# Carbon Exchange in Ecosystems

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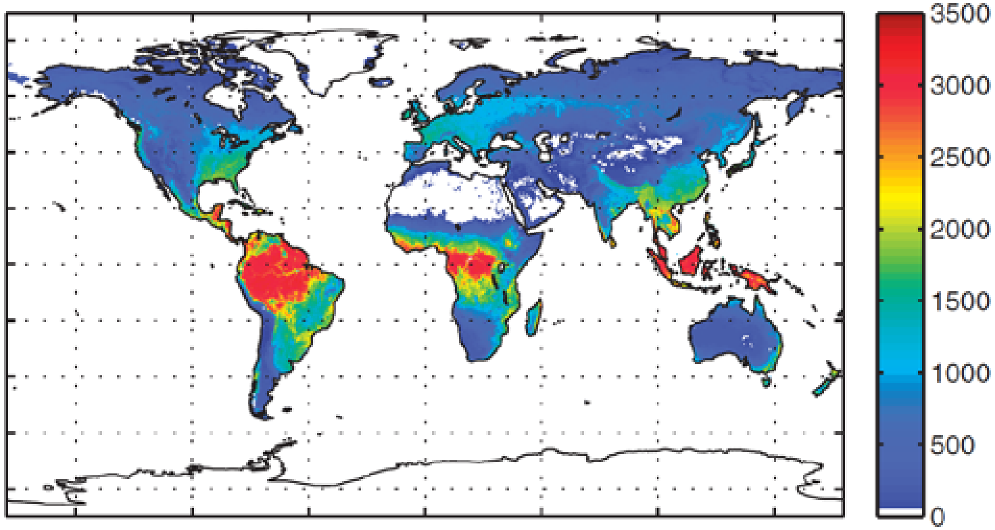
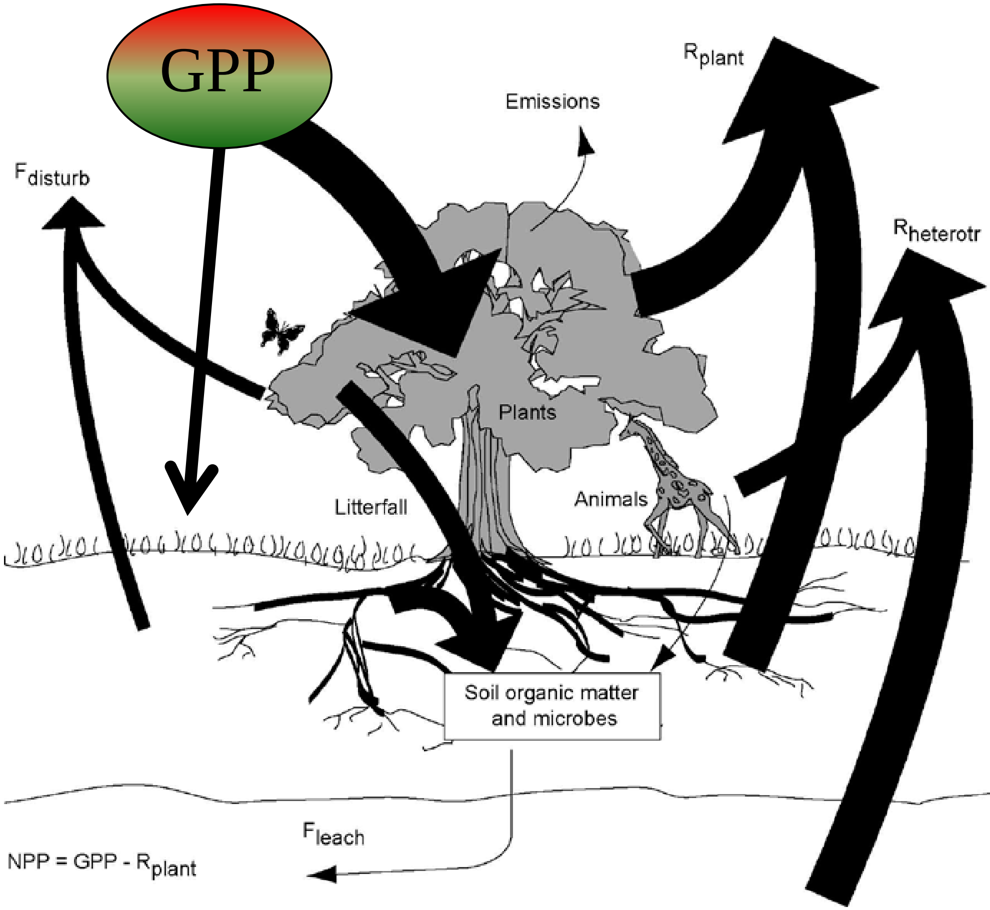
1. Introduction
    - Carbon Terminology
    - Separation of NEE into GPP and TER
    - Land cover change and the carbon cycle
2. Method
    - Eddy Covariance
3. Paper – Wolf et al., 2011
    - Carbon sequestration potential of pasture vs afforestation

# Carbon Input to Ecosystems – Terminology
**Chapin et al., 2006**

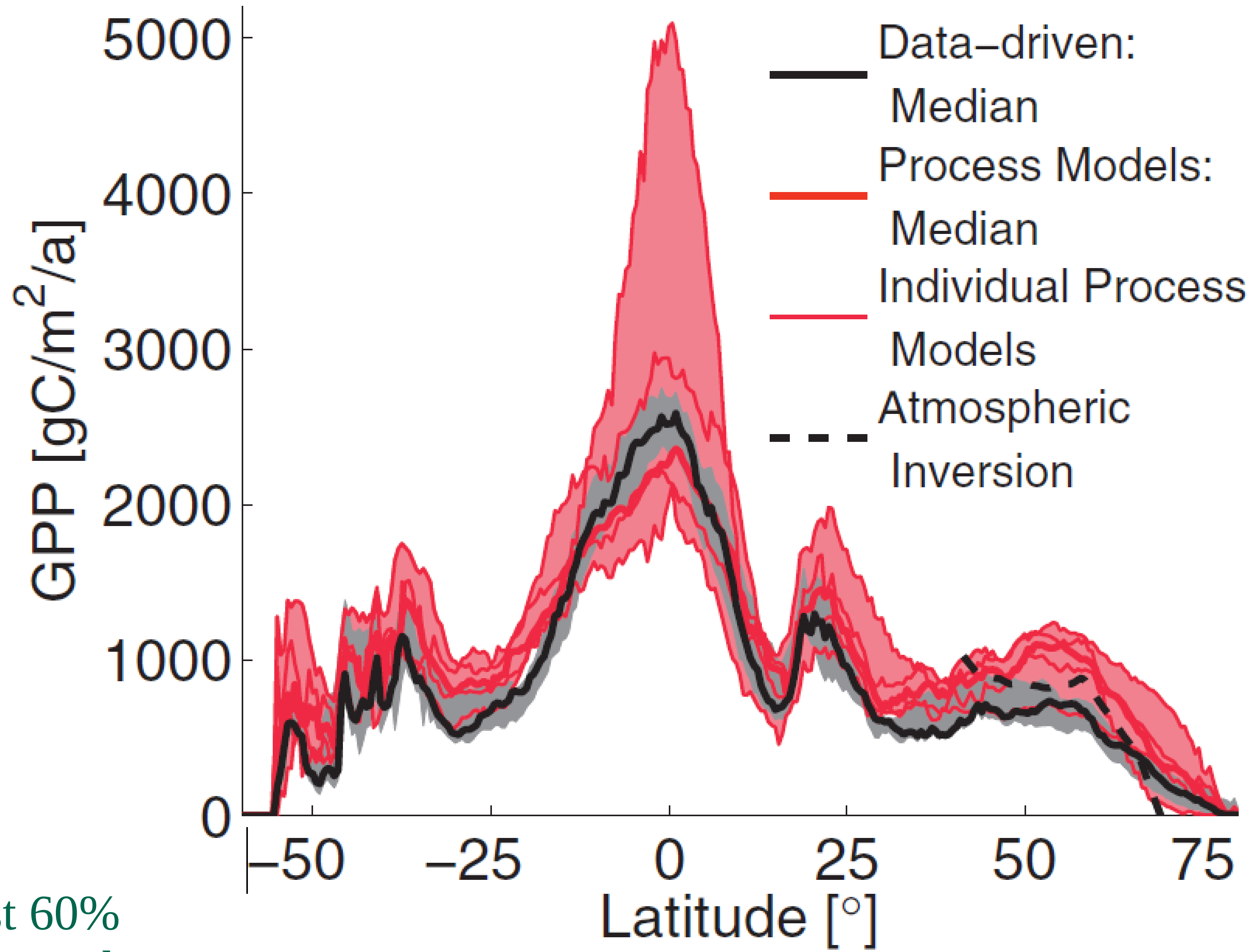
- GPP: Gross Primary Production = Net photosynthesis
  - Measured directly at individual leaf scale 
  - Usually determined indirectly at the ecosystem to global scale




MODIS derived GPP (Zhao et al., 2005)



Beer et al., 2010



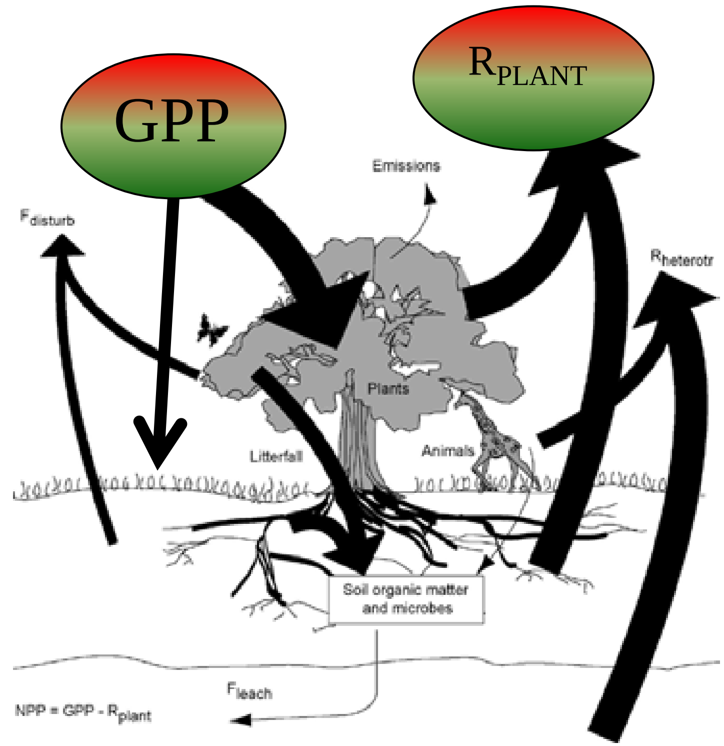

Almost 60%
Of GPP in the tropics

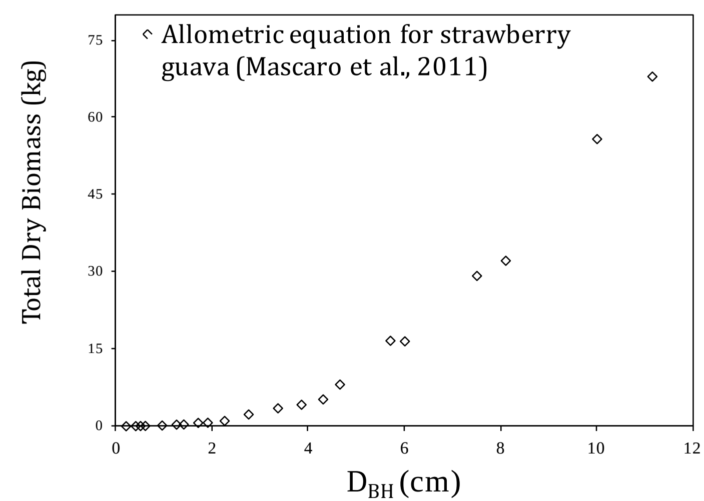
# Carbon Input to Ecosystems – Terminology

