

"How do we scale ecosystem-atmosphere exchanges?"

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8 Jan 2015, AOSS Seminar, U Michigan

A photograph of a dense tropical forest. The scene is filled with various types of palm trees, some with long, slender trunks and others with more complex fronds. The ground is covered in a thick layer of green plants, including large-leafed shrubs and smaller ground cover. Sunlight filters through the canopy, creating dappled light on the forest floor. A semi-transparent dark band across the middle of the image contains the text.

Why is this so damn hard to model?

A large, complex scientific instrument, likely a synchrotron beamline, is situated in a grassy field. The instrument features a large, dark, horizontal beam pipe supported by a white metal frame. A large, cylindrical, silver-colored component is visible in the foreground. The background shows a green field, a fence, and a line of trees under a clear sky. The text "What does it have to do with scale?" is overlaid on the image.

What does it have to do with scale?

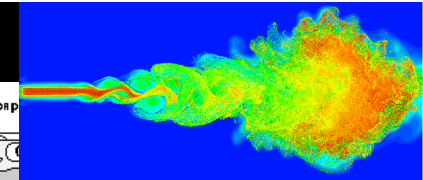
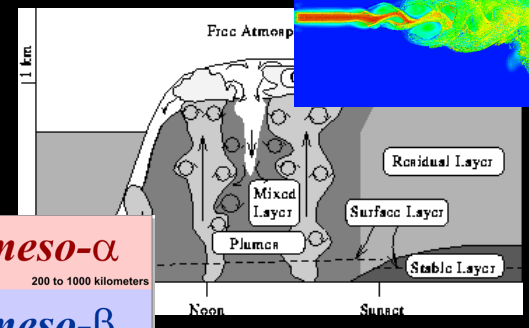
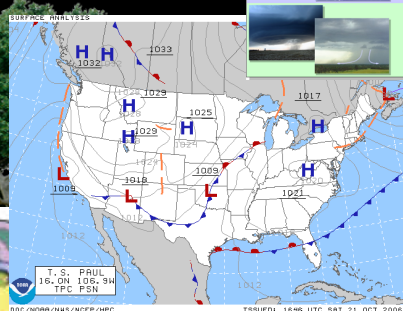
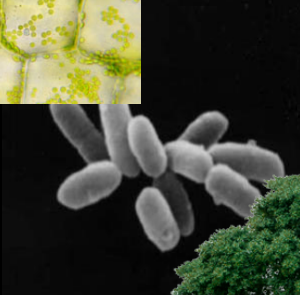
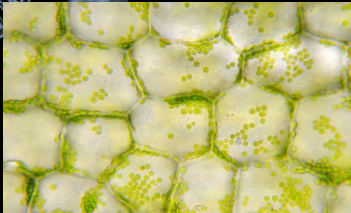
We face a fundamental scale mismatch



Between **observations** &
models

Between the **atmosphere** &
ecosystems

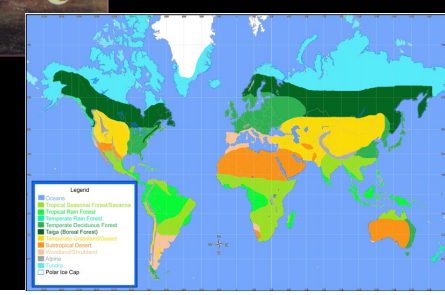
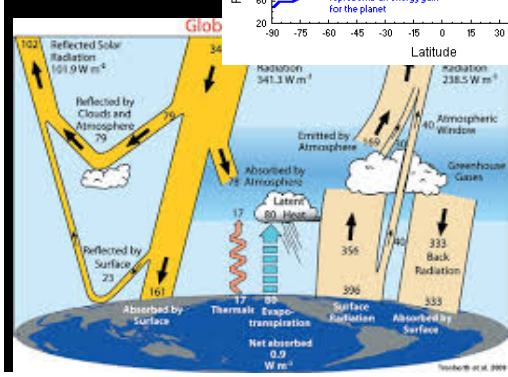
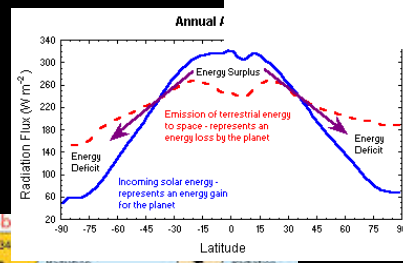




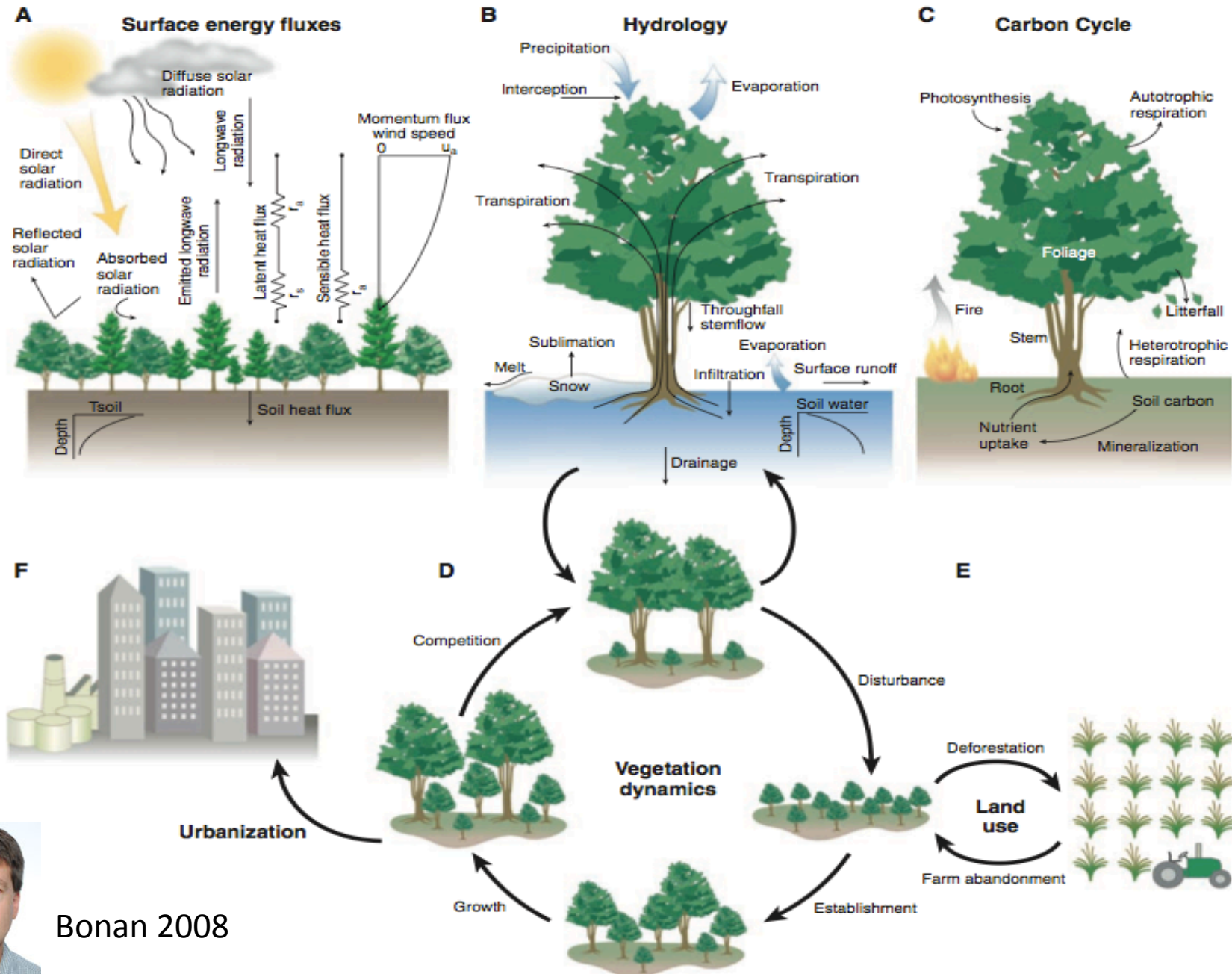
meso- α
200 to 1000 kilometers

meso- β
20 to 200 Kilometers

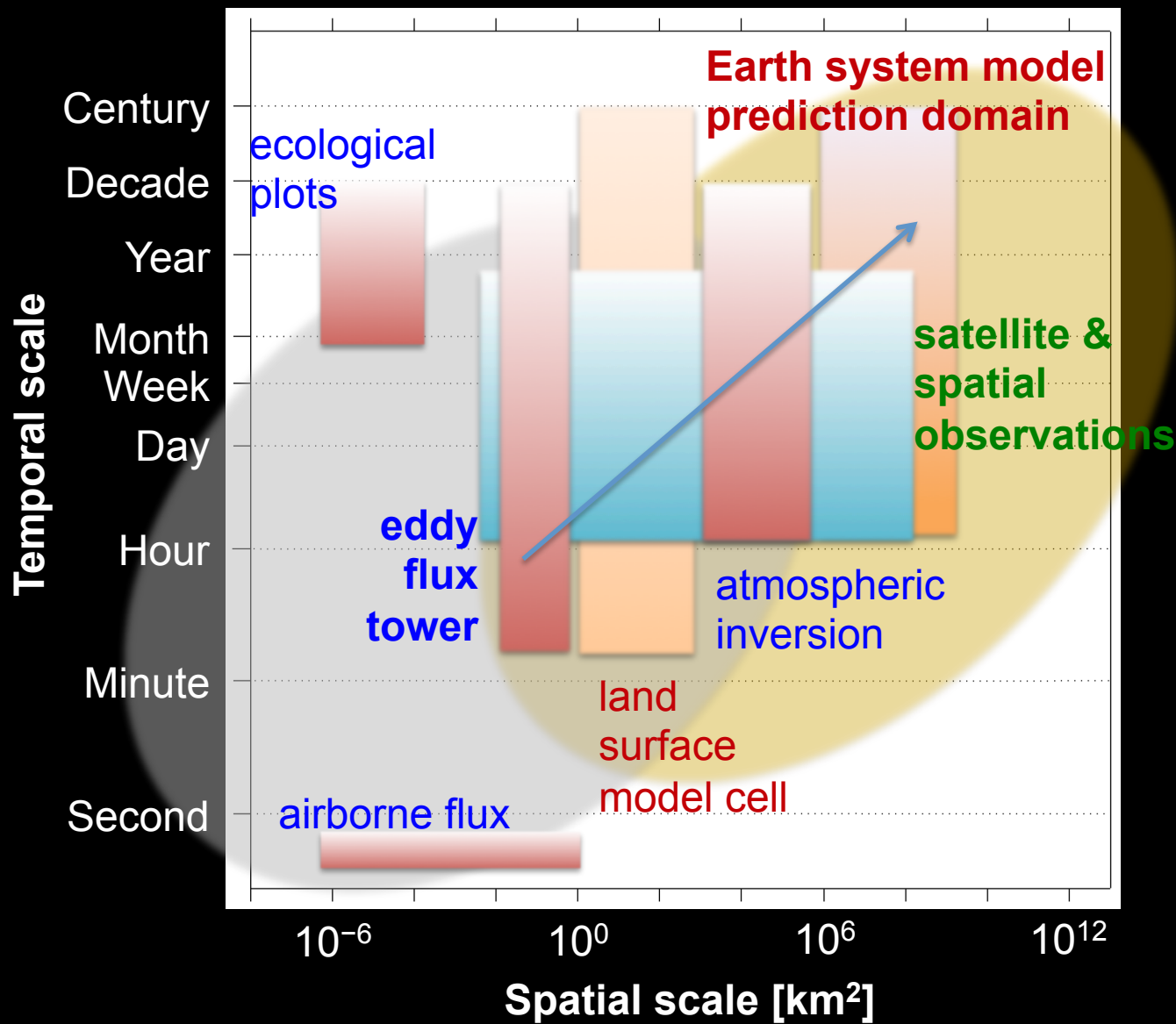
meso- γ
2 to 20 kilometers



Forests in Flux



Bonan 2008



THE PROBLEM OF PATTERN AND SCALE IN ECOLOGY

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

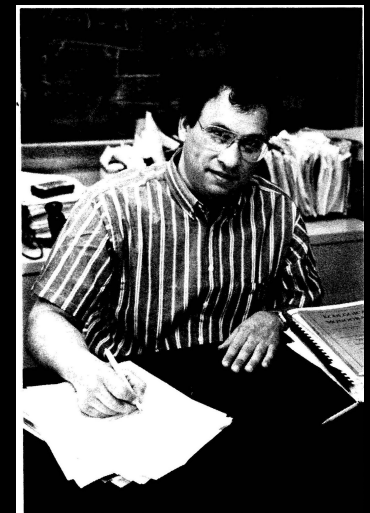
by

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



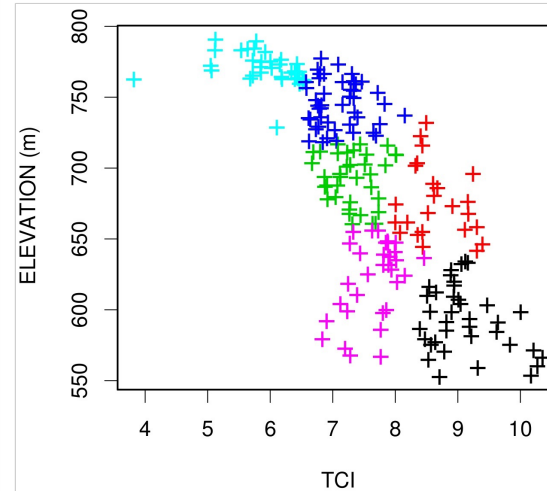
- How do spatio-temporal patterns and variability change with the scale of description?
- Develop laws for their aggregation!



Simon A. Levin
MacArthur Award Recipient



Scales as
the sum of it's parts



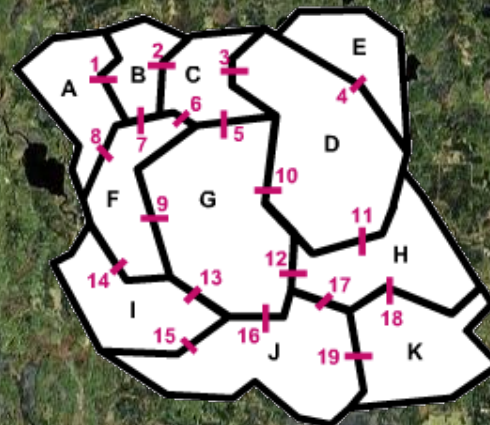
Spatial Heterogeneity

- Amount
- Frequency
Distribution



45.805901 , -90.079903
US-WCr

Difficult to Scale



Spatial Process

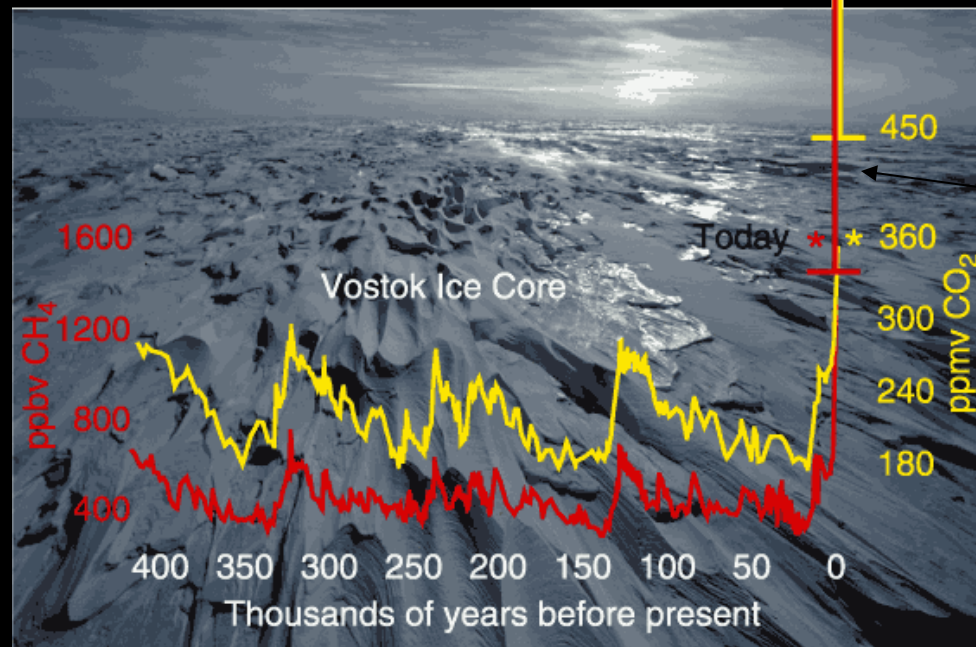
- Arrangement
- Location
- Distance

10000 meters

Why does it matter?



Atmospheric CO₂
has increased rapidly
to levels above
anything in Earth's
recent past



2100?

Today

400 ppm CO₂

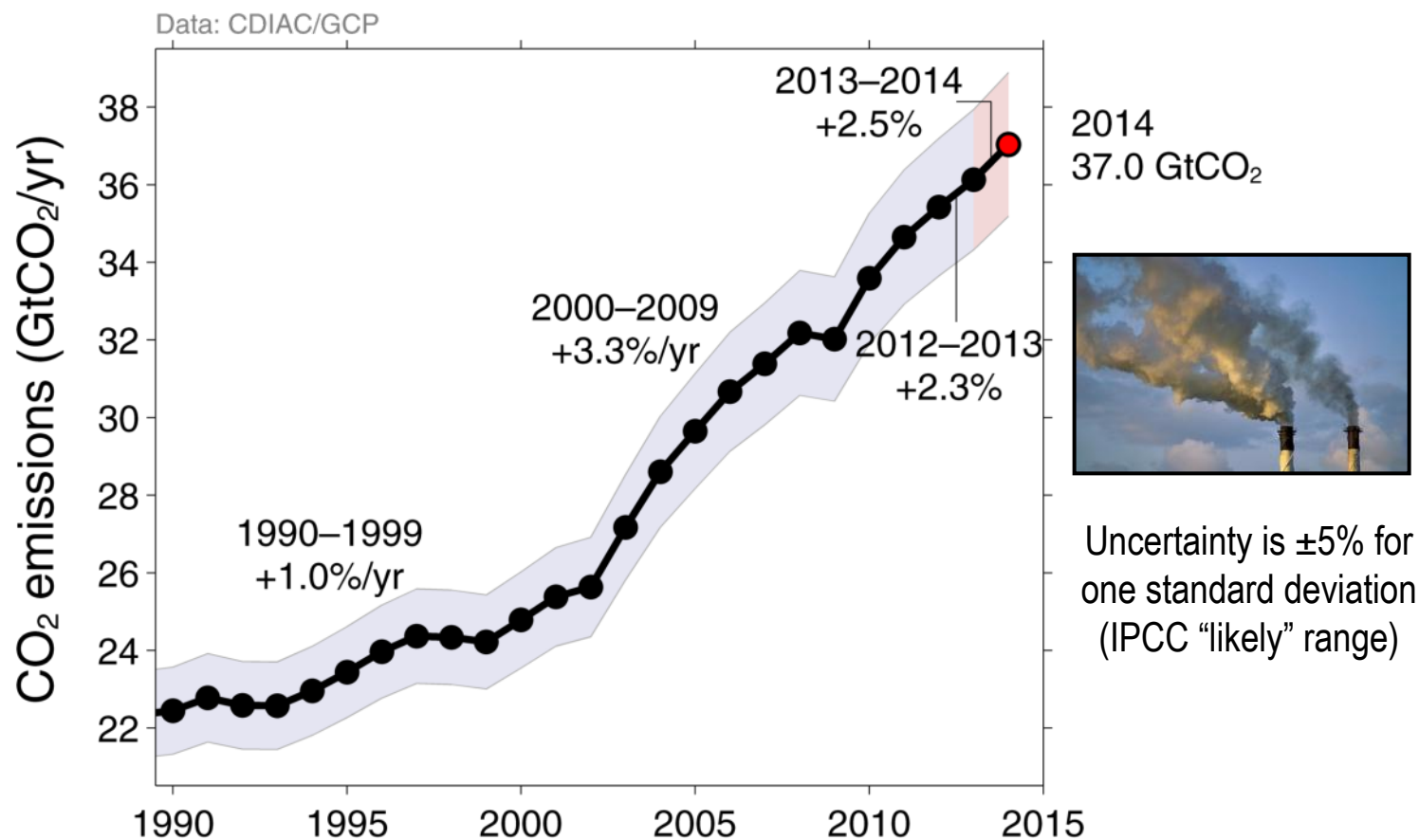
2 ppm CH₄

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

Fossil Fuel and Cement Emissions

Global fossil fuel and cement emissions: 36.1 ± 1.8 GtCO₂ in 2013, 61% over 1990

- Projection for 2014 : 37.0 ± 1.9 GtCO₂, 65% over 1990



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)

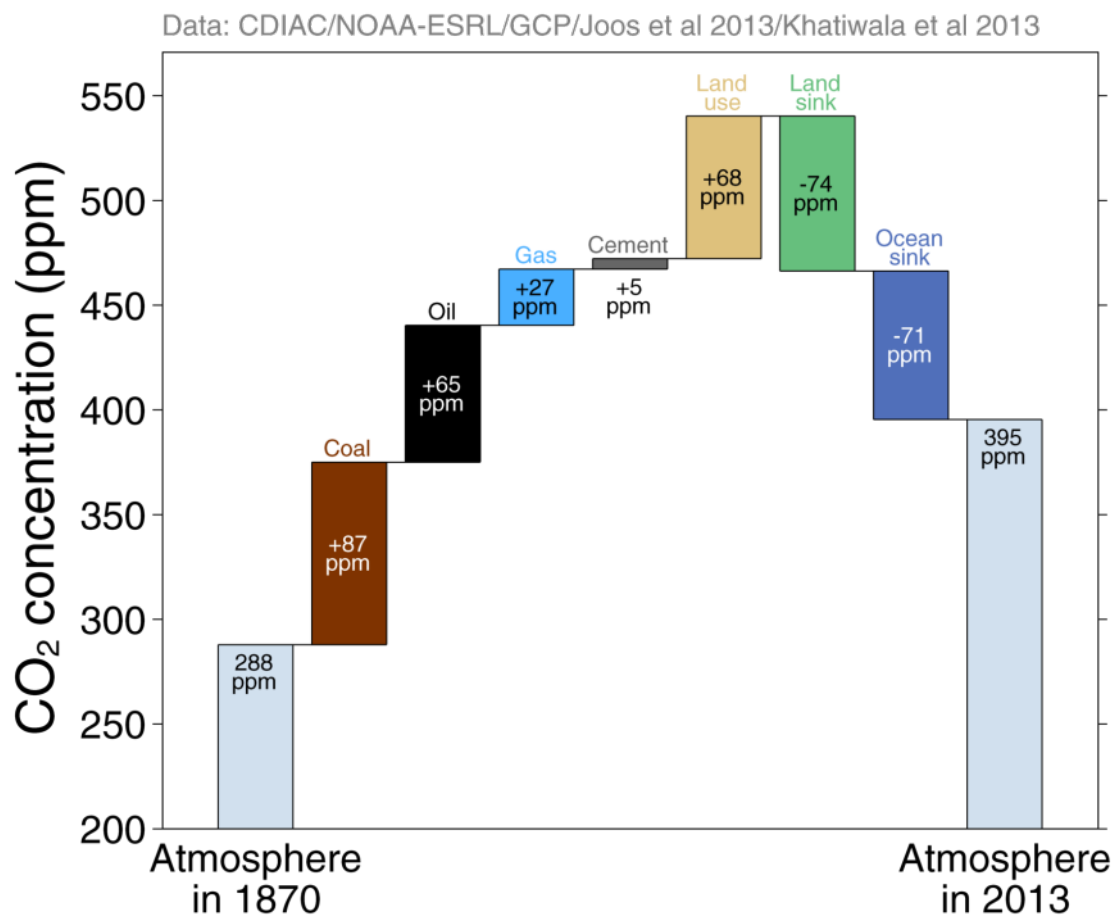
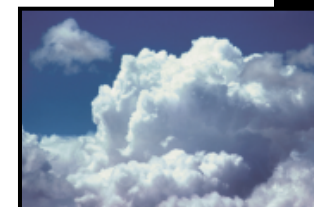
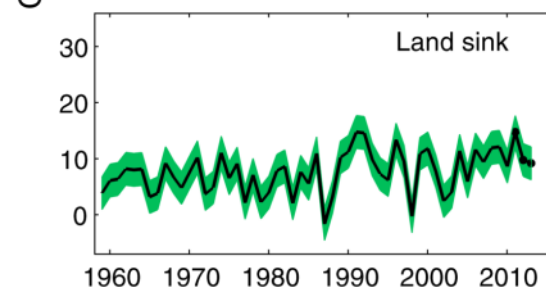
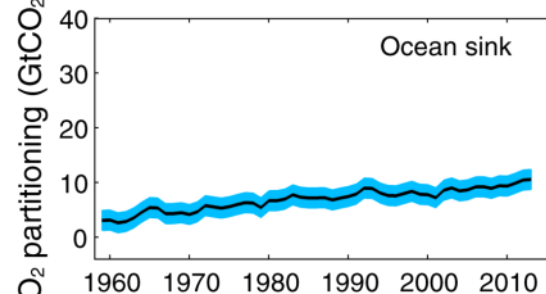
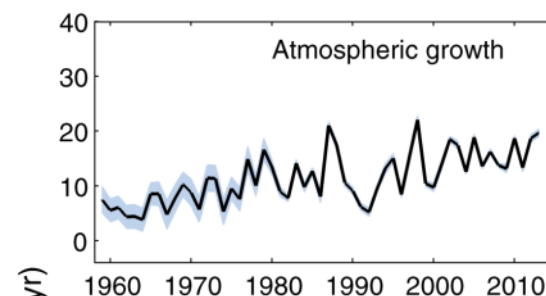
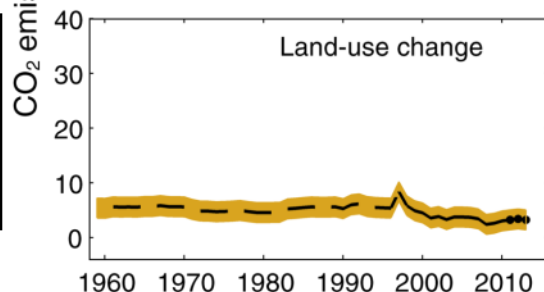
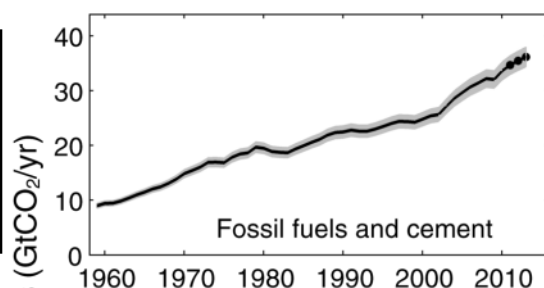


