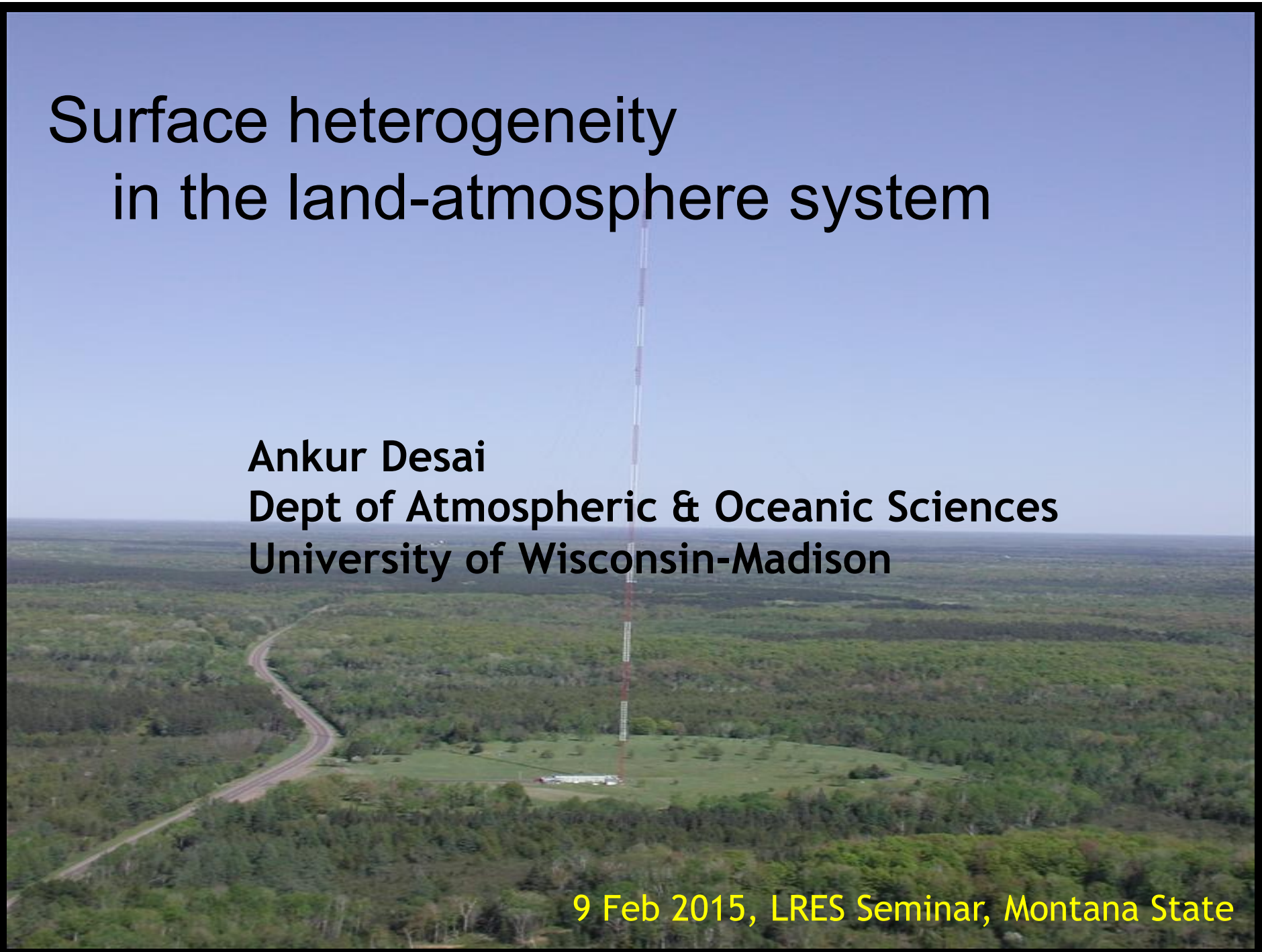
Surface heterogeneity in the land-atmosphere system



Ankur Desai
Dept of Atmospheric & Oceanic Sciences
University of Wisconsin-Madison

9 Feb 2015, LRES Seminar, Montana State

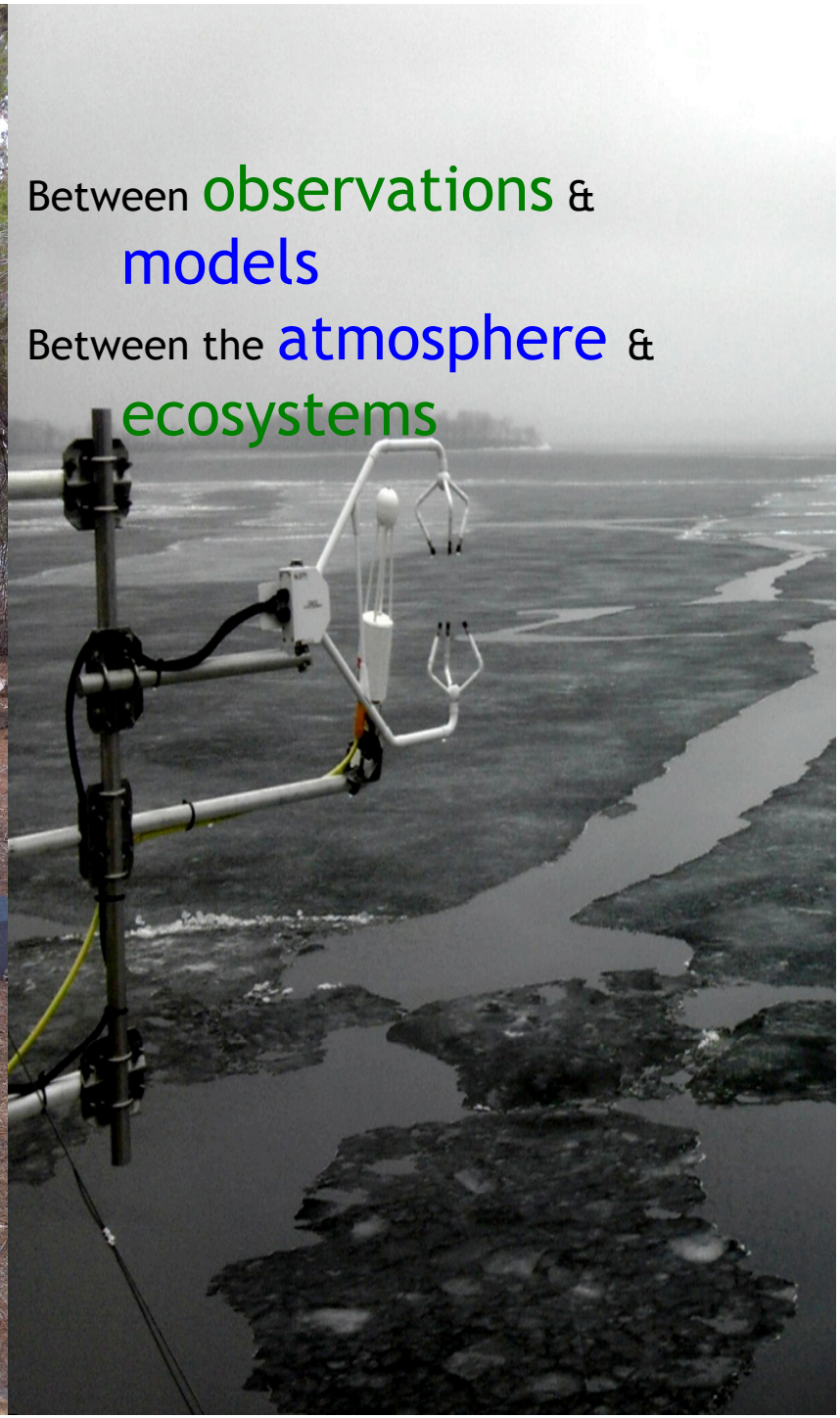

Why is this so damn hard to model?

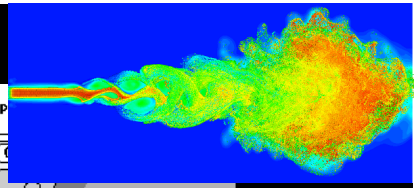

What does it have to do with scale?

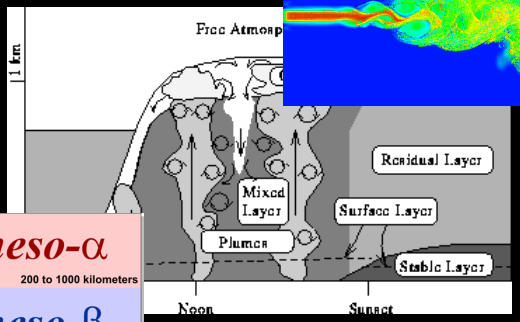
We face a fundamental scale mismatch

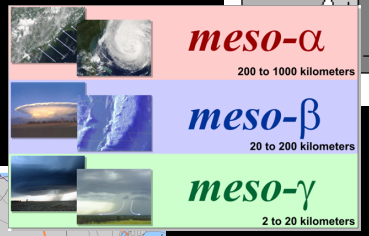
Between observations & models

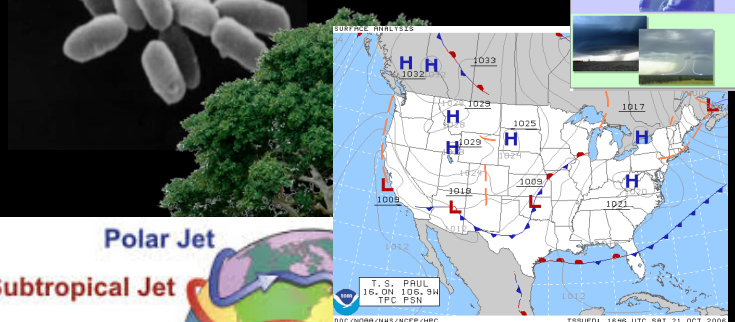
Between the atmosphere & ecosystems



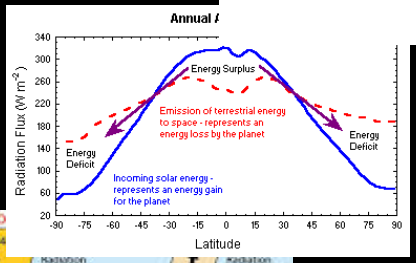


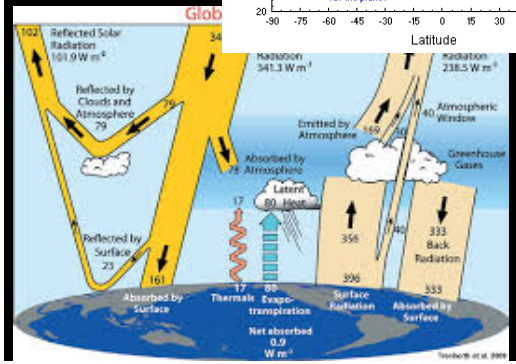

Free Atmosp
1 km
Residual Layer
Mixed Layer
Surface Layer
Plume
Stable Layer
Noon
Sunset

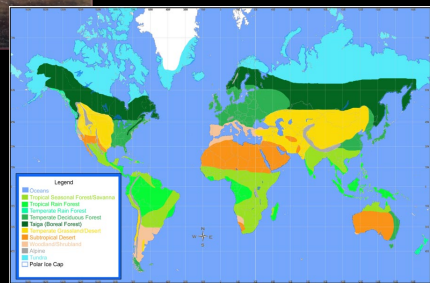

meso-α
200 to 1000 kilometers
meso-β
20 to 200 kilometers
meso-γ
2 to 20 kilometers



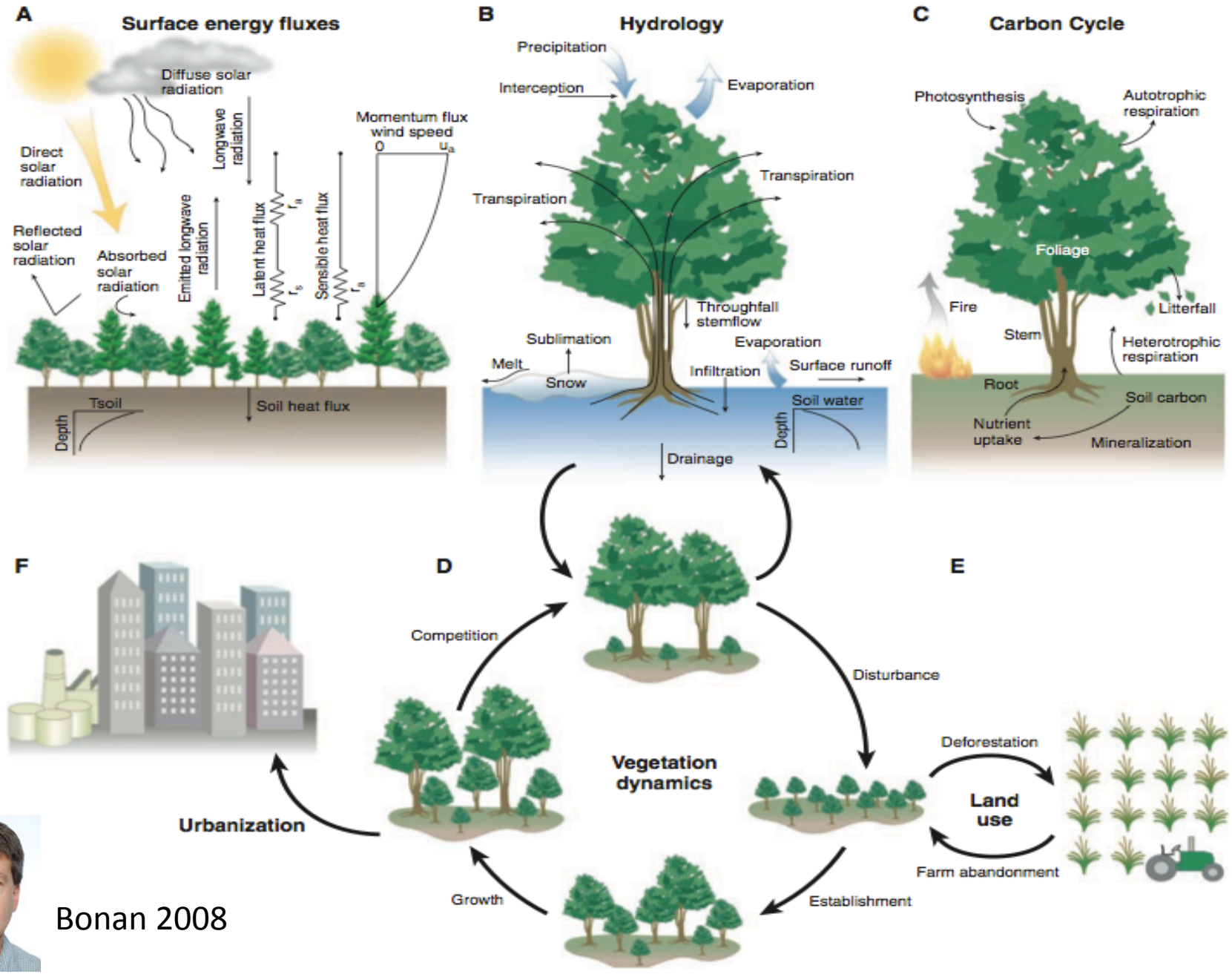

Polar Jet
Subtropical Jet


Annual
Energy Surplus
Emission of terrestrial energy to space - represents an energy loss by the planet
Energy Deficit
Energy Deficit
Incoming solar energy - represents an energy gain for the planet
Radiation Flux (W m-2)
Latitude

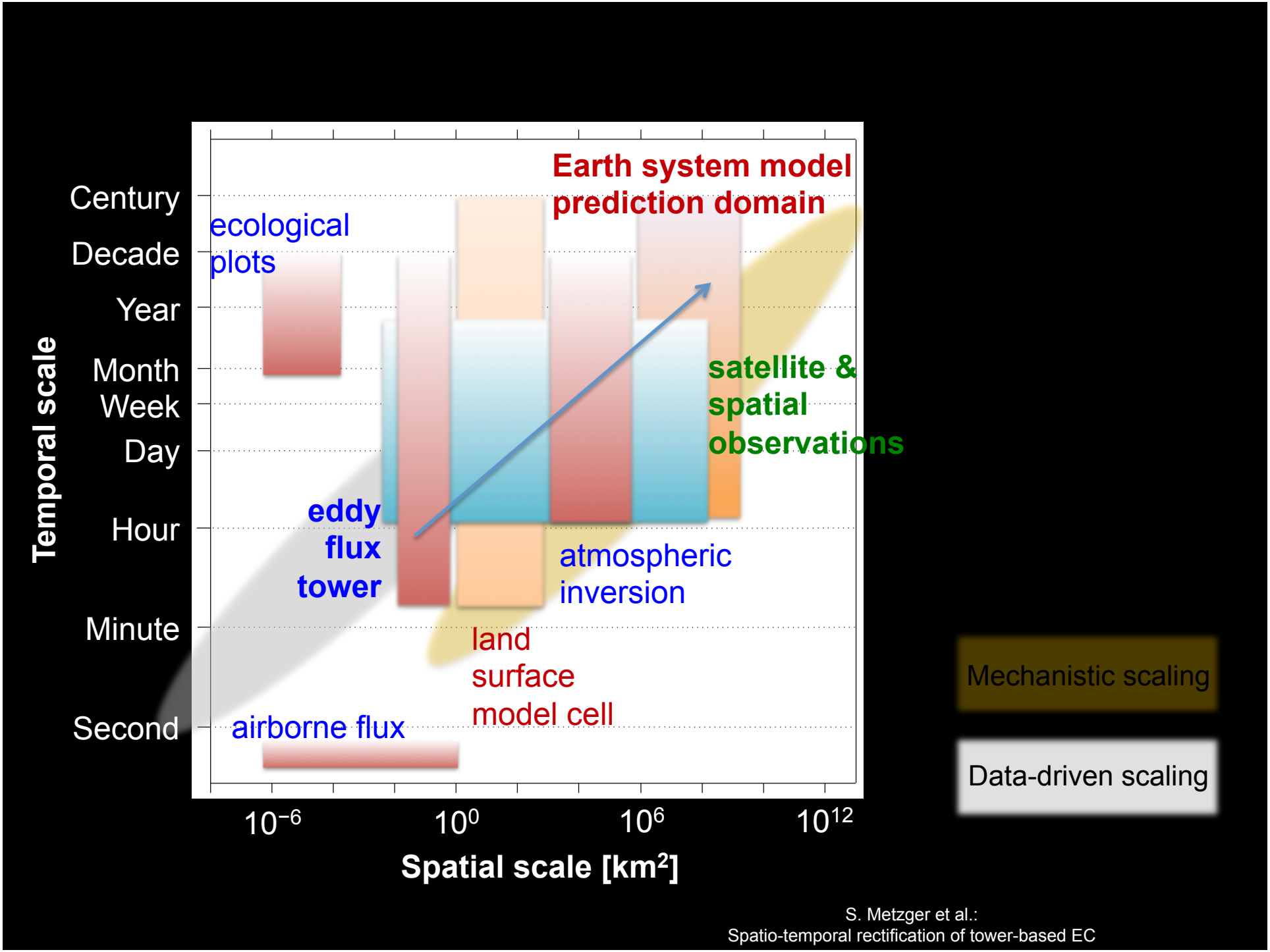

Reflected Solar Radiation
Reflected by Clouds and Atmosphere
Reflected by Surface
Absorbed by Surface
Emitted by Atmosphere
Atmospheric Window
Greenhouse Gases
Absorbed by Atmosphere
Latent Heat
Thermals
Evapo-transpiration
Surface Radiation
Back Radiation
Absorbed by Surface
Net absorbed 0.9 W m-2



Forests in Flux



Bonan 2008



S. Metzger et al.:
Spatio-temporal rectification of tower-based EC

Ecology, 73(6), 1992, pp. 1943–1967

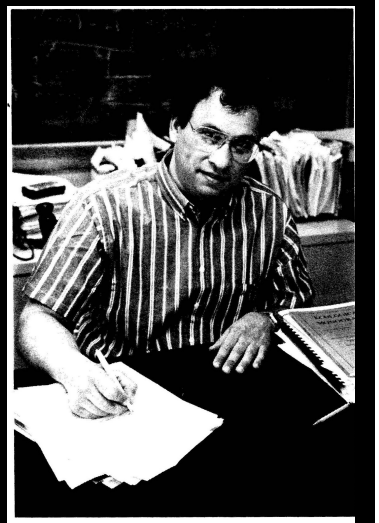
THE PROBLEM OF PATTERN AND SCALE IN ECOLOGY

THE ROBERT H. MACARTHUR AWARD LECTURE
Presented August 1989
Toronto, Ontario, Canada

by

SIMON A. LEVIN
Department of Ecology and Evolutionary Biology, Princeton University, Princeton, New Jersey 08544-1003 USA, and Section of Ecology and Systematics, Cornell University, Ithaca, New York 14853-2701 USA

- How do spatio-temporal patterns and variability change with the scale of description?
- Develop laws for their aggregation!



Simon A. Levin
MacArthur Award Recipient

Global NPP 1983 version

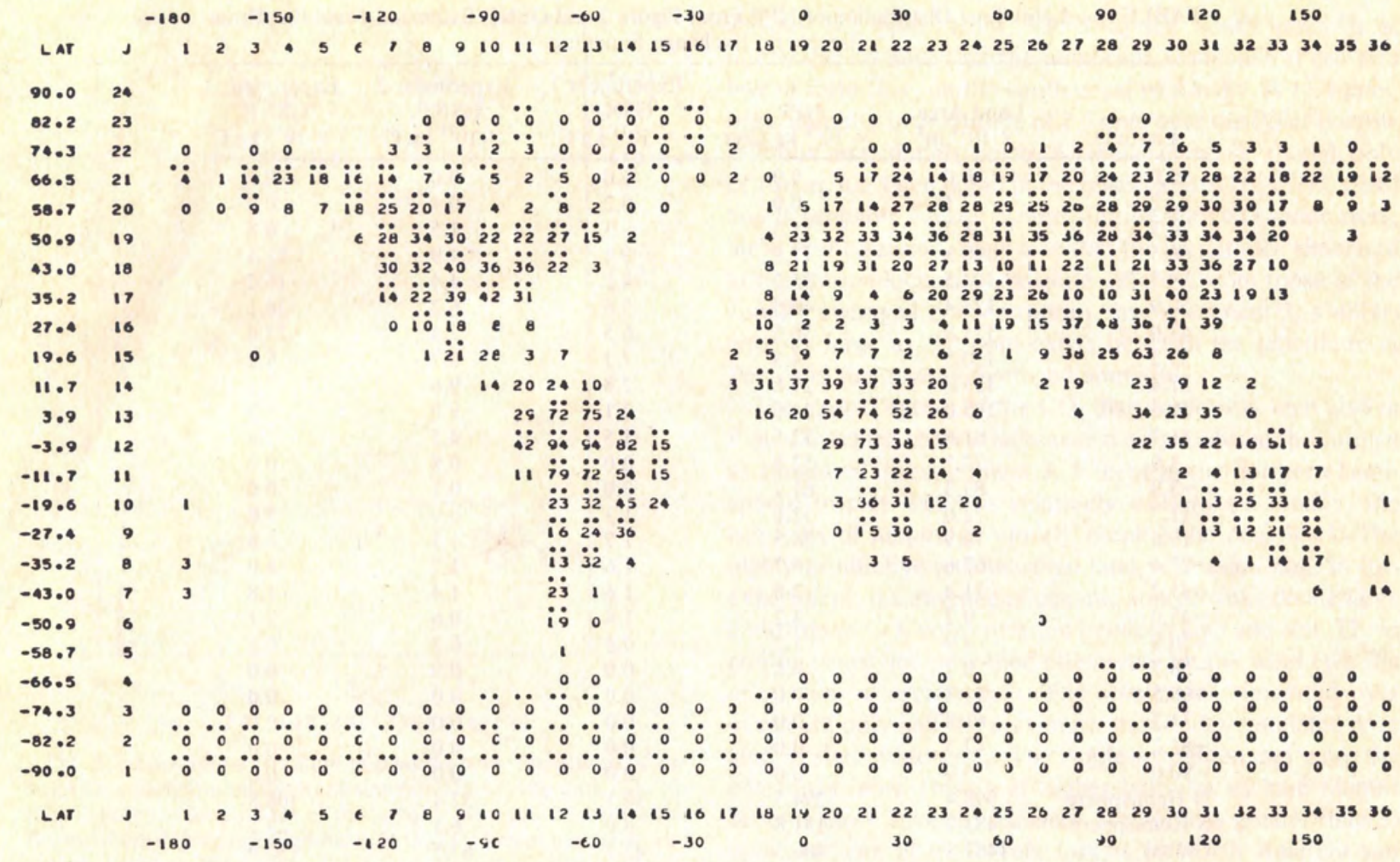
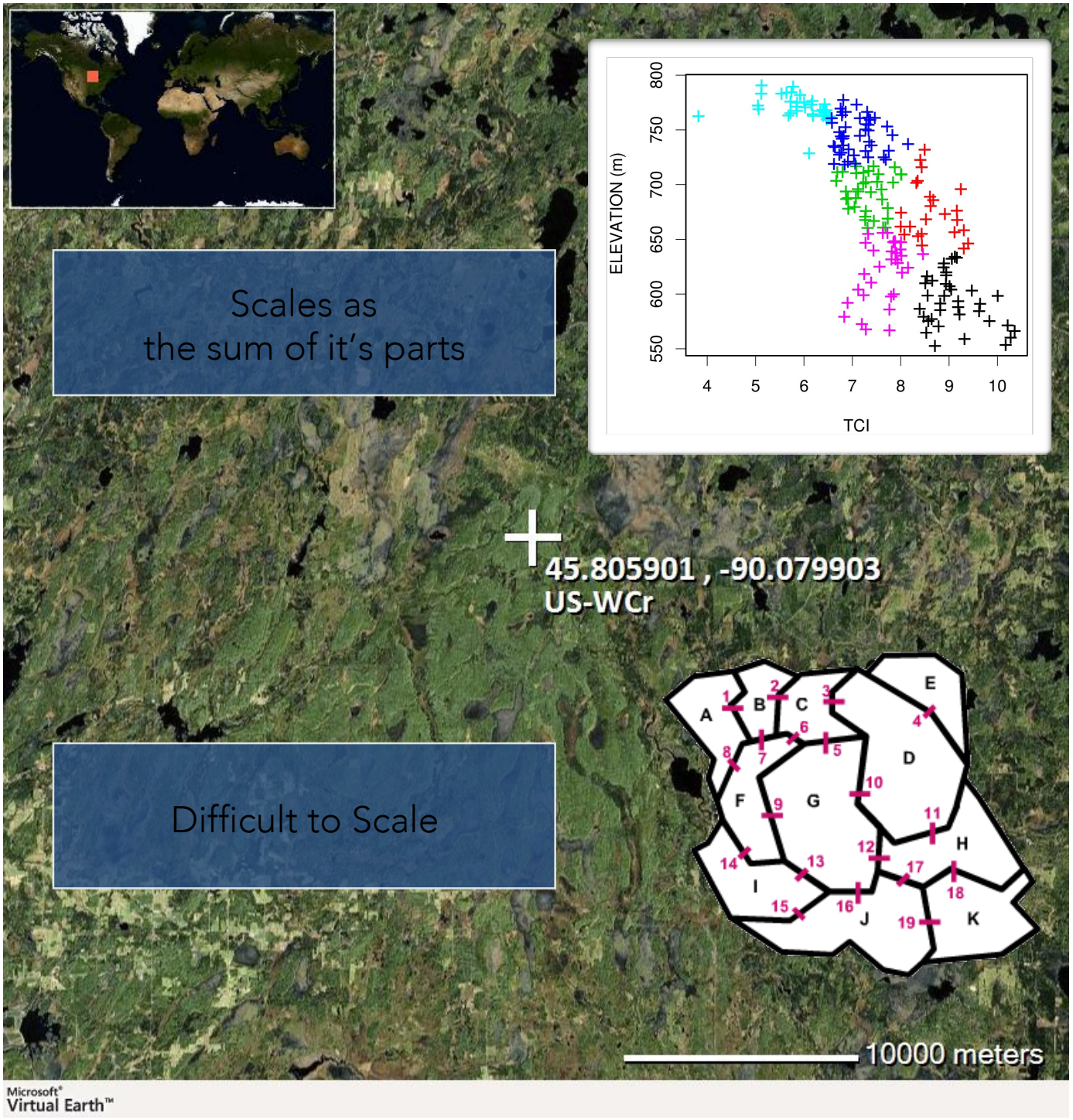


Fig. 2. Global distribution of NPP (× 10 gm C/m^2/yr) at the tracer model resolution.