- NPP: Net Primary Production

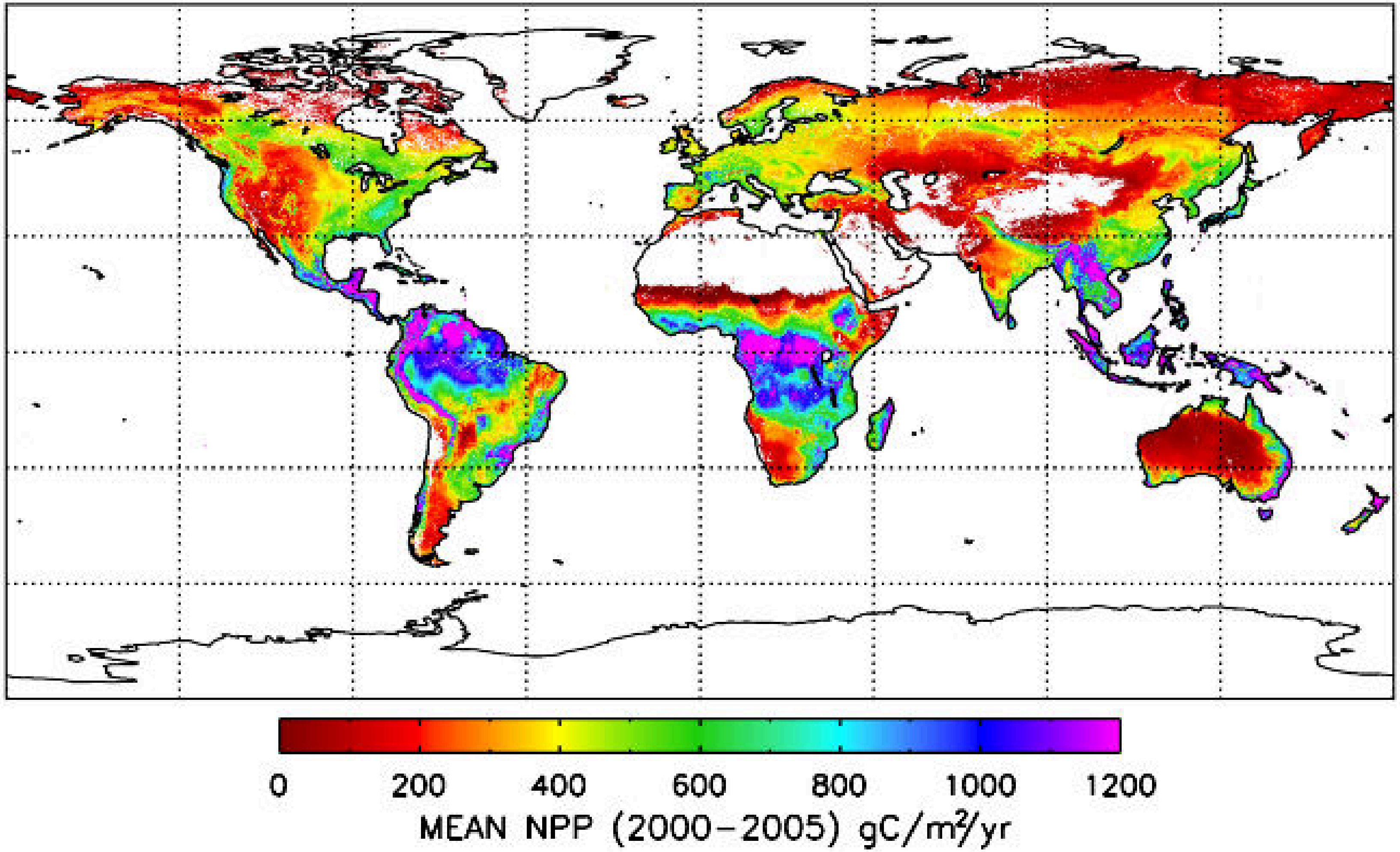
  **NPP = GPP – Respiration from primary producers.**

  - Vegetation  Survey plots – Tree allometry to scale from diameter to biomass.
  - Carbon is ~ 50% of biomass.
  - Growth estimated from difference between sequential measurements



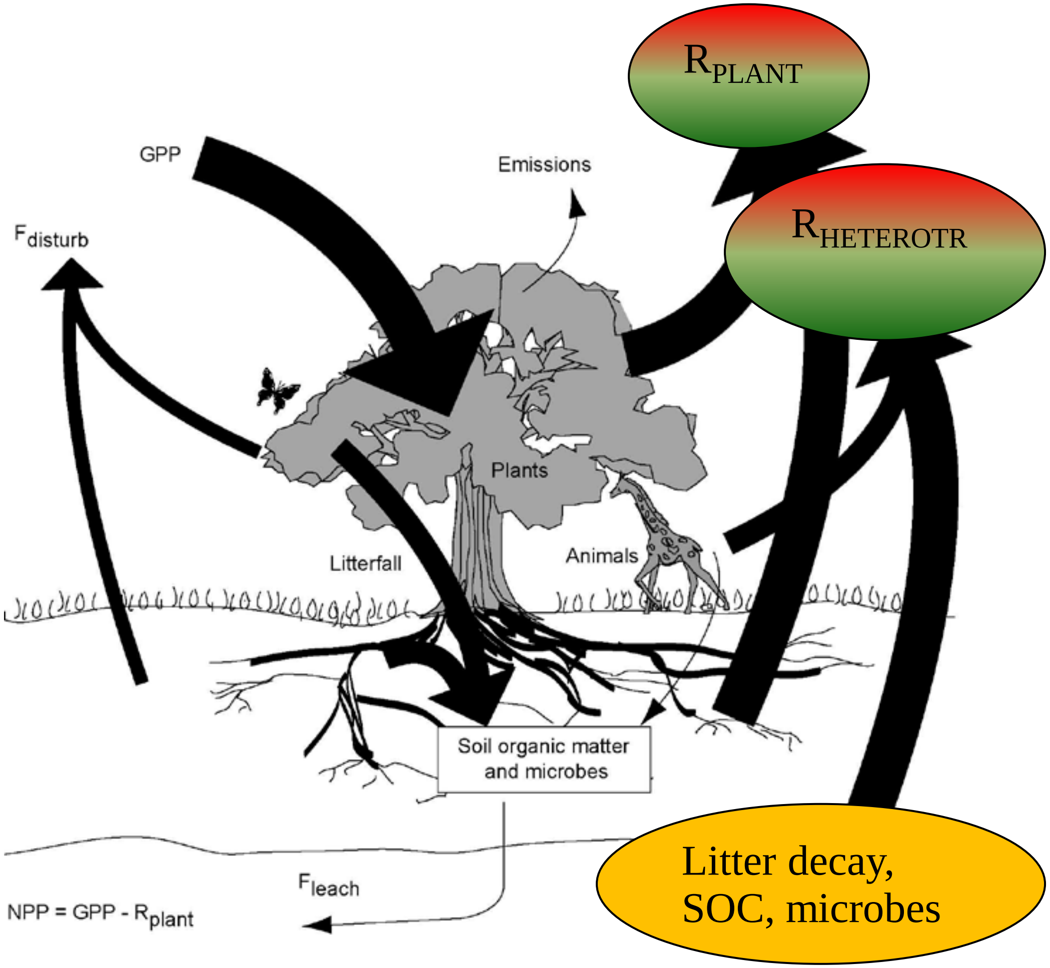
# Carbon Input to Ecosystems
# NPP




MODIS derived NPP (Zhao et al., 2005)

# Carbon Release from Ecosystems – Terminology

- **TER**: Total Ecosystem Respiration
  - **Autotrophic Respiration**
    - Leaves, stems, and roots of primary producers
  - **Heterotrophic Respiration**
    - Litter and CWD decomposition
    - Soil organic matter
    - Microbial and animal respiration.



# Carbon Exchange in Ecosystems – Terminology

- **NEP**: Net Ecosystem Production

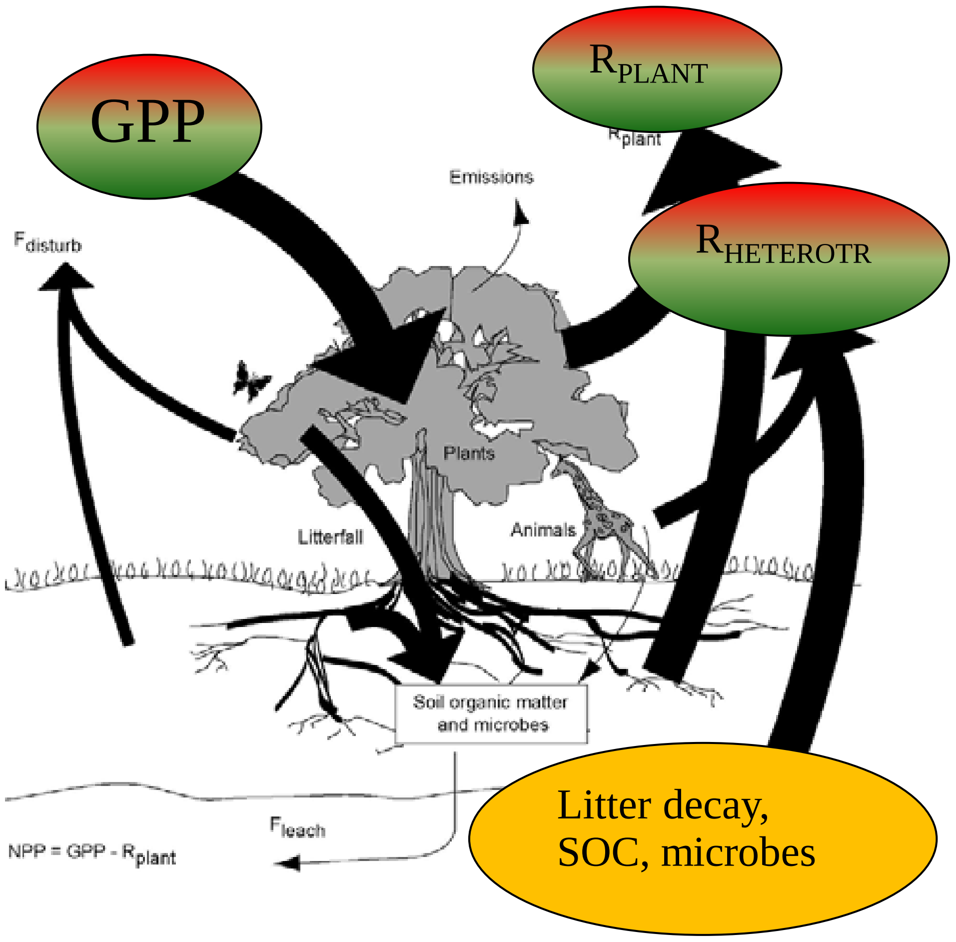
  NEP = NPP – Heterotrophic Respiration

  - Carbon budgets, carbon balance (indirect method)

  NEP = ΔBio + Litter - $R_{HETEROTR}$

  - Heterotrophic respiration difficult to measure.

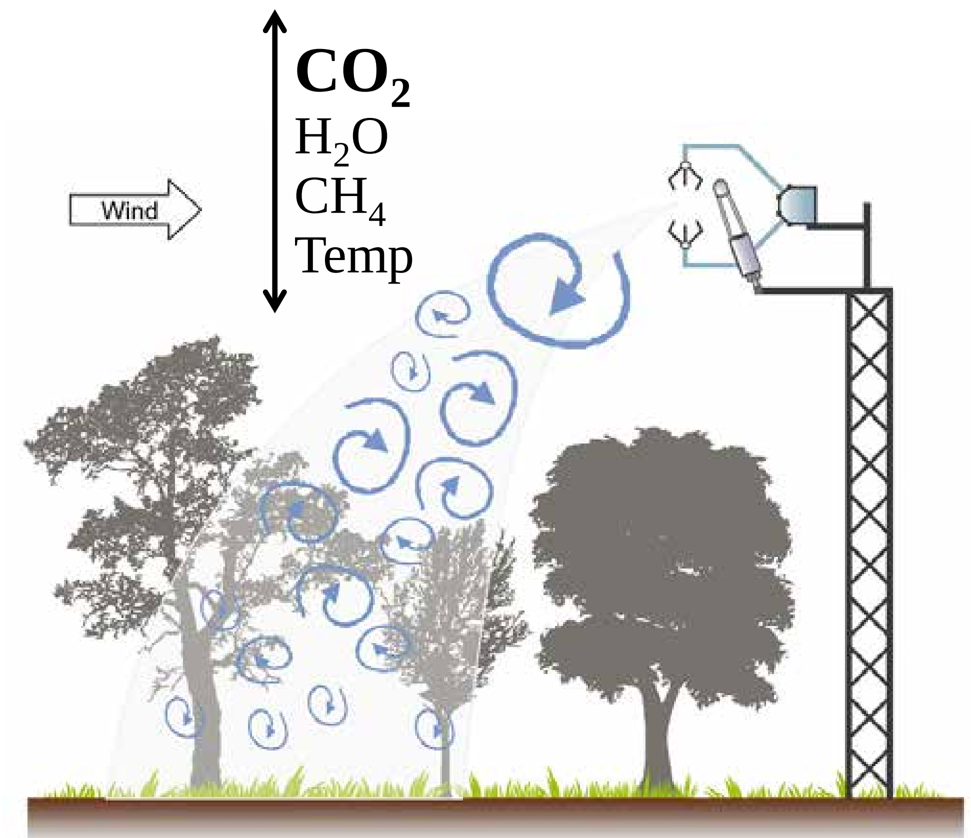
- Soil Respiration = root + microbial



# Carbon Exchange in Ecosystems – Terminology

- **NEE**: Net Ecosystem Exchange of $CO_2$
  - Eddy covariance (direct method)

    Above canopy flux measurement




http://www.ethlife.ethz.ch/

# Carbon Exchange in Ecosystems – Terminology

- **NEE** and **NEP** can be compared to validate fluxes.

**NEE = NEP ?**

- Two approaches have not always agreed in the past (Curtis et al., 2002), however, results seem to be converging (Gough et al, 2008)
- Important because valuation of carbon stock in vegetation and soil (REDD+, CDM's)
- Tropical forests play critical role in the global carbon cycle

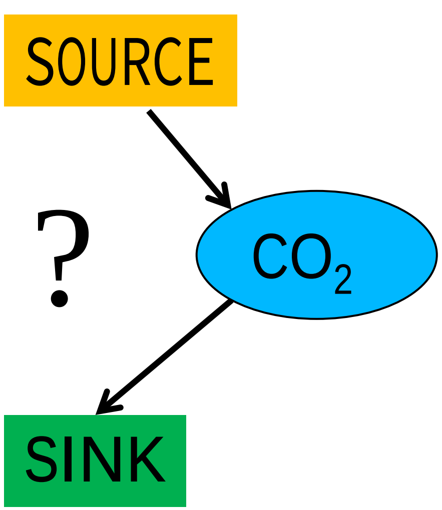



**Table 1 – Annual amount of net ecosystem exchange (NEE), total ecosystem respiration (RE), soil respiration (REsoil) and gross ecosystem production (GPP) for 2003, 2004 and 2005, estimated with the assumption that nighttime soil respiration was 50% of total ecosystem respiration [line (5) in Fig. 8]**

| Year | NEE ($gC\ m^{-2}\ yr^{-1}$) | RE (REsoil) ($gC\ m^{-2}\ yr^{-1}$) | GPP ($gC\ m^{-2}\ yr^{-1}$) |
|---|---|---|---|
| 2003 | −79 | 3176 (1588) | 3255 |
| 2004 | −147 | 3130 (1565) | 3277 |
| 2005 | −146 | 3052 (1526) | 3198 |
| 3-year average | −124 | 3119 (1560) | 3243 |

Tropical Rainforest, Pasoh Malaysia
Kosugi et al, 2008

## Carbon Exchange in Ecosystems – Terminology

**Chapin et al., 2006**

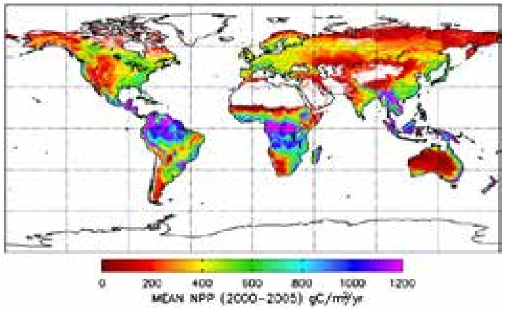
- **NEBP**: Net Exchange Biome Production
    - **Net exchange of all C fluxes at all timescales**
    - Lateral flows and leeching
    - Disturbance
- Other carbon-based GHG's
    - VOC's
    - $CH_4$ fluxes

# Separation of NEE into GPP and TER

- Net Ecosystem $CO_2$ Exchange measured by EC tower

Why do we separate NEE into components GPP and TER?

