Carbon balance and seasonality in an old-growth Amazon rainforest: Seeing both the forest and the trees

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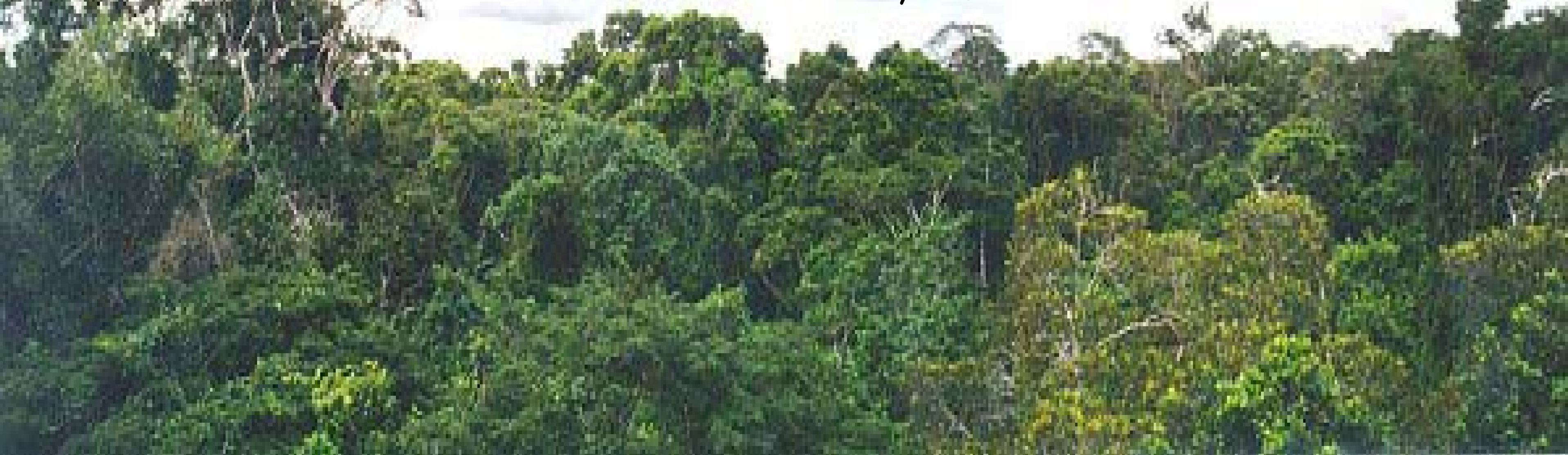


Introduction

Obligatory Keeling
Plot / Global
Carbon Cycle
picture goes here

Two linked hypotheses about Carbon-cycling in tropical forests:

(1) CO_2 fertilization Hypothesis: undisturbed forests are, on average, a net carbon sink due to growth stimulation by high CO_2

(2) Climate-mediation Hypothesis: long-term net sink is mediated by interaction of climate and plant physiology, with *high uptake* during wet periods and *loss* during dry periods

(1) CO_2 fertilization hypothesis:

- models (Lloyd & Farquhar, 1996; Tian et al. 1998, 2000) predict [CO_2]-driven increase in uptake
- Initial tower-based eddy-covariance studies in Amazonia show substantial net uptake (Fan et al., 1990; Grace et al., 1995; Mahli et al., 1998)

→ *but these studies were short (≤1 yr); + meteorology issues?*

- Long-term tropical forest plots show accumulation of biomass (Phillips, et al., 1998)

→ *but some sites logged; selection issues Clark 2002; Phillips et al., 2002)*

(2) Climate mediation hypothesis:

- Basic tree physiology in water-limited environment + studies of tree growth rates: trees grow more in wet season
- models (Tian et al. 1998, 2000; Botta & Foley 2002) show strong dependence on seasonal precip & El Nino cycle: net uptake in wet years & seasons, net loss in El Nino years and dry season
- One Amazon eddy-covariance site shows modest seasonality (Mahli et al., 1998; Williams et al 1998; Araujo et al. 2002)

Outstanding Issues

- Claims of large uptake have attracted much attention:

  "Towers indicate a high uptake of CO_2, ranging between 3 and 7 ton C ha^{-1} y^{-1}"

  (Kabat, et al., 2000: review of initial LBA results)

- This is a huge uptake:
  - 3-7 tC/ha/yr x (5×10^8 ha undisturbed Amazon forest) = 1.5 – 3.5 Gt C/yr
    - 1-5 times the global "missing carbon" sink
  - Enough to double the live biomass in a typical tropical forest (~150 tC/ha) in 25 – 50 years

Outstanding Issues (cont'd)

- Focus on claims of large uptake is unfortunate:
  - Evidence for the claim is weak
  - Distracts from the more important and useful things eddy flux studies can tell us
- Questions:
  - Is there really a sink of such magnitude?
  - Can expected seasonal pattern be observed?
  - Can we learn about ecological/climatic mechanisms controlling C-exchange

Approach of this study

Integration of:

(1) Eddy Covariance: whole-system C-balance ("the forest")

\+ *response to environmental forcing factors; below-ground included;*

\- *long term averages require validation; technologically intensive; limited disaggregation*

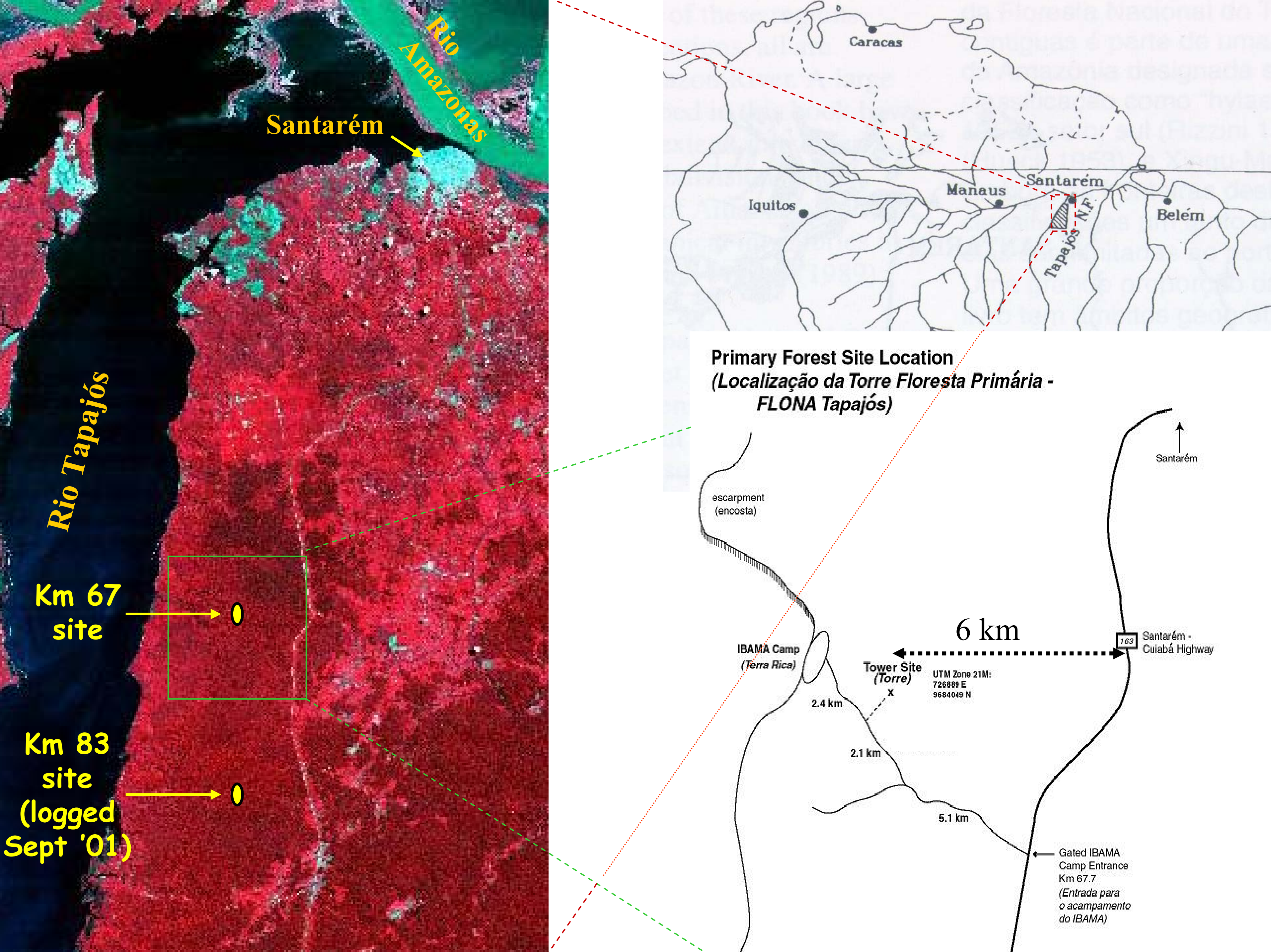
Including Validation/cross-check with independent ecosystem-scale data

- *inter-site comparison with eddy flux data from companion site control period (Goulden, de Rocha)*
- *using Radon as transport tracer (Martens and Shay)*

(2) Biometry: C-balance check and disaggregation ("the trees")

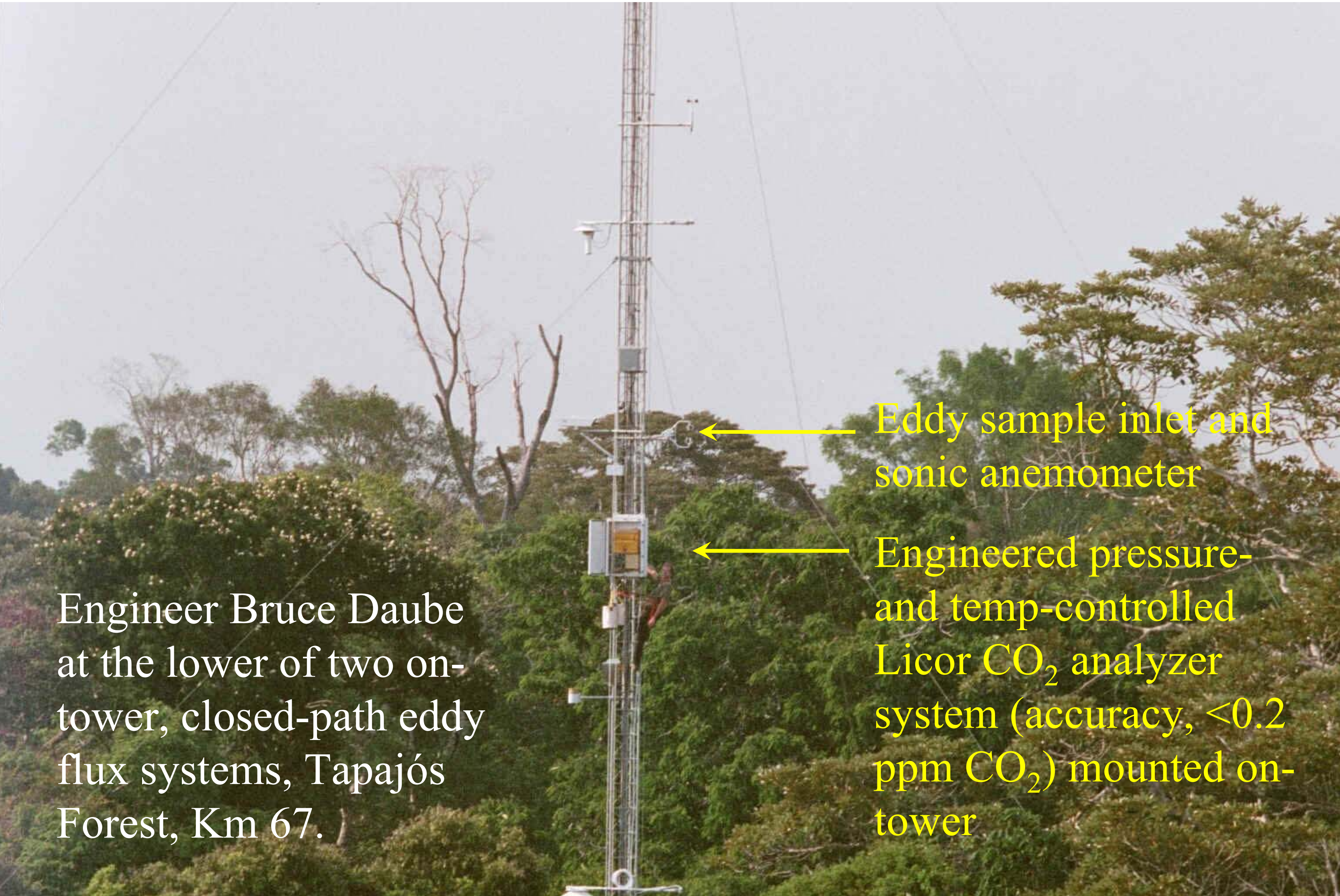
\+ *long-term average; biological factors, disaggregation; technologically simple*

\- *response to environmental forcing factors, below-ground inaccessible, aggregation errors*


Rio Amazonas
Santarém
Rio Tapajós
Km 67 site
Km 83 site (logged Sept '01)
Caracas
Manaus
Santarém
Iquitos
Belém
Tapajós N.F.
Primary Forest Site Location
(Localização da Torre Floresta Primária - FLONA Tapajós)
Santarém
escarpment (encosta)
6 km
IBAMA Camp
(Terra Rica)
Tower Site
(Torre)
UTM Zone 21M:
9684049 N
Santarém - Cuiabá Highway
163
2.4 km
2.1 km
5.1 km
Gated IBAMA Camp Entrance Km 67.7
(Entrada para o acampamento do IBAMA)

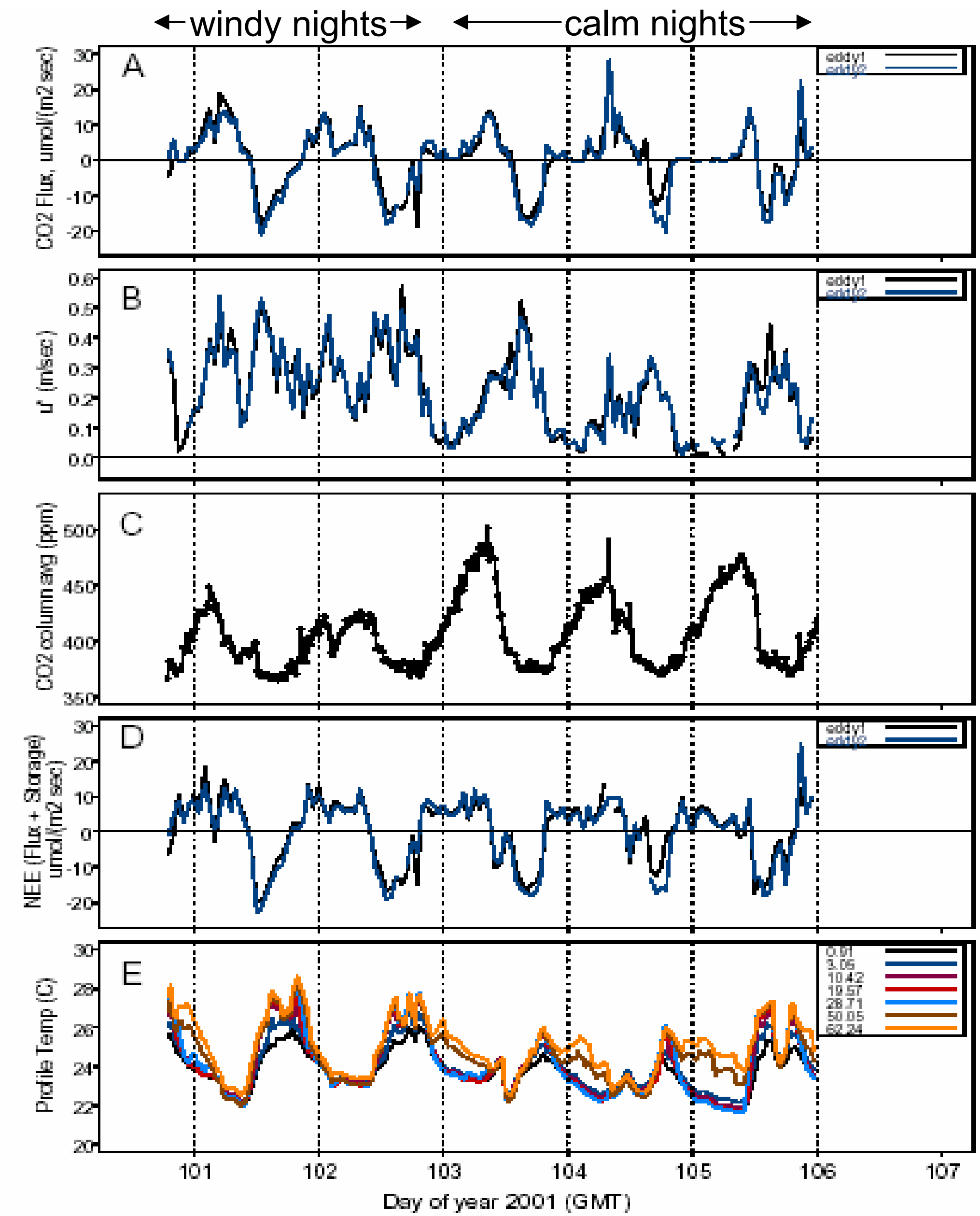
Part 1 (“the forest”)

64m tall tower: Tapajos forest, Km 67



Engineer Bruce Daube at the lower of two on-tower, closed-path eddy flux systems, Tapajós Forest, Km 67.