Spatial Heterogeneity

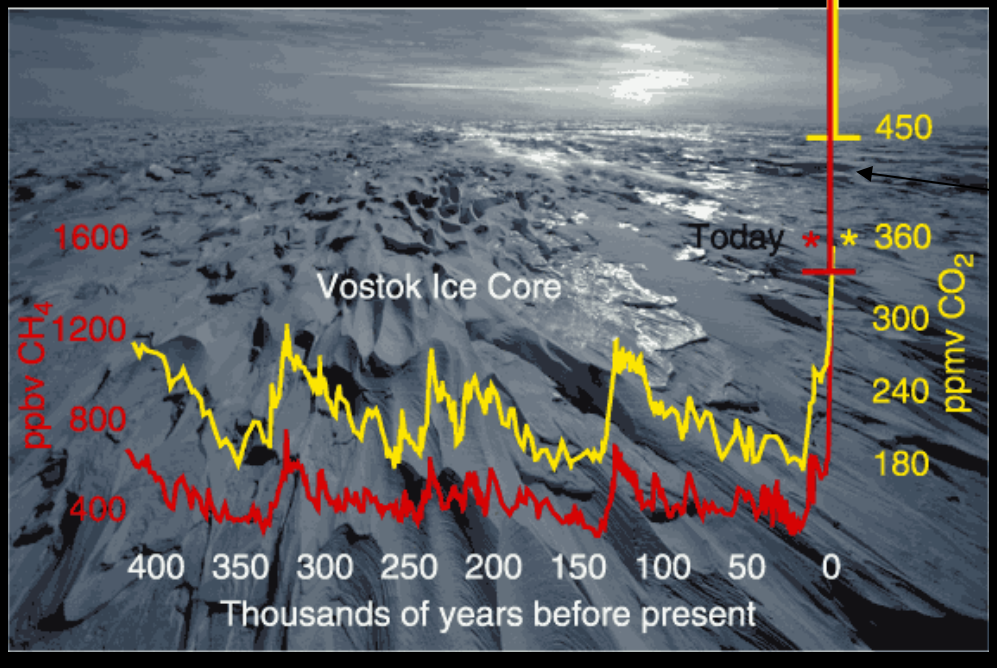
- Amount
- Frequency Distribution

Spatial Process

- Arrangement
- Location
- Distance

Why does it matter?

Atmospheric CO_2 has increased rapidly to levels above anything in Earth's recent past



1100

3700

2100?

Today

400 ppm CO_2

2 ppm CH_4

Sources: Petit et al (1999) Nature 399:429-436 and IPCC(2000)

THE GREAT ACCELERATION

SOCIO-ECONOMIC TRENDS

EARTH SYSTEM TRENDS

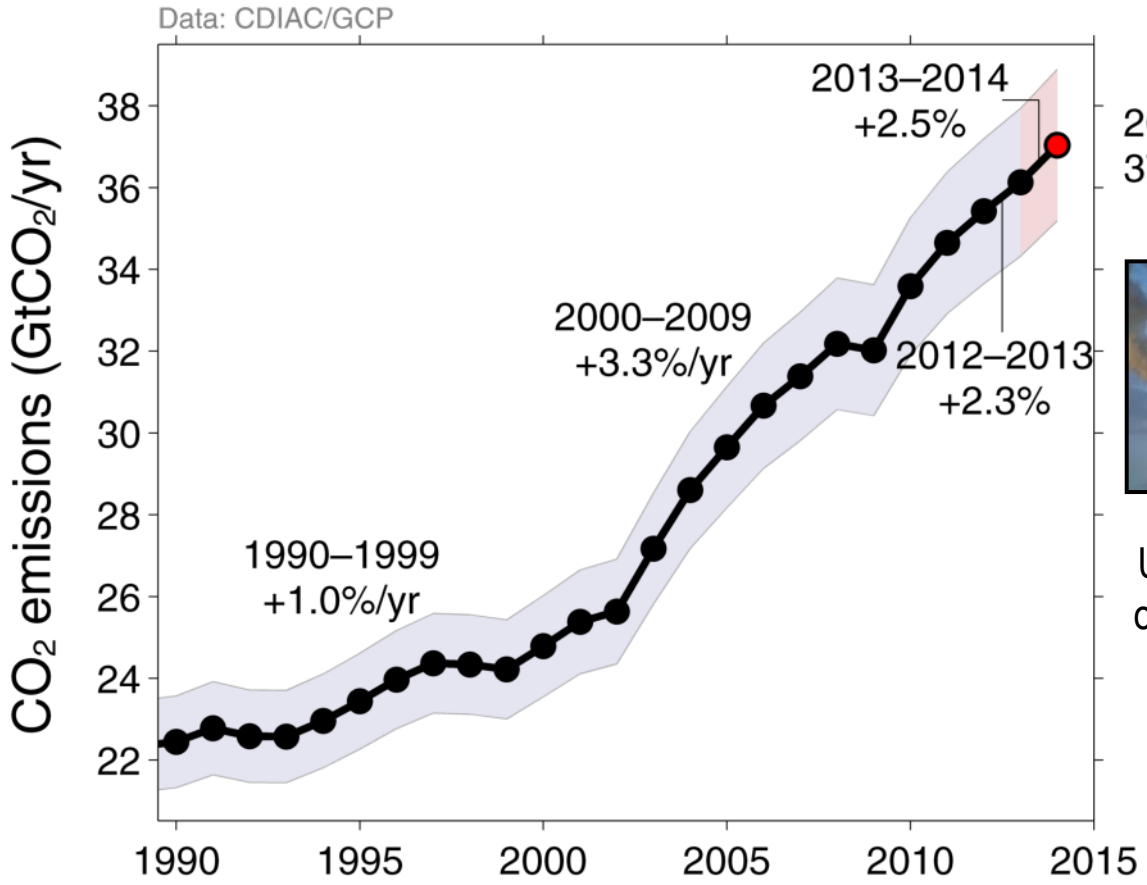
REFERENCE: Steffen, W., W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig (2015), The Trajectory of the Anthropocene: the Great Acceleration, Submitted to *The Anthropocene Review.*

MAP & DESIGN: Félix Pharand-Deschênes / Globaïa

Fossil Fuel and Cement Emissions

Global fossil fuel and cement emissions: 36.1 ± 1.8 $GtCO_2$ in 2013, 61% over 1990

- Projection for 2014 : 37.0 ± 1.9 $GtCO_2$, 65% over 1990



Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

Estimates for 2011, 2012, and 2013 are preliminary

Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

Global Carbon Budget

The cumulative contributions to the Global Carbon Budget from 1870
Contributions are shown in parts per million (ppm)

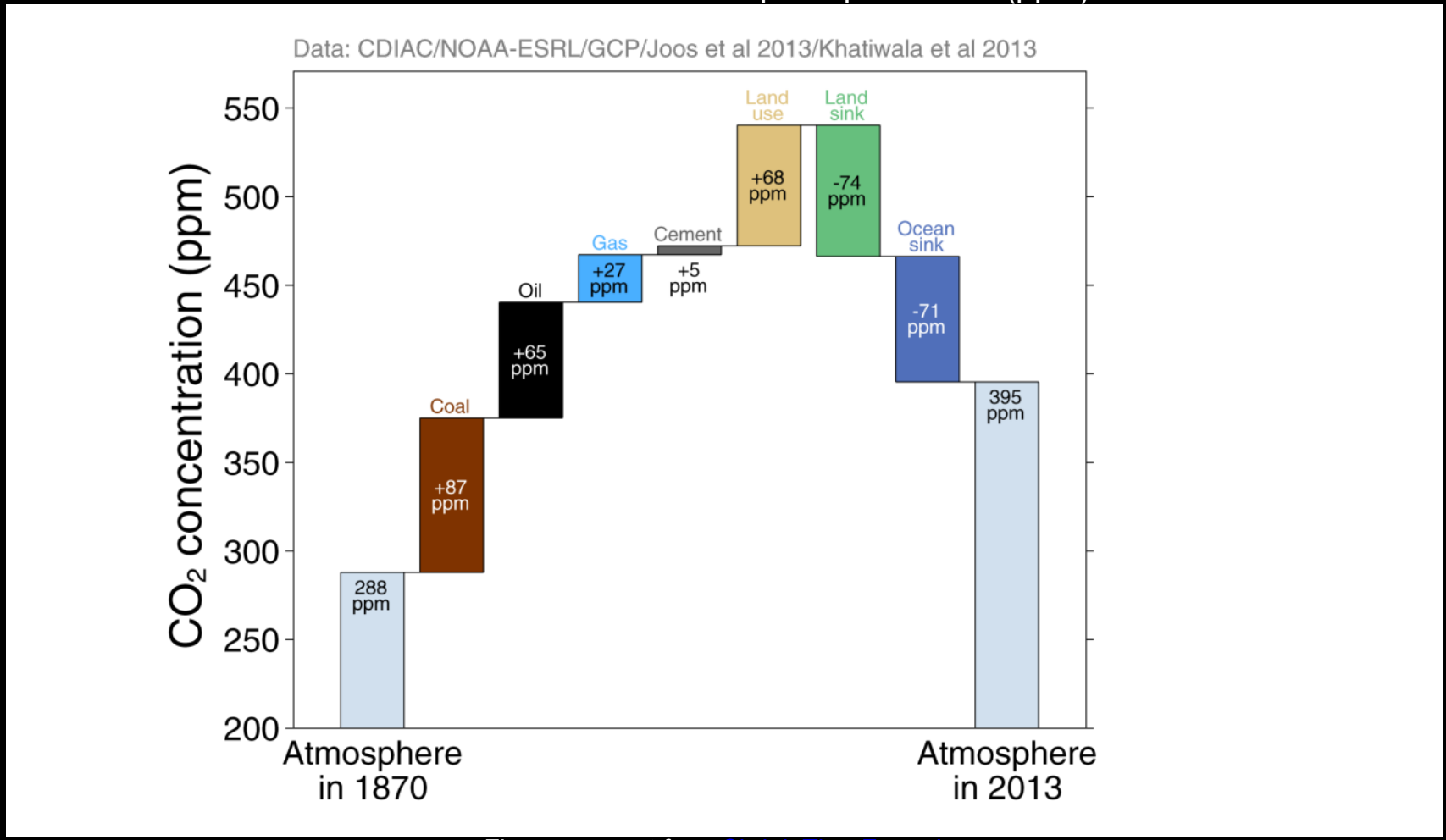
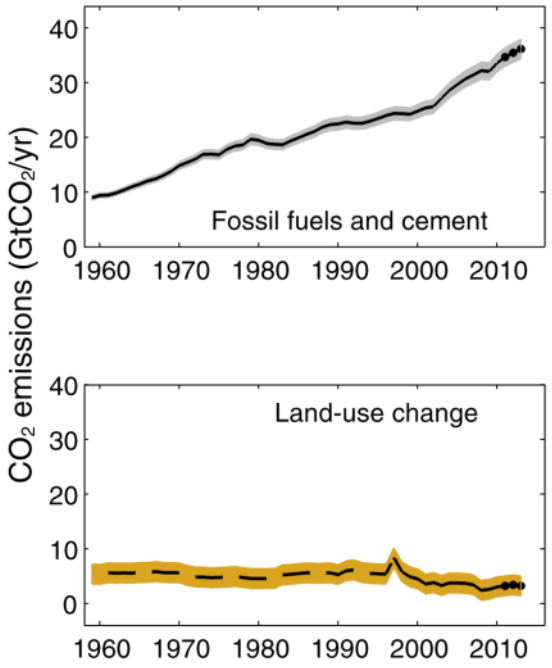


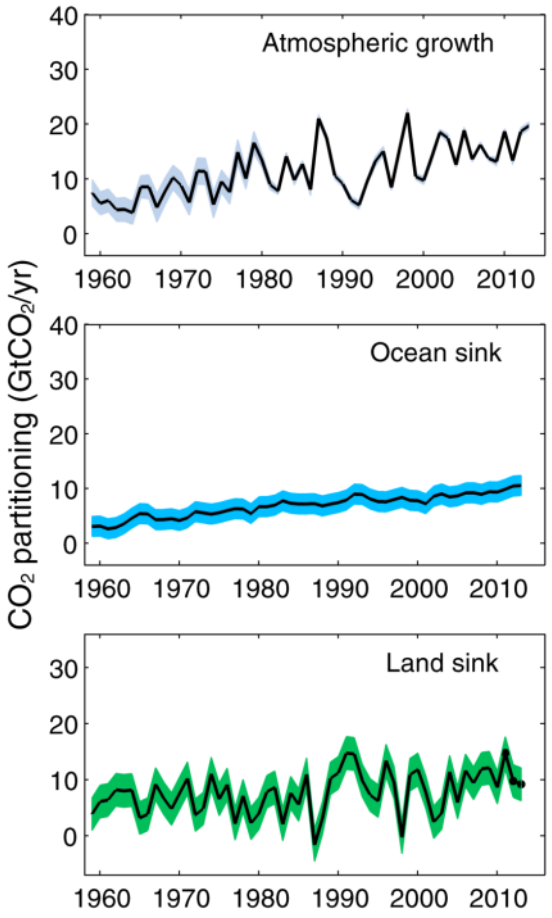
Figure concept from Shrink That Footprint

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Joos et al 2013; Khatiwala et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

Changes in the Budget over Time

The sinks have continued to grow with increasing emissions, but climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere





Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

Terrestrial Biosphere CO_2 Flux Dominates Carbon Cycle Prediction Uncertainty

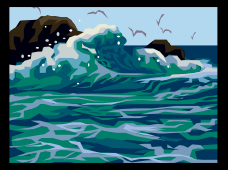
+

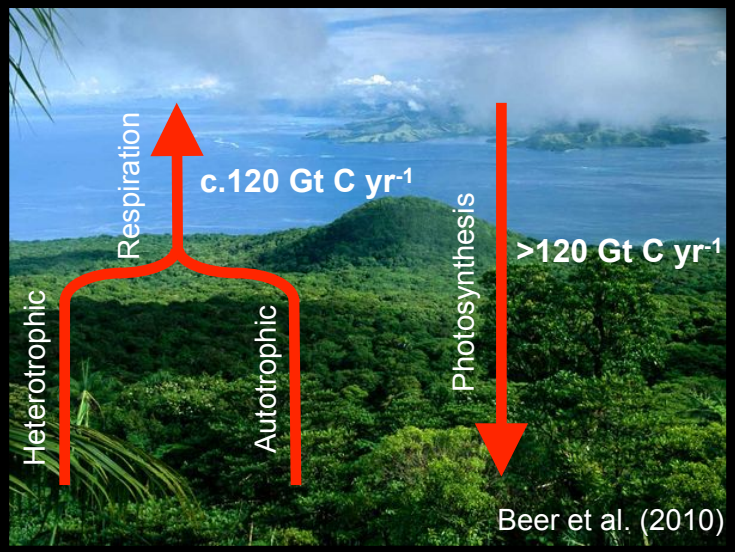
Le Quéré et al (2013)

