Sam Upton and Jake Nelson's presentation can be found here:

http://bgc-jena.mpg.de/~jnelson/UpscalingWorkshop2024

Upscaling workshop
Jul 9-10, 2024

BERKELEY LAB

Beyond Boundaries: The Future of Land Surface Fluxes through Hyper-Resolution Remote Sensing across Space, Time, and Spectrum

Youngryel Ryu, Ph.D.

서 울 대 학 교
SEOUL NATIONAL UNIVERSITY

Acknowledgements

NRF 한국연구재단
KEITI
산림청
NASA
KOPRI 극지연구소
AL SENSING AI LAB
Seoul National University
과학기술정보통신부
KARI 한국항공우주연구원 Korea Aerospace Research Institute
농촌진흥청
JAXA
SCHMIDT FUTURES

MOTIVATION

Model evaluation against X by X pixels centered on flux tower over Y days

meteorological data and GPP estimates for 2001. Every 8 days, a window of the MODIS daily GPP (7 by 7 pixels) is retrieved at the exact location of these towers, and we make a direct comparison between the MODIS GPP and tower measurements of vegetation GPP (figure 7). This protocol is

Running et al., (2004) BioScience

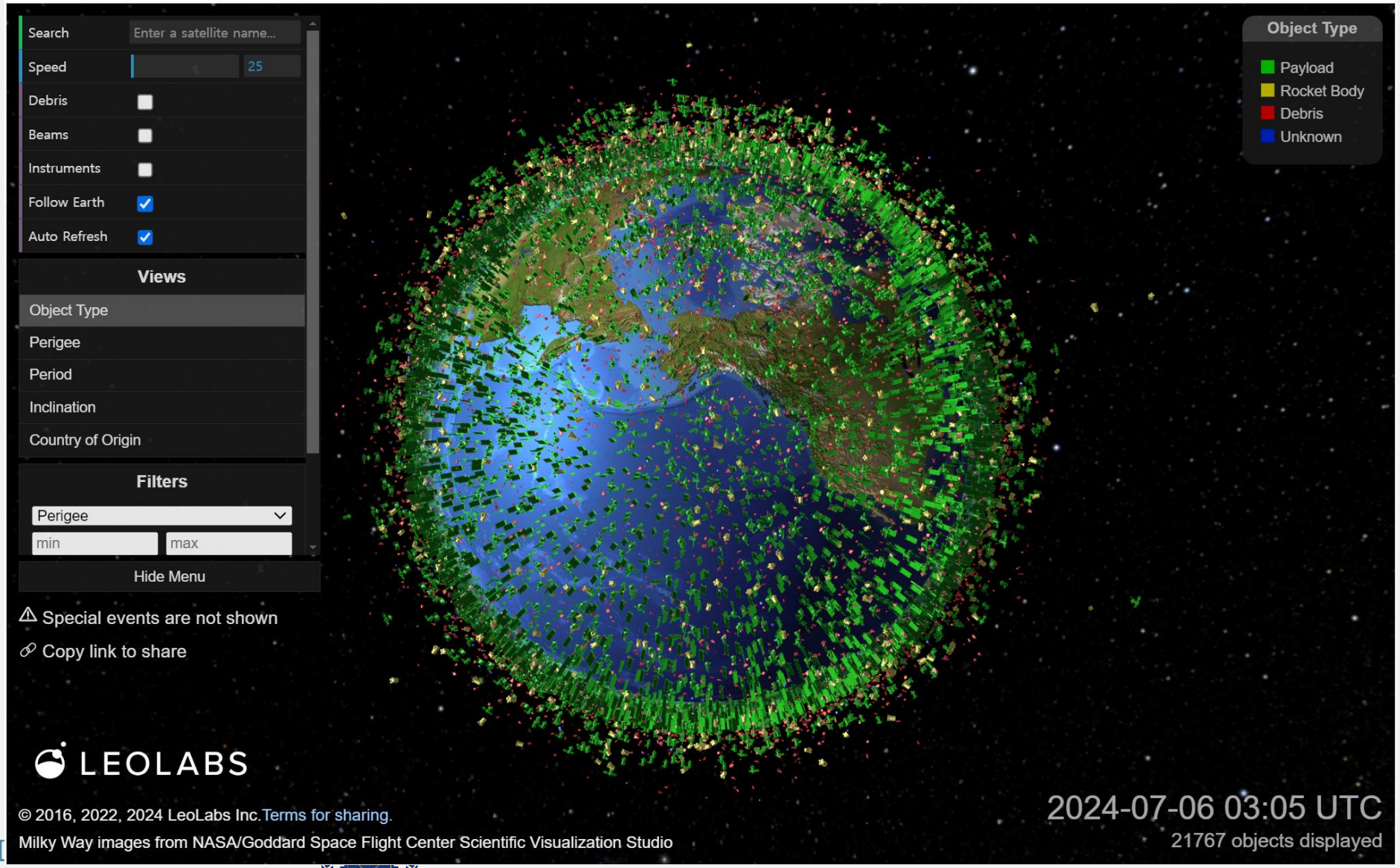
We extracted average values for the central 3 km × 3 km area within the 7 km × 7 km cutouts to better represent the flux tower footprint

Xiao et al., (2010) RSE

We further evaluated the performance of BESS in comparison with two benchmark products, FLUXCOM and GLASS, at a monthly step against FLUXNET tower pixels (Fig. 3). All three products were resampled to a 0.05° spatial resolution. Overall, all three products agreed well