Figure concept from [Shrink That Footprint](#)

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](#)

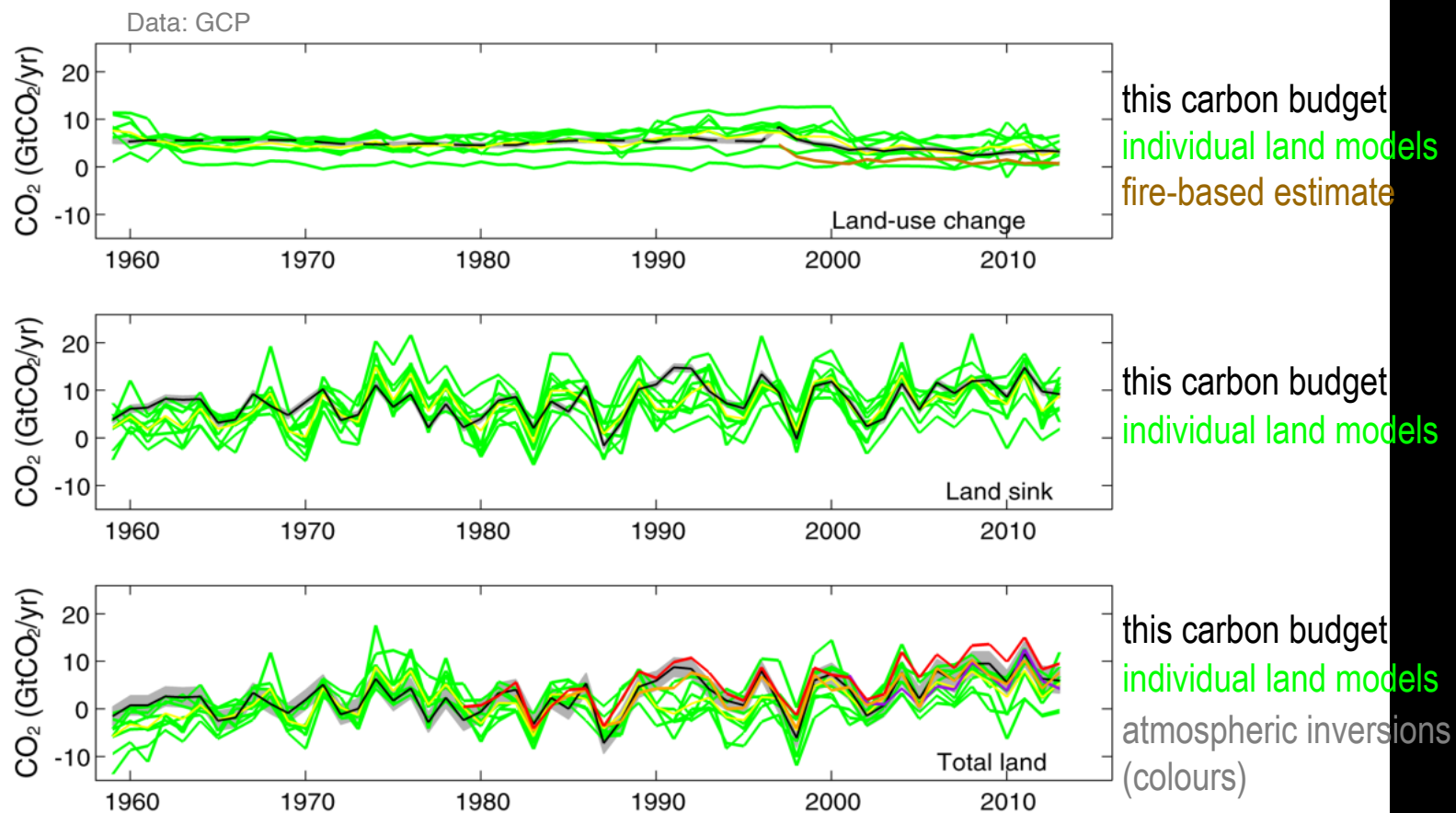
Changes in the Budget over Time

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 CO₂ in the atmosphere



Terrestrial Sink

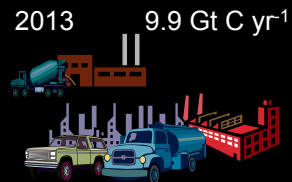
The residual land sink is increasing with time to $9.2 \pm 1.8 \text{ GtCO}_2/\text{yr}$ in 2013, with large variability
Total CO_2 fluxes on land (including land-use change) are constrained by atmospheric inversions



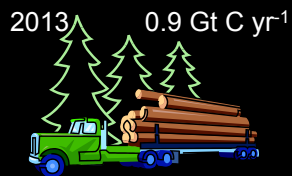
Source: [Le Quéré et al 2014](#); [Global Carbon Project 2014](#)

Individual estimates from Zhang et al. (2013); Oleson et al. (2013); Jain et al. (2013); Clarke et al. (2011); Smith et al. (2001); Sitch et al. (2003); Stocker et al. (2013); Krinner et al. (2005); Zeng et al. (2005); Kato et al. (2013); Peters et al. (2010); Rodenbeck et al. (2003); Chevallier et al. (2005). References provided in Le Quéré et al. (2014).

Terrestrial Biosphere CO₂ Flux Dominates Carbon Cycle Prediction Uncertainty



+



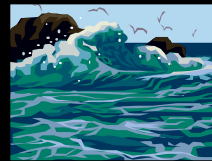
Atmosphere
45%



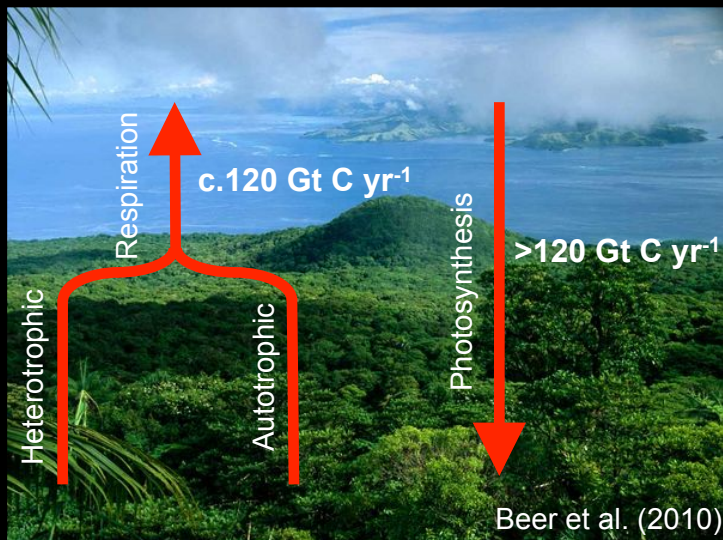
Land
29%



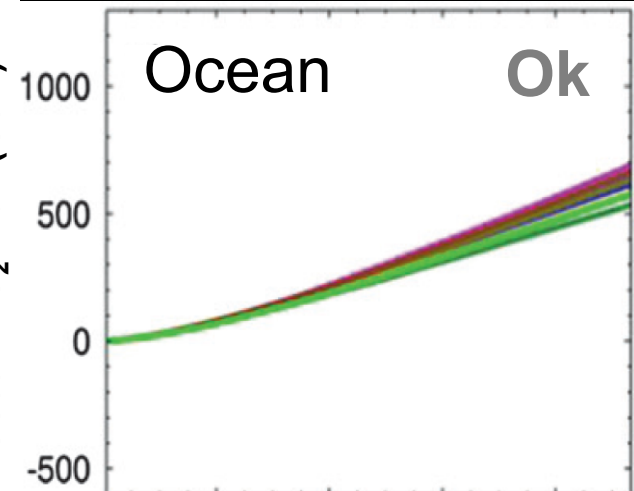
Oceans
26%



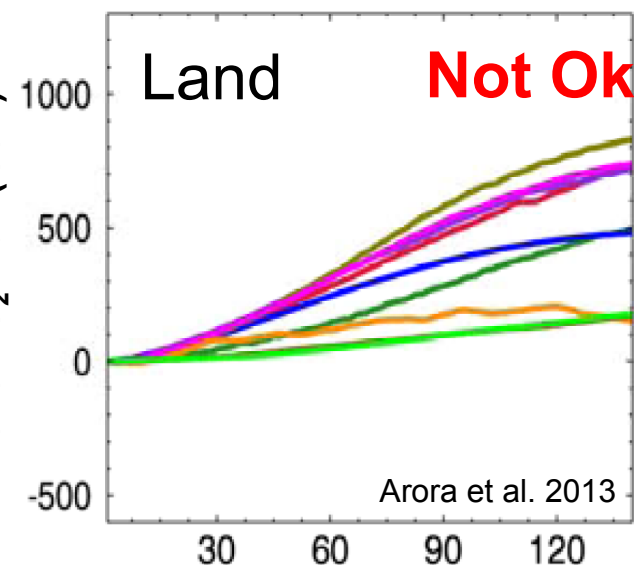
Le Quéré et al (2013)



Cumulative Atmosphere to
Ocean CO₂ Flux (Gt C)

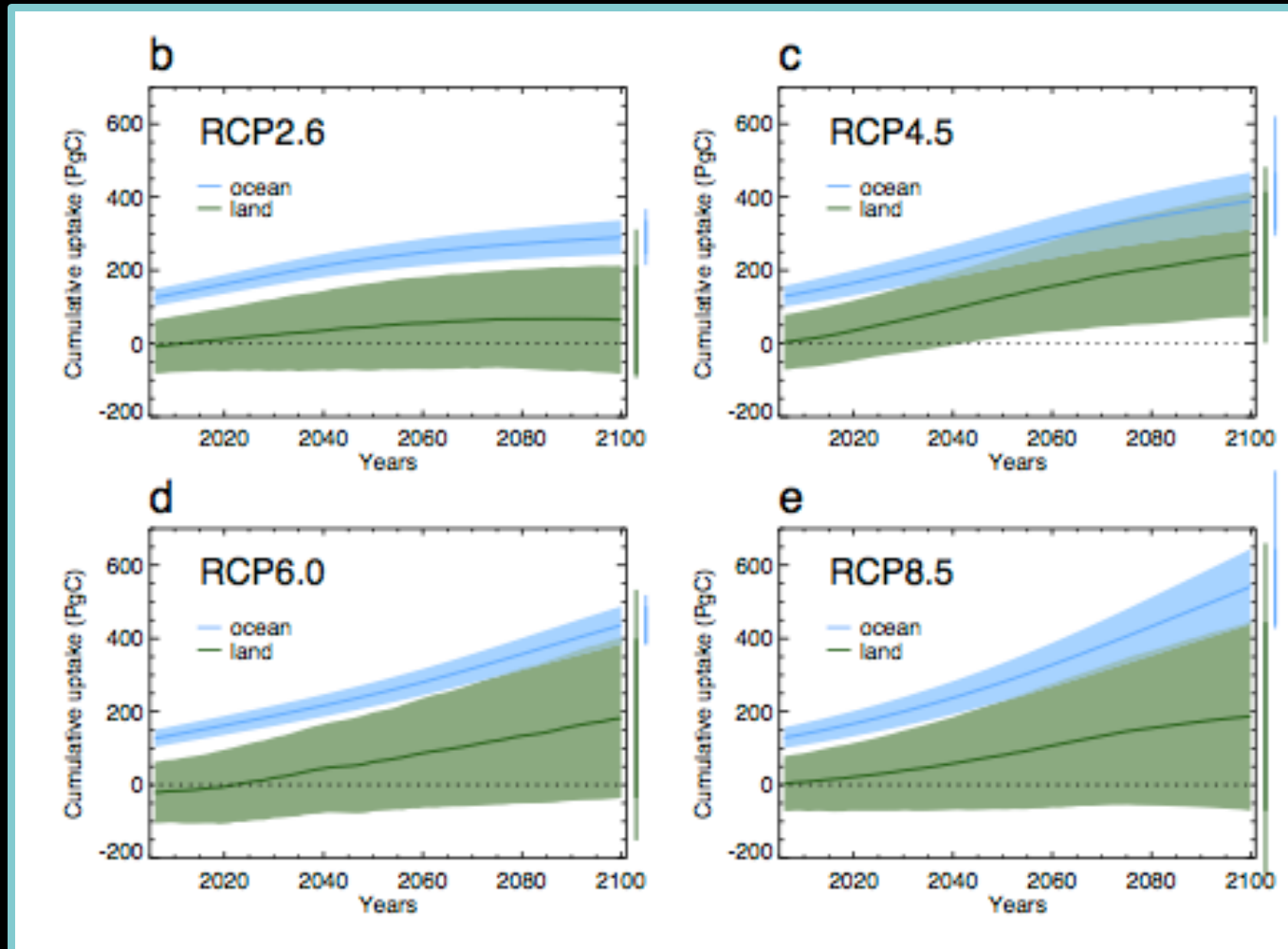


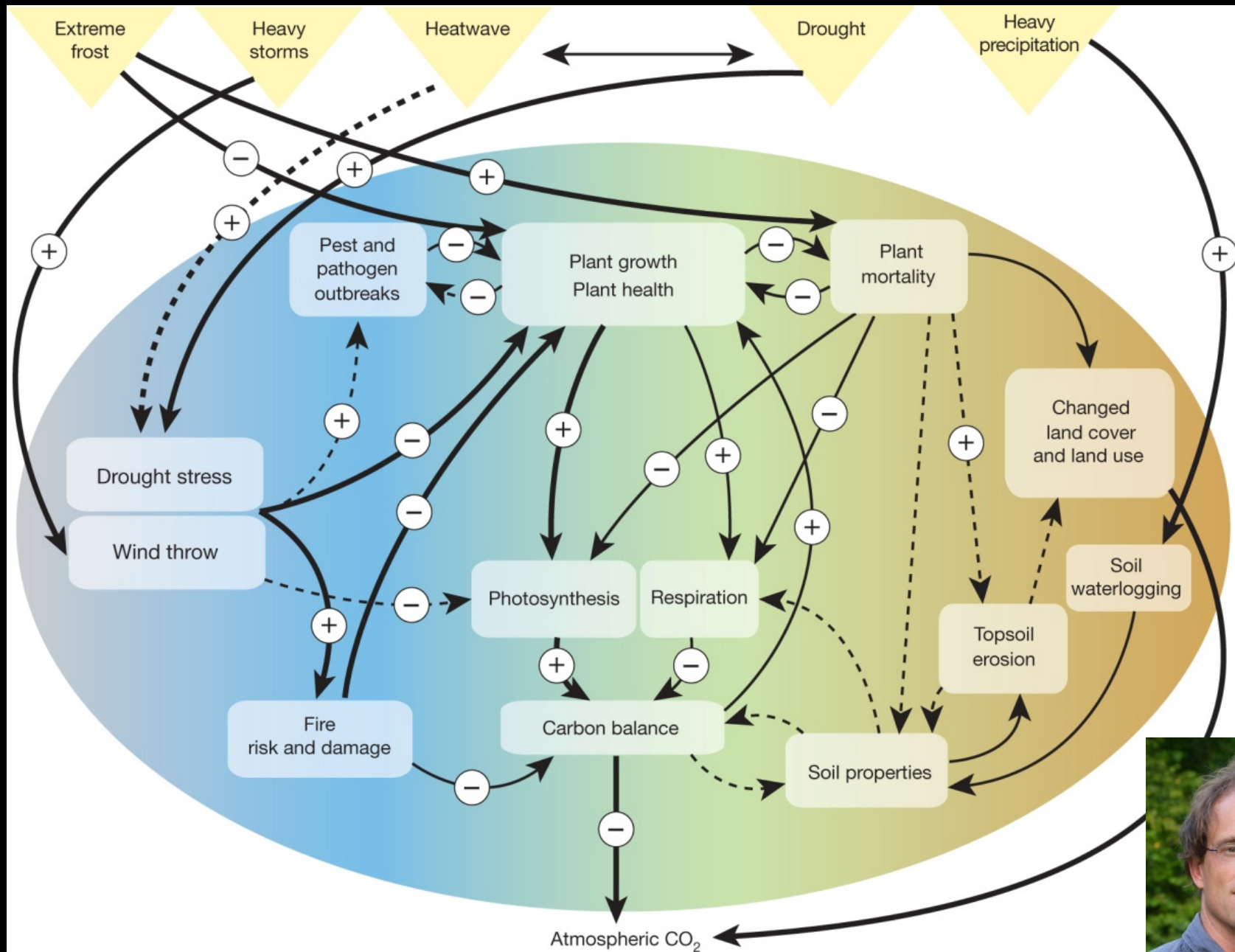
Cumulative Atmosphere to
Land CO₂ Flux (Gt C)



Year

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



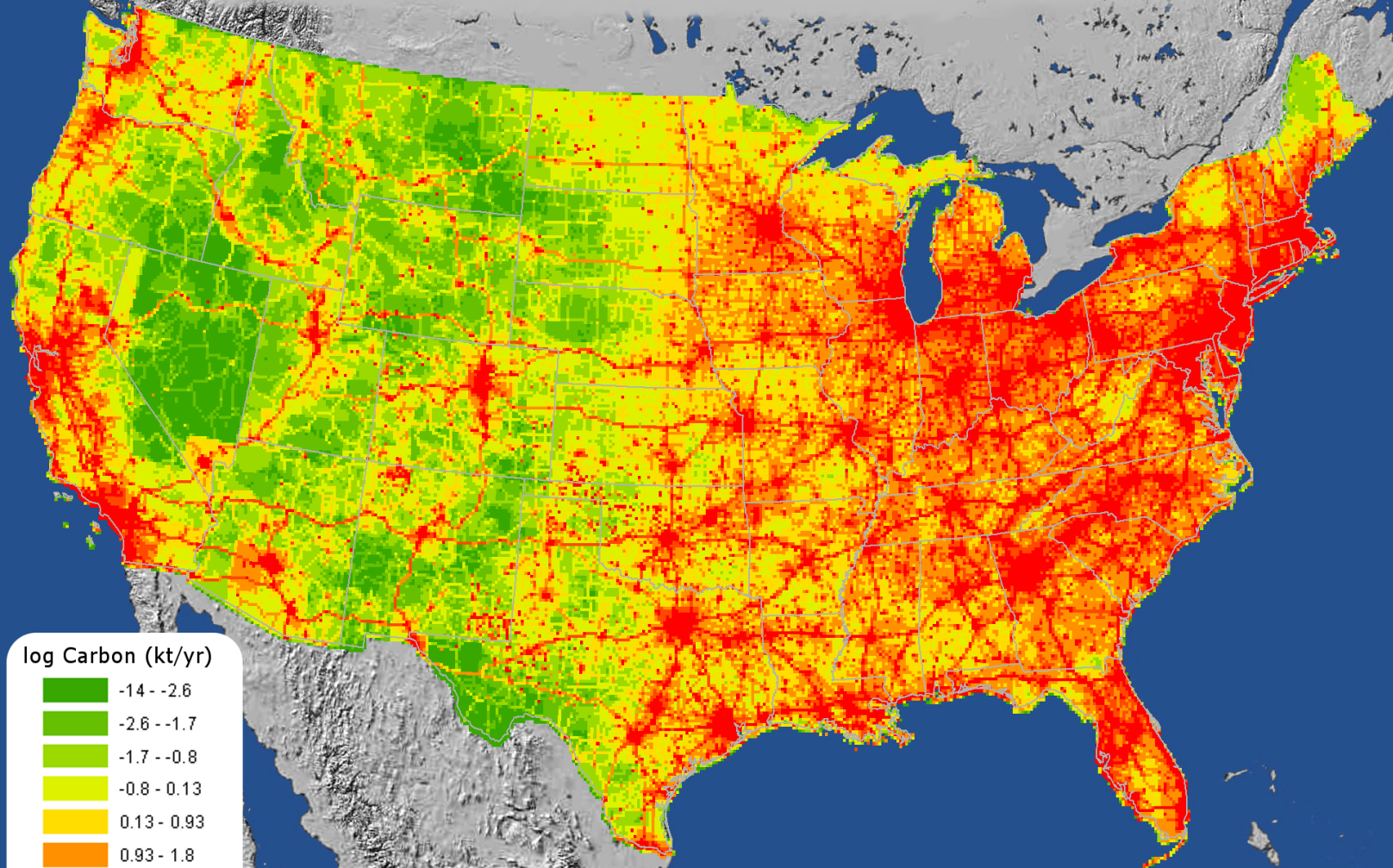


M Reichstein *et al.* *Nature* **500**, 287-295 (2013) doi:10.1038/nature12350

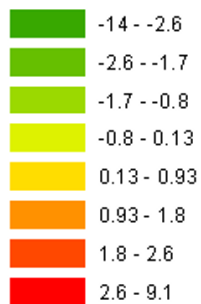


The Vulcan Project

Total Emissions of Fossil Fuel Carbon Dioxide, 2002



log Carbon (kt/yr)



Dr. Kevin Robert Gurney
Arizona State University
Support: NASA, DOE, NSF
<http://vulcan.project.asu.edu>



What do I (we) do?

