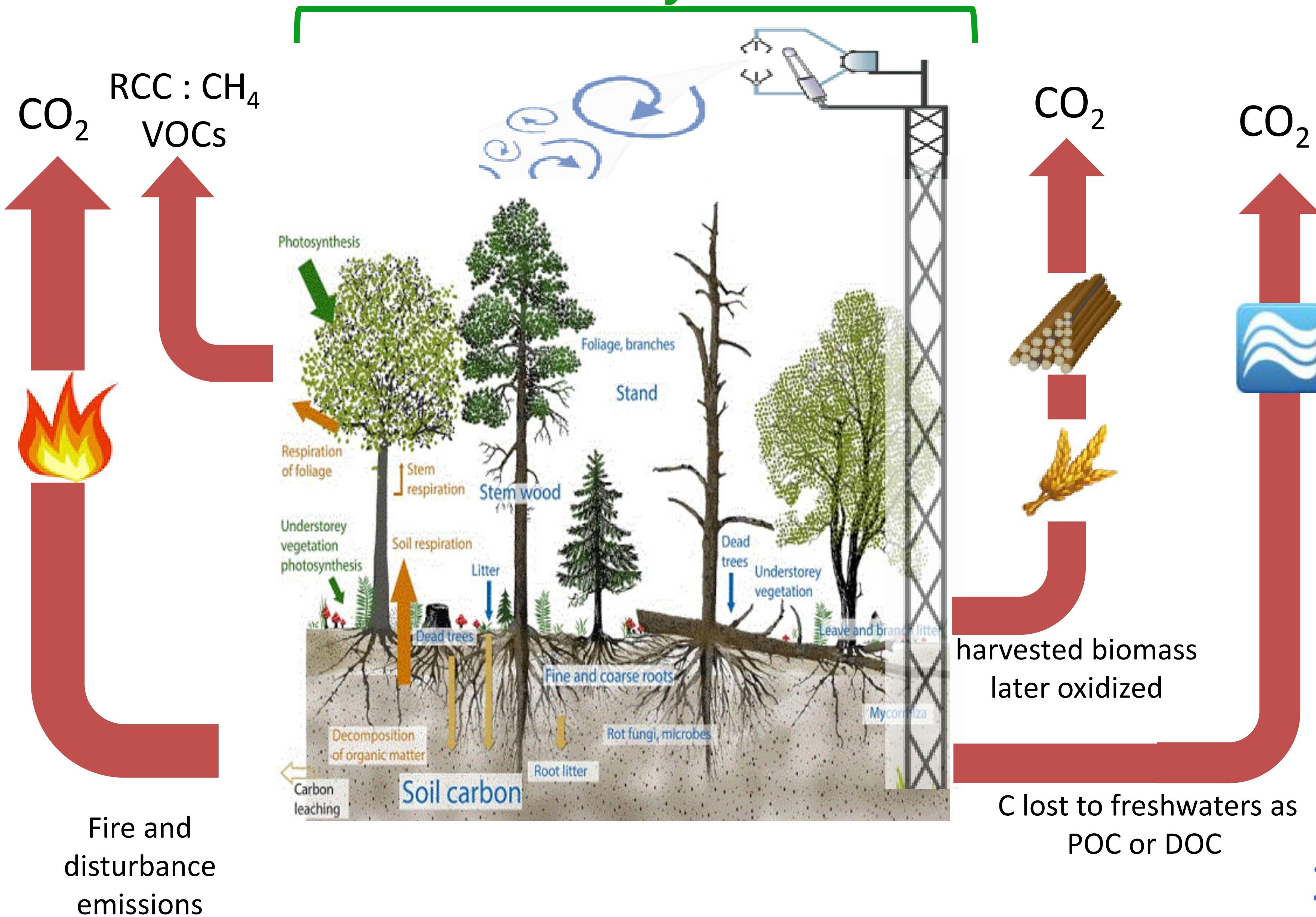


Forest NEP decadal budgets

	Net Ecosystem Productivity NEP	
	AC	**BAC**
Boreal	0.7	0.5
Temperate	2.1	2.1
Tropics	3.1	3.6
Wet tropics	*1.6*	*2.1*
Dry tropics	*1.6*	*1.5*
Globe	**6.6 ± 0.7**	**6.5 ± 0.7**

PgC y^{-1}

NEP measured by flux towers



From NEP to NBP

- NBP = NEP – D
- D = forest fire emissions - C lost to rivers – Wood harvest – reduced C emissions

$$NBP = 6.5 - 0.8 - 0.54 - 0.8 - 0.4 = 4.0 \pm 0.8 \text{ PgC } y^{-1}$$

- Fire emissions from GFED4.1 (forest only)
- C lost to rivers extrapolated from Regnier et al. 2014
- RCC from MEGAN model
- Global wood harvest (FaoStat)