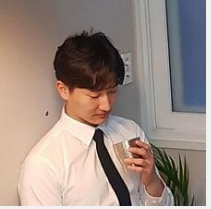
Li et al., (2023) RSE

Opportunities

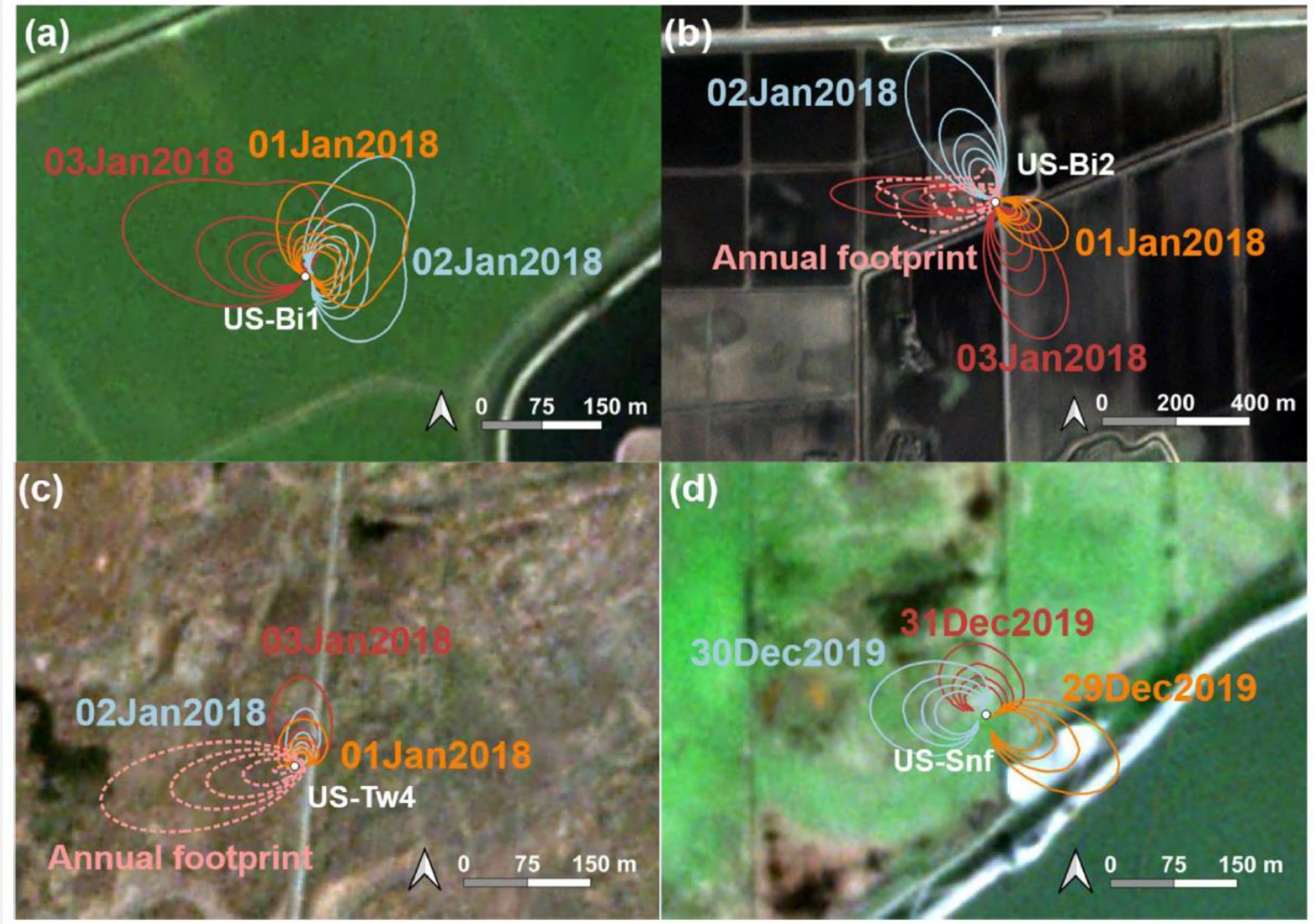


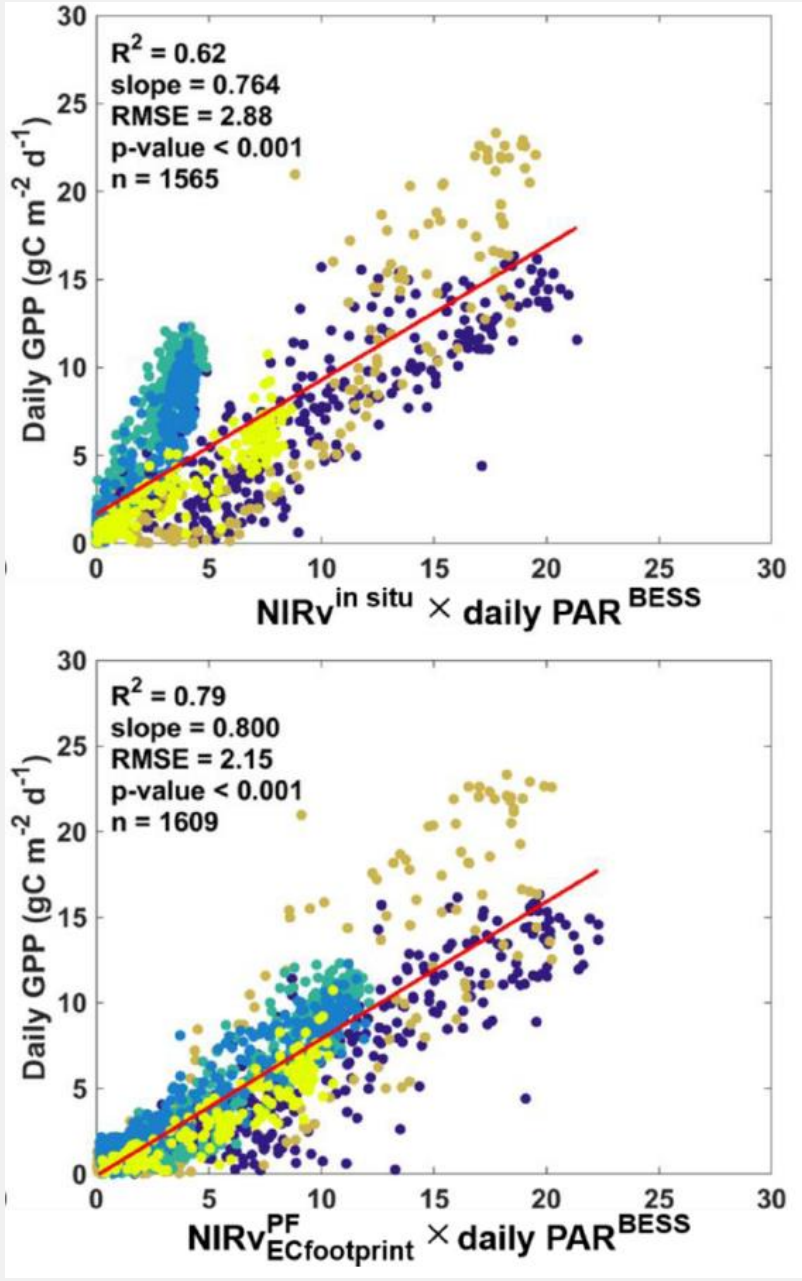
https://platform.leolabs.space/visualization

SPACE



Pixels into the flux footprint - 3 m, daily Planet Fusion





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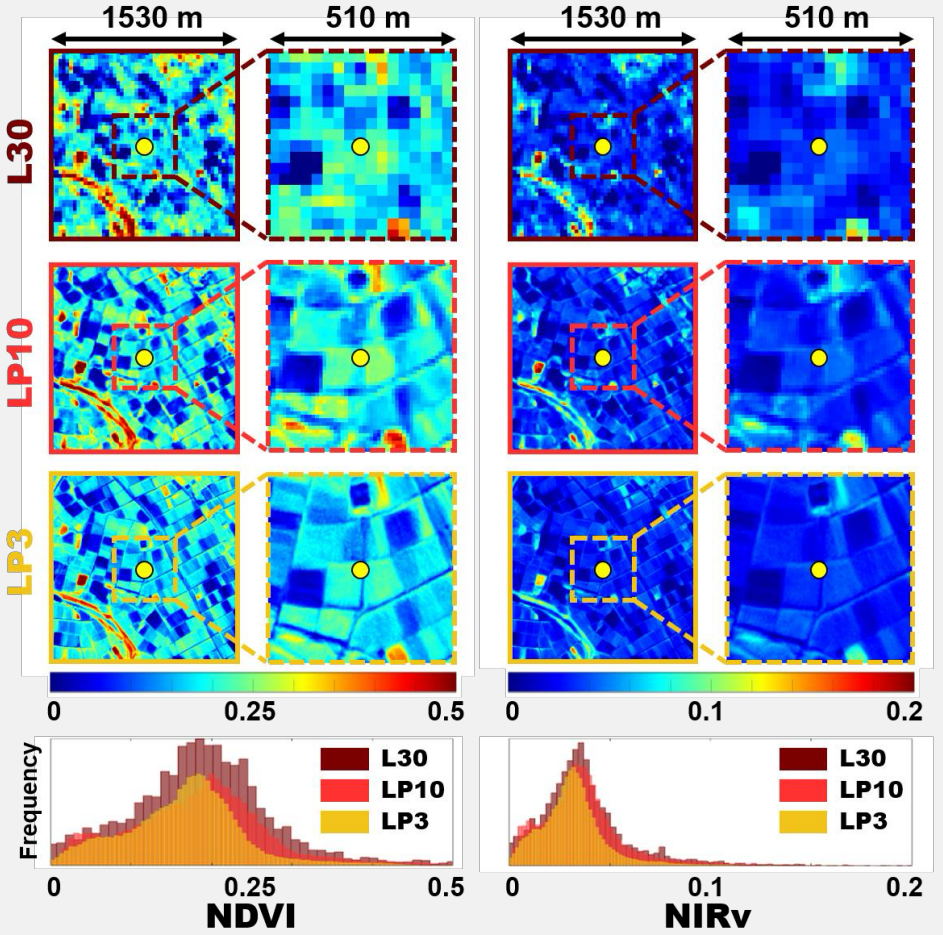
Kong et al., (2022) Agricultural and Forest Meteorology