<http://flux.aos.wisc.edu>

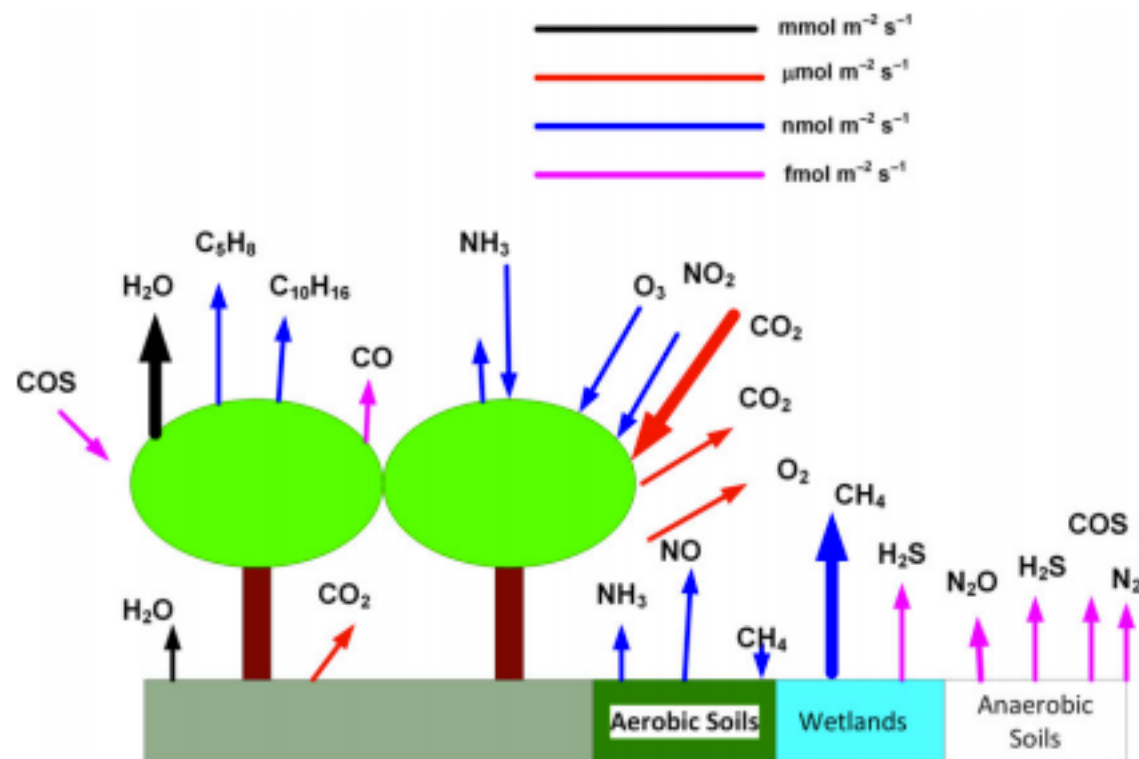
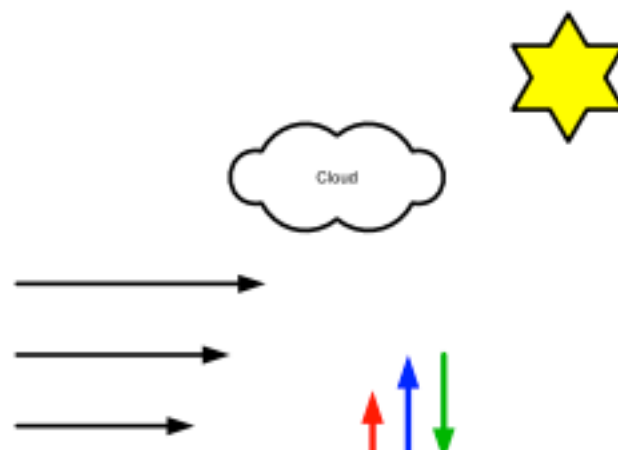
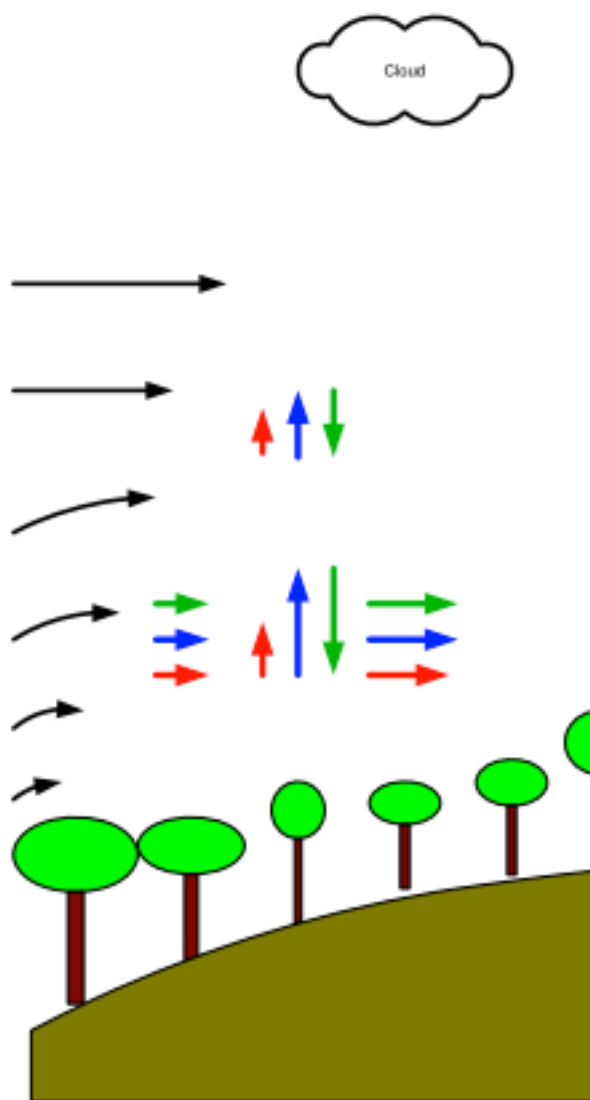
- Probe spatial heterogeneity in biologically-mediated surface-atmosphere exchanges from sites to regions (meters-1000s km)
 - Forests, wetlands, lakes, urban (temperate-boreal-tropical-Mediterranean-alpine, terrestrial-aquatic, management gradients)
 - Multiple greenhouse gases (methane), esp. with 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



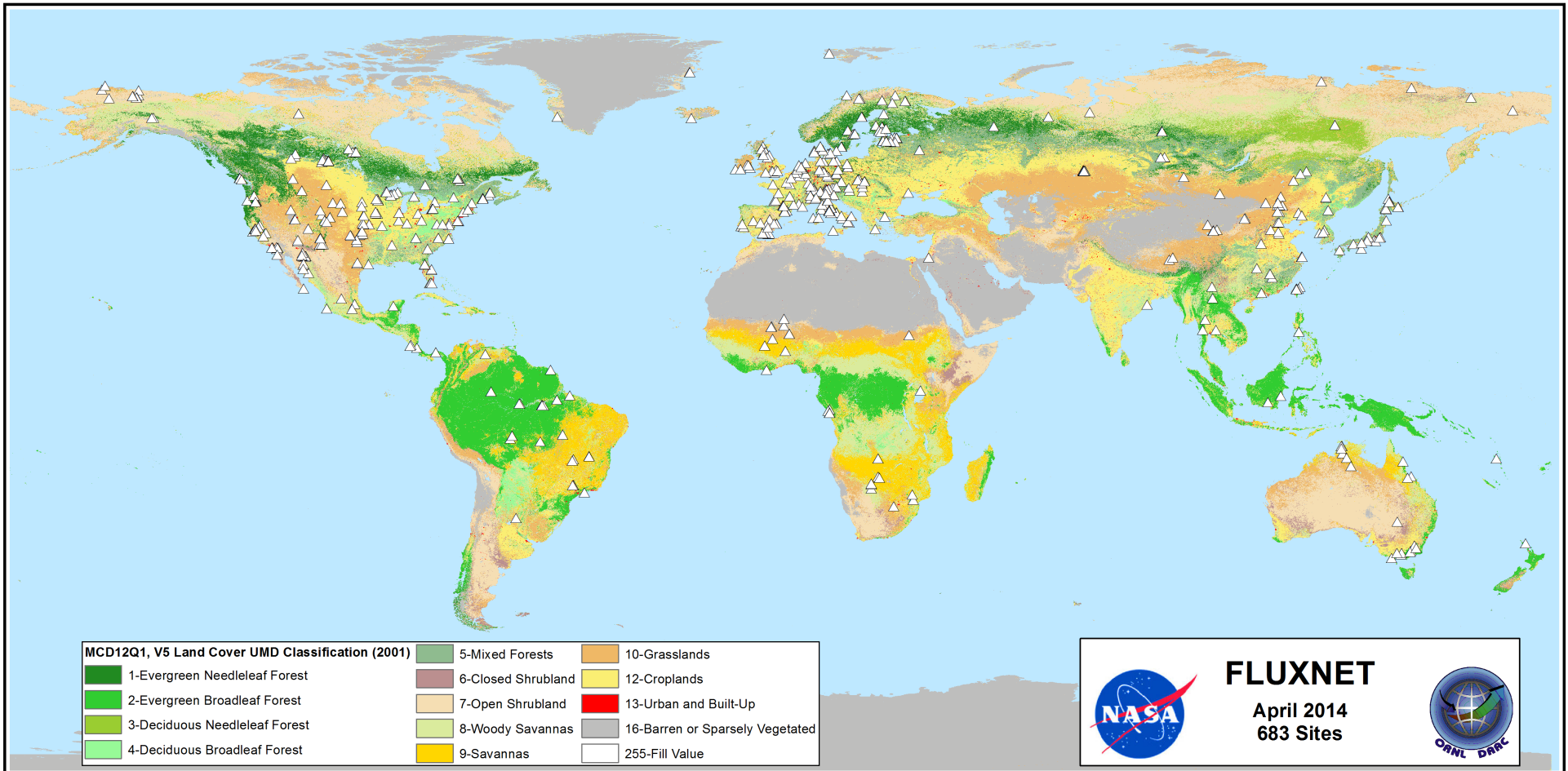
What the flux?

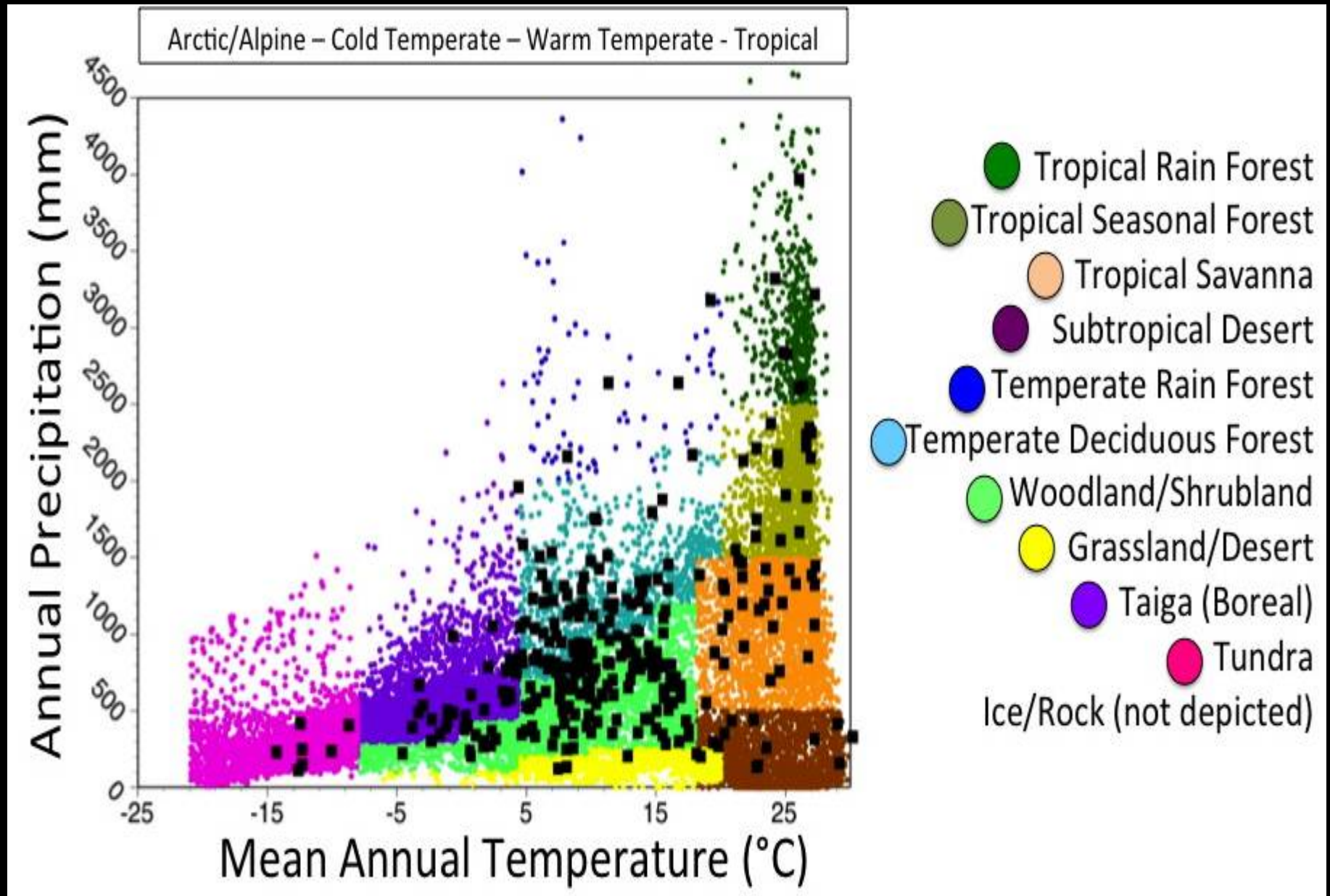




D. Baldocchi

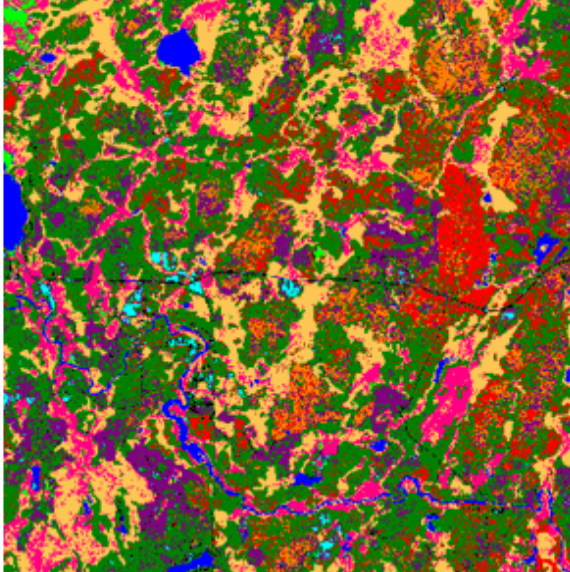
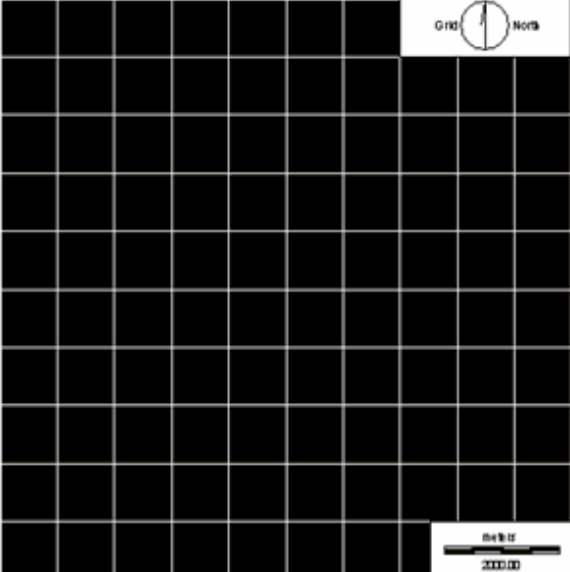
700 points of light?



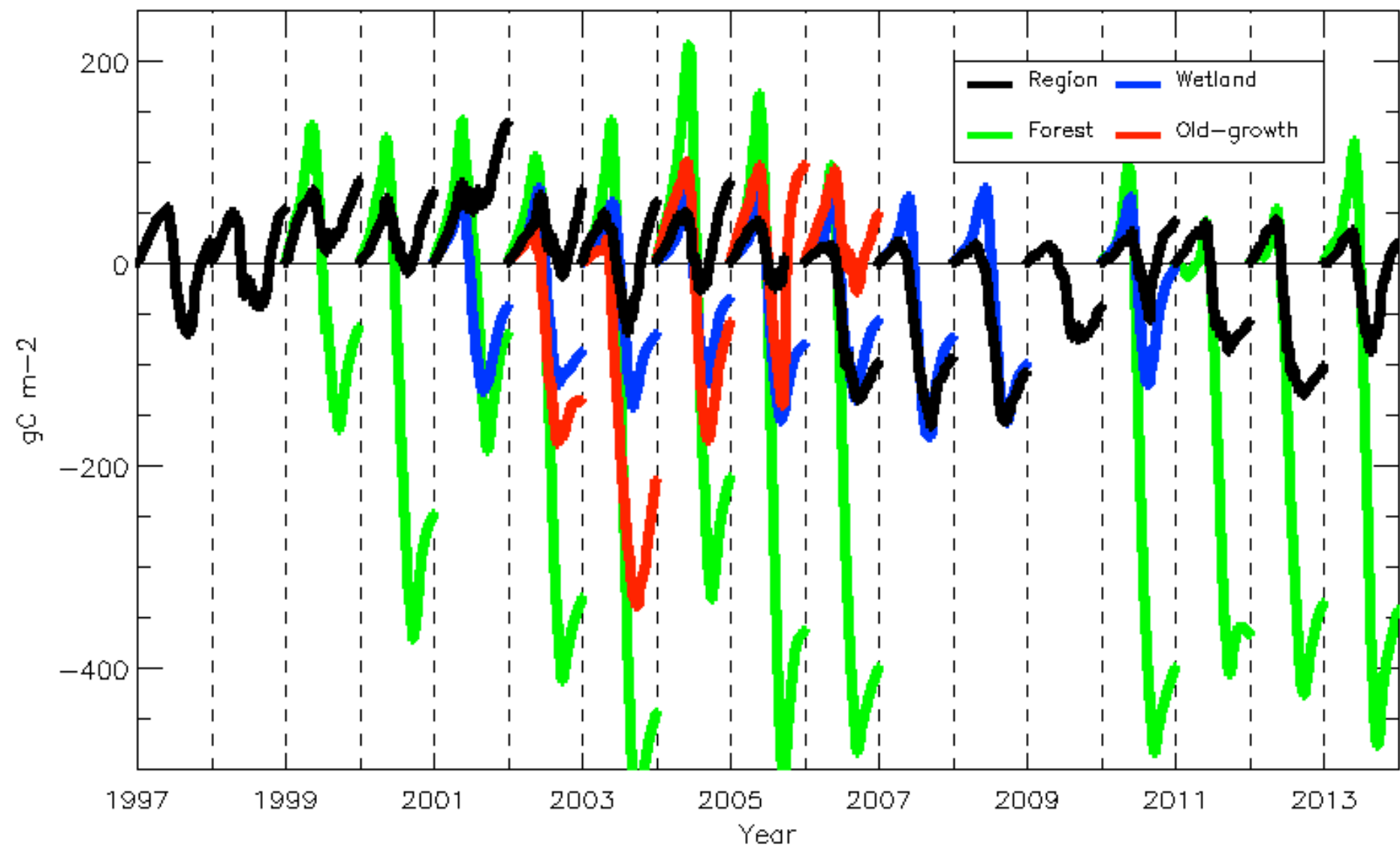


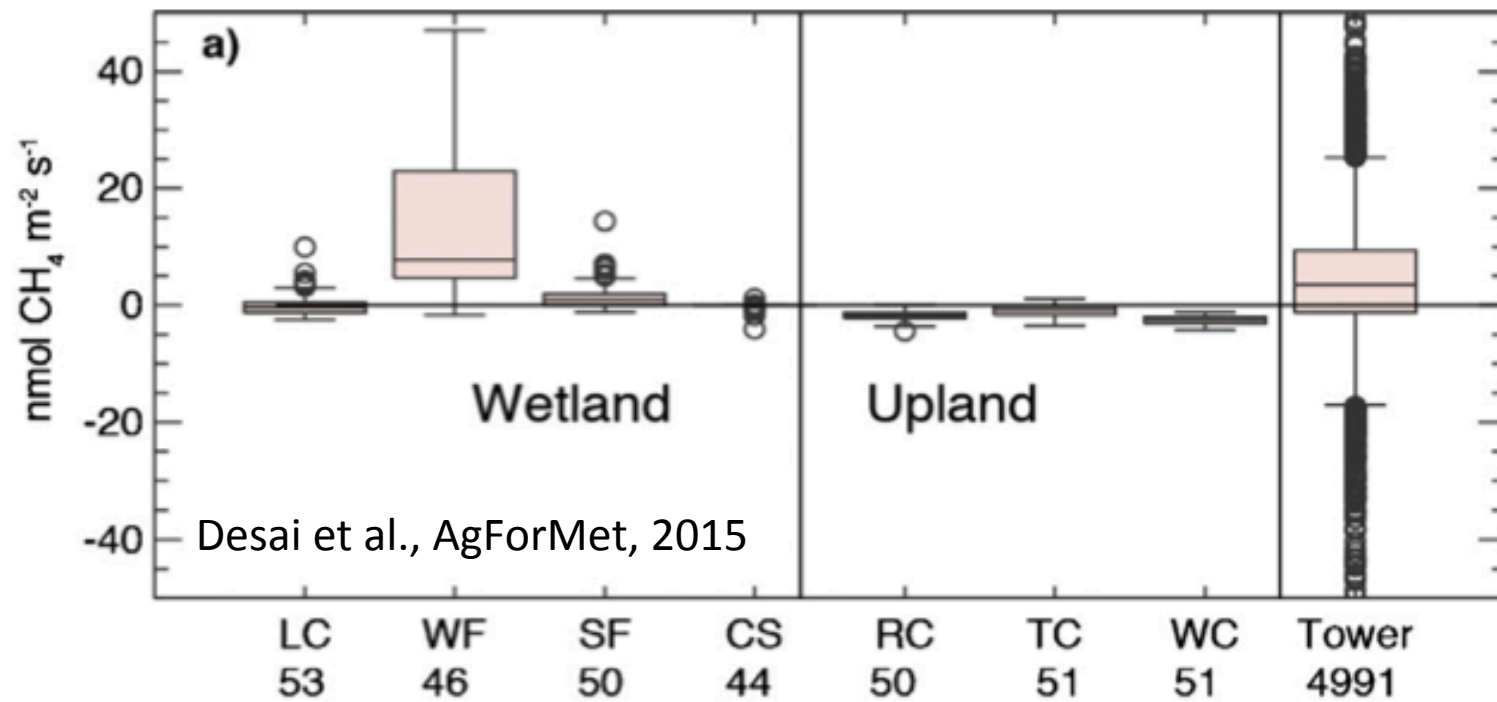


Complex Regions: 1+1≠2

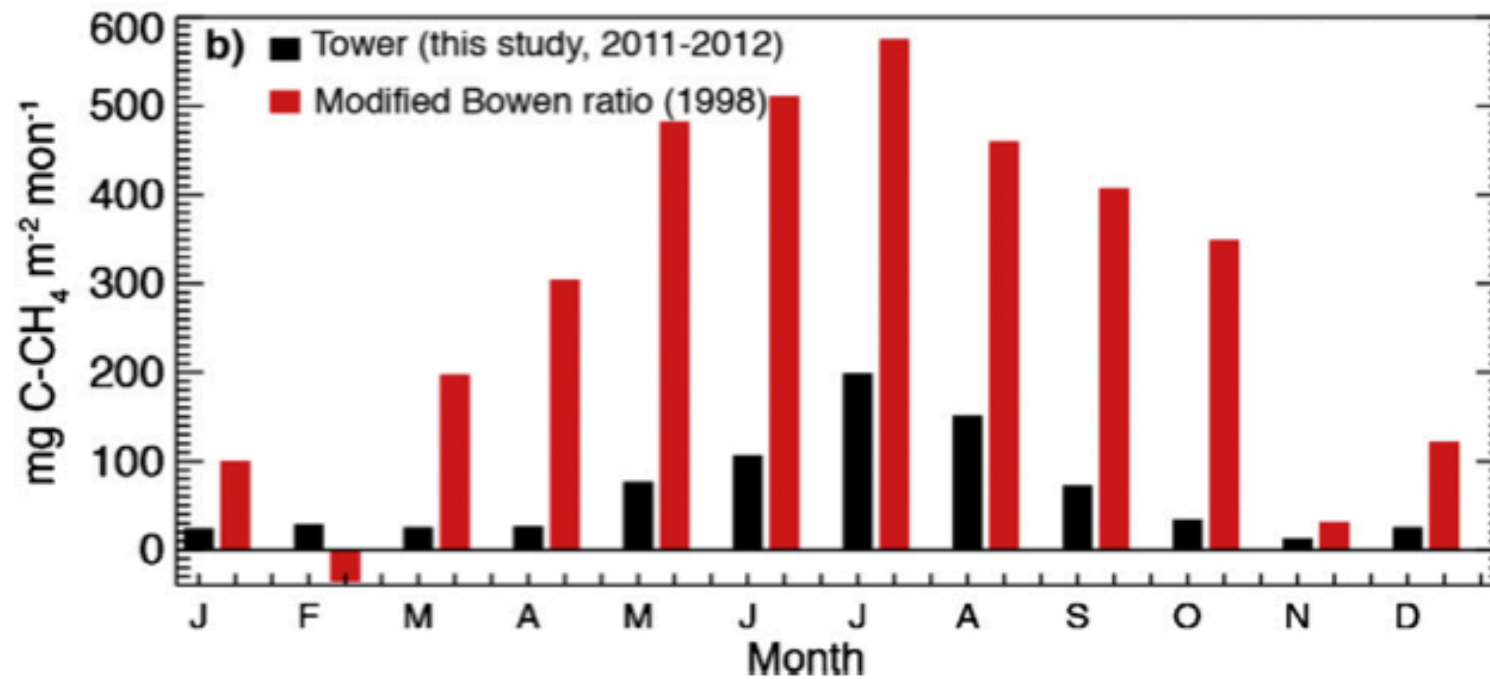
a) IKONOS.	b) WISCLAND.	c) MODIS-UMD and IGBP.
		