FLUXNET NBP vs. inventories

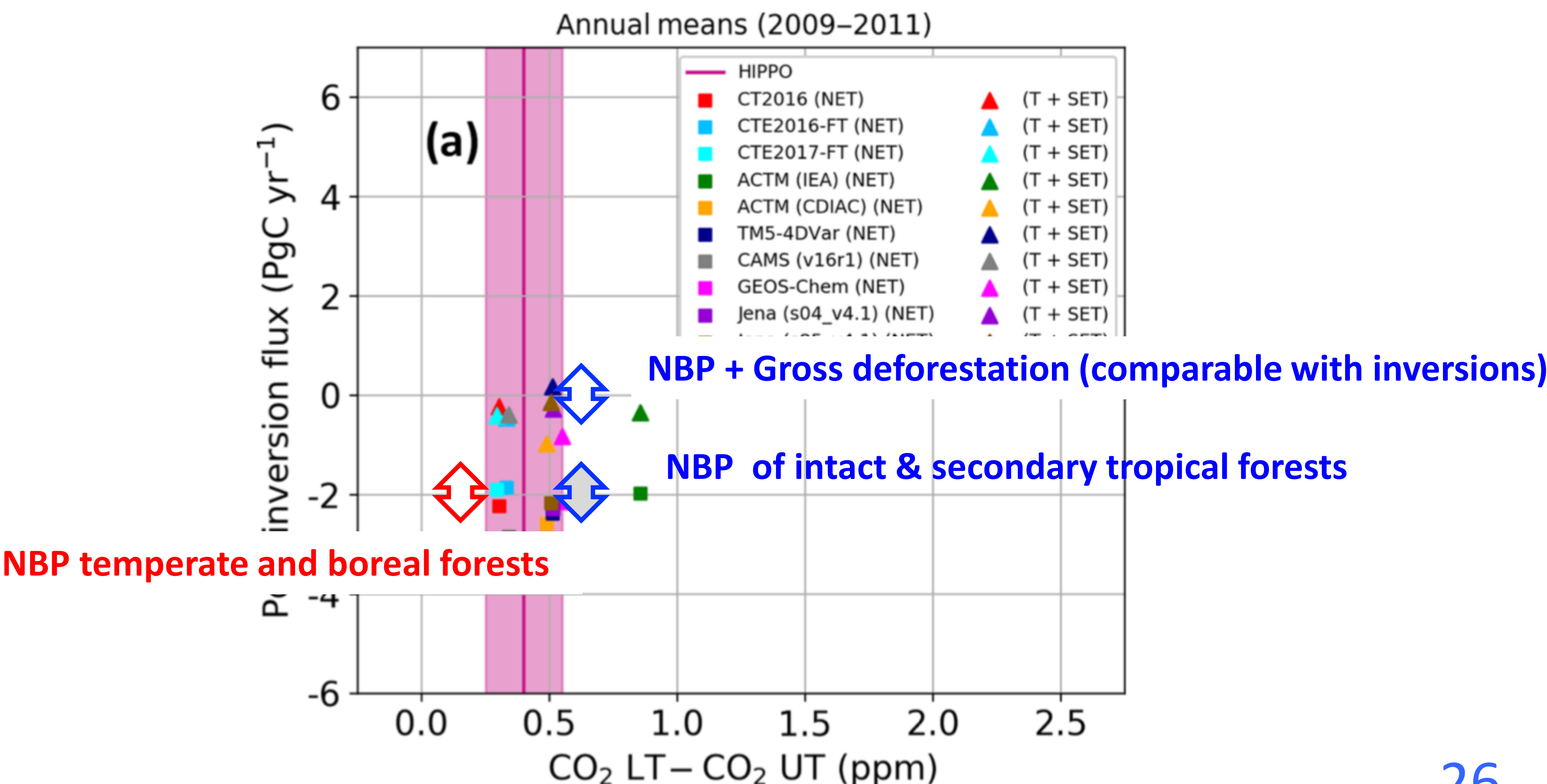
	Net Ecosystem Productivity NEP		Net Carbon Balance NBP		NBP from biomass inventories
	AC	**BAC**	**AC**	**BAC**	**Pan *et al.***
Boreal	0.7	0.5	0.3 ± 0.2	0.1 ± 0.2	0.5 ± 0.1
Temperate	2.1	2.1	1.7 ± 0.2	1.7 ± 0.2	0.8 ± 0.1
Tropics	3.1	3.6	1.8 ± 0.5	1.8 ± 0.5	2.8 ± 0.7
Wet tropics	*1.6*	*2.1*	*0.8 ± 0.3*	*1.0 ± 0.3*	*N/A*
Dry tropics	*1.6*	*1.5*	*1.0 ± 0.2*	*0.9 ± 0.2*	*N/A*
Globe	**6.6 ± 0.7**	**6.5 ± 0.7**	**4.0 ± 0.9**	**3.9 ± 0.8**	**4.1 ± 0.7**