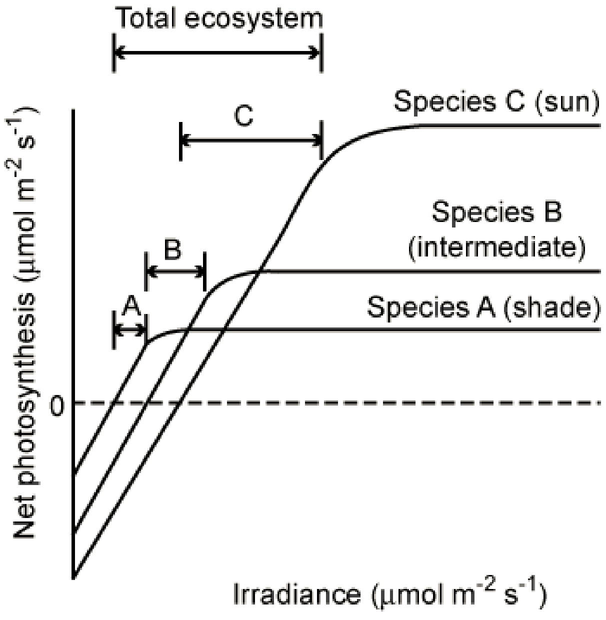
- Ecosystem response to climate variation.
  - What happens to respiration when it is hot?
  - What happens to productivity when it is dry?
- Validation of global and regional models that predict GPP and NPP



# Separation of NEE into GPP and TER

We already learned..

- § GPP related to light availability
- § Ecosystem light response curve



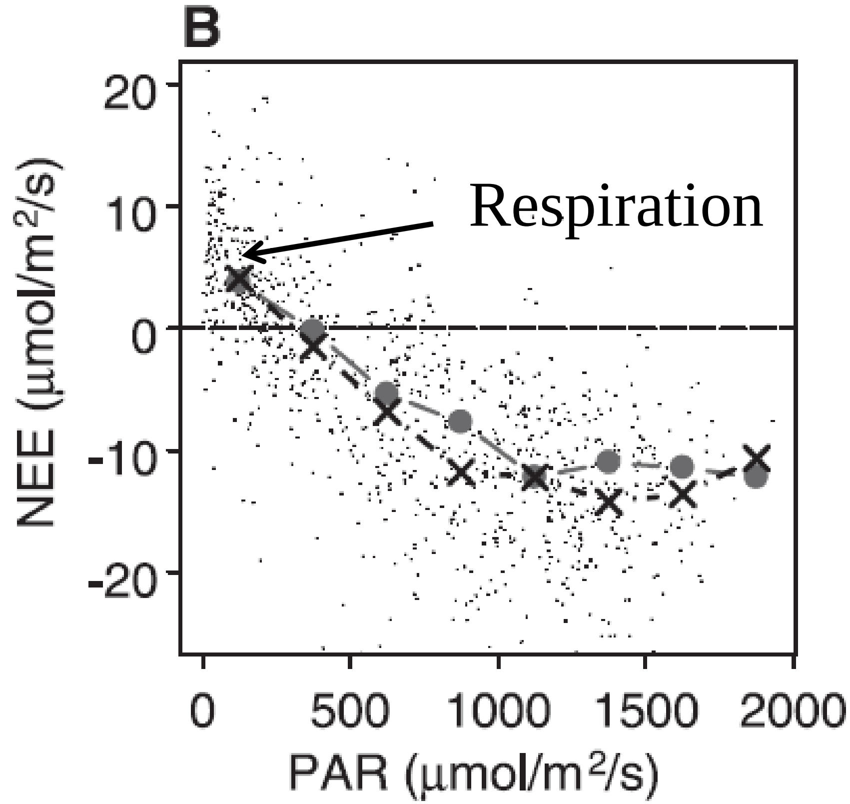
# Separation of NEE into GPP and TER; Approaches

- NEE also related to light

<u>2 approaches (Lasslop et al., 2010):</u>

- (1) Respiration measurements made at night are extrapolated to the daytime.
- (2) light–response curves are fit to daytime NEE measurements and respiration is estimated from the intercept of the ordinate.

Saleska et al., 2003)

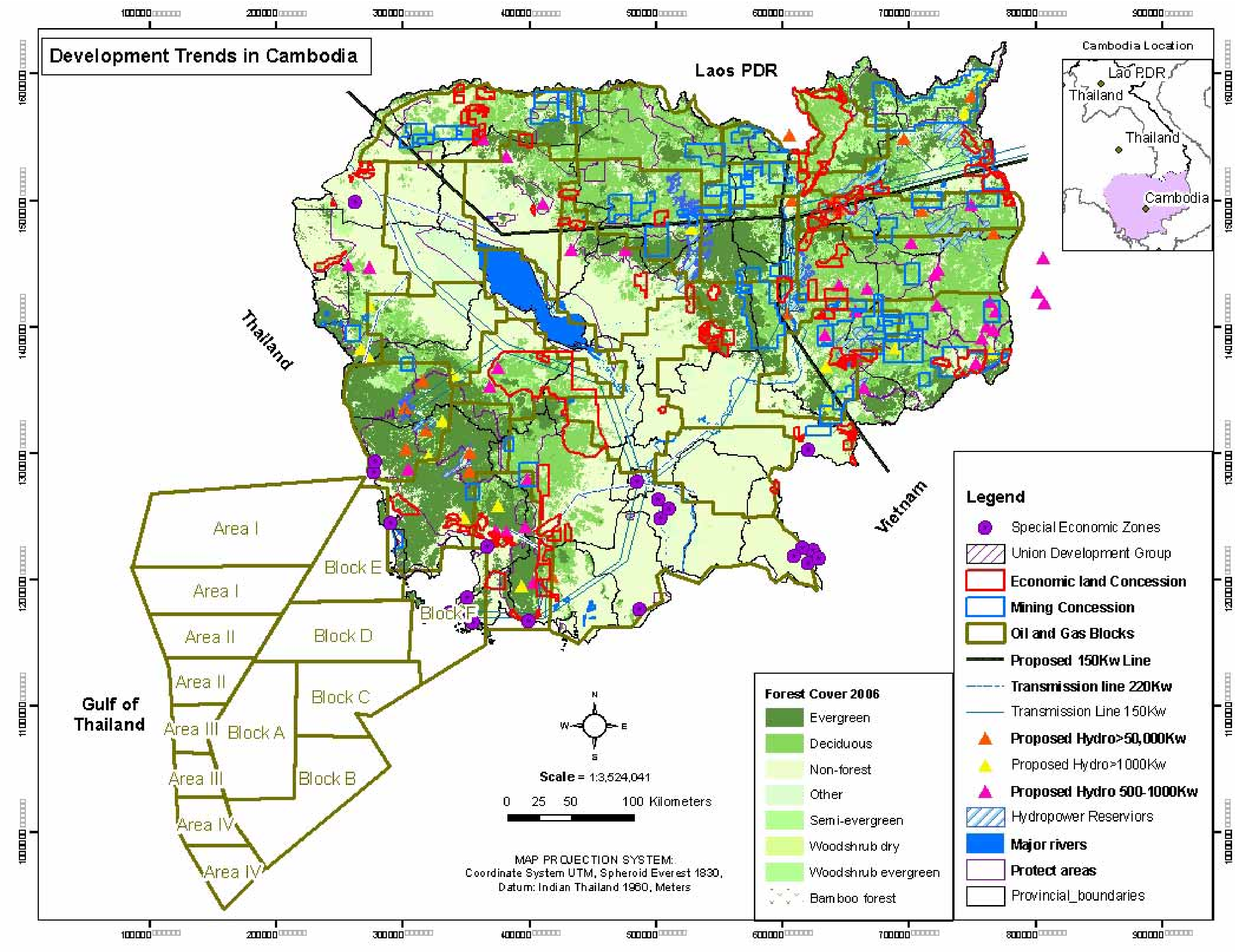


# Another way to look at carbon input - stocks

## IPCC 2013 Carbon Stock Estimates

| | Area | Global Carbon Stocks (Gt C) | | |
|---|---|---|---|---|
| **Biome** | **($10^9$ ha)** | **Vegetation** | **Soil** | **Total** |
| Tropical forests | 1.76 | 212 | 216 | 428 |
| Temperate forests | 1.04 | 59 | 100 | 159 |
| Boreal forests | 1.37 | 88 | 471 | 559 |
| Tropical savannas | 2.25 | 66 | 264 | 330 |
| Temperate grasslands | 1.25 | 9 | 295 | 304 |
| Deserts and semideserts | 4.55 | 8 | 191 | 199 |
| Tundra | 0.95 | 6 | 121 | 127 |
| Wetlands | 0.35 | 15 | 225 | 240 |
| Croplands | 1.6 | 3 | 128 | 131 |
| Total | **15.12** | **466** | **2011** | **2477** |

# Land Cover/Land Use Change and the Carbon Cycle



# Land Cover/Land Use Change and the Carbon Cycle

## Conversion to rubber

2003


2011

Expansion of tree crops

Might store more carbon than an annual cropping system..and less carbon than a forest

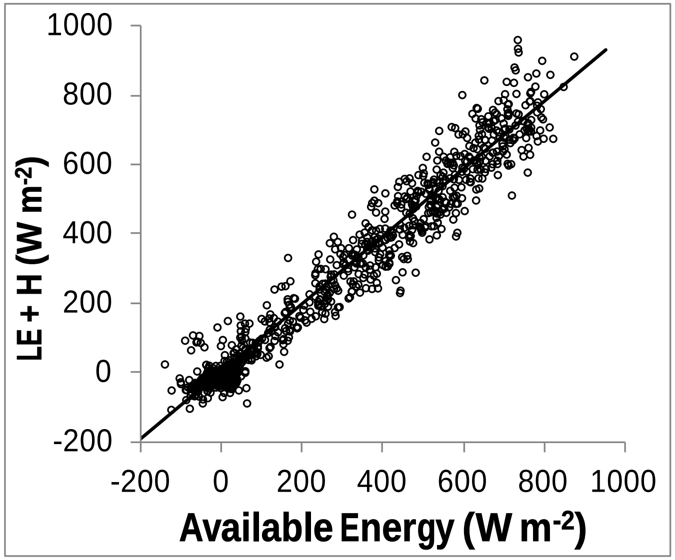
WATER for CARBON
Tradeoffs and Compromises

# METHOD
# Eddy Covariance
# Measuring ecosystem fluxes

- Above-canopy high-frequency 3D wind and scalar measurements (10-20hz).

- Mean vertical transport of sensible heat, water vapor ($H_2O$) , and $CO_2$.

- Capabilities:
  - Landscape-scale observations, ~500 m
  - Direct measurements of ET and NEE
  - Evaluated by assessing energy balance




- Applications:
  - Ecohydrology and carbon cycle science
  - Ecosystem response to climate variability and disturbance
  - Global and regional land surface model verification

# Eddy Covariance

- <u>Disadvantages</u>
  - Complex theory and subject to uncertain results
  - Energy closure error
  - Problematic when atmospheric conditions are stable
  - Flat terrain necessary for ideal site
  - Missing data requires gap-filling to get annual estimates of NEE
    - Wet or dirty sensor
    - Equipment malfunction

# Methods: Net $CO_2$ Uptake of an ecosystem

(1)

1. Eddy Covariance - mean covariance between vertical velocity (w') and scalar (c') fluctuations (e.g., $CO_2$, water vapor, and temperature)

