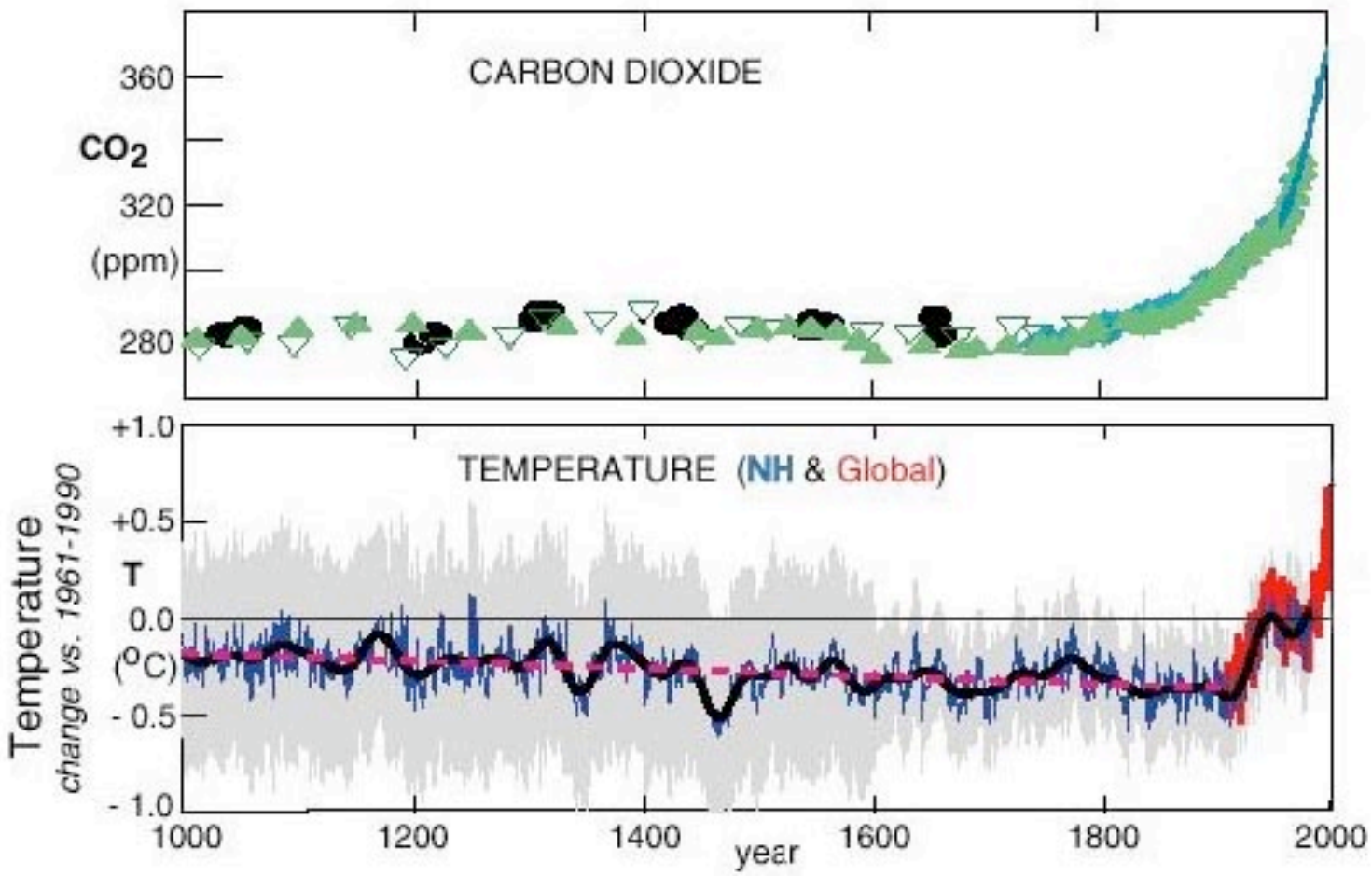
Carbon Cycling
in Tropical and Boreal Forests

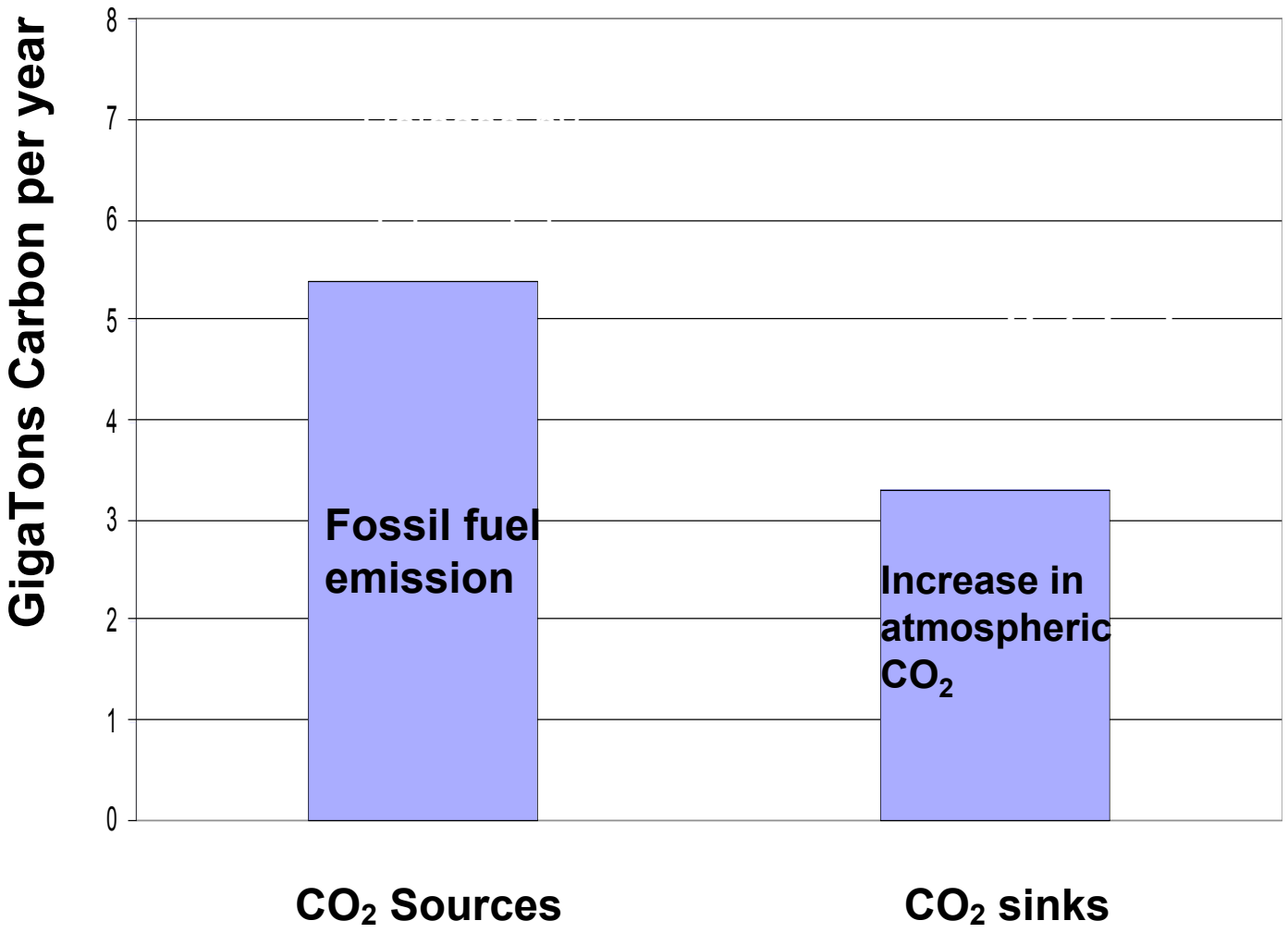
Scott Miller
University of California, Irvine

Is the increase in global mean temperature a result of increases in Greenhouse gases (CO_2, CH_4, N_2O)?

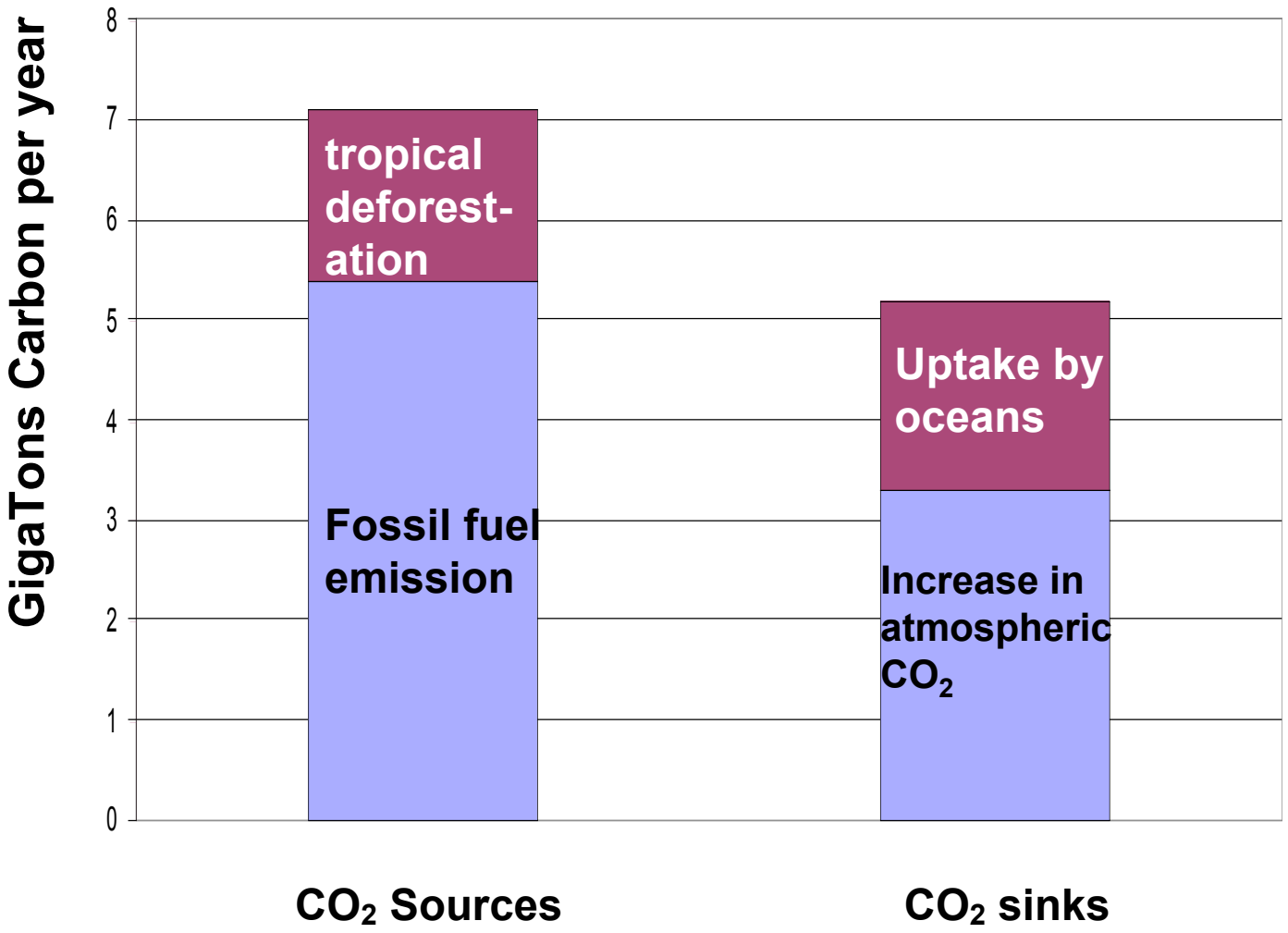


From: IPCC, Third Assessment Report, 2000

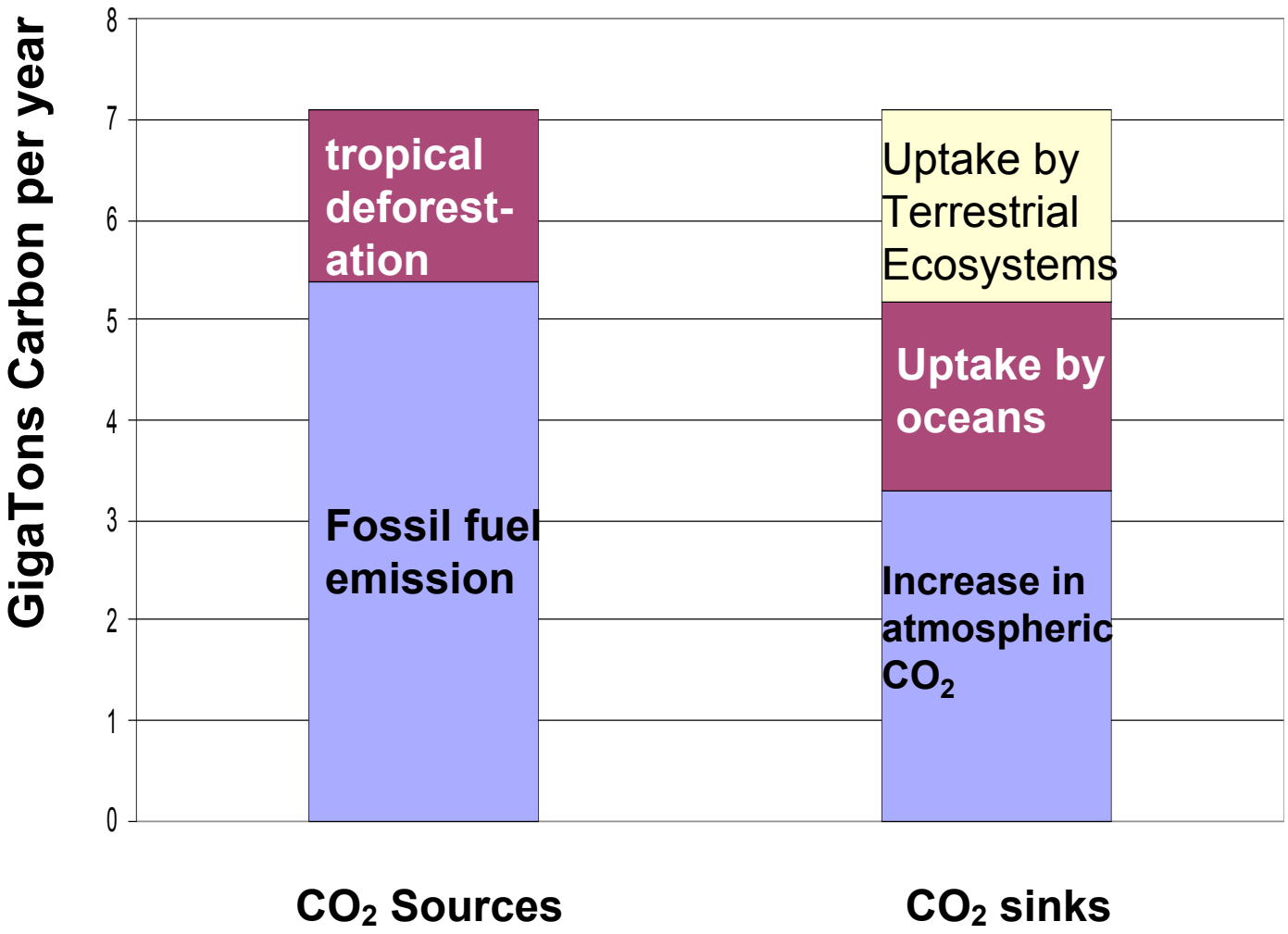
The Global Carbon Budget: Terms we *know well*



The Global Carbon Budget: Terms we *kind of know*



The Global Carbon Budget: Terms we *don't know well*



Big, unanswered questions include:

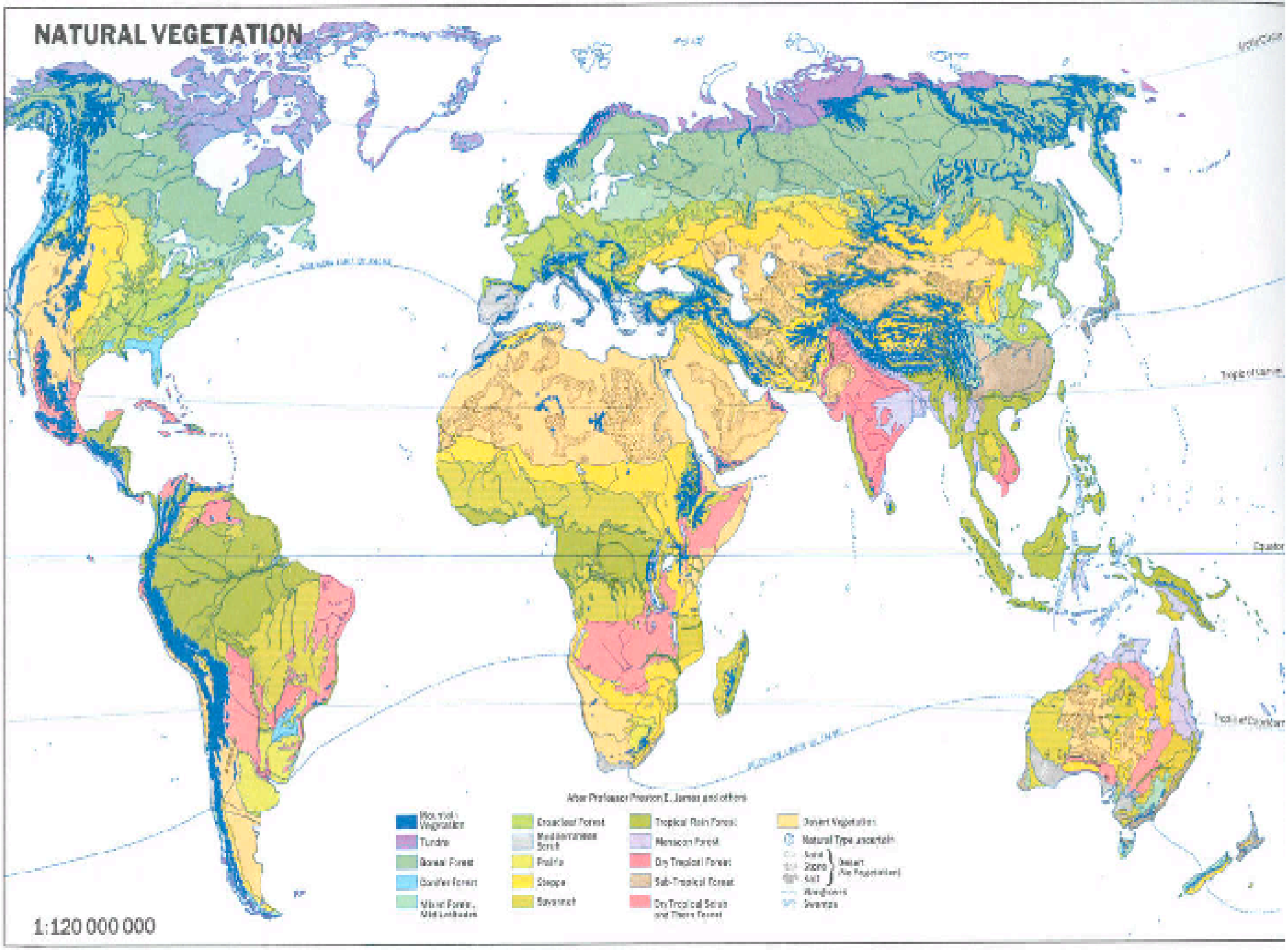
What ecosystems are storing carbon?