larger sink than Pan

smaller sink than Pan

FLUXNET NBP vs. Atmospheric inversions

Stephens *et al.* Science 2007
Gaubert *et al.* Biogeosciences 2019



Better age maps
or
forest structure maps

Tropical dry forest chronosequences

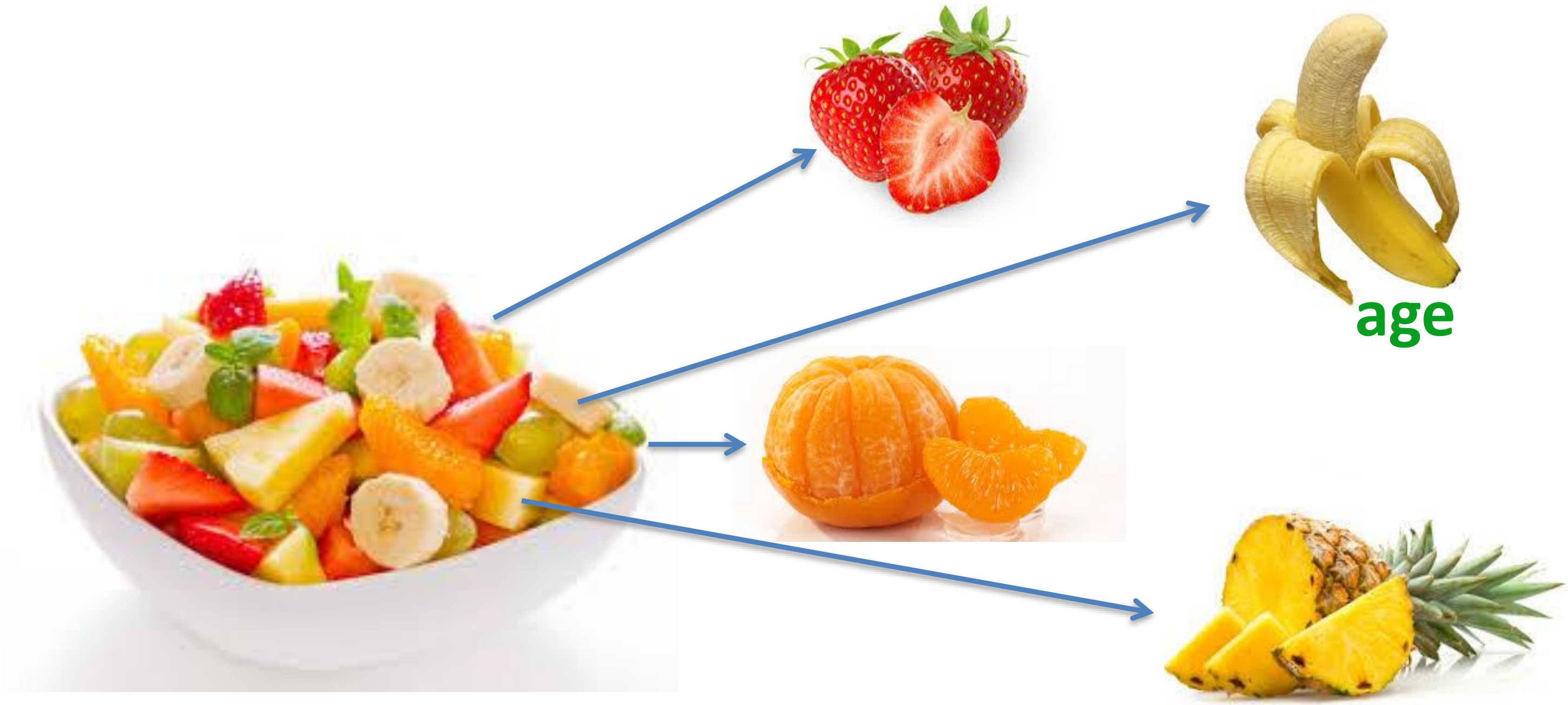
Flux towers in disturbed forests

Take home

Rather than a FLUXNET fruit salad

Use NEP chronosequences
(we need more of them)

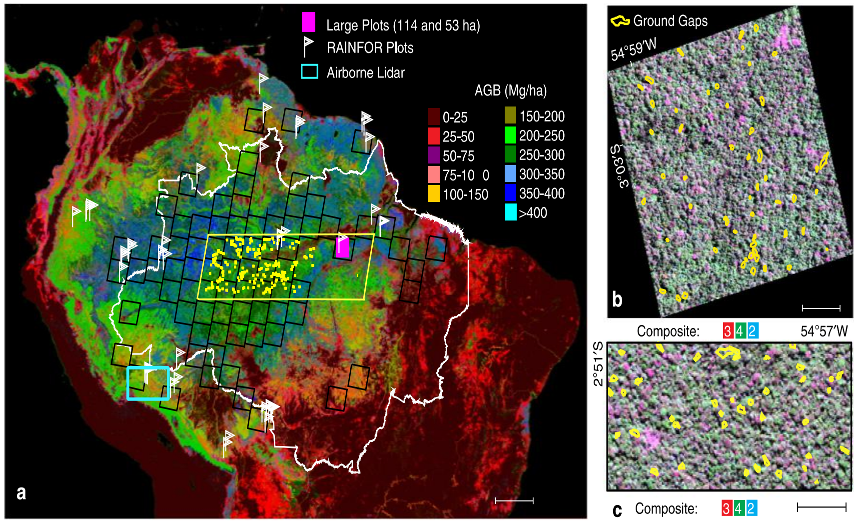
Take home (alternative)