Initial Results: Hourly time series from the Primary Forest eddy flux tower at km 67



(A) Eddy flux of CO_2 for eddy1 (58m) and eddy2 (47m);
(B) friction velocity (u*);
(C) mean CO_2 concentration 0-60m ("canopy storage");
(D) net ecosystem exchange (NEE = Eddy flux + d/dt<storage>); and
(E) temperature profiles.

On ***windy nights*** (days 100-102, U*>0.2 m/s (B)) CO_2 efflux (A) is strongly positive, temperature profiles (E) are well-mixed; CO2 storage (C) is low, and NEE (D) ≈ flux (A).

On ***calm nights*** (104-105), flux (A) and u* (B) are virtually zero, temperature profiles (E) are stratified, and CO_2 storage is high, causing NEE to be significantly higher than eddy flux.

Checking for lost flux (the "Diogenes Dilemma" of Eddy Flux measurements)

- Unlike (perhaps) virtue, mass is conserved; continuity equation works

$$\frac{\partial \overline{c}}{\partial t} + \overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{w}\frac{\partial \overline{c}}{\partial z} + \frac{\partial \overline{u'c'}}{\partial x} + \frac{\partial \overline{w'c'}}{\partial z} = \overline{s}$$

Storage

Flux Divergence terms *assumed = 0 (horizontal homogeneity, mean vertical wind =0)*

Vertical eddy flux divergence

Flux to be measured

Checking for lost flux (the "Diogenes Dilemma" of Eddy Flux measurements)

- Unlike (perhaps) virtue, mass is conserved; continuity equation works

$$\underbrace{\frac{\partial \overline{c}}{\partial t}}_{\text{Storage}} + \underbrace{\overline{u}\frac{\partial \overline{c}}{\partial x} + \overline{w}\frac{\partial \overline{c}}{\partial z} + \frac{\partial \overline{u'c'}}{\partial x}}_{\text{Flux Divergence terms}} + \underbrace{\frac{\partial \overline{w'c'}}{\partial z}}_{\text{Vertical eddy flux divergence}} = \overline{s}$$

Storage

Flux Divergence terms *assumed = 0 (horizontal homogeneity, mean vertical wind =0)*

Vertical eddy flux divergence

Flux to be measured ($\overline{s}$)

When are these least likely to be zero?

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Storage

Flux Divergence terms *assumed = 0*
(horizontal homogeneity, mean vertical wind =0)

Vertical eddy flux divergence

Flux to be measured

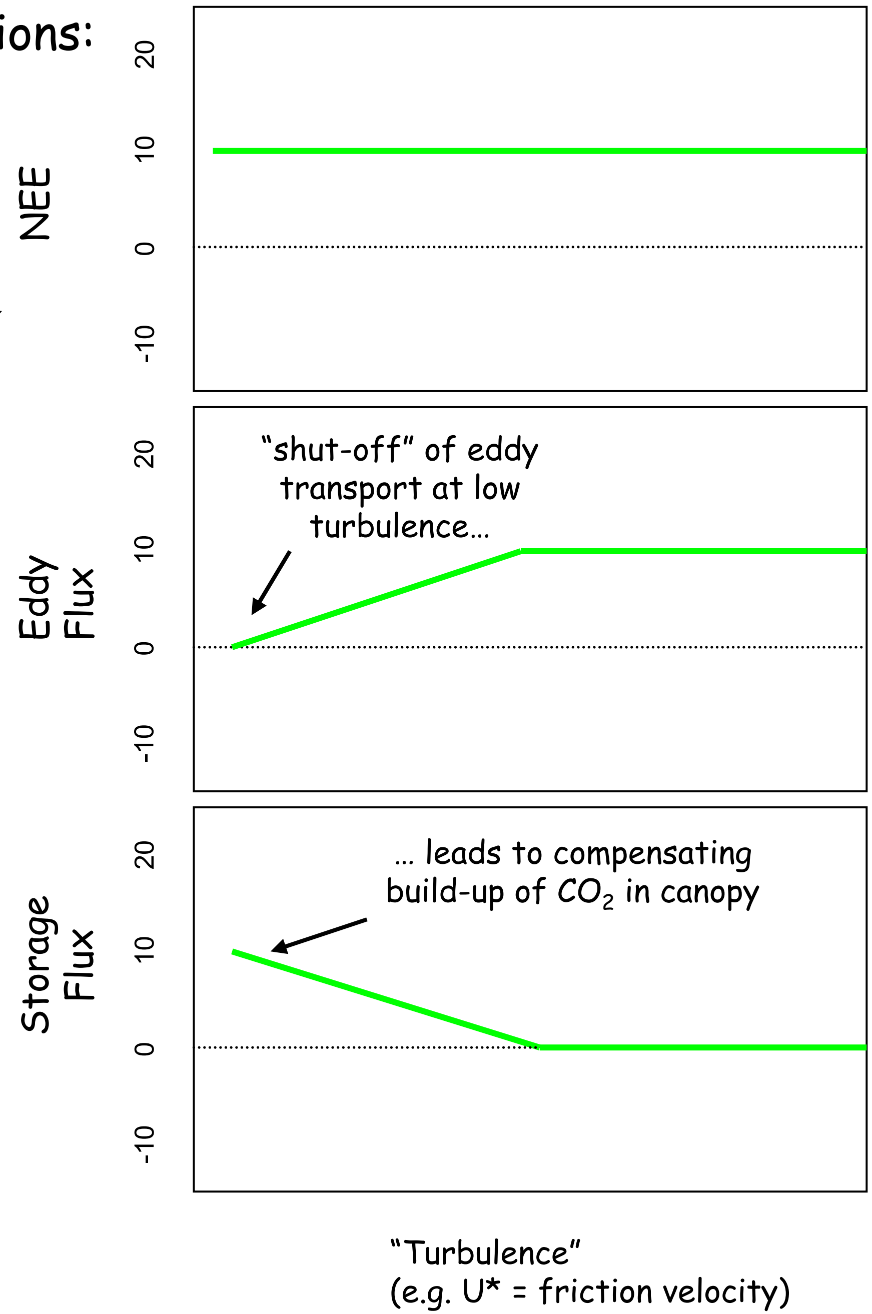
When are these least likely to be zero? → When eddy flux (w'c') is low (i.e., low turbulence)

Q: Is there "lost flux"?

We expect total nighttime *NEE* (which depends only on the physiology of forest respiration), to be essentially *independent* of atmospheric turbulence.

NEE components, however, are expected to depend on turbulence, but in opposite directions.

Expected Relations:



Definition: Net Ecosystem Exchange:

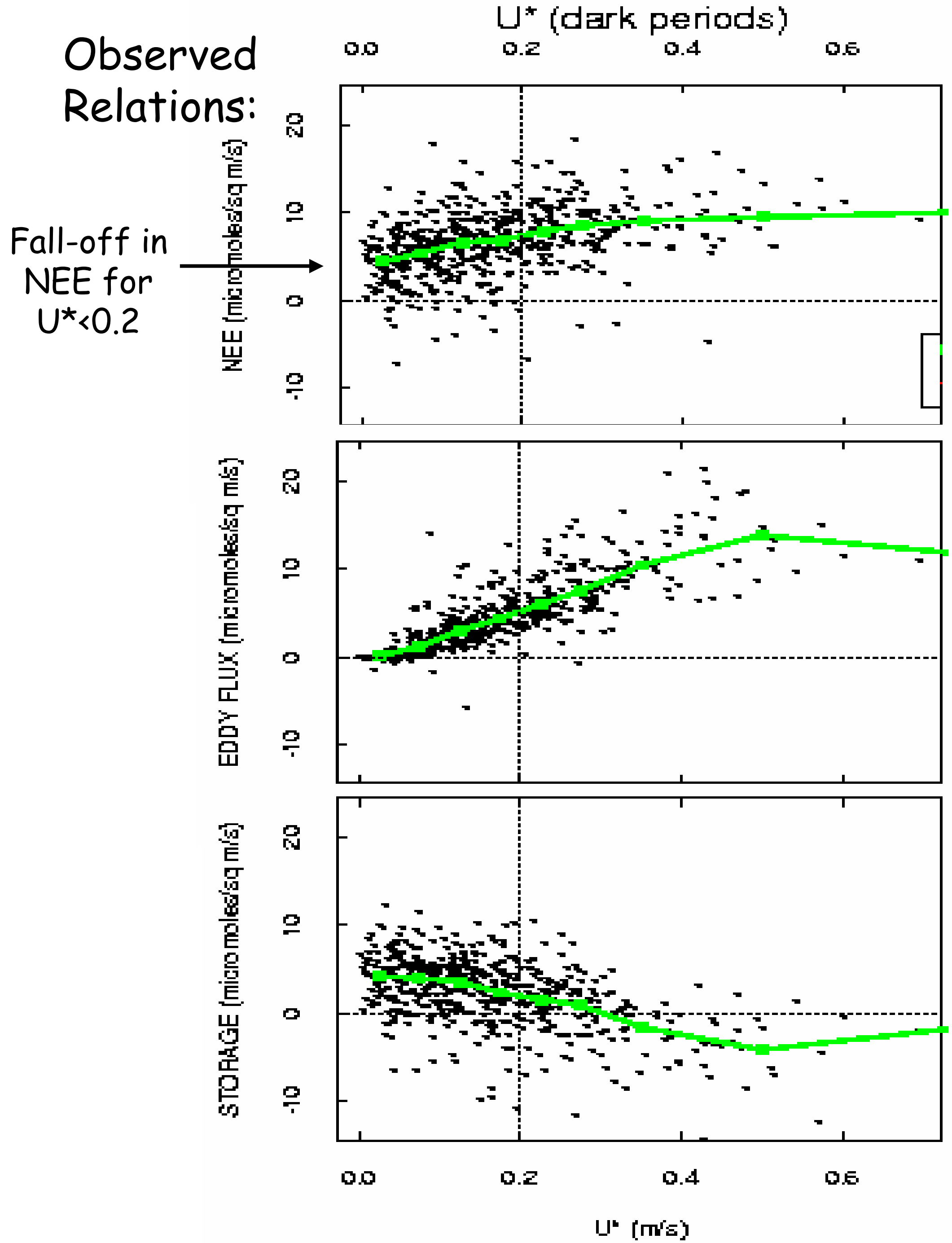
$$NEE = \underbrace{\text{Eddy Flux}}_{\text{Flux out the top}} + \underbrace{\frac{d}{dt}\langle \text{canopy storage} \rangle}_{\text{"Storage flux"}}$$

Q: Is there "lost flux"?

We expect total nighttime *NEE* (which depends only on the physiology of forest respiration), to be essentially *independent* of atmospheric turbulence.

Answer: Yes, it looks like it. As U* → 0, eddy flux decreases and storage flux increases as expected, but their sum (NEE) declines for U* < 0.2 m/sec:

Observed Relations:



Q: Is there "lost flux"?