Super resolution Landsat learned from Cubesats

- GAN (generative adversarial network) was applied to make 30 m Landsat into 3 and 10 m images by learning finer spatial patterns from Cubesats
- It can open a new opportunity to map photosynthesis at highly fragmented landscapes back to several decades



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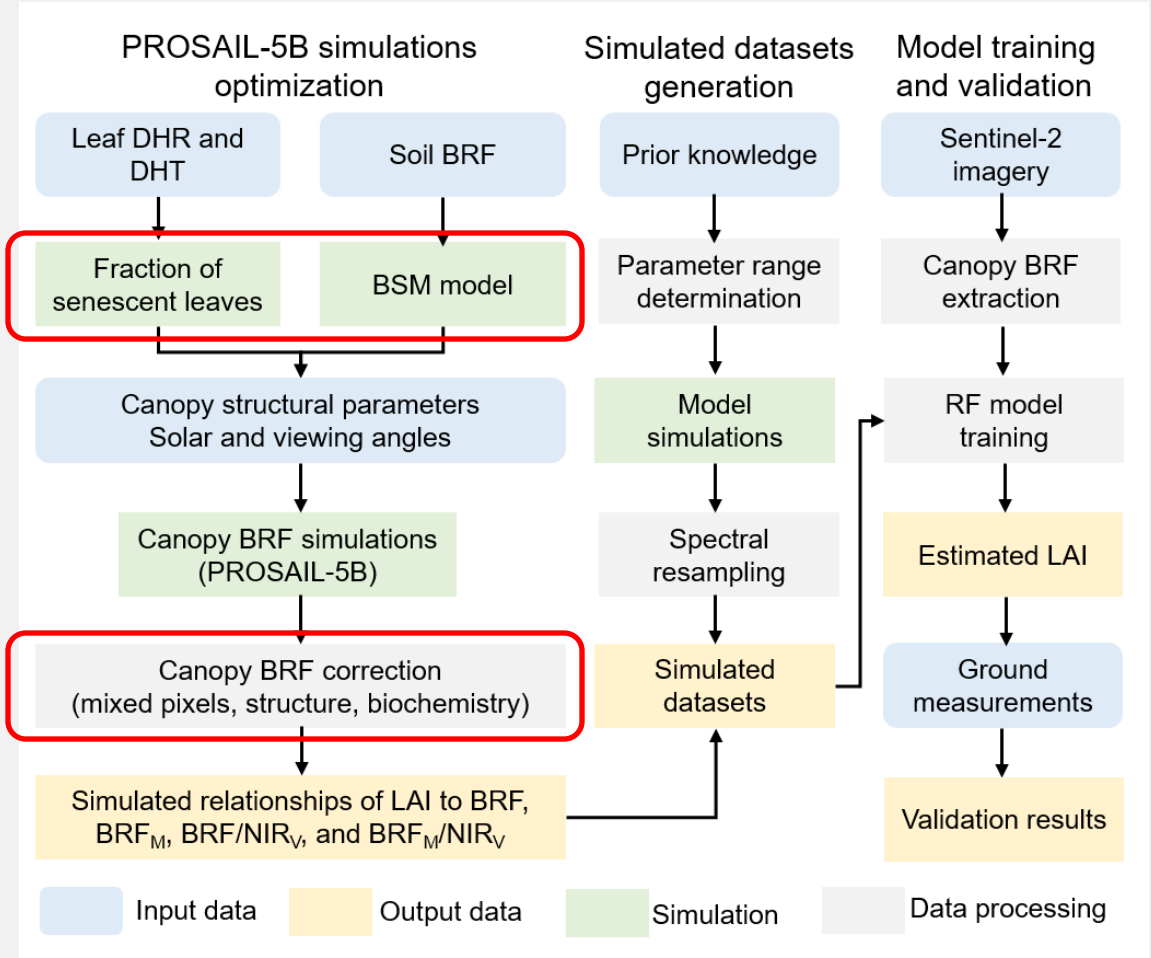
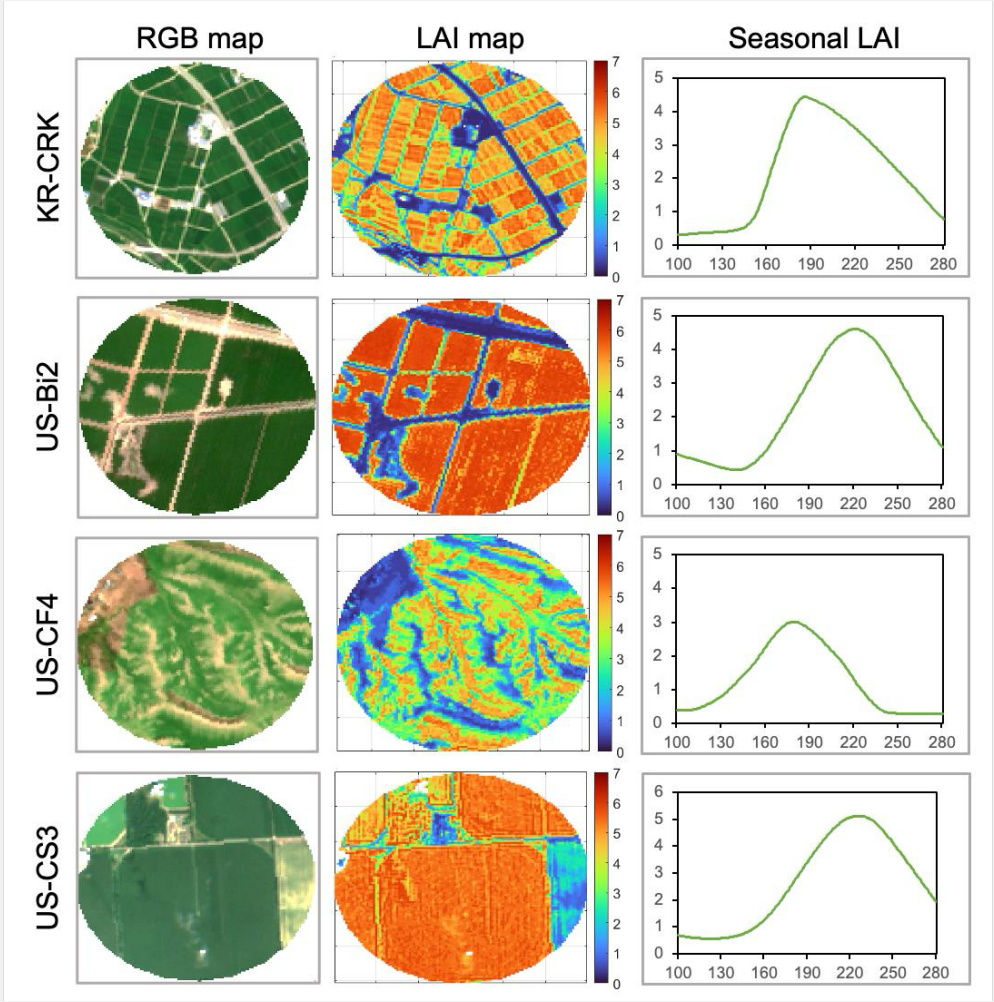
Kong et al., (2023) ISPRS Photogrammetry and Remote Sensing