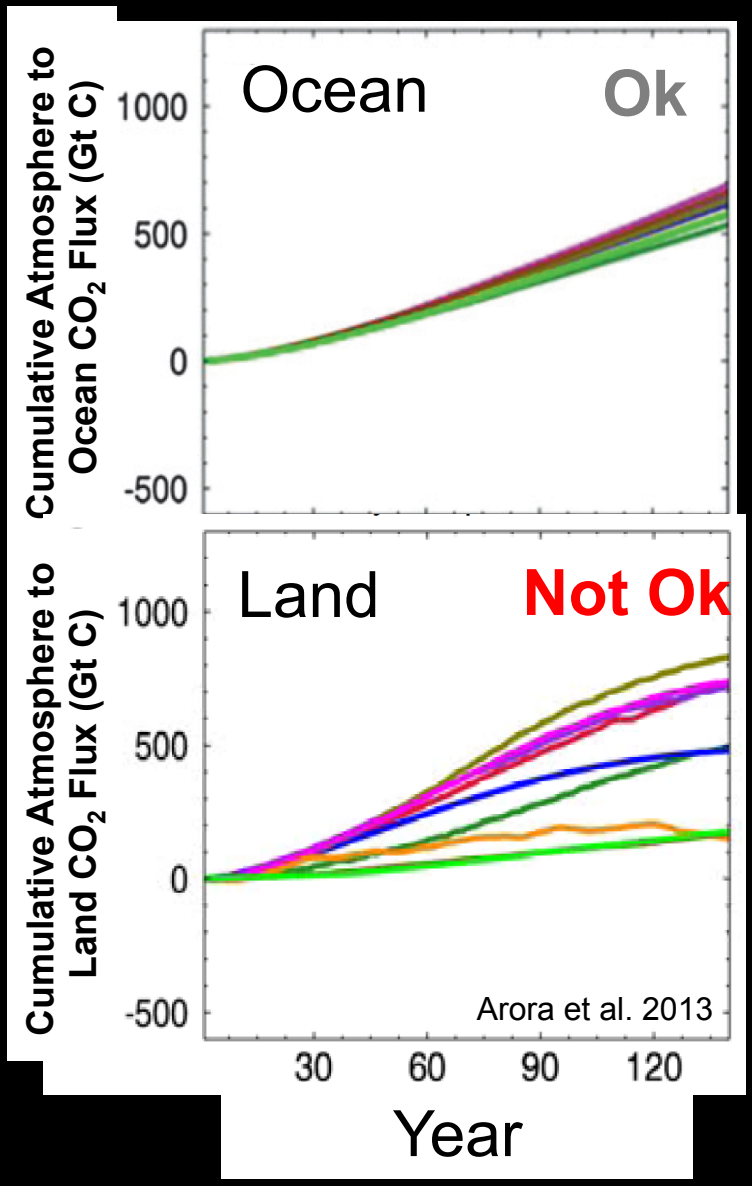
Atmosphere 45%

Land 29%

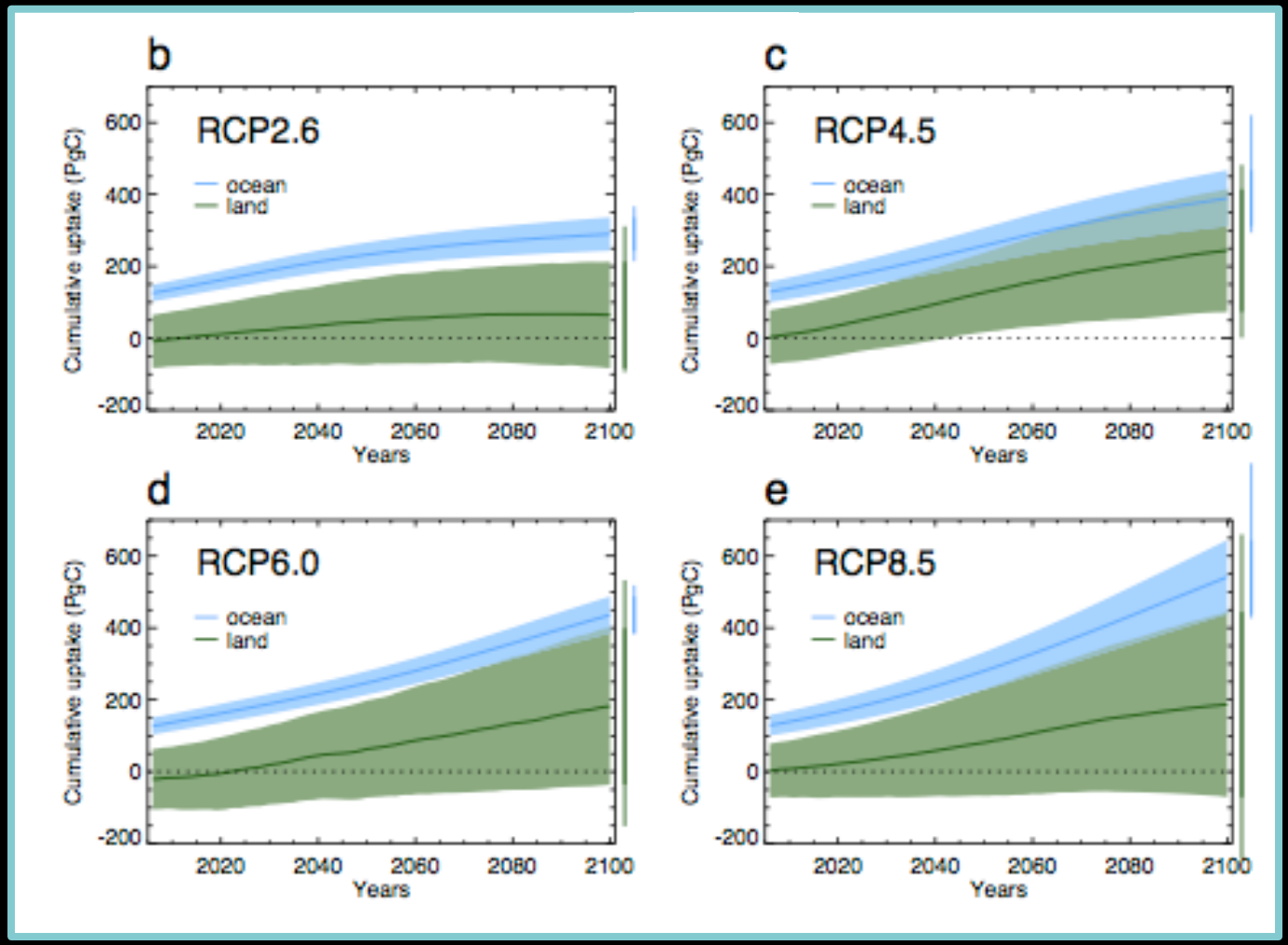
Oceans 26%



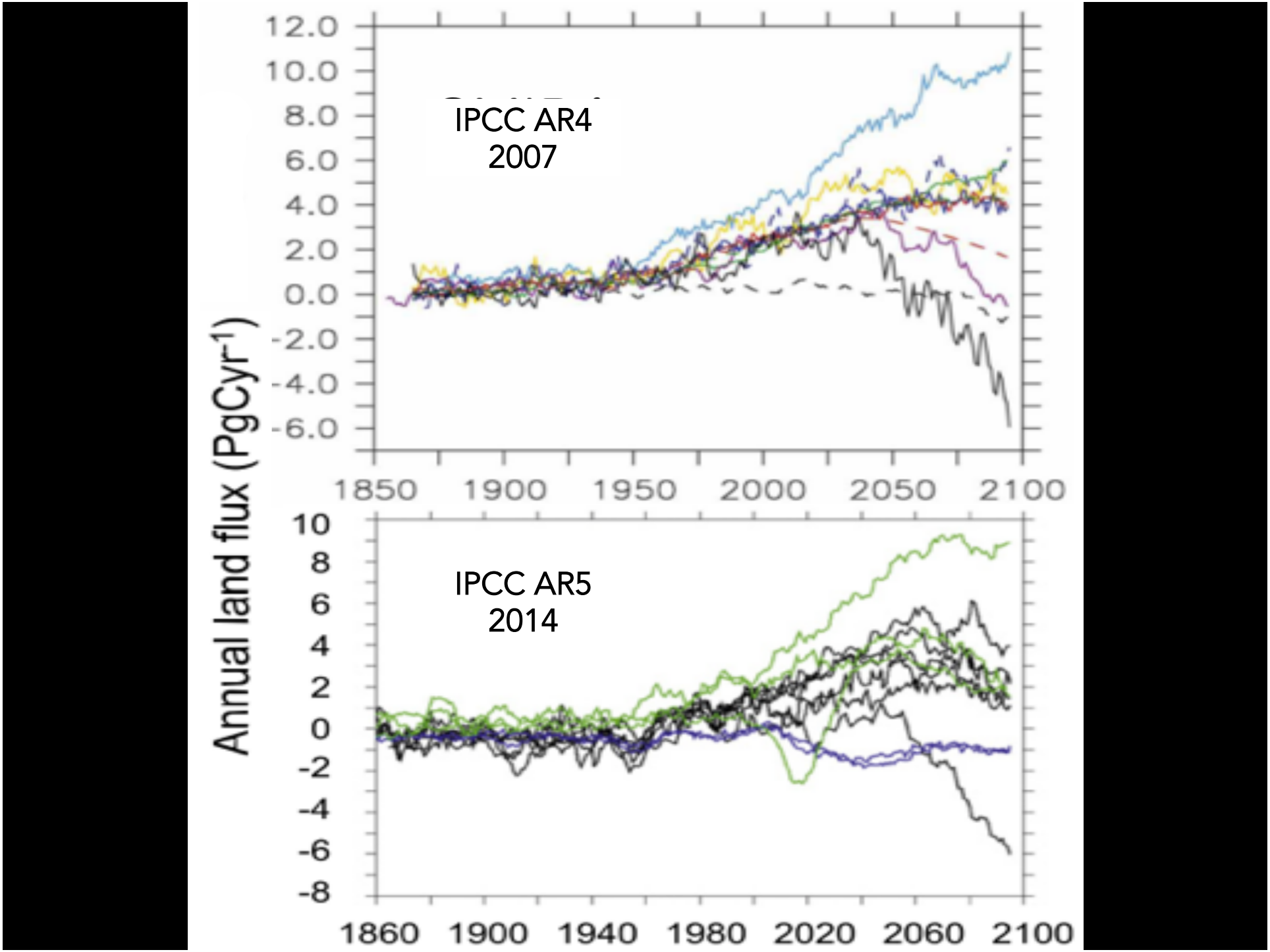


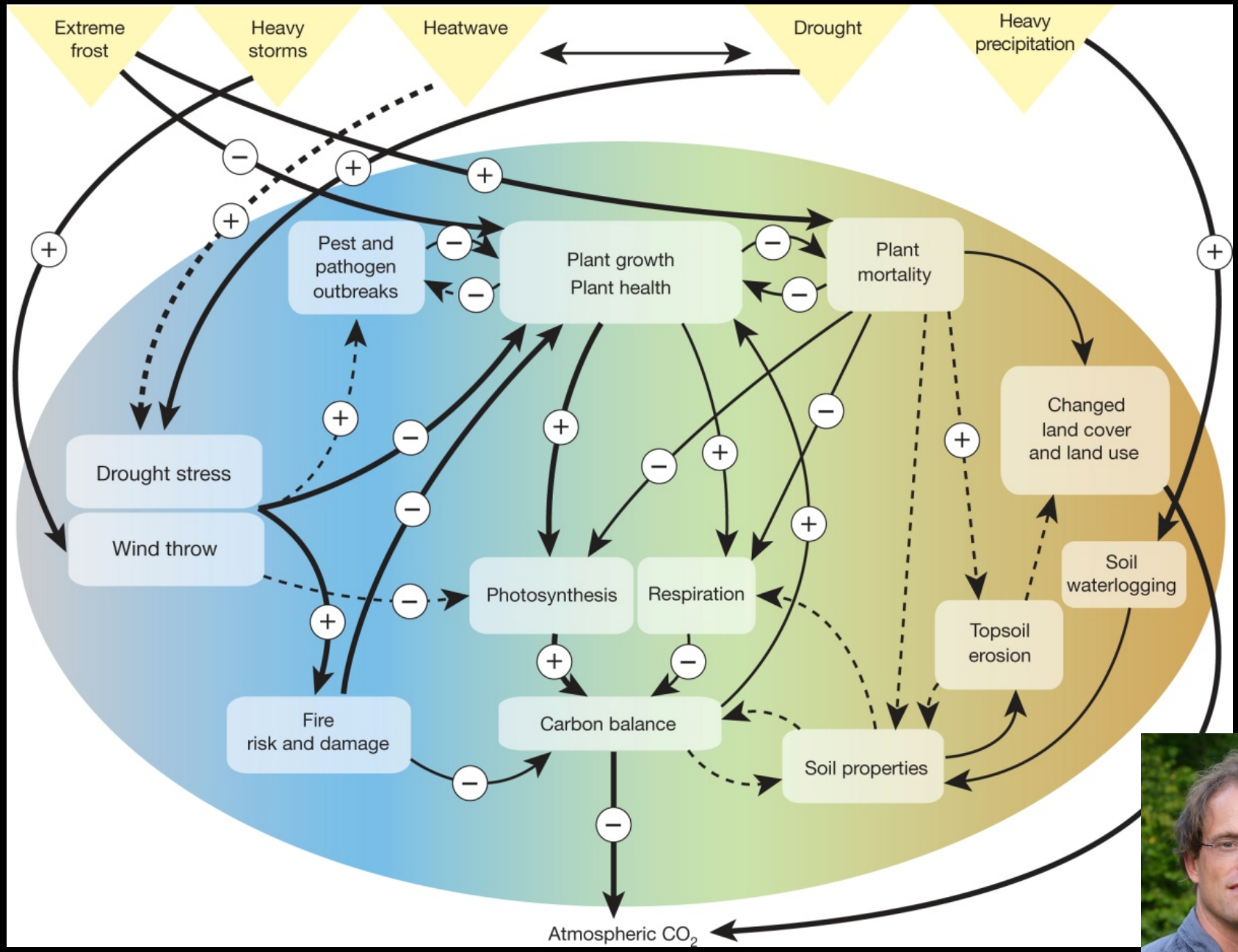


Terrestrial carbon cycle feedback is a leading order uncertainty for climate simulation



IPCC AR5 WG1 CH6


IPCC AR4
2007
IPCC AR5
2014
Annual land flux (PgCyr-1)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
1850
1900
1950
2000
2050
2100
10
8
6
4
2
0
-2
-4
-6
-8
1860
1900
1940
1980
2020
2060
2100



M Reichstein *et al. Nature* **500**, 287-295 (2013) doi:10.1038/nature12350

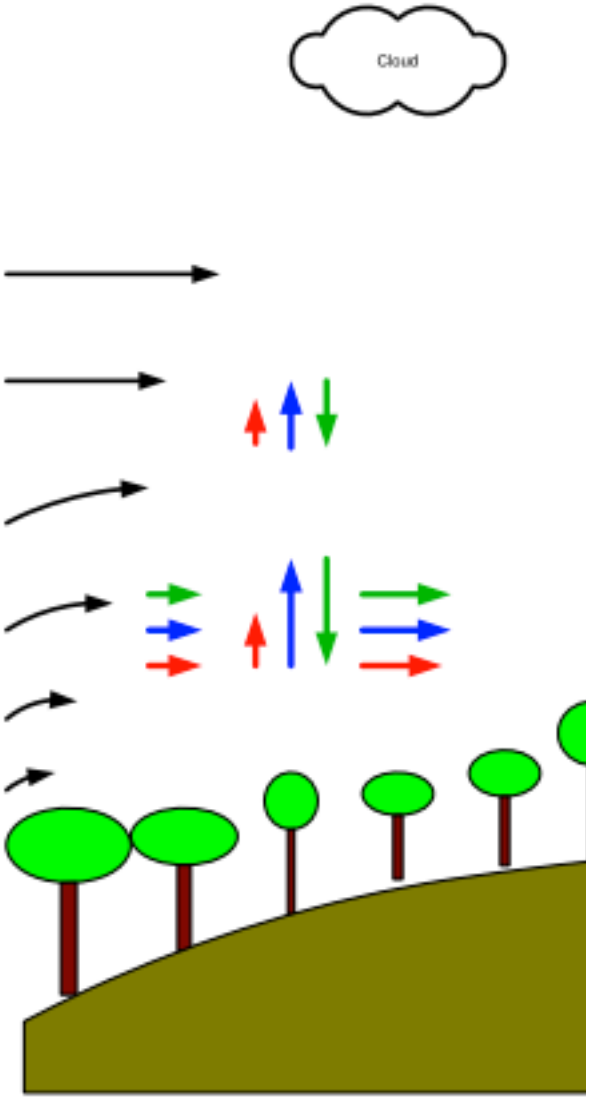
What do I (we) do?

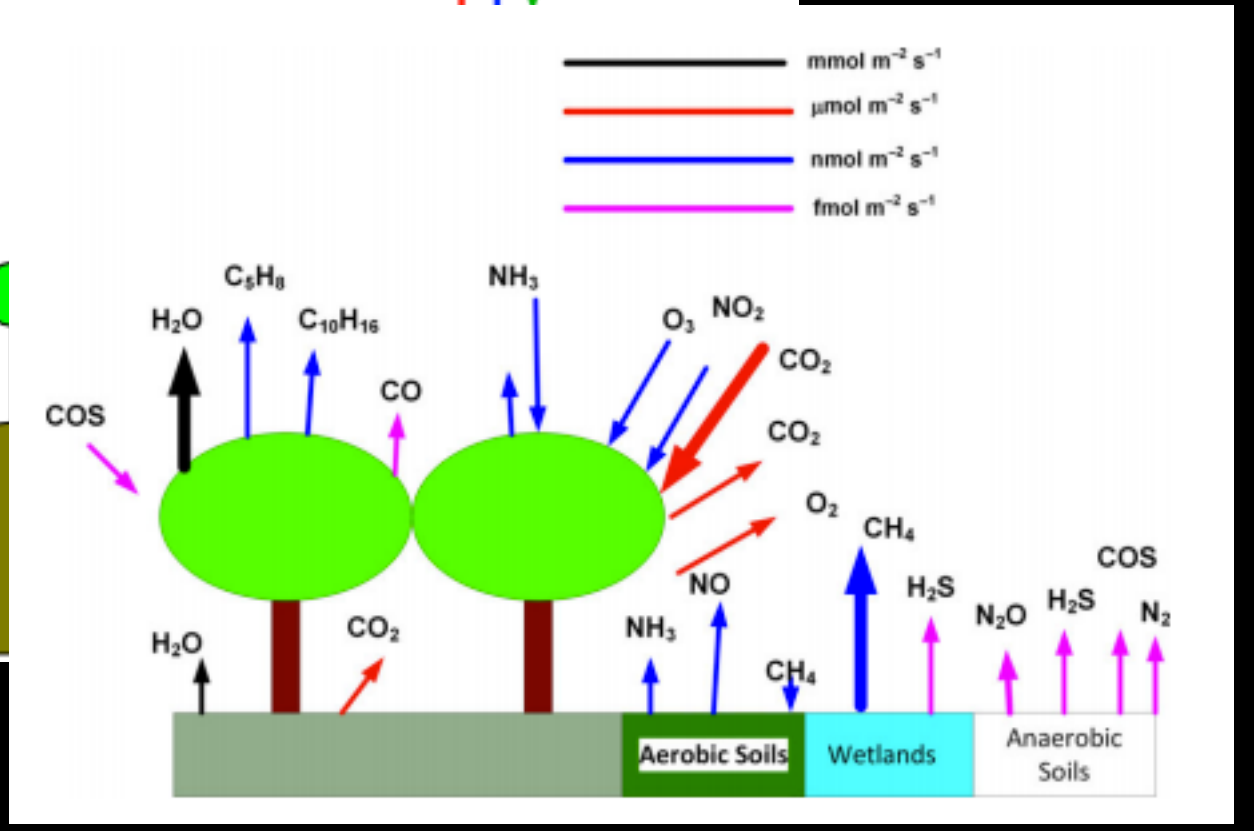
http://flux.aos.wisc.edu

- Probe spatial heterogeneity in biologically-mediated surface-atmosphere exchanges from sites to regions (meters-1000s km)
  - Forests, wetlands, lakes, urban (temperate-boreal-tropical-Mediterranean-alpine, terrestrial-aquatic, management gradients)
  - Multiple greenhouse gases (methane), esp. with eddy covariance
  - Feedbacks from energy balance and a land surface variability on the atmospheric boundary layer and synoptic-PBL interactions in observations and models (LES, PBL, mesoscale, climate)
  - Up/down scaling across multiple measurements: eddy covariance, biometric, airborne budgets, inverse modeling, hyperspectral remote sensing (leaf to satellite)
  - Informing ecosystem and atmospheric models with diverse measurements across space (data assimilation, model informatics) – http://pecanproject.org

Who we are

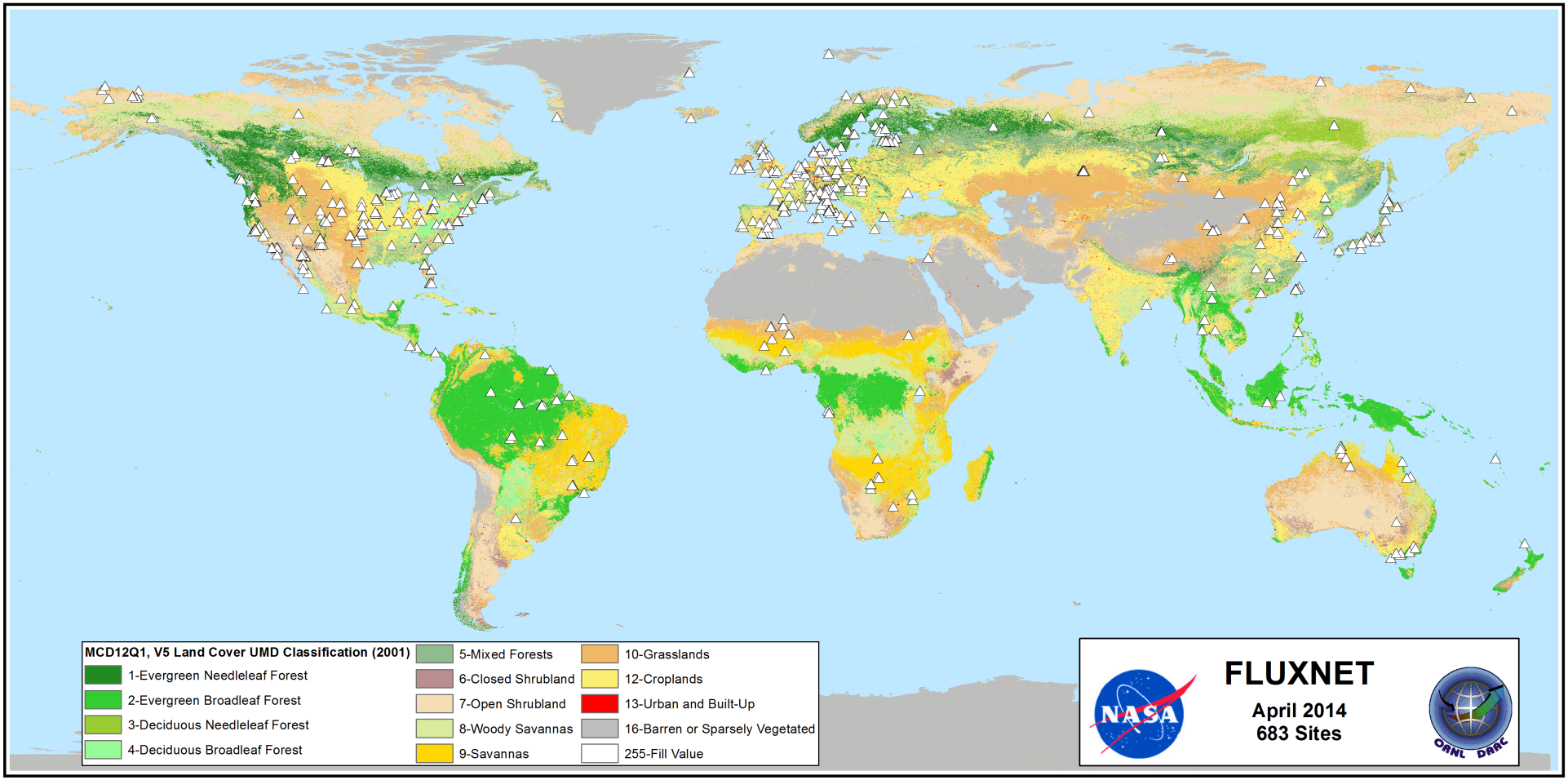
What the flux?

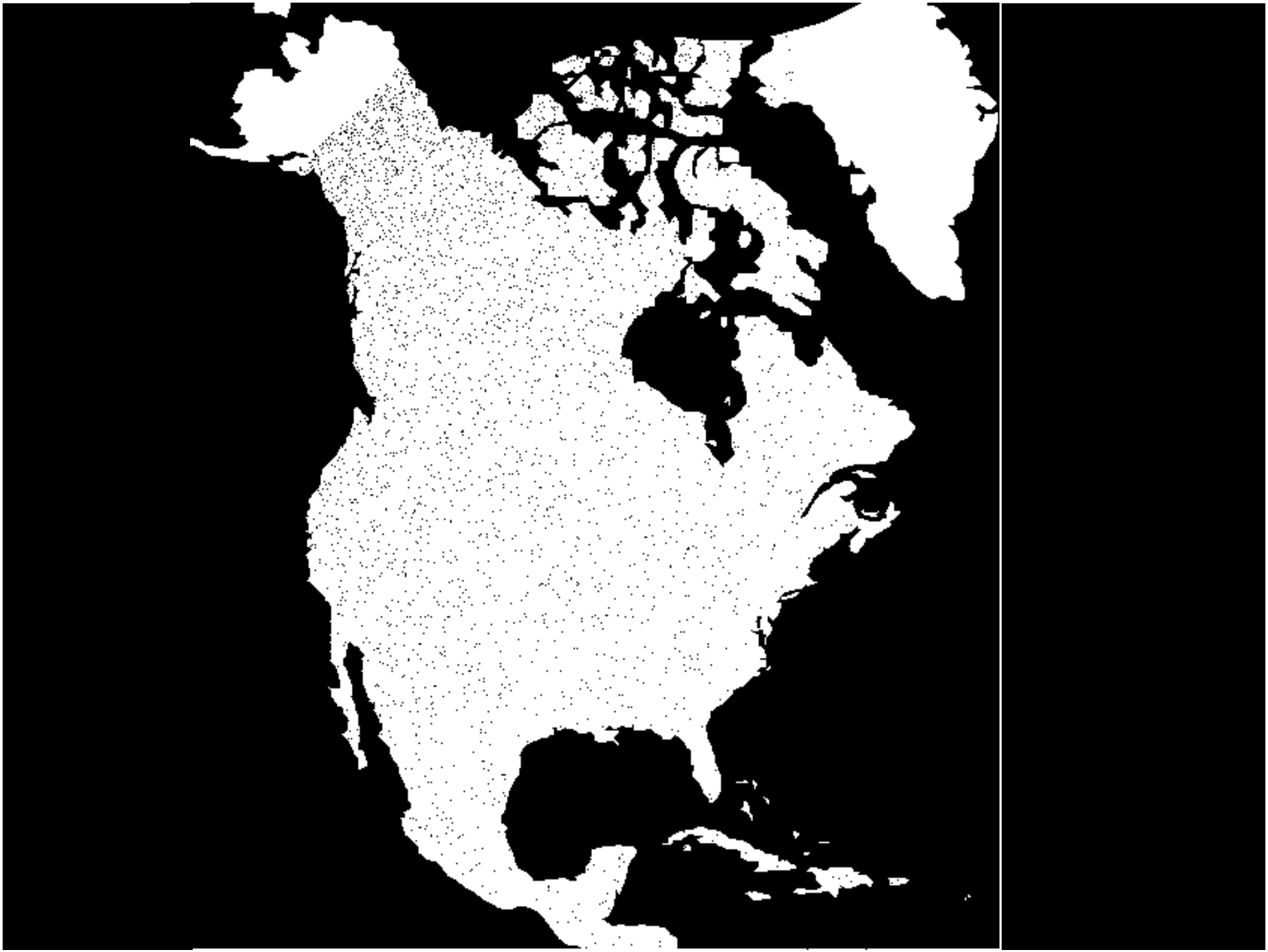

Cloud
Cloud

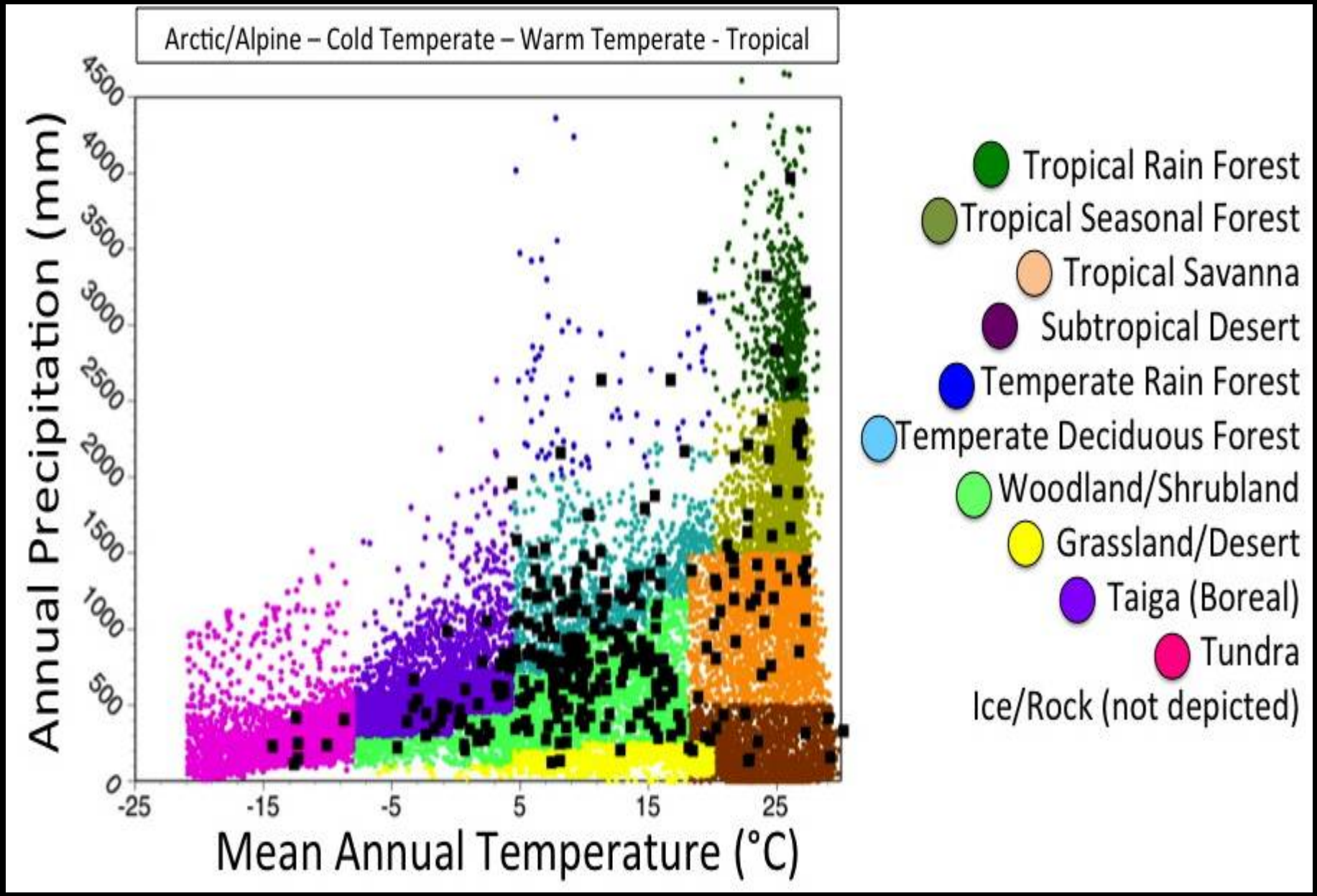

mmol m⁻² s⁻¹
μmol m⁻² s⁻¹
nmol m⁻² s⁻¹
fmol m⁻² s⁻¹
C5H8
H2O
C10H16
CO
COS
NH3
O3
NO2
CO2
CO2
O2
CH4
COS
H2S
NO
N2O
H2S
N2
NH3
CH4
H2O
CO2
Aerobic Soils
Wetlands
Anaerobic Soils

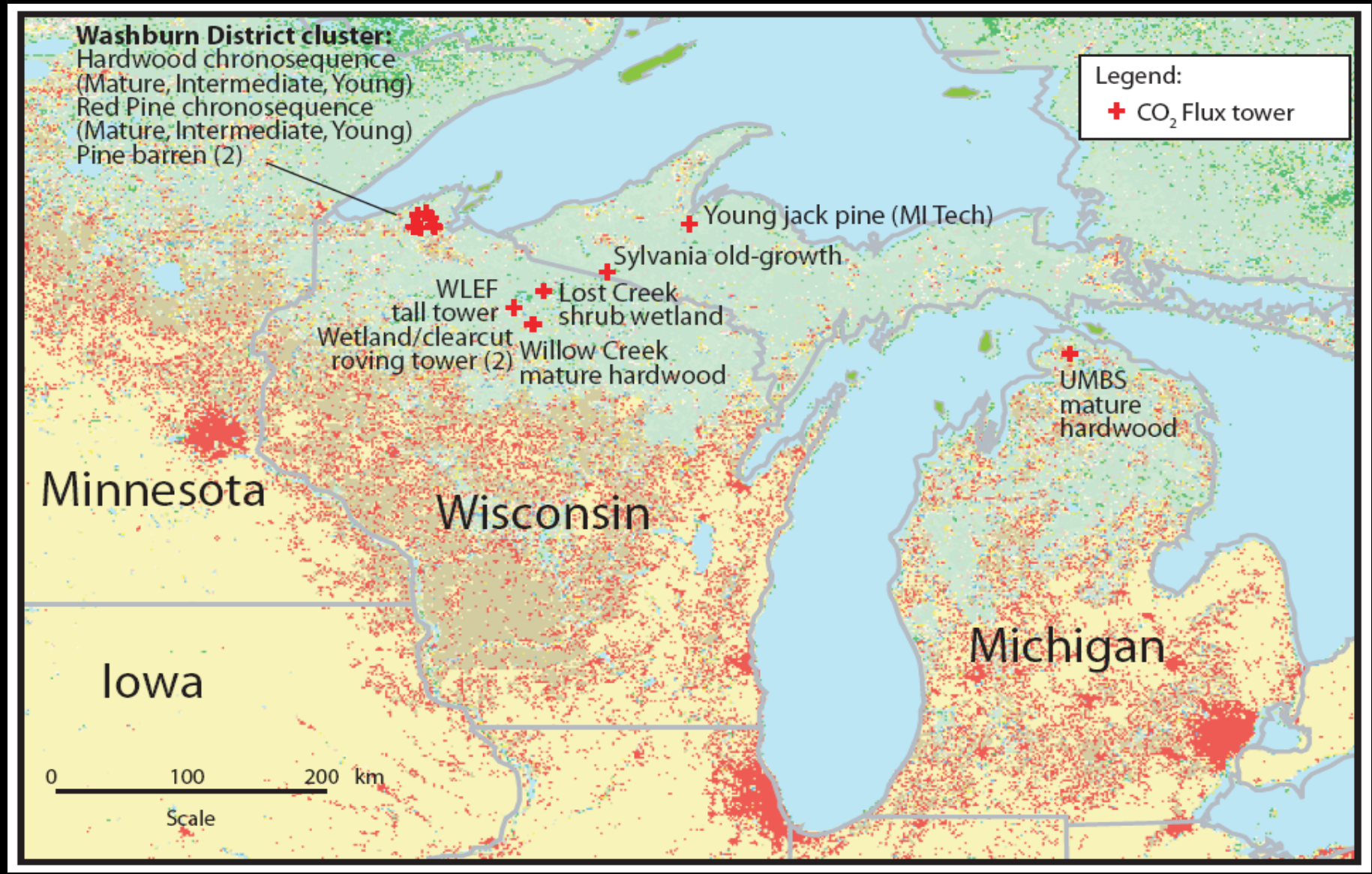
D. Baldocchi

700 points of light?