Why are ecosystems storing carbon?

What determines how much carbon an ecosystem stores?

How much longer will ecosystems continue storing carbon?

Kyoto Protocol (1997) - carbon trading, credits for carbon sequestration


NATURAL VEGETATION
Equator
After Professor Preston E. James and others
Mountain Vegetation
Tundra
Boreal Forest
Conifer Forest
Mixed Forest, Mild Latitudes
Deciduous Forest
Mediterranean Scrub
Prairie
Steppe
Savannah
Tropical Rain Forest
Monsoon Forest
Dry Tropical Forest
Sub-Tropical Forest
Dry Tropical Scrub and Thorn Forest
Desert Vegetation
Natural Type uncertain
Sand
Stone
Salt
Desert (No Vegetation)
Mangroves
Swamps
1:120 000 000

Distribution of Carbon Pools

	Area (10^{12} m^2)	Plant C (kg C m^{-2})	Soil C (kg C m^{-2})	Total C (10^{15} gC)
Tropical forest	**18.1**	**11.5**	**10.4**	**400**
Temperate forest	9.2	8	11.8	170
Boreal forest	**15**	**9.5**	**14.9**	**370**
Desert	18.2	0.3	5.6	110
Tundra	11	0.8	21.6	250
Wetland	2.9	2.7	68.6	210
Global				**~2000**

Tropical and boreal forests account for about 50% of terrestrial carbon

Tropical forest carbon is in biomass, boreal is in soil.

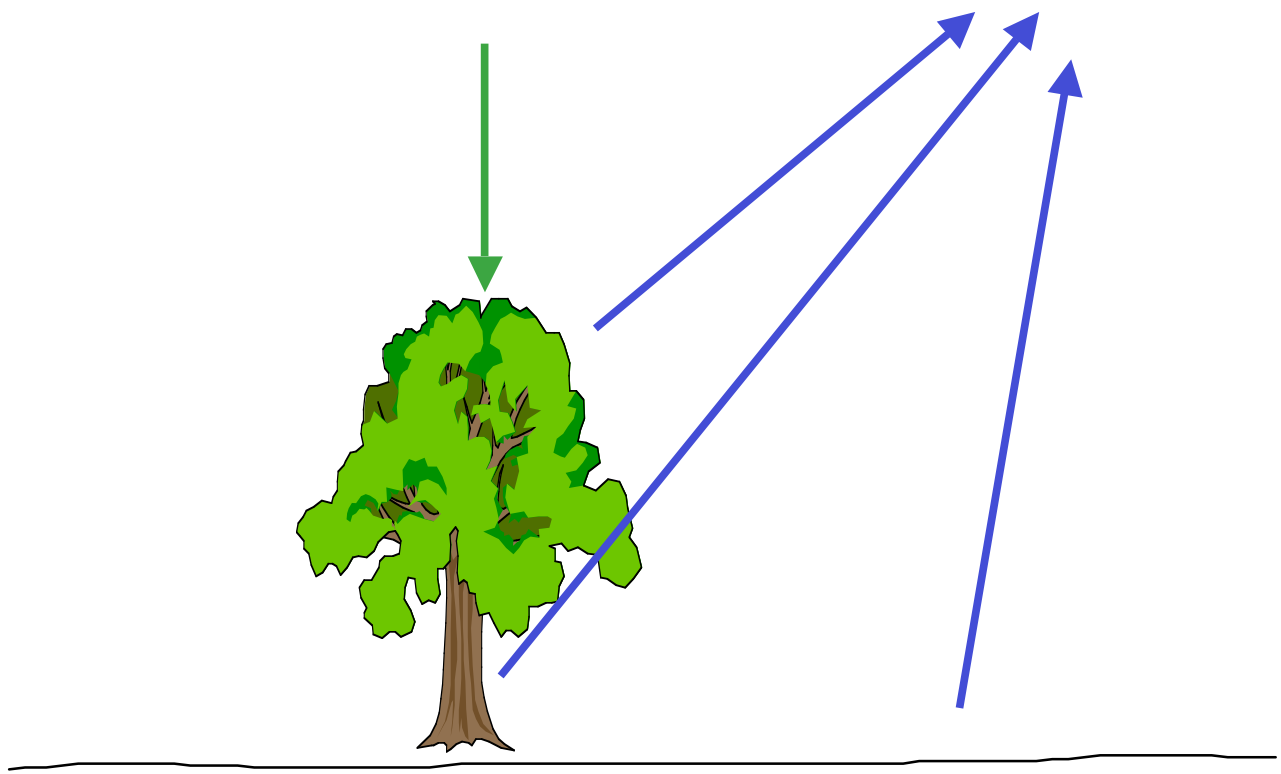
Net Ecosystem Exchange (NEE)

NEE = Photosynthesis - Respiration

sign → ??

(big negative #)

(big positive #)



How to track the carbon balance?

Land use monitoring: satellite surveys

Study intact forests: biometry (takes a long time) <--

Study the CO_2 budget:

- small scale: chambers (1 m^2)
- tower scale: several km^2, turbulence method. <--
- region/synoptic scale: 1000's km^2, budget methods.

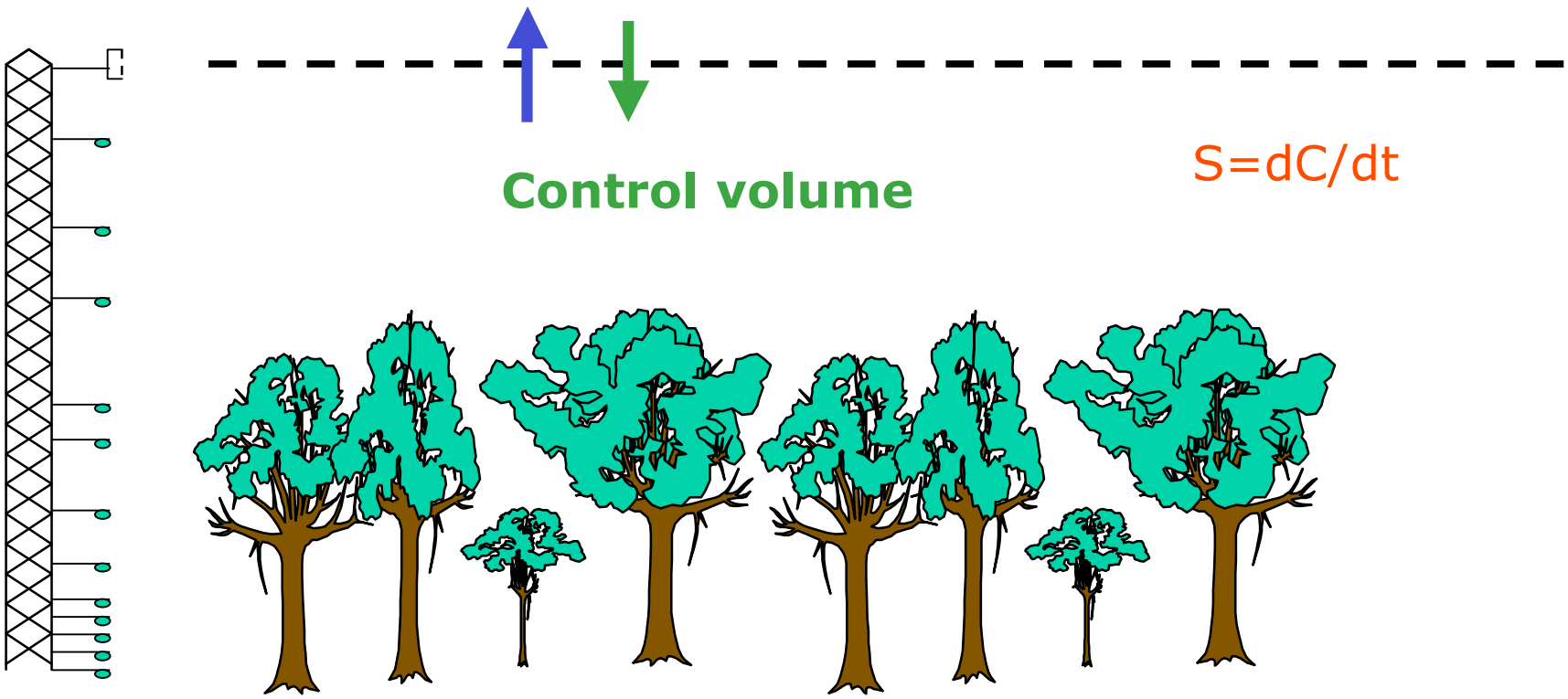
Species Conservation Equation

ASSUMING 1-D forest-atmosphere coupling

$$\mathrm{NEE} = F_c + S$$

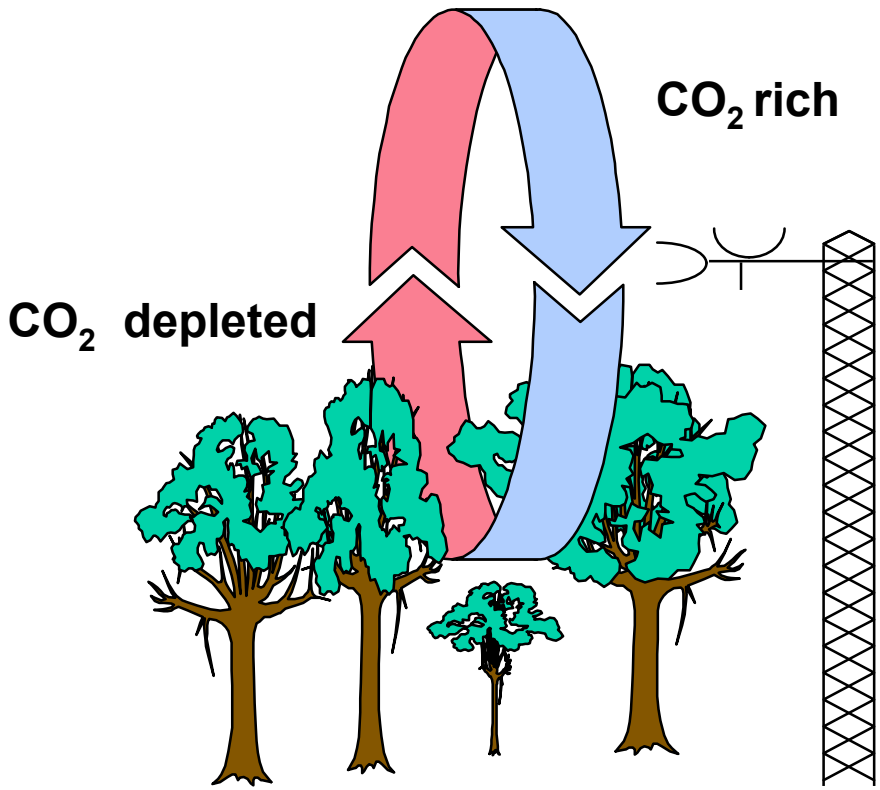
Turbulent flux

Storage "flux"



Eddy Covariance

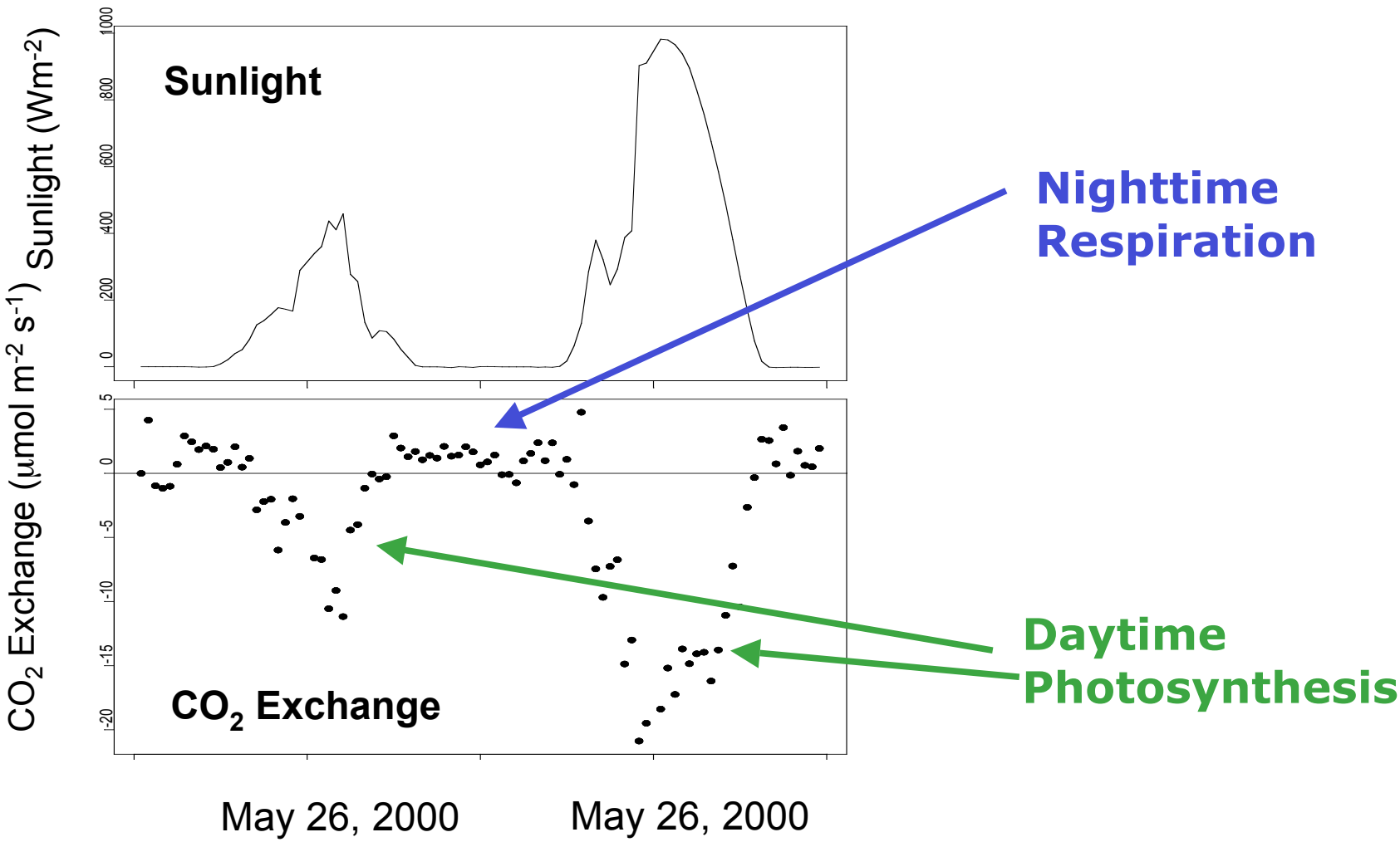
- **Direct** measurement of turbulent flux, $F_c = \langle w'c' \rangle$
- High **Precision**
- Large **Footprint** (many km^2)



Example (2 days)

Fluxes are calculated each **30 minutes**.

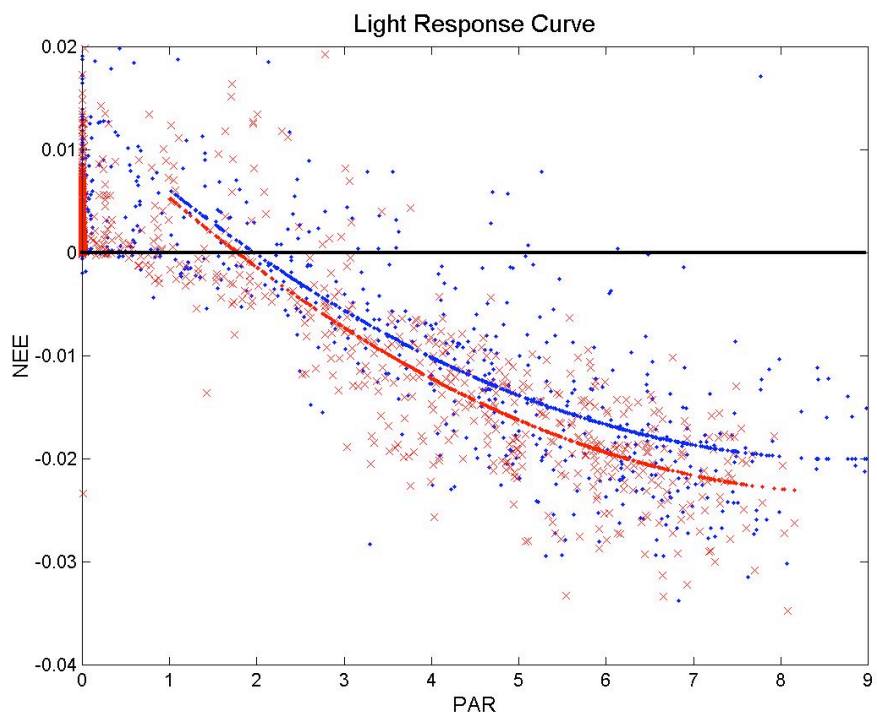
Units of flux are micromoles CO_2 m^{-2} s^{-1}



How do we use eddy flux data?

1. Classical Approach: Parameterization / modeling

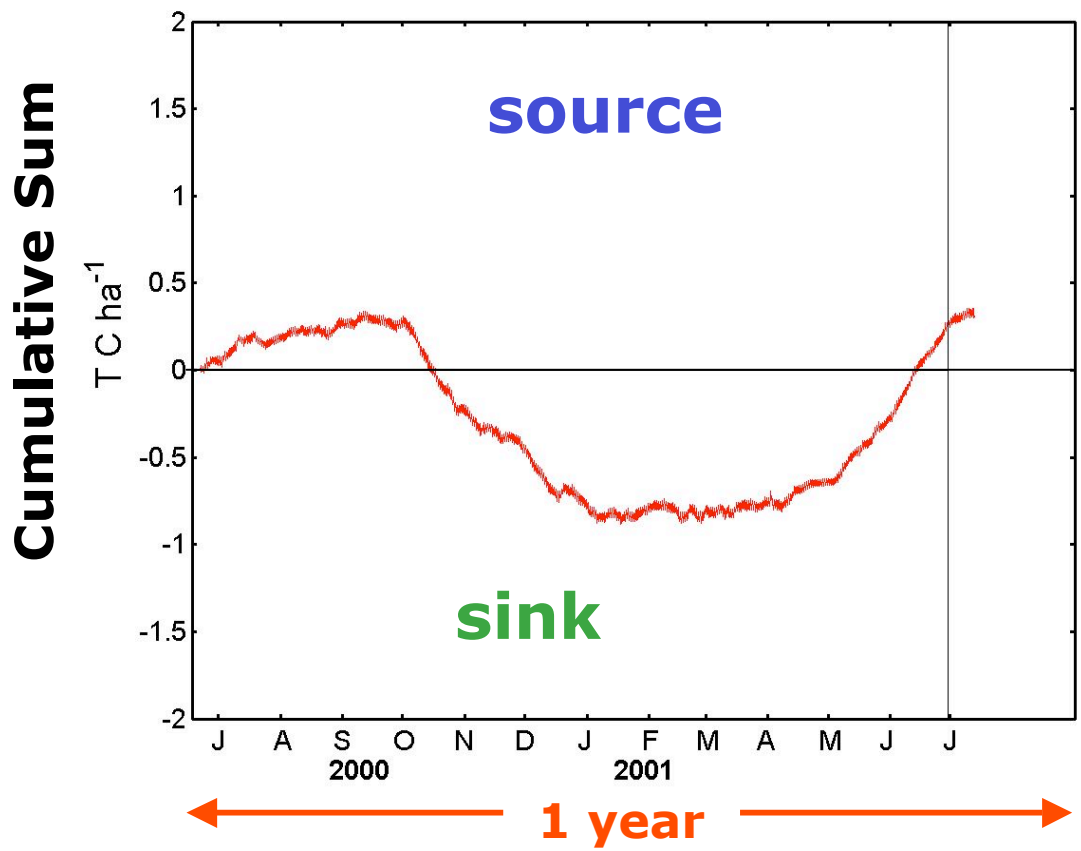
NEE = f(PAR,T,soil h2o, etc)



How do we use eddy flux data?