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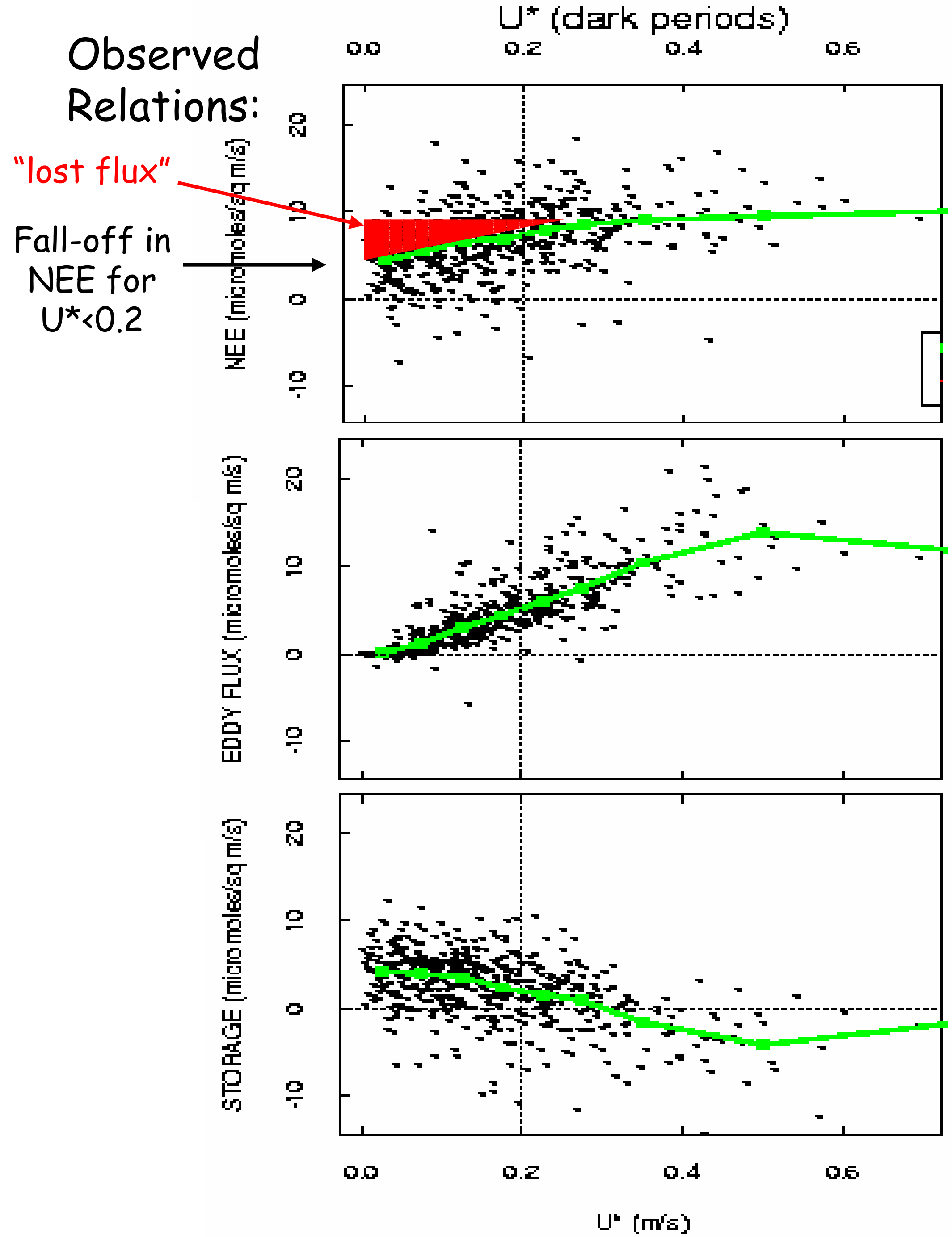
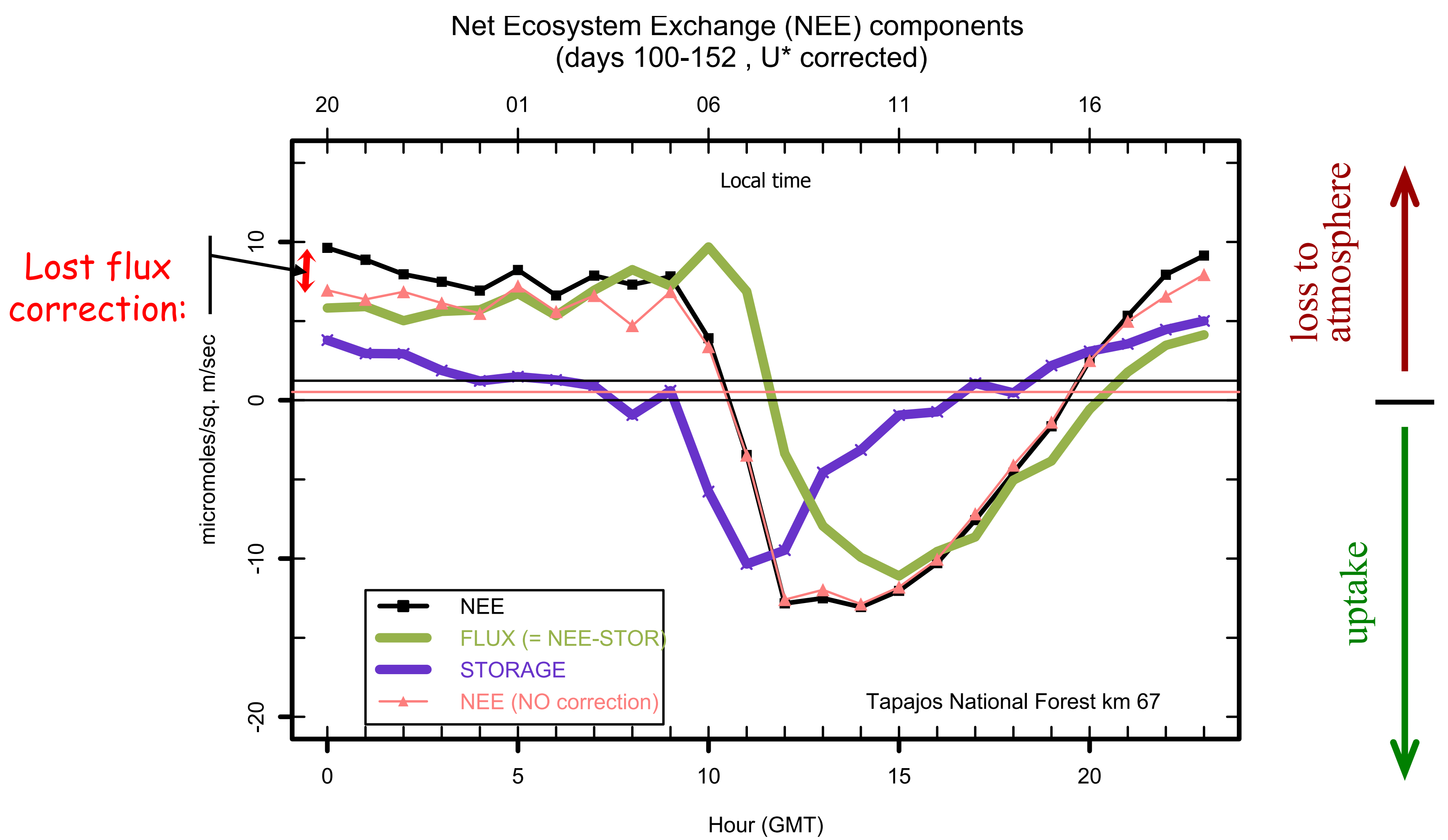
Answer: Yes, it looks like it. As U* → 0, eddy flux decreases and storage flux increases as expected, but their sum (NEE) declines for U* < 0.2 m/sec:

We take this as evidence of ***lost flux.***

Solution: u*-filter data, then fill with interpolation



Diurnal Flux pattern



Checks and tests of "lost flux" correction

1. Comparison between different towers in similar sites
2. Using continuous radon measurements as transport tracer
3. Scale up from small-scale chambers
4. Boundary layer budgets
5. Etc …

1st Comparison:

eddy flux data

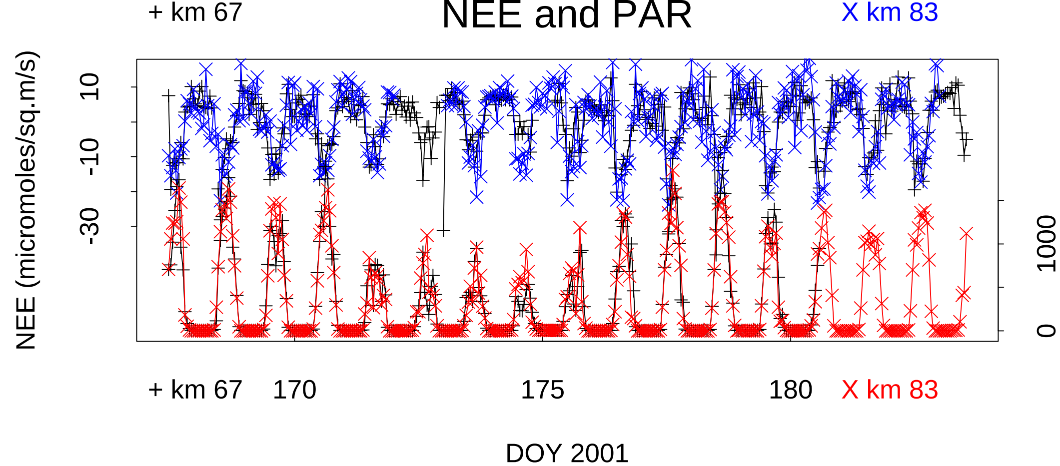
Km 67 site (Harvard), Tapajos forest

versus

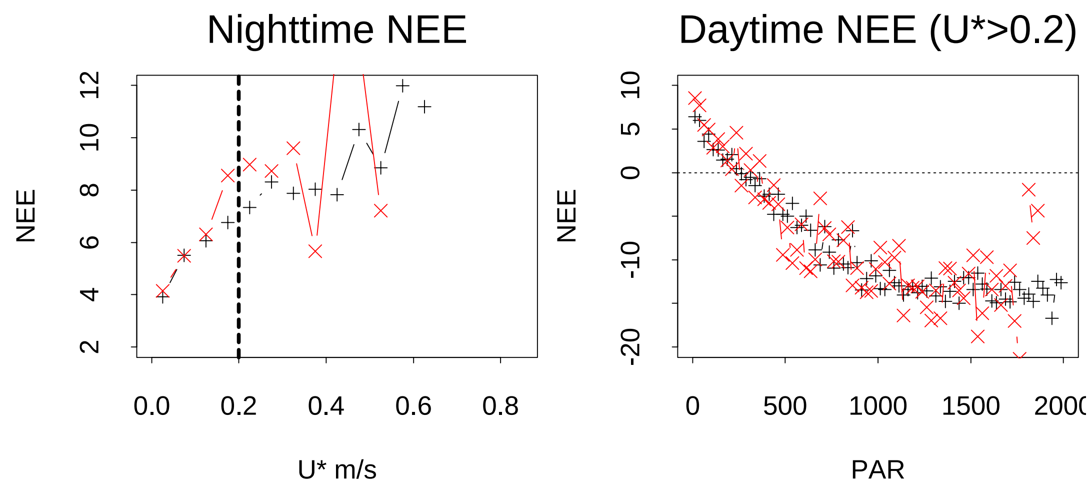
Km 83 site (UC Irvine), Tapajos forest

(1) Comparison between Tapajos sites: km67 vs. km83

(1) High coherence in timeseries of NEE and PAR

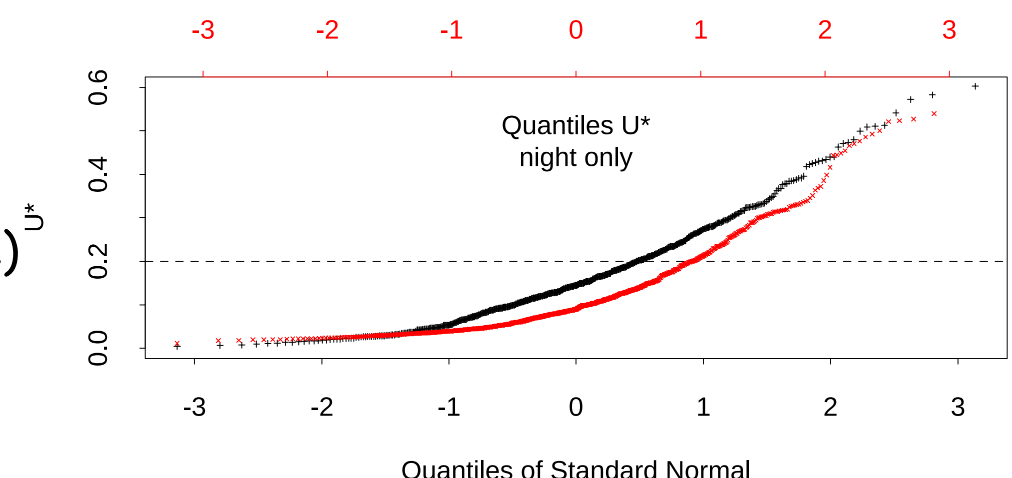


(2) Similar patterns in:
(a) Nighttime NEE vs. U*
(b) Daytime NEE vs. PAR

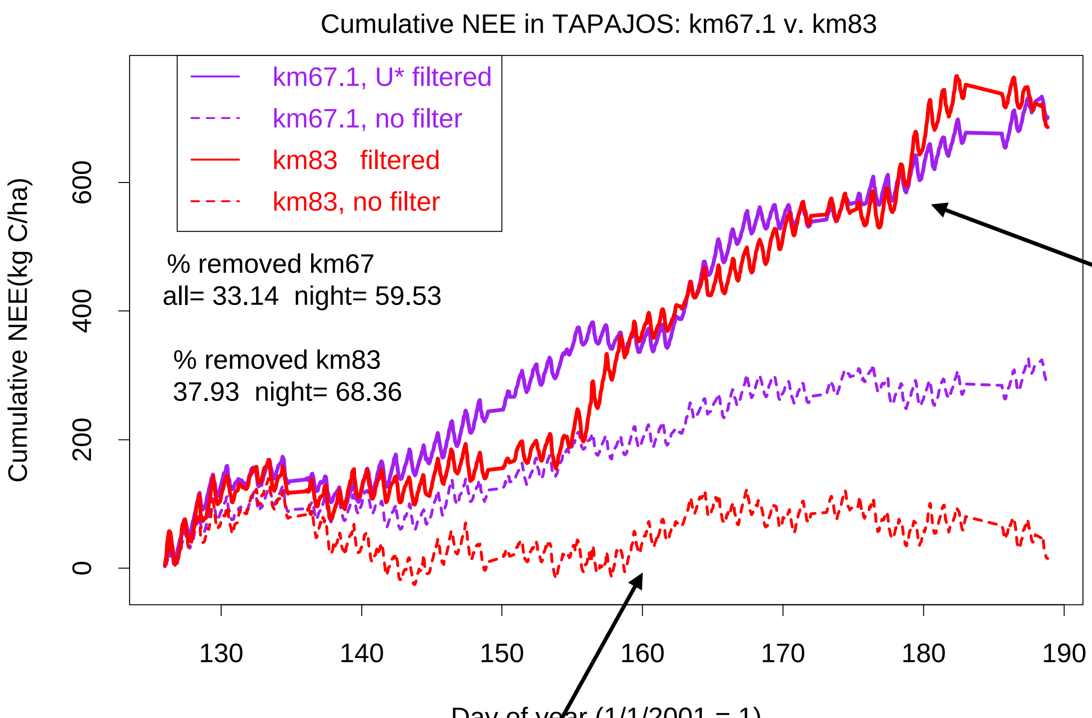


(3) Differing distributions in nighttime u*

(less turbulence at km 83 site)



Overlap time period between km67 and km83 eddy flux towers: cumulative NEE



…but u*-corrected NEE is almost identical between sites

Raw uncorrected uptake is higher (NEE less) at km83 (because of lower u* distribution…

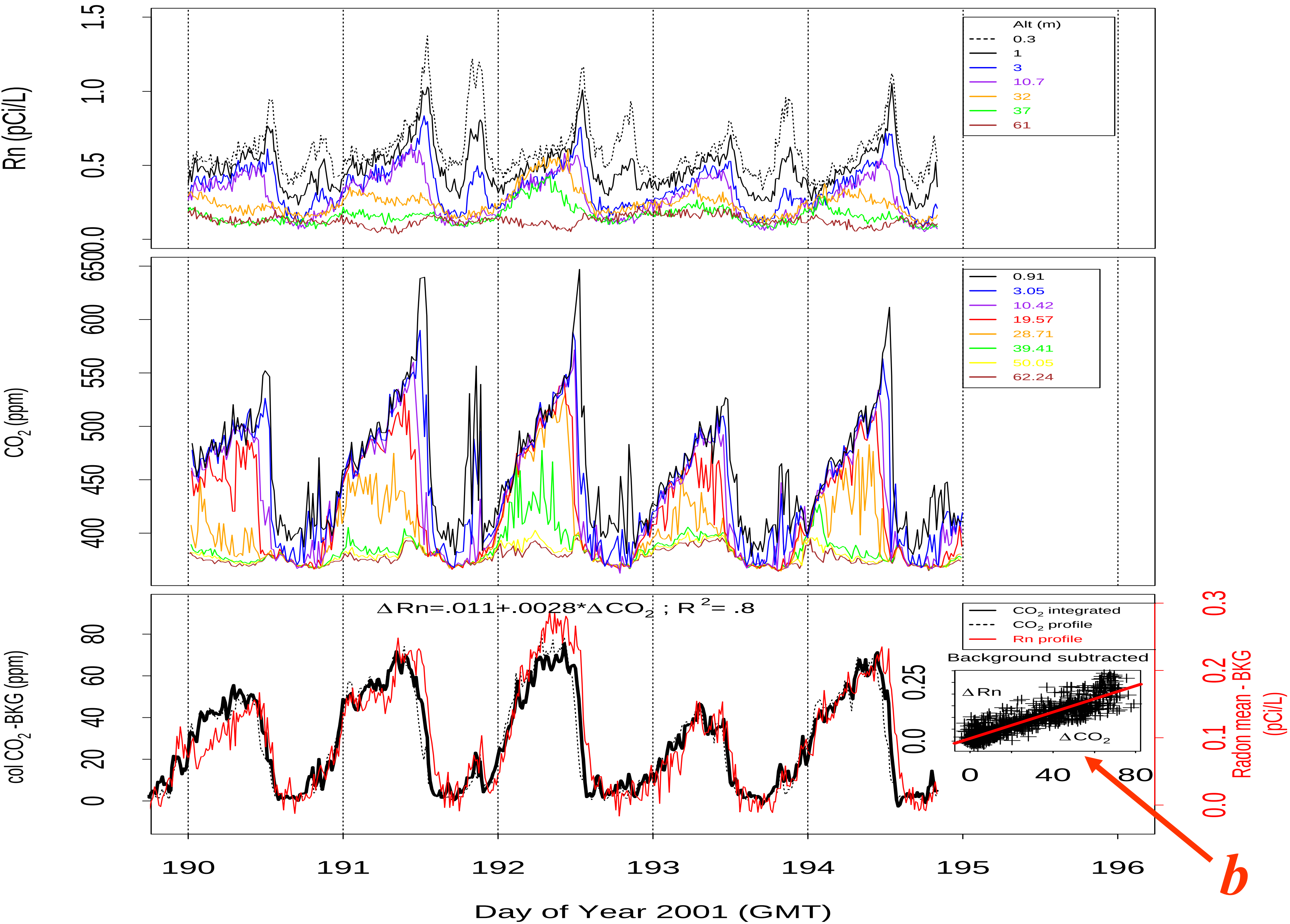
2^{nd} Comparison:

eddy flux data

with

continuous atmospheric radon (Rn) measurements

(collaboration with *Martens, Shay, UNC; Moraes, USP*)



$$(\langle Rn\rangle - Rn_t) = 0.011 + 0.0028\cdot(\langle CO_2\rangle - CO_{2\text{-}t}),\ R^2=0.8$$