— Mixed Forest 13.3% Upland Conifer 34.8% Aspen-Birch 5.7% Upland Hardwood 12.0% Upland Opening/Shrub 0.9% Grassland 17.8% Lowland Conifer 0.7% Lowland Deciduous 10.6% Lowland Shrub 0.6% Wet Meadow 2.6% Open Water 1.0% Road	7.1% Mixed Forest 13.0% Upland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



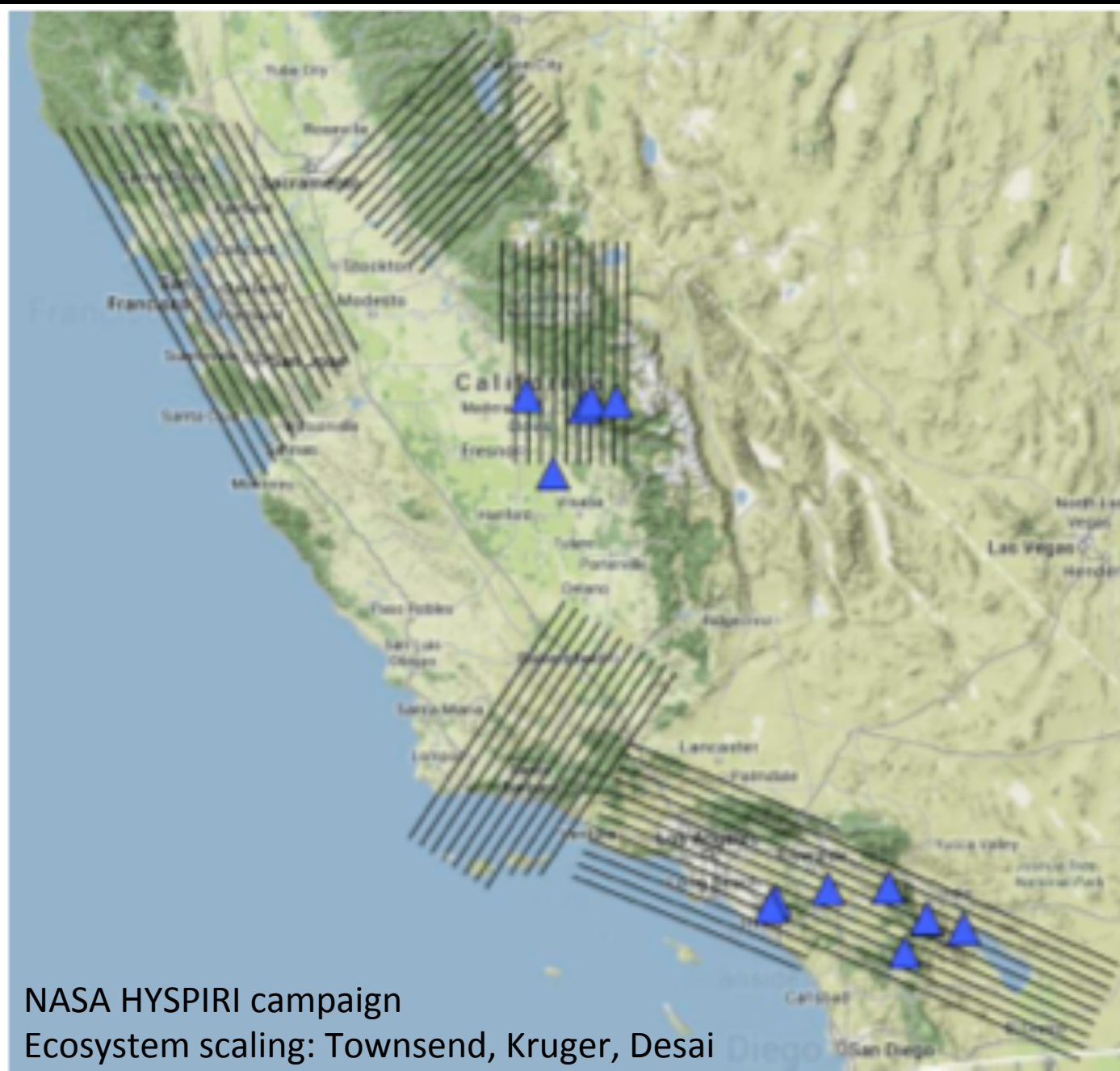


Desai et al., AgForMet, 2015



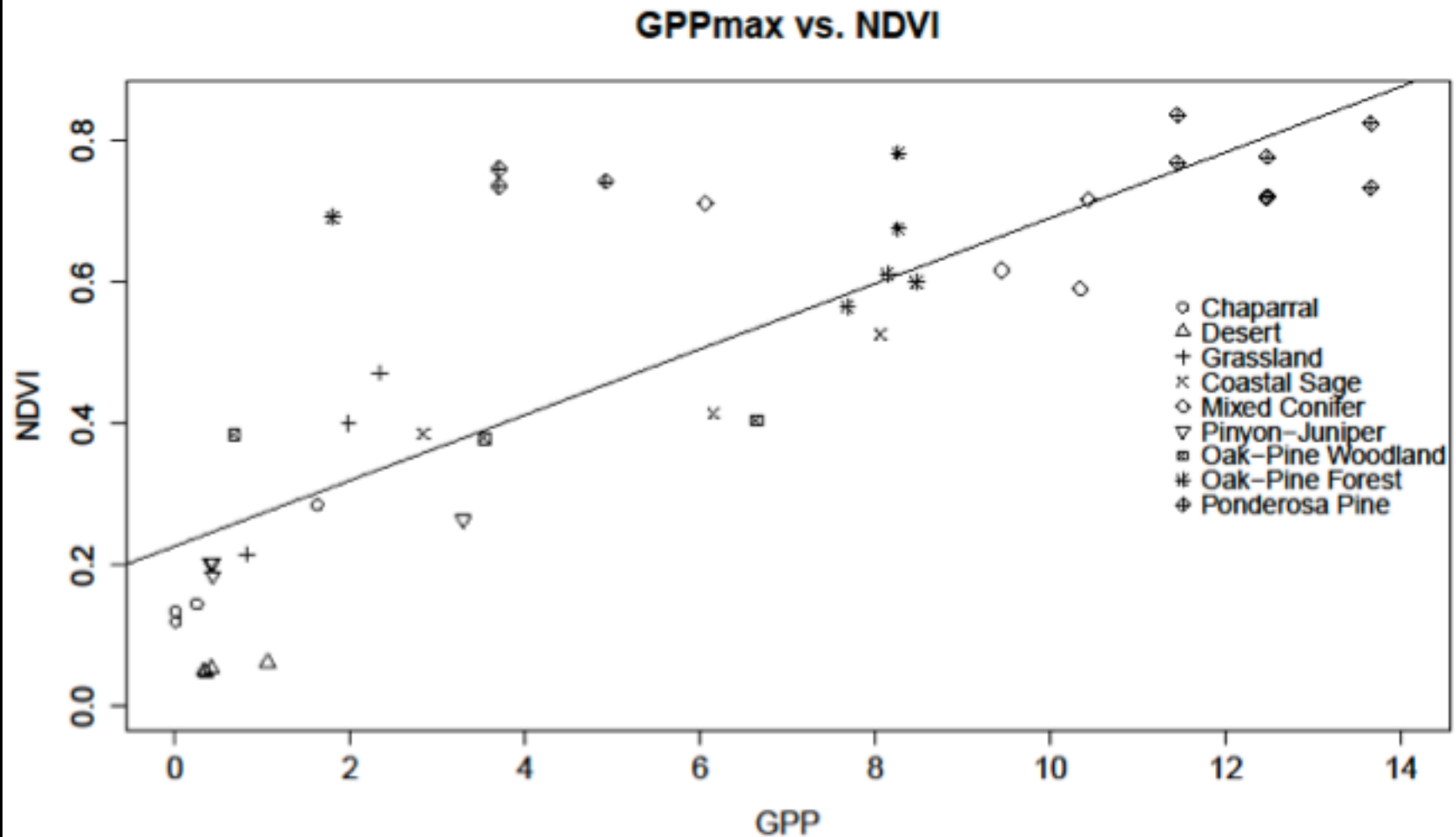
Didn't remote sensing solve the problem?





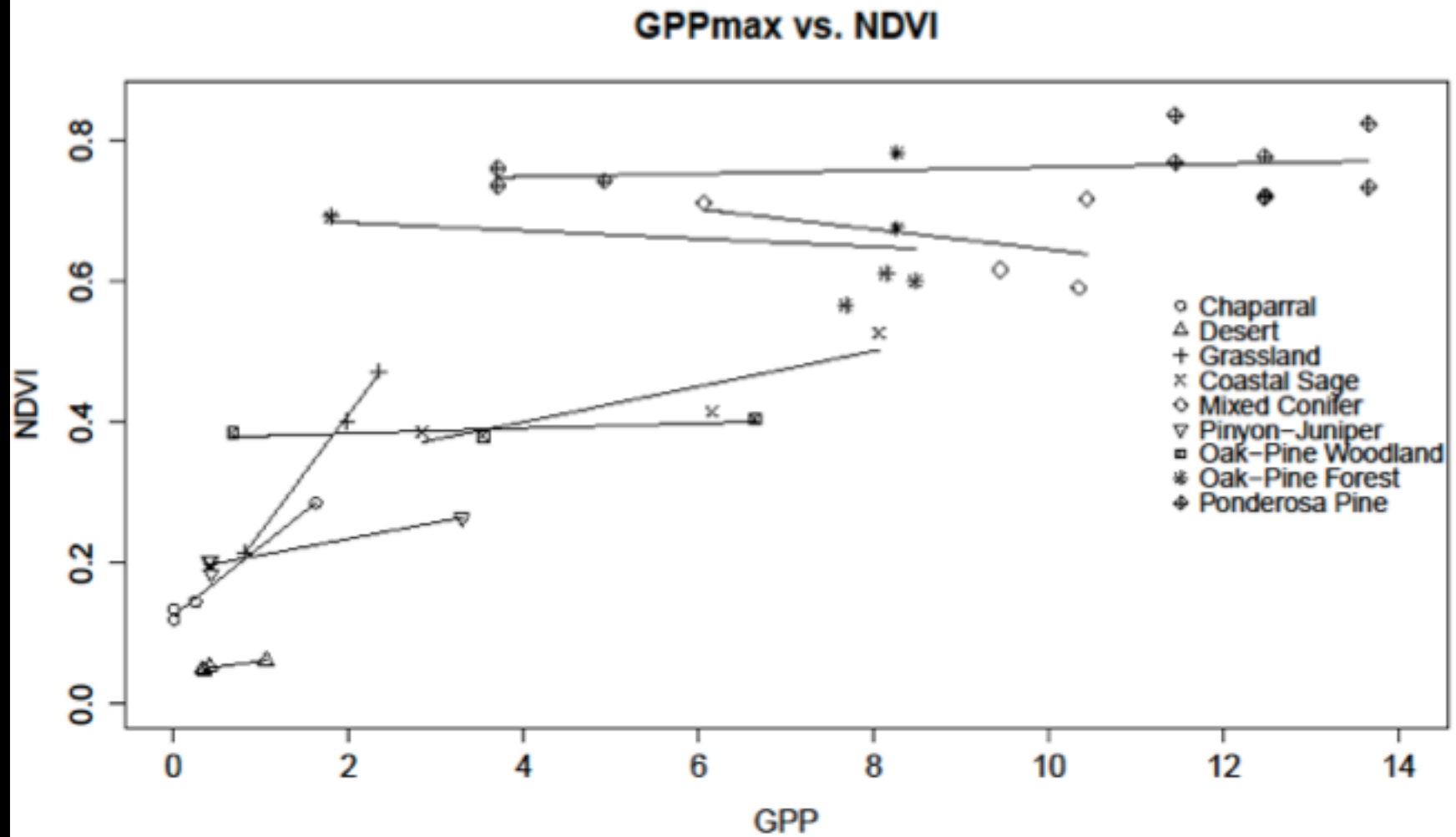
NASA HYSPRI campaign
Ecosystem scaling: Townsend, Kruger, Desai

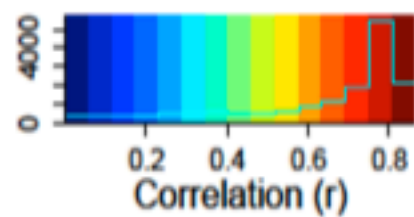
Maybe?



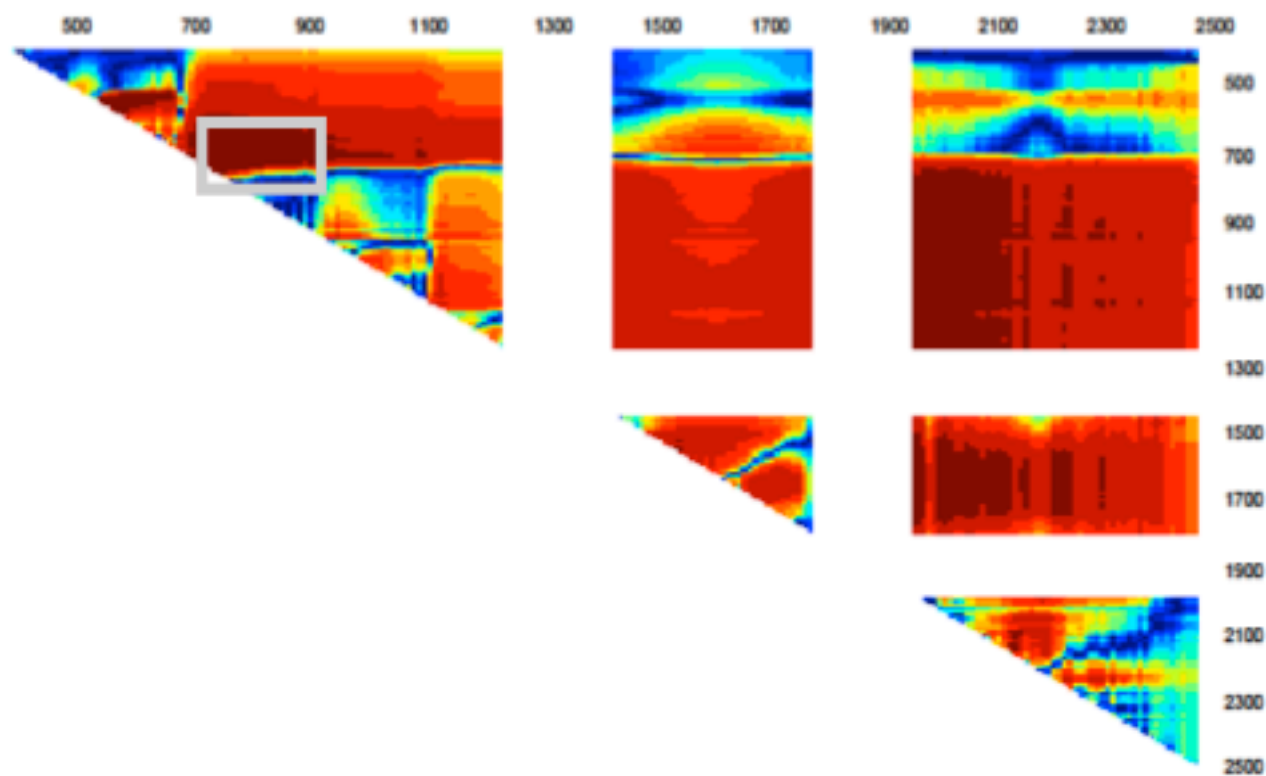
S. Dubois, MS thesis

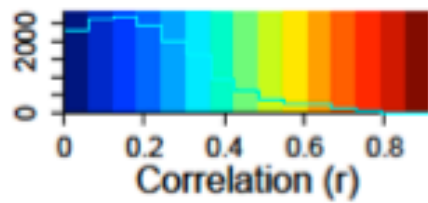
Maybe not?



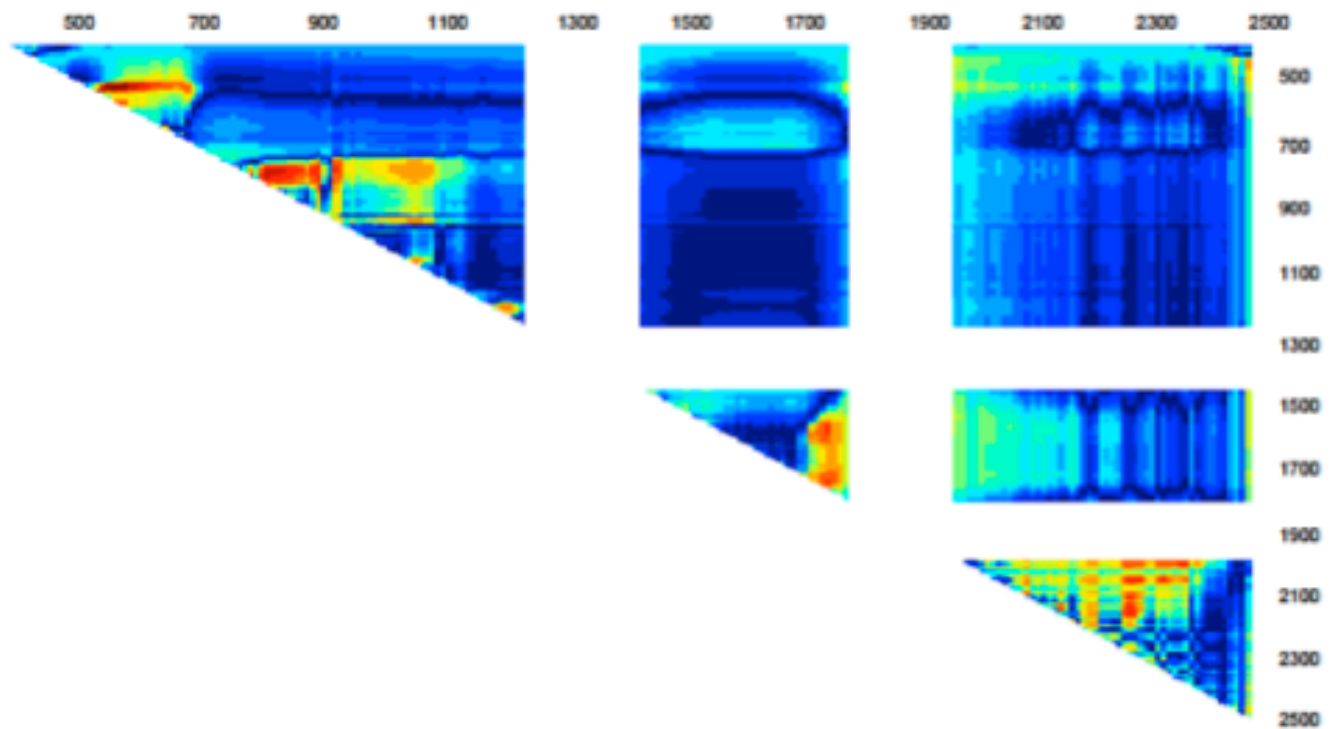


GPPmax vs NDSI





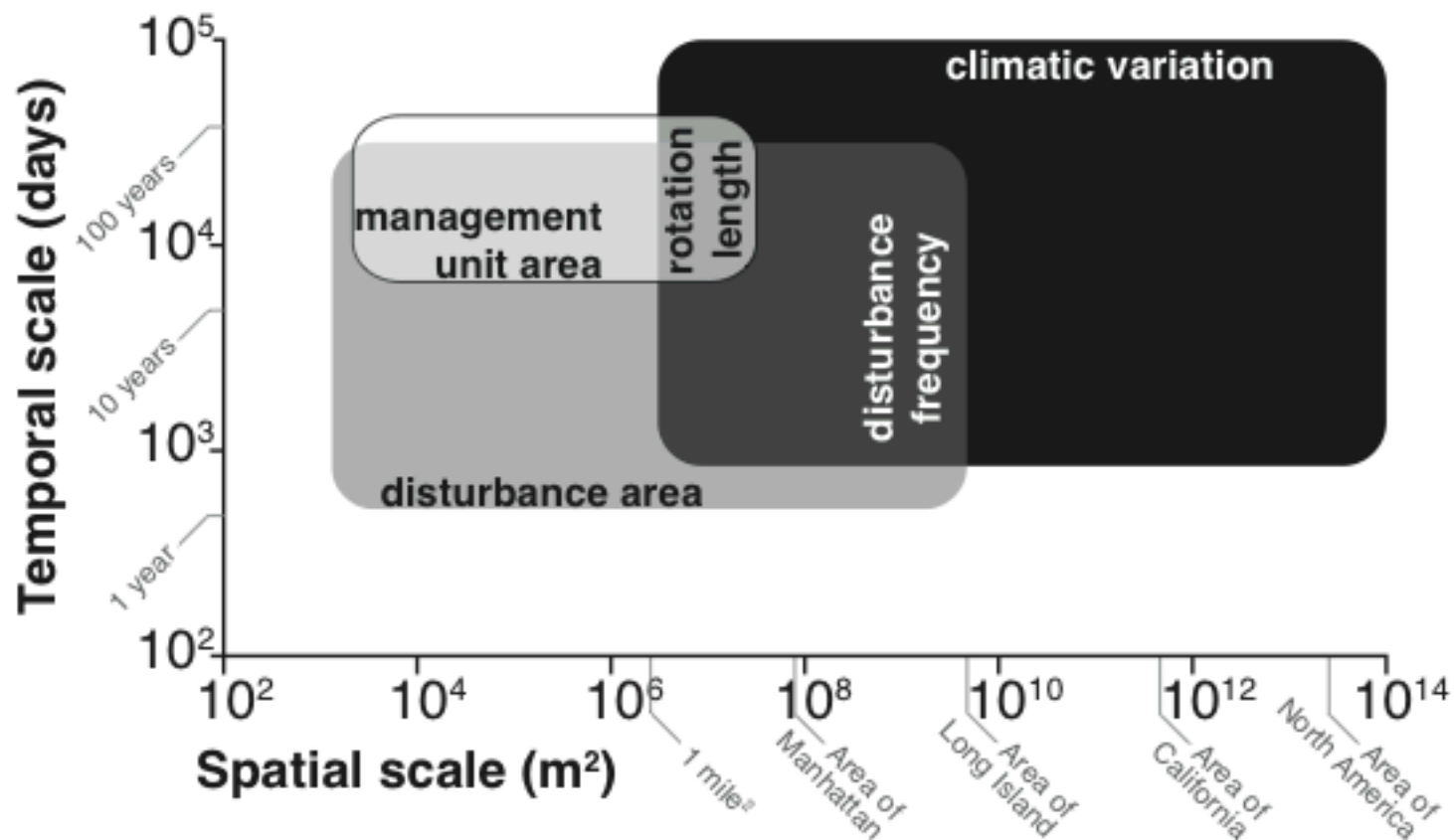
GPPmax vs NDSI



It gets weirder once we put in humans

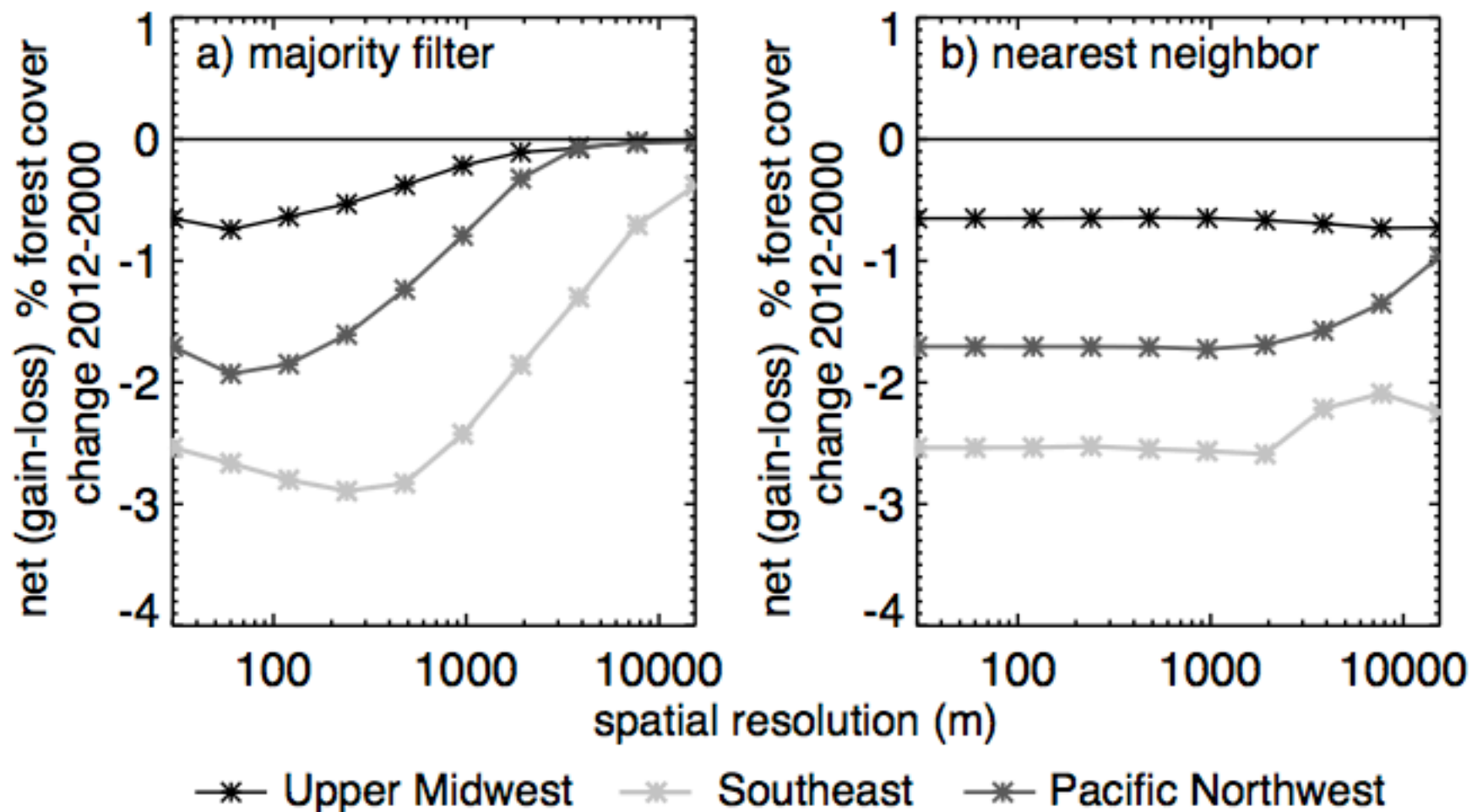


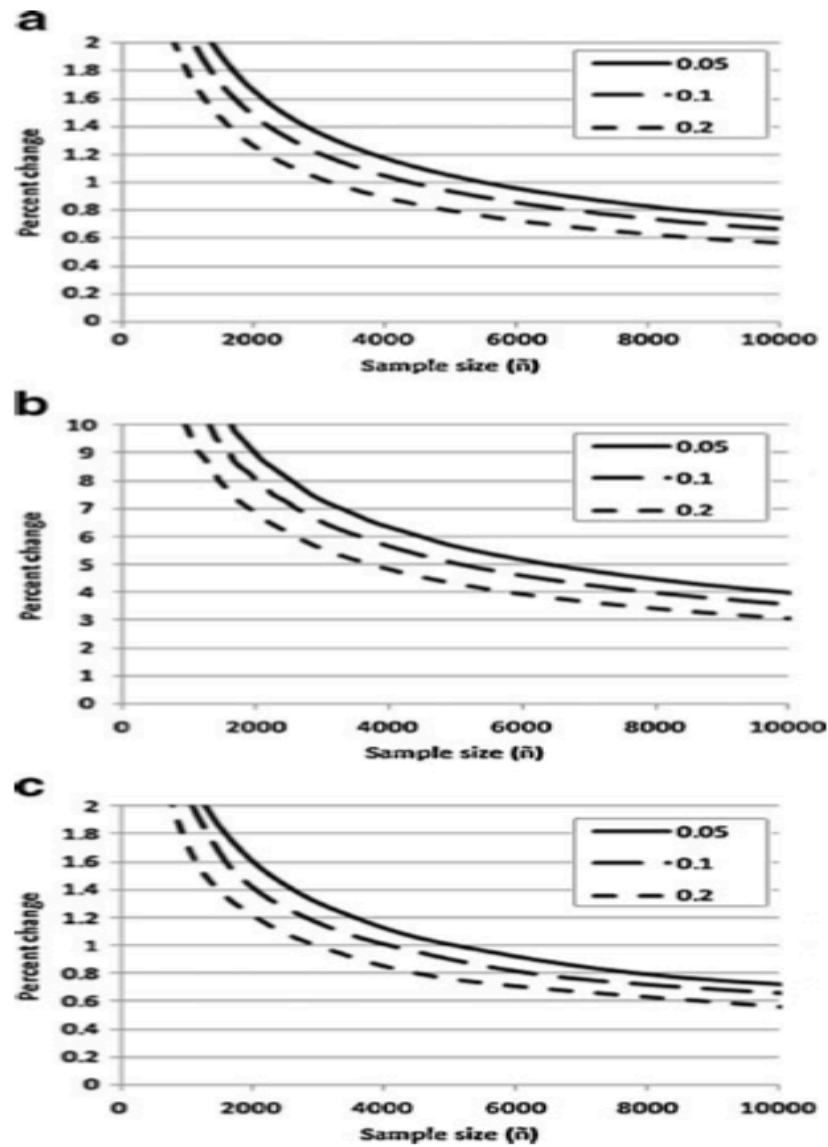
Virtually all the world's forests are managed, at scales quite different from climate and disturbance