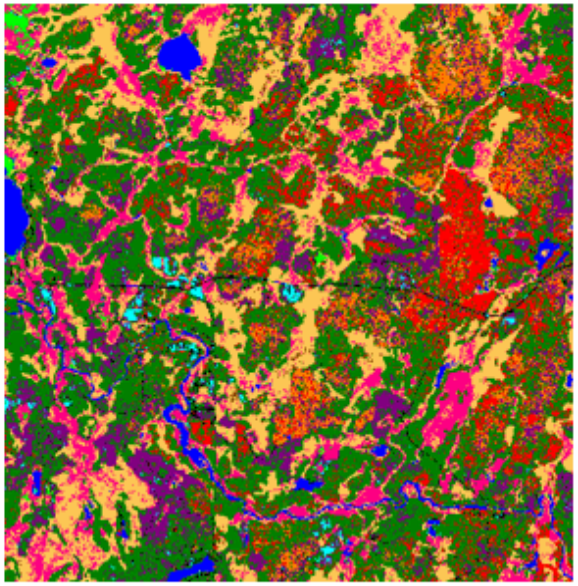
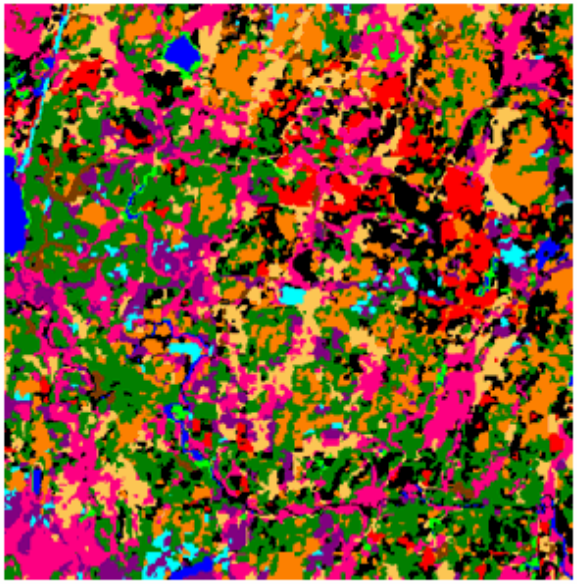
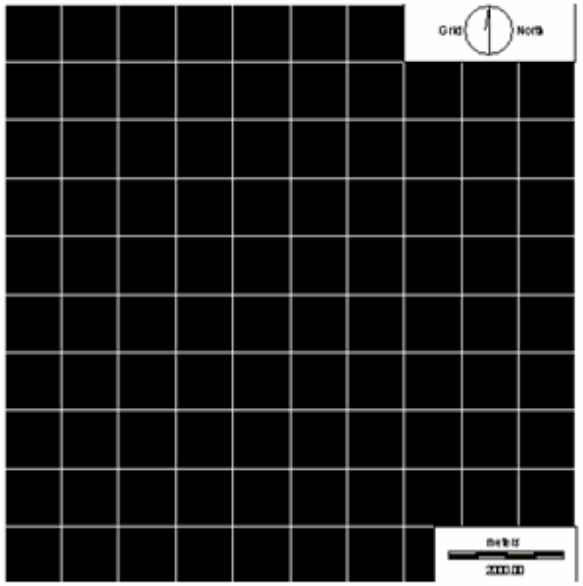


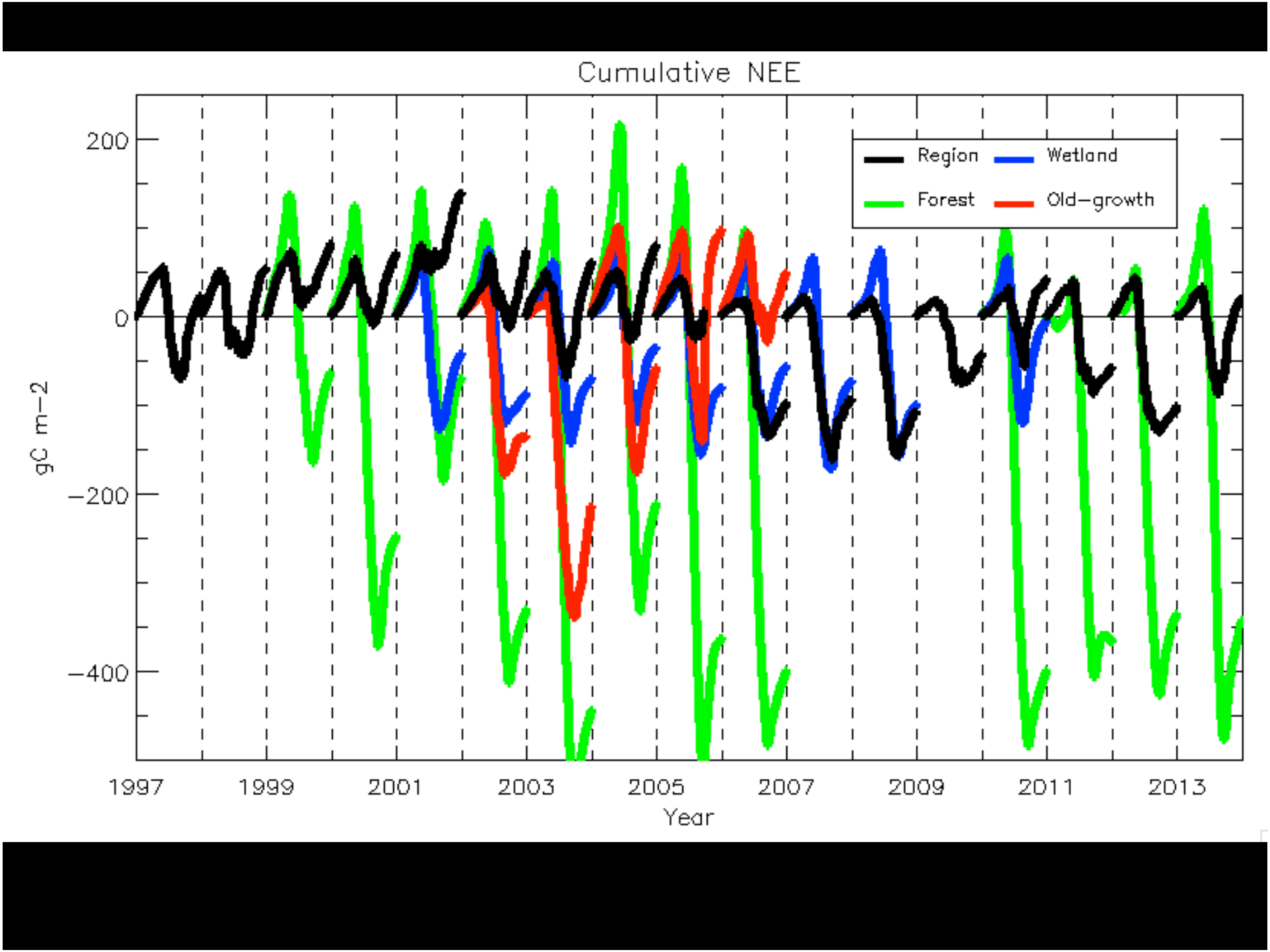


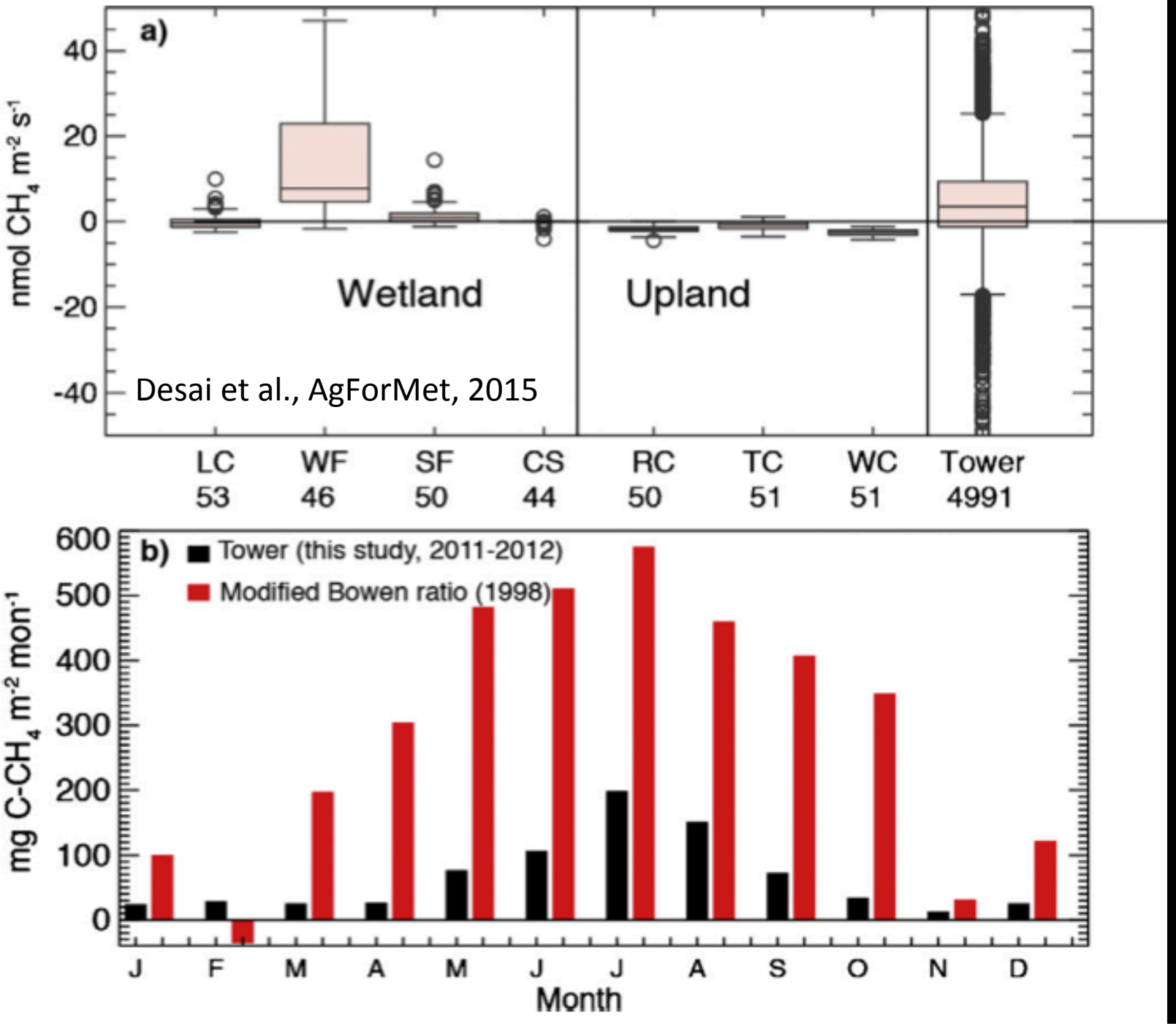

Arctic/Alpine – Cold Temperate – Warm Temperate - Tropical
Annual Precipitation (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
-25
-15
-5
5
15
25
Mean Annual Temperature (°C)
Tropical Rain Forest
Tropical Seasonal Forest
Tropical Savanna
Subtropical Desert
Temperate Rain Forest
Temperate Deciduous Forest
Woodland/Shrubland
Grassland/Desert
Taiga (Boreal)
Tundra
Ice/Rock (not depicted)


Washburn District cluster:
Hardwood chronosequence
(Mature, Intermediate, Young)
Red Pine chronosequence
(Mature, Intermediate, Young)
Pine barren (2)
Legend:
CO2 Flux tower
Young jack pine (MI Tech)
Sylvania old-growth
WLEF
tall tower
Lost Creek
shrub wetland
Wetland/clearcut
roving tower (2)
Willow Creek
mature hardwood
UMBS
mature
hardwood
Minnesota
Wisconsin
Michigan
Iowa
0
100
200 km
Scale

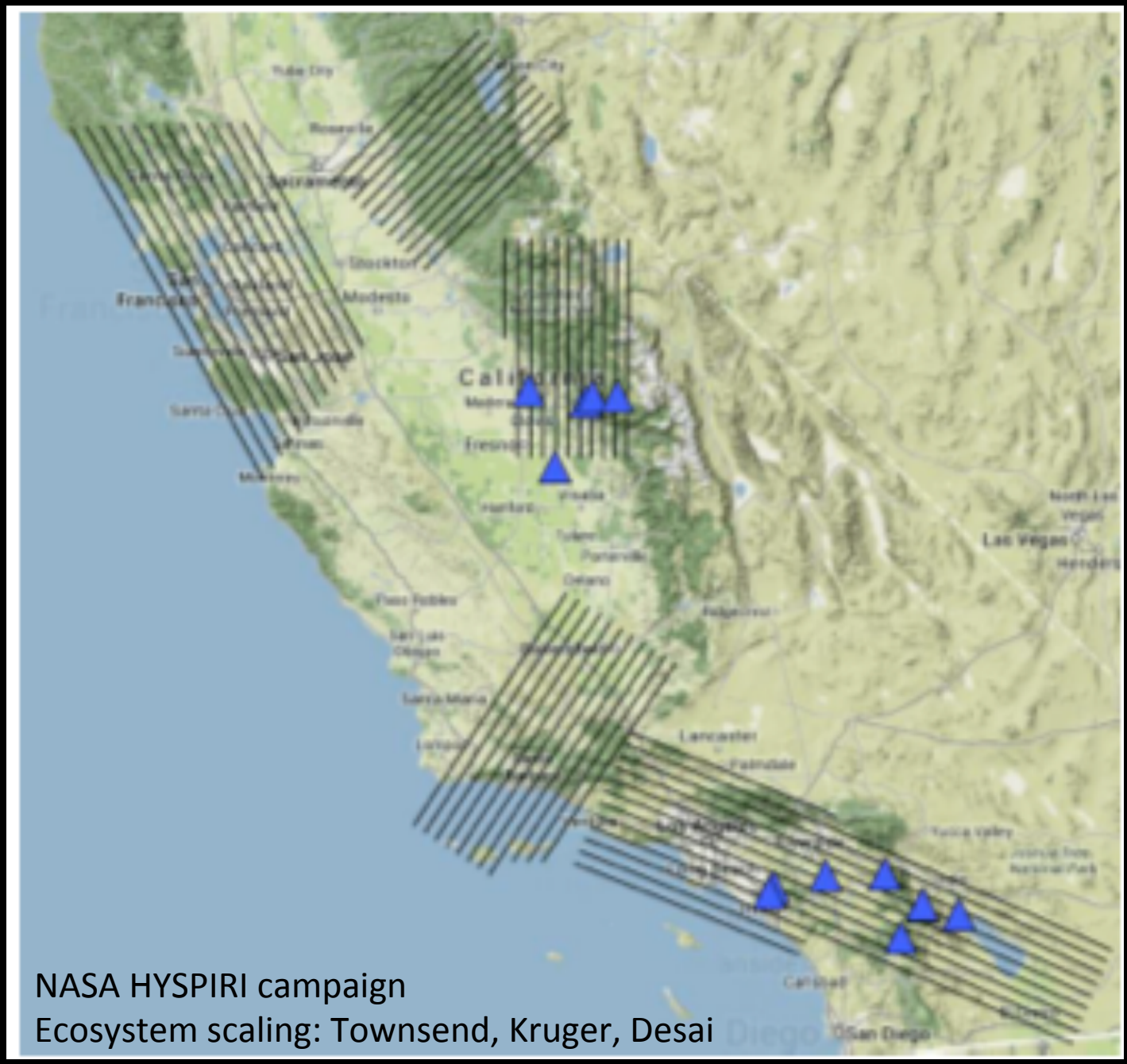
Complex Regions: 1+1≠2

a) IKONOS.	b) WISCLAND.	c) MODIS-UMD and IGBP.
		
— Mixed Forest 13.3% Upland Conifer 34.8% Aspen-Birch 5.7% Upland Hardwood 12.0% Upland Opening/Shrub 0.9% Grassland 17.8% Lowland Conifer 0.7% Lowland Deciduous 10.6% Lowland Shrub 0.6% Wet Meadow 2.6% Open Water 1.0% Road	7.1% Mixed Forest 13.0% Upland Conifer 25.3% Aspen-Birch 14.6% Upland Hardwood 6.8% Upland Opening/Shrub 1.8% Grassland 10.7% Lowland Conifer 1.9% Lowland Deciduous 16.3% Lowland Shrub 1.0% Wet Meadow 1.6% Open Water — Road	100% Mixed Forest


Cumulative NEE
Region
Wetland
Forest
Old−growth
200
0
−200
−400
gC m−2
1997
1999
2001
2003
2005
2007
2009
2011
2013
Year

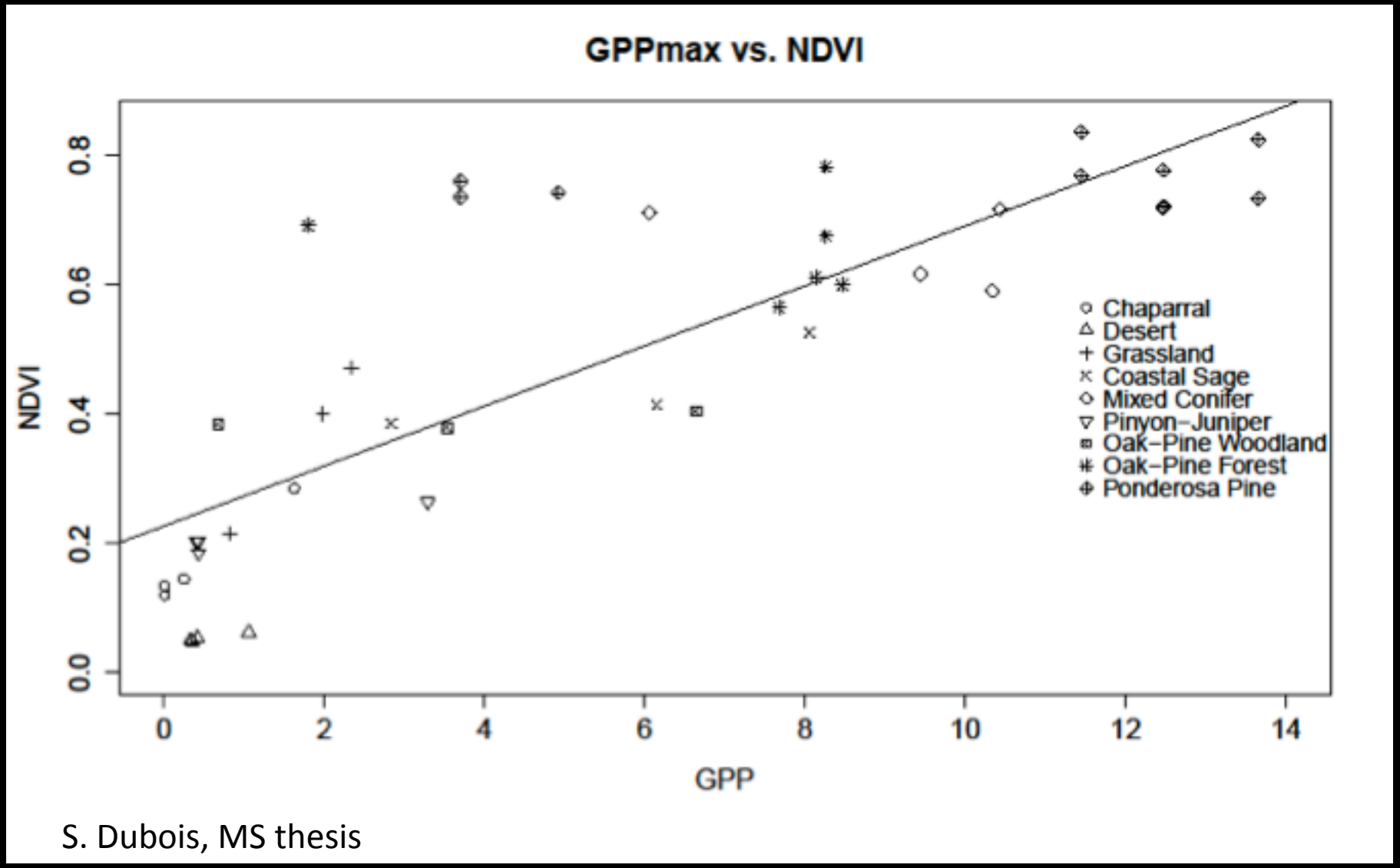

a)
nmol CH_4 m^{-2} s^{-1}
40
20
0
-20
-40
Wetland
Upland
Desai et al., AgForMet, 2015
LC 53
WF 46
SF 50
CS 44
RC 50
TC 51
WC 51
Tower 4991
b)
Tower (this study, 2011-2012)
Modified Bowen ratio (1998)
mg C-CH_4 m^{-2} mon^{-1}
600
500
400
300
200
100
0
J F M A M J J A S O N D
Month

Didn’t remote sensing solve the problem?



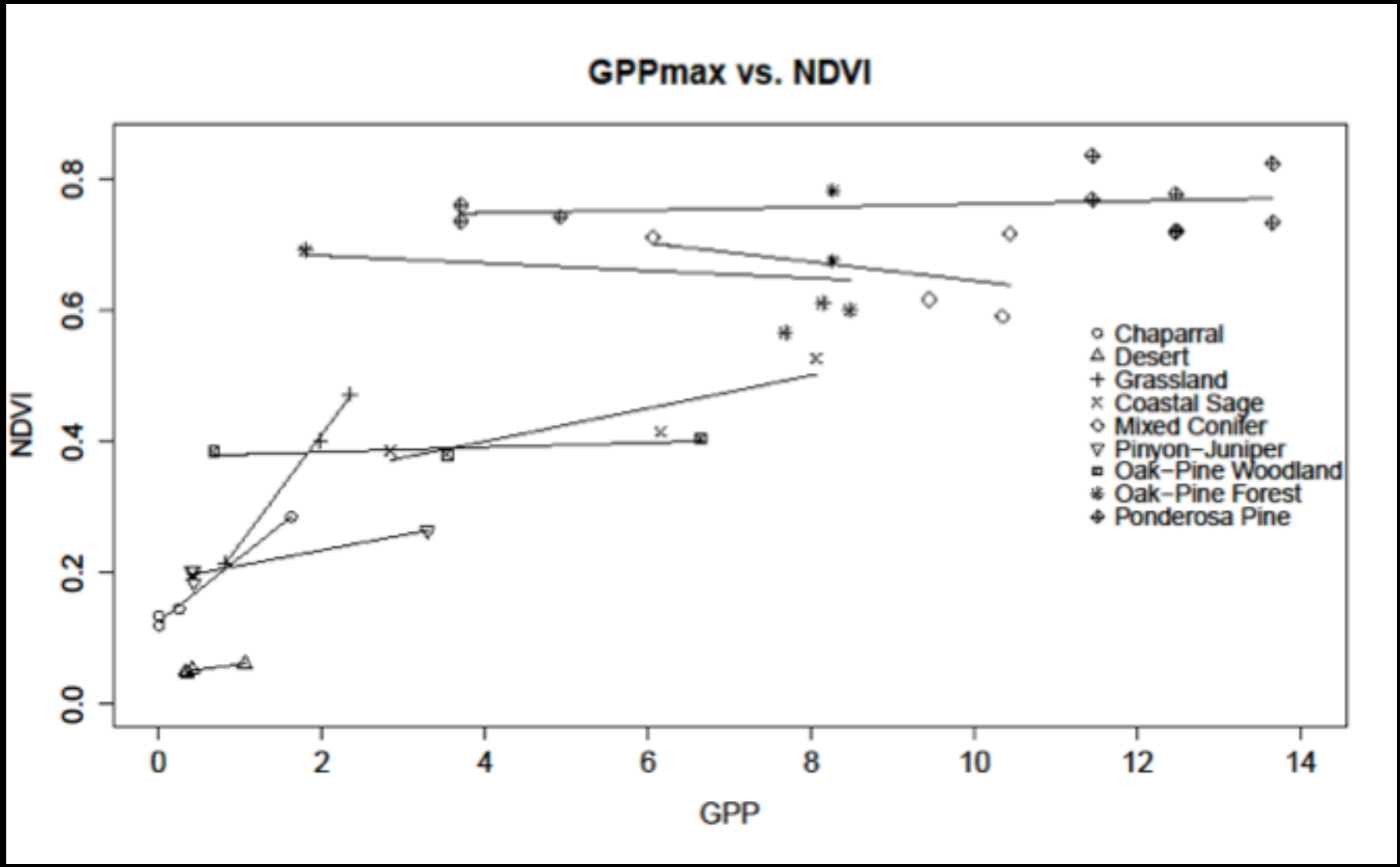
NASA HYSPIRI campaign
Ecosystem scaling: Townsend, Kruger, Desai

Maybe?