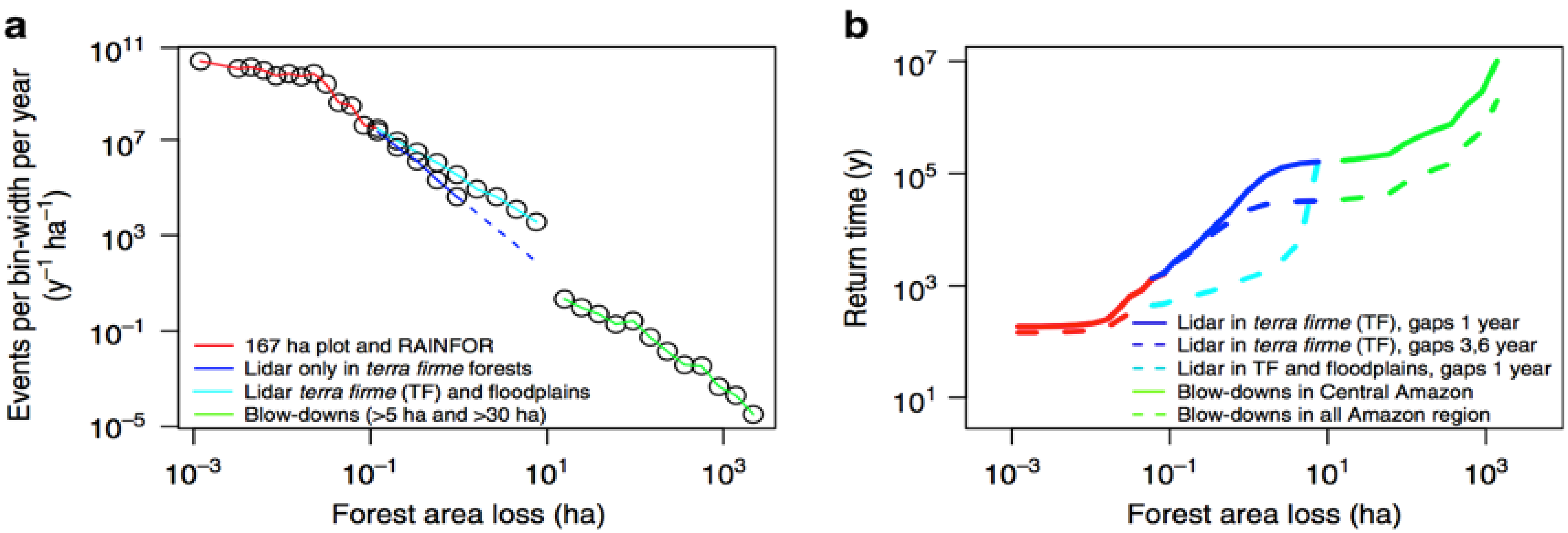
Rather than a FLUXNET fruit salad

Use geostatistics to separate age from other (covariate) variables

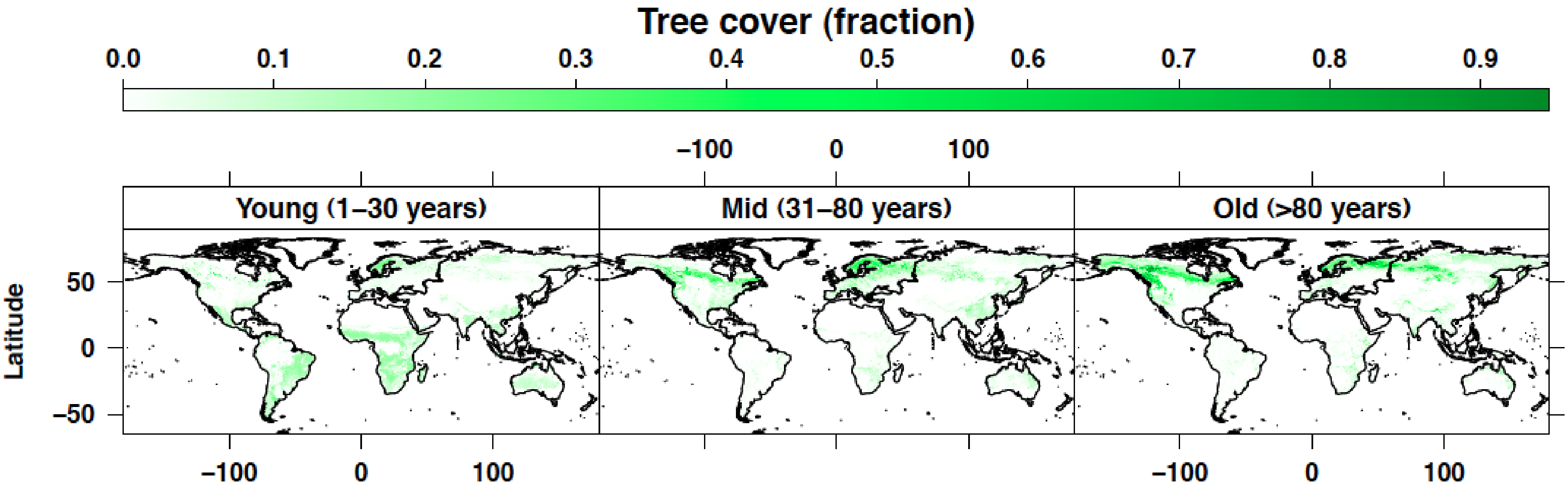
Role of small size disturbances



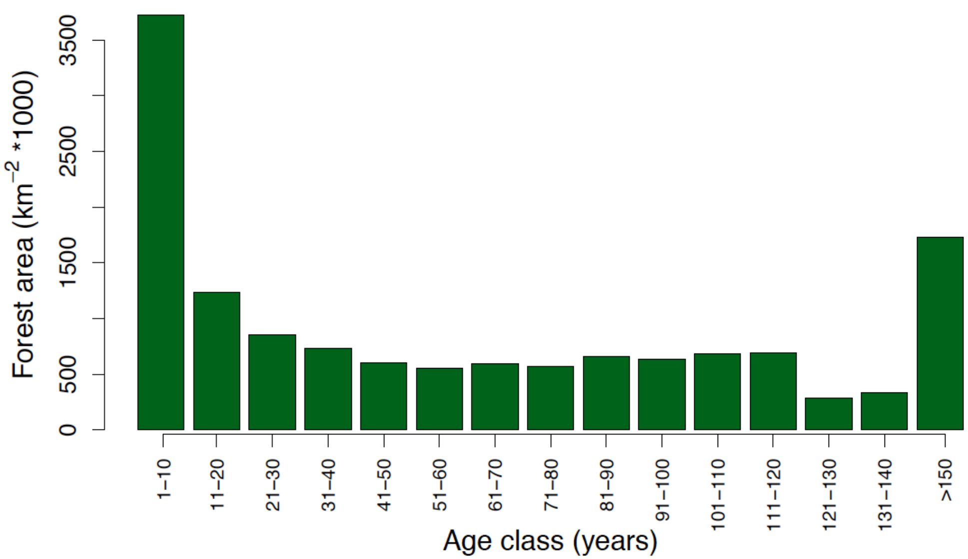
Espirito Santo et al. Nature Comm.