Becknell et al., Bioscience, in press

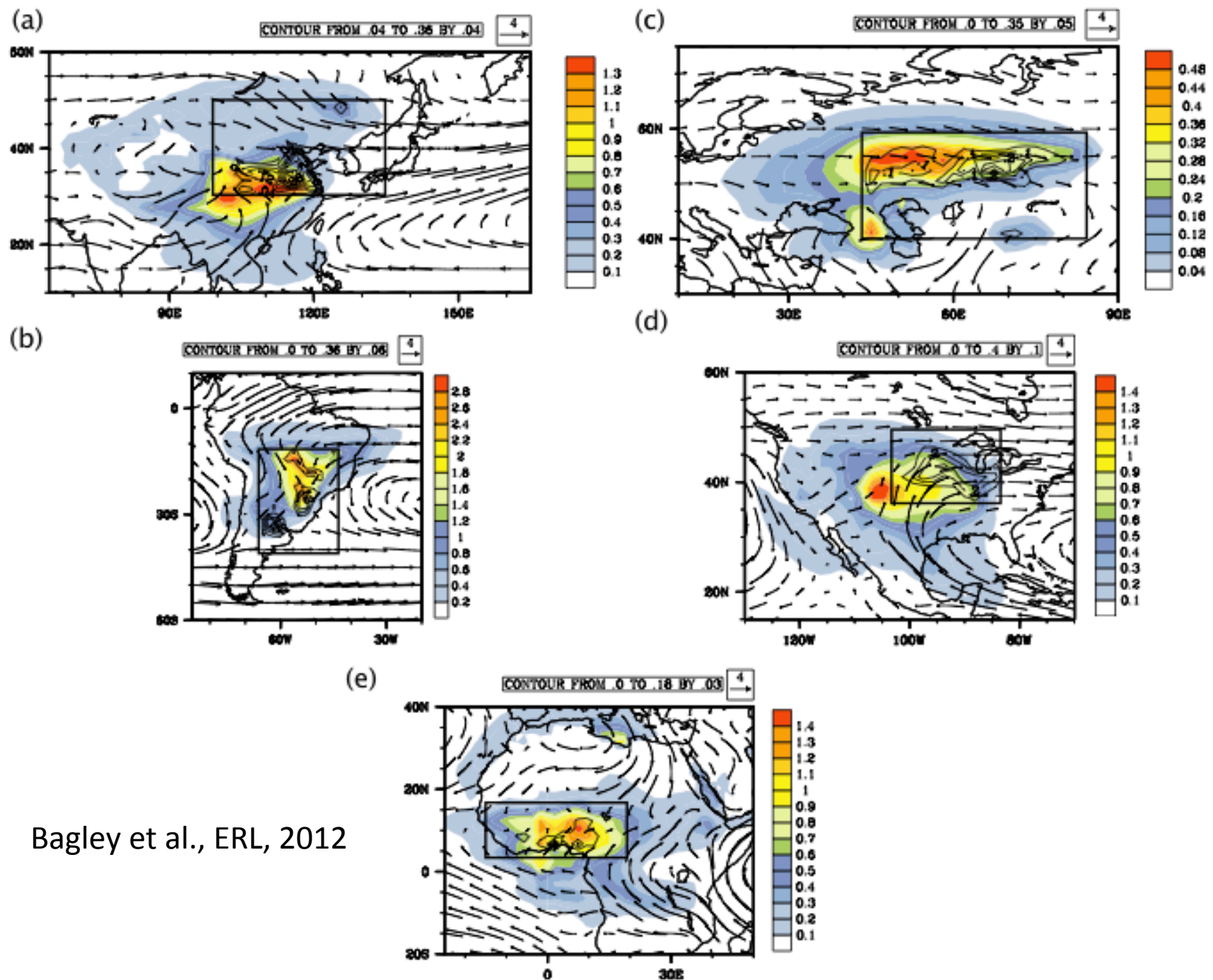
The scale and method we monitor land use matters





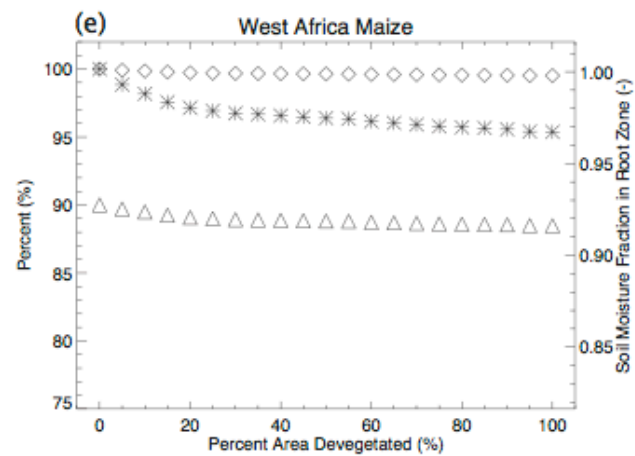
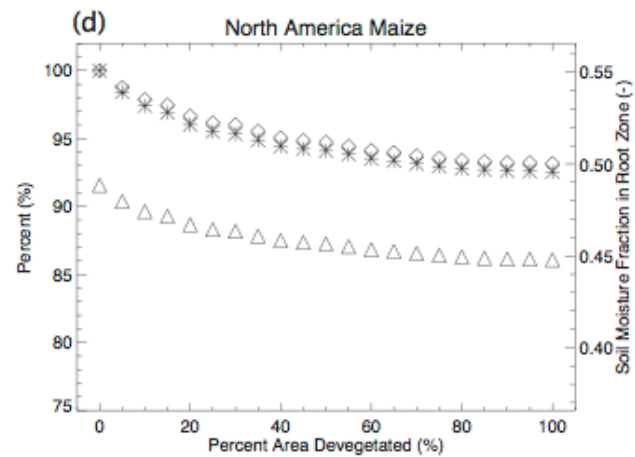
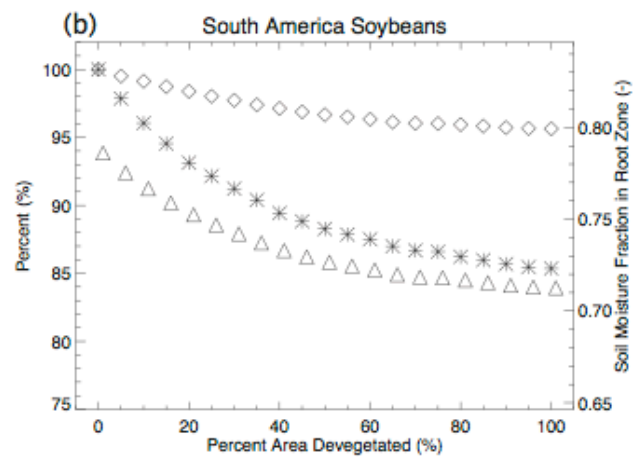
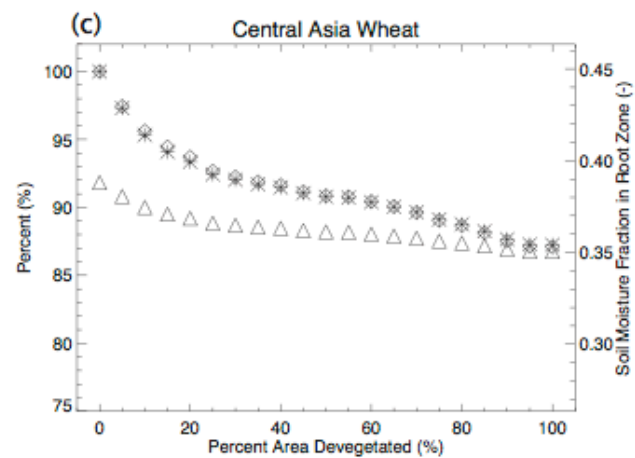
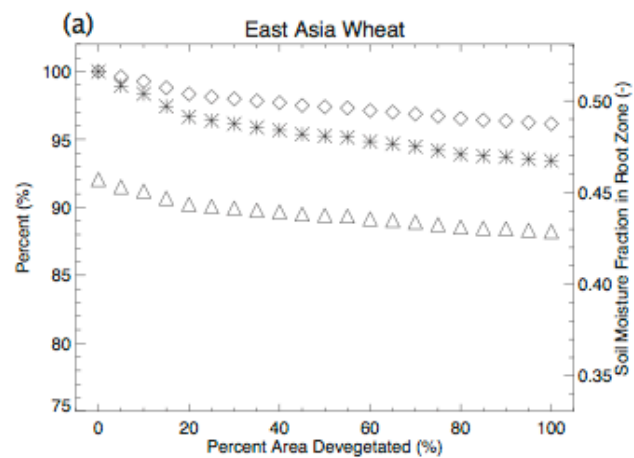
Does the atmosphere care?



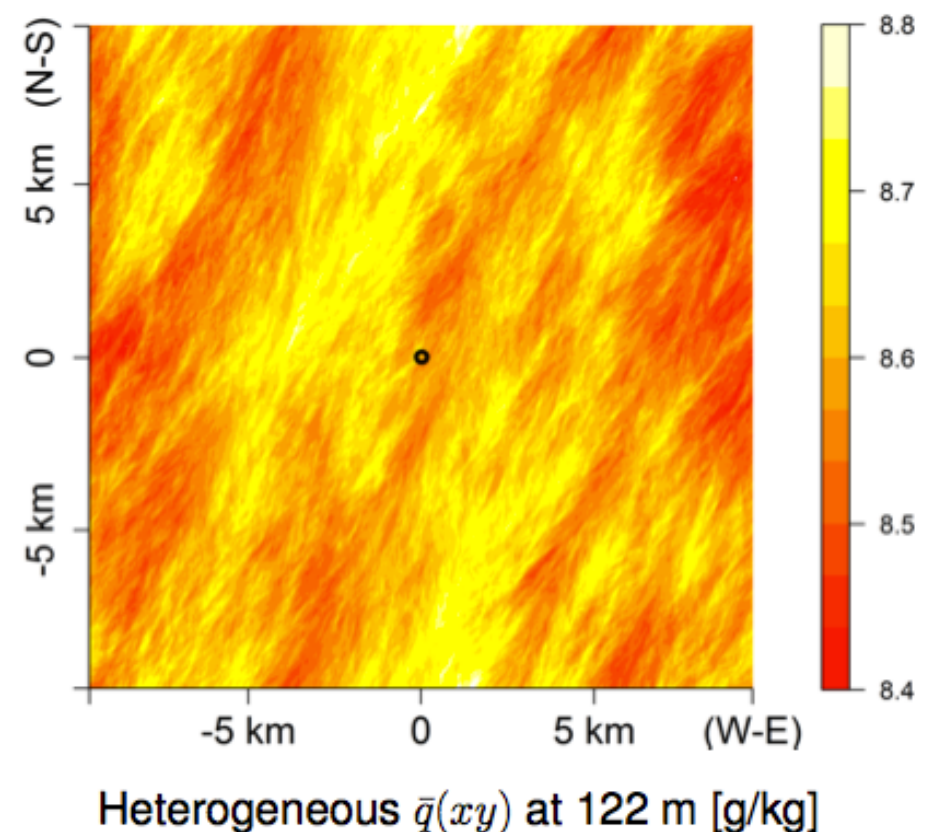
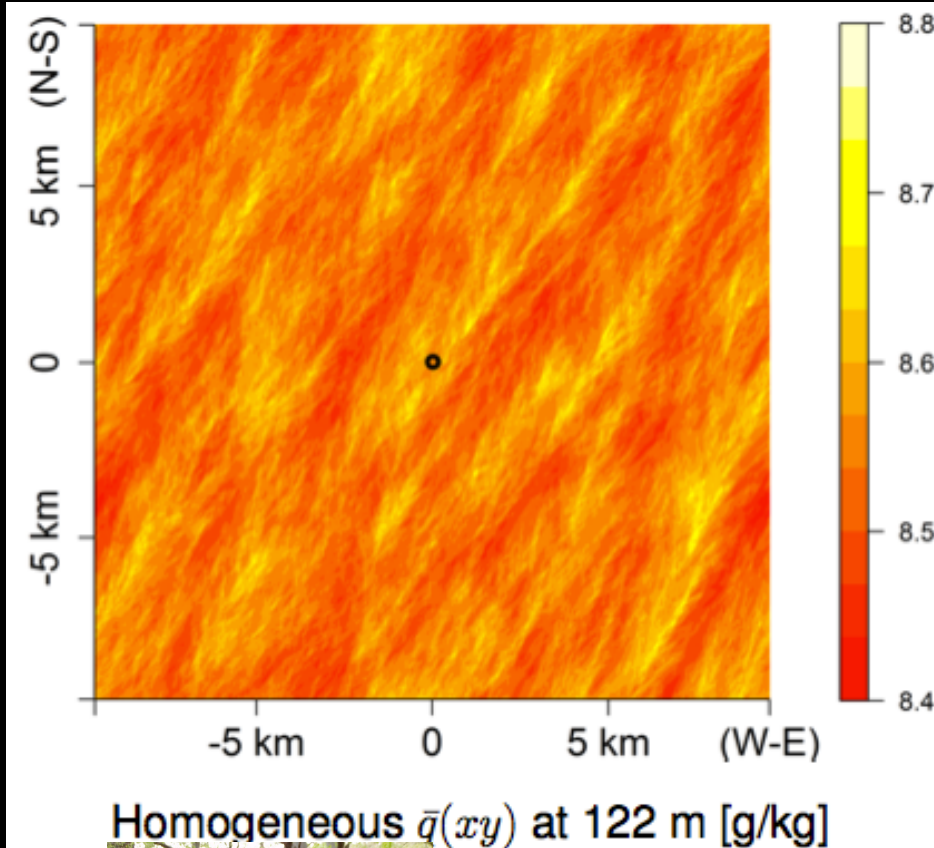


Bagley et al., ERL, 2012

Figure 3. Representative regions (from $U \cdot Q = -2$) of some sampling regions of each region during its sampling season as defined by the

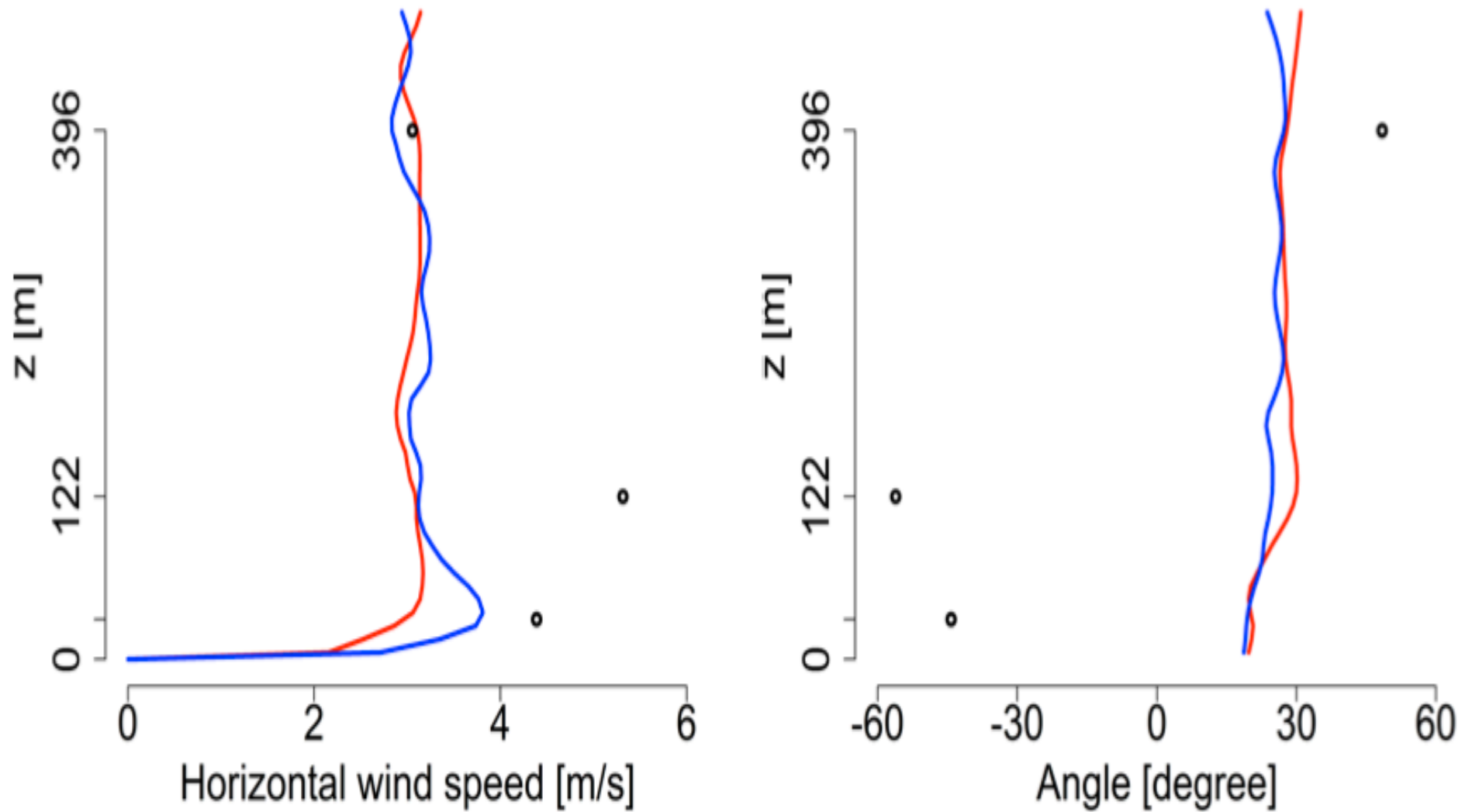


LES simulations around the tall tower show shifts in organized structures with heterogeneity of surface forcing



Frederick deRoo (KIT IMK-IFU), TERRENO

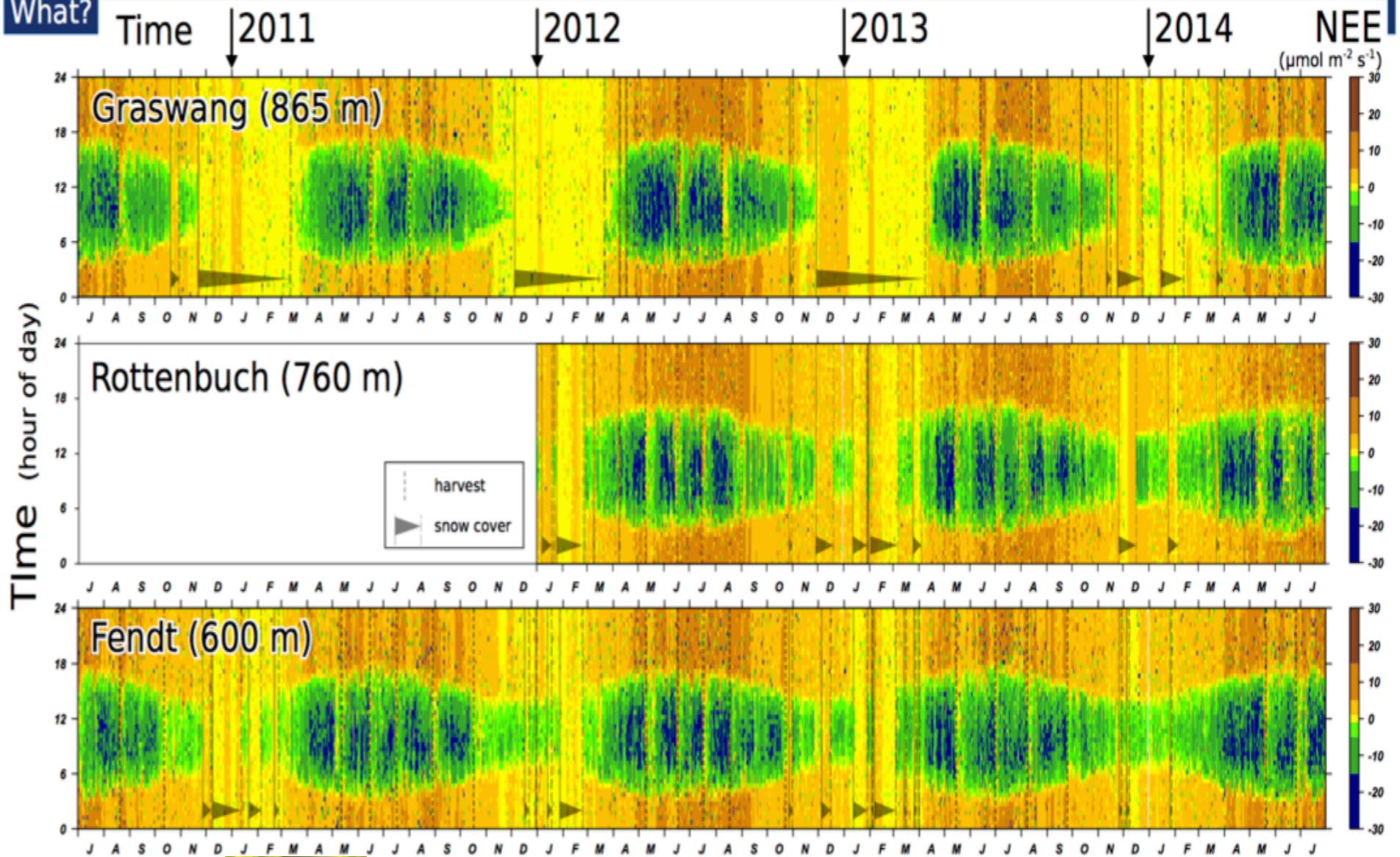
But it's tricky to model well



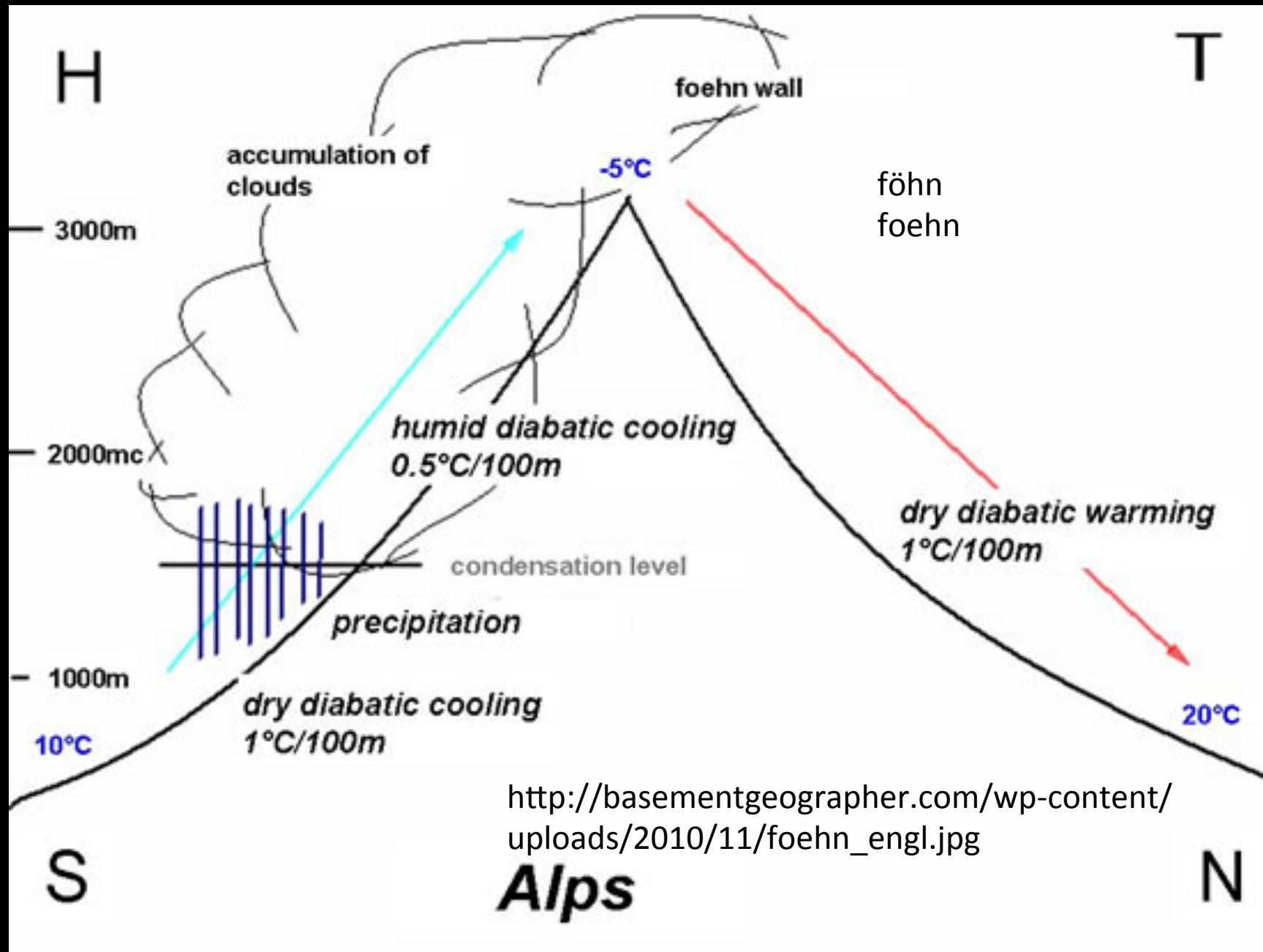
What scale does climate change intersect with ecosystems?