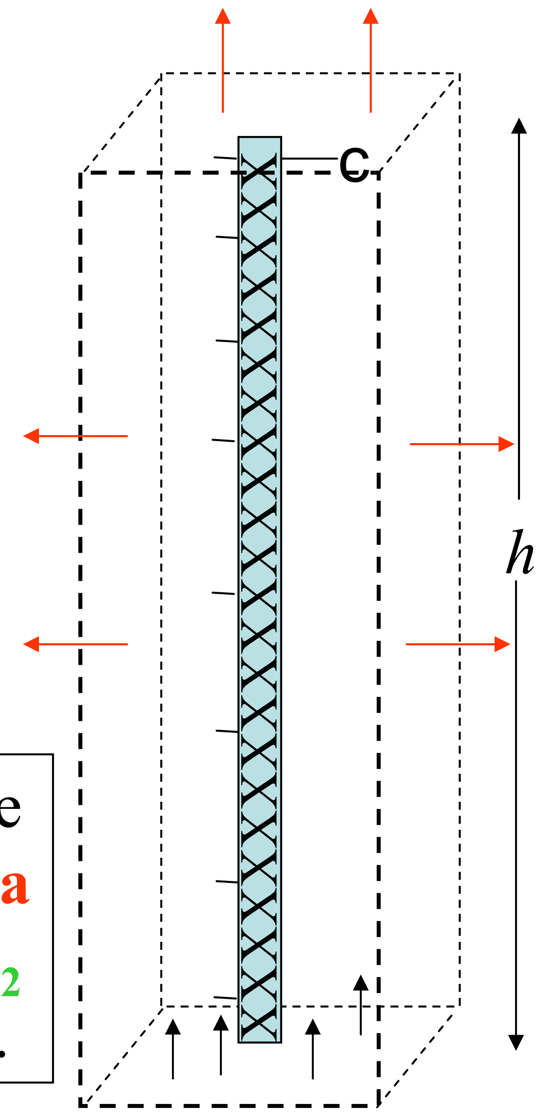
. Radon data from C. Martens, T. Shay, and O. Moraes.

Rn: *surface (soil) flux*

= storage flux

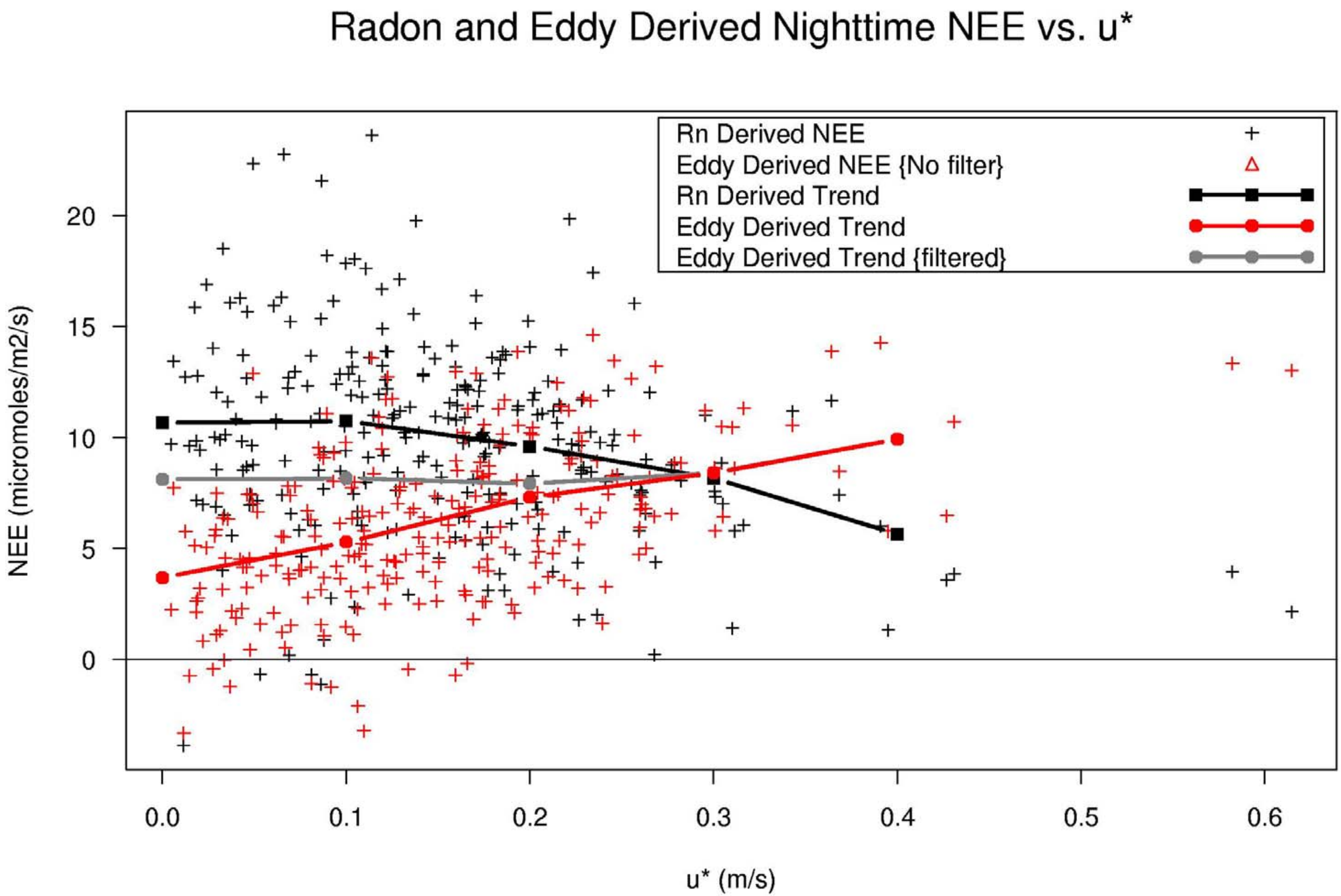
+ atmospheric transport flux

(Measured directly: surface (soil) flux, storage flux)



Independent CO_2 Net Ecosystem Exchange can be derived from **atmospheric and soil emission data for Rn**, plus **atmospheric concentrations of CO_2** (omitting reference to eddy flux data)(night only).

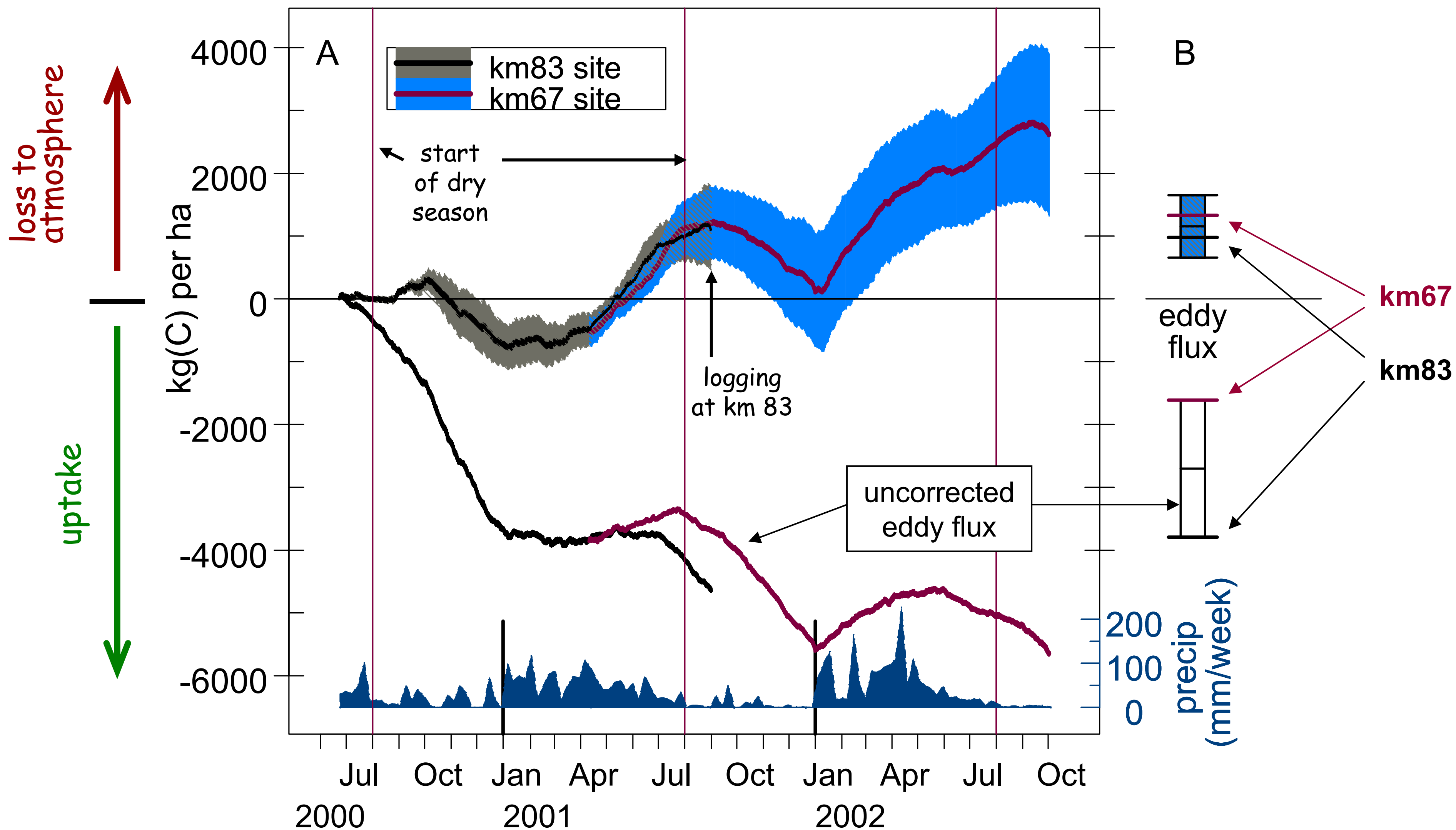
$$NEE = (1/h)\ \partial/\partial t \int CO_2\, dz + b \times \text{Rn-}transport\ flux$$


Radon and Eddy Derived Nighttime NEE vs. u*
Rn Derived NEE
Eddy Derived NEE {No filter}
Rn Derived Trend
Eddy Derived Trend
Eddy Derived Trend {filtered}
NEE (micromoles/m2/s)
0
5
10
15
20
0.0
0.1
0.2
0.3
0.4
0.5
0.6
u* (m/s)

Summary for Part 1

Cumulative Net Ecosystem Exchange (NEE) and precip

Average annual C-balance



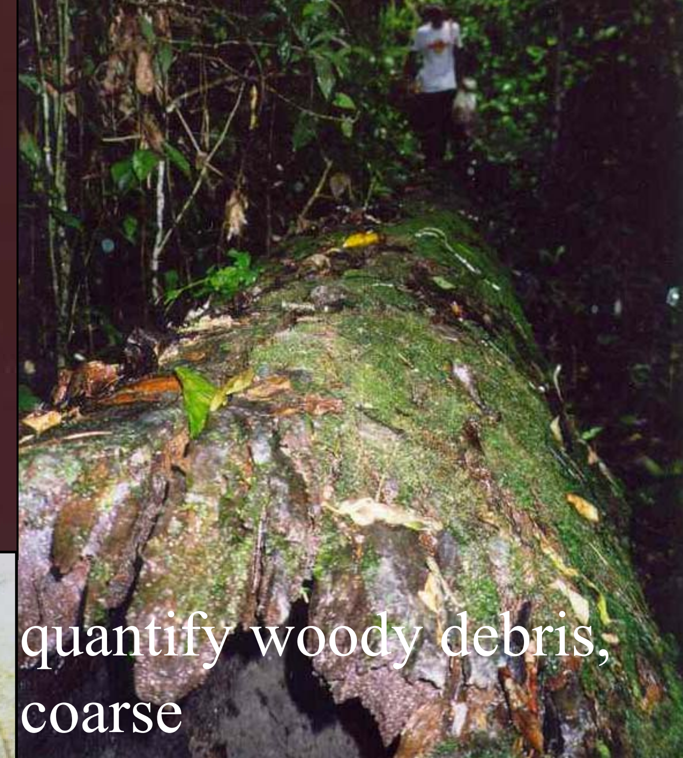
Some Questions

1. Why is the forest not in carbon balance?
2. Why is C-exchange seasonality the opposite of expectation?

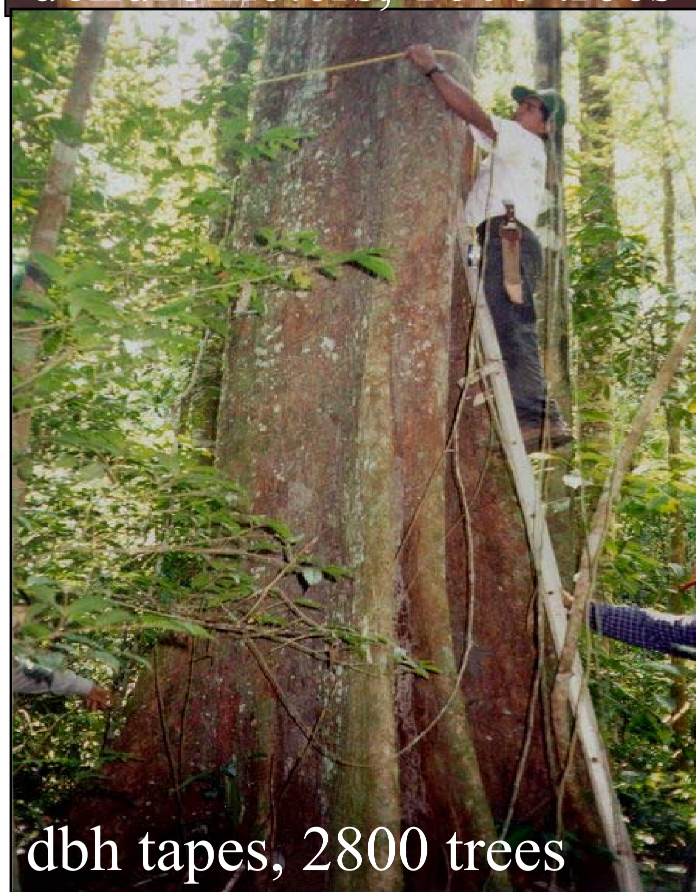
Part 2 (“the trees”):