**w' = mean vertical wind speed**

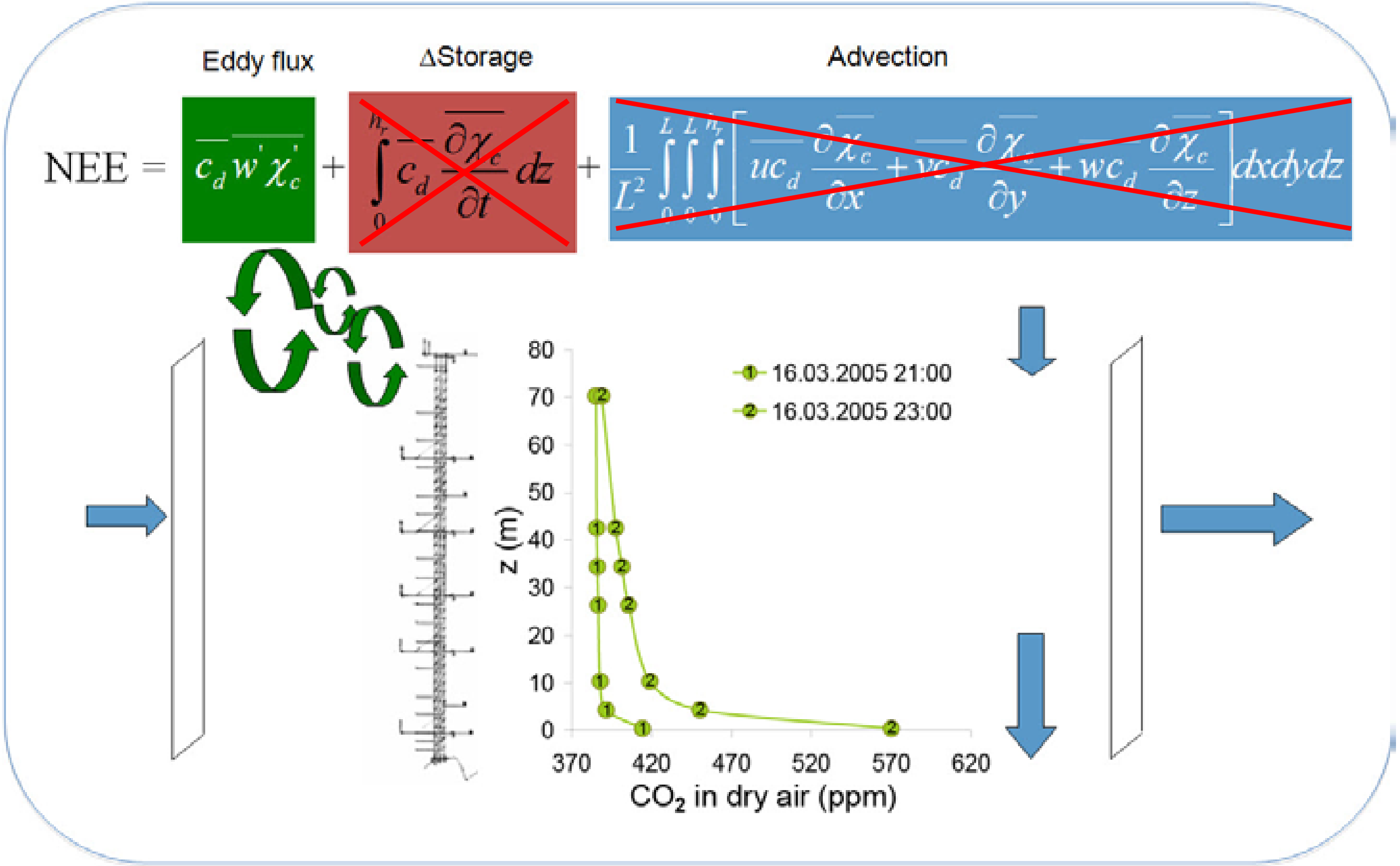
**$X_C$' = concentration of scalar ($CO_2$)**

**$c_d$ = molar density of dry air**

**Site selection critical**

**Low observation height**

## Mass conservation equation




$$NEE = \overline{c_d}\,\overline{w'\chi_c'} + \cancel{\int_0^{h_r} \overline{c_d}\frac{\partial \overline{\chi_c}}{\partial t} dz} + \cancel{\frac{1}{L^2}\int_0^L\int_0^L\int_0^{h_r}\left[\overline{u}\,\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial x} + \overline{v}\,\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial y} + \overline{w}\,\overline{c_d}\frac{\partial \overline{\chi_c}}{\partial z}\right]dxdydz}$$

Courtesy of Eva van Gorsel & Ray Leuning, CSIRO Marine & Atmospheric Research

# Eddy Covariance Method – Field Data Collection

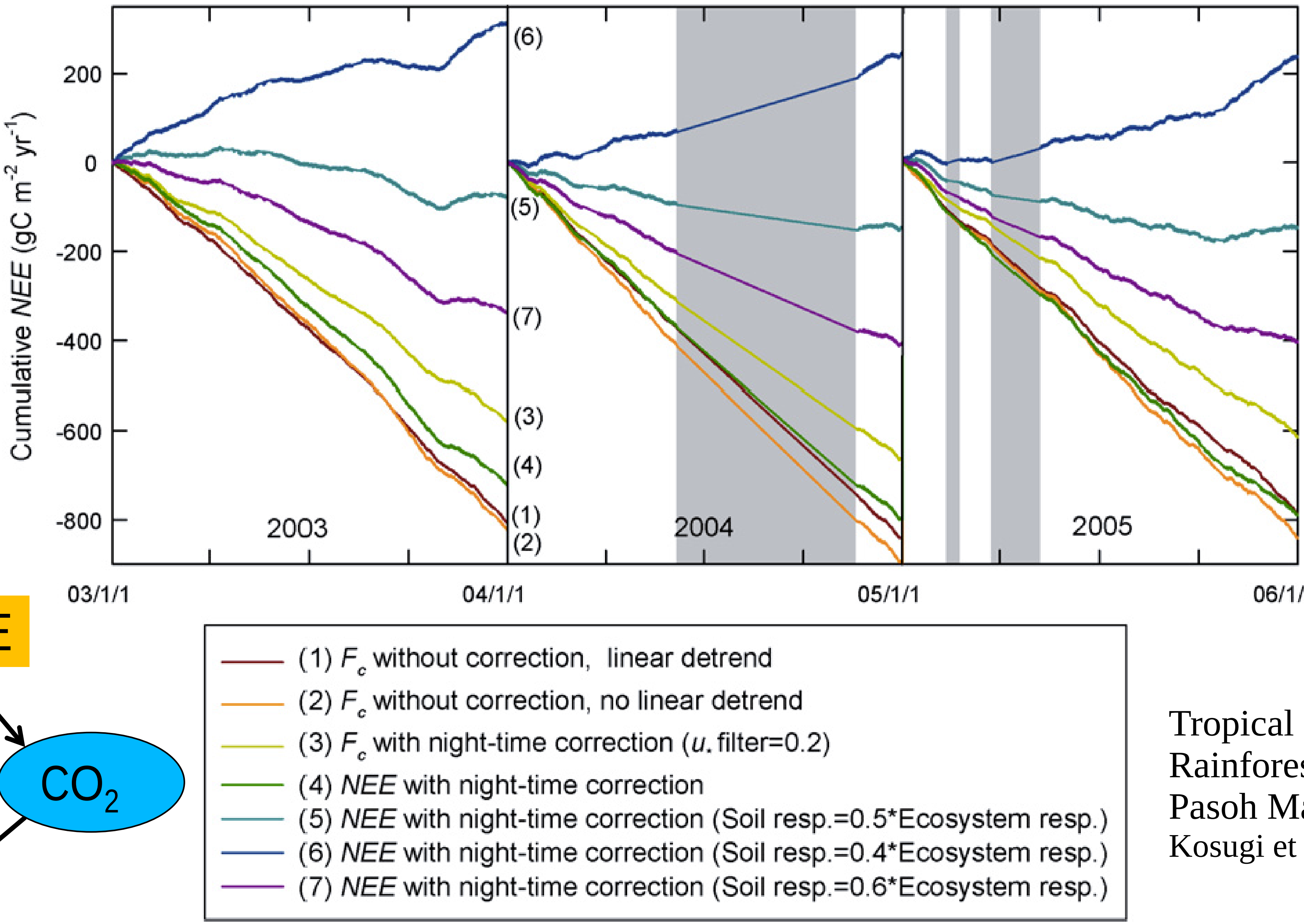
$CO_2$ and $H_20$ concentration
3D windspeed Stored at 10 to 20 hz

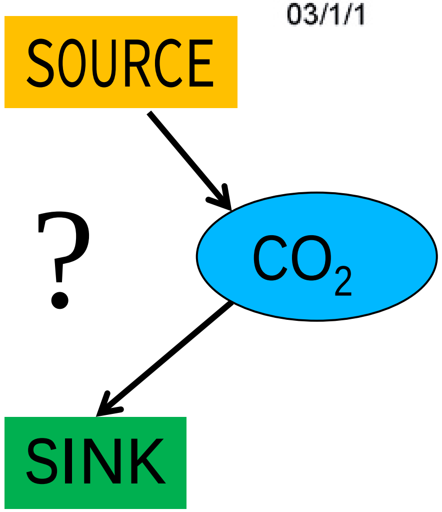
Data is post-processed to determine mean sub-hourly vertical transport of water vapor and $CO_2$.

<u>Correct for:</u>
Damping losses
Optical sensor contamination
Density fluctuations
Periods of low turbulence removed
Filter out-of-range data points