10 m LAI from Sentinel2 towards global land

-correcting canopy structure, biochemistry, soil background effects-





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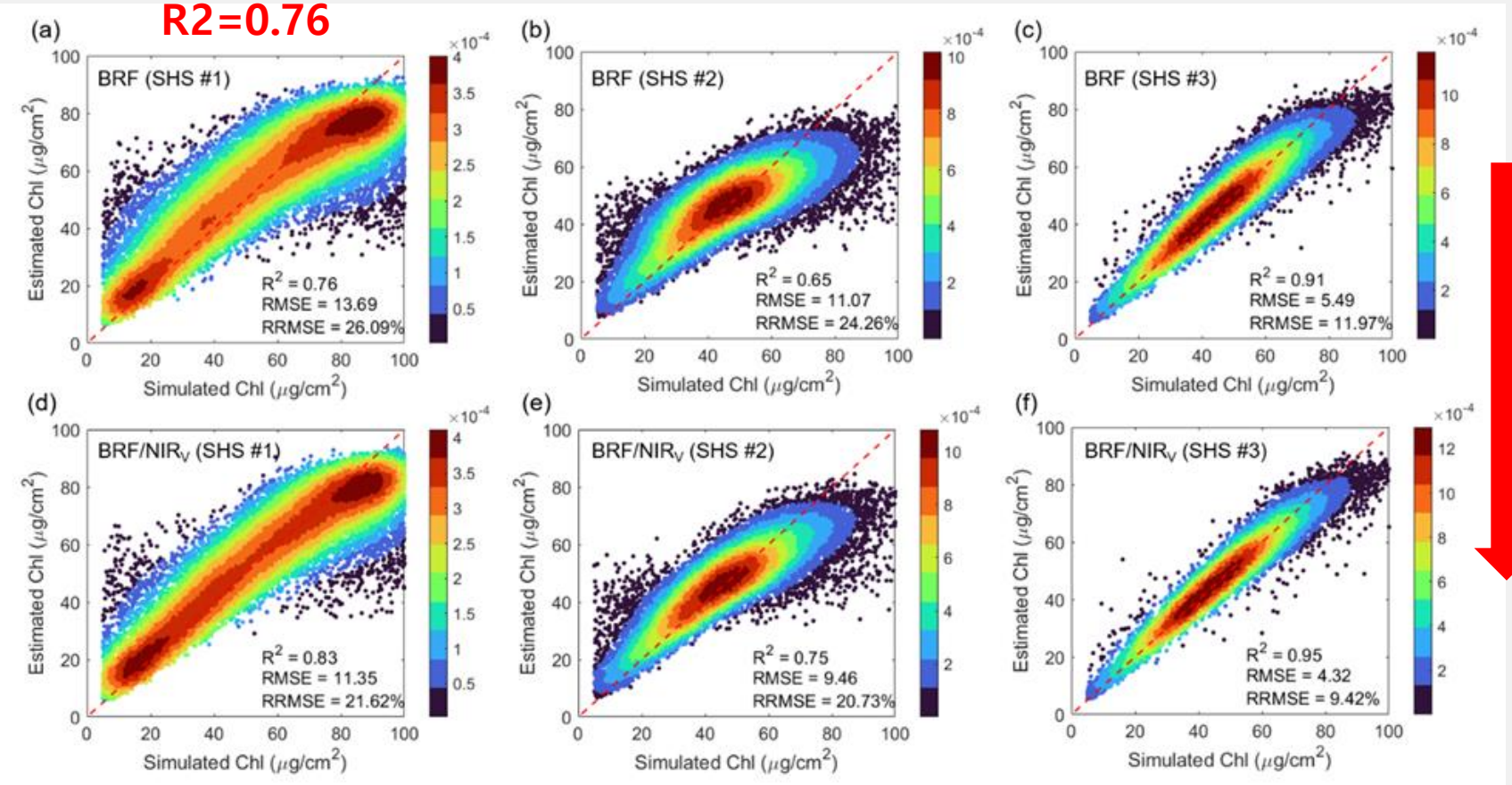
Wan et al (2024a) Remote Sensing of Environment