What?



M. Zeeman et al., TERRENO



ORF T

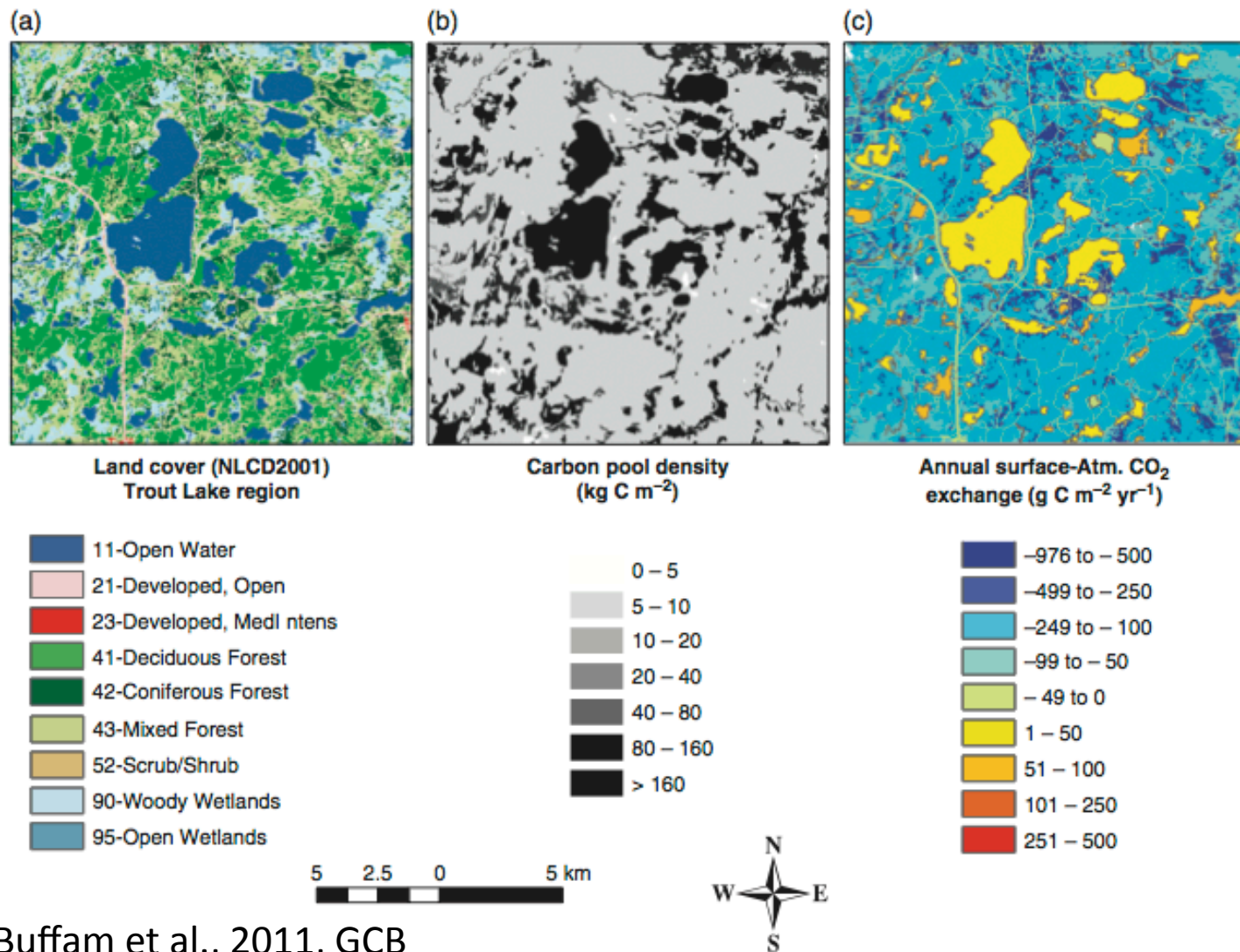
Erhard Berger vom Patscherkofel

T WETTER

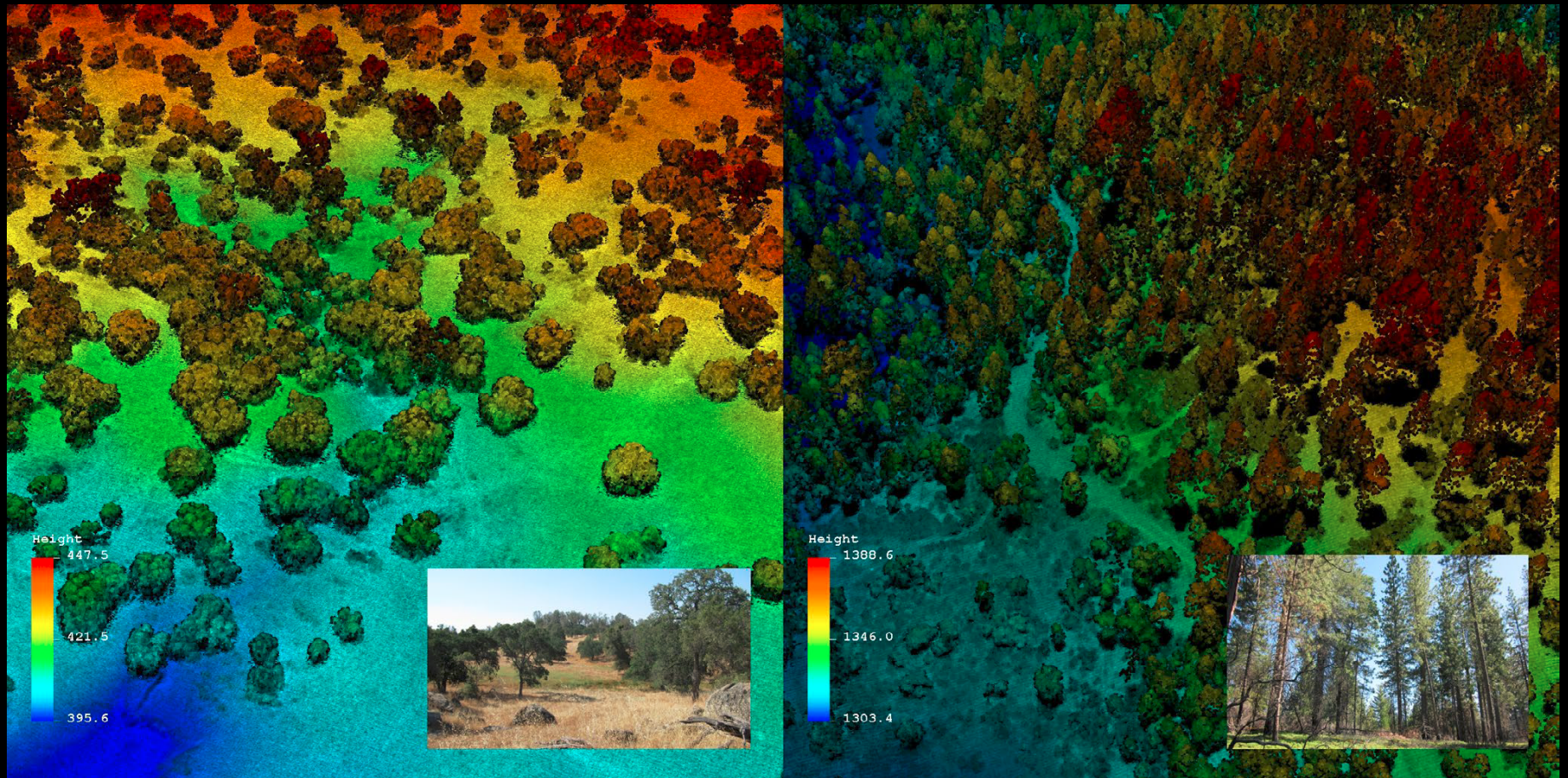
What are we trying to do about it?



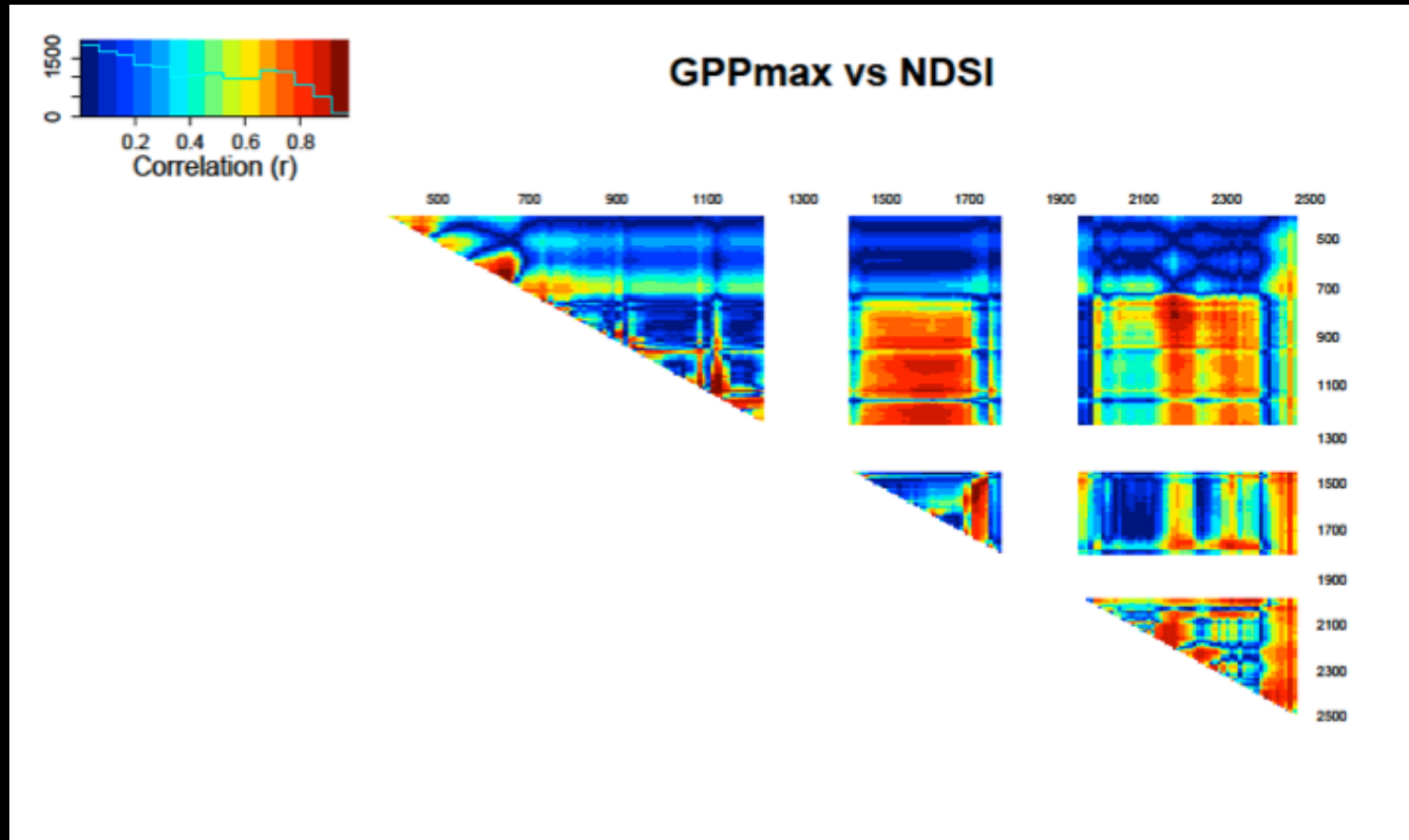
1. Be smarter about scaling



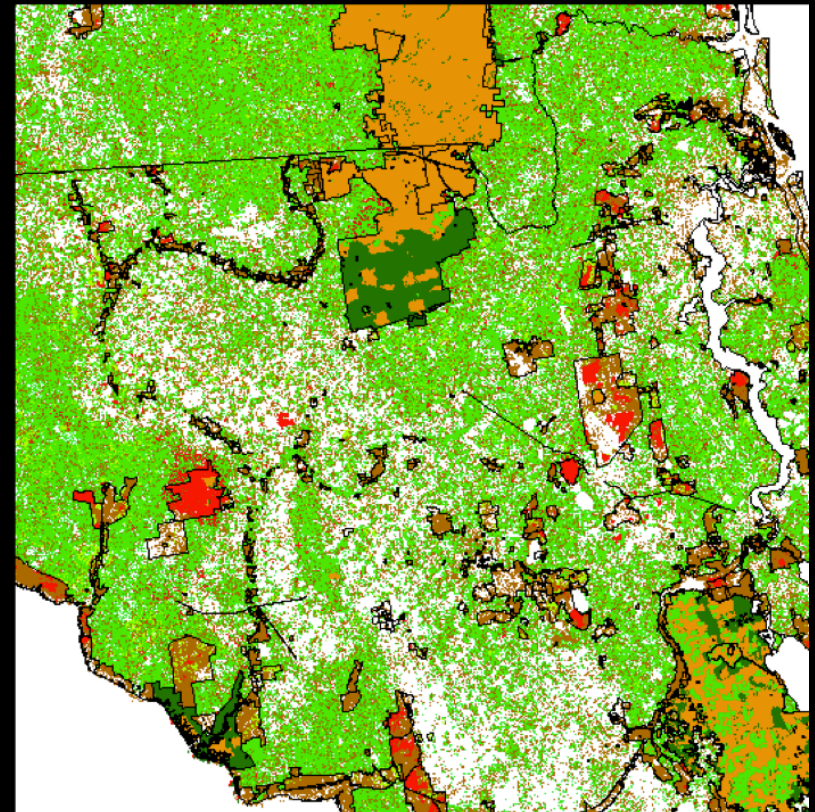
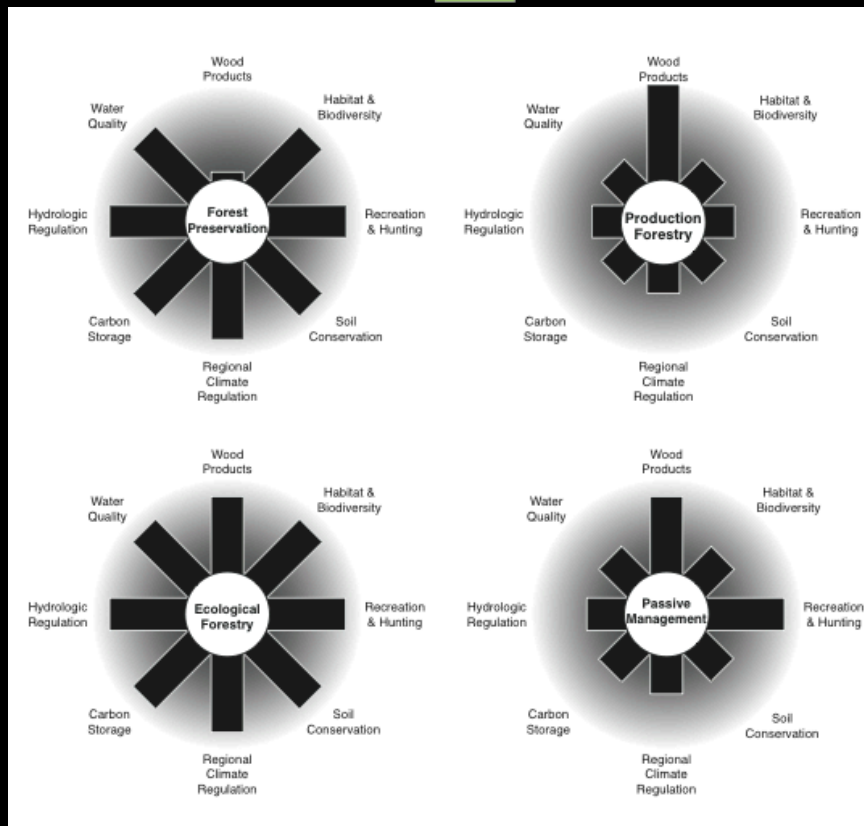
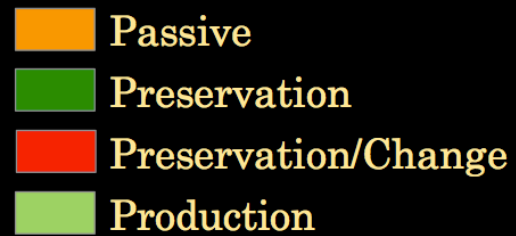
2. Be big data



3. Find the appropriate scale

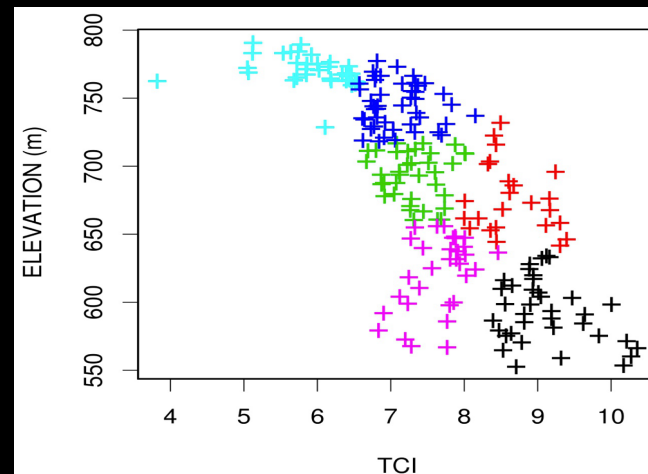
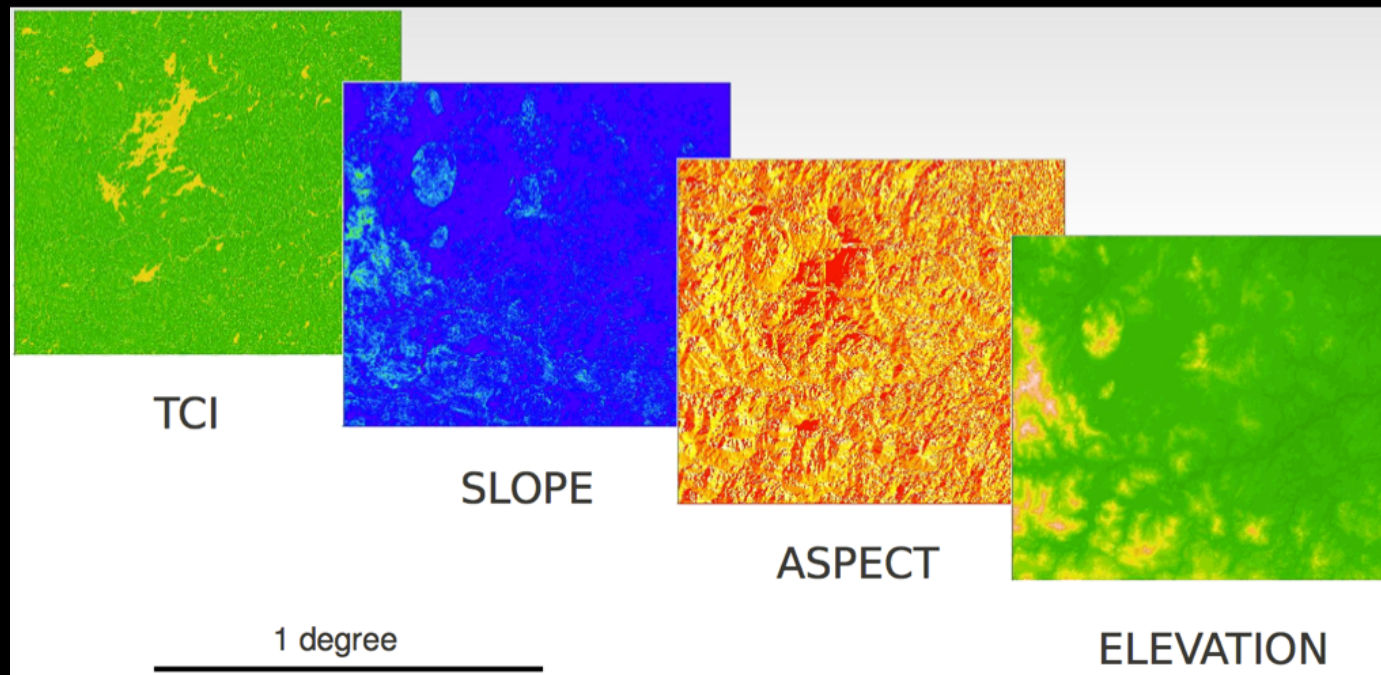