2. Direct Approach: Integrate long (years), continuous flux data sets to calculate **directly** a site carbon budget

Requires **accuracy** of fluxes (difficult)!



How do we use eddy flux data?

3. Response: to perturbation, e.g. logging, fire.

Requires **precision**, eddy covariance well suited!


LBA
EXPERIMENTO DE GRANDE ESCALA DA BIOSFERA-ATMOSFERA NA AMAZÔNIA - LBA

Objective in Tropical Forest

- **Classic Approach**: understand factors controlling CO_2 exchange (Goulden et al, 2002).

- **Direct Approach**: integrate long term measurements - is undisturbed forest a carbon **source** or **sink?** (Miller et al, 2002).

- **Response**: How does **Selective-Logging** affect CO_2 cycling in tropical forest. Stay tuned…

Previous tower-based **annual** carbon budgets in primary tropical forest

Site	Reference	NEE	
Rhondonia	Grace et al. 1996	-1	(sink)
Manaus	**Malhi et al. 1998**	**-5.9**	**(sink)**
Several Sites	Kabat 2000	-3 to -7	(sink)

Units: Tons of Carbon per hectare per year [T C ha^{-1} yr^{-1}]

Recall, **unknown global terrestrial sink** is about **2 Gt C yr^{-1}**

Amazon Basin is about **6 million km^2**

Carbon sink of about 3-4 T C ha^{-1} yr^{-1} across the Amazon would account for the entire unknown global terrestrial sink!

Question: Are the tower-based annual sums accurate?

LBA-Ecology Sites

Santarem, Para

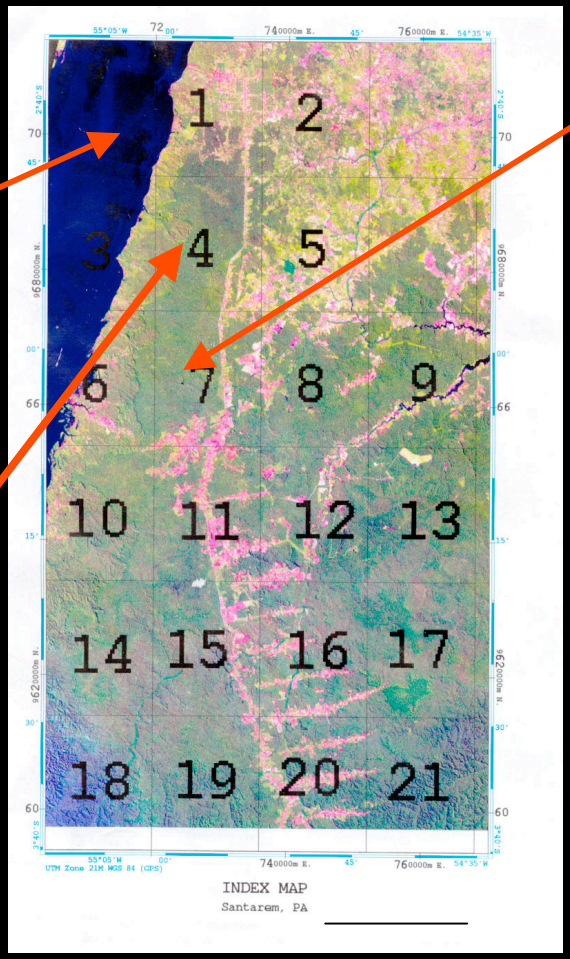
LBA = Large Scale Biosphere-Atmosphere Experiment in Amazonia

Experimental Plan

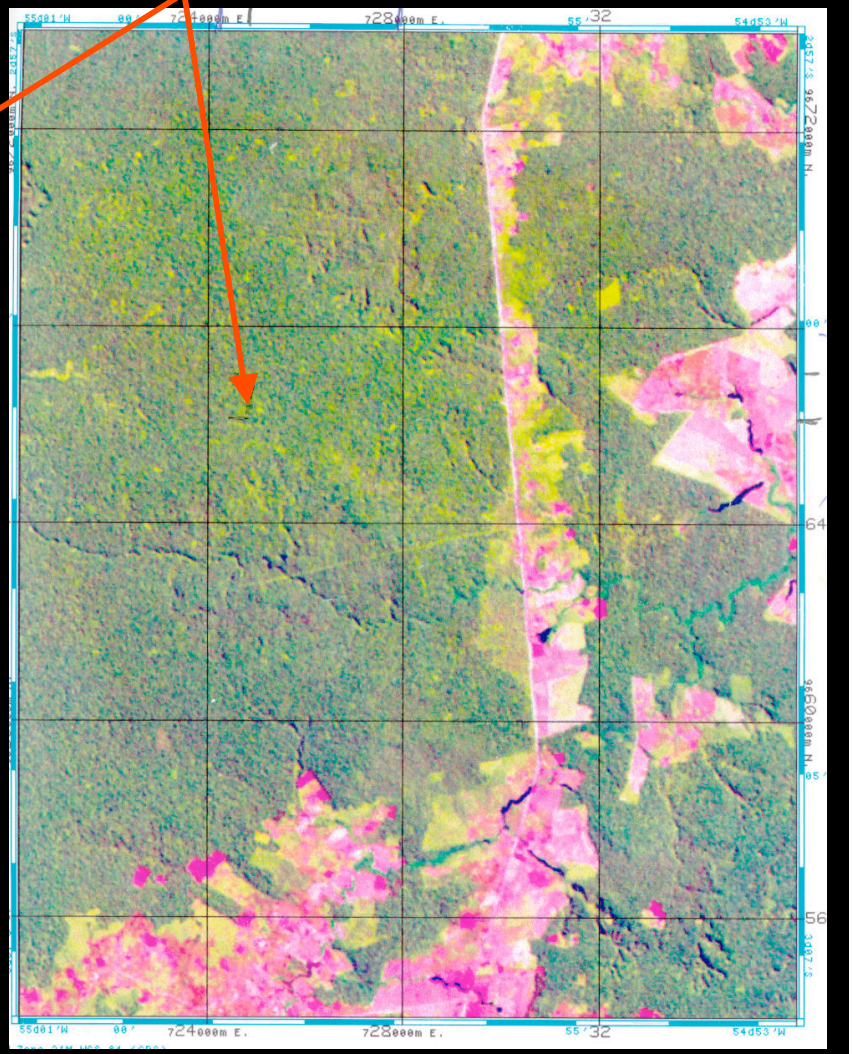
Logged Site

Tapajos River

Control Site



Wind dir



60 km

16 km

Tower Measurements

METEOROLOGY

PAR (up/down)
Radiation (short and long wave, up and down)
Rain

PROFILES

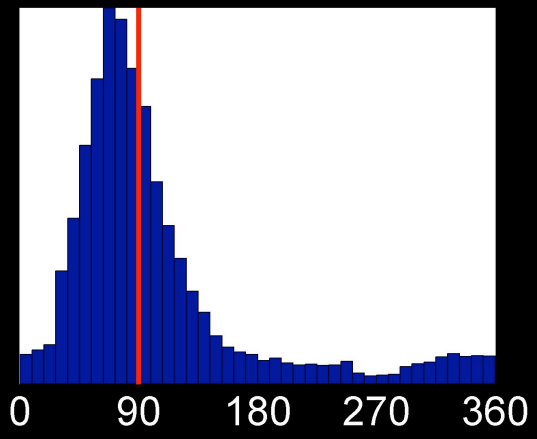
Wind (6 levels cups and 2D Sonics)
Temperature (6 levels)
CO_2/H_2O (12 levels)

FLUXES (64 meters)

Momentum/Heat	sonic anemometer
CO_2/H_2O	Infrared Gas Anayzer

Air Inlet for **Closed Path IRGA**

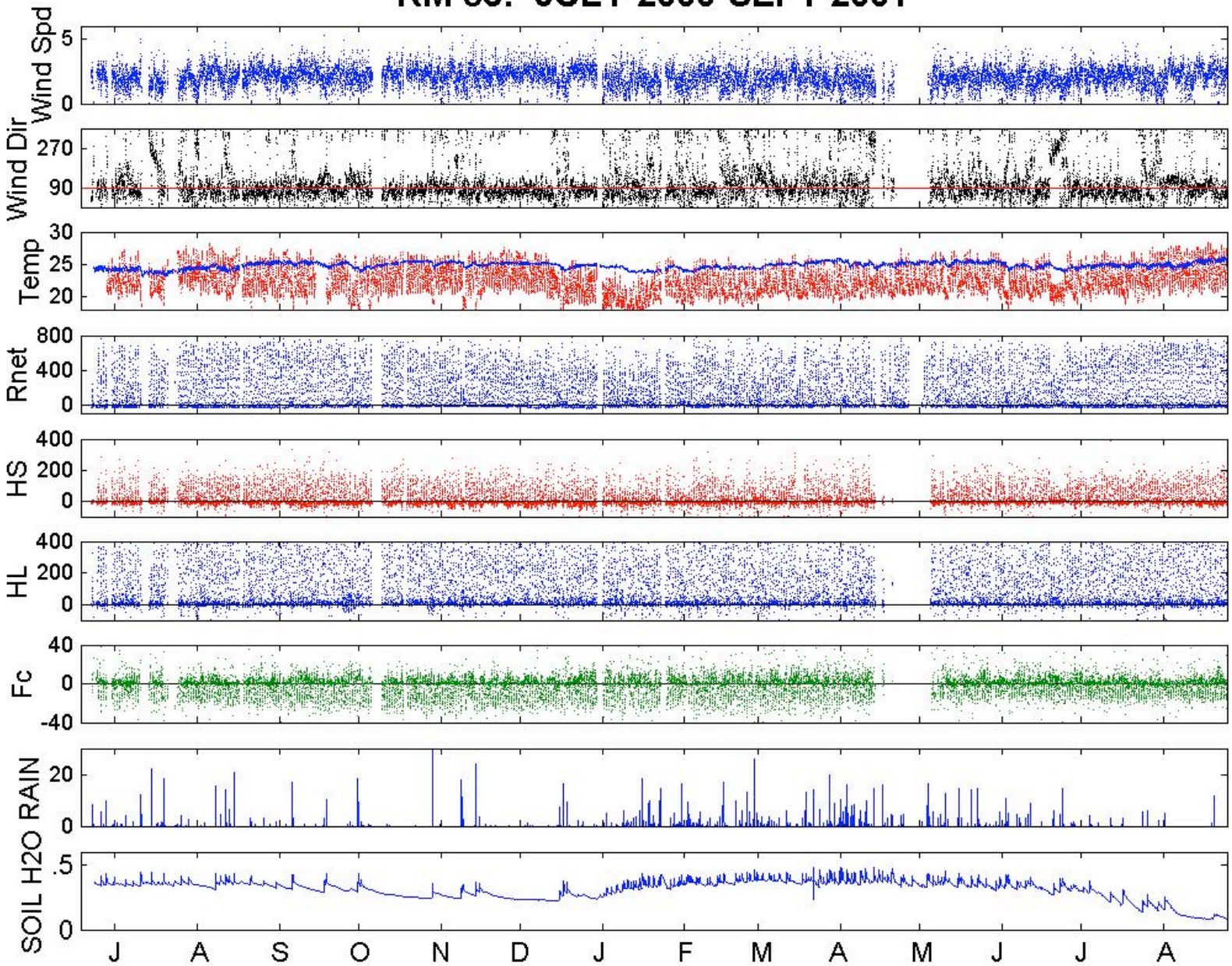
Open Path IRGA



Sonic anemometer looks **East**, the most common wind direction

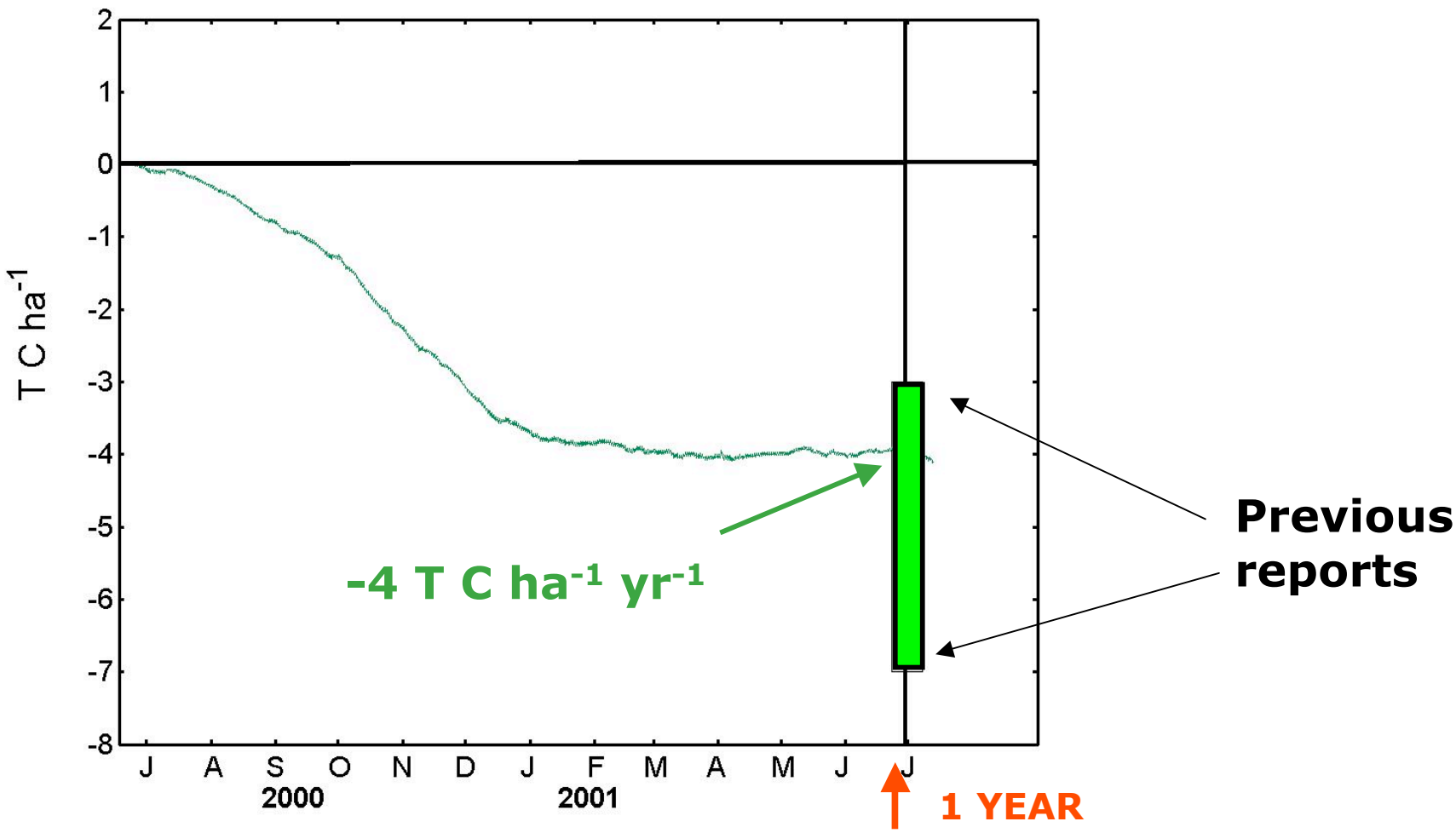
Elevator to raise and lower eddy flux sensors.

KM 83: JULY 2000-SEPT 2001



Annualized NEE

We **measure** a large carbon sink, similar to previous reports.
Sink of **-4** across **Amazonia** will absorb entire **global carbon budget deficit**



How confident can we be in this result?

Case 1: TRUE

Where is the Carbon going?

- Trees (Biometry)? (Malhi et al., 1998)
- Soil? (Malhi et al., 1999)
- Rivers? (Richey et al, 2002)

Case 2: FALSE

Is there a bias in the tower-based measurement?

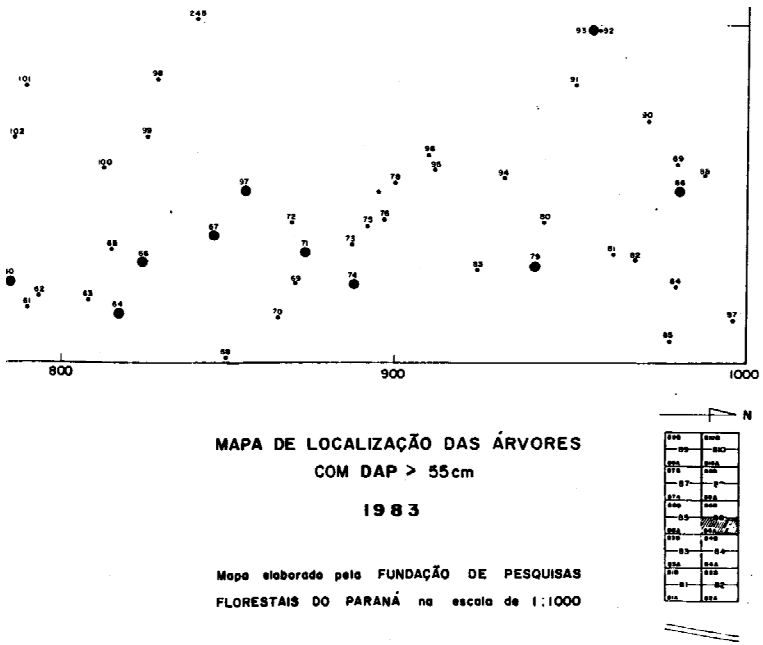
- Hardware/software techniques?
- Meteorological bias?

Trees: Ground Based Inventories

Tree inventories (diameter, DBH>55cm) quantify carbon density

- 1984 Tree biomass **105** Tons Carbon per hectare
- 2000 Tree biomass **106**

Over 16 years, carbon was essentially neutral (**not** a source or sink).



1984 stem map

Soil: Isotopes

0 +/- 0.5 T C ha^{-1} yr^{-1} (Trumbore)

Biometric Summary

0 +/- 1.5 T C ha^{-1} yr^{-1}

Tower --> 4 T C ha^{-1} yr^{-1}

How confident can we be in this result?