10 m Chl from Sentinel-2 towards global land

Different distributions in parameters

BRF/NIRv to mitigate canopy structure effects

R2=0.76



BRF

Vs

BRF/NIRv

PROSAIL-5B inversion

Train the model with RF

Forced w/S2 BRF and NIRv

Generate 10 m Chl maps

R2=0.95

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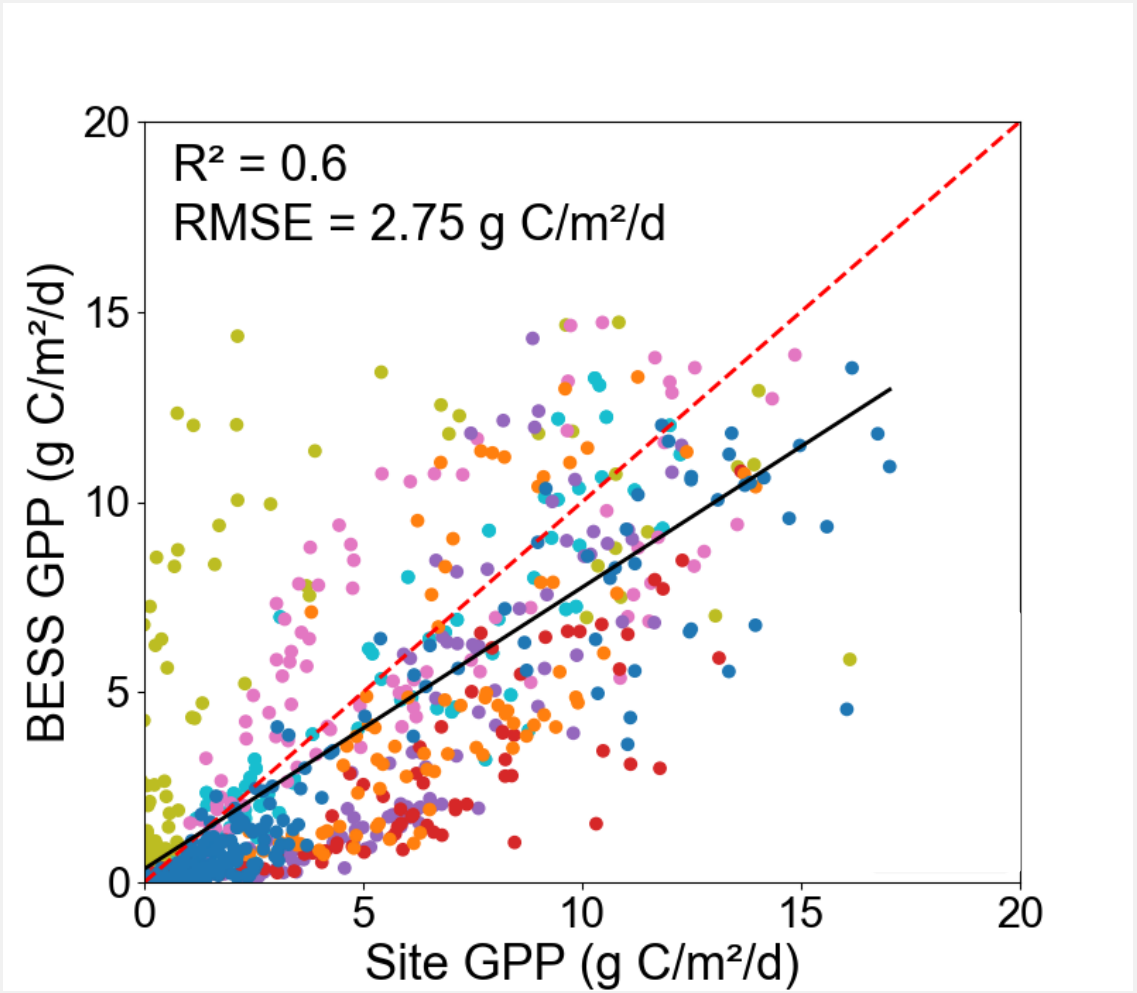
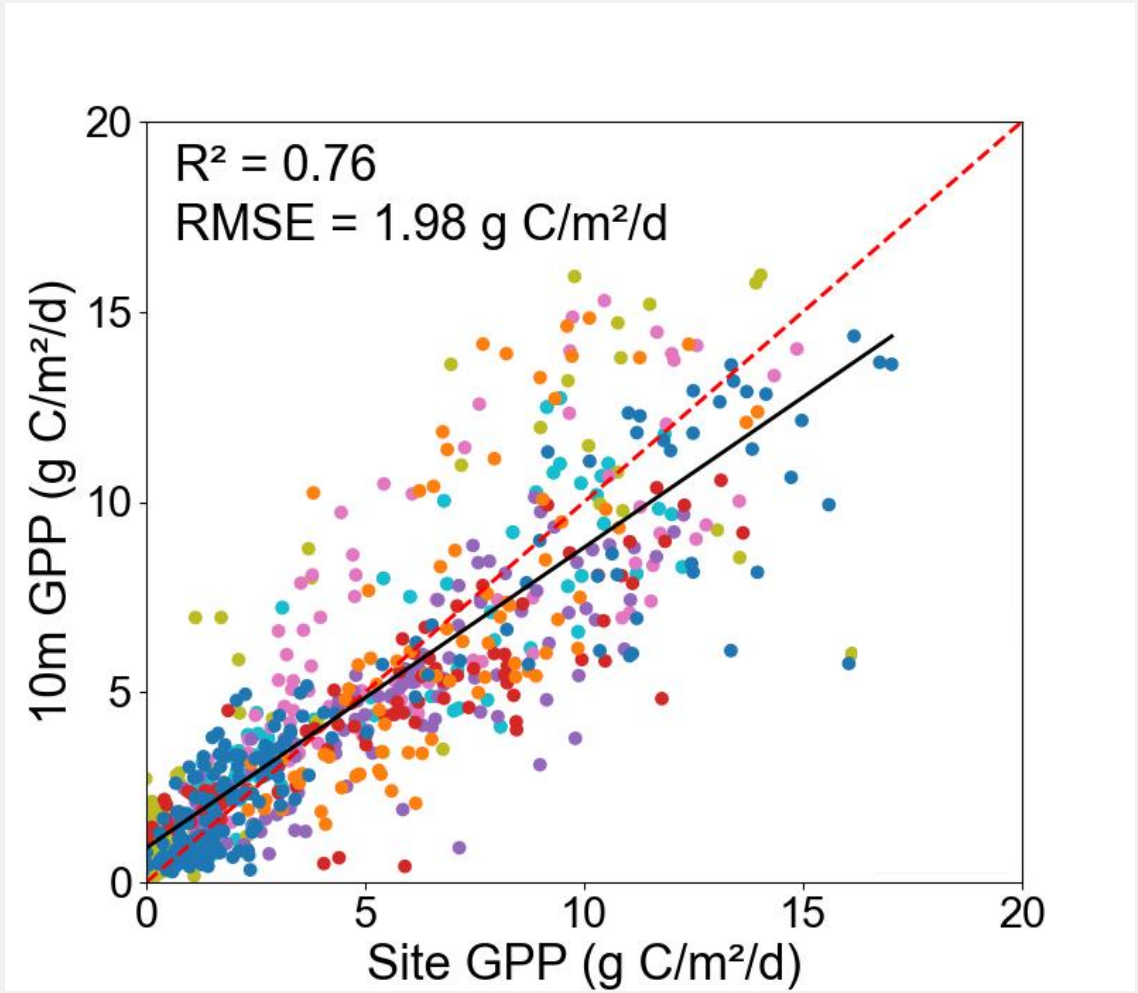
Wan et al (2024b) Remote Sensing of Environment

0.05 degree vs 10 m BESS GPP in Korea

-Ready to run BESS at 10 m-





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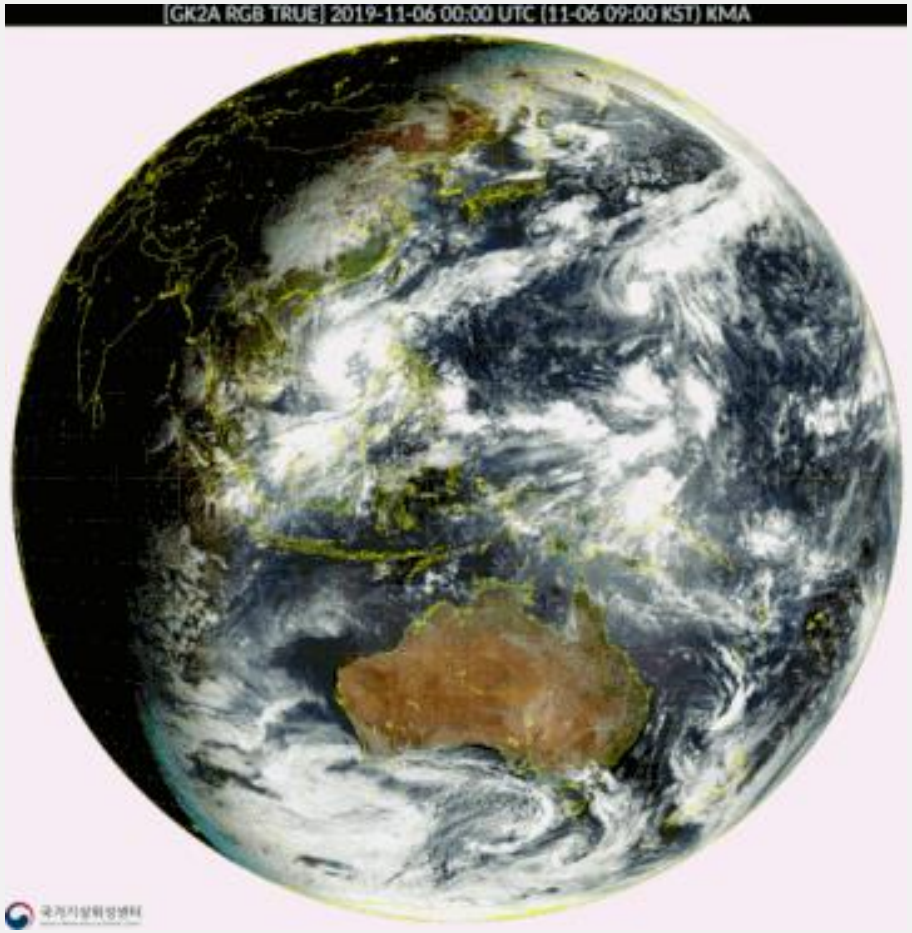
Zhang et al (in preparation)