4. Map human impacts like ecosystems



MANDIFORE
Macrosystems Biology

5. Capture the statistics of heterogeneity



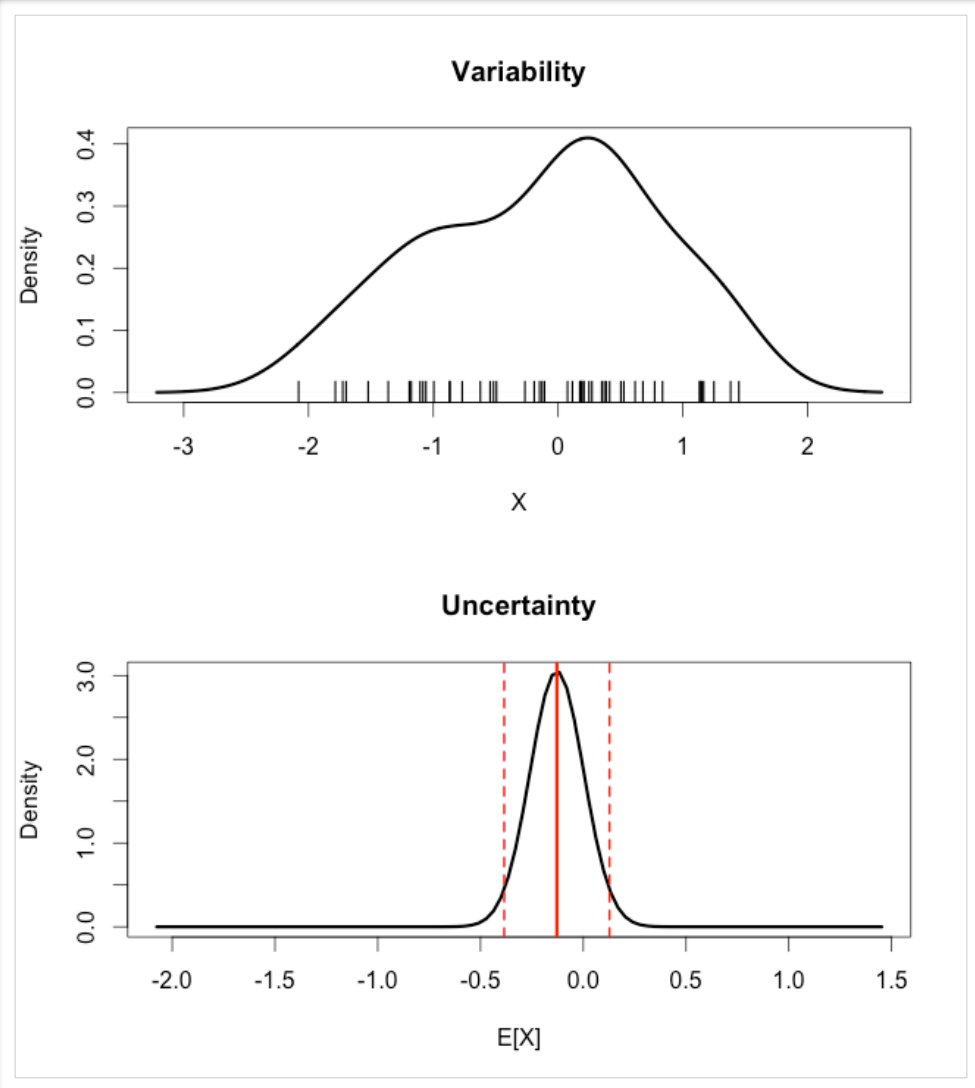
M.C. Dietze, ED2 model

6. Partition uncertainty and variability in land surface models

Variability

describes the process

can be better characterized
but doesn't decrease



Uncertainty

describes our ignorance

decreases asymptotically

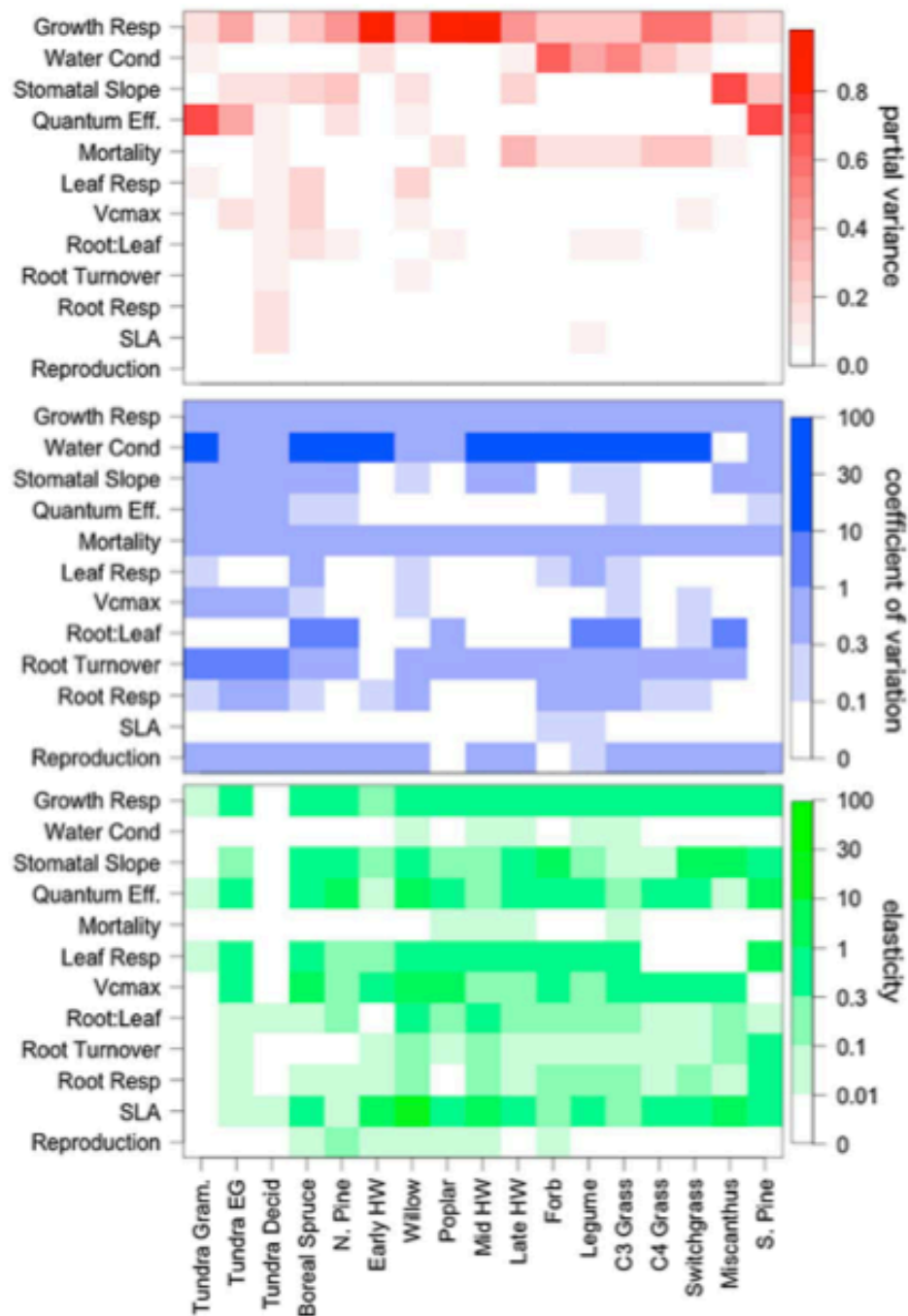


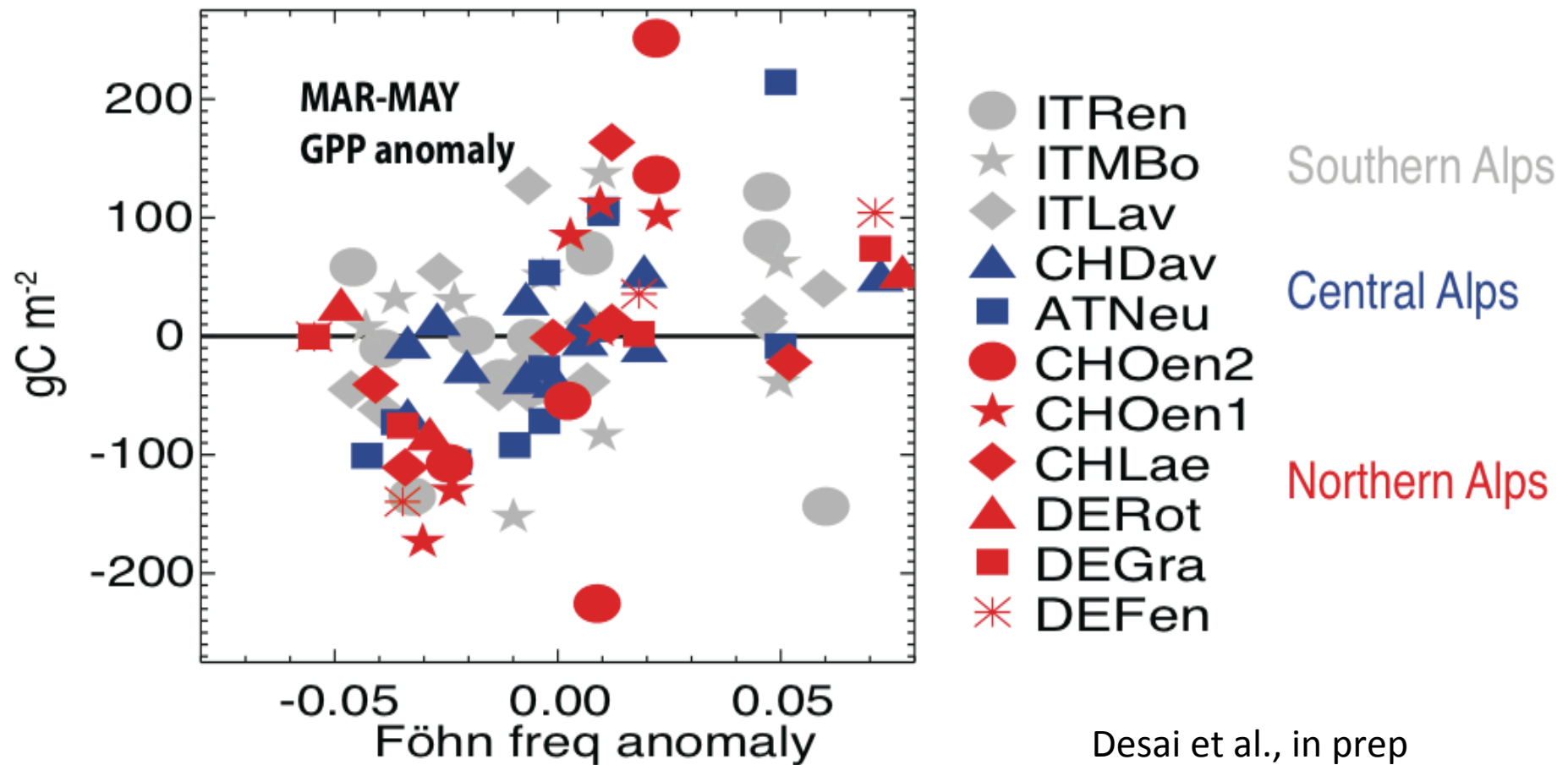
Table 3. Plant Functional Types

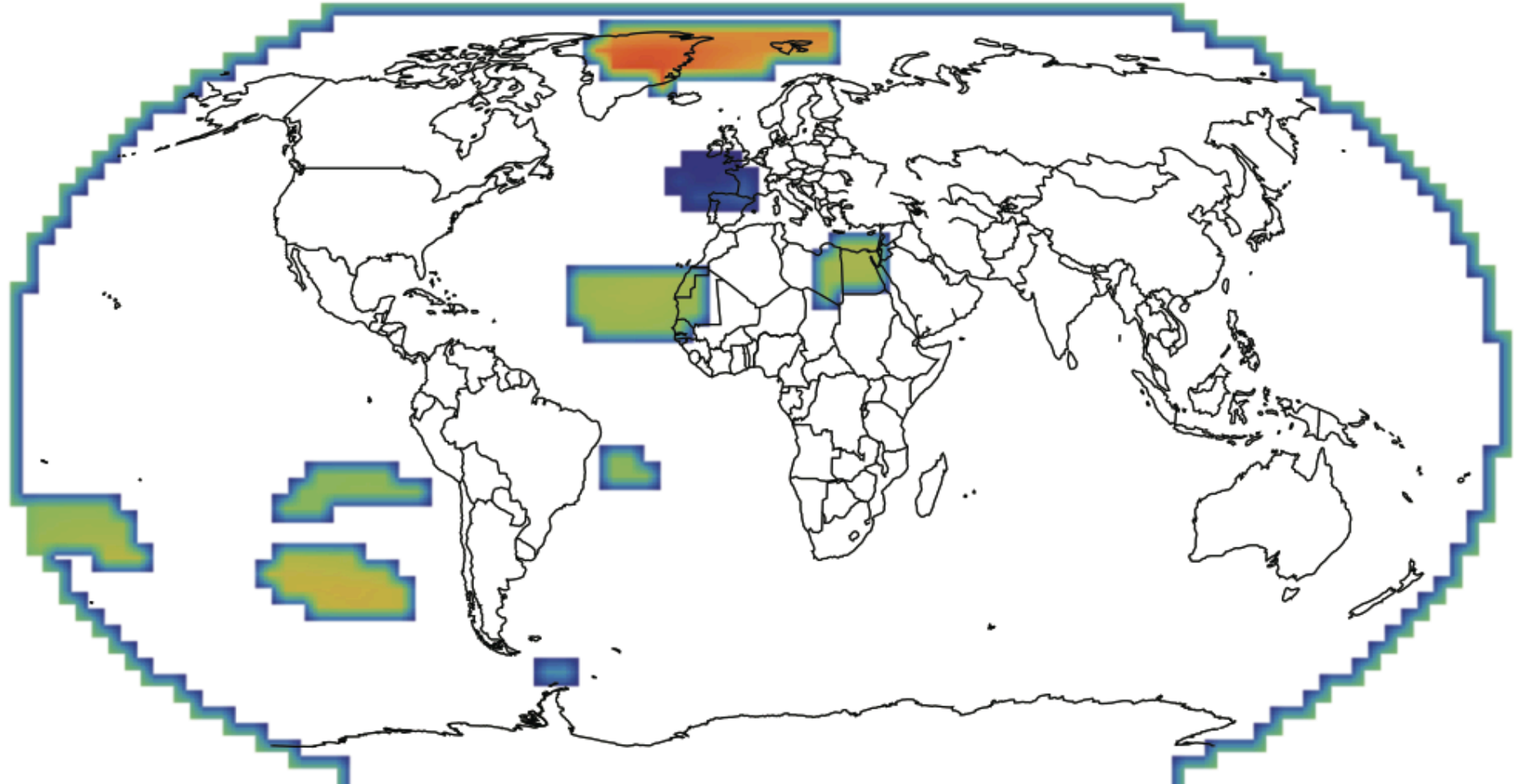
Biome	PFT	Site
Tundra	Graminoid	Toolik
	Evergreen Shrub	Toolik
	Deciduous Shrub	Toolik
Boreal	Spruce	BOREAS
Temperate forest	Early Successional	WLEF
	Hardwood	Rhineland
	Poplar	Tully
	Willow	WLEF
	Midsuccessional	WLEF
	Hardwood	WLEF
	Late Successional	WLEF
	Hardwood	WLEF
	Northern Pine	US-NC2
	Southern Pine	US-NC2
Temperate grassland	Forb	EBI Farm
	Legume	EBI Farm
	C3 Grass	EBI Farm
	C4 Grass	EBI Farm
	Switchgrass	EBI Farm
	Miscanthus	EBI Farm
		EBI Farm

Pecanproject.org

Dietze et al., 2014, JGR-G

7. Focus on modes of atmospheric variability beyond mean climate





Significant change in 500 hPa geopotential height (meters)

NOVEMBER 1 - MARCH 31



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

**In-situ measurement of
turbulence statistics and
meteorological drivers**

**High-resolution turbulent
exchange “response” from
time-frequency analysis**

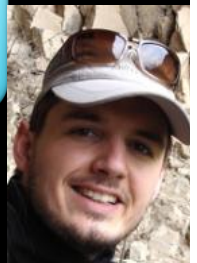
**Environmental
response function**

**Extraction of relationships
from machine learning**

**Biophysical land surface drivers
from footprint modelling**



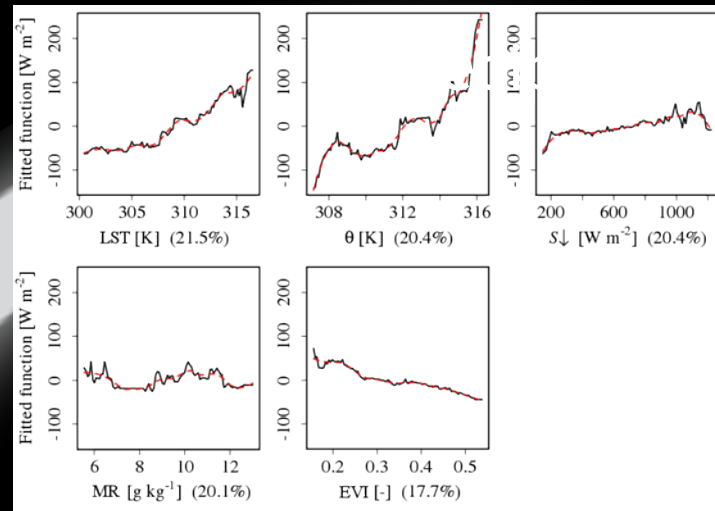
Ke Xu, UW and Stefan Metzger, NEON



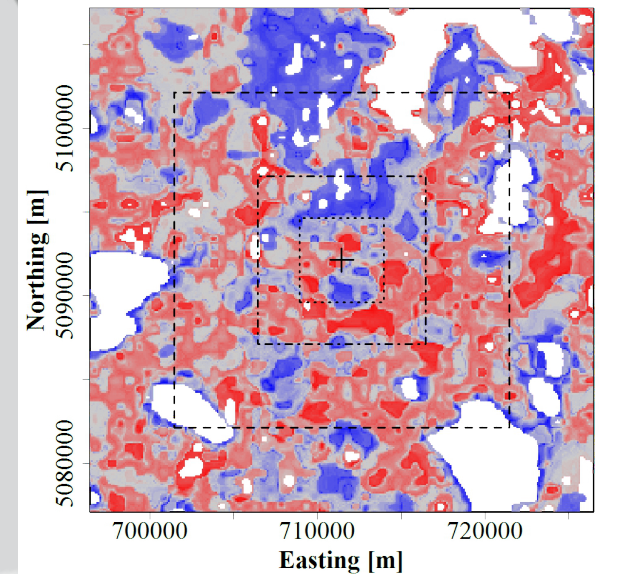
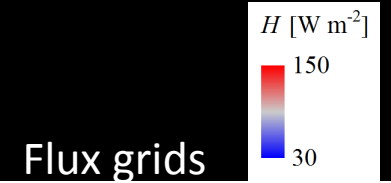


Ameriflux Park Falls 'very tall tower' (447 m):
Eddy flux at 122 m.

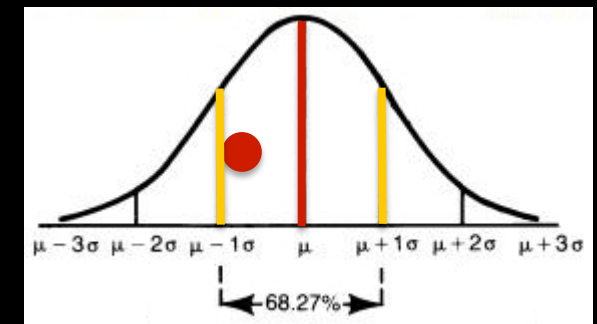
Credit: Matt Rydzik (U Wisconsin)



Environmental response functions

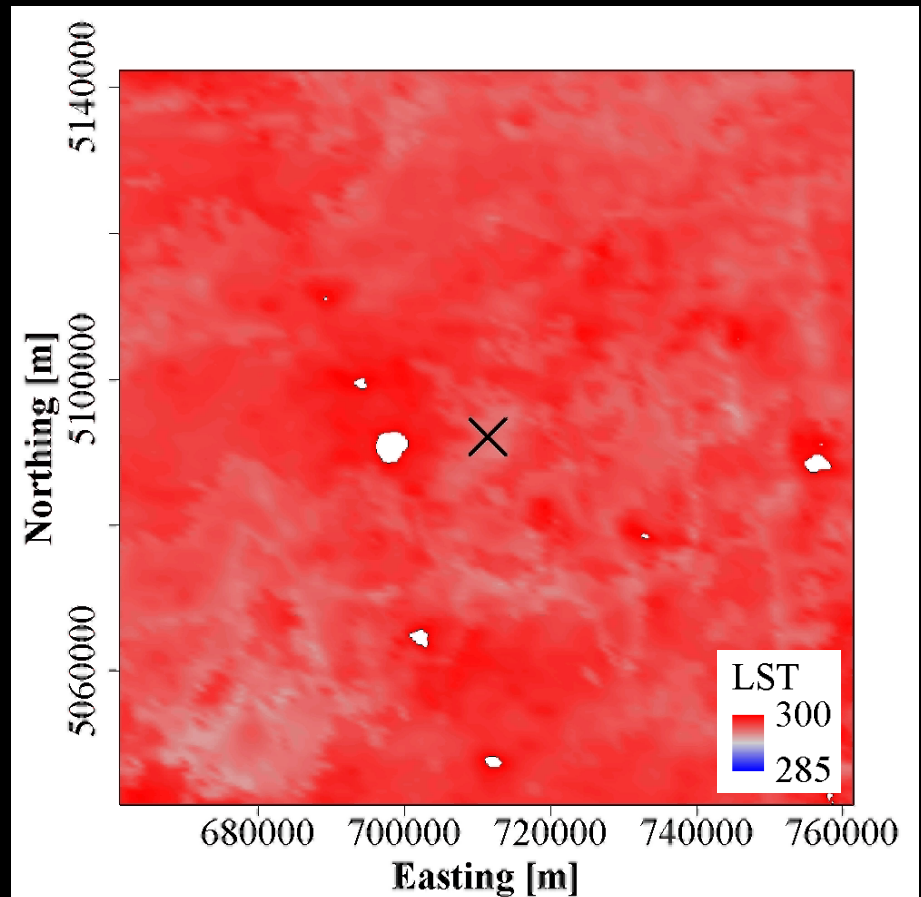
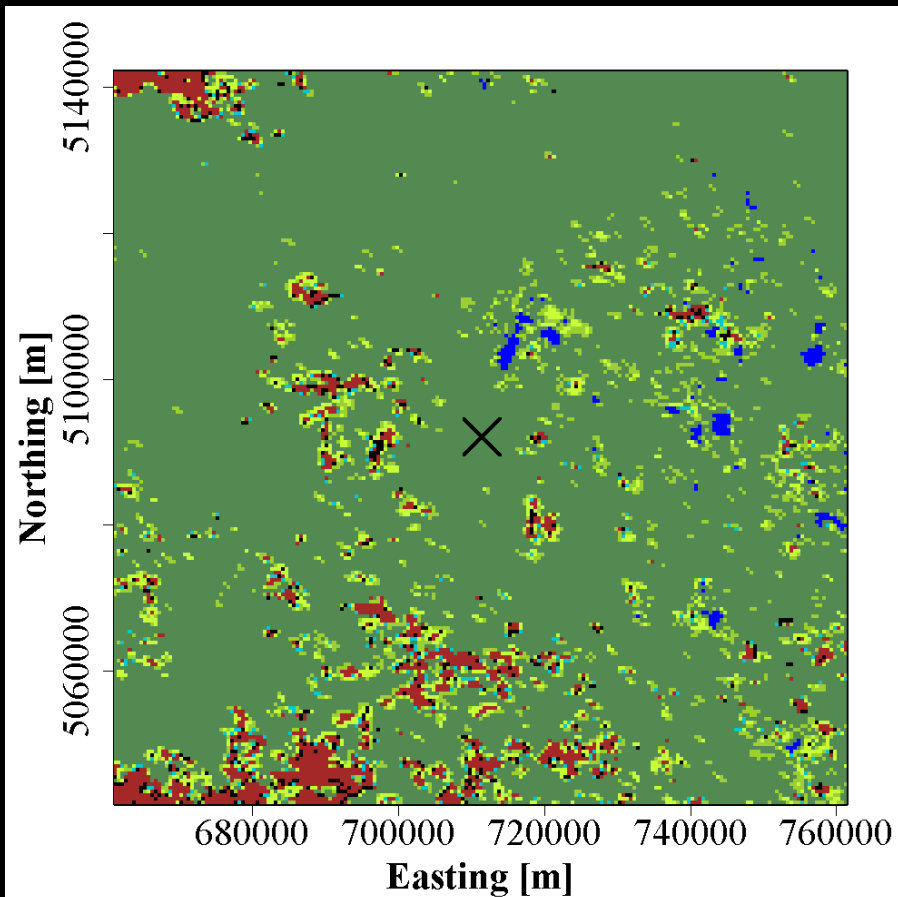


Before:

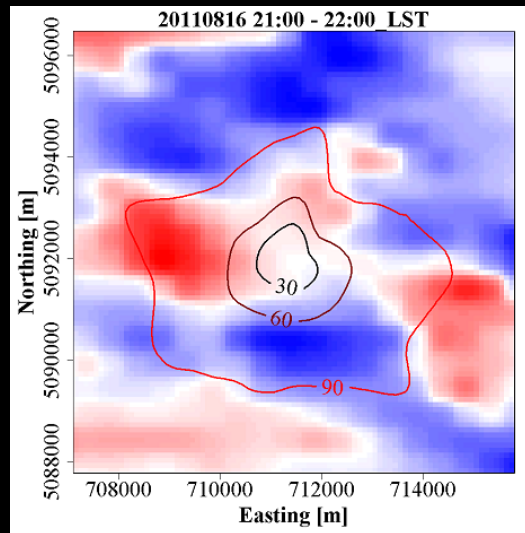


Park Falls/Chequamegon National Forest region

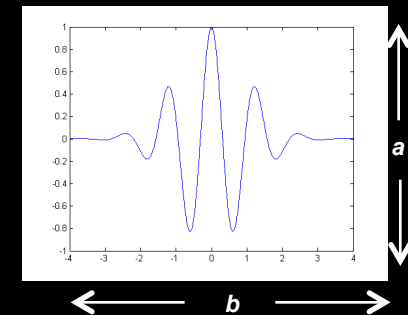
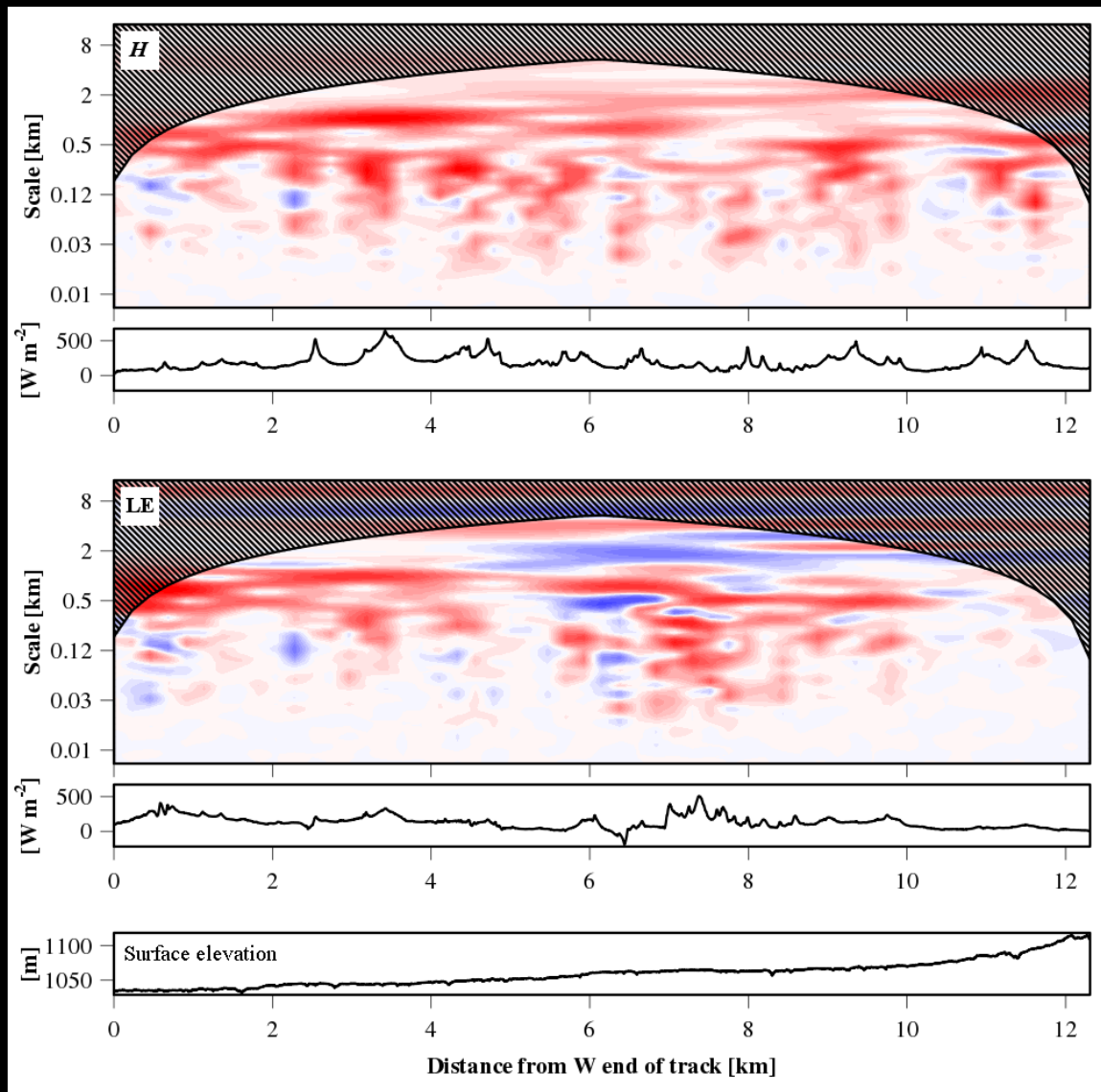
- Relative homogenous...
 - But biophysical properties transient in space and time!