Forest Age Structure and the Carbon Cycle



Needleleaf Evergreen



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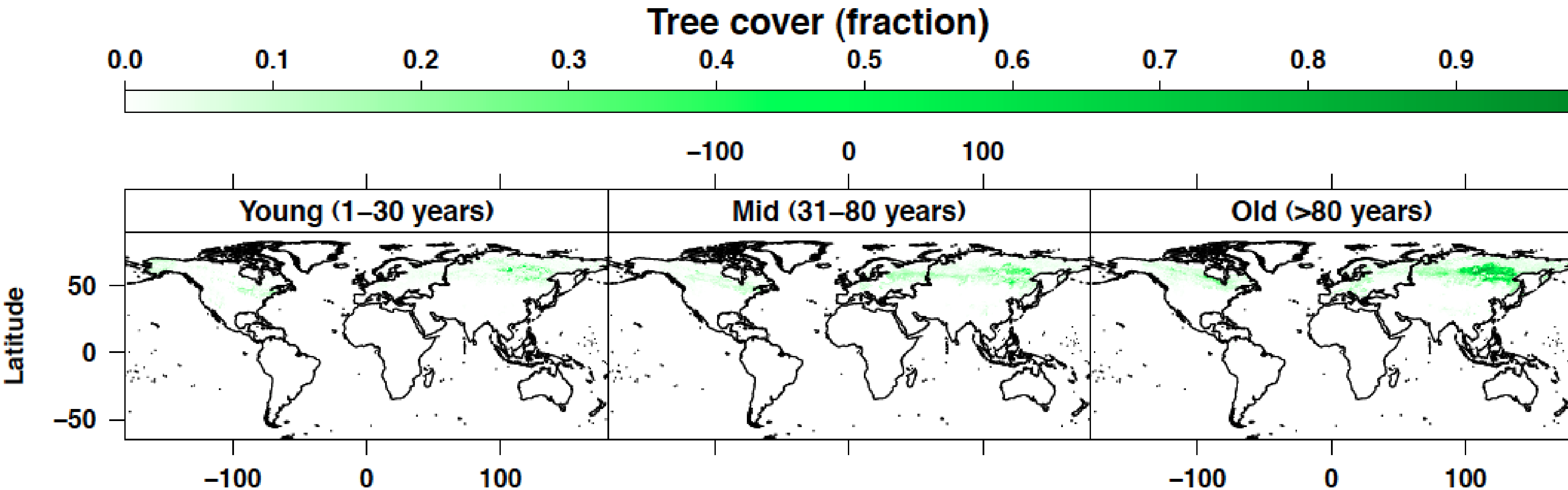
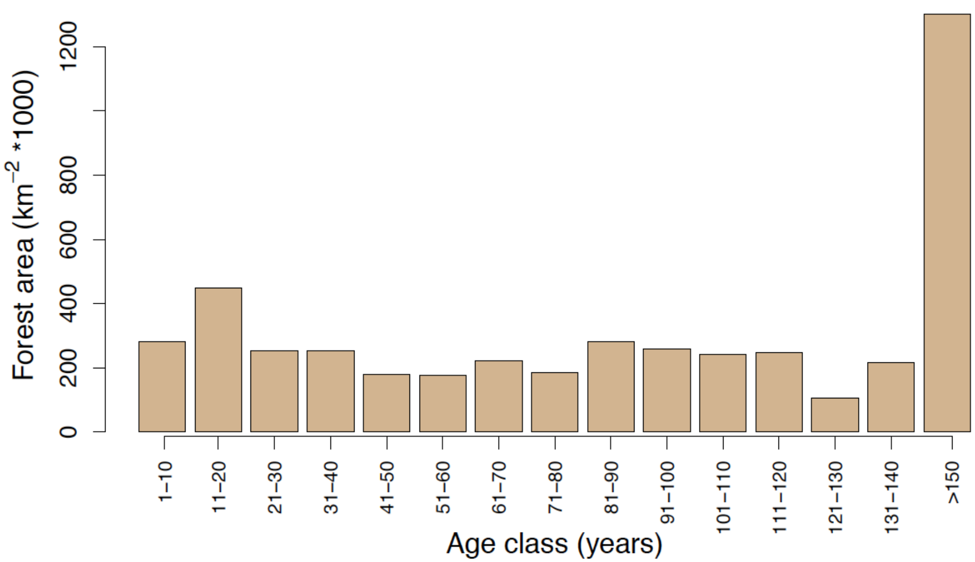
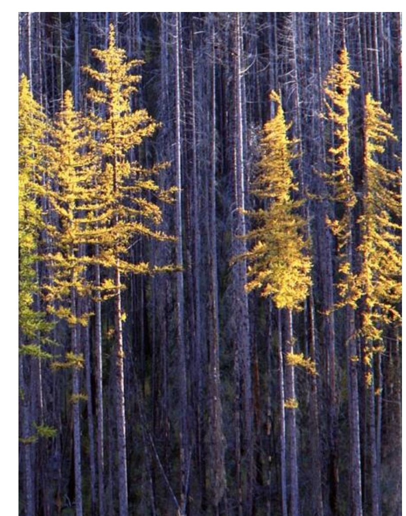
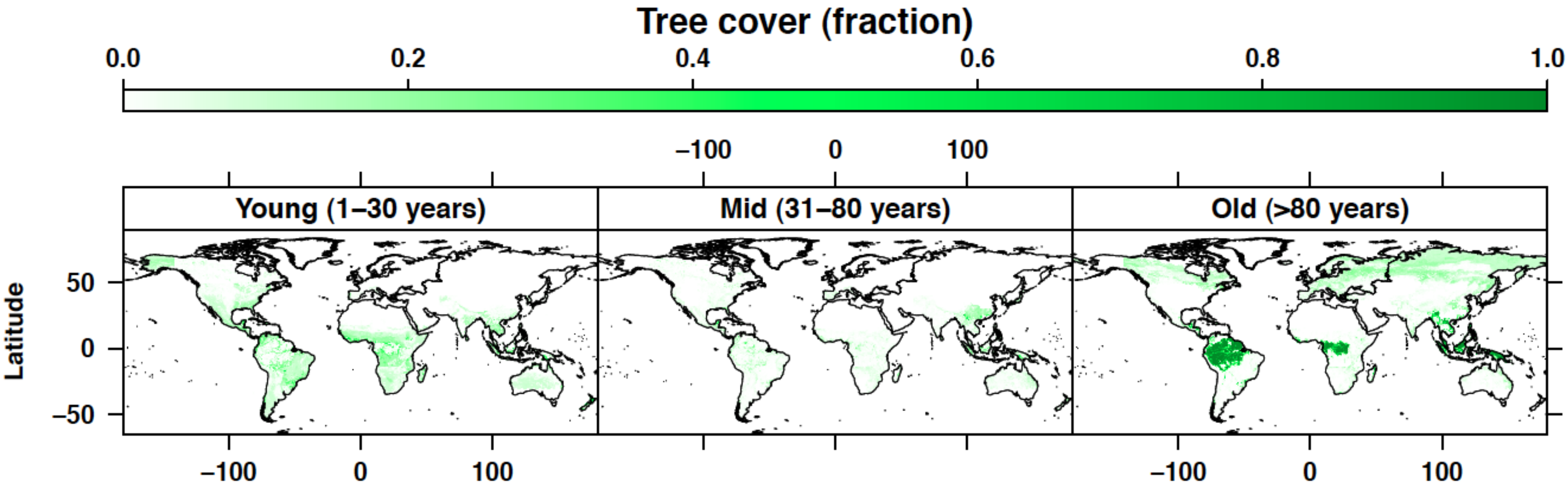