Further post-processing…

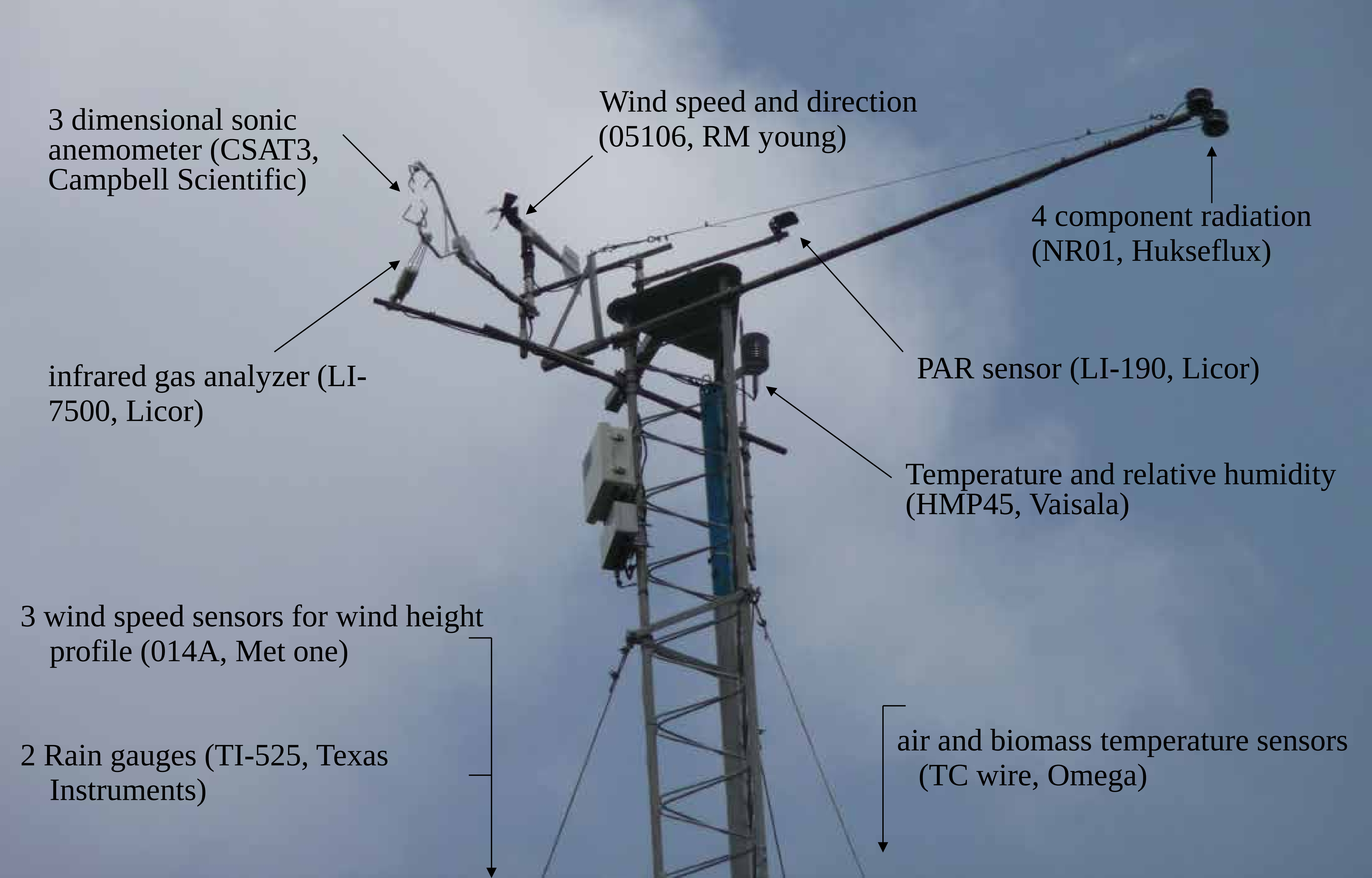
# Eddy Covariance Method – Corrections




Tropical Rainforest, Pasoh Malaysia
Kosugi et al, 2008

# Eddy Covariance and Micrometeorological Instruments



# $CO_2$ concentration profile


# Radiation Measurement


Kipp and Zonen CNR1
4 component radiation

Rebs Q 7.1 net radiometer

Shortwave radiation

Licor solar radiation

# Underground Sensors

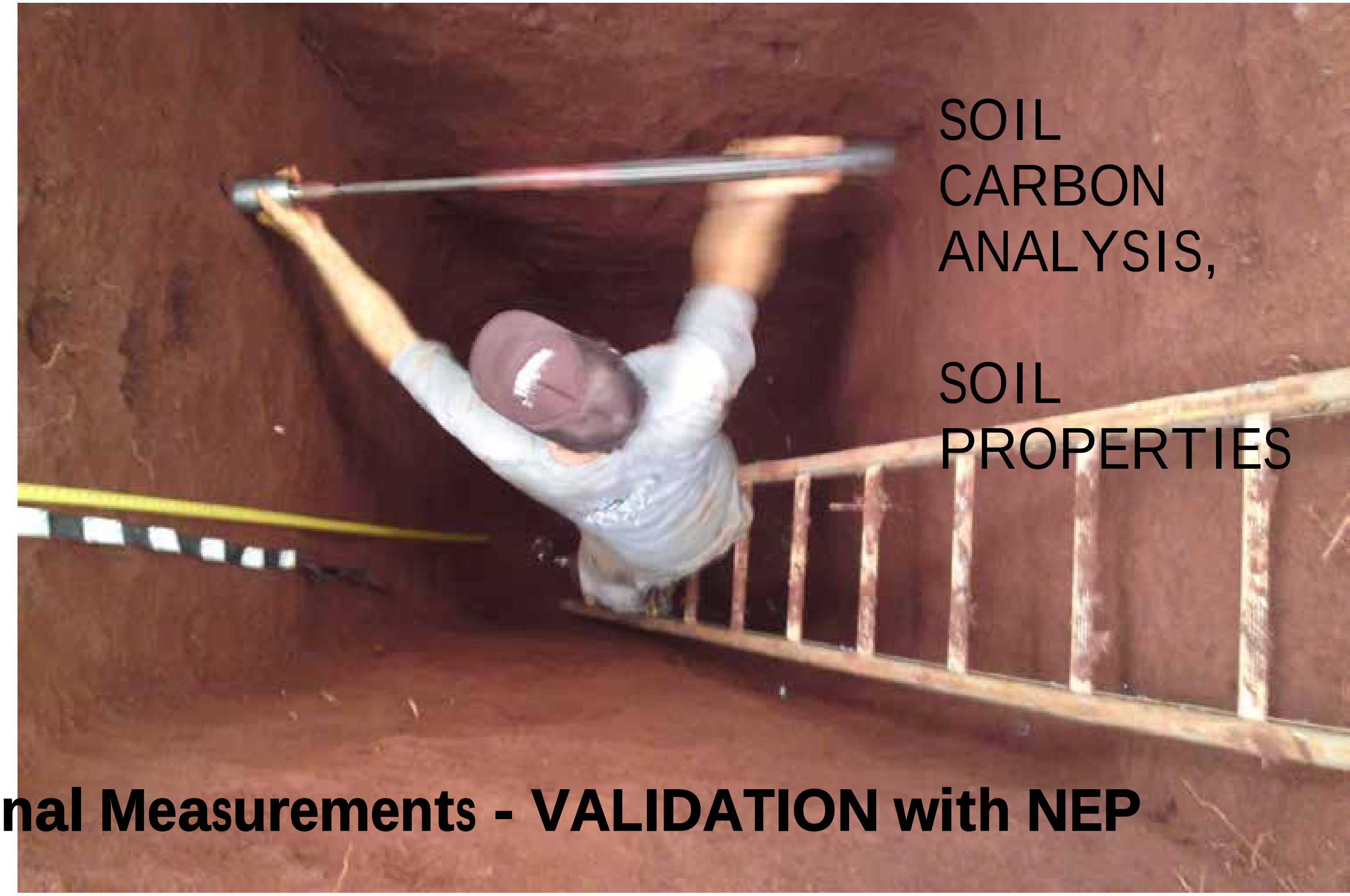
- **soil temperature** sensors
- **soil heat flux** plates
- TDR **soil moisture** sensors
- ADR **soil moisture** sensors

# Dataloggers and power systems

Datalogger in weatherproof enclosure

12V charging system inside secure box

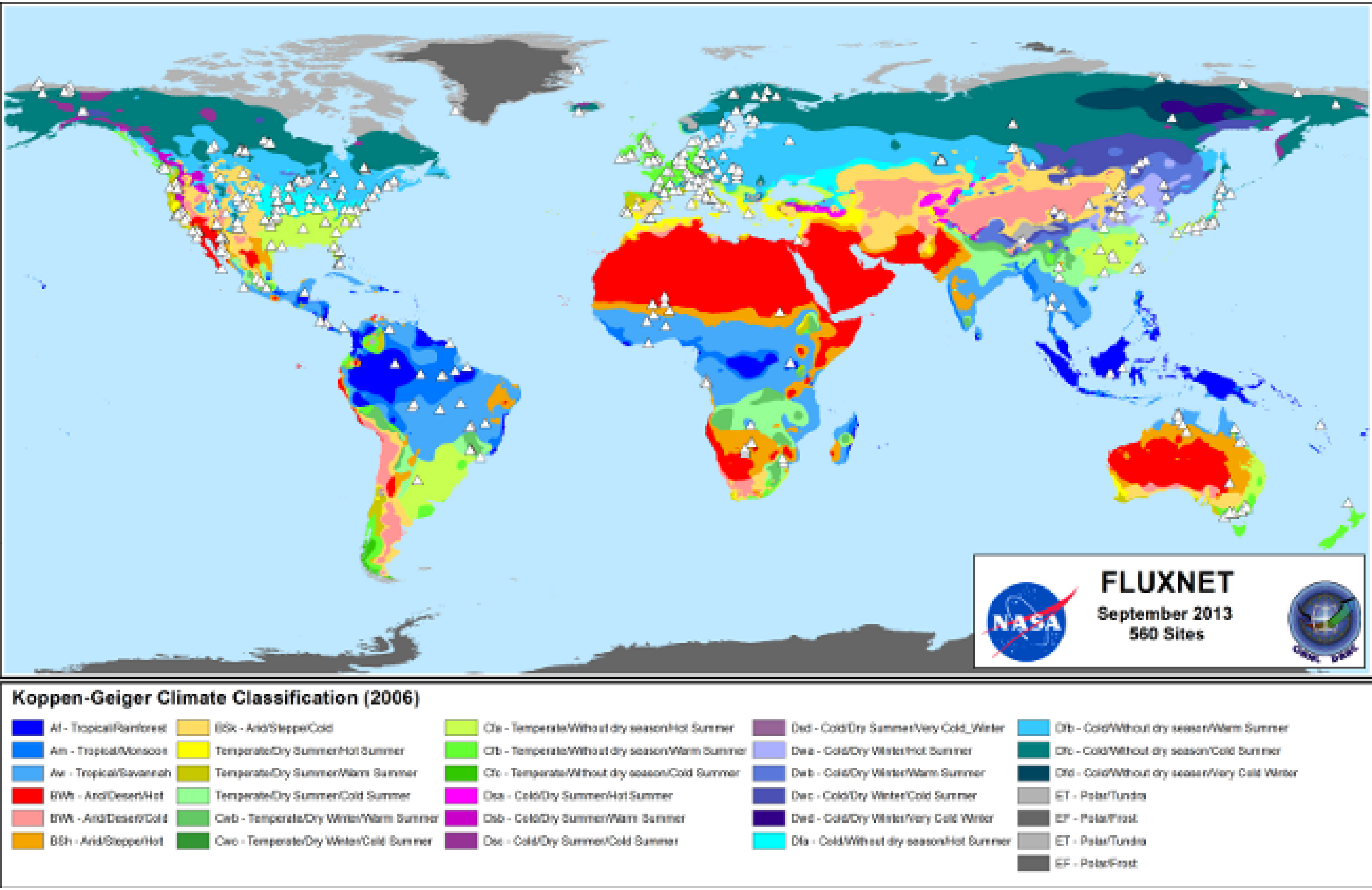




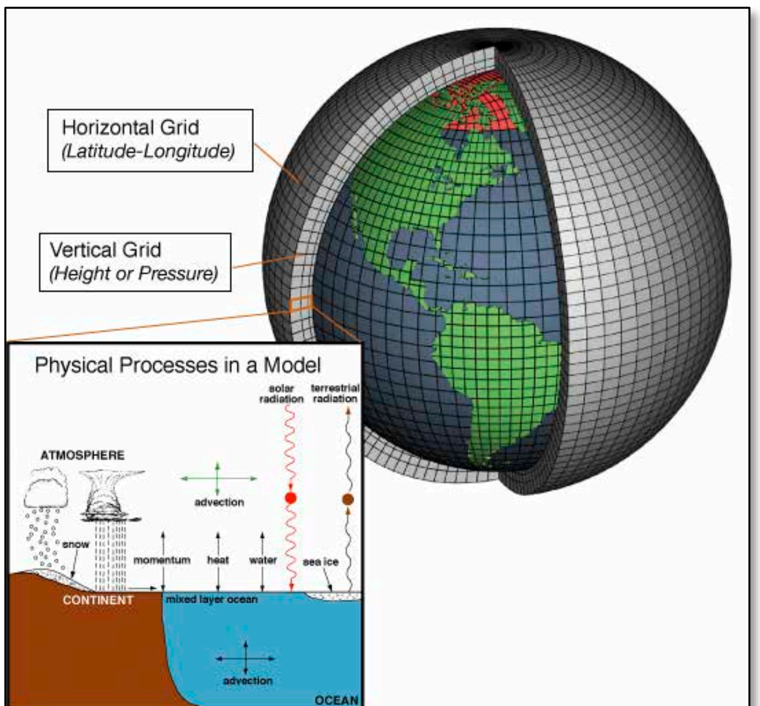

**Additional Measurements - VALIDATION with NEP**

# Eddy Covariance Measurement Systems

# Network of Flux Stations



# Modelling Global Ecosystem Function




# Additional validation using quantitative (SVAT) models.

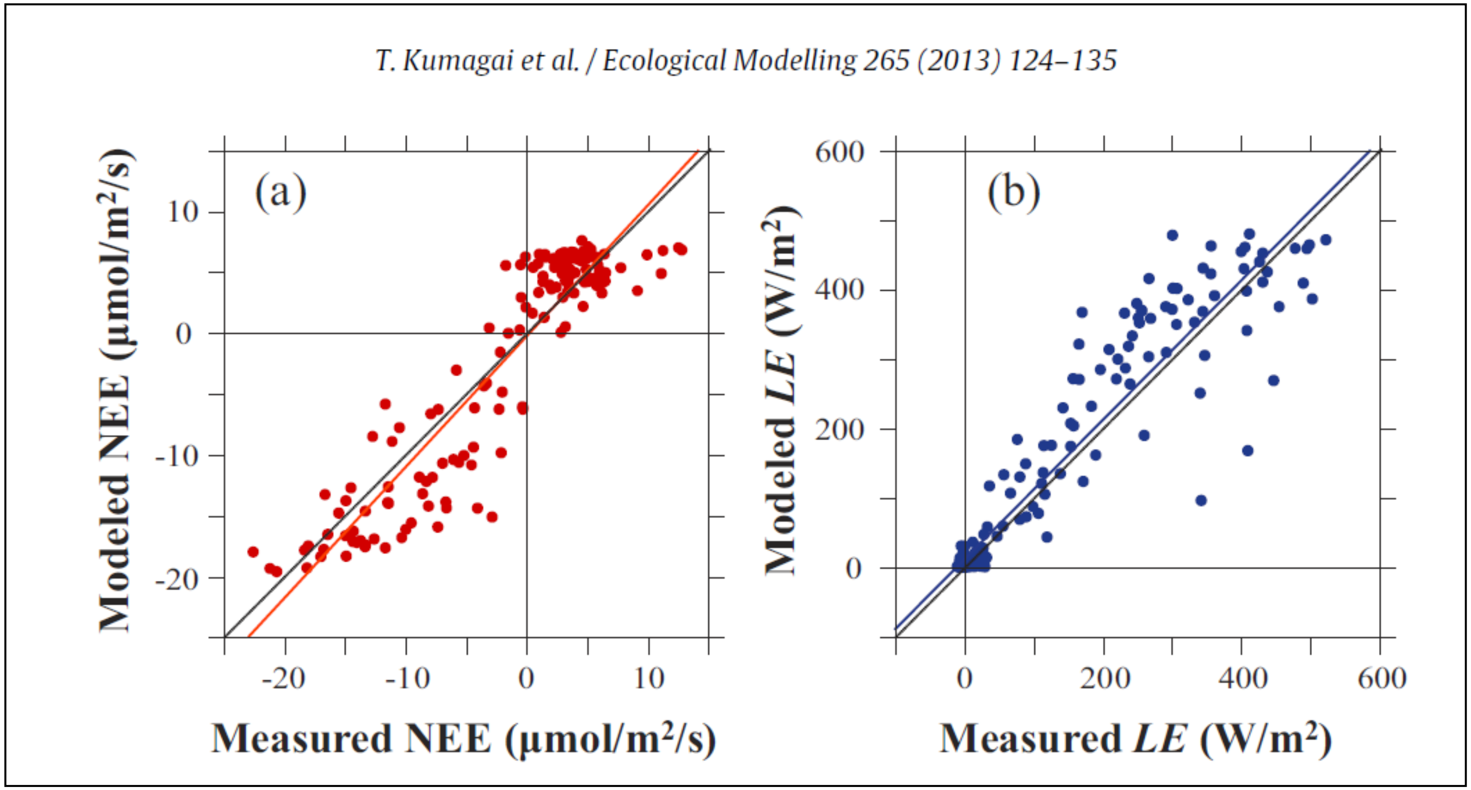
Parameter inputs from literature and field data

Leaf level photosynthetic characteristics

Leaf area index (LAI)

Meteorological data

Sapflow



# Carbon sequestration potential of tropical pasture compared with afforestation in Panama. *Global Change Biology*

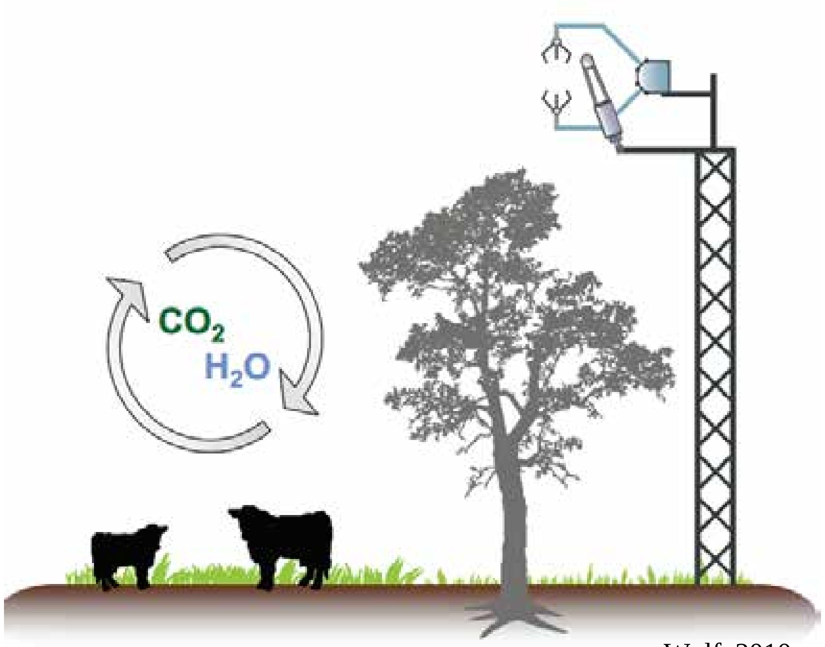

- **Sebastian Wolf** – Postdoctoral Fellow at UC Berkely -Department of Environmental Science, Policy and Management

- **Werner Eugster** - Senior Scientist in Micrometeorology - Institute of Plant, Animal and Agroecosystem Sciences, ETH Zürich

- **Catherine Potvin** –Department of Biology – McGill University - Neotropical Ecological Laboratory in Sardinilla, Panama.