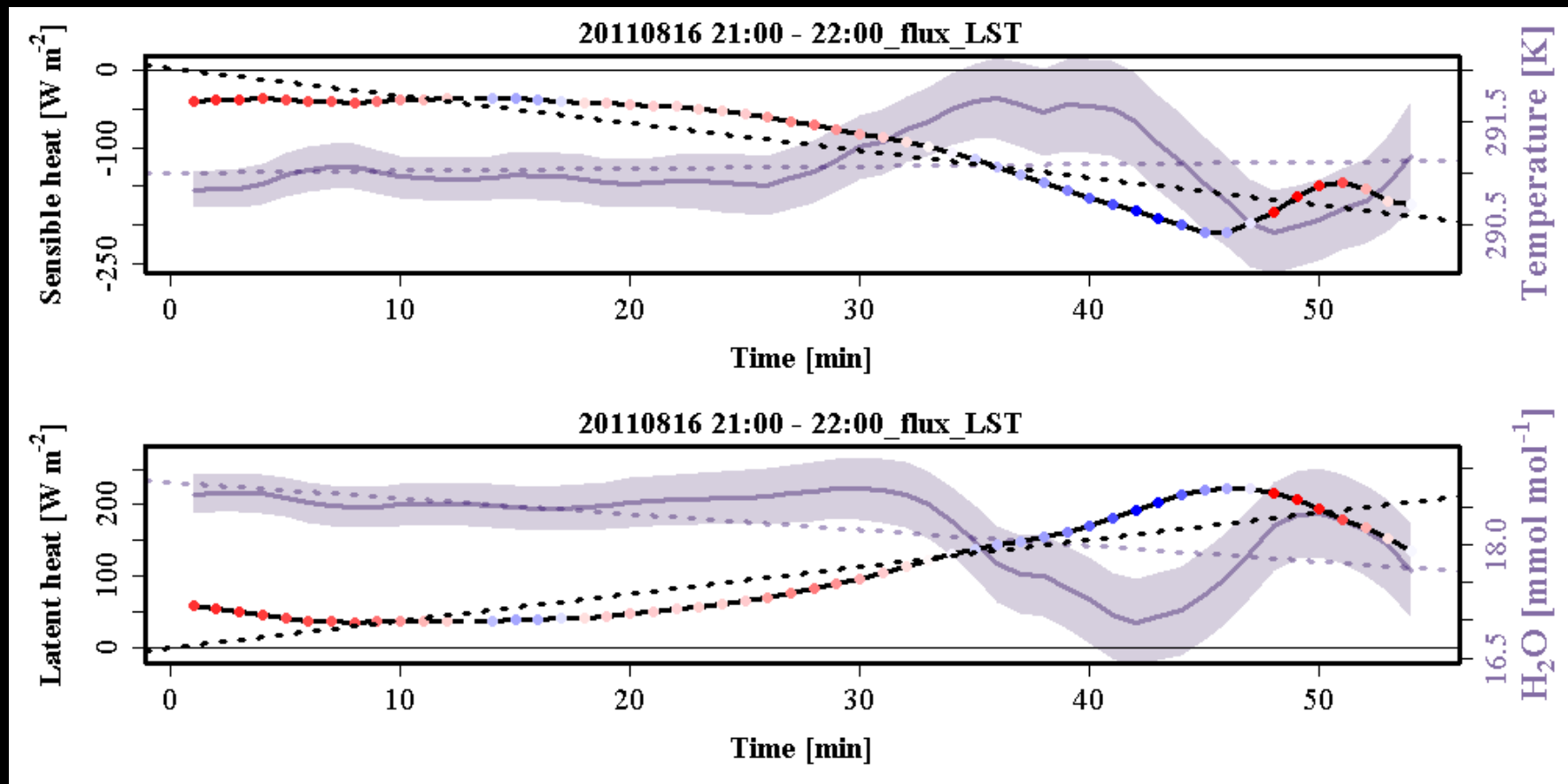
What does the tower flux measurement “see”?



Wavelet cross-scalogram



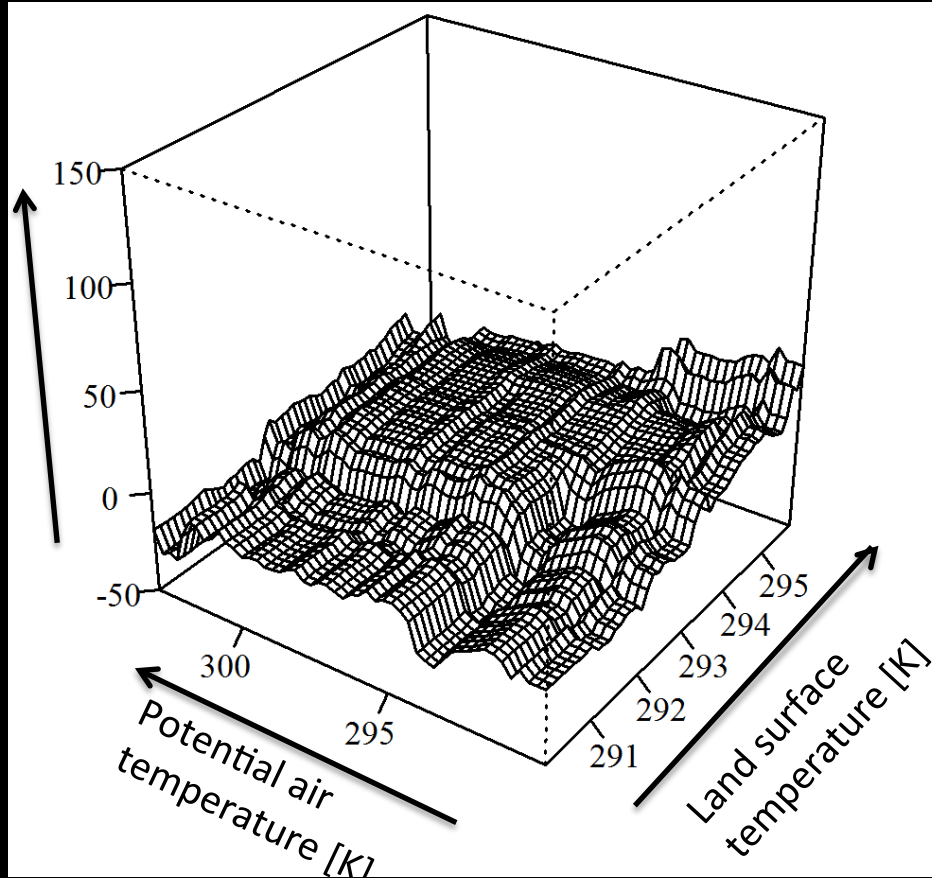
- ...Process attribution!



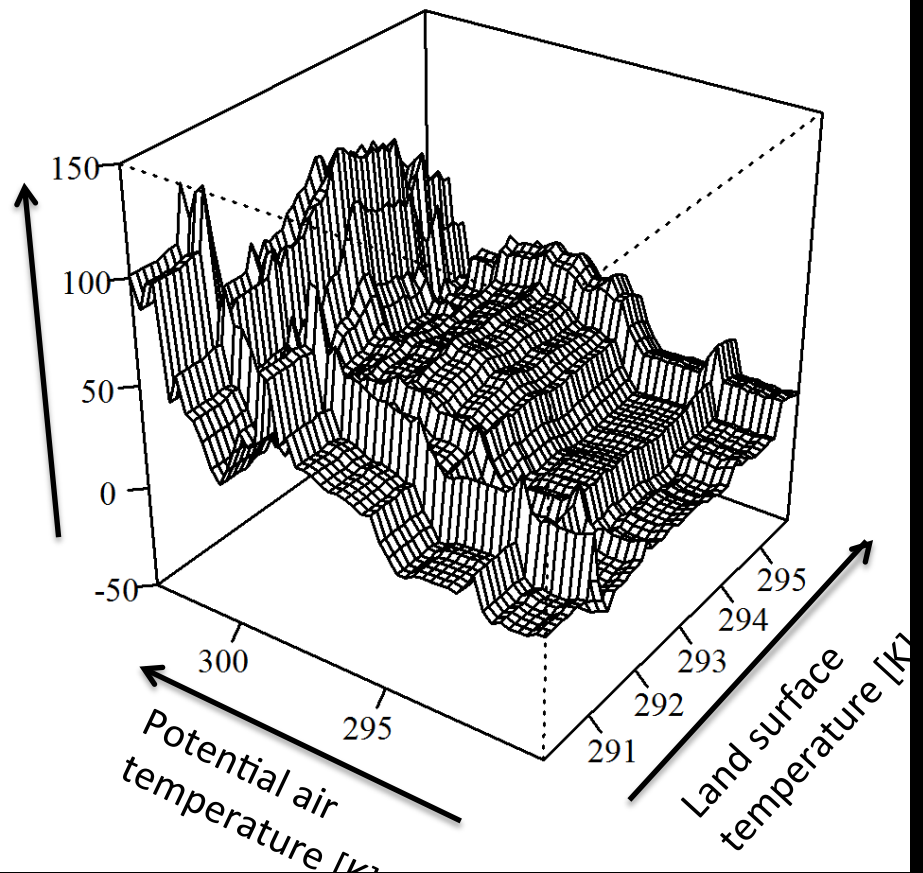
What does the tower flux measurement “see”?

- Multivariate responses of surface-atmosphere interactions!

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



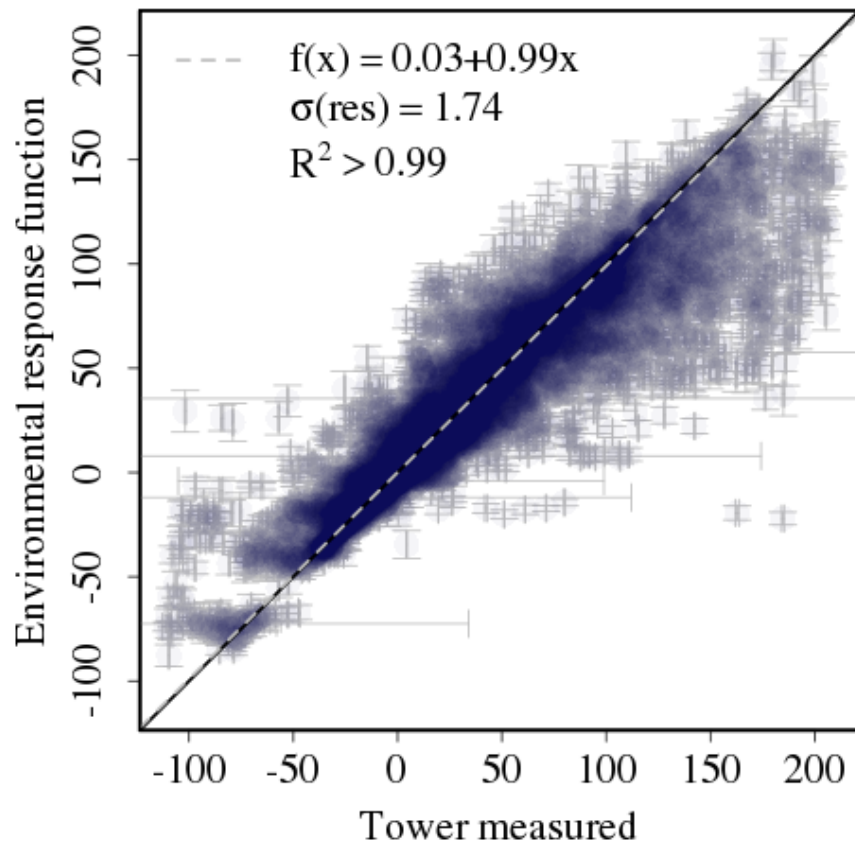
Latent heat flux [W m^{-2}]



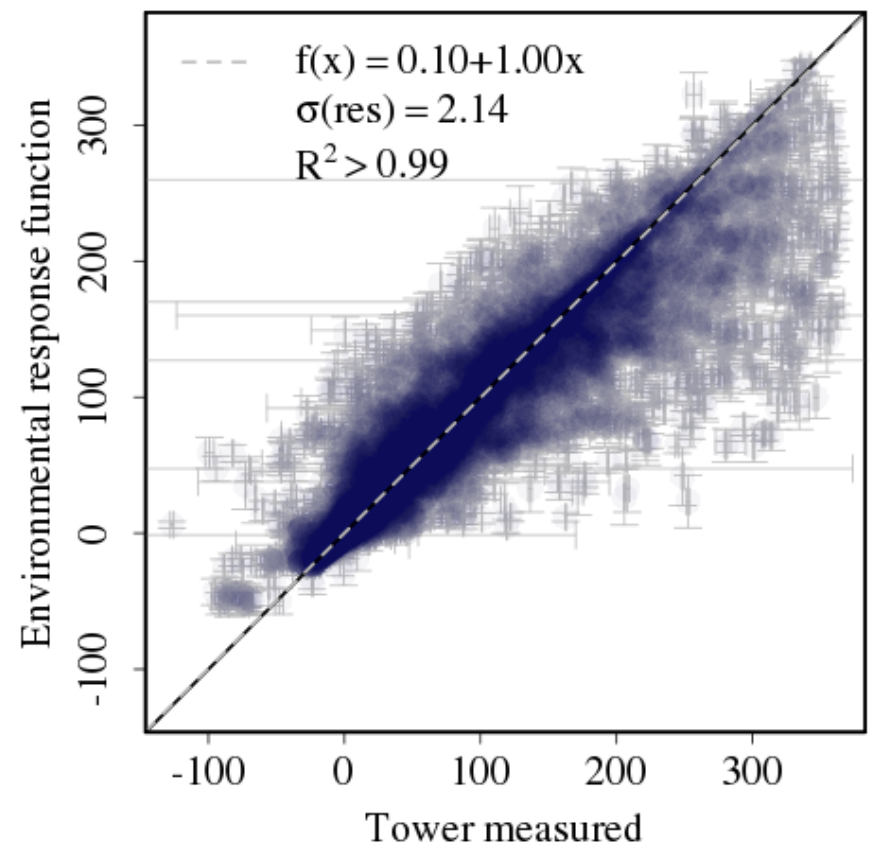
How do tower environmental response functions perform?

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

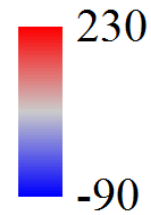
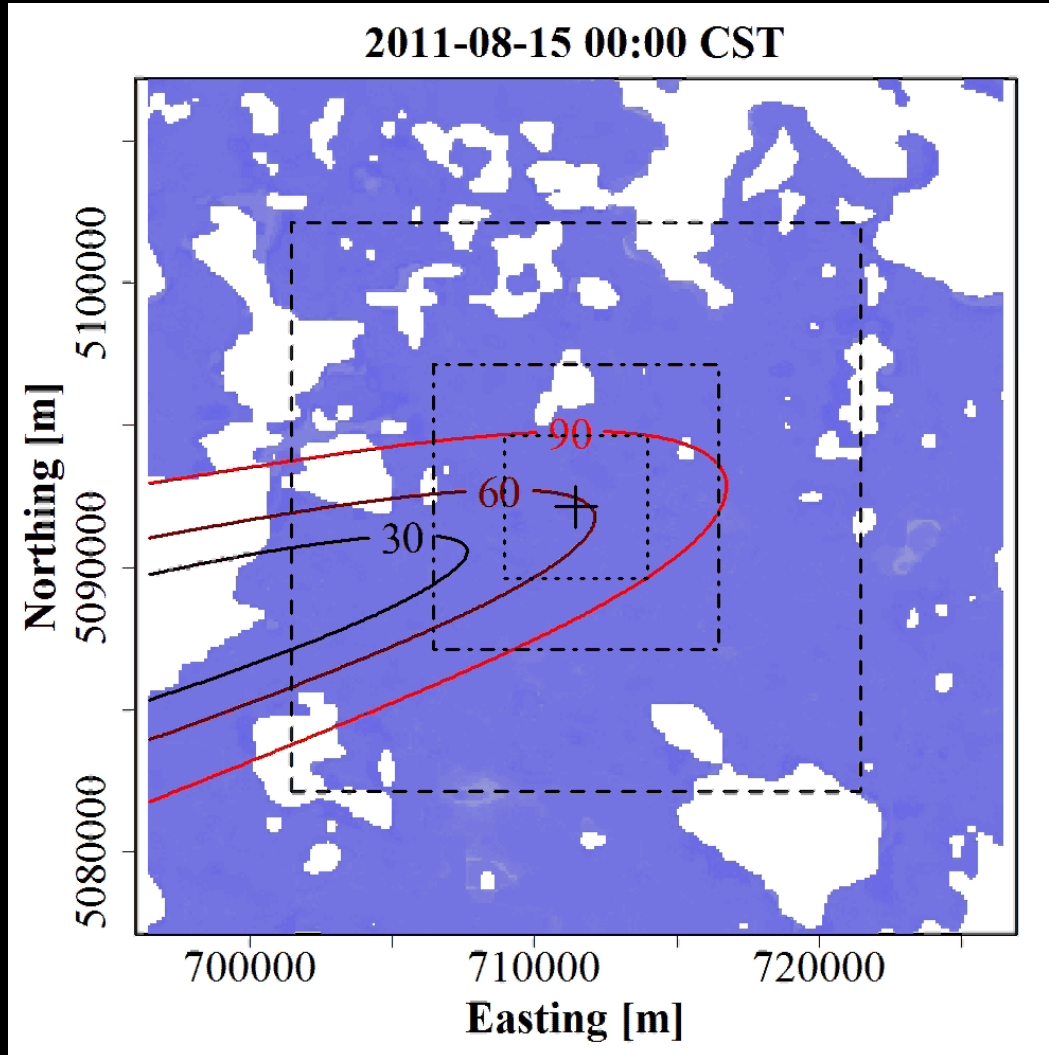
Sensible heat flux [W m^{-2}]



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



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

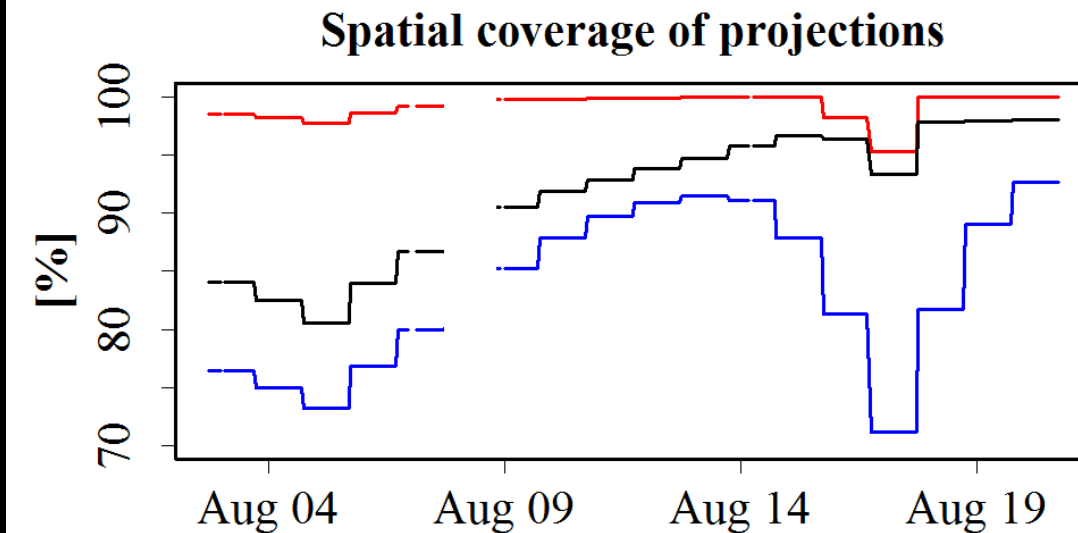


Flux footprint varies in space,
projected flux grid varies in time

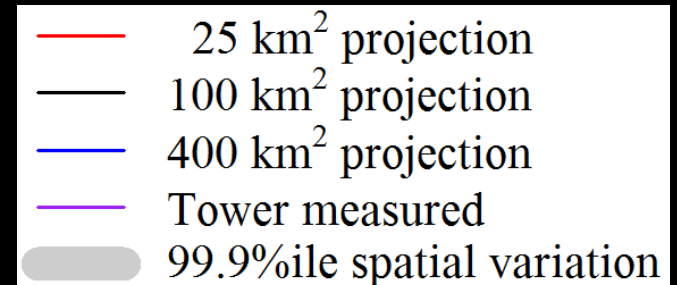
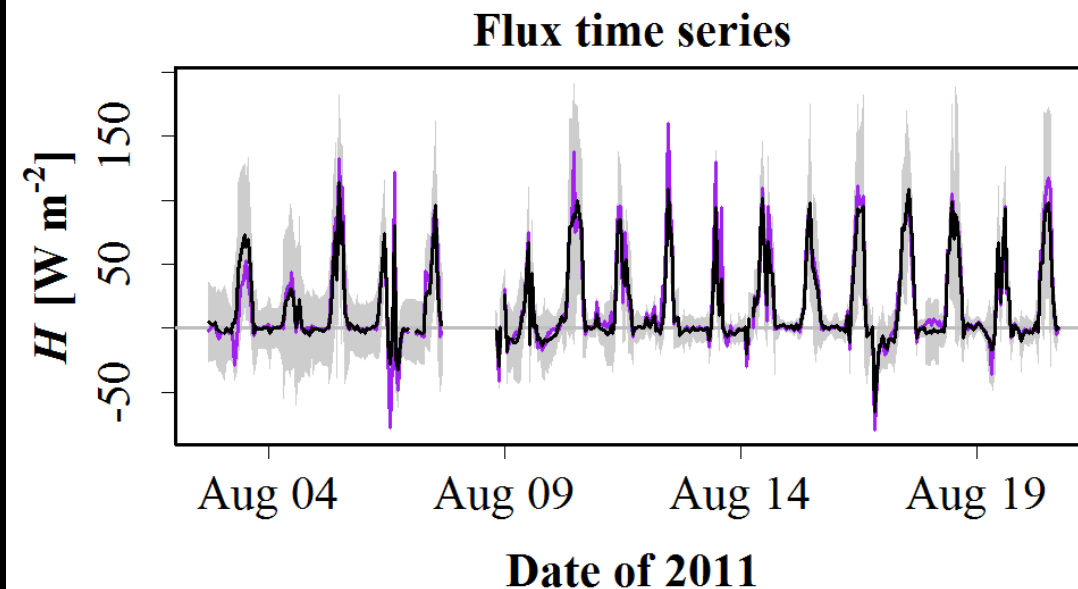
Tower represents different surfaces
at different times

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



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!