Biometric Study of Tapajós Forest, km 67


dendrometers, 1000 trees

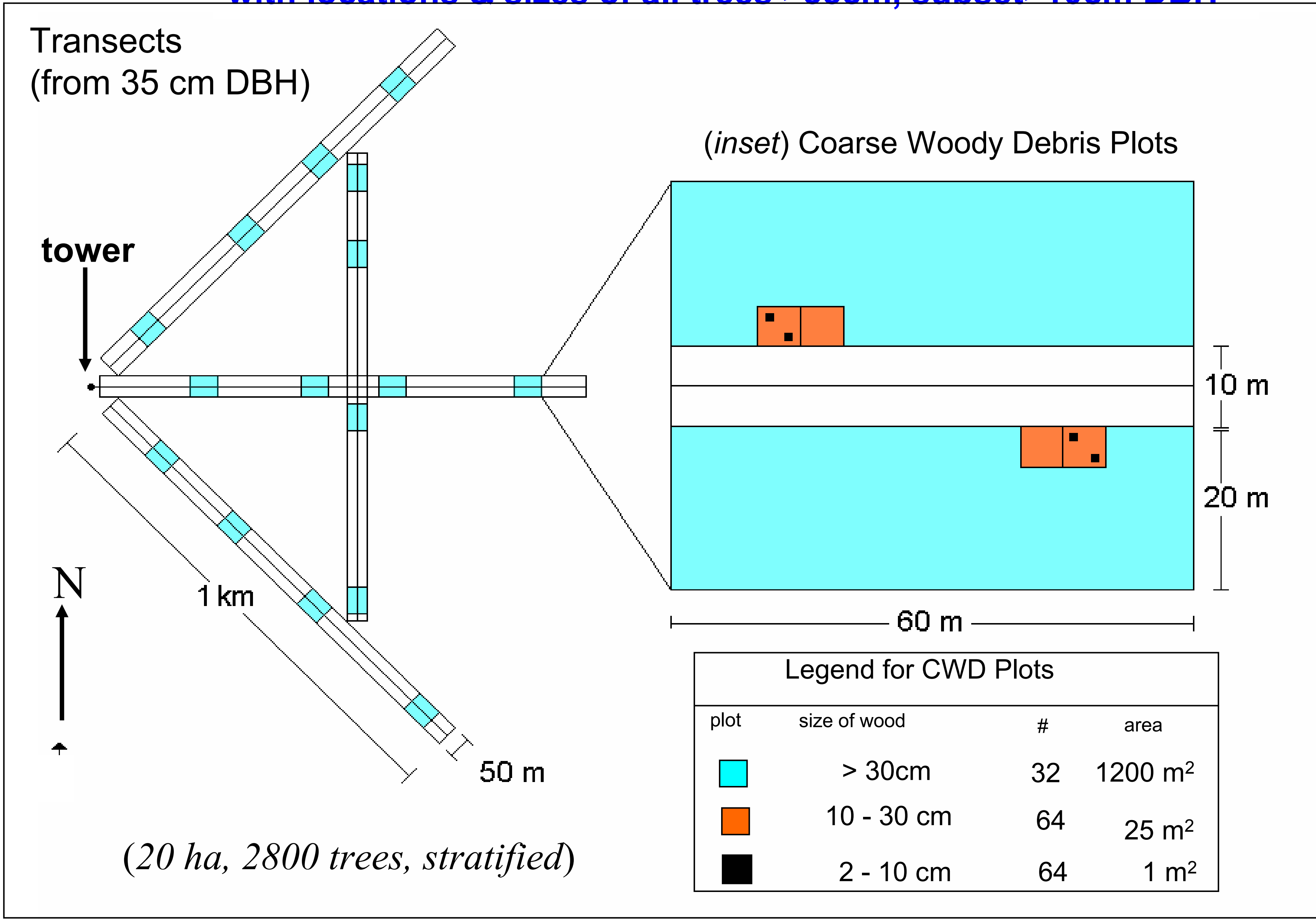

quantify woody debris, coarse


fine, and litter

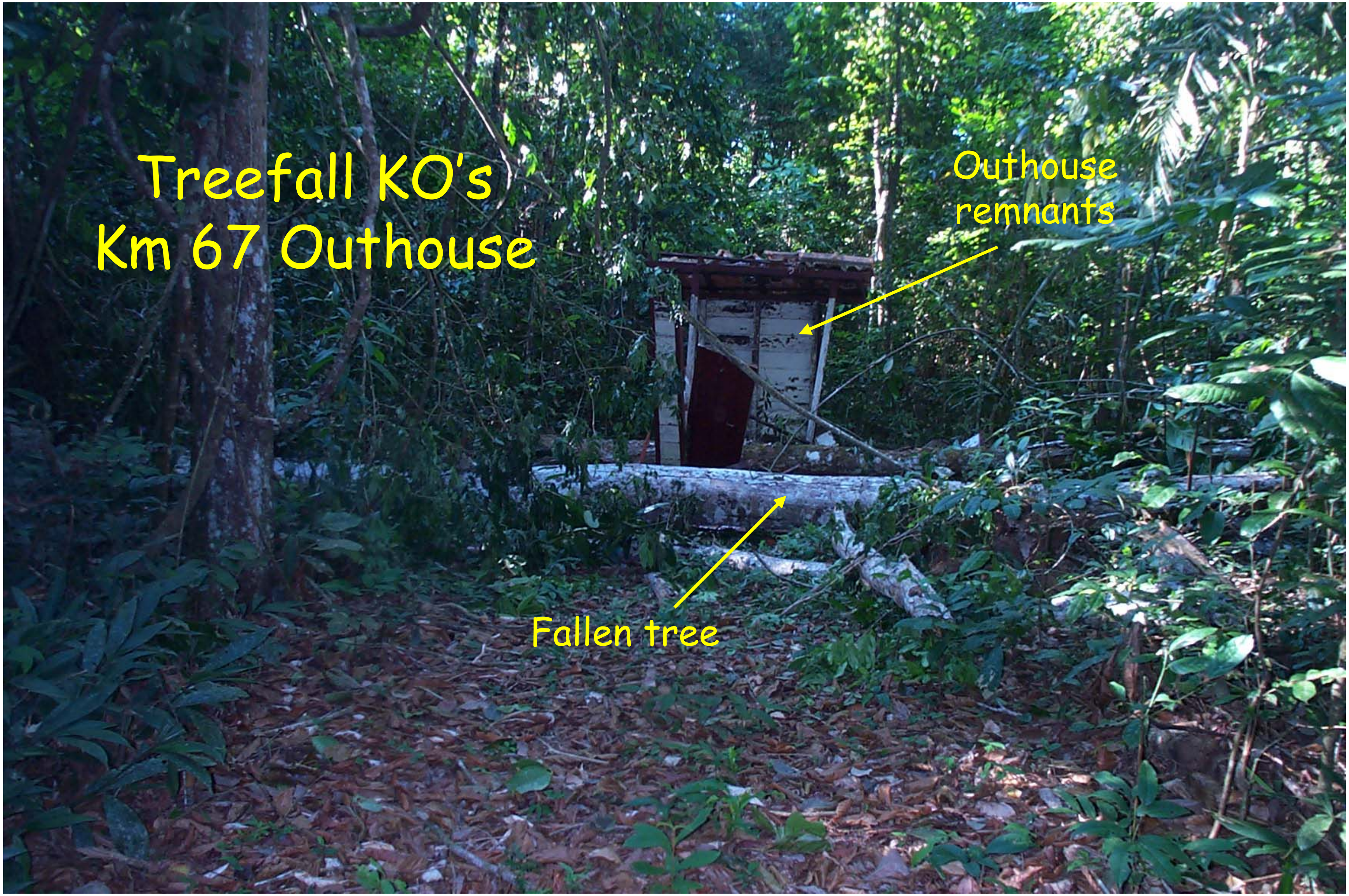

dbh tapes, 2800 trees

Biometry plots upwind of flux tower,

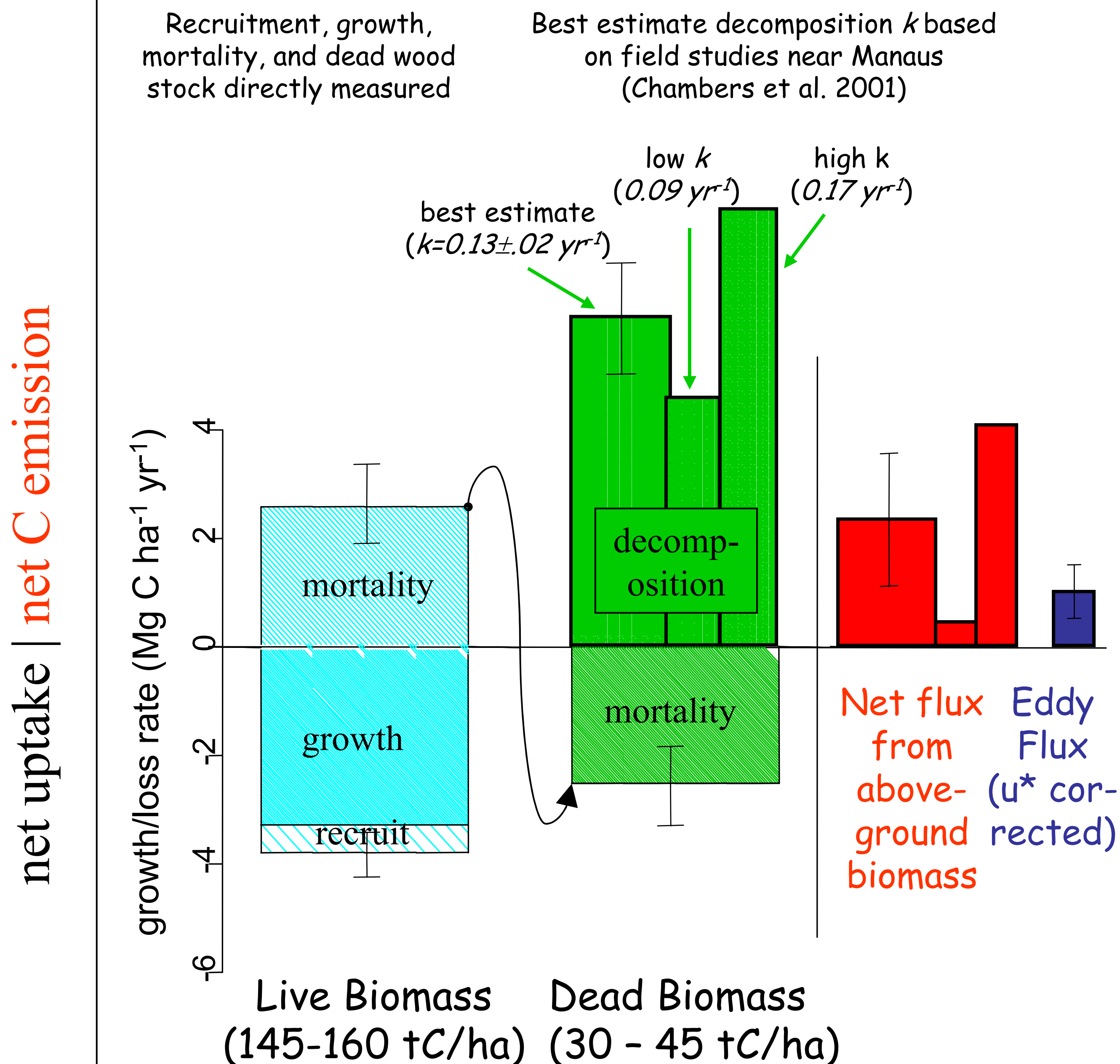
with locations & sizes of all trees >35cm, subset>10cm DBH



Working in the rainforest has many hazards



Carbon fluxes in live and dead biomass

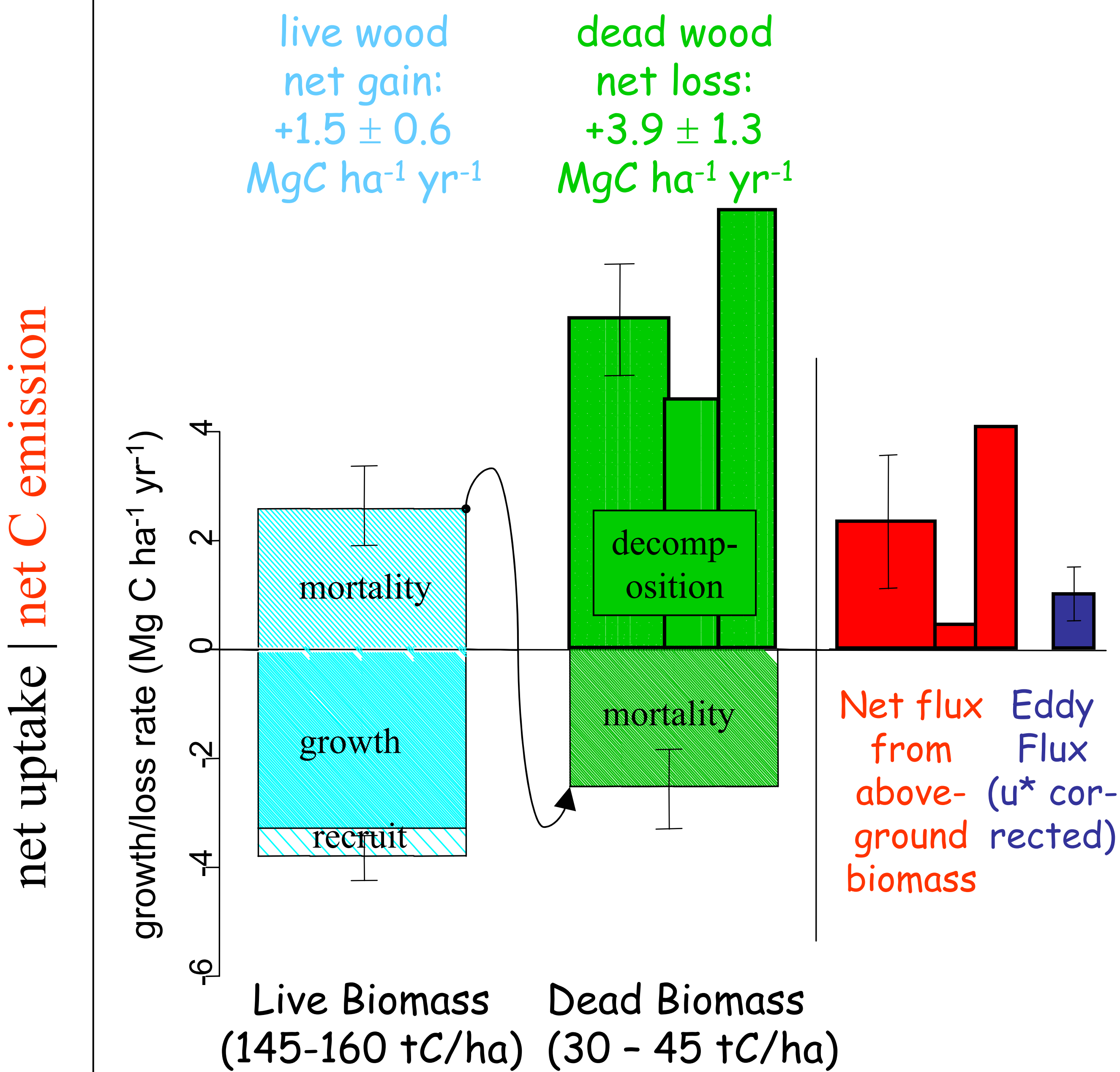


Net Flux for the Tapajos Forest between 1999 and 2001. The magnitude of the net flux is sensitive to the decomposition rate of the dead biomass, *k* (not yet directly measured).

Calculations were made using a maximum plausible range of literature values for *k*, all of which produce a negative net flux over this two year interval.