- **Benjamin Turner** – Soil Scientist and Ecosystem Ecologist - Smithsonian Tropical Research Institute, Panama

- **Nina Buchmann** - Full Professor of Grassland Sciences - Institute of Agricultural Sciences at ETH Zurich


Wolf, 2010

# Wolf et al., 2013

## Context and research design

- Tropical forest carbon stocks are at risk from deforestation and associated land use changes
- Carbon cycling in tropical ecosystems not well understood
- Mitigation potential of tropical afforestation 15% of Global $CO_2$ emissions (Malhi et al., 2002).
- Eddy covariance measurements underrepresented in the tropics

- Deforestation à Pasture à (1) Pasture

  (2) Afforestation

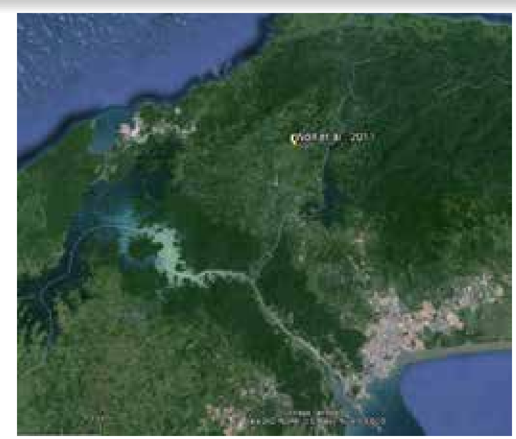
ENVIRONMENTAL CONTROLS ON $CO_2$ FLUXES?

CARBON SEQUESTRATION POTENTIAL?

EDDY COVARAINCE = CARBON BUDGETS?

# Sardinilla, Panama



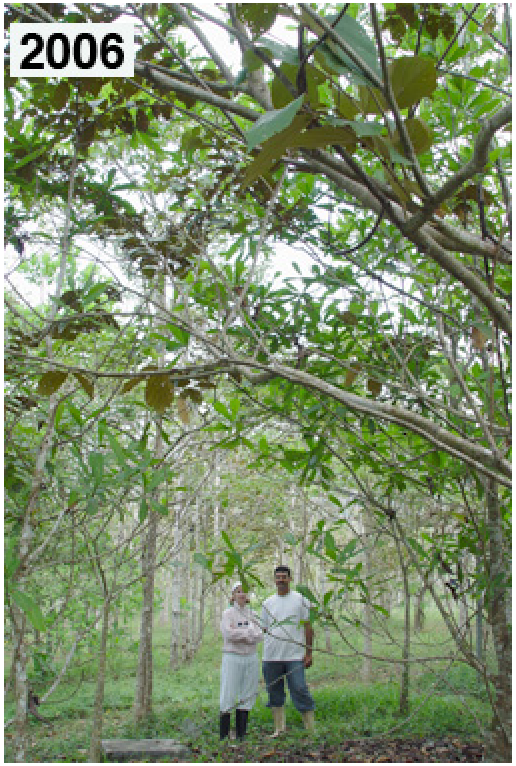
# Afforestation Plot (2002-2011)




*Luehea seemanii*
*Cordia alliodora*
*Anacardium excelsum*
*Hura crepitans*
*Cedrela odorata*
*Tabebuia rosea*

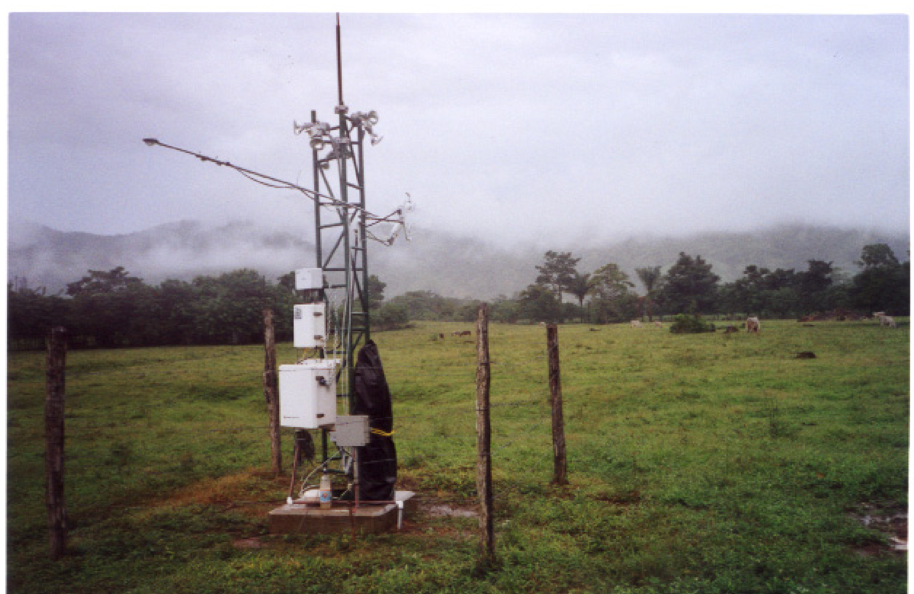

Planted in 2001, study period from 2007-2009 (6-8 years age)

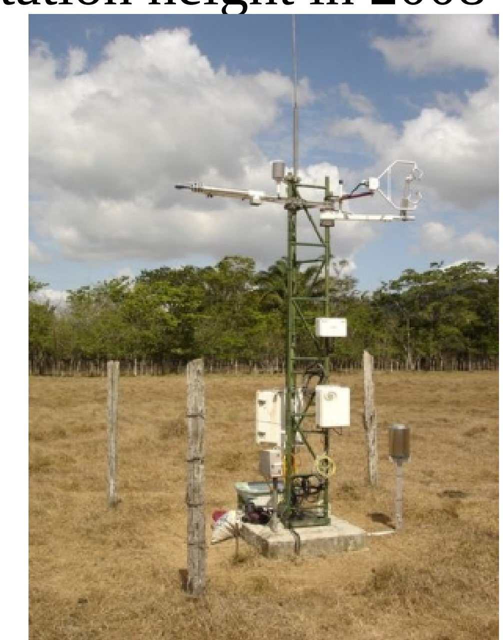
Management: Cutting weeds, residues left on site




10 m canopy height
In 2008


**Pasture** 0.09 m vegetation height in 2008





# Methods (Wolf et al., 2013)

- Eddy covariance micrometeorological stations
  - Meteorological data
    - 3-D windspeed, $CO_2$/$H_2O$ concentration, air temperature, relative humidity, soil moisture, solar radiation, PAR, precipitation
  - Post process to get NEE at 30 minute intervals
  - Fill gaps with seasonal light response curves
  - Partition NEE into its components GPP and TER

  $GPP = - NEE_{daytime} + TER$

    - NEE Measured
    - TER was inferred from mean nighttime data
  - Relate the components to abiotic and biotic drivers.

# Methods (Wolf et al., 2013)

**Carbon Budgets (NEP)**

- Incremental measurements of live biomass
  - Afforestation – annual stem diameter
  - Pasture – bi-weekly removal of all above –ground biomass in 0.25 $m^2$ frame (n=10)
- Allometric equations (Species specific; Potvin et al., 2011).
- Measured litter and coarse woody debris in afforestation plot
- Soil carbon
  - Sampled in 2001 and 2009 to determine change in soil carbon
  - Used isotopes to determine heterotrophic portion of respiration
- Emperical grazing equations for pasture – counting cows daily
  - Overgrazing

COMPARE NEE WITH NEP

# Results

- Climate:
  - MAP = 2553, 2074, and 2233 mm, for 2007-2009
  - MAT = 25.2° C – small seasonal variation
  - PPFD: – 5.2-58.5 mol m-2 d-1
- Carbon Exchange
  - Pasture: Lost 261 g C $m^{-2}$ $yr^{-1}$ from June 2007 to December 2009. SOURCE
  - Afforestation: Gained 292 - 442 g C $m^{-2}$ $yr^{-1}$ over a 3-year period. SINK

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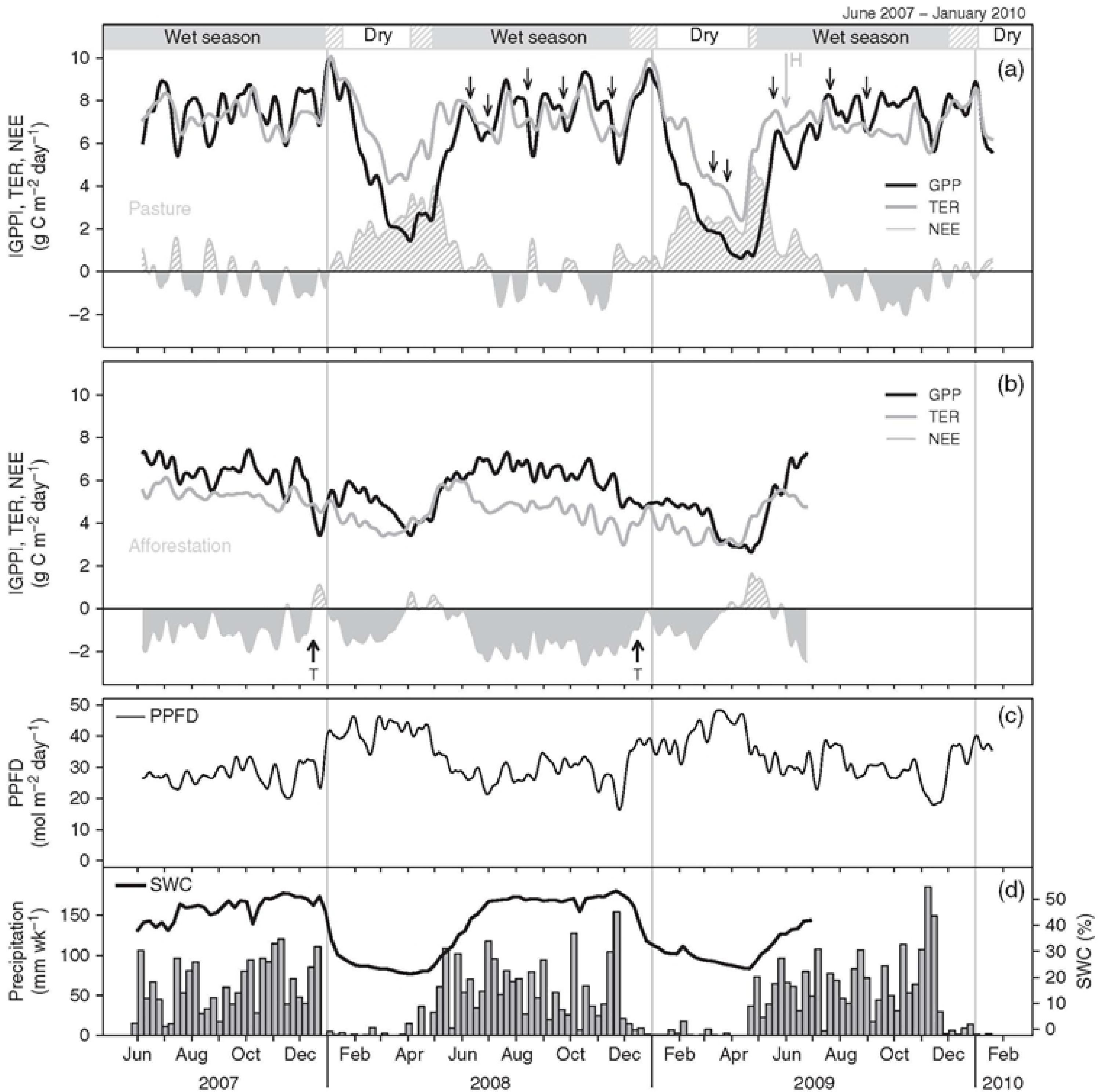
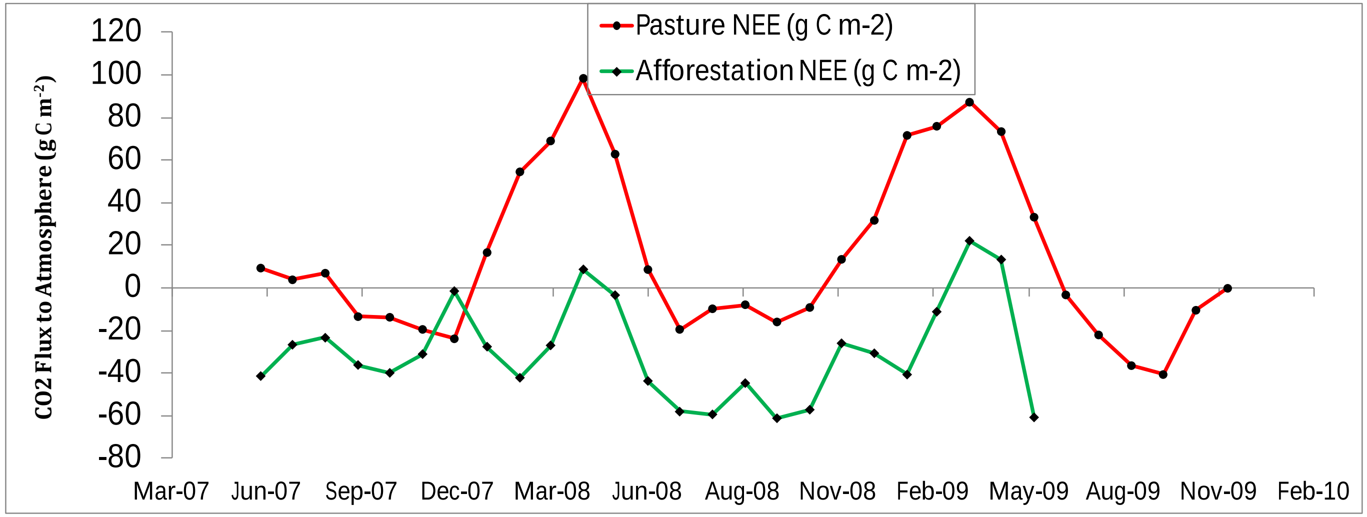
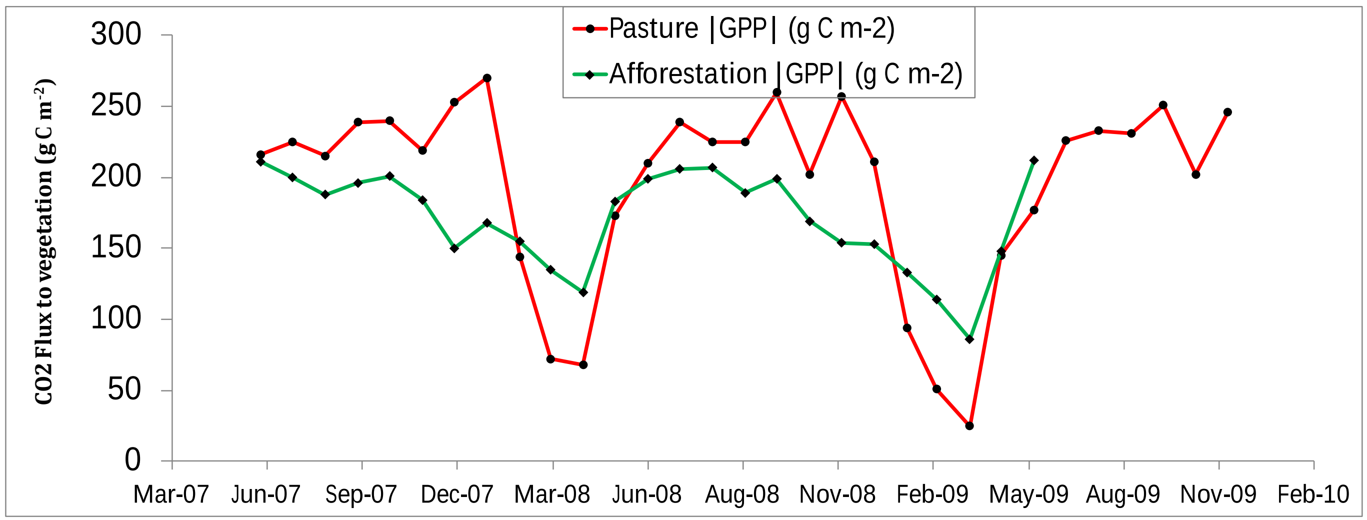