Needleleaf Deciduous

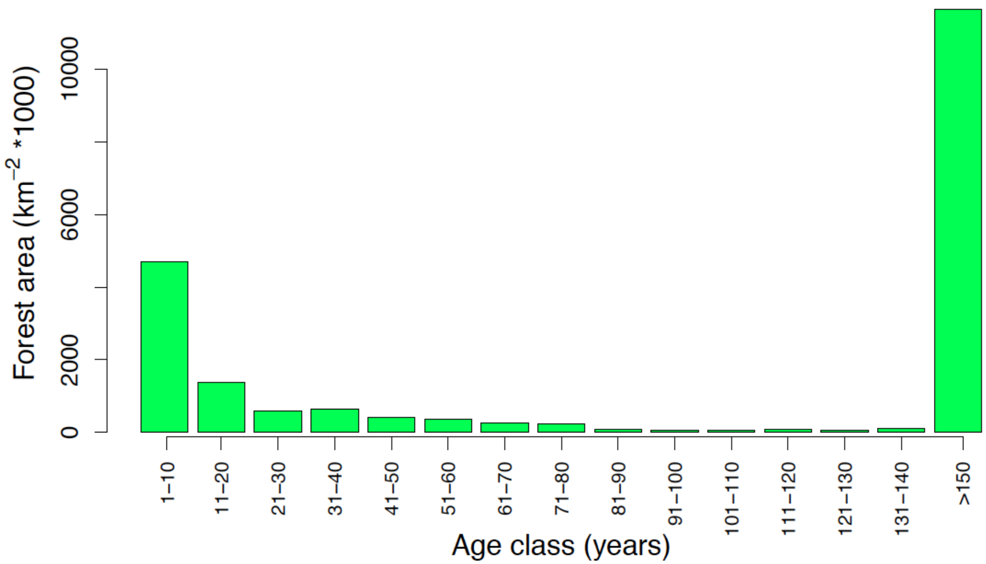




Forest Age Structure and the Carbon Cycle



Broadleaf Evergreen



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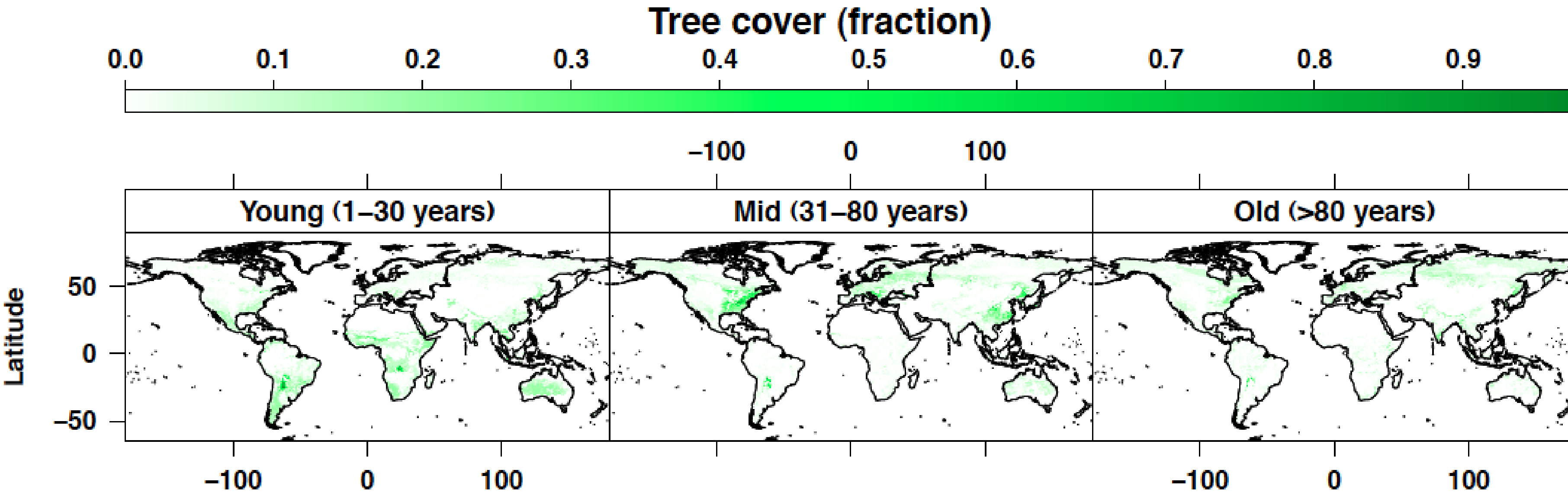
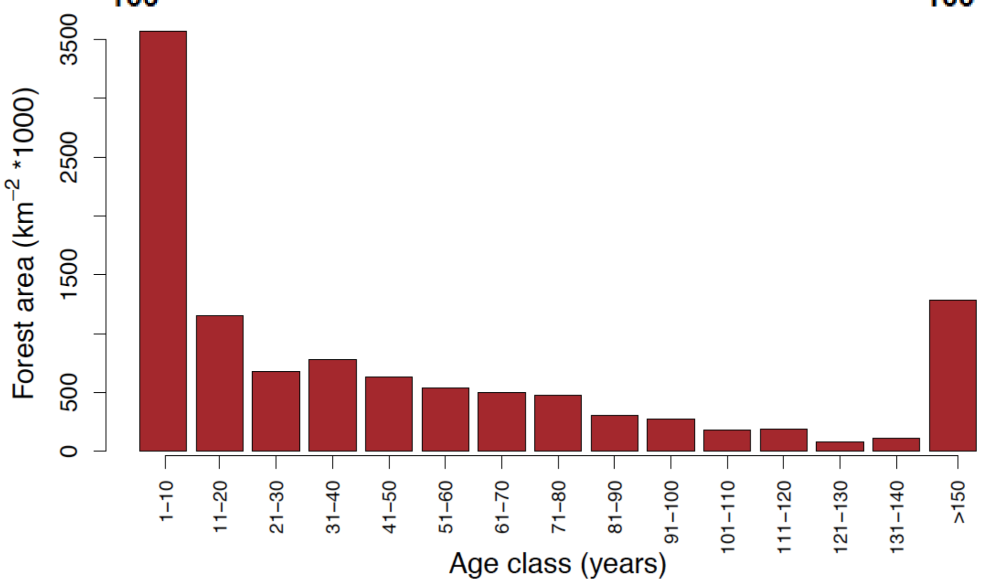
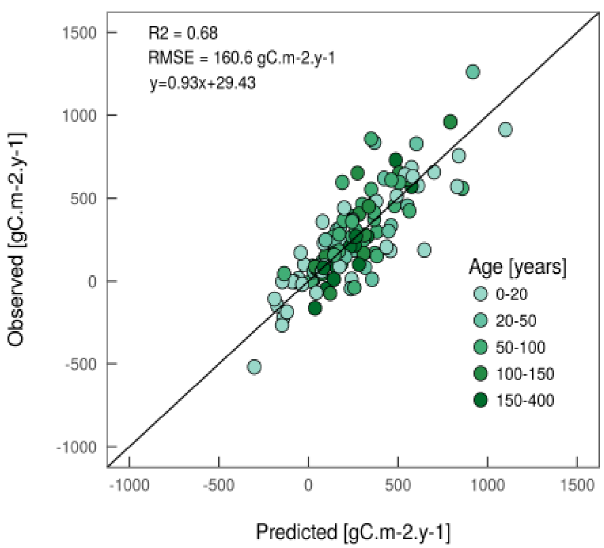