Biometry agrees with u*-corrected eddy flux

Carbon fluxes in live and dead biomass



Question 1:

Why is this forest not in carbon balance?

Three observations to consider:

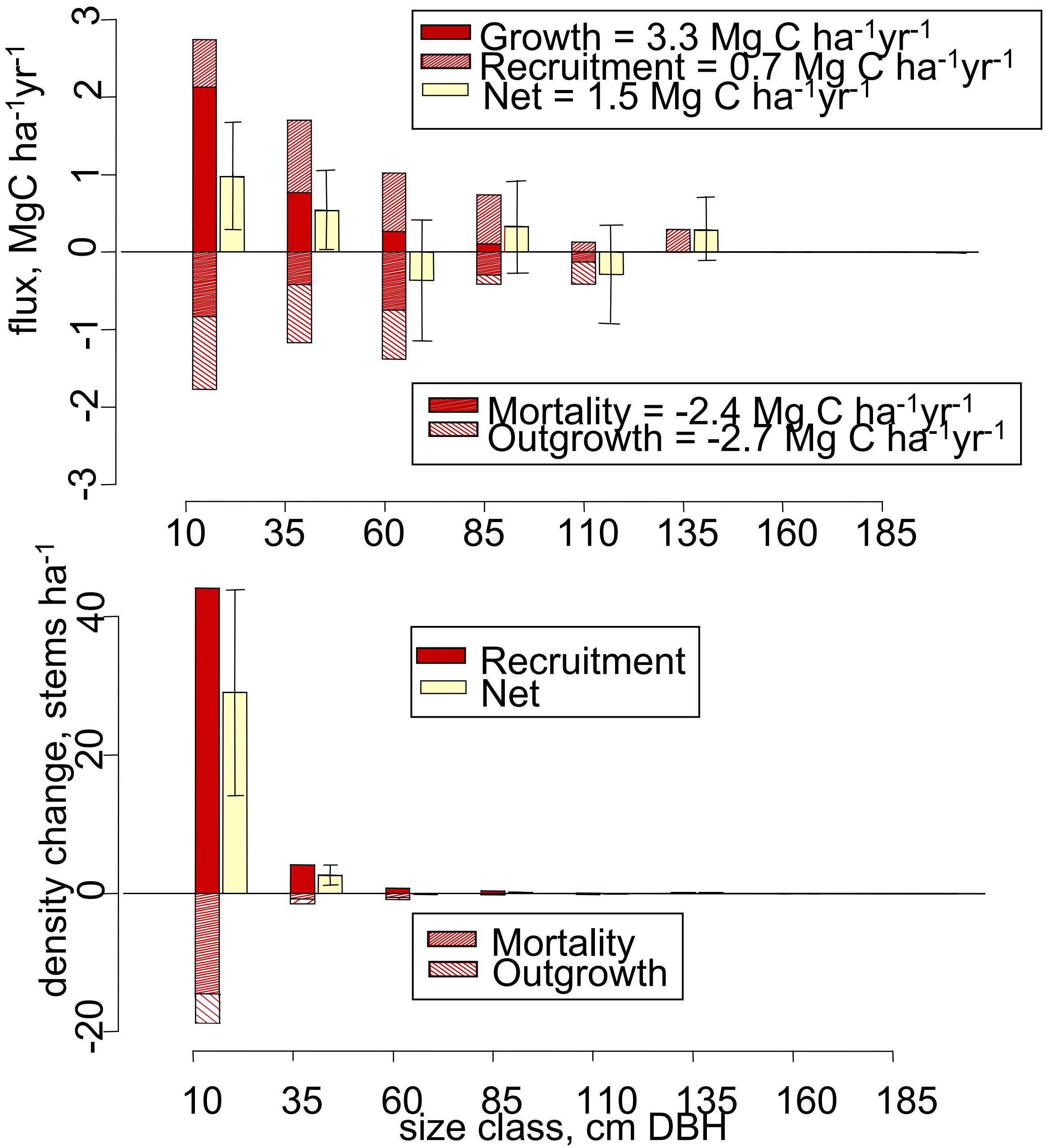
(1) The balance for live wood and dead wood is in opposite directions

(2) Stock of above-ground dead wood is exceptionally large:

- in comparison to other sites;
- relative to what is needed for steady-state

(≈ decade of mortality inputs to accumulate the excess dead wood stock)

Changes in biomass and tree number density, by size class



Question 1 (cont'd):

Why is this system not in carbon balance?

Observation 3:

Demographic shift:

(a) Increase in number density and biomass in the smaller size classes relative to larger

(b) exceptionally high recruitment (4.8%) compared to intact Amazon forest (0.8% - 2.8%; Phillips & Gentry, 1994)

Question 1:

Why is this forest not in carbon balance?

Hypothesis:

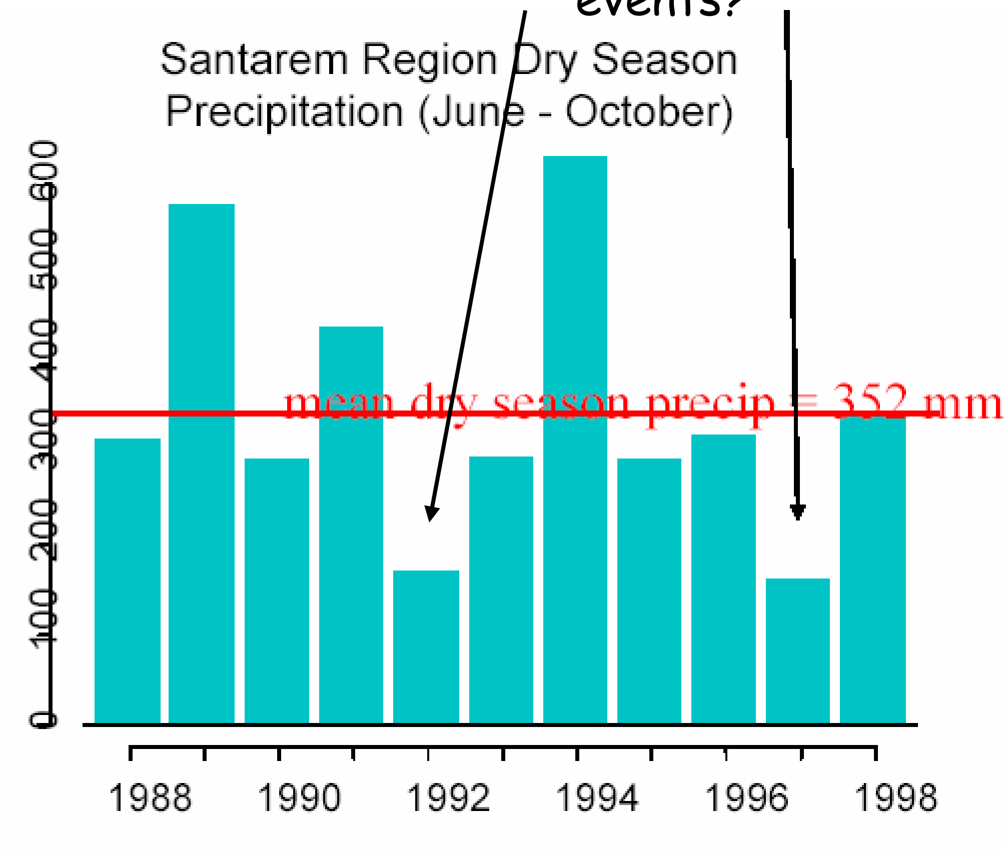
Tapajós forest site is recovering from recent episode(s) of disturbance which:

(1) Caused sharply elevated mortality preceeding onset of this study.

(2) Caused a large increase in dead wood pool (to the point where losses exceed inputs)

(3) Opened canopy gaps causing significant new growth and recruitment into smaller size classes of live wood (making overall growth uptake exceptionally high)

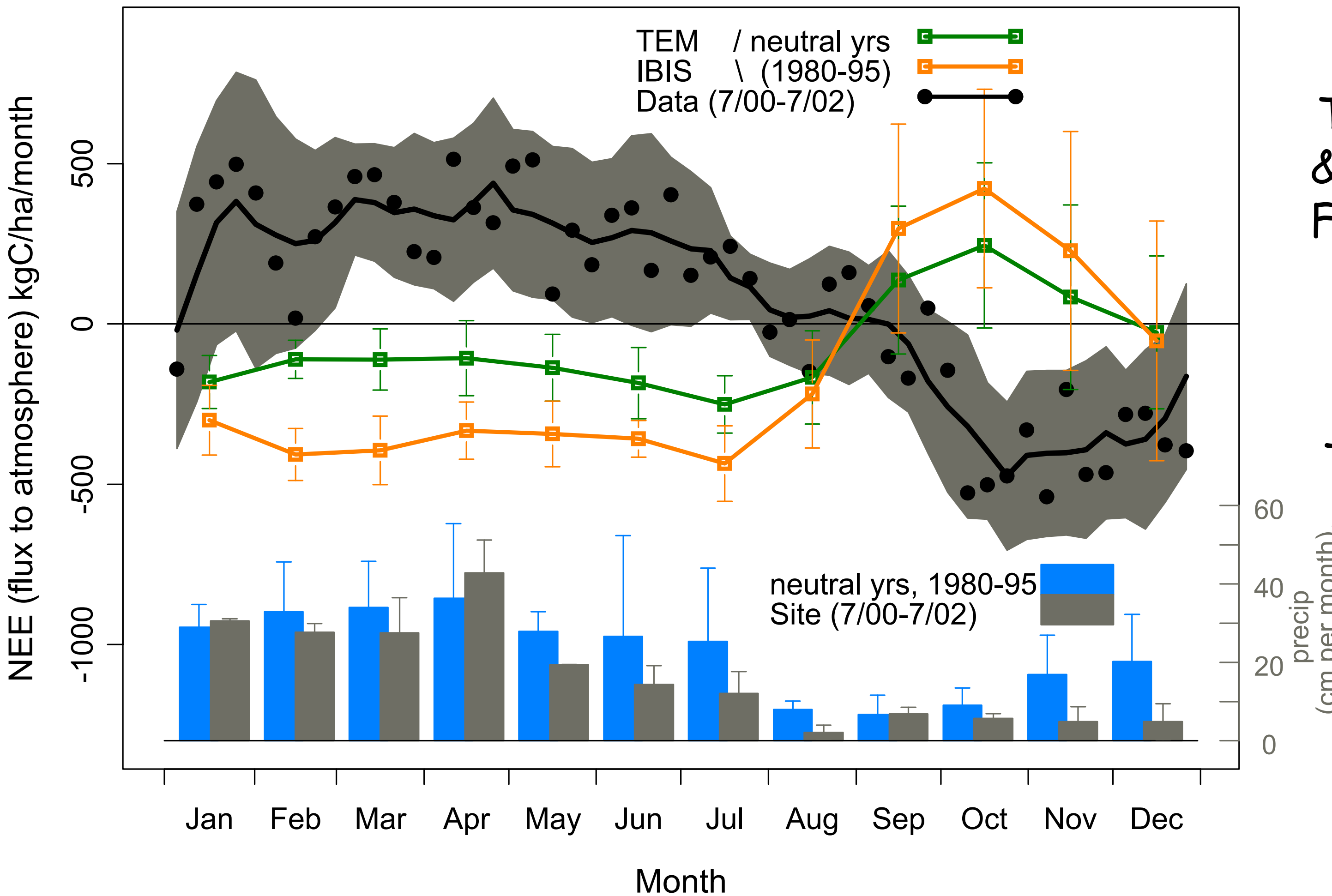
Perhaps contributed to by recent El Niňo events?



Condit et al. (1995), Williamson et al. (2000) link El Nino to elevated tree mortality

Question 2: Why is C-exchange seasonality the opposite of expectation?

Mean seasonal NEE and precipitation (± SD of interannual variation)



Output from:

TEM (Tian et al) & IBIS (Botta & Foley) models (8 years, colored lines)

data from Tapajos Forest sites (2 years, black line)

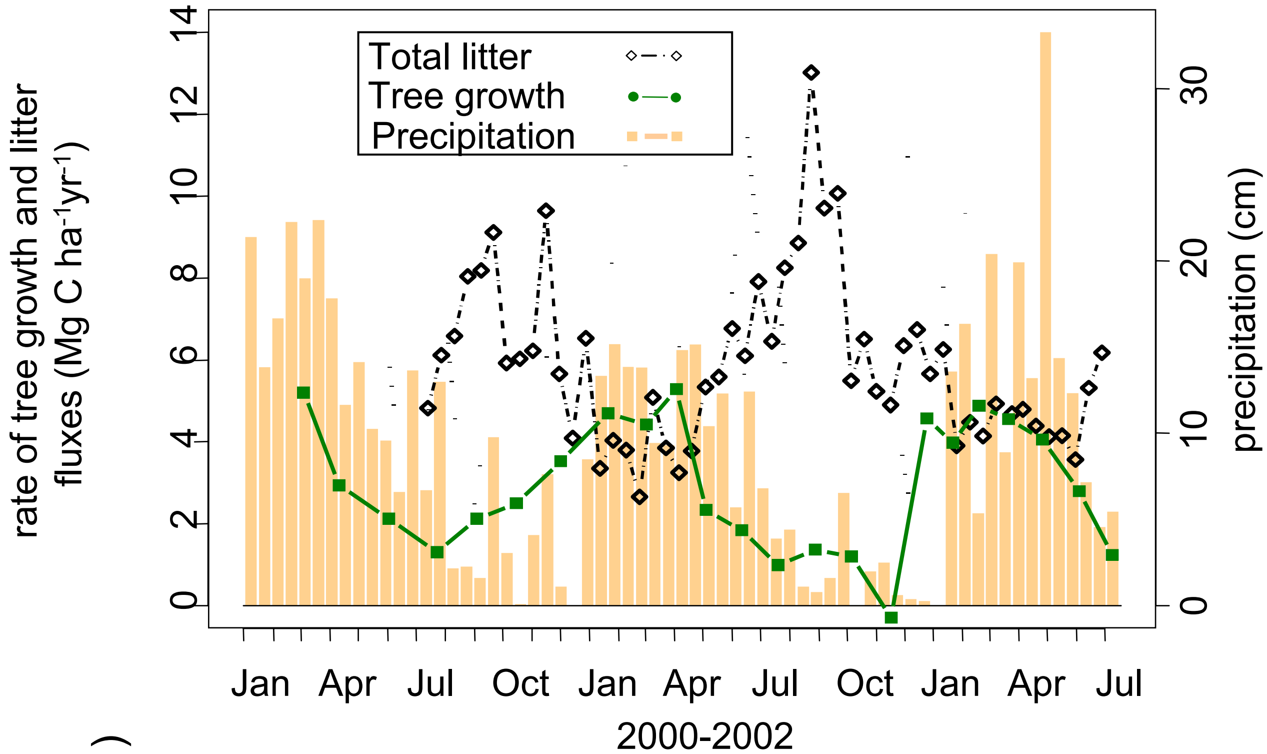
Model output is mean of 4 gridpoints: -54.5 > longitude > -55.5, -2.5 > latitude > -3.5, for neutral years 1980-81,1984-85,1990, & 1993-95.
Data is from Tapajos, km67 site (2.85 S, 55 W, from 10-Apr-01 to 08-May-02) & km83 site (3.05 S, 55 W, from 1-Jul-00 to 1-Jul-01).