TIME

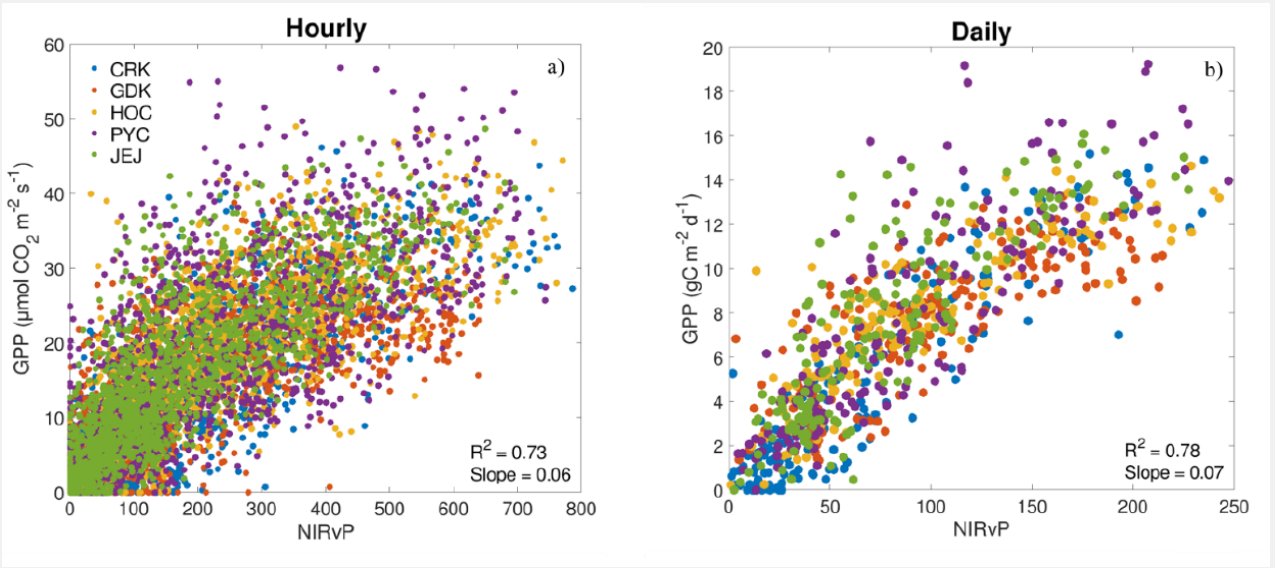
Every min sensing on the Earth disc

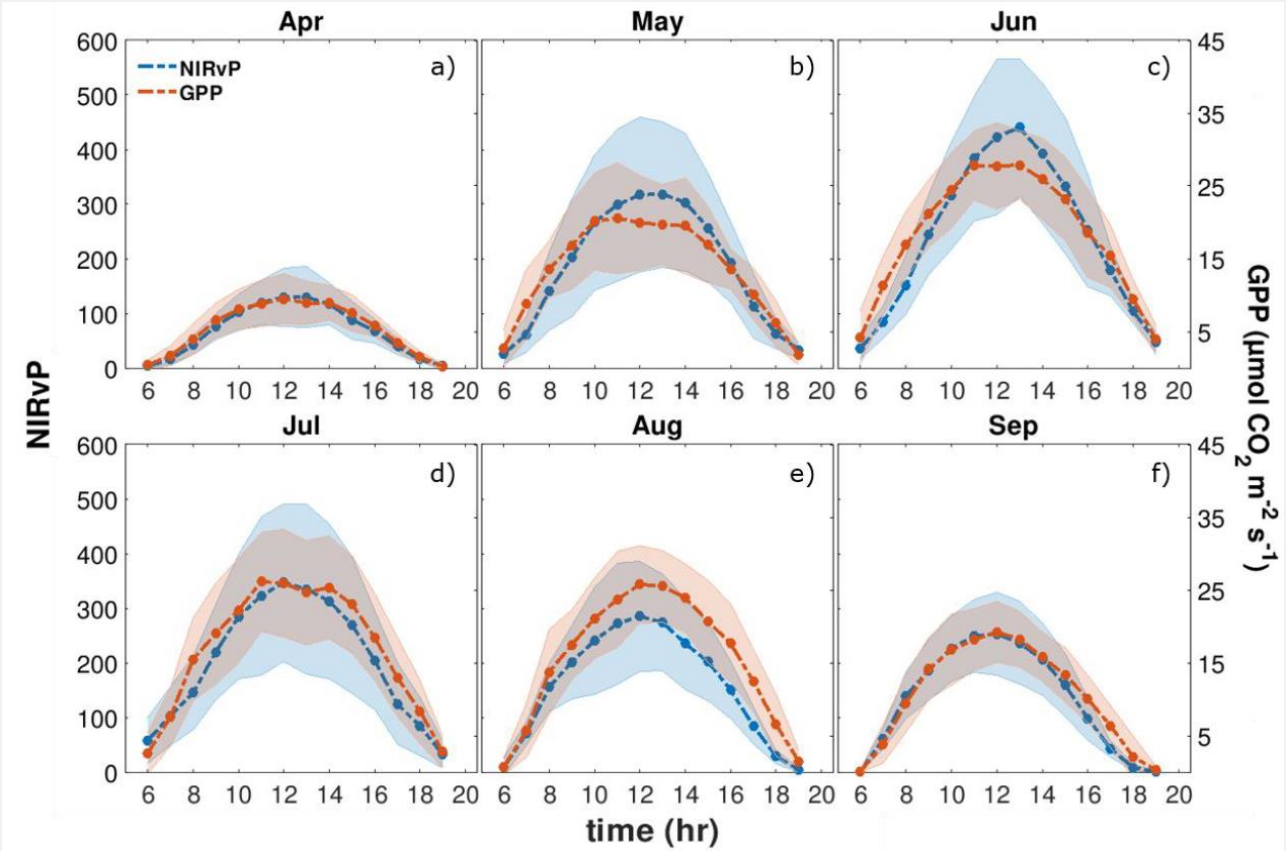


- Opens new opportunity to monitor diurnal variations of GPP
- But solar zenith angle variations are so large
- Sensor view angle is not nadir except for Equator
  - Strong BRDF effects!