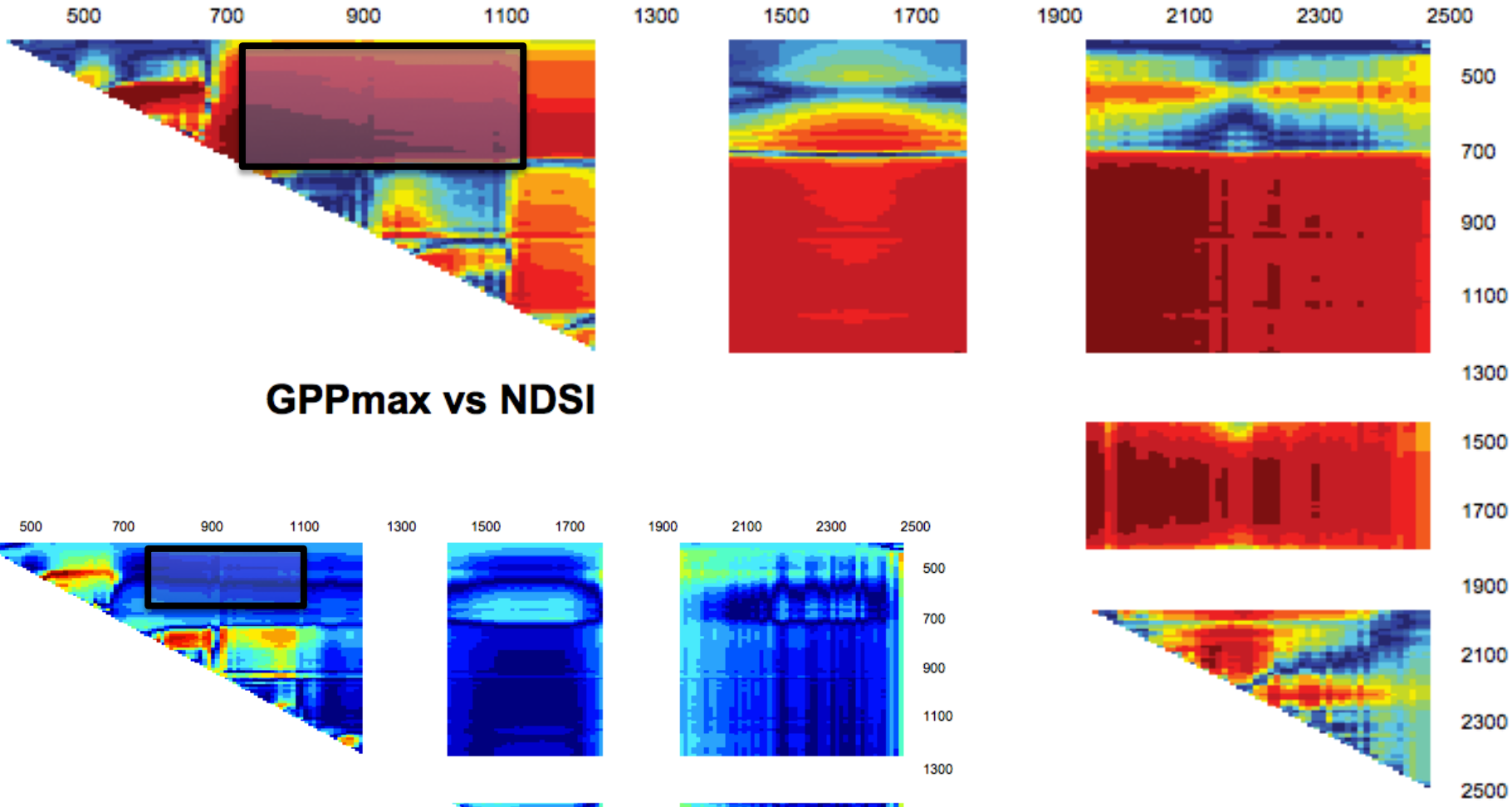


S. Dubois, MS thesis

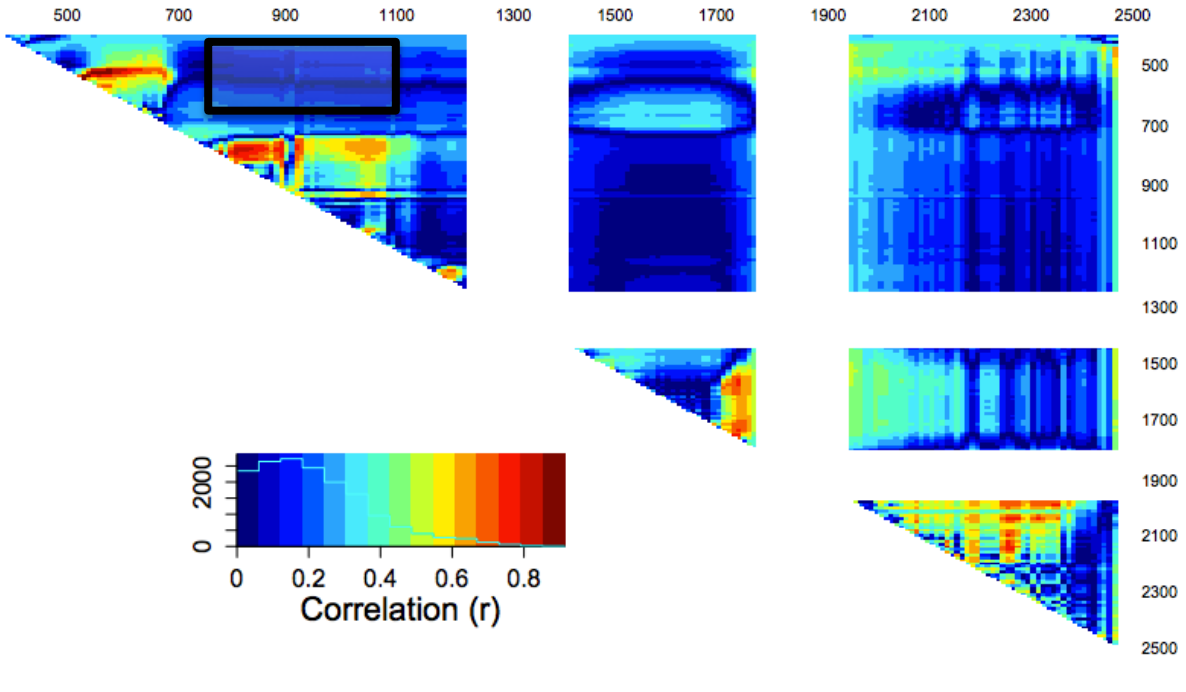
Maybe not?


GPPmax vs. NDVI
NDVI
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
12
14
GPP
Chaparral
Desert
Grassland
Coastal Sage
Mixed Conifer
Pinyon–Juniper
Oak–Pine Woodland
Oak–Pine Forest
Ponderosa Pine

GPPmax vs NDSI for all sites

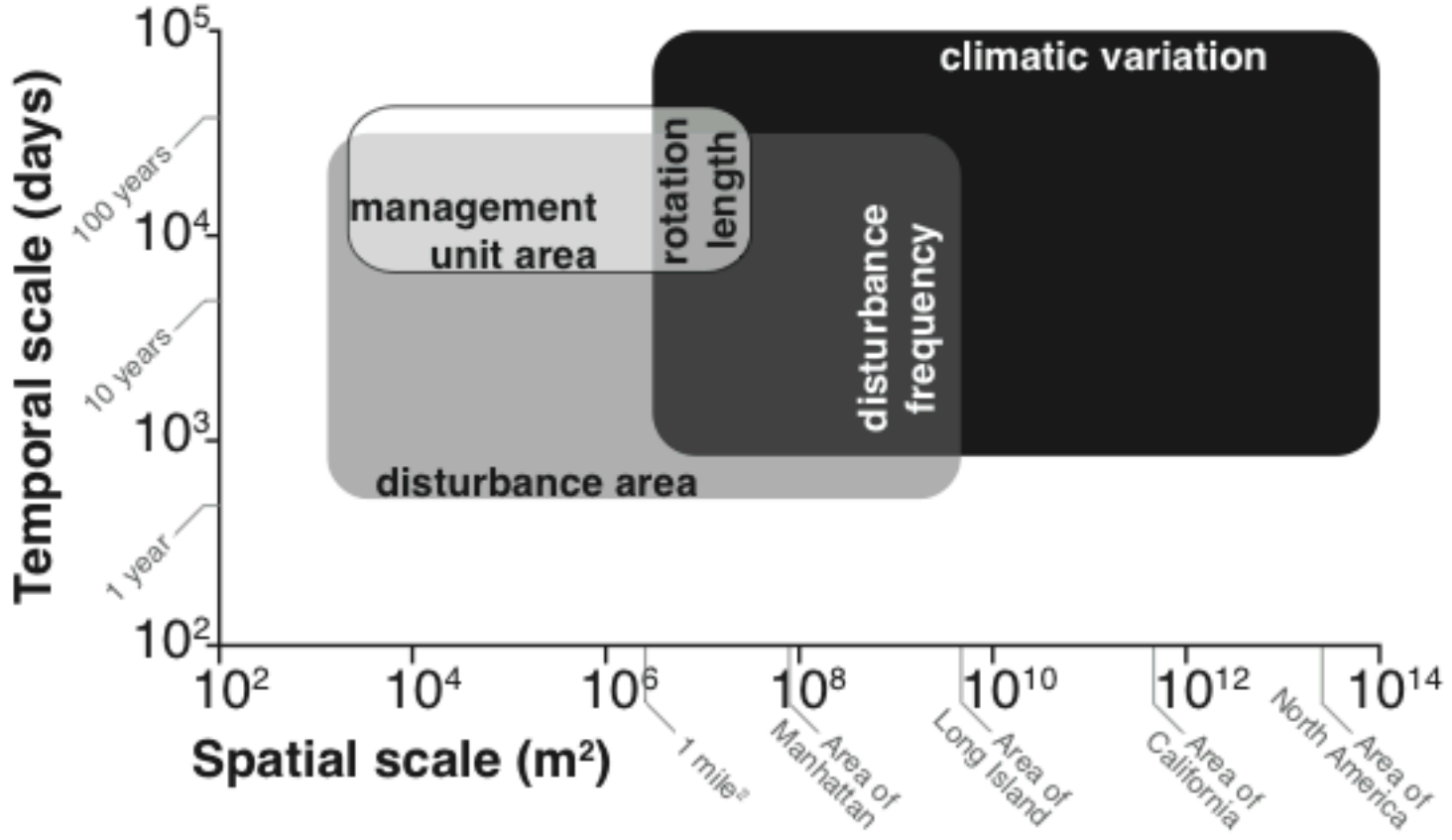


GPPmax vs NDSI



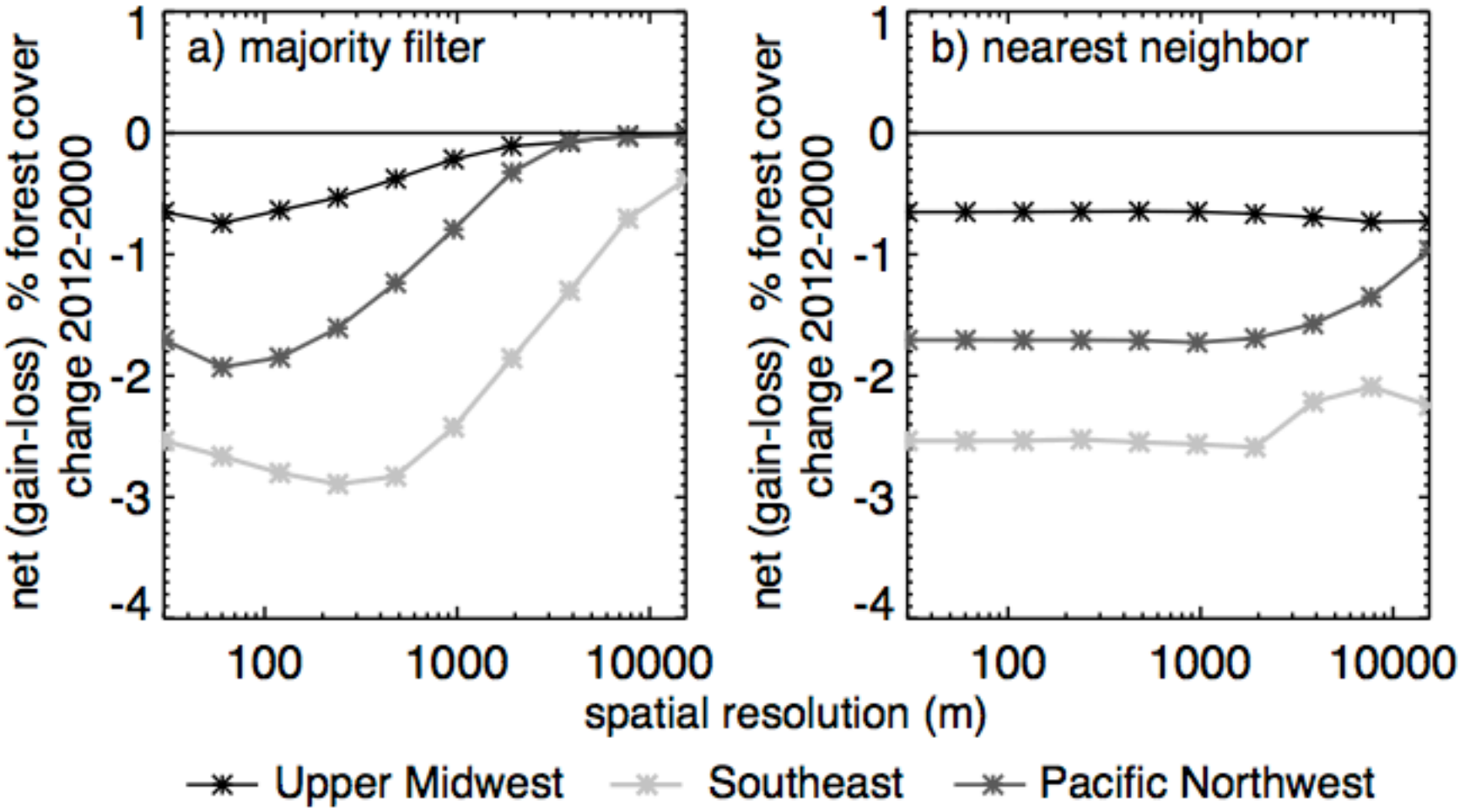
It gets weirder once we put in humans

Virtually all the world's forests are managed, at scales quite different from climate and disturbance

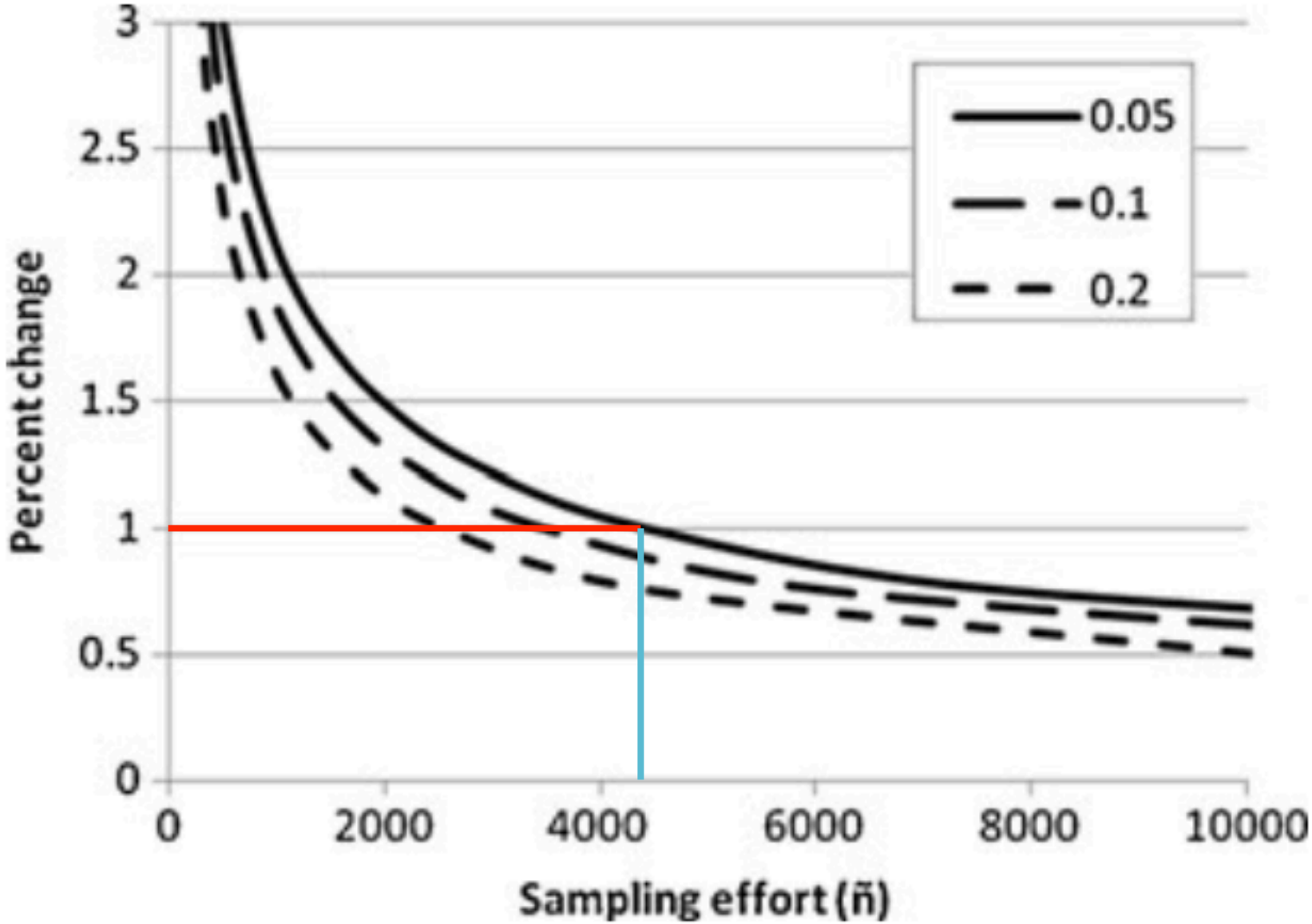


Becknell et al., Bioscience, in press

The scale and method we monitor land use matters



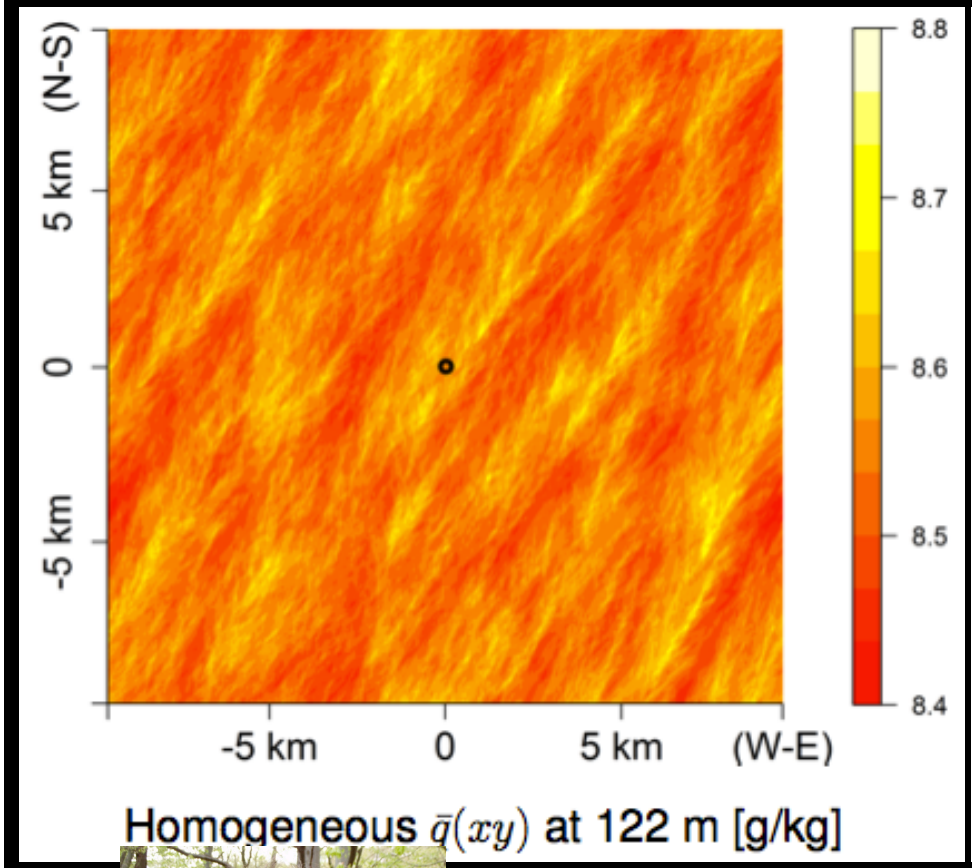
Becknell et al., Bioscience, in press

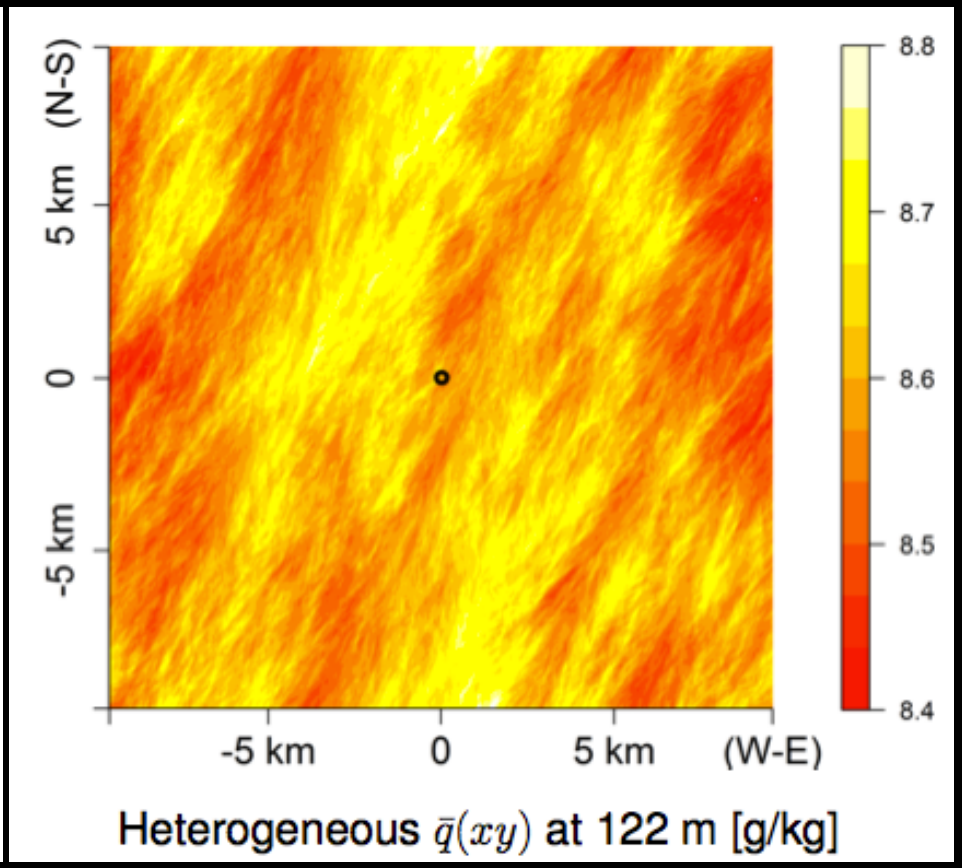


Westfall et al., Climatic Change, 2013

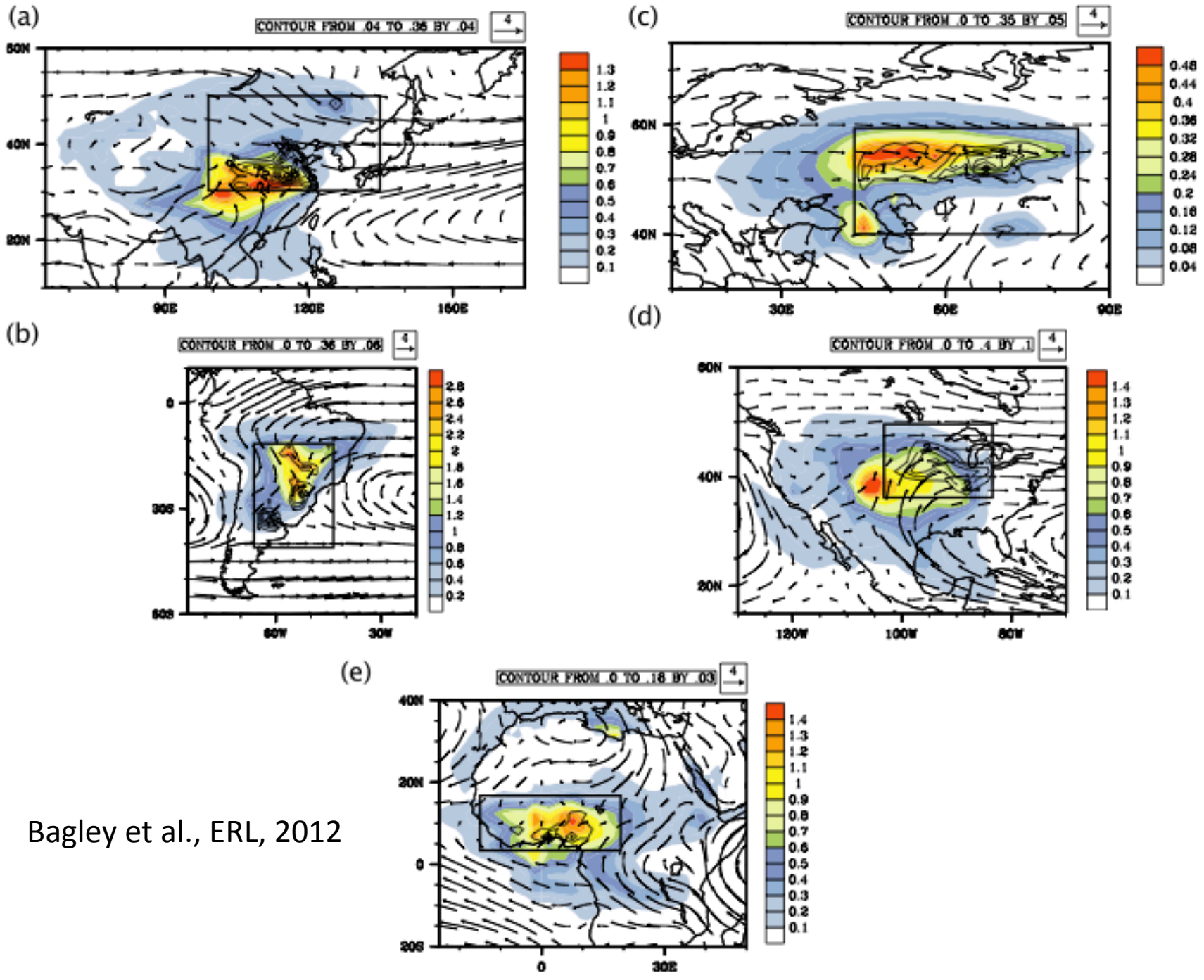
Does the atmosphere care?