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Rivers?
(Nature, April 2002)

Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2

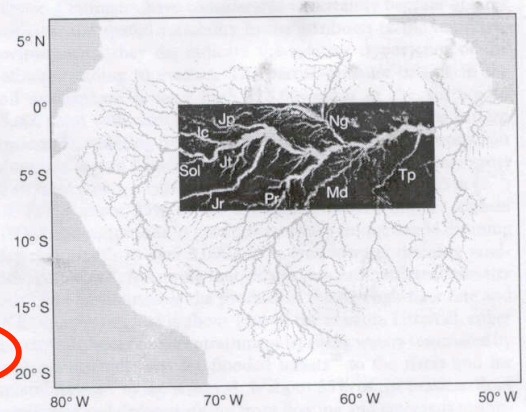
Jeffrey E. Richey*, John M. Melack†, Anthony K. Aufdenkampe*, Victoria M. Ballester‡ & Laura L. Hess†

* School of Oceanography, University of Washington, Seattle, Washington 98195, USA
† Institute for Computational Earth System Science, University of California, Santa Barbara, California 93106, USA
‡ Centro de Energia Nuclear na Agricultura, Caixa Postal 96, Piracicaba SP, Brazil

Terrestrial ecosystems in the humid tropics play a potentially important but presently ambiguous role in the global carbon cycle. Whereas global estimates of atmospheric CO_2 exchange indicate that the tropics are near equilibrium or are a source with respect to carbon[1,2], ground-based estimates indicate that the amount of carbon that is being absorbed by mature rainforests is similar to or greater than that being released by tropical deforestation[3,4] (about 1.6 Gt C yr^{-1}). Estimates of the magnitude of carbon sequestration are uncertain, however, depending on whether they are derived from measurements of gas fluxes above forests[5,6] or of biomass accumulation in vegetation and soils[3,7]. It is also possible that methodological errors may overestimate rates of carbon uptake or that other loss processes have yet to be identified[3]. Here we demonstrate that outgassing (evasion) of CO_2 from rivers and wetlands of the central Amazon basin constitutes an important carbon loss process, equal to 1.2 ± 0.3 Mg C ha^{-1} yr^{-1}. This carbon probably originates from organic matter transported from upland and flood[illegible] forests, which is then respired and outgassed downstream. Extrapolated

periods. Combined with extensive measurements of [illegible] CO_2 across the region we were able to compute the water-to-air fluxes of CO_2 for each environment.

We partitioned the quadrant into hydrographic environments—the Amazon mainstem channel, the mainstem floodplain, tributaries (channels and floodplains over 100 m in width, as constrained by the pixel dimensions of JERS-1 radar mosaics), and streams (channels and riparian zones less than 100 m in width). As computed from the radar mosaics, the flooded area of the mainstem and tributaries rose from 79,000 km^2 (about 4% of the quadrant area) in October 1995 to 290,000 km^2 (16% of the quadrant area) by May–June 1996. The low (21,000 km^2) and high water (51,000 km^2) areas estimated for streams were comparable to the area of the mainstem floodplain and greater than the area of the mainstem channel itself.



1.2 T C ha^{-1} yr^{-1}

Malhi/Grace viewpoint

Global change

Carbon dioxide goes with the flow

John Grace and Yadvinder Malhi

Measurements of the rate at which carbon dioxide is released from rivers running through tropical forests provide a surprise. They will help in developing an improved picture of the carbon cycle.

Rainforests contain not only trees but also lots of water, largely in the form of river systems. The Amazon is by far the largest such system in the world, contributing 20% of all water flowing from rivers to the ocean. But how this and other great rivers participate in the global carbon cycle is a puzzle — relatively small quantities of carbon are detected in the outflow, yet organic material from the adjacent forest is commonly observed as floating debris. On page 617 of this issue[1], Richey *et al.*

from repeated measurements of the number and size of trees in sample plots), and studies of the global atmosphere[5] (calculations of the geographical distribution of CO_2 sources and sinks made from frequent and precise measurements of concentration in the Earth's atmosphere).

Several studies of eddy covariance suggest that about 5×10^6 g of carbon accumulate per hectare per year in the dry-land — '*terra firme*' — forests of the Amazon basin. This is a surprisingly large amount, but

How does carbon get to the river?

How confident can we be in this result?

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- Soil? (Malhi et al., 1999)
- Rivers? (Richey et al, 2002)

Case 2: FALSE

Is there a bias in the tower-based measurement?

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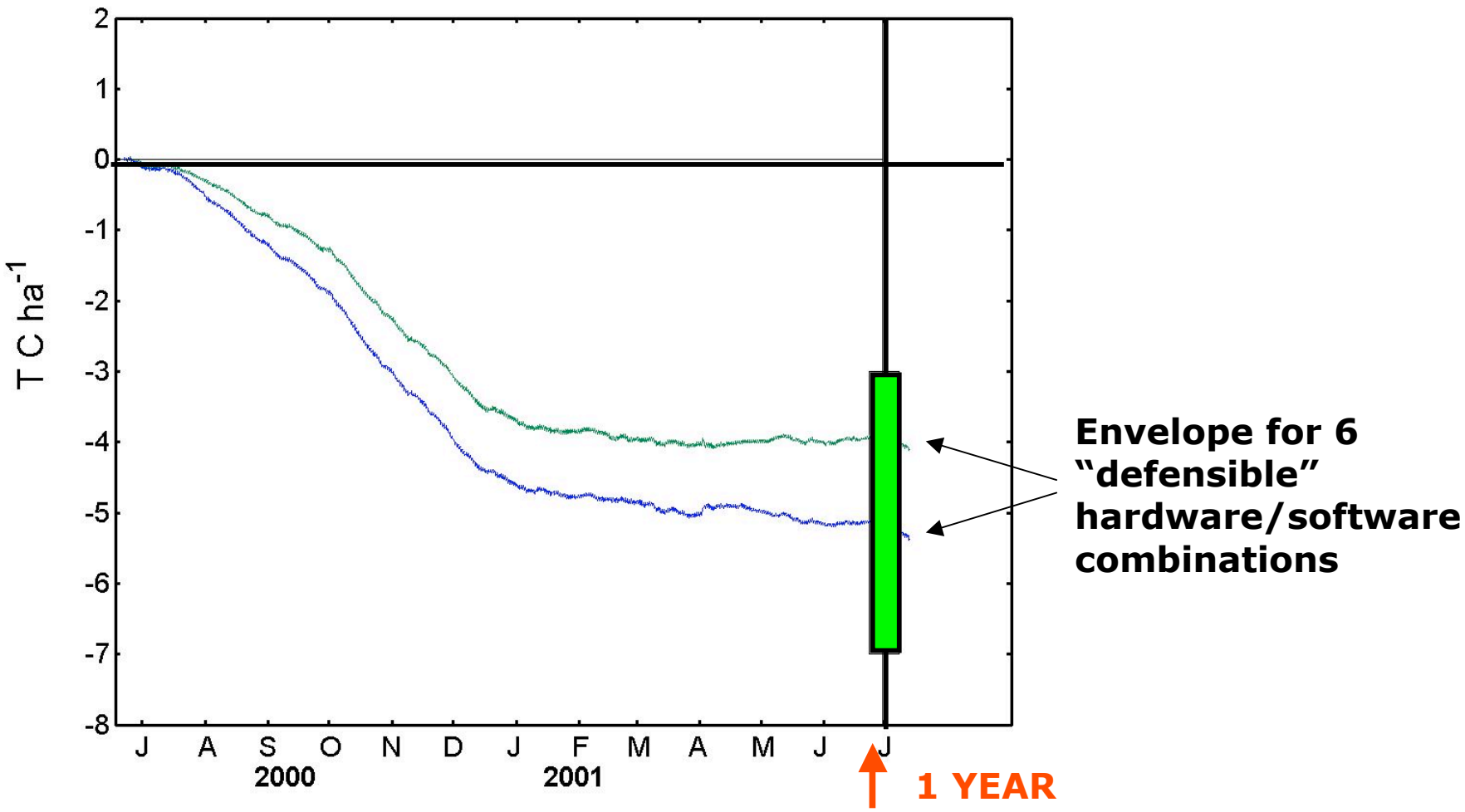
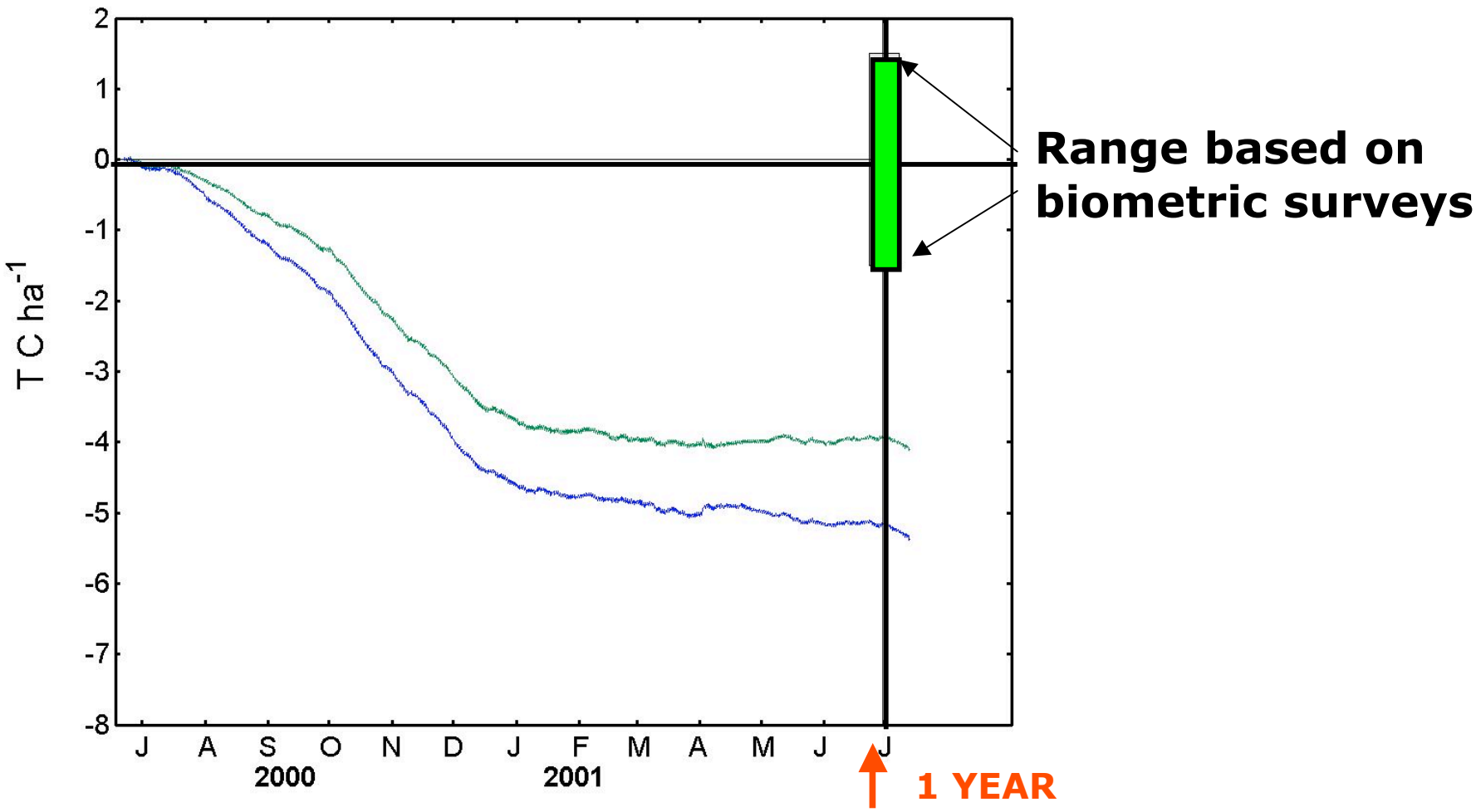
Hardware and Software techniques have a small effect…

Rotations, averaging time, open/closed path systems, high frequency corrections, density corrections



And there remains a large gap between **tower** and **biometric** estimates of carbon exchange



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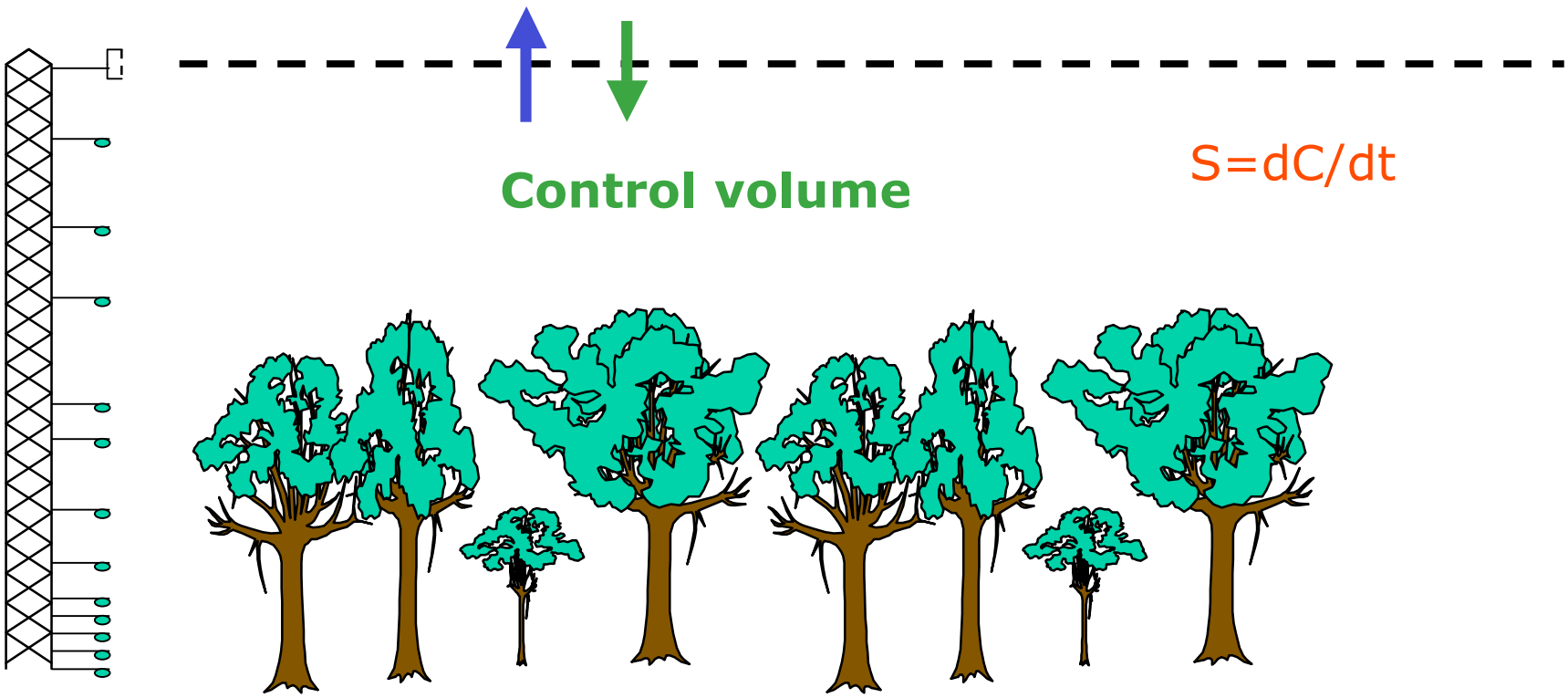
Species Conservation Equation

ASSUMING 1-D forest-atmosphere coupling

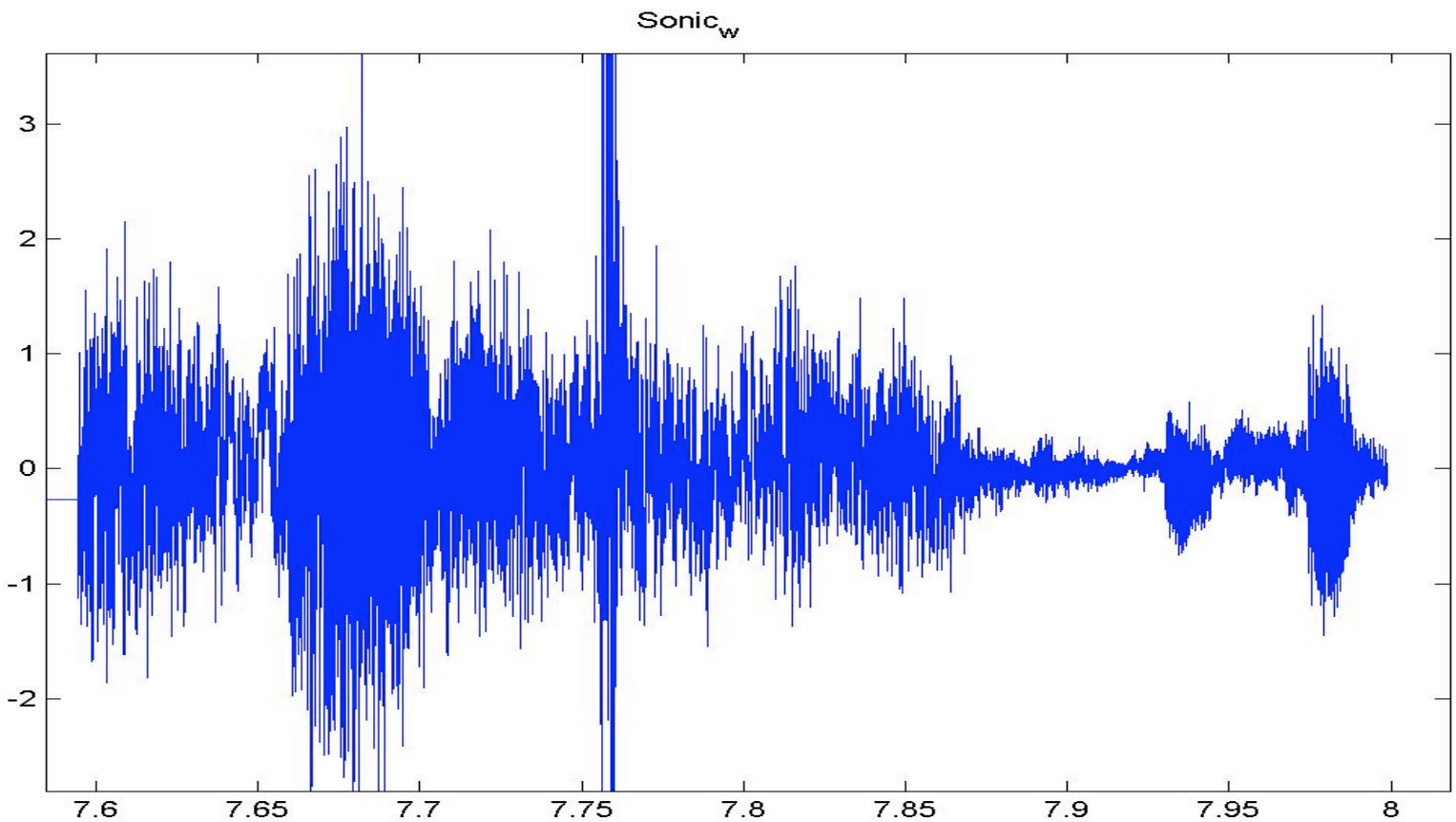
$$NEE = F_c + S$$

Turbulent flux

Storage "flux"



Nighttime above the forest is **very stable**, and mixing is not necessarily turbulent (Fitzjarrald et al. 1998)