Diurnal variations of GPP from GEO-NIRvP

Five flux towers in South Korea
: 3 DBF, 1 MF, 1 CRO





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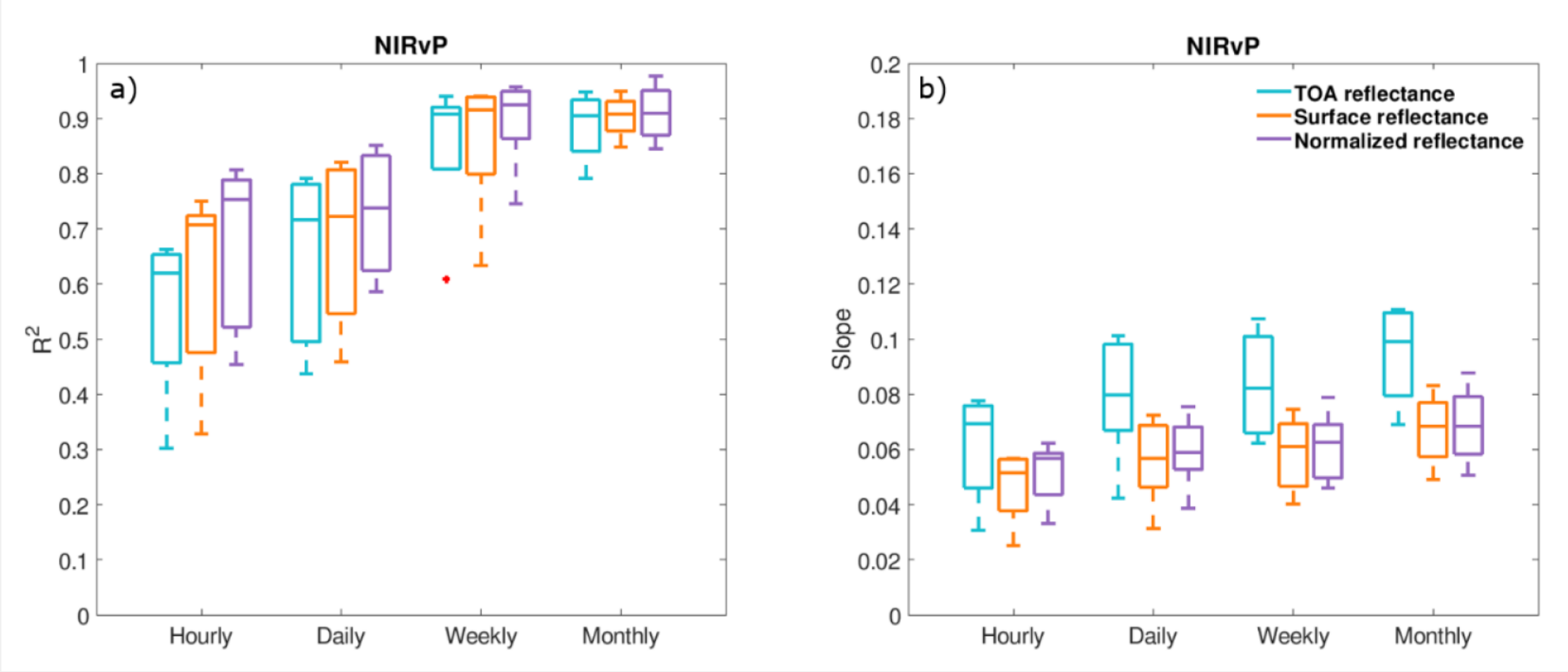
Jeong et al., (2023) Remote Sensing of Environment

Atmos & BRDF corrections matter in NIRvP~GPP relationships!



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Jeong et al., (2023) Remote Sensing of Environment