Tree growth and precipitation are correlated:

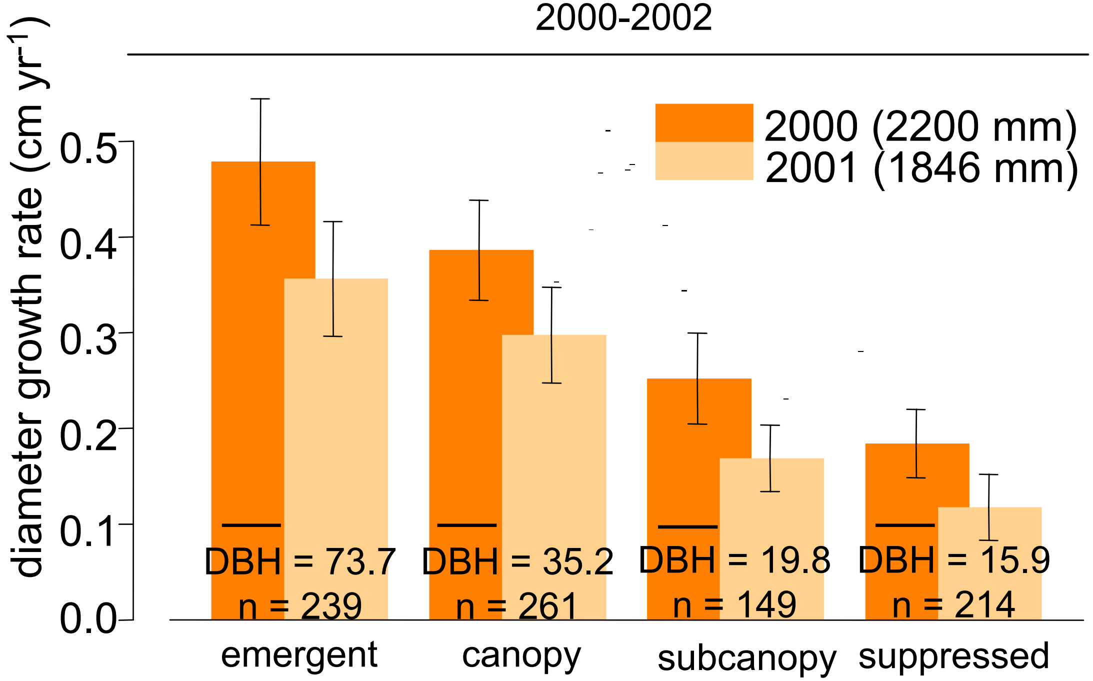
across months:

Tree growth = 1.1 + 0.31 * **precip** (mm/day)

(R^2 = 0.52)

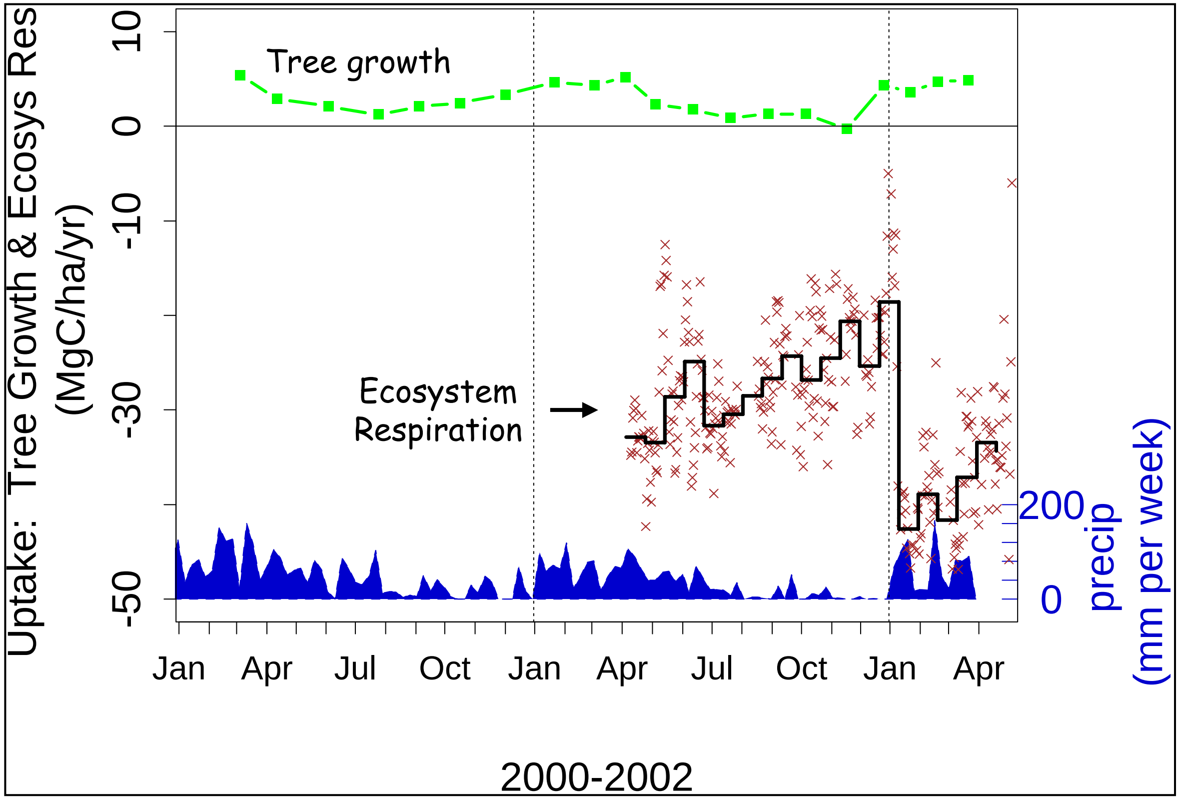


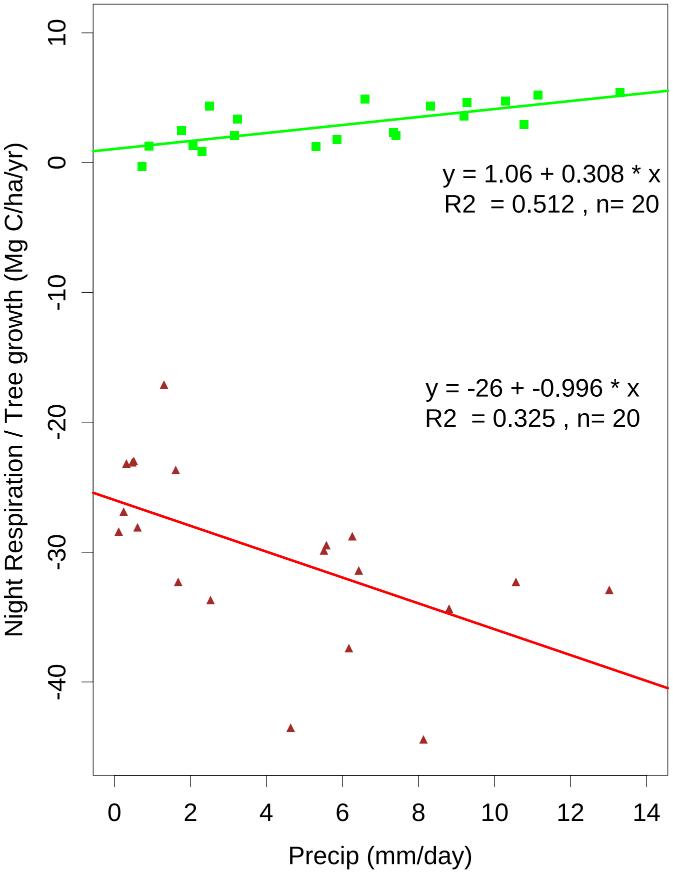
and across years:



Tree Growth & Ecosystem Respiration (nighttime NEE) both correlate with precipitation, but in opposite directions…

…but the Respiration response (negative) is stronger than the positive tree growth:



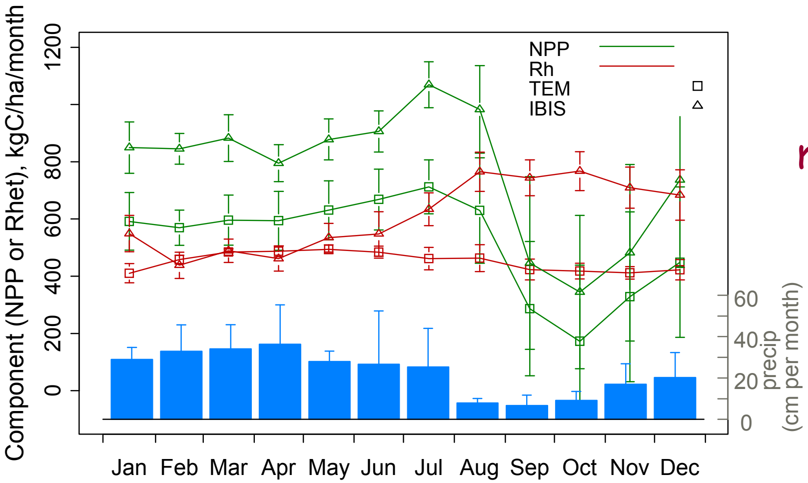


Data-model comparison

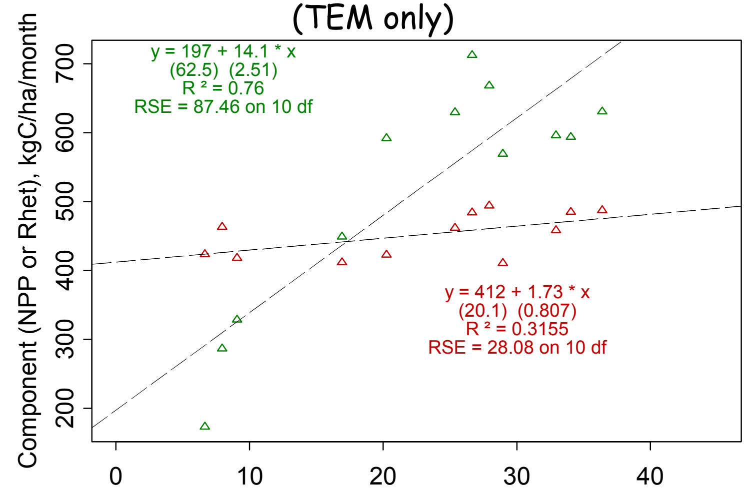
Components of modeled and measured seasonal NEP (TEM & IBIS models) and precip inputs (monthly mean +/- SD across 8 neutral years in 1980-1995)

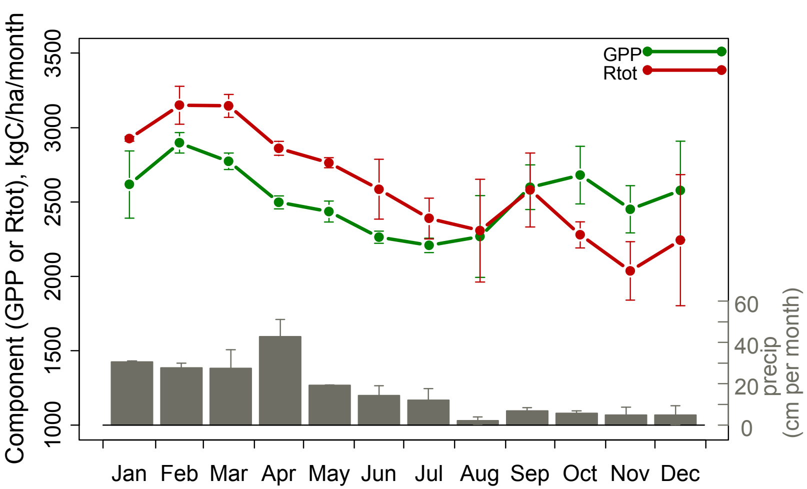
NEP components vs. precip inputs
monthly means of: Rh,
lagged NPP (next months NPP vs this months precip)

(TEM only)



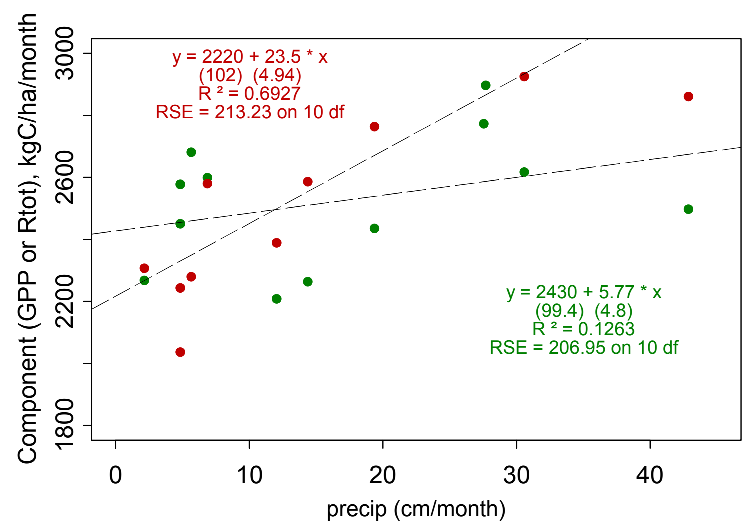
modeled





measured

(average across 2 sites & 2 years)



Note: Preliminary estimation of components based on assuming measured nighttime Rtot is representative of daytime Rtot. Note GPP/Rtot (B) are larger than NPP/Rhet (A) by R-autotroph.

Summary

- <u>Carbon balance:</u> net loss, because respiration losses from excess dead wood dominate gains from tree growth
  → transient disturbance-recovery dynamic – probably typical of old-growth forest, but not seen in eddy flux studies so far

Summary

- Carbon balance: net loss, because respiration losses from excess dead wood dominate gains from tree growth
  → transient disturbance-recovery dynamic – probably typical of old-growth forest, but not seen in eddy flux studies so far
- Seasonality: net loss during the wet season (even though tree growth is high), and uptake during the dry season
  → uptake processes less sensitive, respiration more sensitive } to short-term surface water variations
  than ecosystem models currently predict

Implications

- <u>for Eddy covariance studies:</u>
  ⟶ correcting for nighttime bias in eddy flux measurements (e.g. with a u* filter) is key

The u* filter is widely used for calculating annual sums

Published reports using u* filter

Valentini (1996)	Italy
Valentini (2000)	Italy
Pilegaard (2001)	Denmark
Cited in Valentini (2000)	Iceland
Black (1996)	Saskatchwan
Lee (1999)	Borden, Ontario
Schmid (2000)	Indiana
Aubinet, M Cited in Valentini	Belgium
Lindroth (1998)	Sweden
Valentini PI	Italy
Berbigier (2001)	France
Valentini (2000)	Germany
Bernhofer PI Cited in Valentini	Germany
A Ibrom PI Cited in Valentini	Germany
Dolman PI Cited in Valentini	Netherlands
Moncrieff PI Cited in Valentini	UK
Vesala PI Cited in Valentini	Finland
Hollinger (1999)	Howland
Goulden (1996)	Boreas
Malhi (1999)	Saskatchwan
Valentini (2000)	Italy
Suyker (2001)	Oklahoma
Barford (2001)	Harvard

Published reports not using u* filter

Malhi (1998)	(-5.9 tC/ha/yr)	Amazon
Grace (1996)	(-2.2 tC/ha/yr)	Amazon

E.g. Araujo et al. (2002), applied u* correction to data from the same site as Malhi et al. (1998), reducing uptake by 5 to 6 t C ha-1 yr^{-1}