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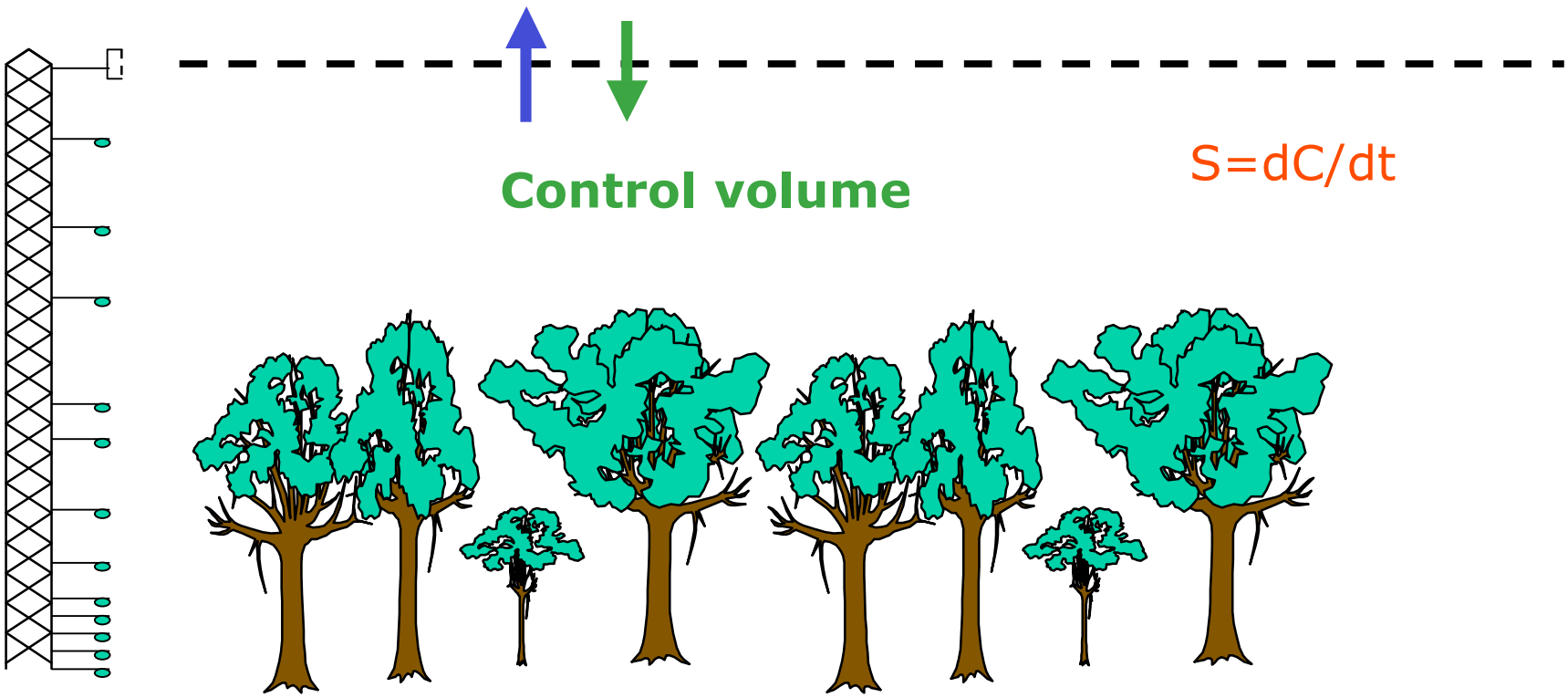


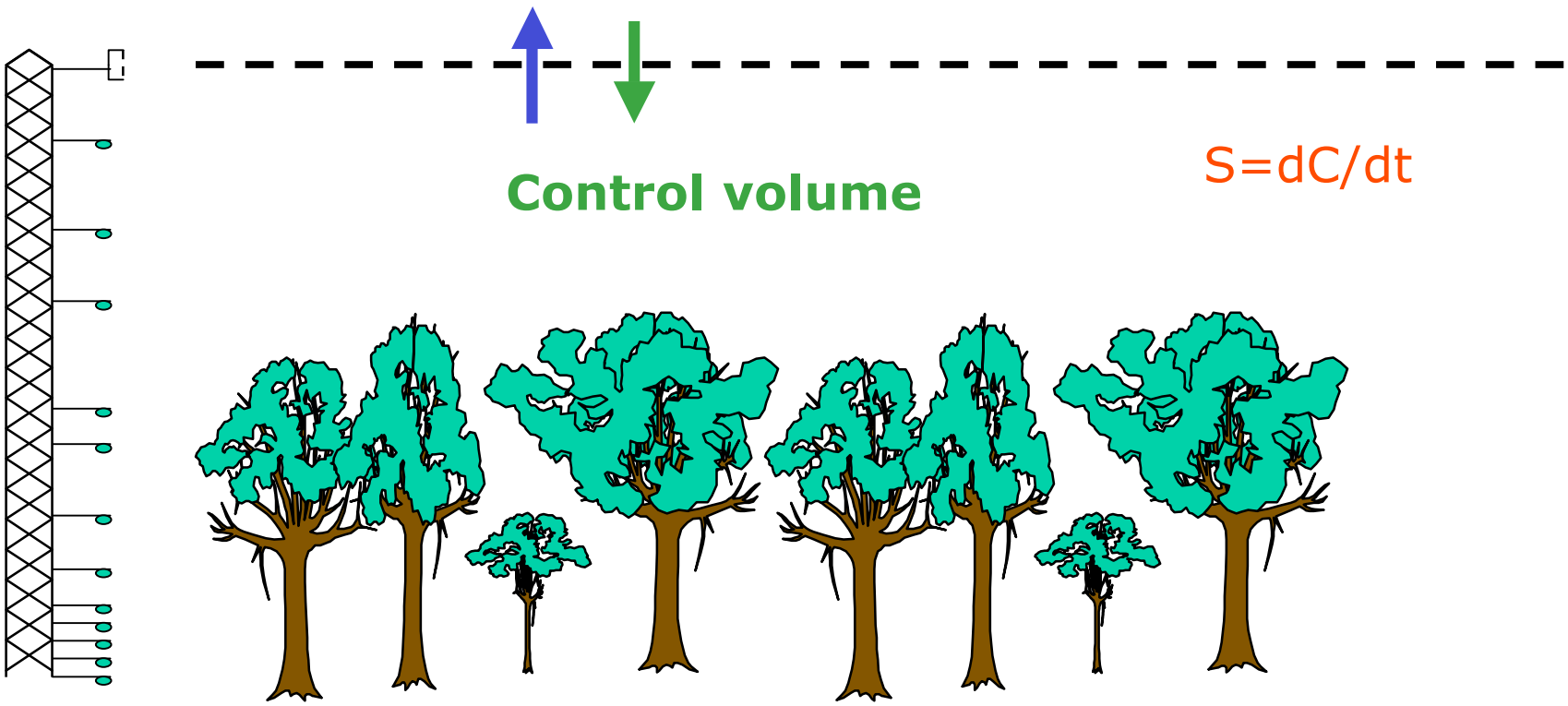
Species Conservation Equation

ASSUMING 1-D forest-atmosphere coupling

$$NEE = F_c + S + ???$$

Turbulent flux

Storage "flux"



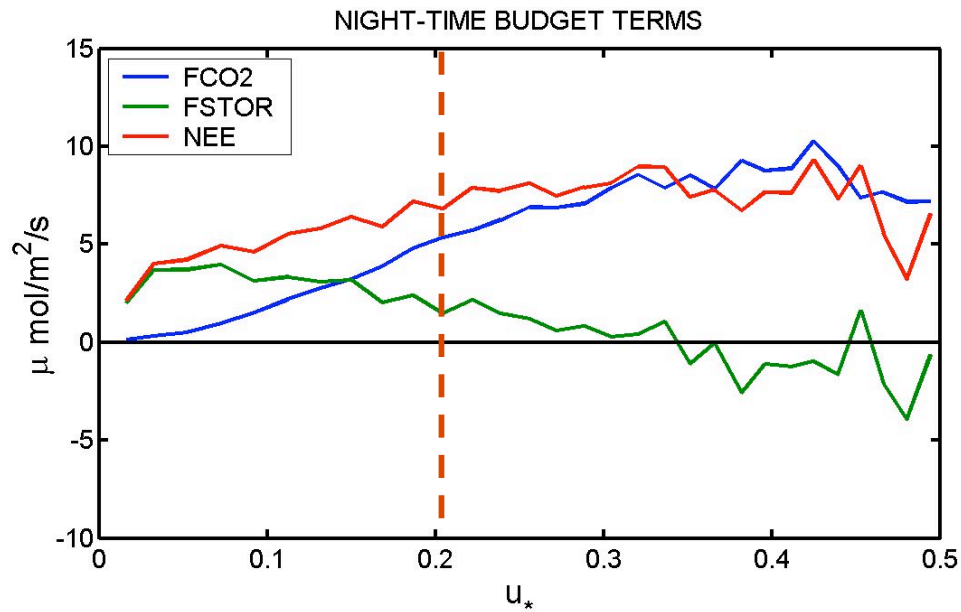
Can we trust the towers?

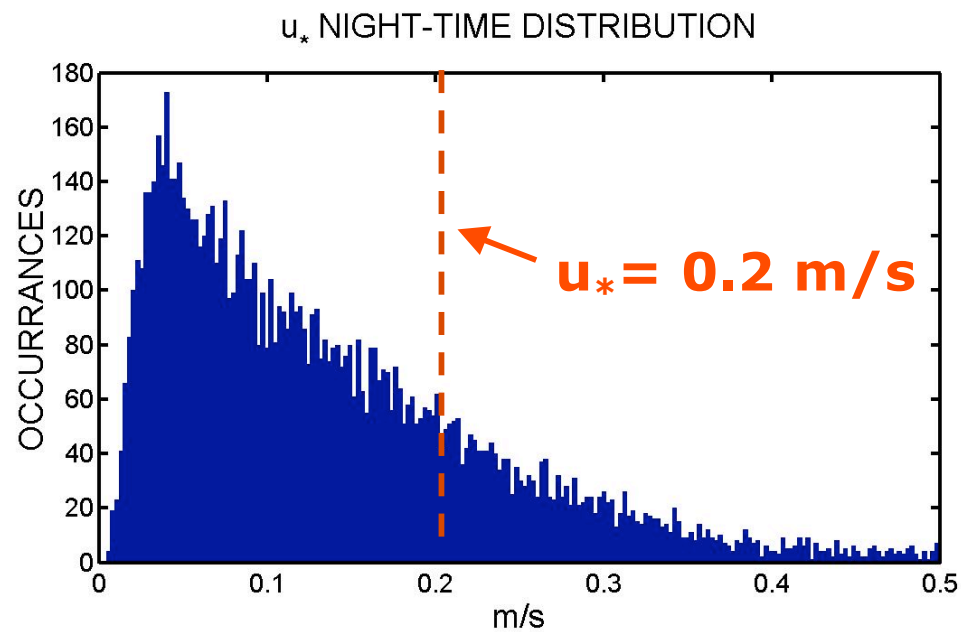
u_* correction

Assumption: nighttime respiration and turbulent mixing above the forest u_* are **independent**

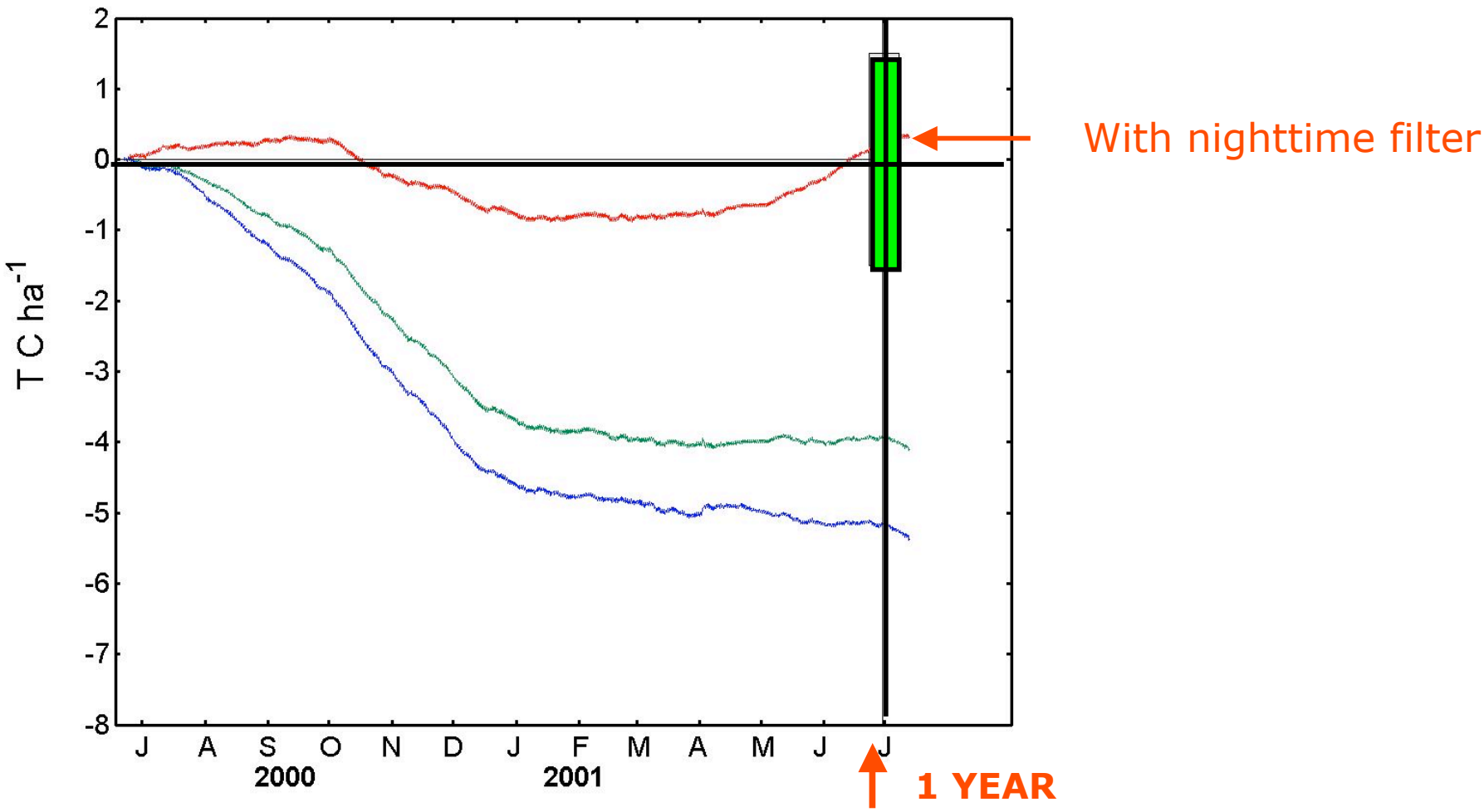
Procedure: **reject** flux data during **calm nights**

Difficulty: **Most** nights are **very calm**. What cutoff u* to use?





Using this “filter” dramatically changes the annual sum!



Our best estimate **(corrected tower, plus biometry)**

~0 T C ha^{-1} yr^{-1} (approximately carbon neutral)

but, because of the poorly understood nighttime exchange. we assign a very large uncertainty, with limits of

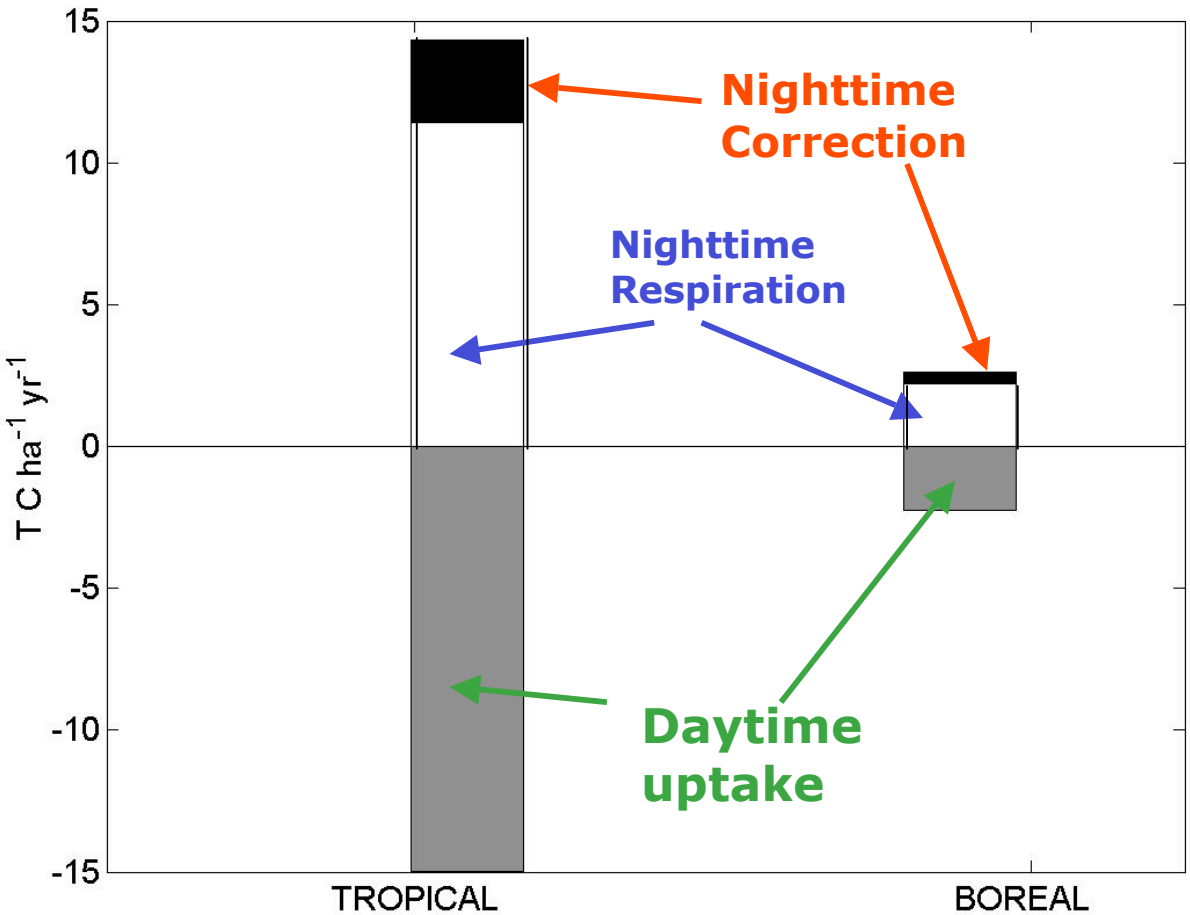
-5.2 to +1

Uncertainty spans 6 T C ha^{-1} yr^{-1} , compared to only 0.5 T C ha^{-1} yr^{-1} in boreal forests.

Why is the uncertainty so large?