LES simulations around the tall tower show shifts in organized structures with heterogeneity of surface forcing

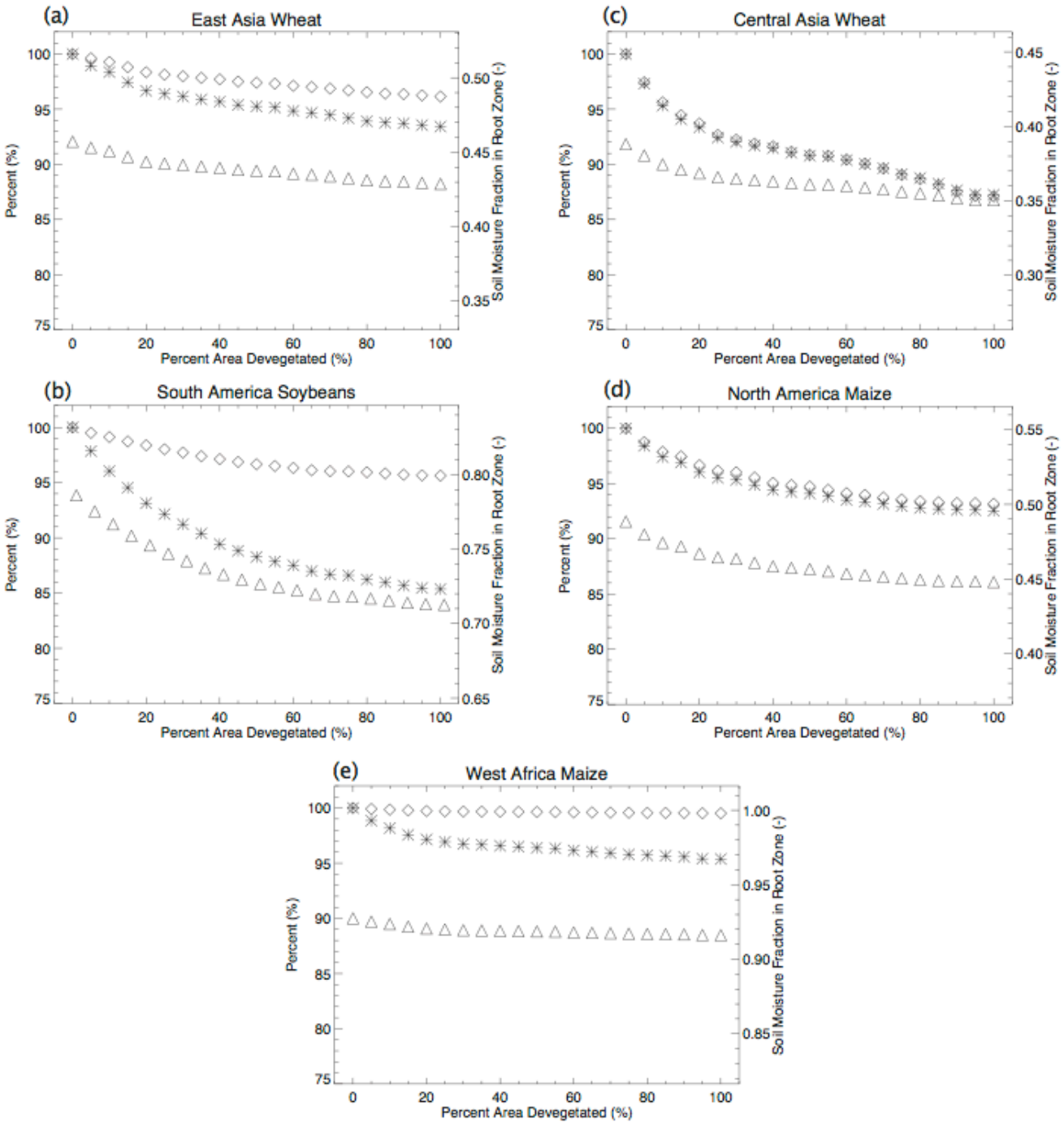




Frederick deRoo (KIT IMK-IFU), TERRENO

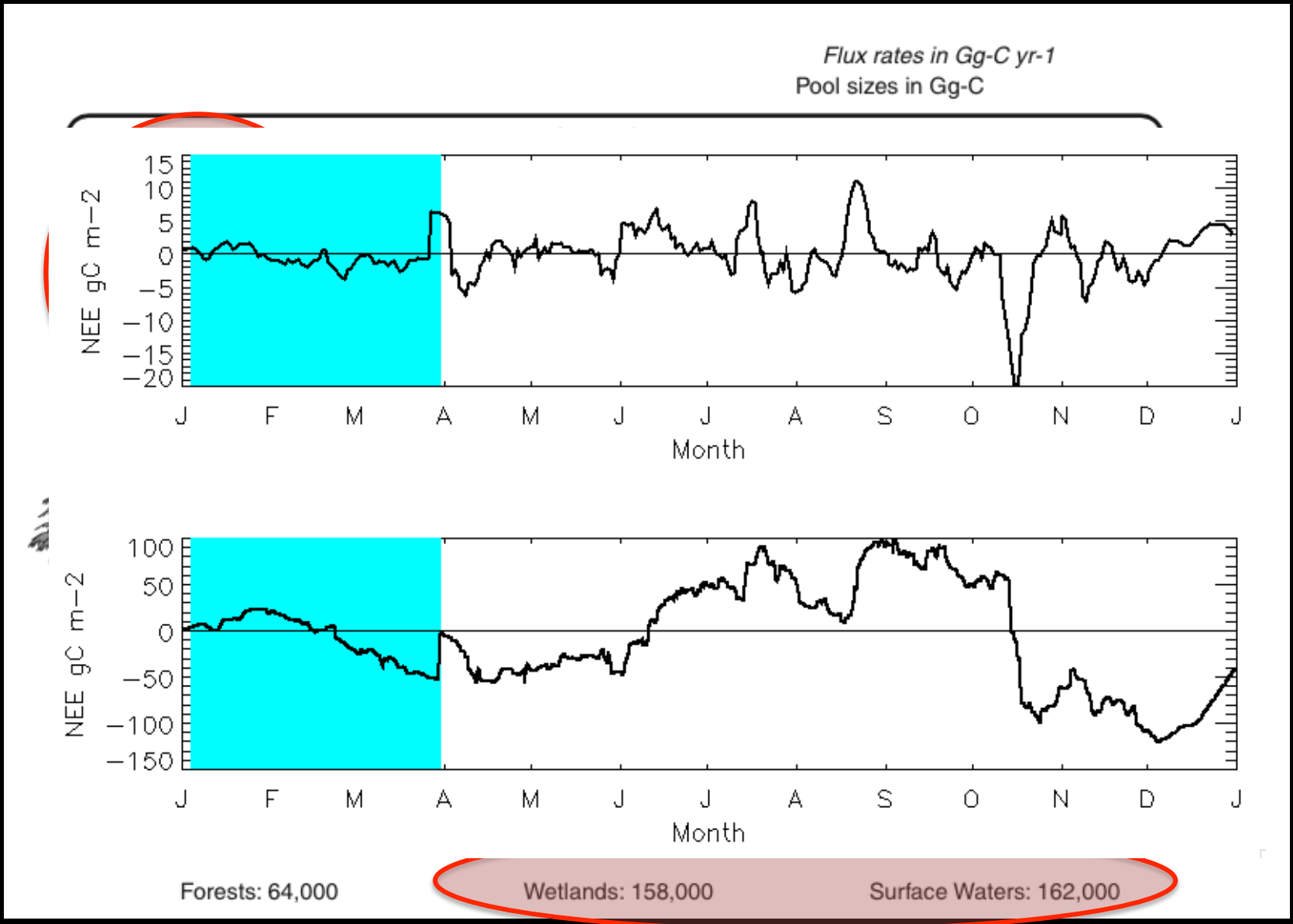


Bagley et al., ERL, 2012

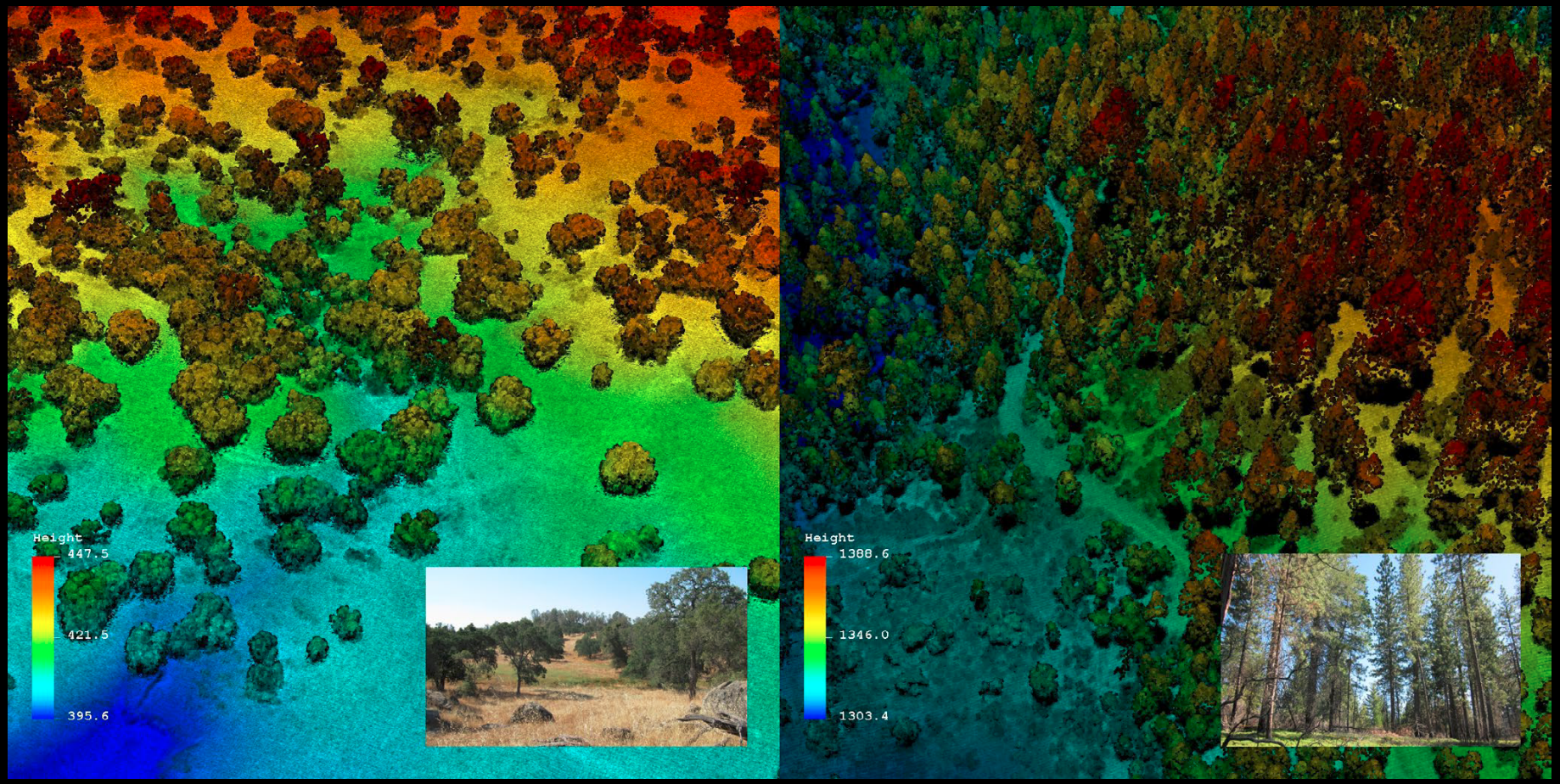

(a)
East Asia Wheat
(c)
Central Asia Wheat
(b)
South America Soybeans
(d)
North America Maize
(e)
West Africa Maize
Percent (%)
Soil Moisture Fraction in Root Zone (-)
Percent Area Devegetated (%)

What are we trying to do about it?

1. Be smarter about scaling

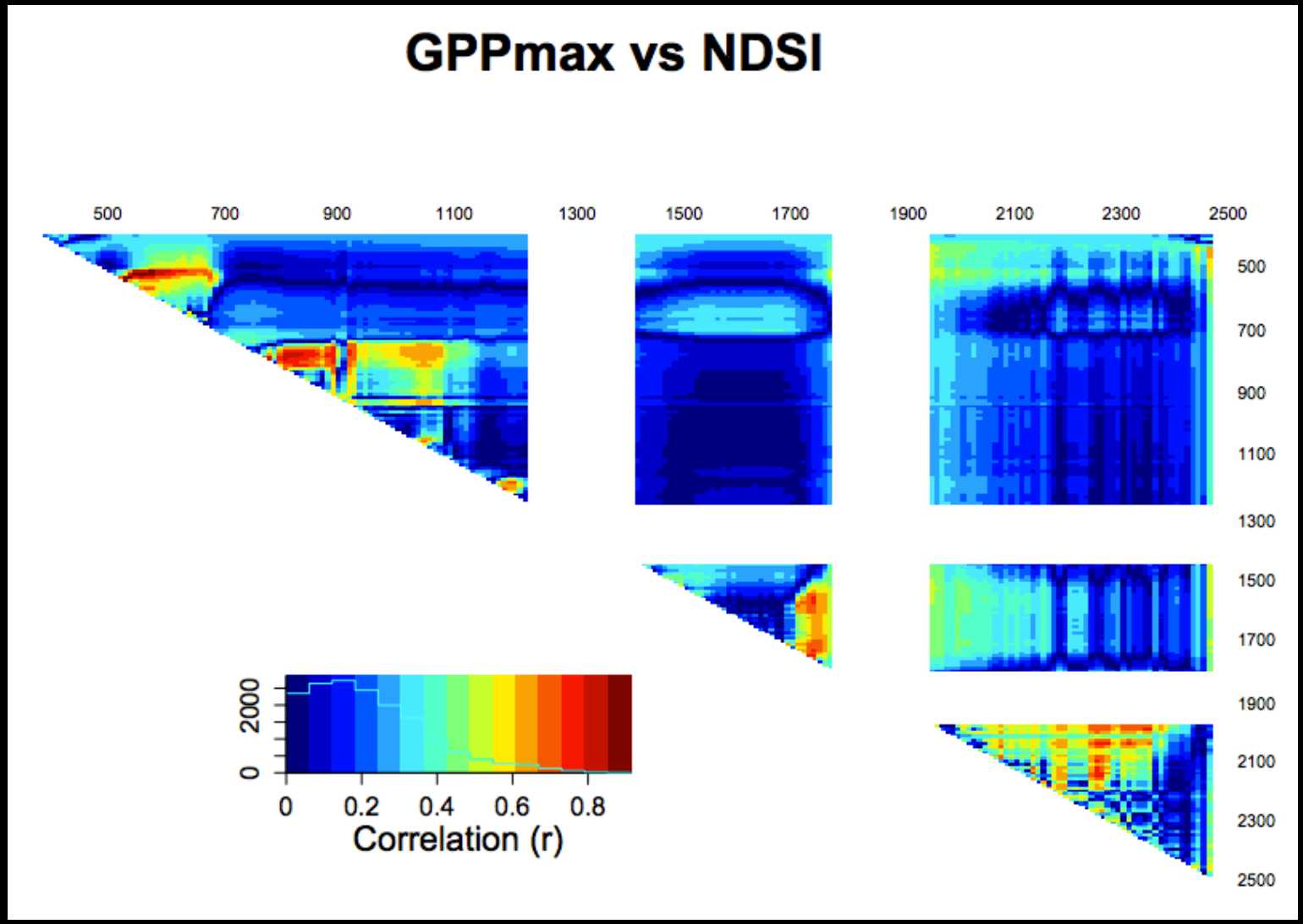


2. Be big data



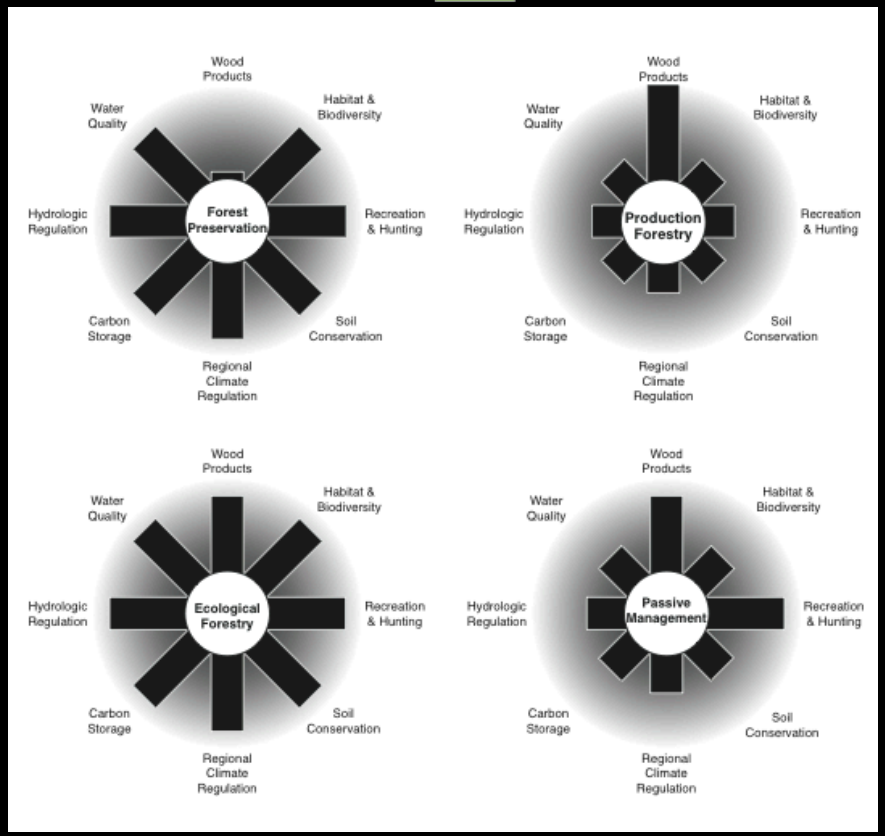
NEON, Inc.

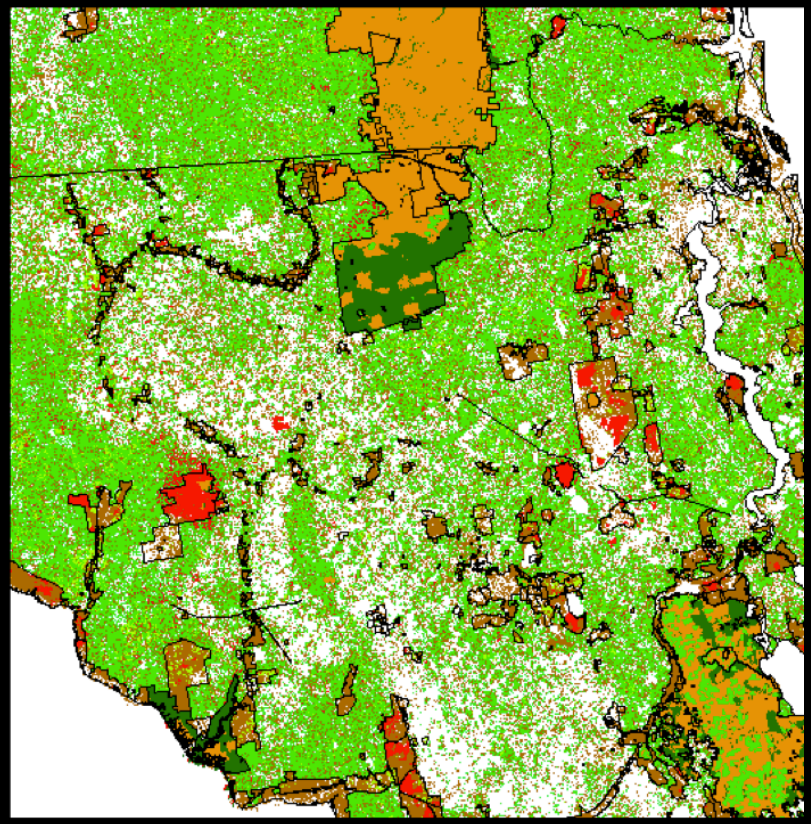
3. Find the appropriate scale



4. Map human impacts like ecosystems

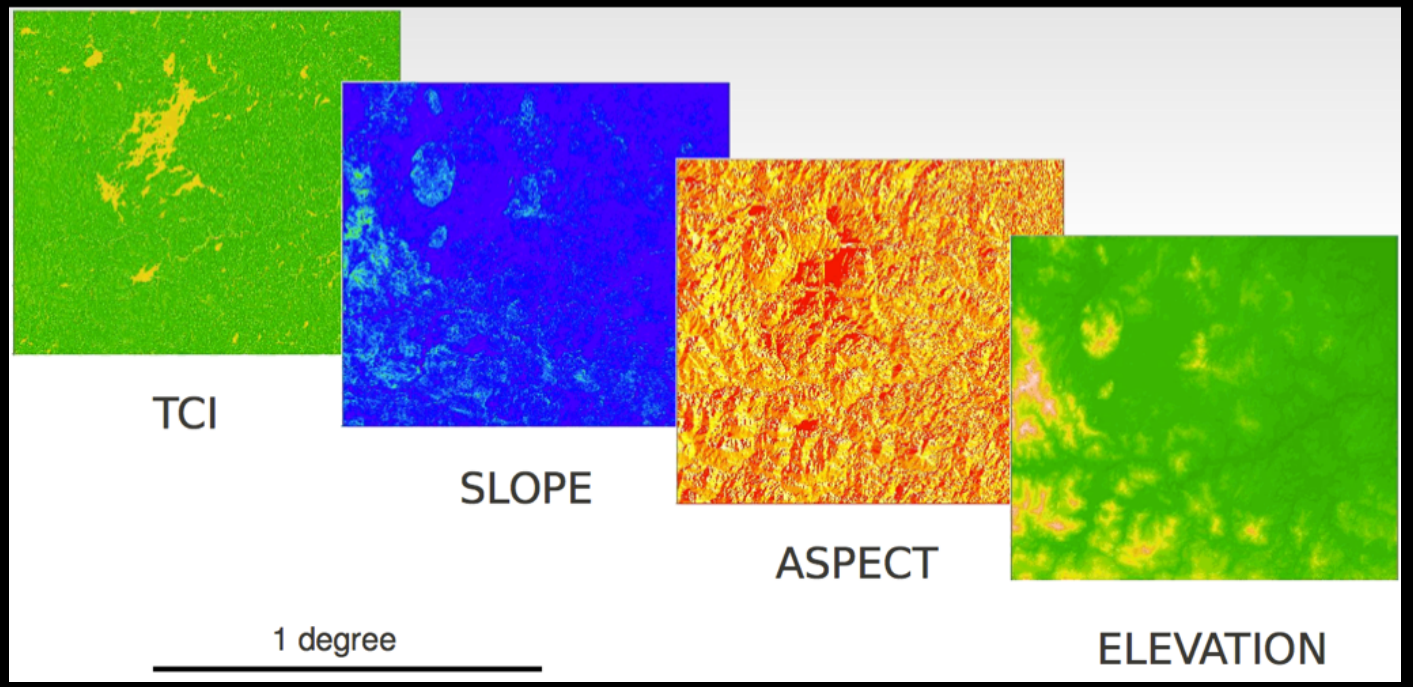
Passive
Preservation
Preservation/Change
Production