Implications

- for Eddy covariance studies:
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- for forest plot-based biometry studies:
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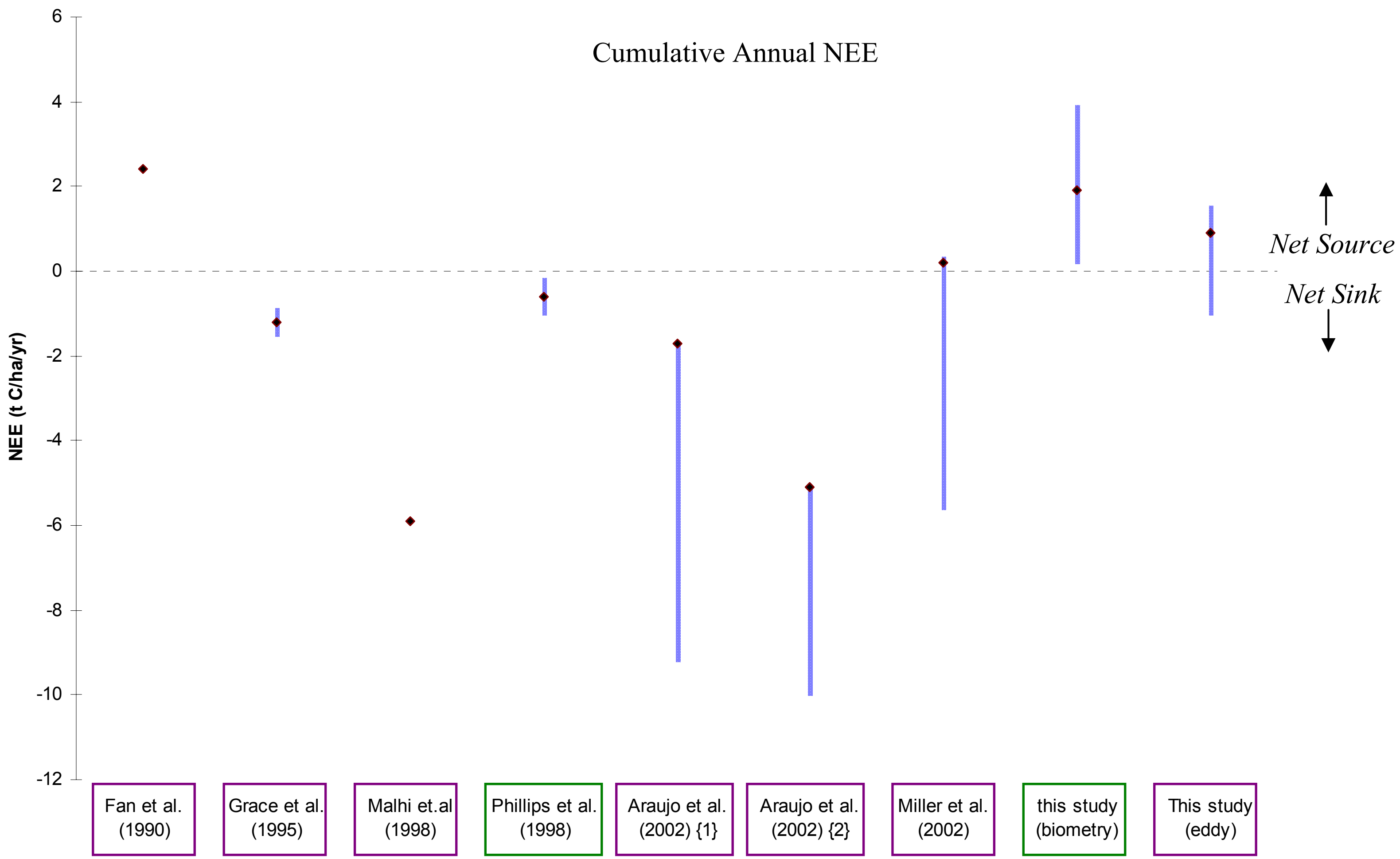
← the $64K question (not yet answerable by this study)

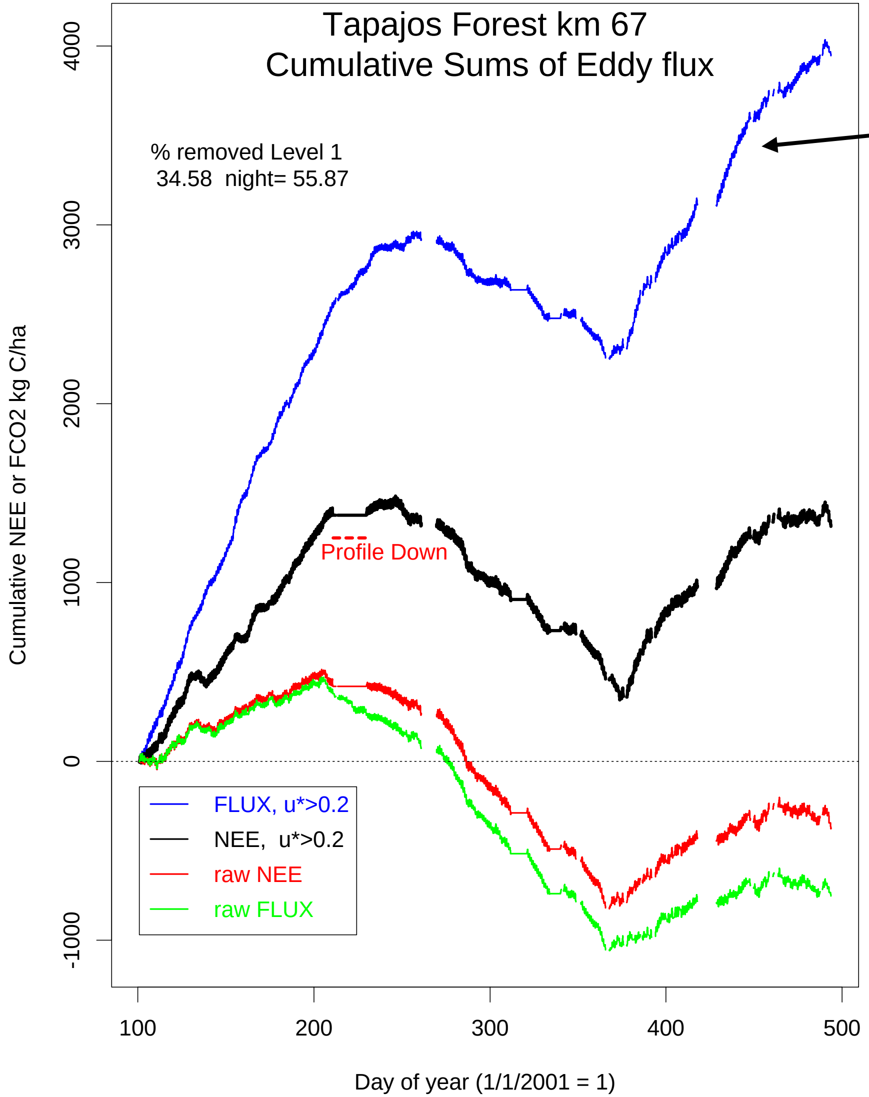
Undisturbed Amazonian forests: source or sink?

Summary of recent studies



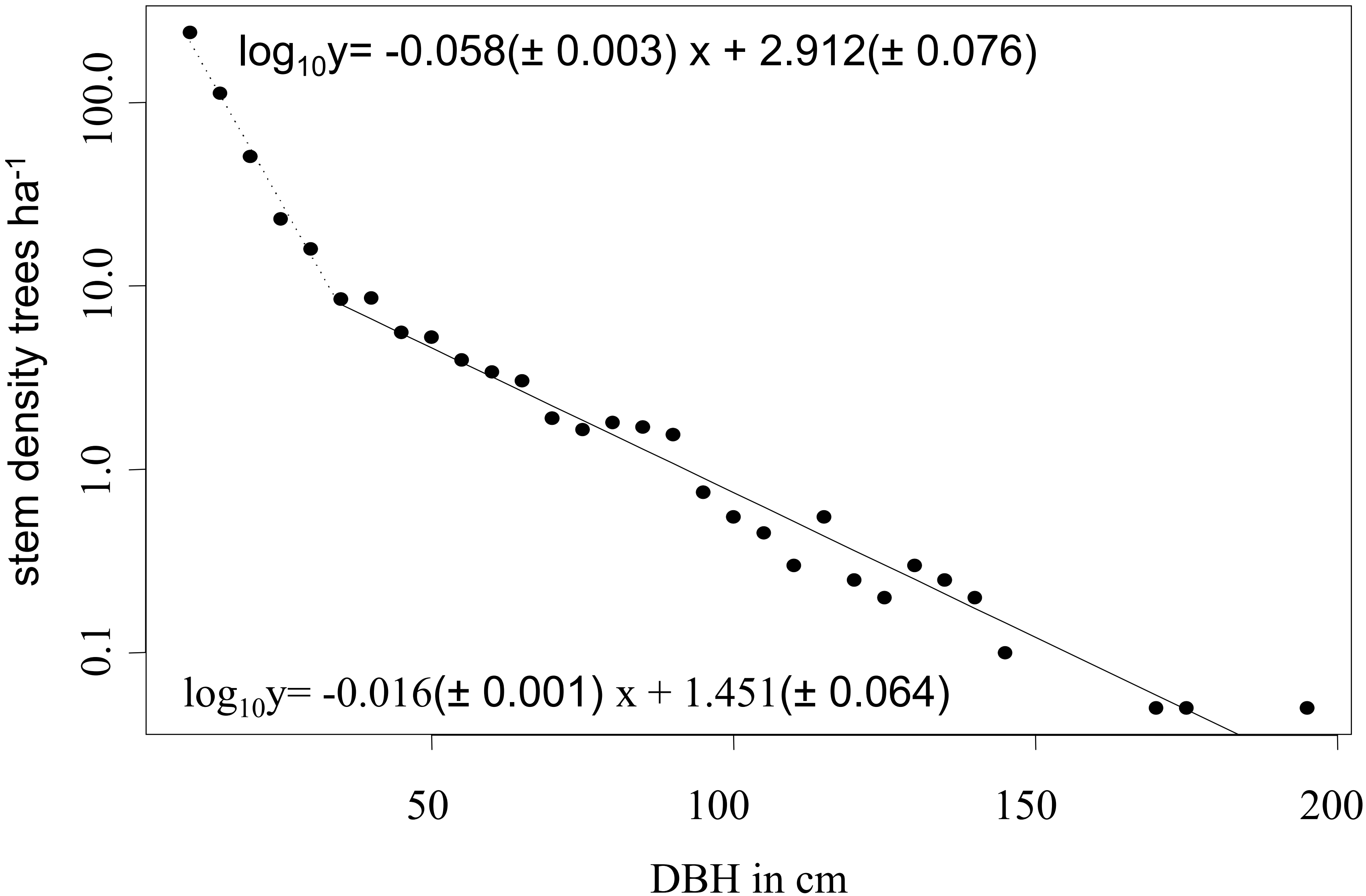
Caution!

There is a big difference between filtering and filling on FLUX versus on NEE



WRONG! This one double-counts efflux

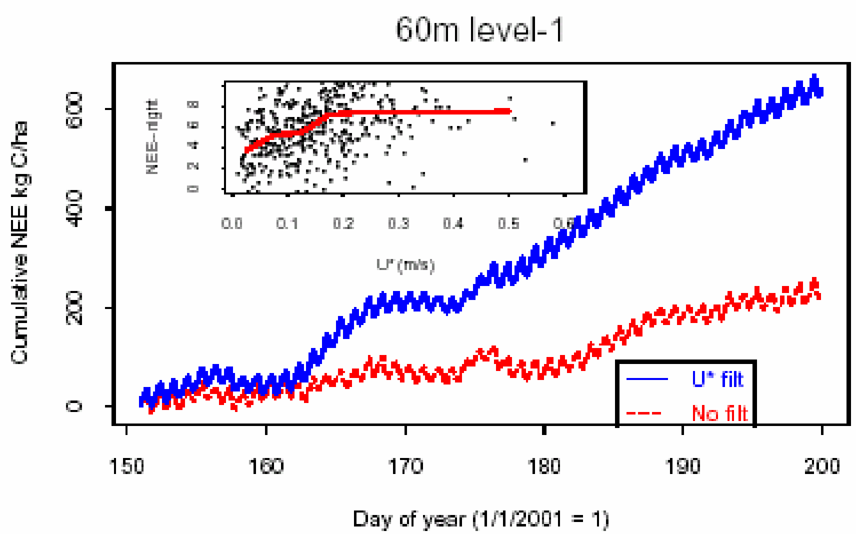
Log-linear stem density distribution



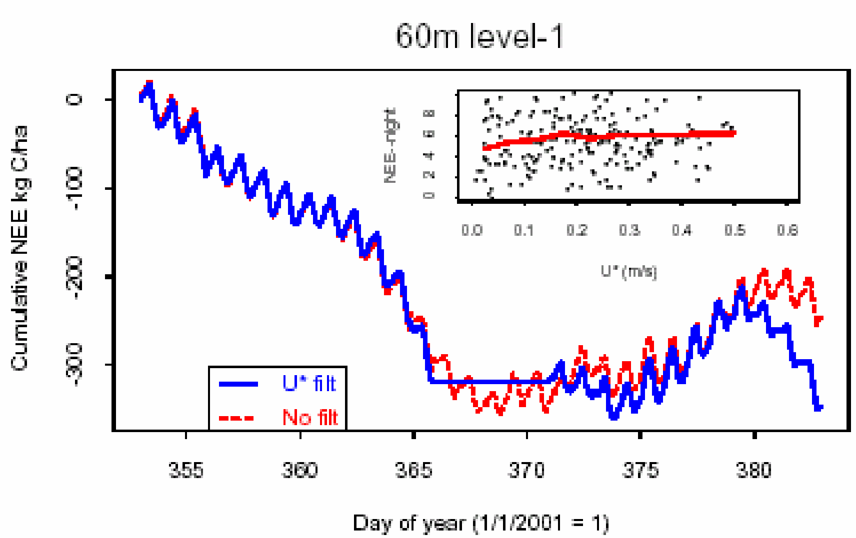
The U* filter correction:

- Is applied day and night
  (but has very little effect during most days)
- Needs to be applied to NEE (= sum of measured flux and storage), NOT to eddy flux alone.
- Is not always needed even at night

Mid wet-season (days 152-199) cumulative NEE showing net carbon loss and a significant effect of the u* filter correction.

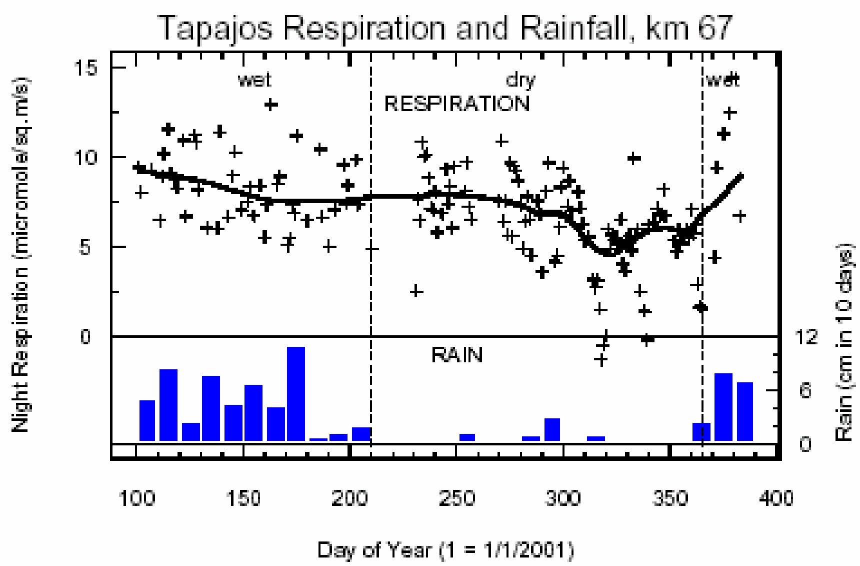


Late dry-season (days 355 – 380) cumulative level 1 NEE showing carbon uptake and little effect of u* filter.



(Inset graphs show the different relationships between nighttime NEE and U*, with very little "lost flux" in the dry season.)

Ecosystem respiration R (night NEE, U*>0.2), shows reduced R during the dry season, abruptly increasing when rains start (histogram);



NEE vs. PAR for dry season and wet season, showing greater net uptake in the dry season. Most of the increased uptake could be attributed to lower respiration rates.