Tower-based Annual sums in Tropical forest are less certain than other forest types because:

high productivity, long growing season, calm nights



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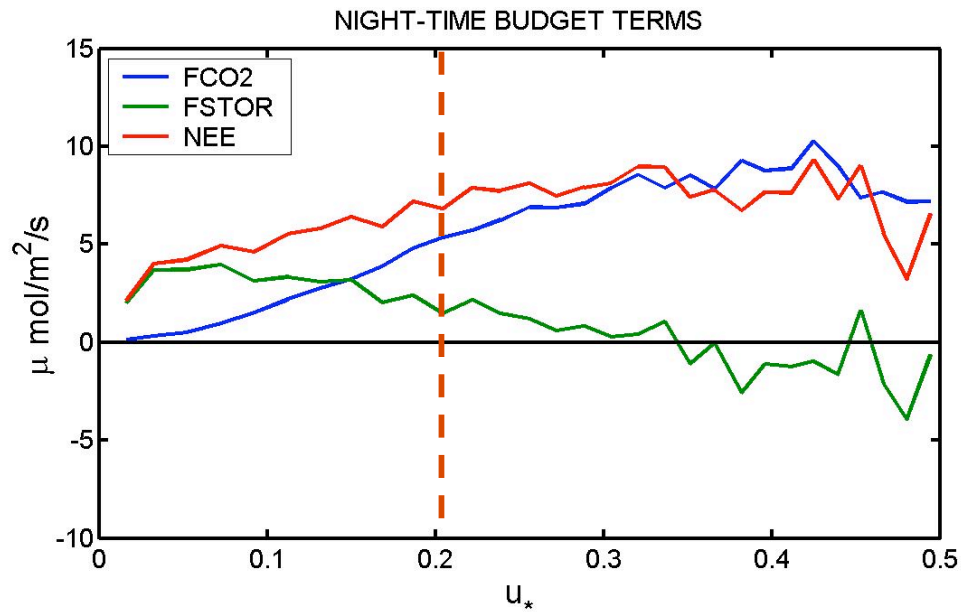
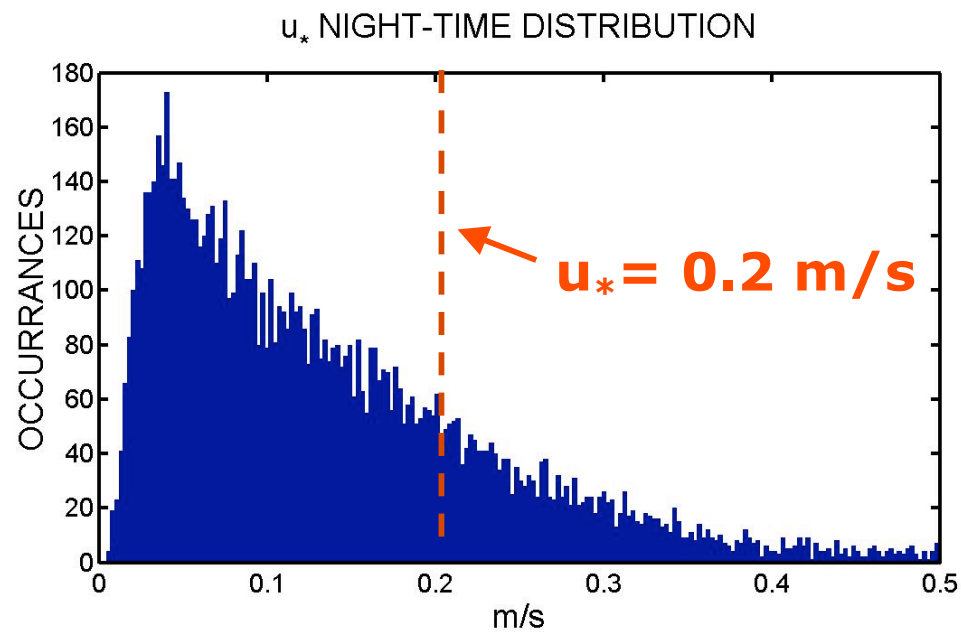
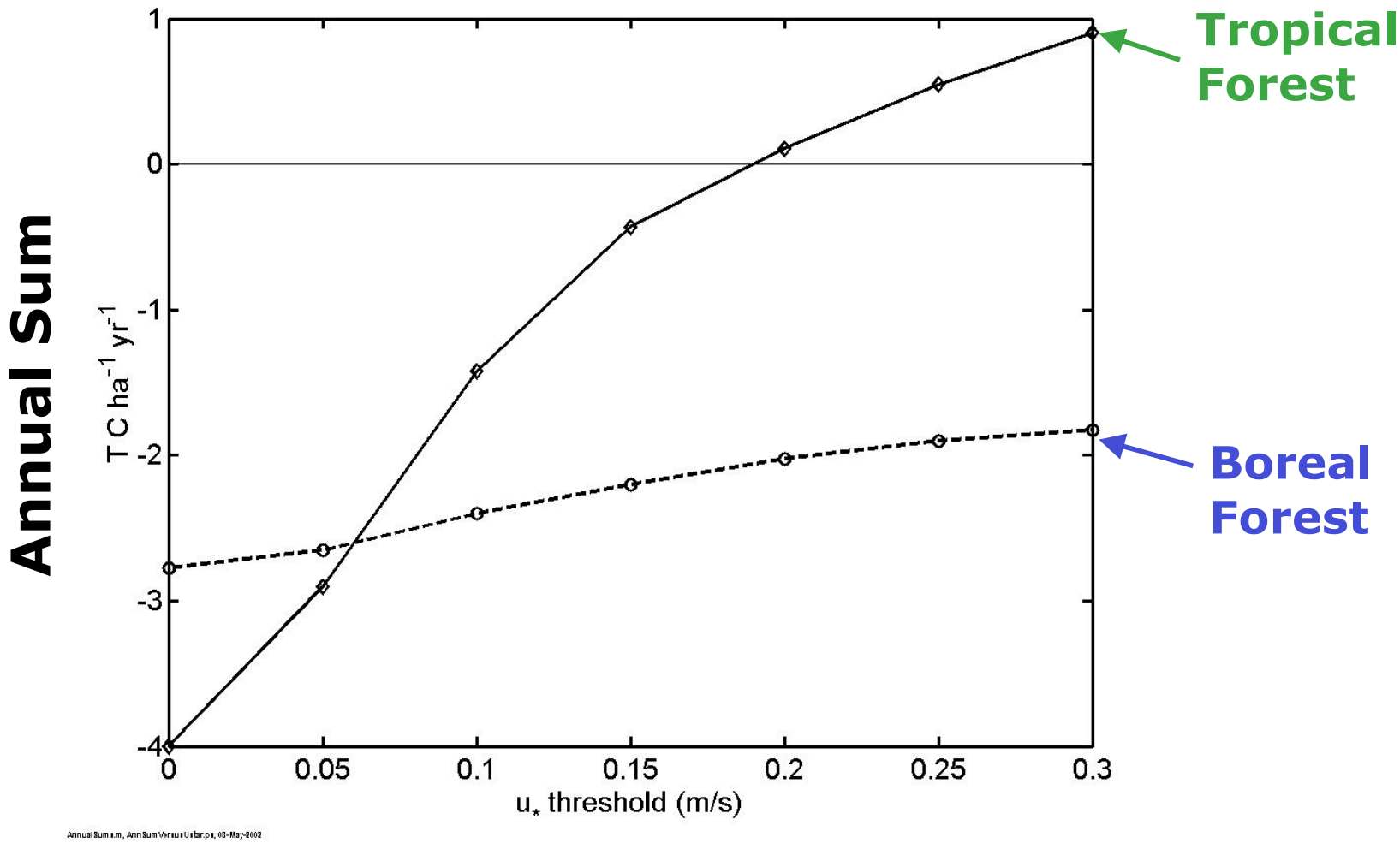




In addition, the tropical nighttime correction is more sensitive to the subjective choice of turbulence threshold



turbulence threshold

What next?

Continue data analysis, including logging effects

Continue ground based surveys

Targeted additional carbon cycle measurements

Additional micrometeorological measurements

Dendrometers measure short term wood increment

What next?

Continue data analysis, including logging effects

Continue ground based surveys

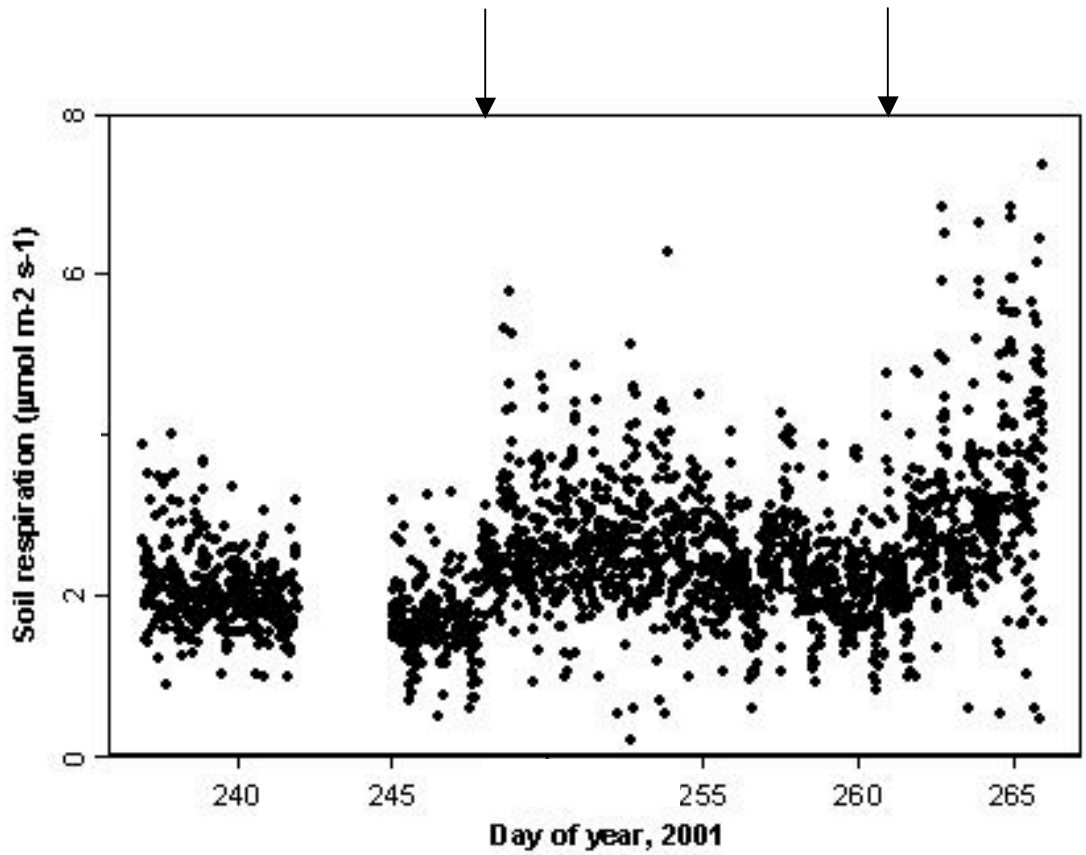
Targeted additional carbon cycle measurements

Additional micrometeorological measurements

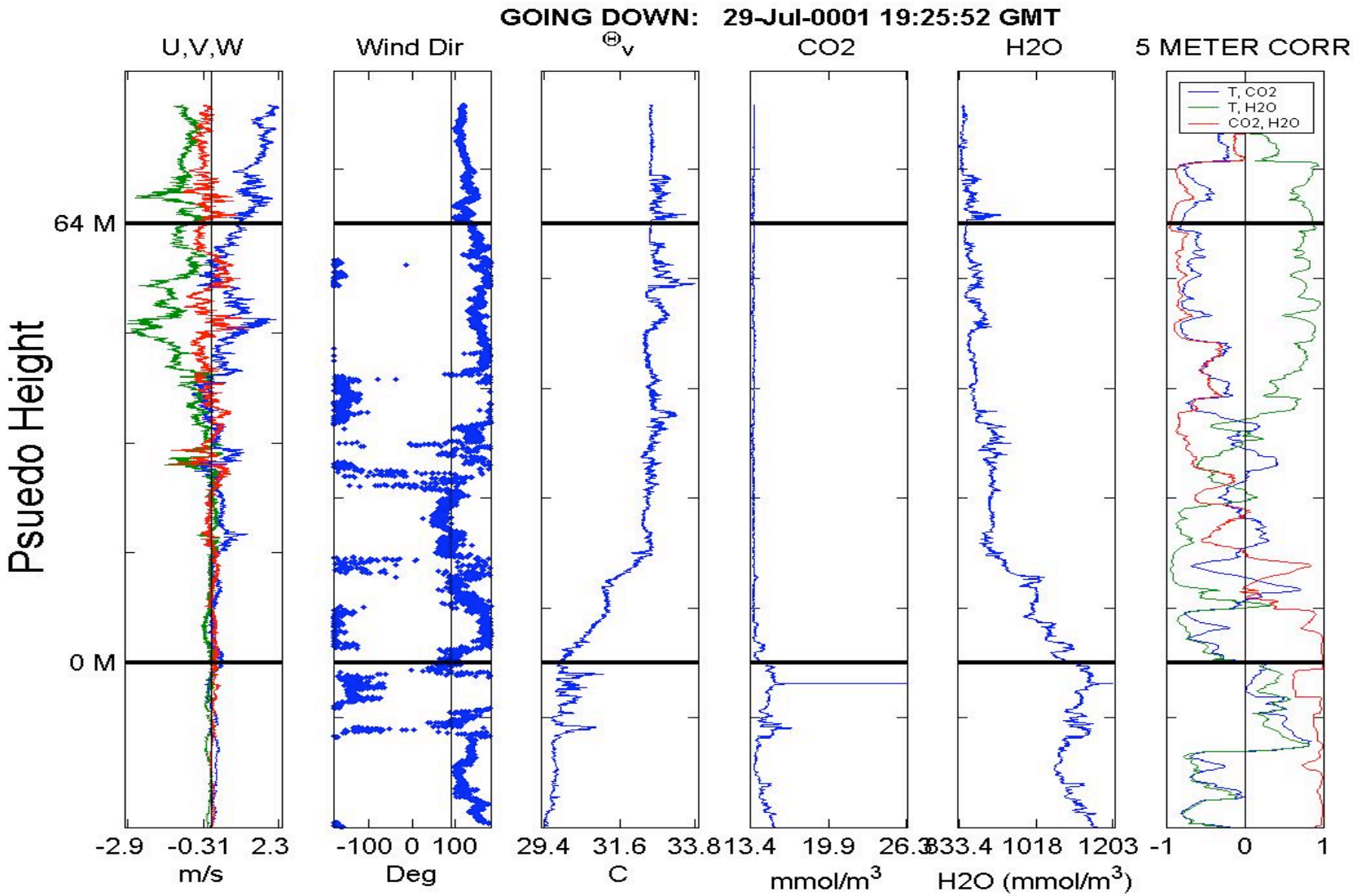
Soil respiration (presumably decomposition) strongly affected by rain (presumably litter moisture)

Autochamber measurements of soil respiration

Heavy rains interrupt 2001 dry season



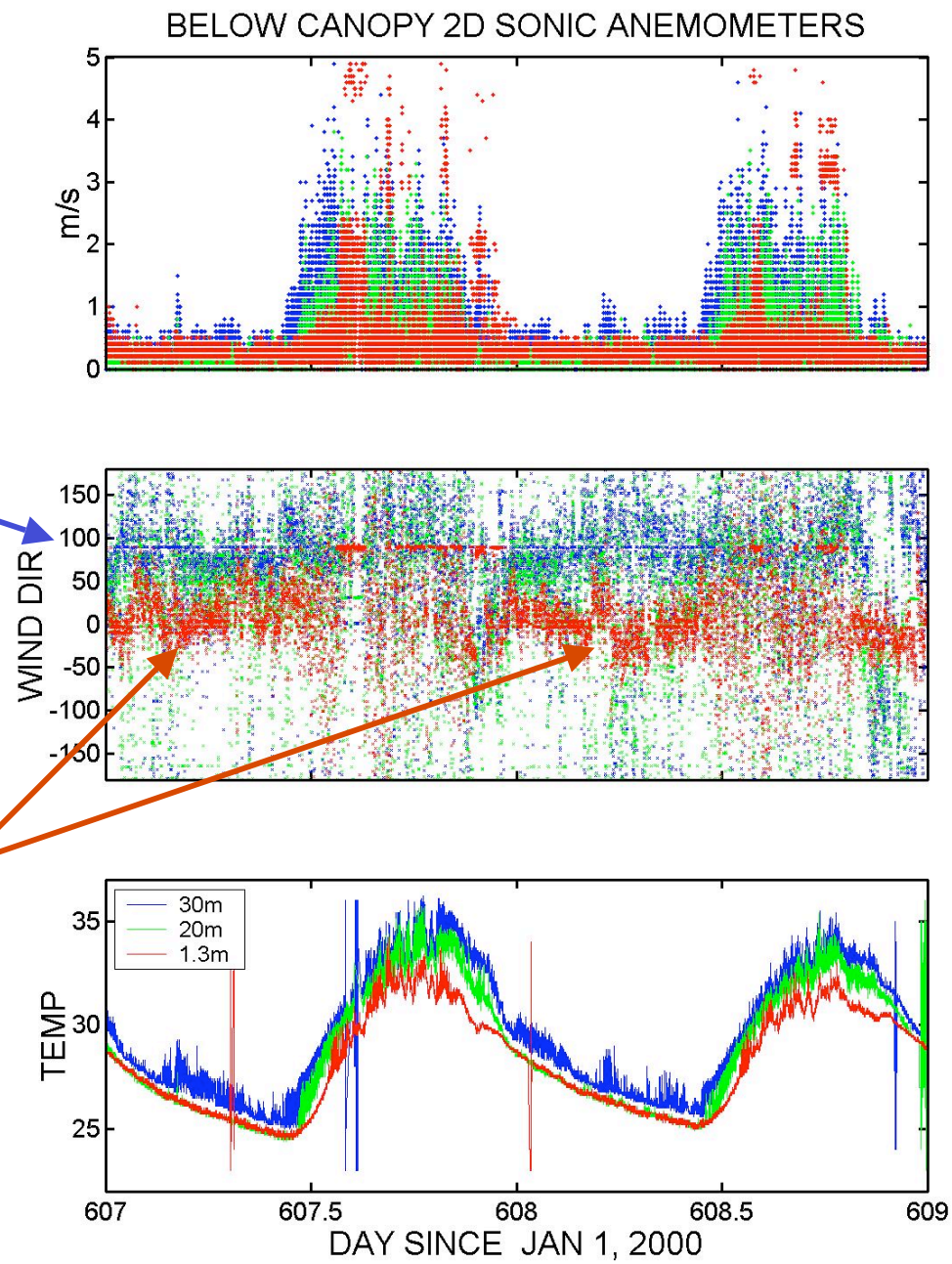
We can make high-resolution soundings with elevator



Sub Canopy Micrometeorology

Above canopy wind easterly, night and day

Night-time low level (1.3 m) wind not aligned with above canopy wind.



Tethered balloon study of
CO2 and water vapor accumulation
In the stable boundary layer.
July 2001 (2nd phase October 2001)

Balloon profiling done by the
UFSM team.

L. to R: Otávio Acevedo, Rodrigo. da Silva,
and Osvaldo Moraes

Original inhabitants of field
visit Acevedo.