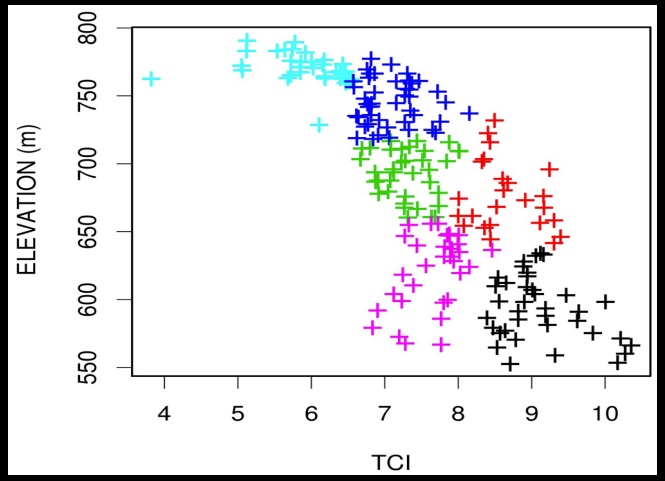




MANDIFORE
Macrosystems Biology

5. Capture the statistics of heterogeneity





M.C. Dietze, ED2 model

Partition ur ace models

Variability

describes the proce

can be better charac
but doesn't decreas

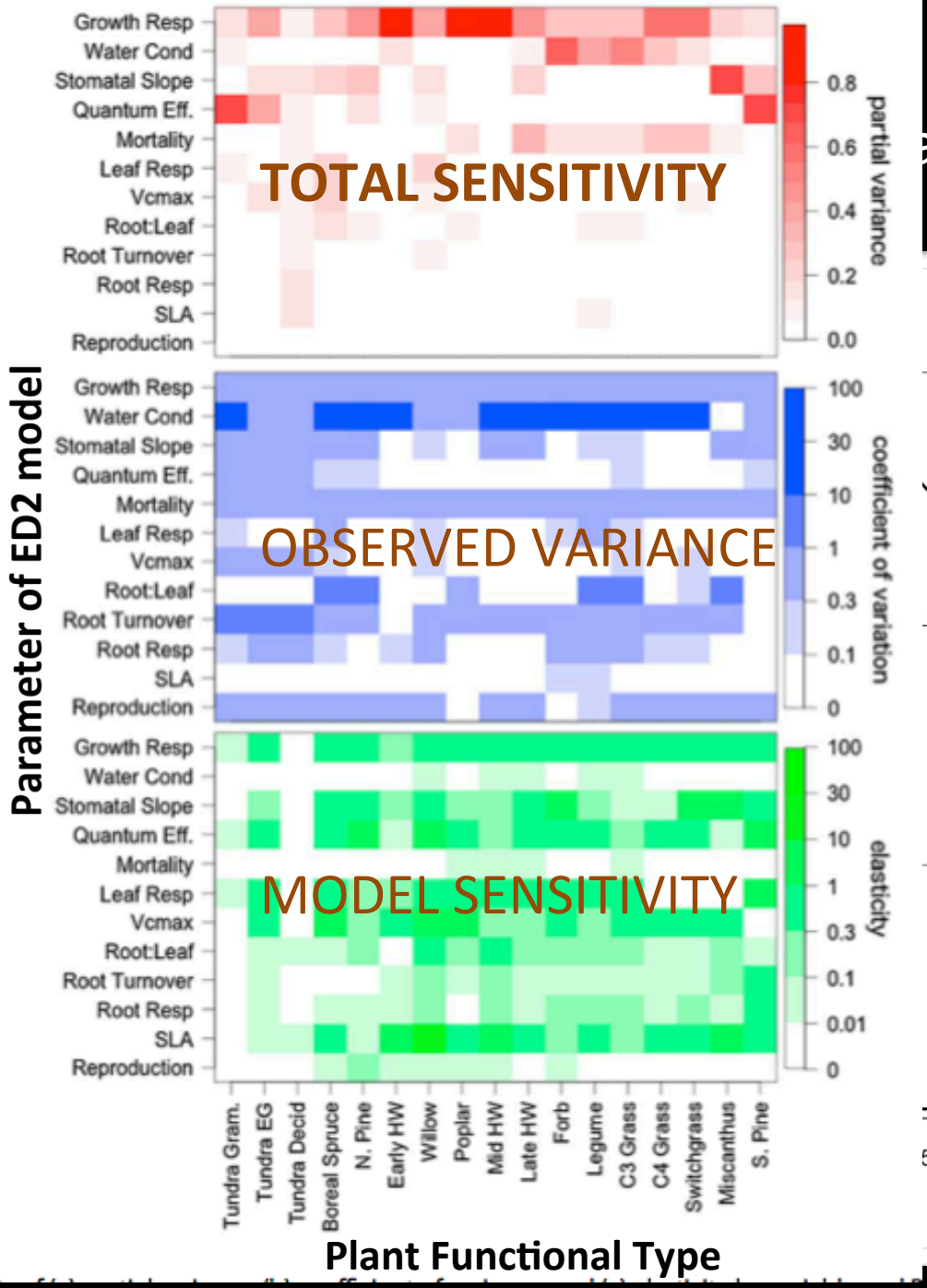
Uncertainty

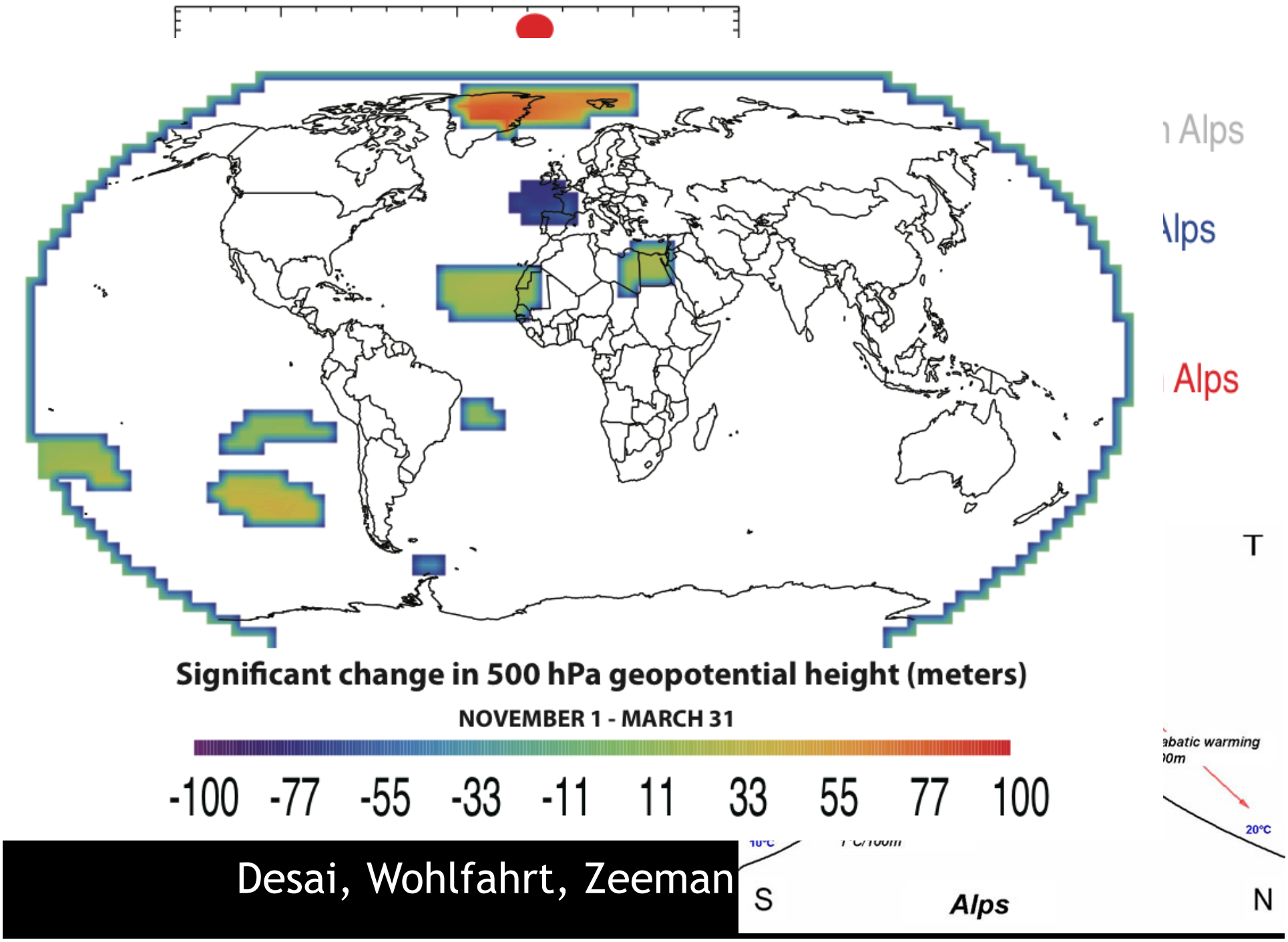
describes our ignor

decreases asympto

Pecanproject.org

Dietze, 2014, JGR-G



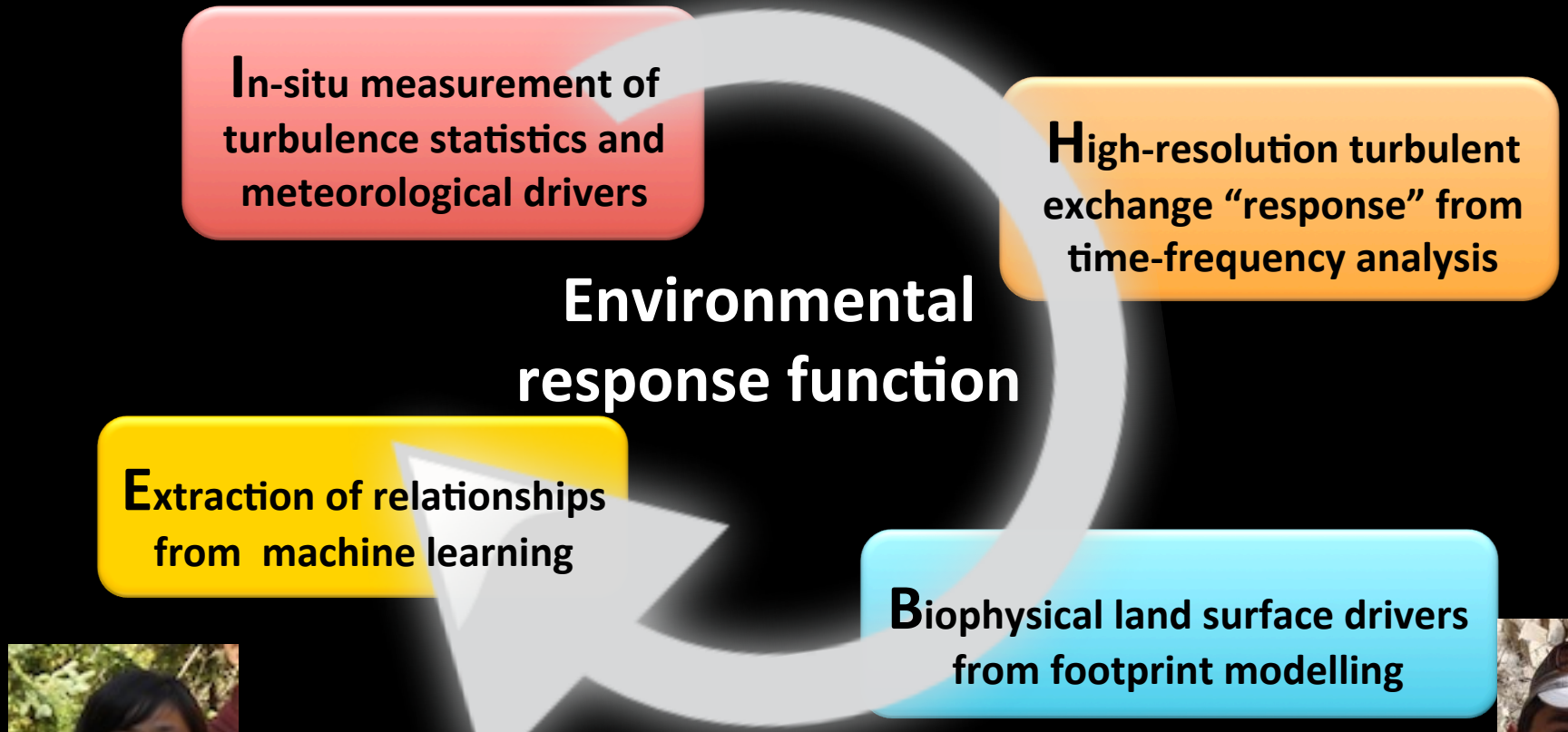


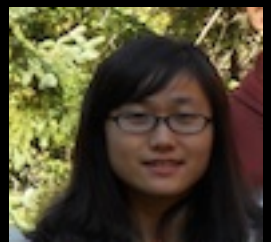
Desai, Wohlfahrt, Zeeman

8. Make flux towers useful

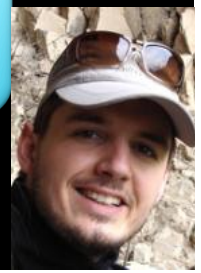
Environmental response functions

- Two principal steps:
  - Extracting the relationships between environmental drivers and responses
  - Applying this knowledge to bridge scale-gaps in space and time



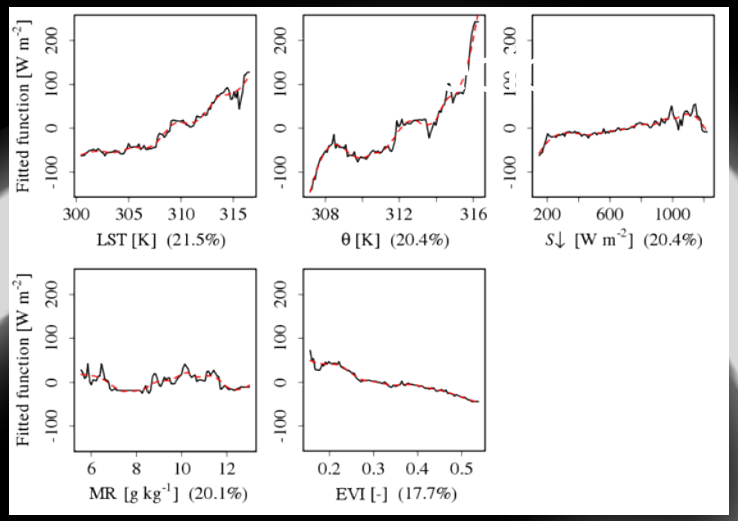


Ke Xu, UW and Stefan Metzger, NEON



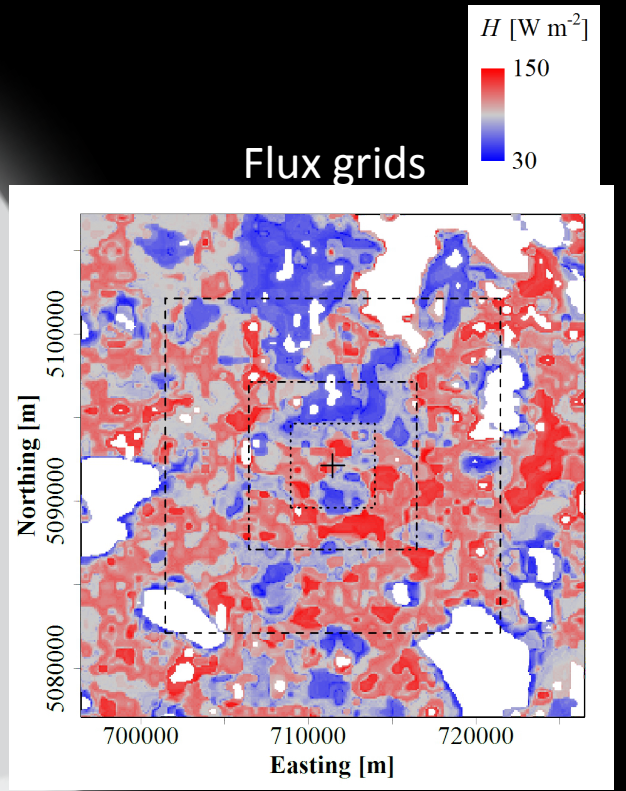
Ameriflux Park Falls ‘very tall tower’ (447 m): Eddy flux at 122 m.

Credit: Matt Rydzik (U Wisconsin)

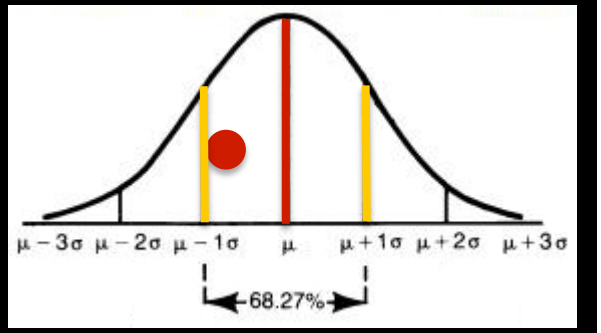


Environmental response functions

Flux grids

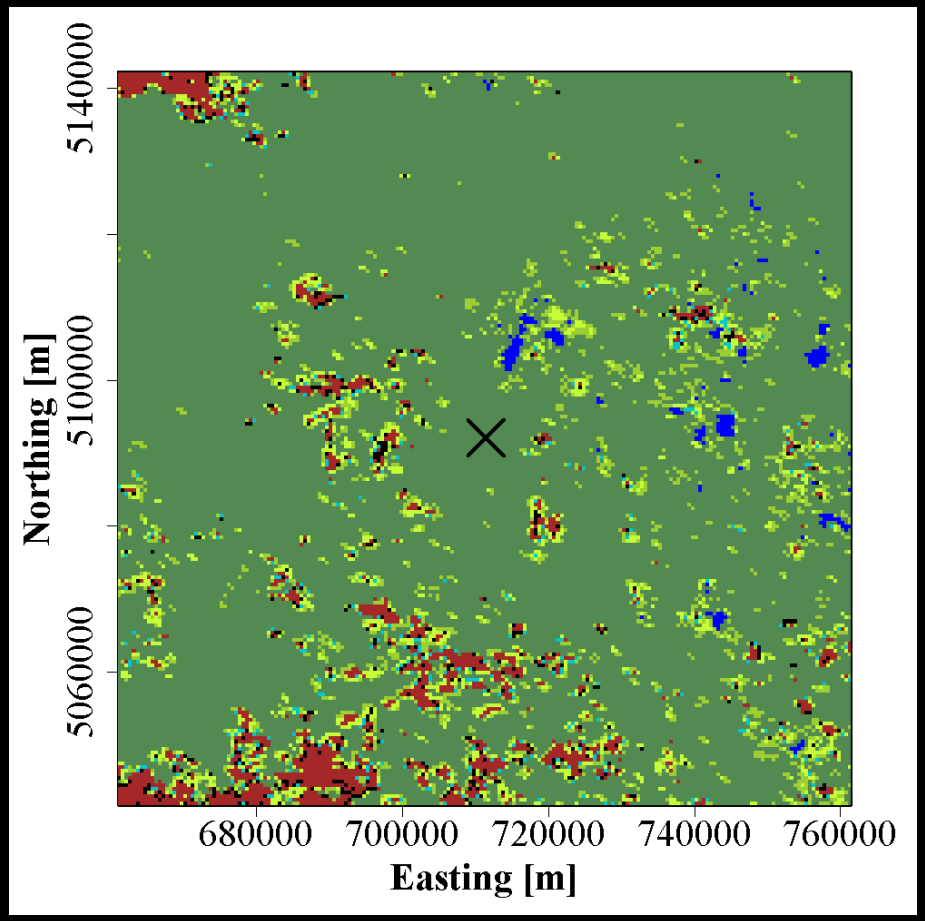


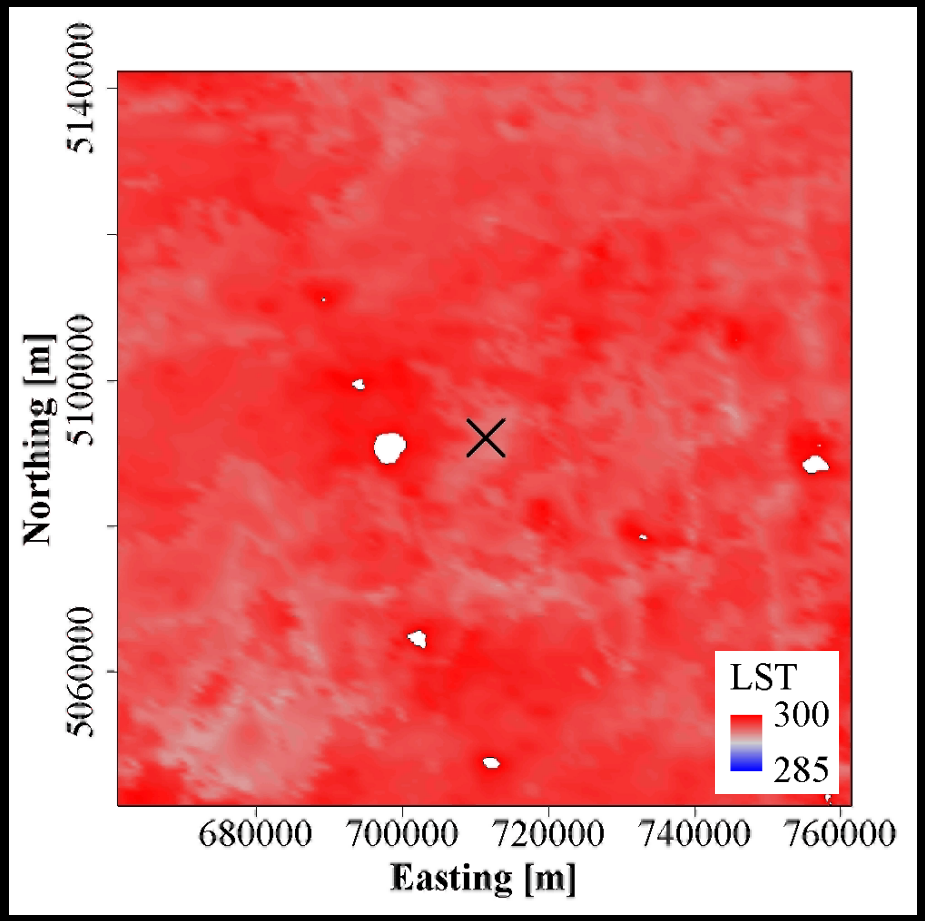
Before:



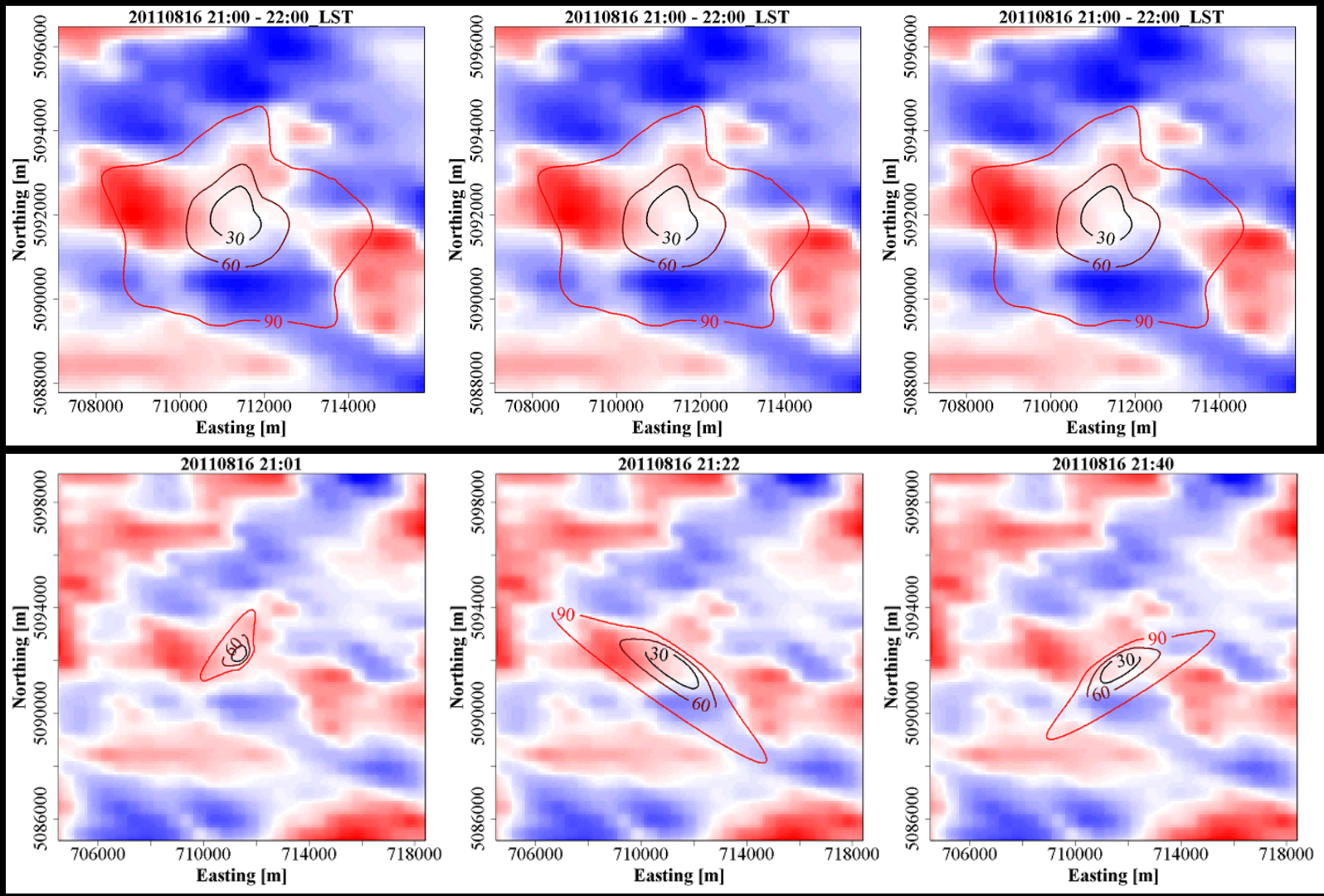
Park Falls/Chequamegon National Forest region

- Relative homogenous…
  - But biophysical properties transient in space and time!