June 2007 – January 2010
Wet season
Dry
Wet season
Dry
Wet season
Dry
(a)
H
Pasture
GPP
TER
NEE
IGPPI, TER, NEE (g C m−2 day−1)
(b)
Afforestation
T
T
(c)
PPFD
PPFD (mol m−2 day−1)
(d)
SWC
Precipitation (mm wk−1)
SWC (%)
Jun
Aug
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
Apr
Jun
Aug
Oct
Dec
Feb
2007
2008
2009
2010

NEE

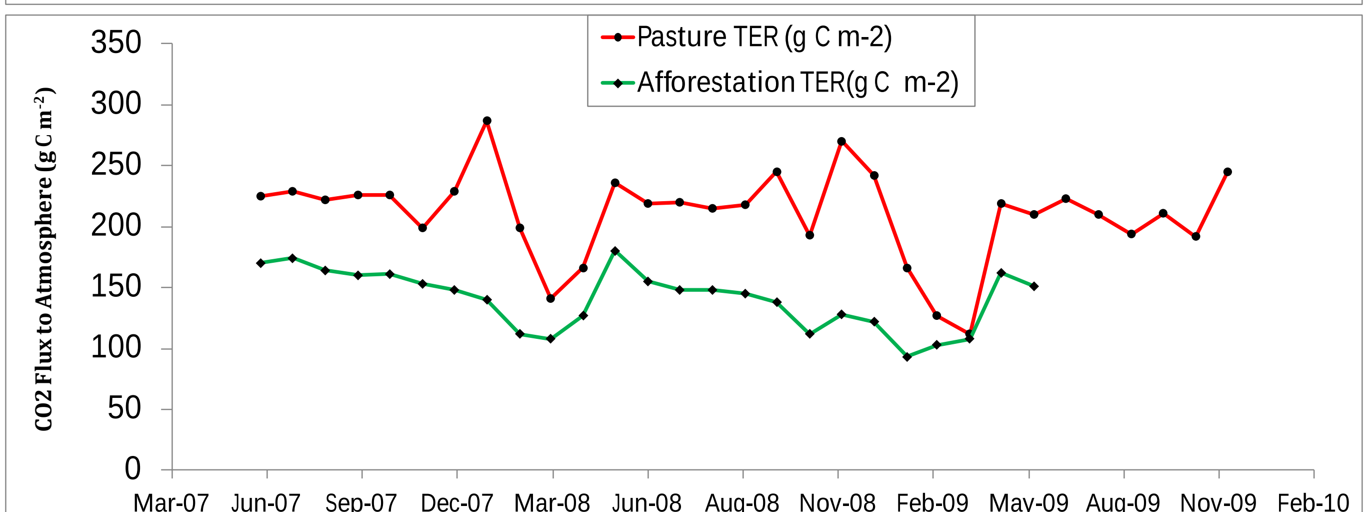



GPP

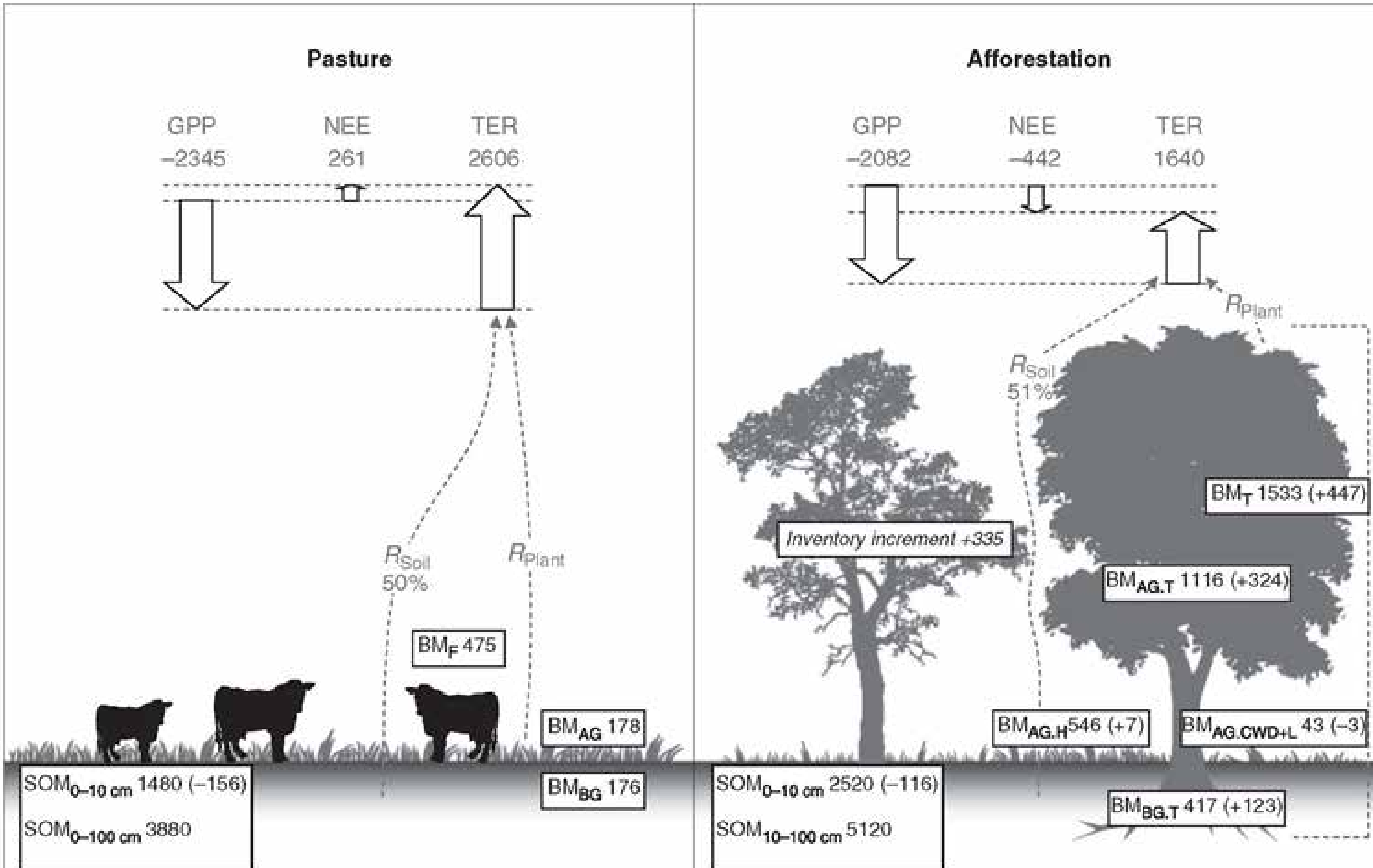



Monthly data from Table 1

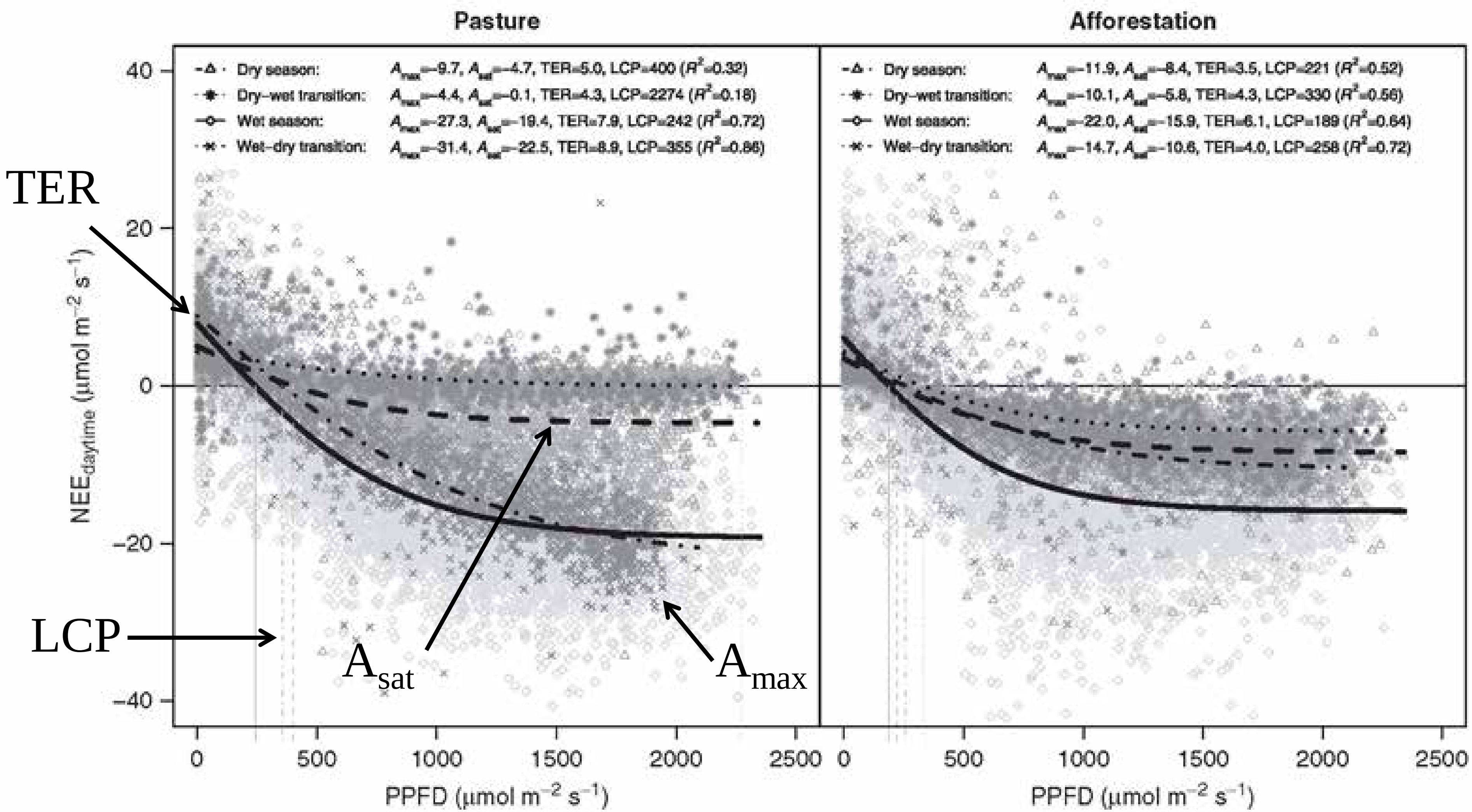
TER



# Results: Carbon Budgets



$$NEE_{daytime} = 2A_{max}\left(0.5 - \frac{1}{1 + e^{\frac{-2xPPFD}{Amax}}}\right) = TER_{daytime}$$