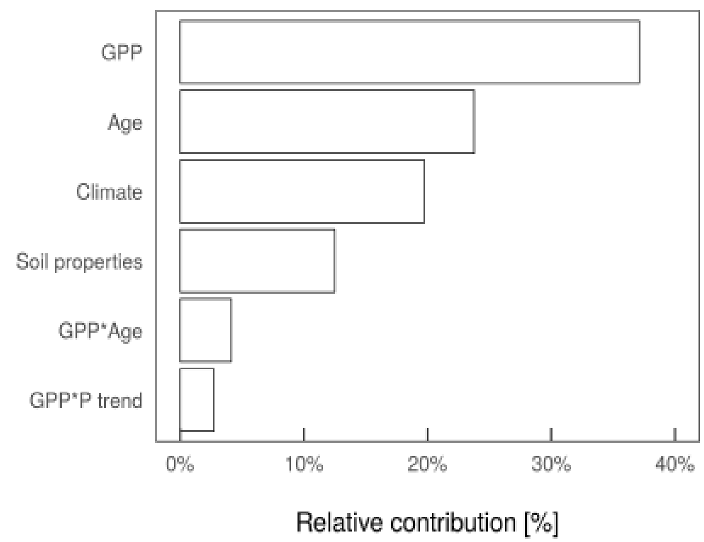
Broadleaf Deciduous



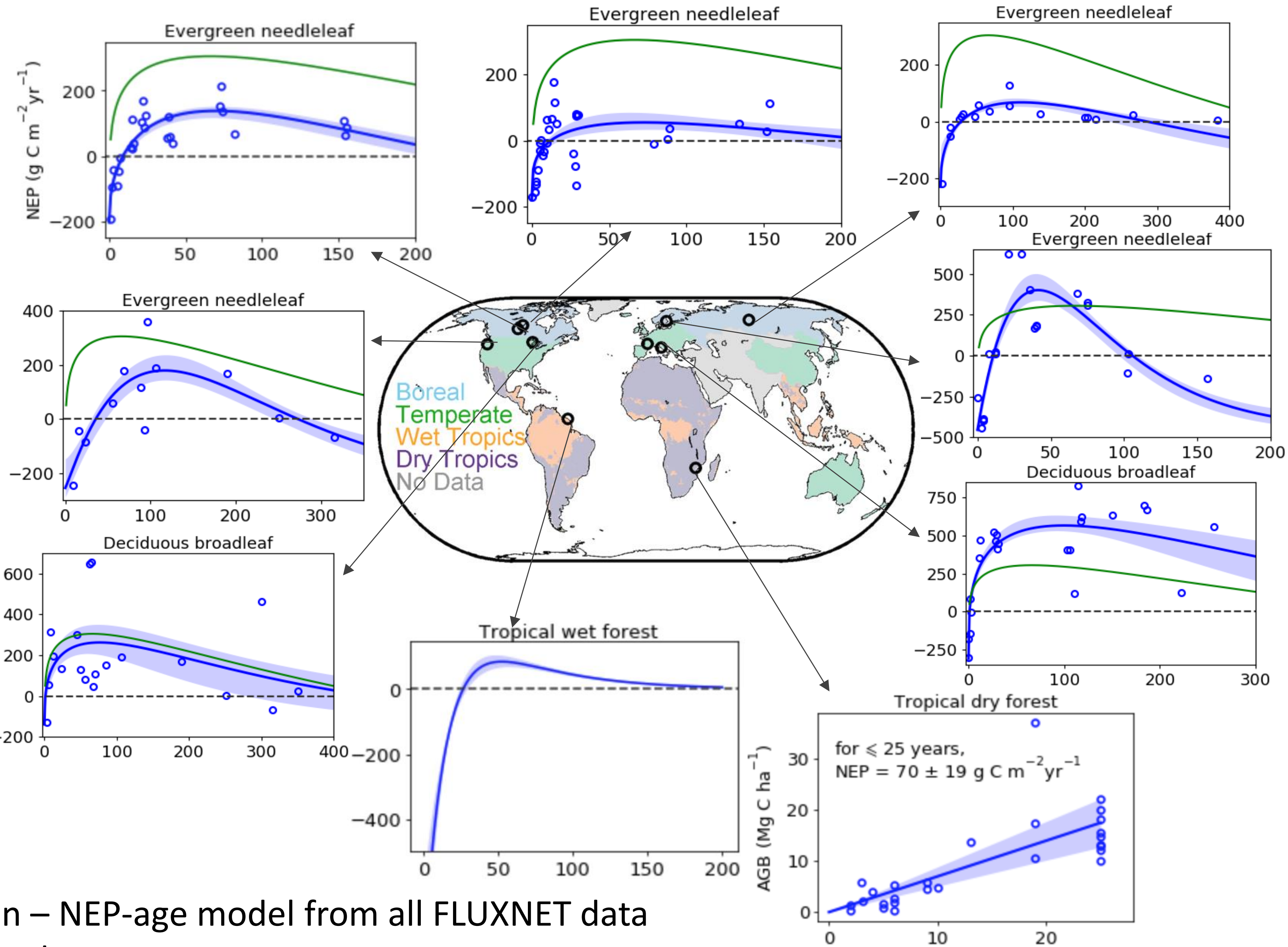
NEP empirical modelling

- Multivariate analysis
- NEP $\sim$ Age$_{nonlinear}$ + GPP + Climate + soil properties
- LOO site cross-validation
- LMG method for variable importance.





Besnard et al.