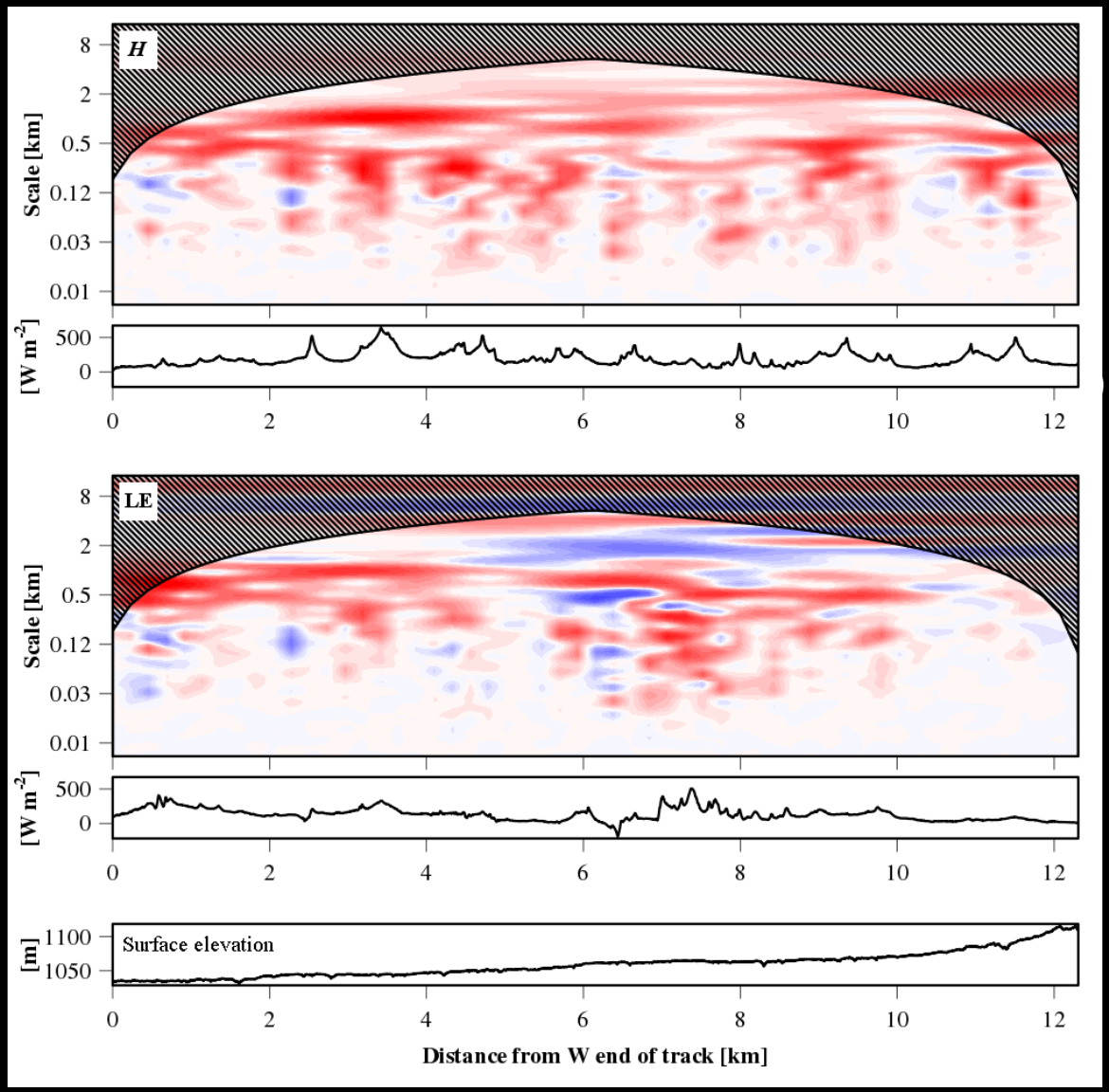


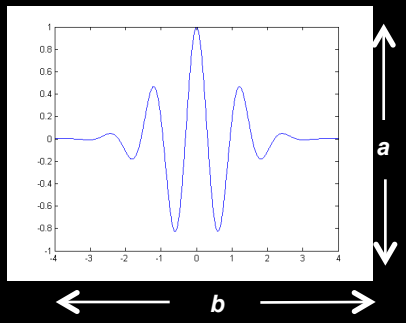


What does the tower flux measurement “see”?

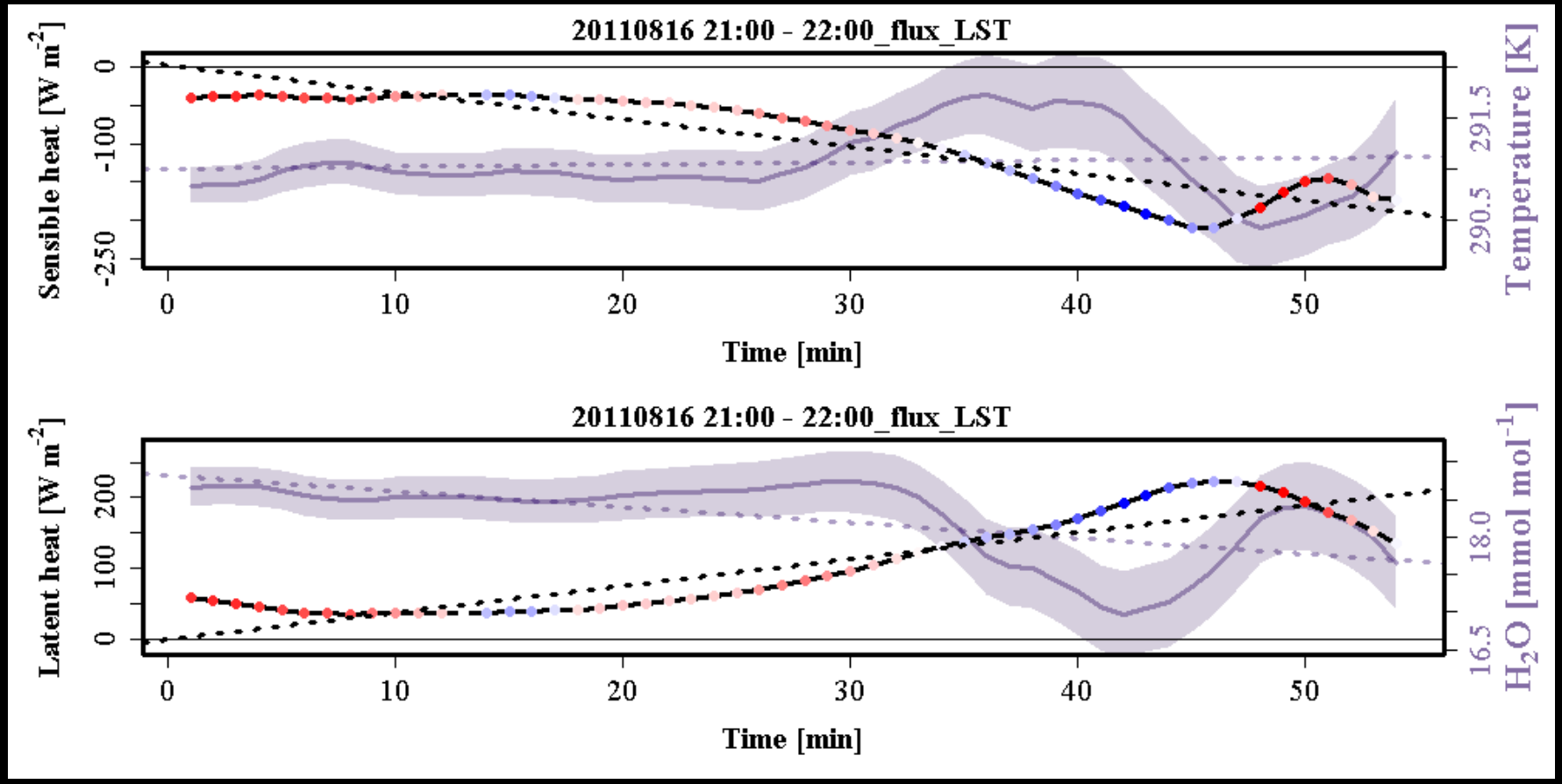


Wavelet cross-scalogram





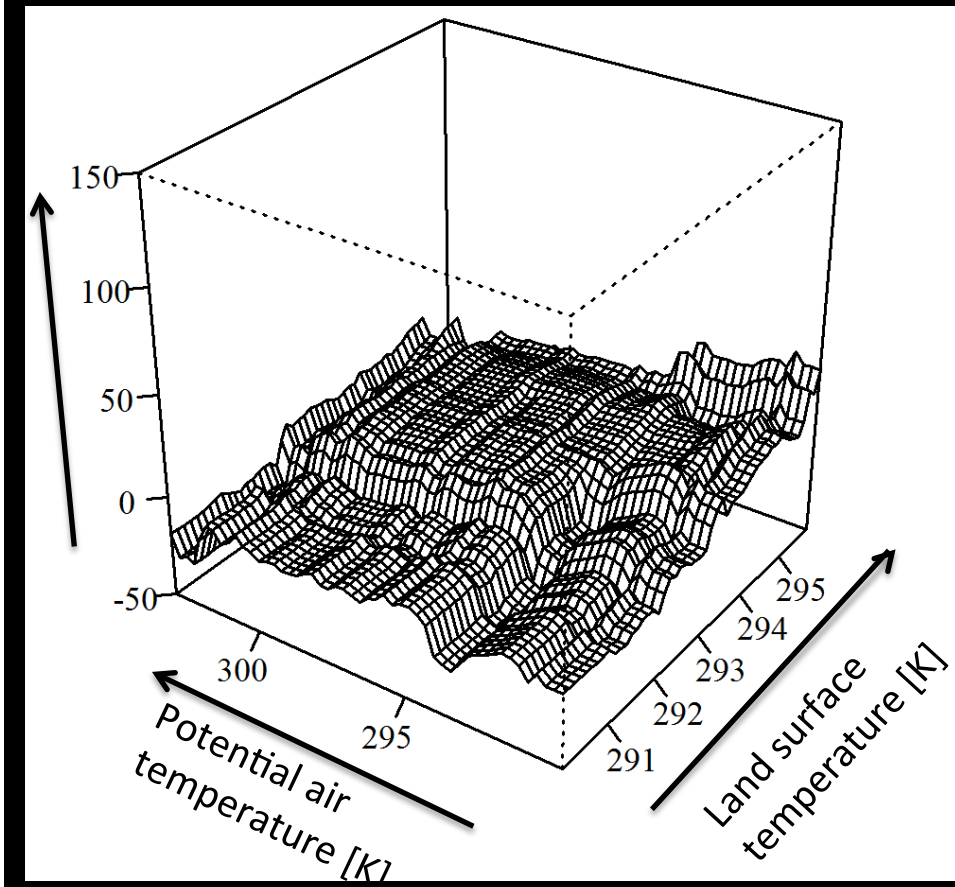
- …Process attribution!



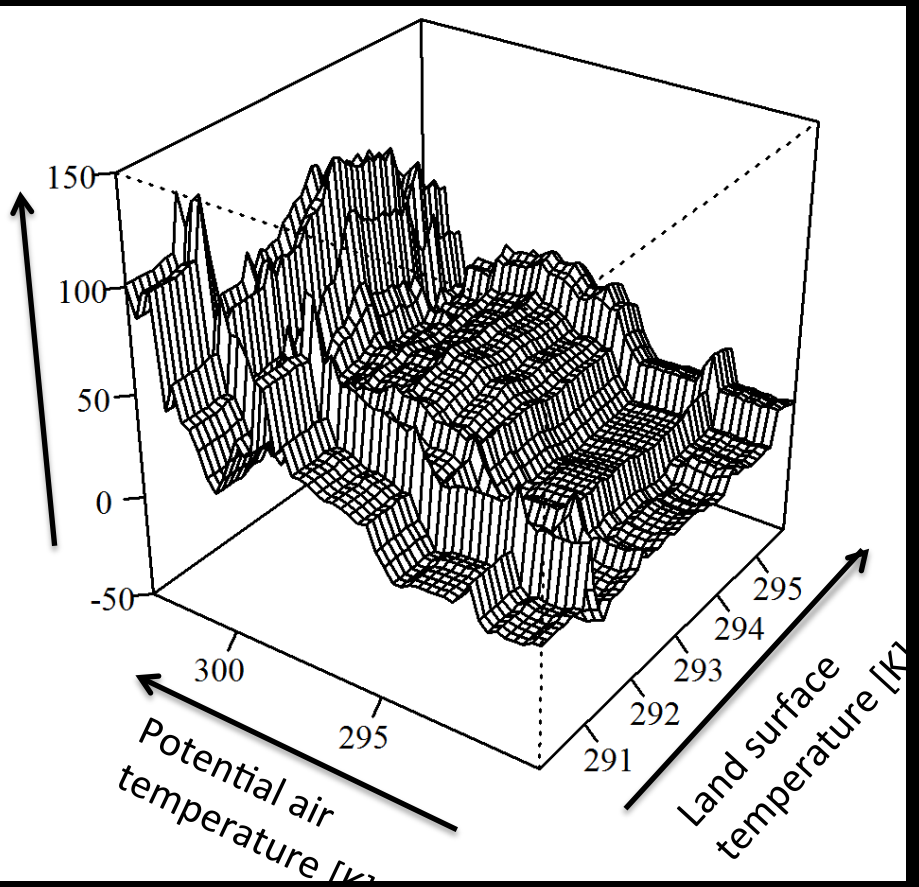
What does the tower flux measurement "see"?

- Multivariate responses of surface-atmosphere interactions!

Sensible heat flux [W m^{-2}]



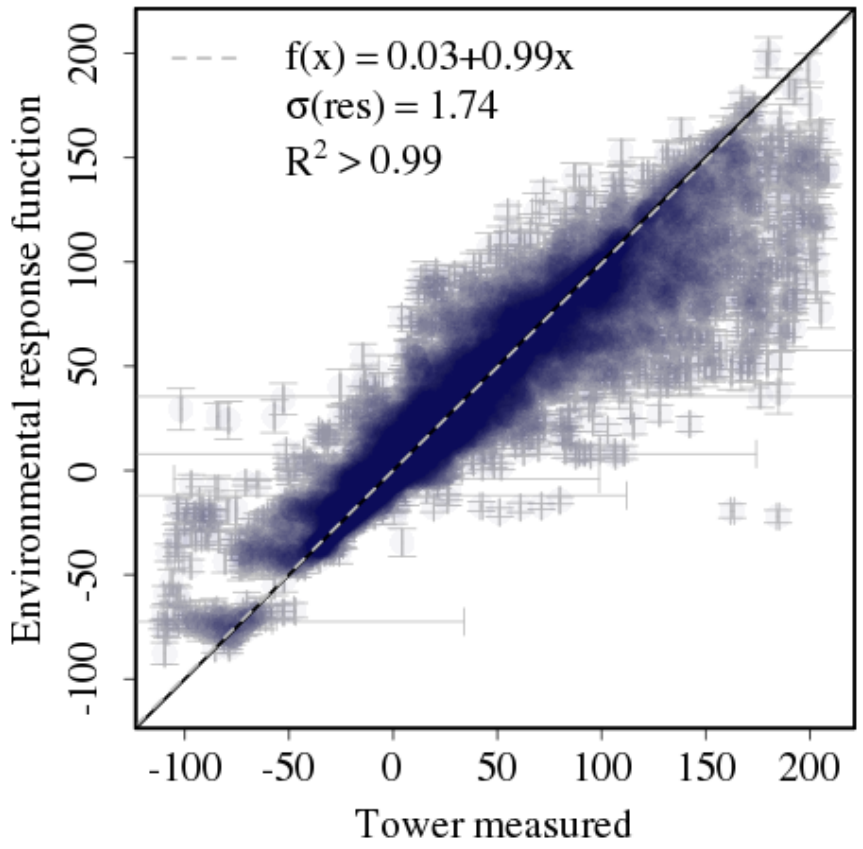
Latent heat flux [W m^{-2}]



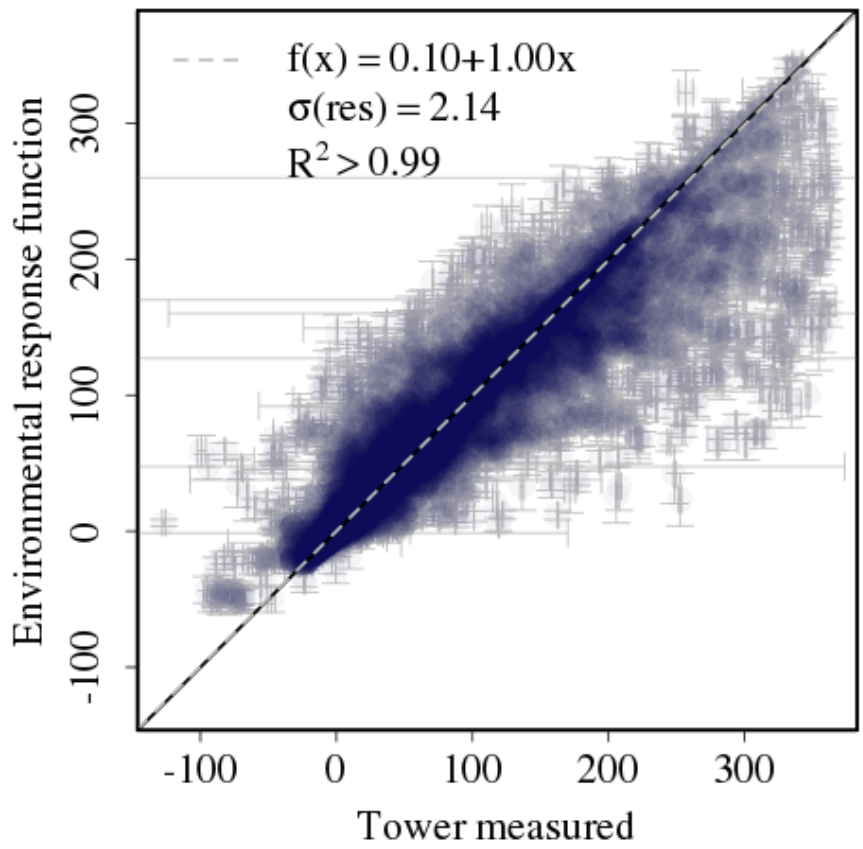
How do tower environmental response functions perform?

- Reasonably good;
  - 1 month of data from summer 2011 at 1 min temporal resolution;
  - > 20000 flux observations after QA/QC;

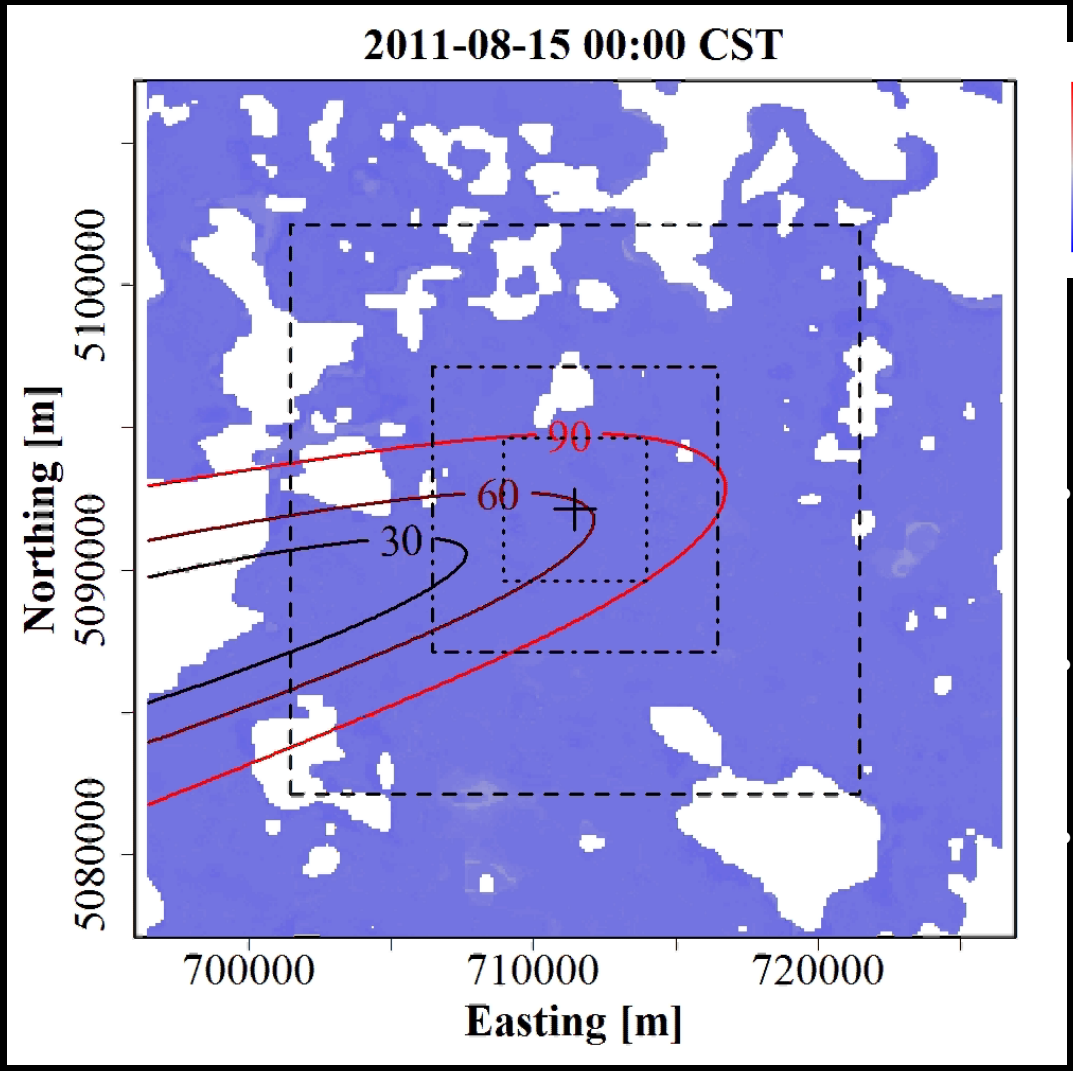
Sensible heat flux [W m^{-2}]



Latent heat flux [W m^{-2}]

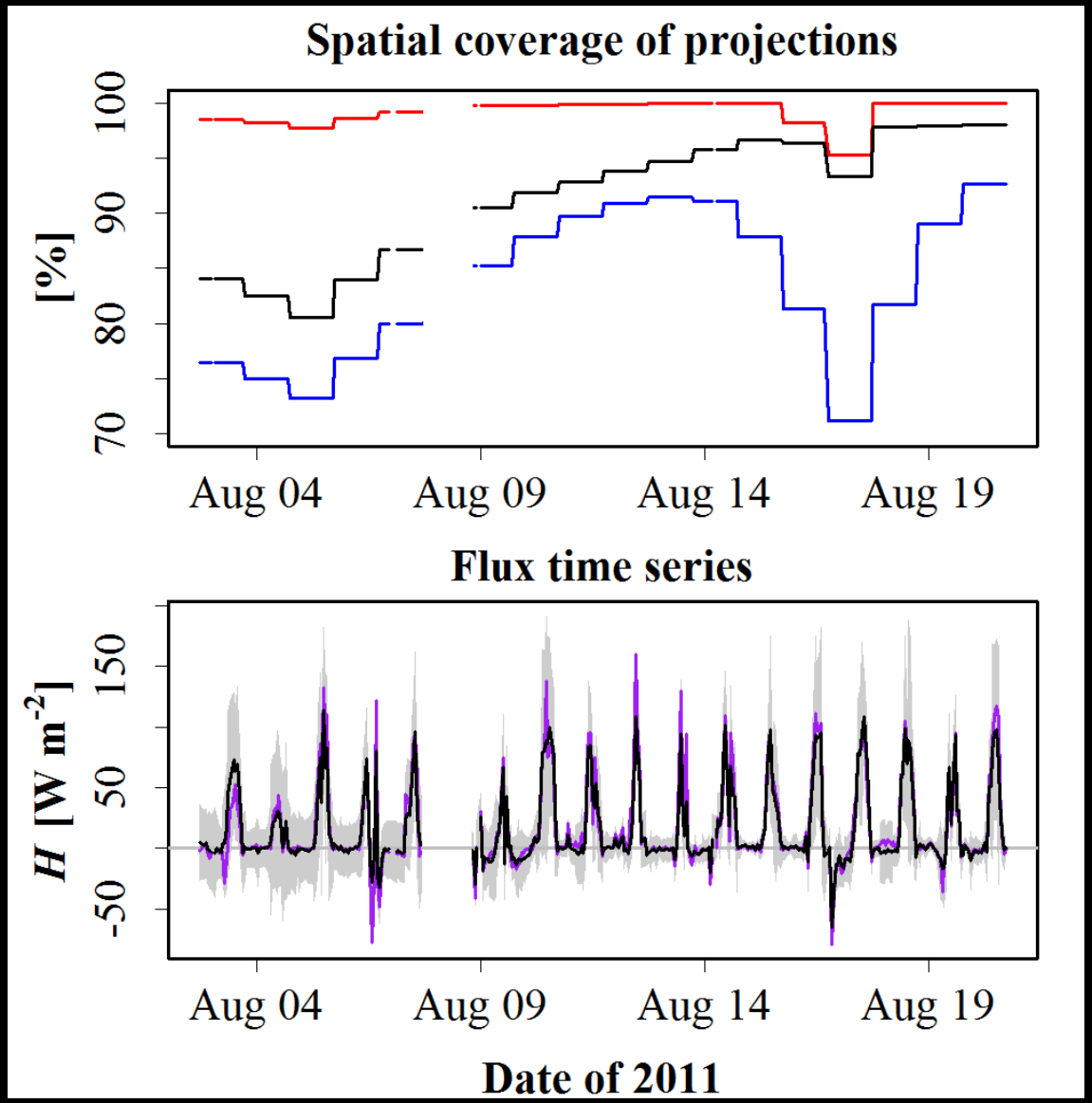


Sensible heat flux [W m^{-2}]



- Flux footprint varies in space, projected flux grid varies in time
- Tower represents different surfaces at different times
- Temporally transient location bias ="location drift"

Target area versus spatio-temporally varying patch II



- ≥70 % spatial coverage
- Spatially pre-blended fluxes less erratic
- Explicit information on spatial variation

25 km^2 projection
100 km^2 projection
400 km^2 projection
Tower measured
99.9%ile spatial variation

Thank you!

- I hope my examples convinced you that scale is fundamental to understanding ecosystem-atmosphere interactions
- I hope some of the innovations I presented actually solve some of our problems of scale
- None of this can be done without my lab, collaborators, funders, and the opportunity to discuss these with you!