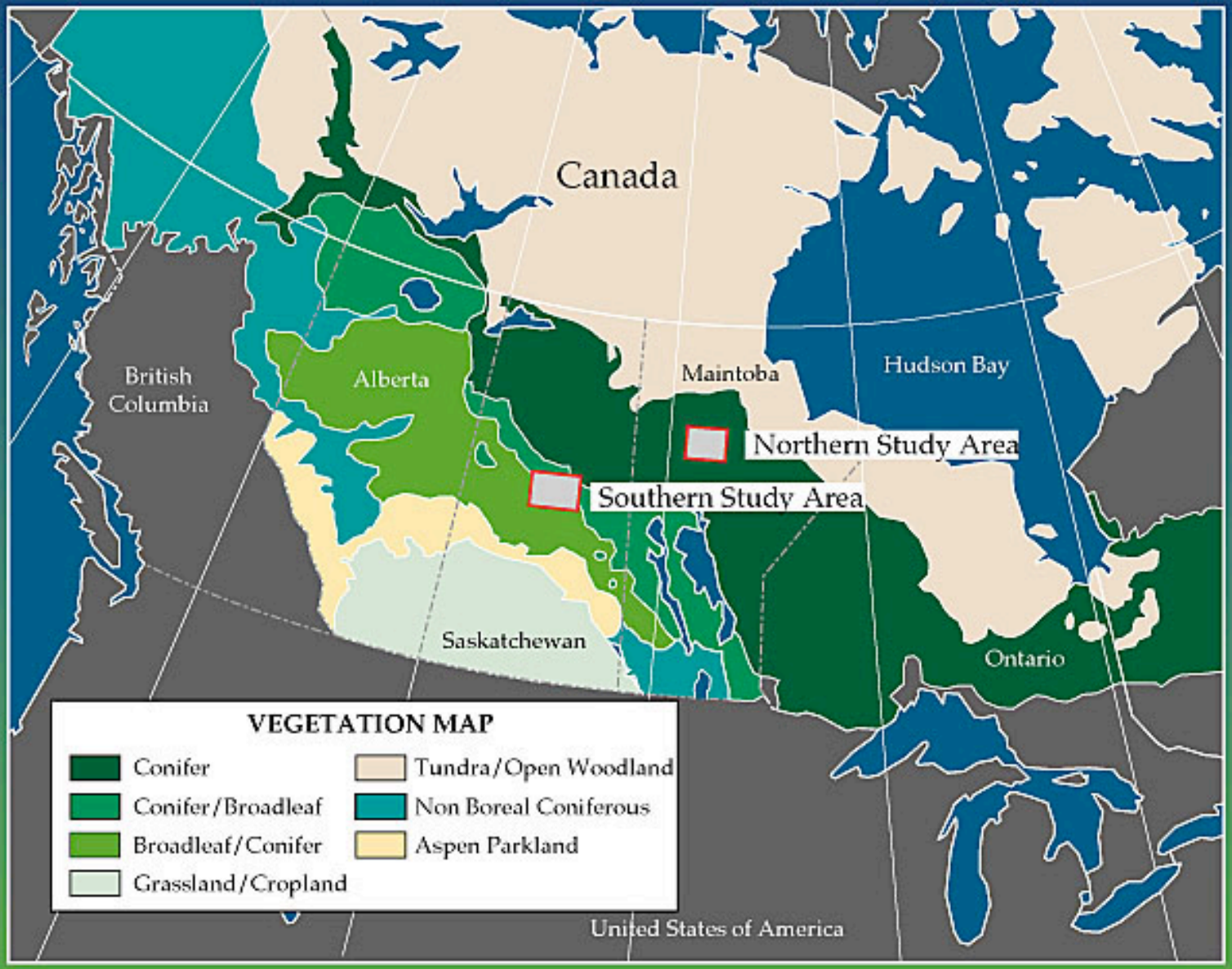
Conclusions

- July 2000-July 2001 - forest appeared to be carbon neutral.

- Annual CO2 Budget is from towers is difficult.

- Eddy flux (towers) alone is not enough.

Thanks: Marcy Litvak, Fernando Alves Leão, Roberto Cardoso, Antonio Oviedo, Dan Hodkinson, Lisa Zweede and Bethany Reed, IBAMA, NASA and INPE.


Canada
British Columbia
Alberta
Maintoba
Hudson Bay
Northern Study Area
Southern Study Area
Saskatchewan
Ontario
VEGETATION MAP
Conifer
Conifer/Broadleaf
Broadleaf/Conifer
Grassland/Cropland
Tundra/Open Woodland
Non Boreal Coniferous
Aspen Parkland
United States of America

L948.032

Fire plays an integral role in boreal forest ecosystems

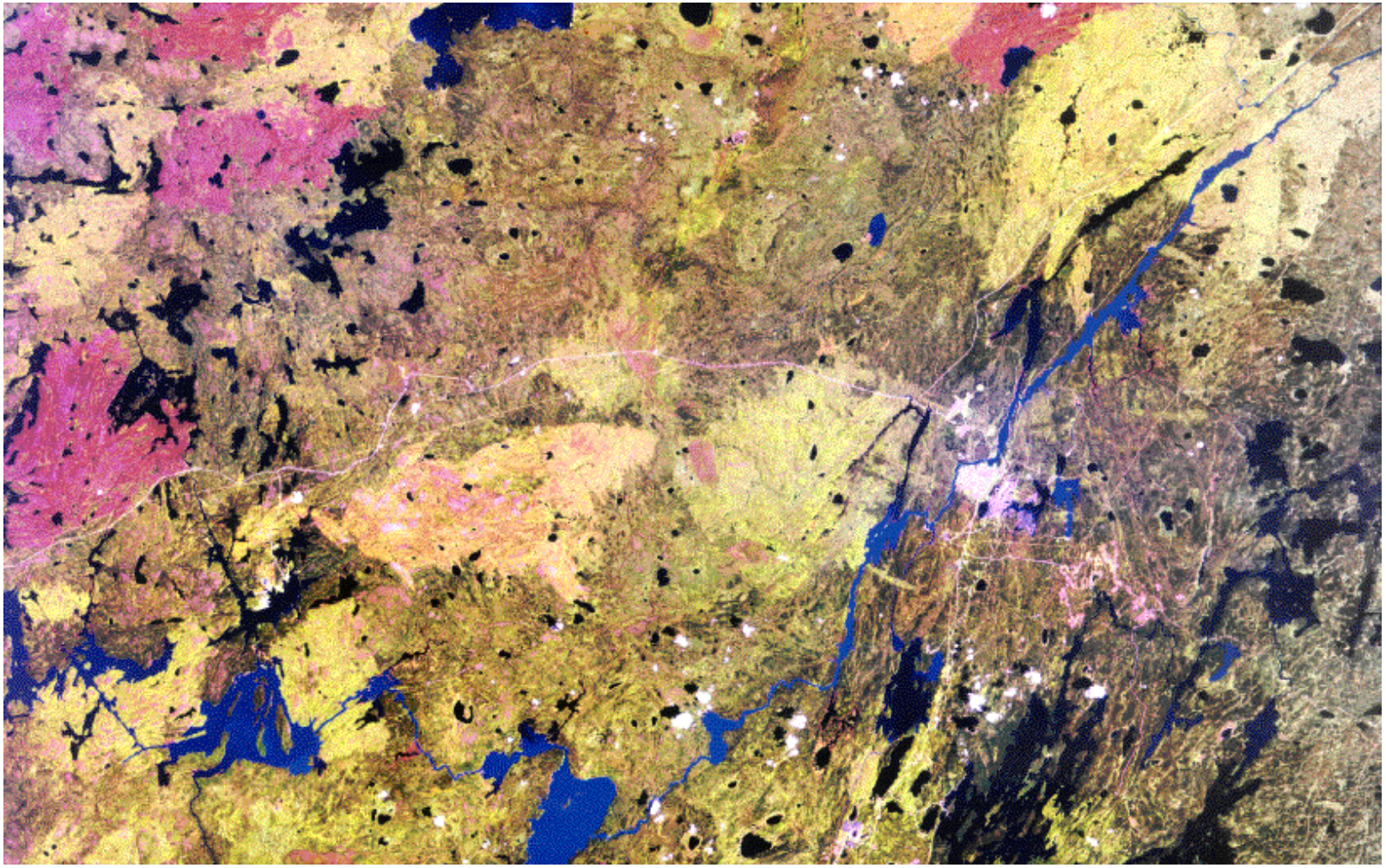
Lightning-induced fire in a stand of black spruce between BOREAS NSA and Churchill in 1994

Dominant disturbance in many regions

Fire returns every 50 to 200 years

Maintains boreal landscape as spatial mosaic of forest patches in different successional stages

BOREAS-Northern Study Area Fire history- TM July 25, 1990



Scale

50 km

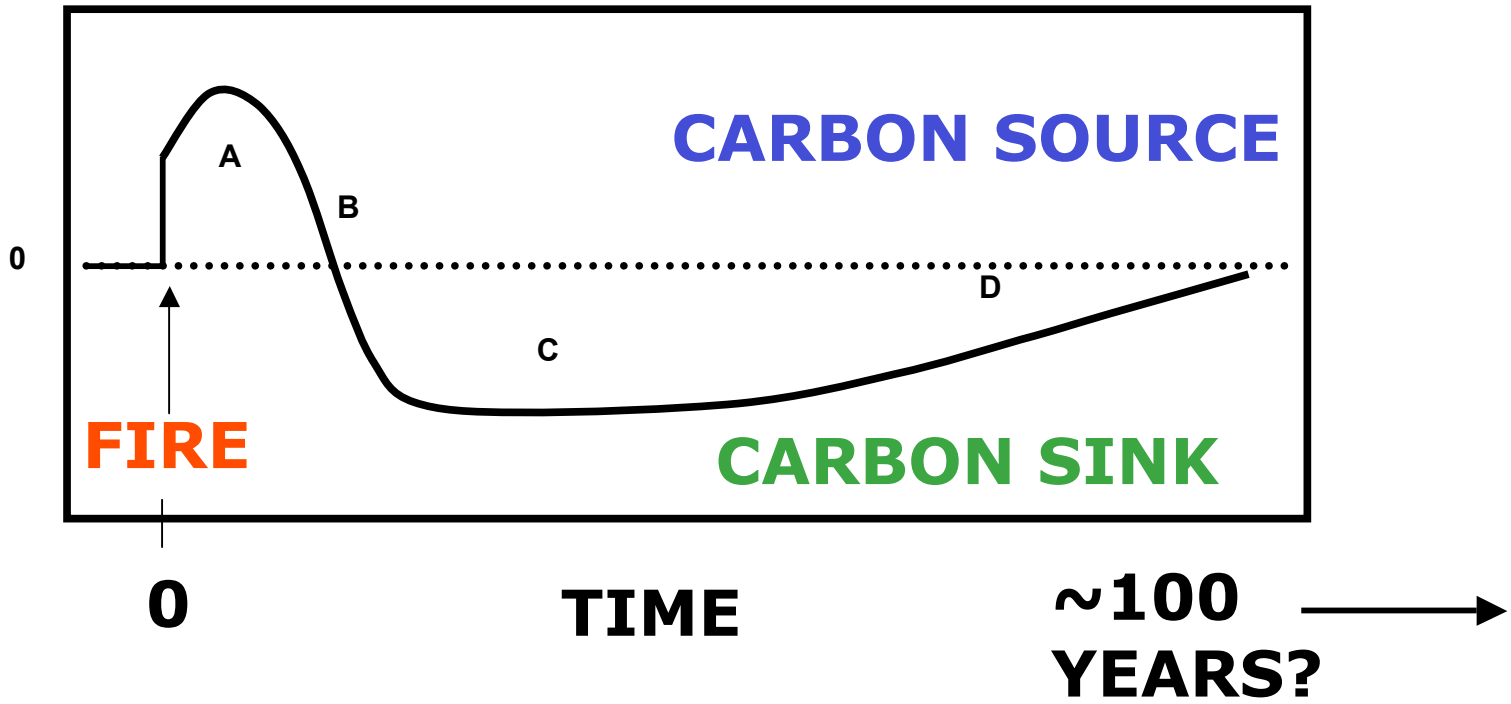
Objectives in Boreal Forest

- **Classic Approach**: understand factors controlling CO_2 exchange (done in **BOREAS**).

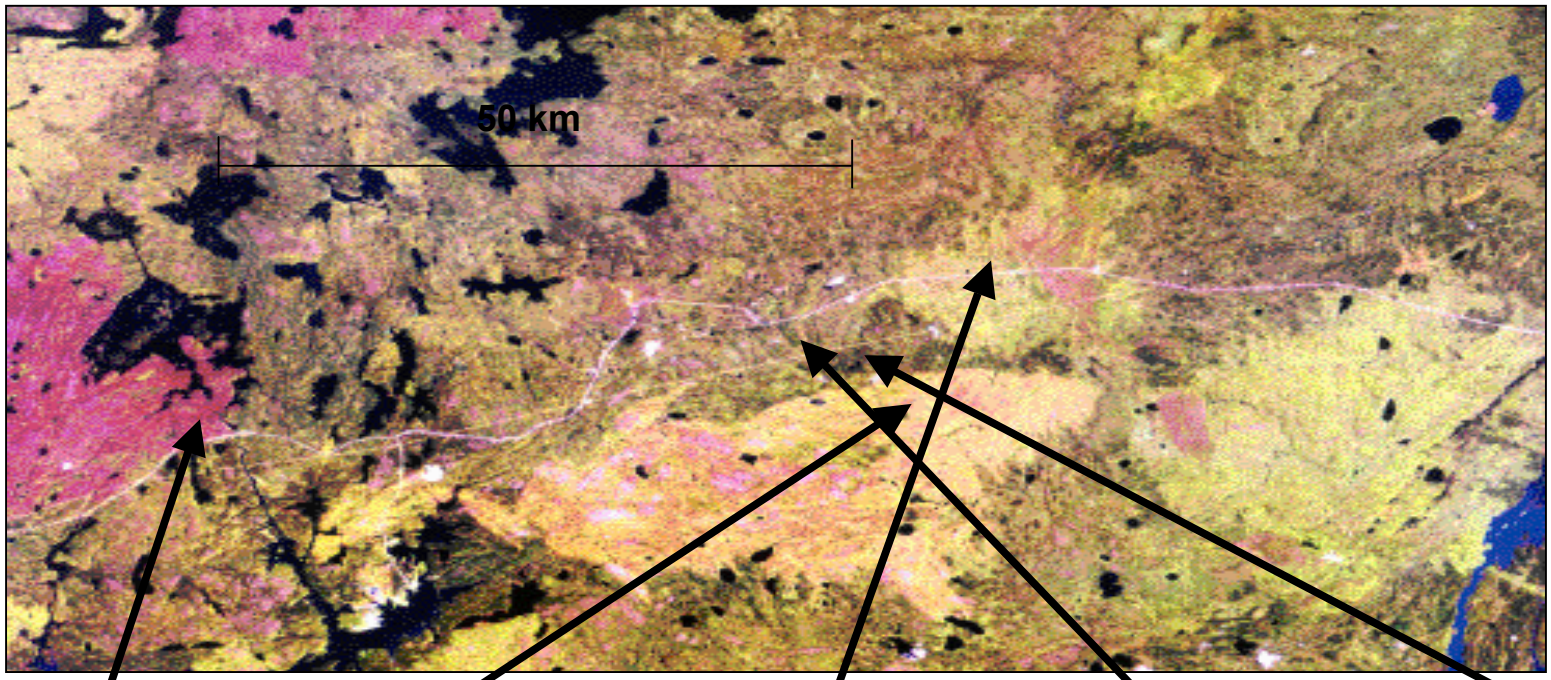
- **Direct Approach**: integrate long term measurements - a carbon **source** or **sink** (done in **BOREAS**)?

- **Response**: How does forest CO_2 cycle recover after **fire**?

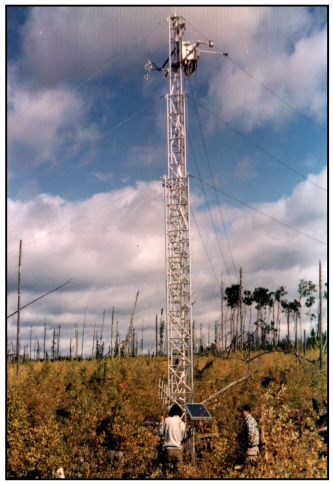
Hypothesis: Recovery from Fire



BOREAS NSA-Chronosequence Study

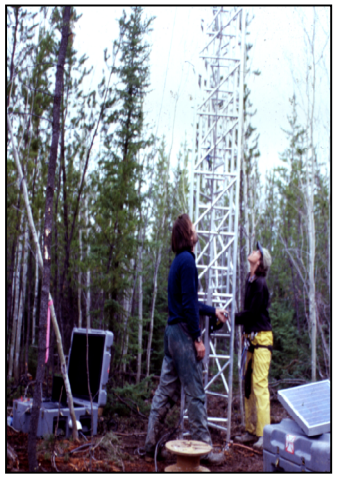


1989



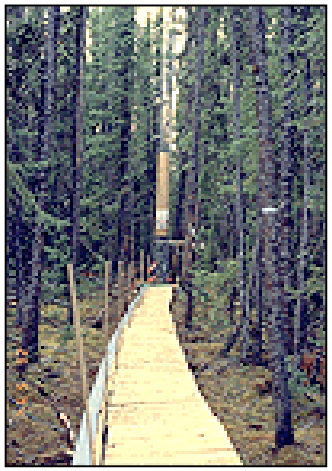
1981

1963



1934

1850



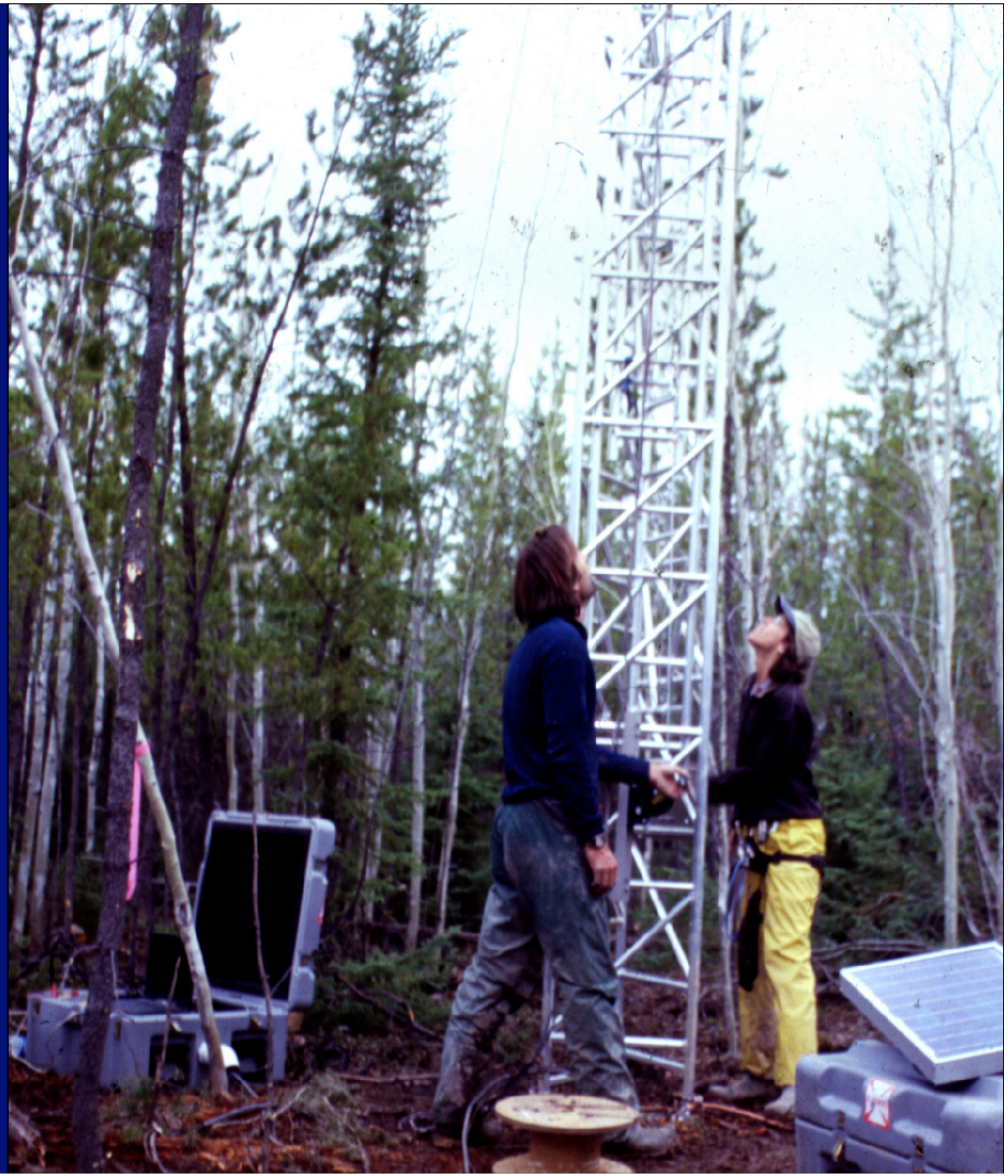
1989 burn:

11 years after fire

1981 burn:

19 years after fire

1963 burn:
37 years after fire

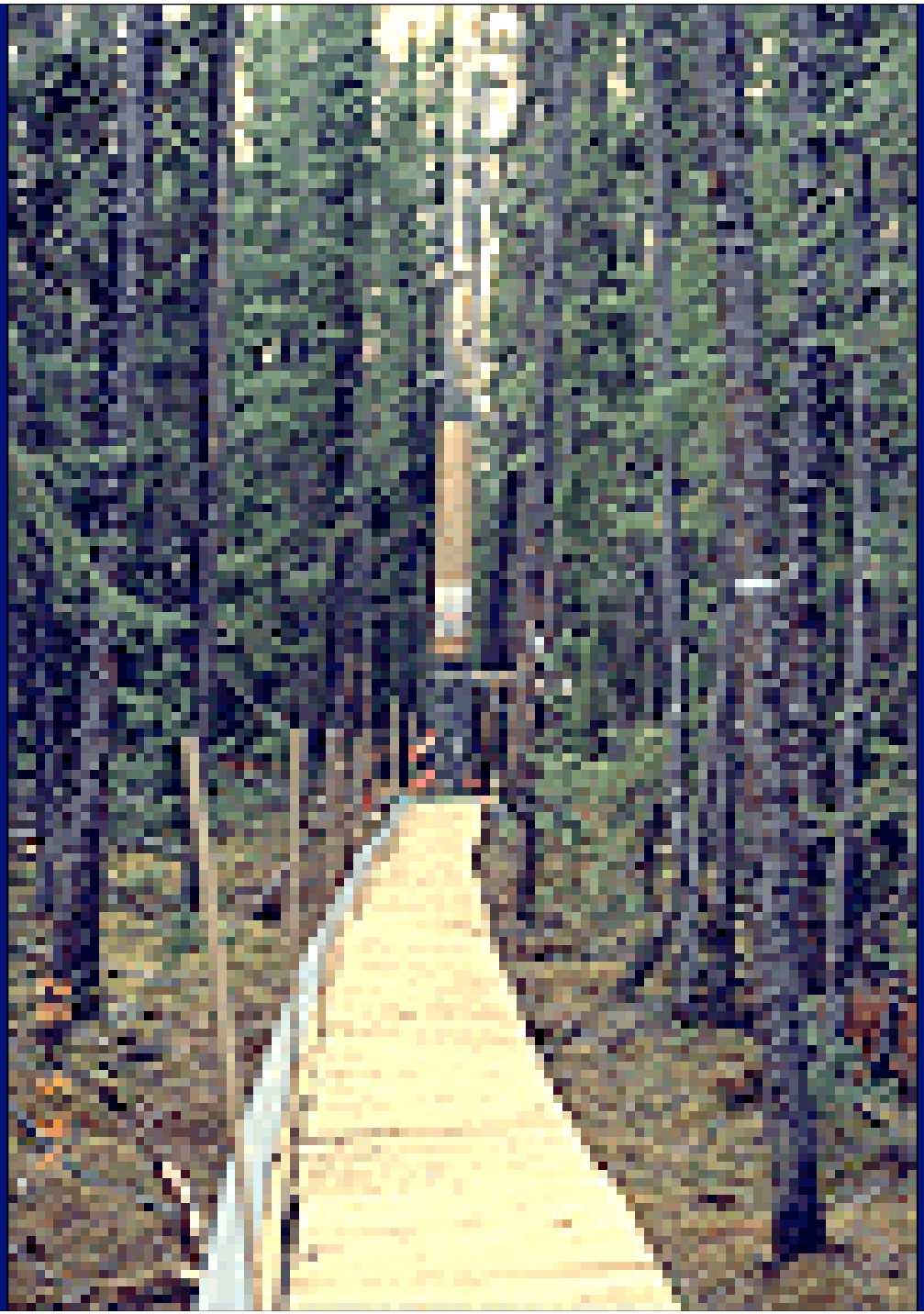


1930 burn:

~70 years after fire

1850 burn:

~150 years after fire



Experimental design: 7 identical, solar powered, automated towers running year round

Temperatures are -40 C in winter, +40 C in summer

Logistical challenges

Solar power

Sunlight

Summer - ~20 hours
Winter - ~ 4 hours

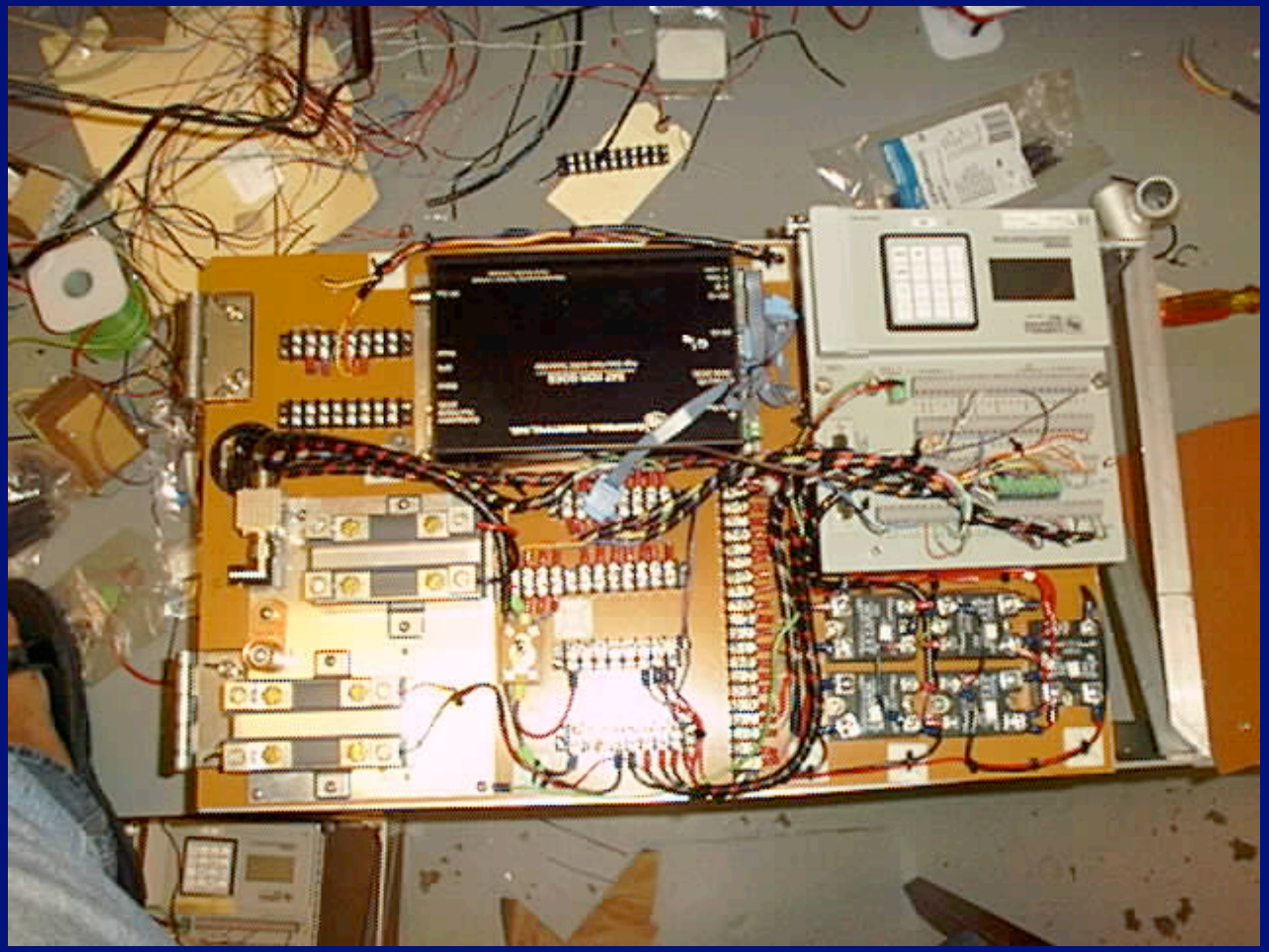
Logistical challenges

Sites are several km from nearest road

Logistical challenges

Access to sites during 6 months of winter is limited.

Data is transmitted via GOES satellite link, every 3 hours

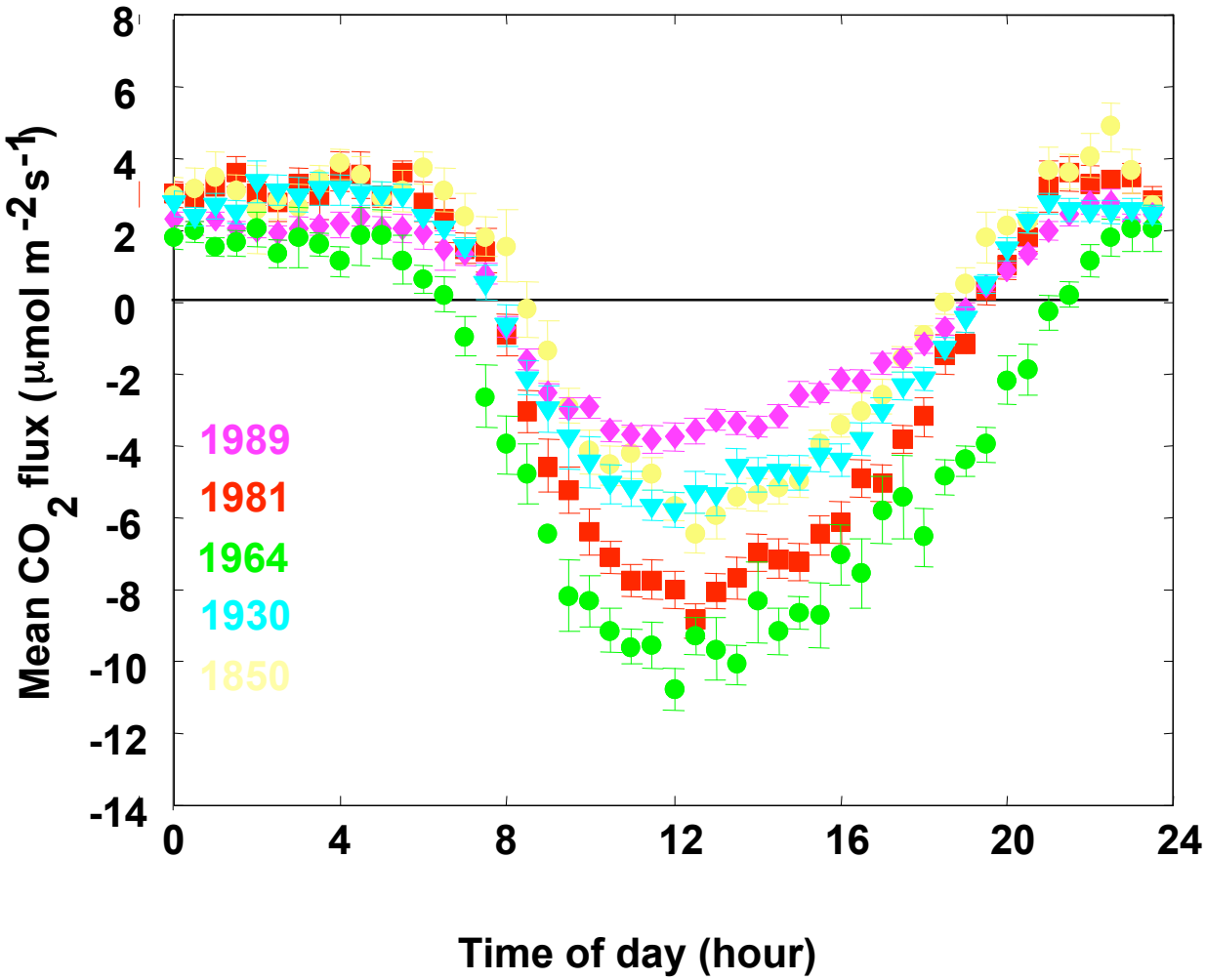


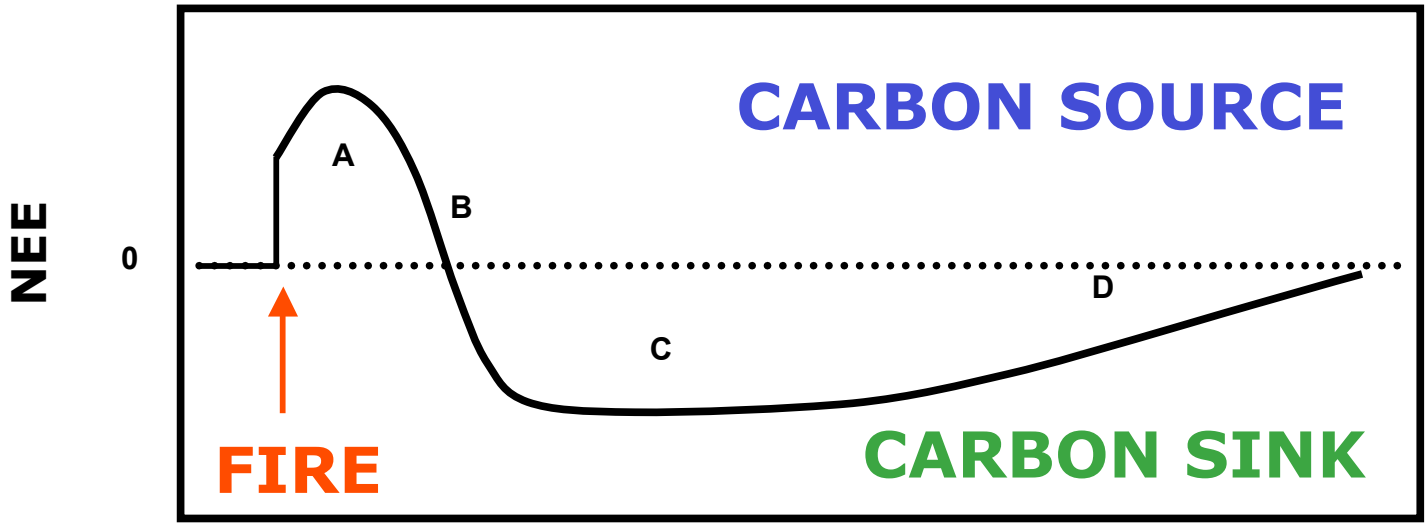
Logistical challenges

Equipment box is buried beneath soil, and covered by snow during winter.

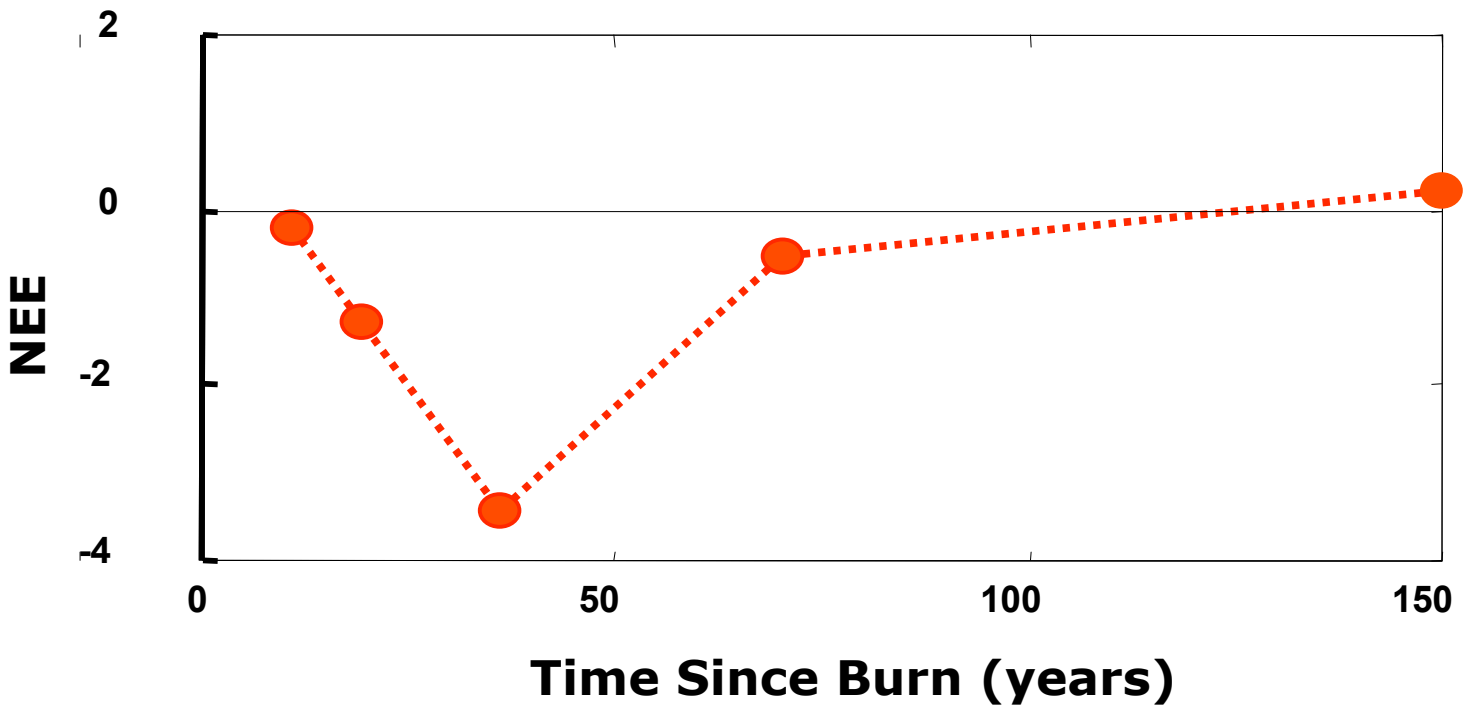
Box temperature remains about 20 C when ambient temp is -40 C.

Comparison of Summer Diurnal CO_2 fluxes




CARBON SOURCE
A
B
C
D
NEE
0
FIRE
CARBON SINK

theory


2
0
-2
-4
NEE
0
50
100
150
Time Since Burn (years)

data