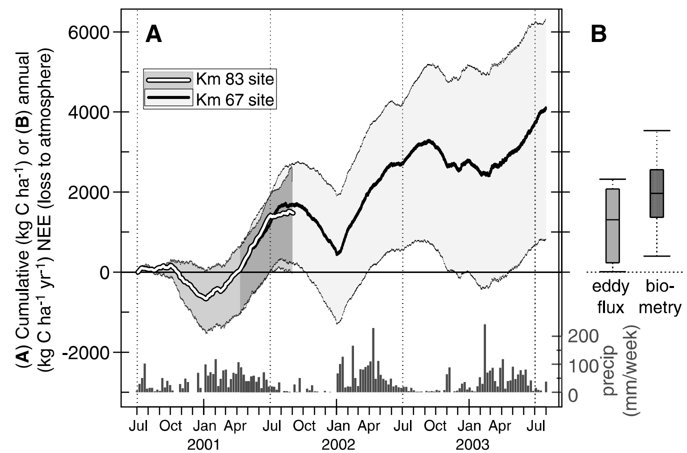


Green – NEP-age model from all FLUXNET data
Blue - chronosequences

Local-scale NEP from flux towers contains (hard to find) age information

Carbon in Amazon Forests: Unexpected Seasonal Fluxes and Disturbance-Induced Losses

Scott R. Saleska,[1*] Scott D. Miller,[2] Daniel M. Matross,[1] Michael L. Goulden,[2] Steven C. Wofsy,[1] Humberto R. da Rocha,[3] Plinio B. de Camargo,[4] Patrick Crill,[5†] Bruce C. Daube,[1] Helber C. de Freitas,[3] Lucy Hutyra,[1] Michael Keller,[5,6] Volker Kirchhoff,[7] Mary Menton,[2] J. William Munger,[1] Elizabeth Hammond Pyle,[1] Amy H. Rice,[1] Hudson Silva[5]

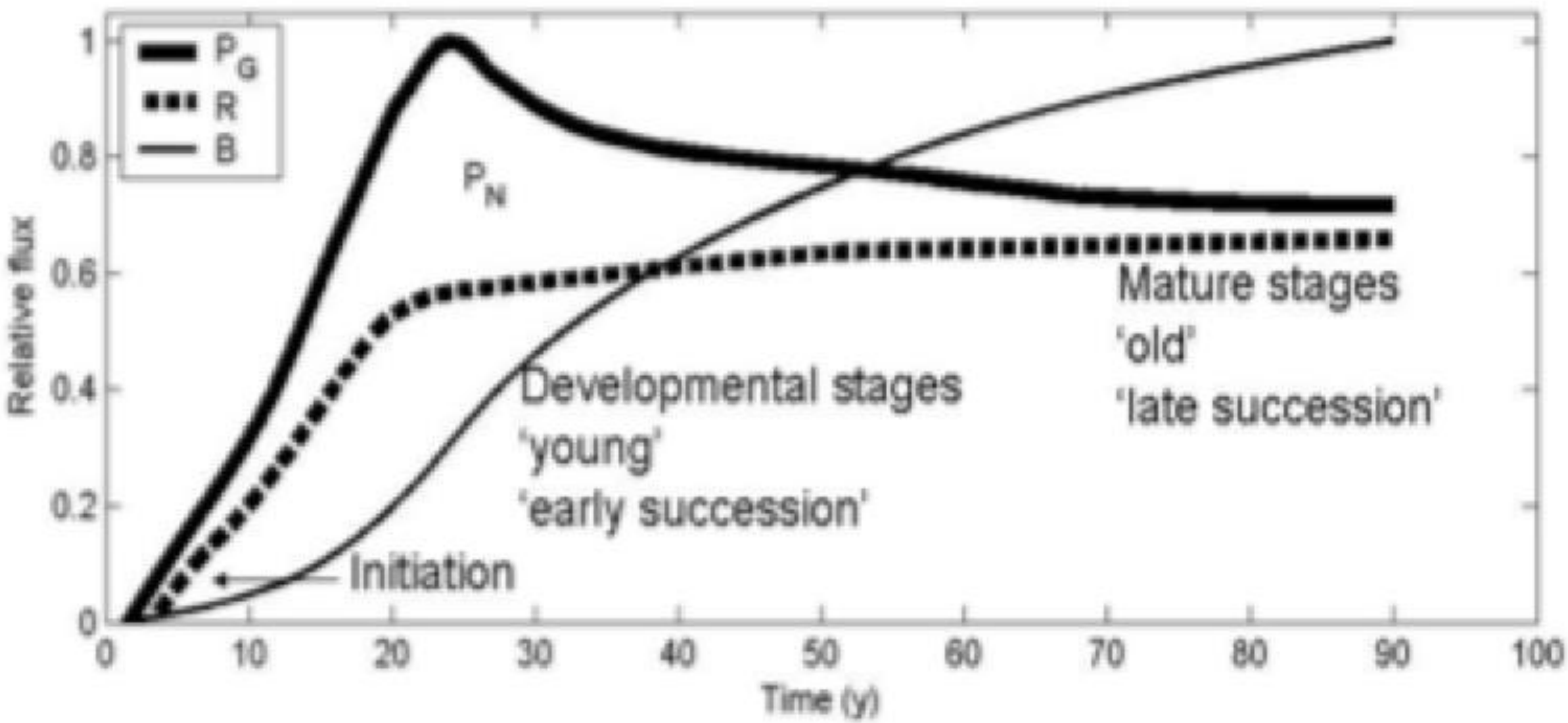


The respiration losses from the large stock of dead wood at km 67 exceeded the uptake of C by live biomass, despite high growth rates (*54*), reflecting disequilibrium of the vegetation assemblage (table S1A). Notably, the C was taken up mostly by small trees

Local-scale NEP is measured by flux towers

- We focus on forest, for which age since disturbance can be more clearly defined
- NEP = f(age) shows usually a transition from source to sink then to small sink
- Few towers sample the full post-disturbance recovery
- Most towers are in middle-aged and old growth forests
- And flux towers do not sample :
  - C losses when disturbance happens
  - C lost by harvested products, leached to rivers, emitted as reduced C-molecules

Age drives biomass increase



Odum et al. 1969
(revised Stoy et al.)

NEP up scaling residuals in age and GPP space