# Results: Grazing and Biomass

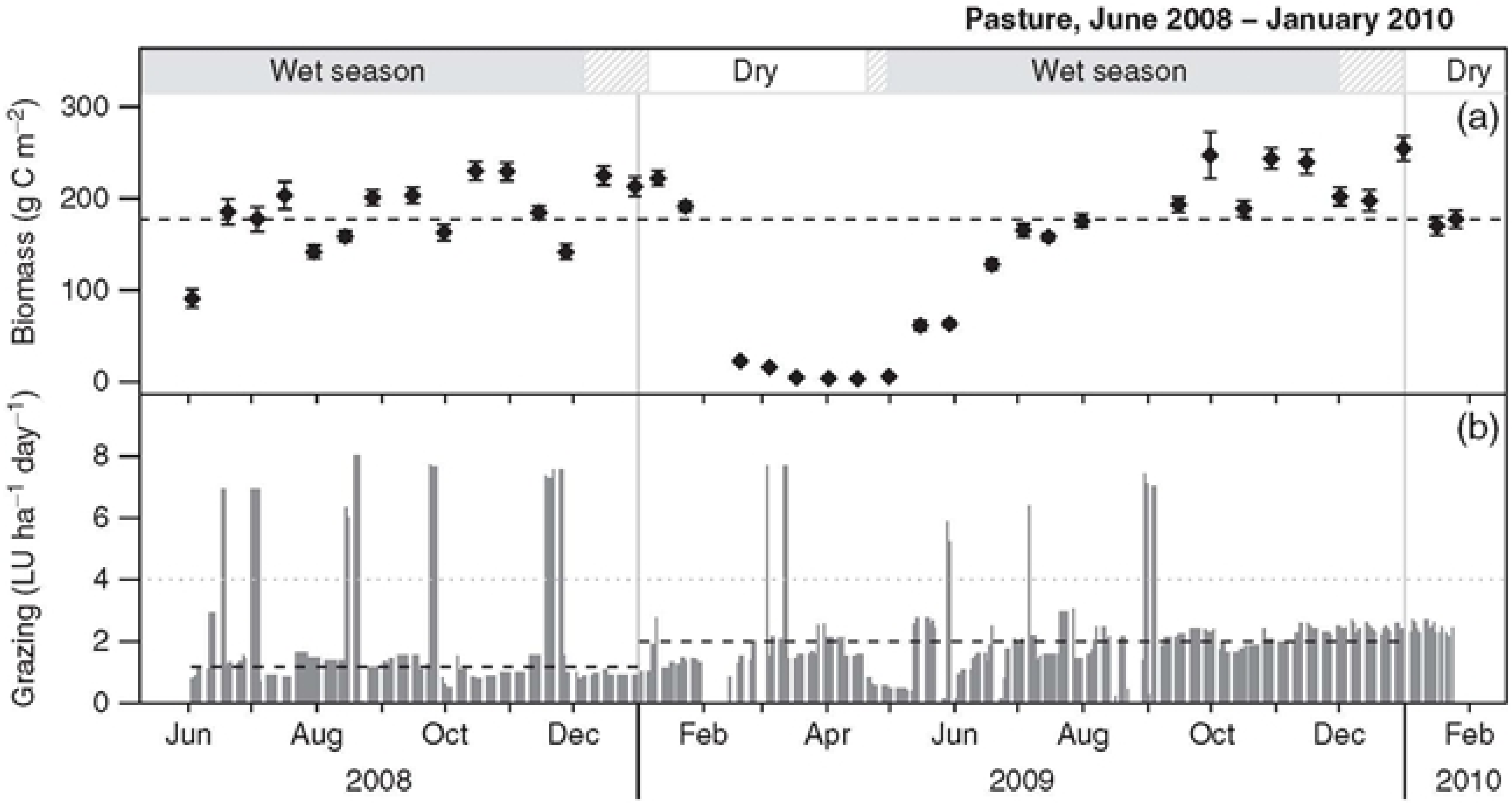



**Fig. 4** Aboveground green biomass (a) and grazing (in livestock units, LU; b) at the Sardinilla Pasture from June 2008 to January 2010. The dashed black lines denote the overall median for biomass (a) and the annual median for grazing (b). The dotted grey line shows the overgrazing threshold of 4 LU.

# Conclusions

- The land-use change from pasture to afforestation reduced seasonal variability of $CO_2$ flux.
- The shallow rooting depth of grasses compared to trees resulted in a higher sensitivity of the pasture ecosystem to water limitation and seasonal drought (biotic control).
- Radiation and soil moisture were the main environmental controls of ecosystem fluxes (abiotic controls).
- Substantial carbon sequestration was observed in the afforestation whereas the pasture ecosystem was a strong carbon source, associated with seasonal drought and overgrazing.
- Results were substantiated using carbon budgets

# Additional related studies

Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD+ policy implications

**Ziegler et al., 2012**

Total Ecosystem Carbon Stocks for various land-cover types in SE Asia region

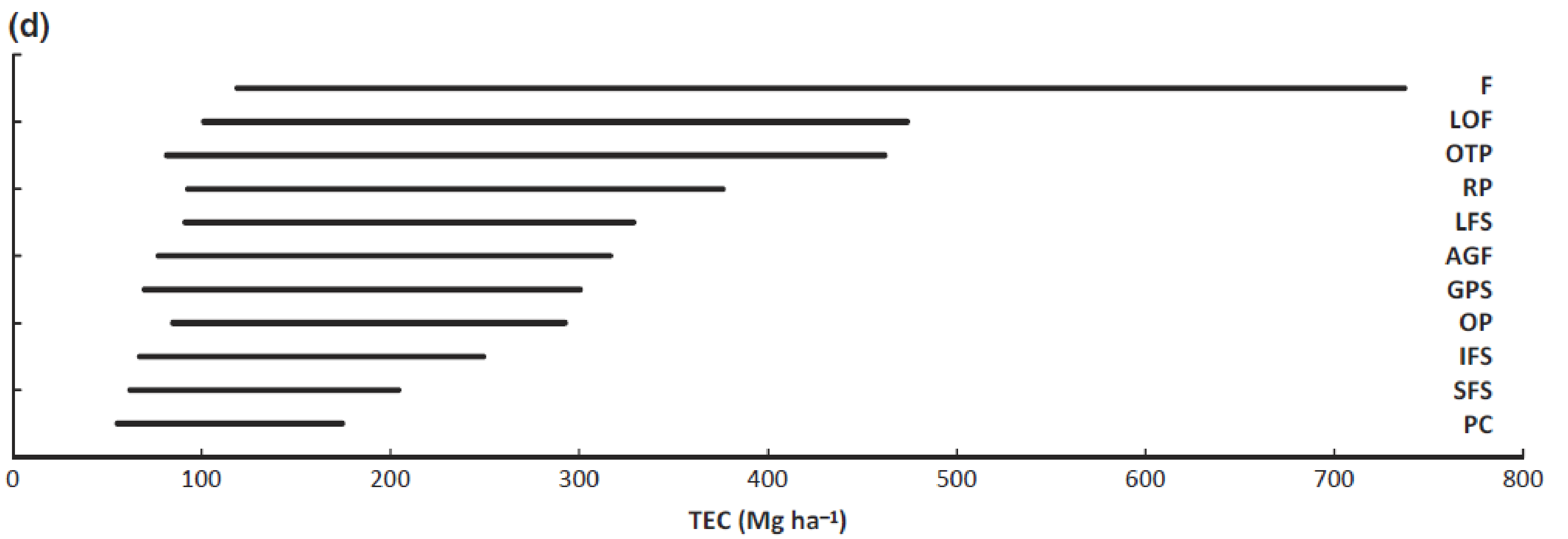



Fig. 2 For the 11 land covers considered in this analysis, plausible ranges of the following: (a) above-ground carbon biomass (AGC); (b) below-ground carbon biomass in vegetation (BGC); (c) soil organic carbon (SOC); and (d) total ecosystem carbon (TEC = AGC + BGC + SOC). Land covers are the following: forest (F); logged over forest (LOF); orchards and tree plantations (OTP); rubber plantations (RP); long-fallow swidden (LFS); nonswidden agroforest (AGF); grassland, pasture, or shrublands (GPS); oil palm plantations (OP); intermediate-fallow swidden (IFS); short-fallow swidden (SFS); and permanent cropland (PC).

- Collected literature values of Carbon stocks for various landcovers - >250 studies
- Found that carbon outcomes of land-cover change are **ambiguous**
  - Highly dependent on soil type and previous land use history
- Any land cover type replaces forest à Net loss of carbon

# Additional related studies

## ‘Breathing’ of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems

**Baldocchi et al., 2008**

- Synthesis and review of global set of eddy covariance measurements
- What are the patterns of ecosystem productivity in terms of time scale, climate, plant functional types, disturbance and land use?

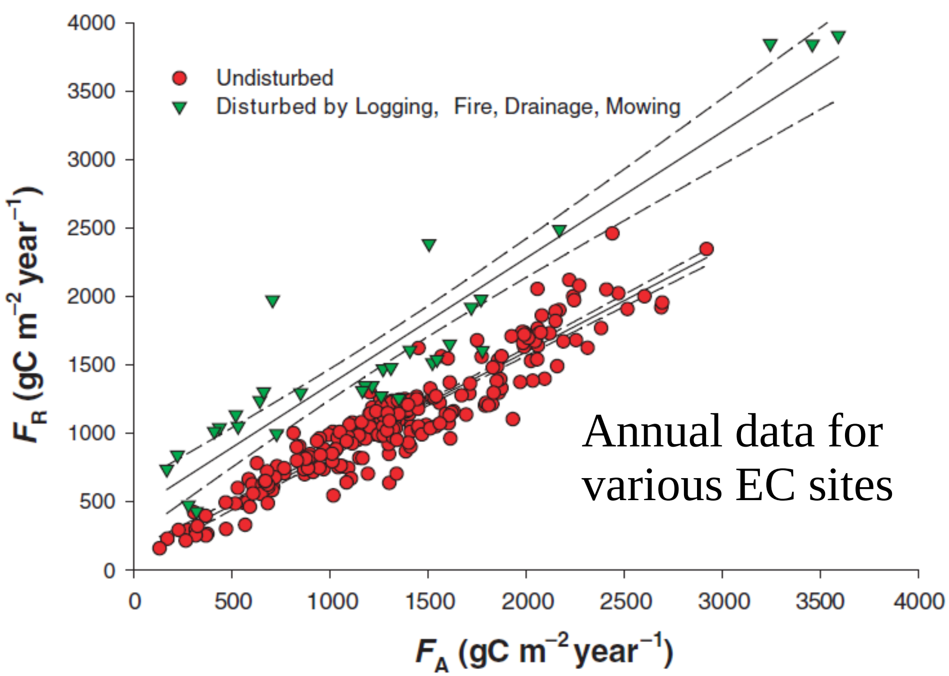



**Fig. 6.** Relationship between published values of gross canopy photosynthesis ($F_A$) and ecosystem respiration ($F_R$).

- Disturbance increases the ratio of TER to GPP.
- Disturbed ecosystems are usually ecosystem sources of CO2
- Undisturbed landcovers are generally carbon sinks
- Disturbance offset caused by $CO_2$ emissions from the soil carbon pool and litter detritus

# Additional related studies

## 'Breathing' of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems

## Baldocchi et al., 2008

Pacific Northwest net carbon exchange over conifers (space for time sampling design)

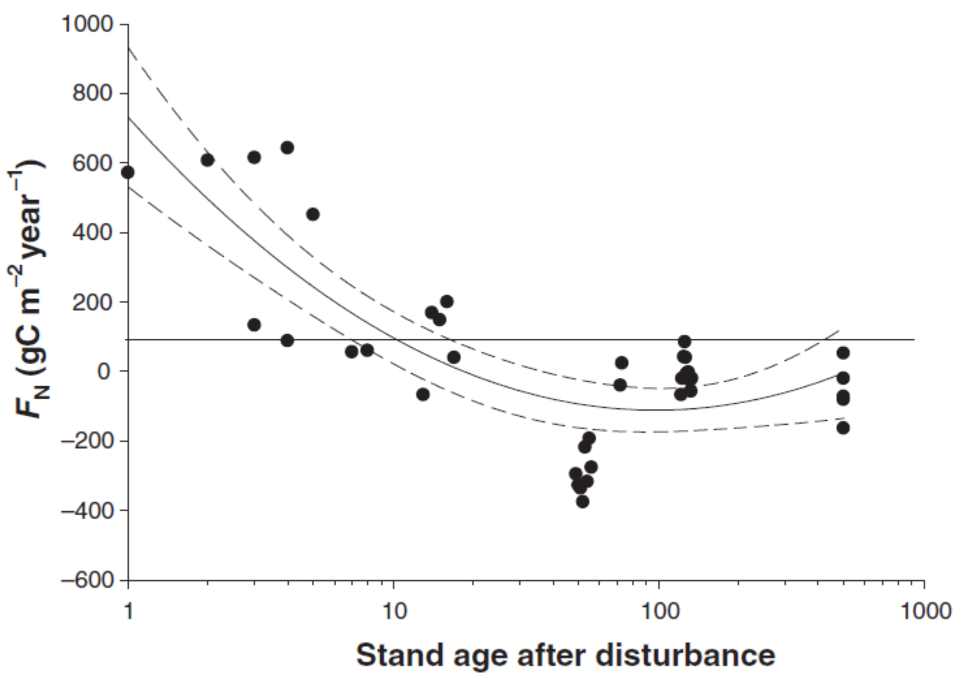



**Fig. 11.** The relationship between net carbon exchange and age since disturbance. The data are drawn from several chronosequence studies done in central and western Canada and the Pacific North-west over conifers. Sources: (Paw U *et al*. 2004; Amiro *et al*. 2006; Dunn *et al*. 2007; Schwalm *et al*. 2007).

- Disturbance followed by large respiratory flux.
- Maximum carbon uptake from 50-100 years
- Afterwards, gradual decline in carbon uptake with forest stand age