Hourly SIF mapping: GEO-SIF

- XGBoost model

- Adjusted GK2A view geometry into OCO3 view geometry through BRDF

$$SIF = f(\text{Blue, Green, Red, NIR reflectance, SW, VPD})$$

OCO-3 **GK-2A**

Jeong et al (2024a) Remote Sensing of Environment

Much more data in GK2A

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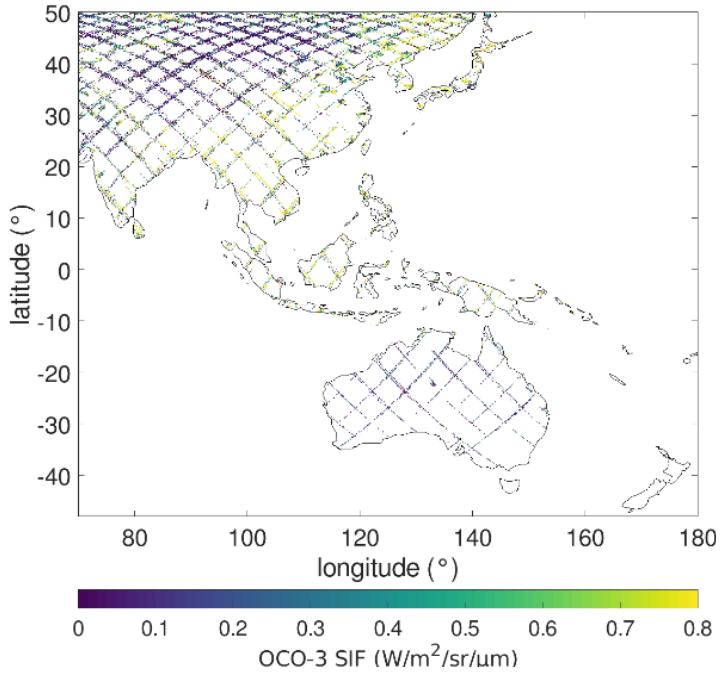
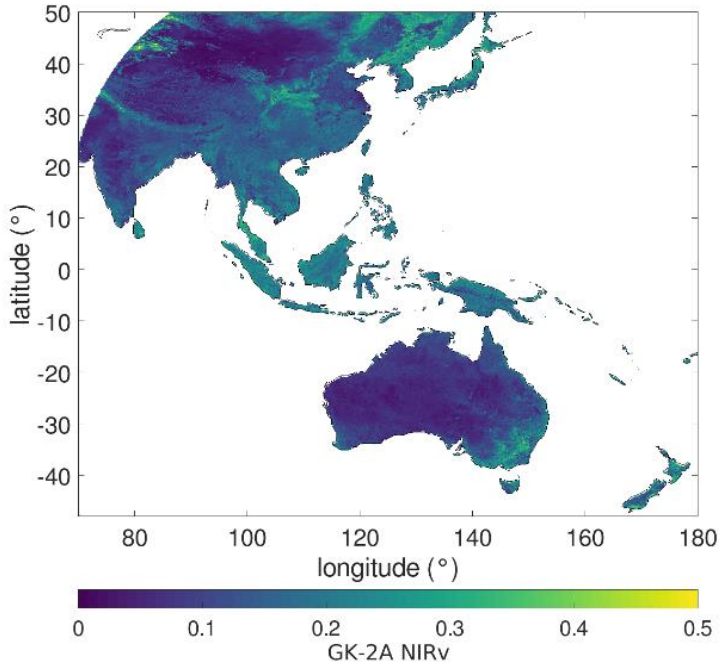
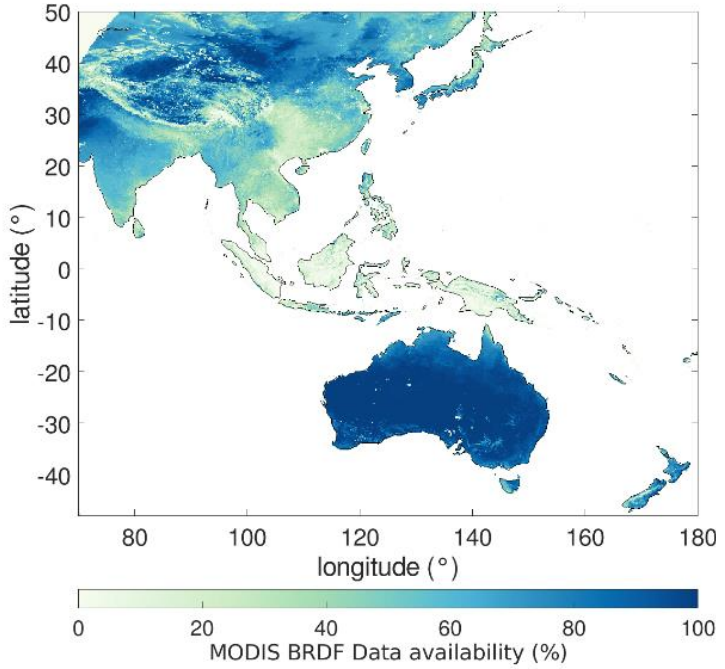
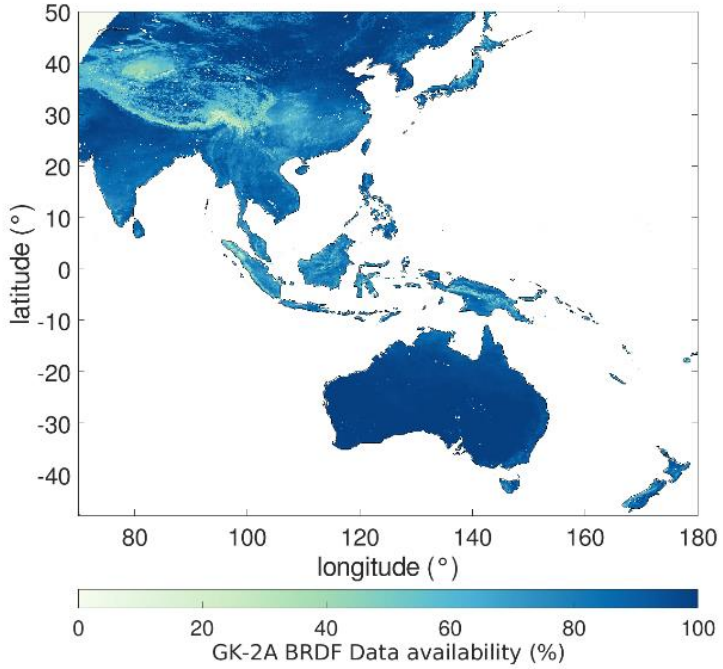
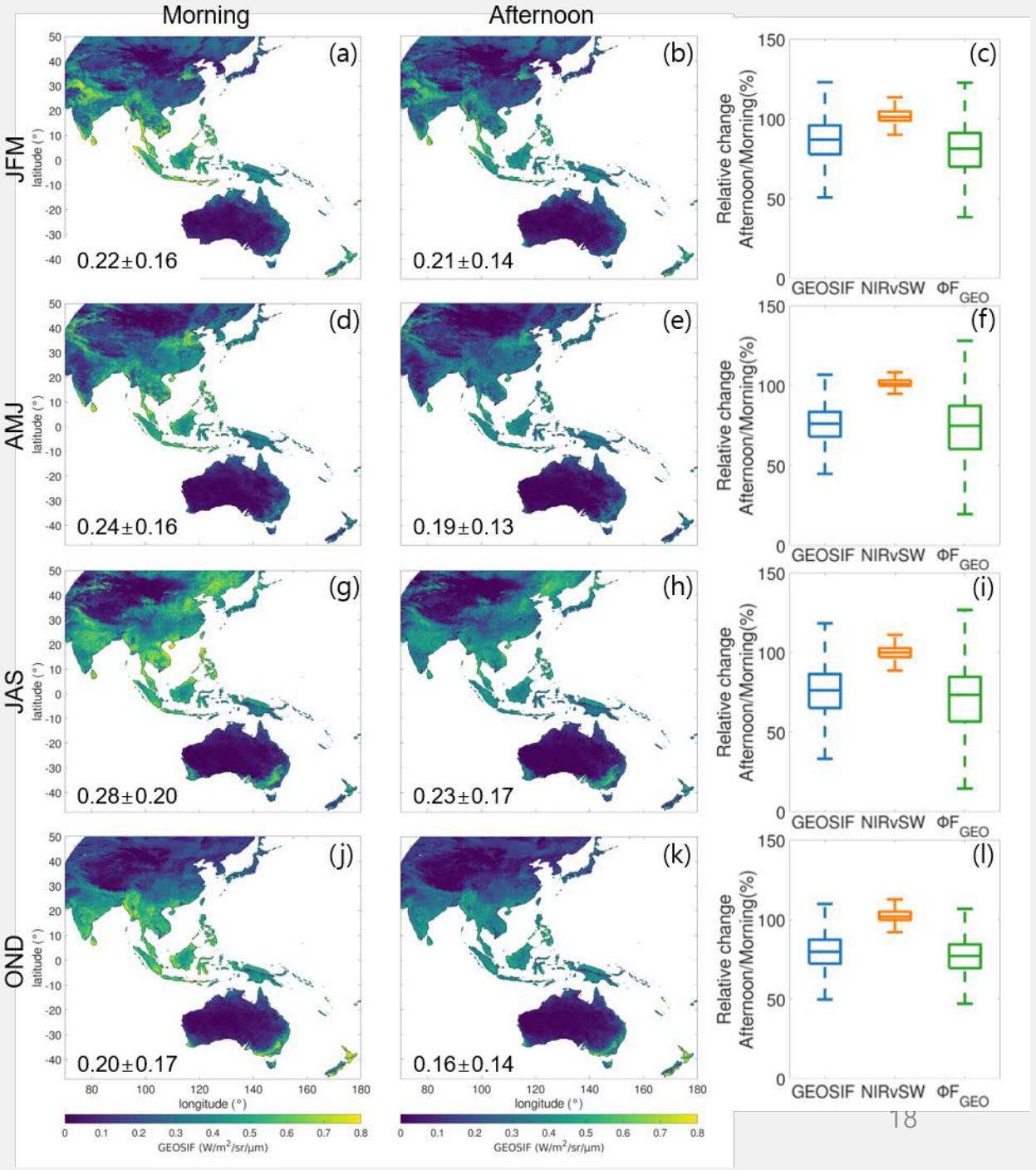








- Overall, morning showed higher SIF and SIFyield than afternoon
- NIRvP showed little difference between morning and afternoon!



Jeong et al (2024a) Remote Sensing of Environment

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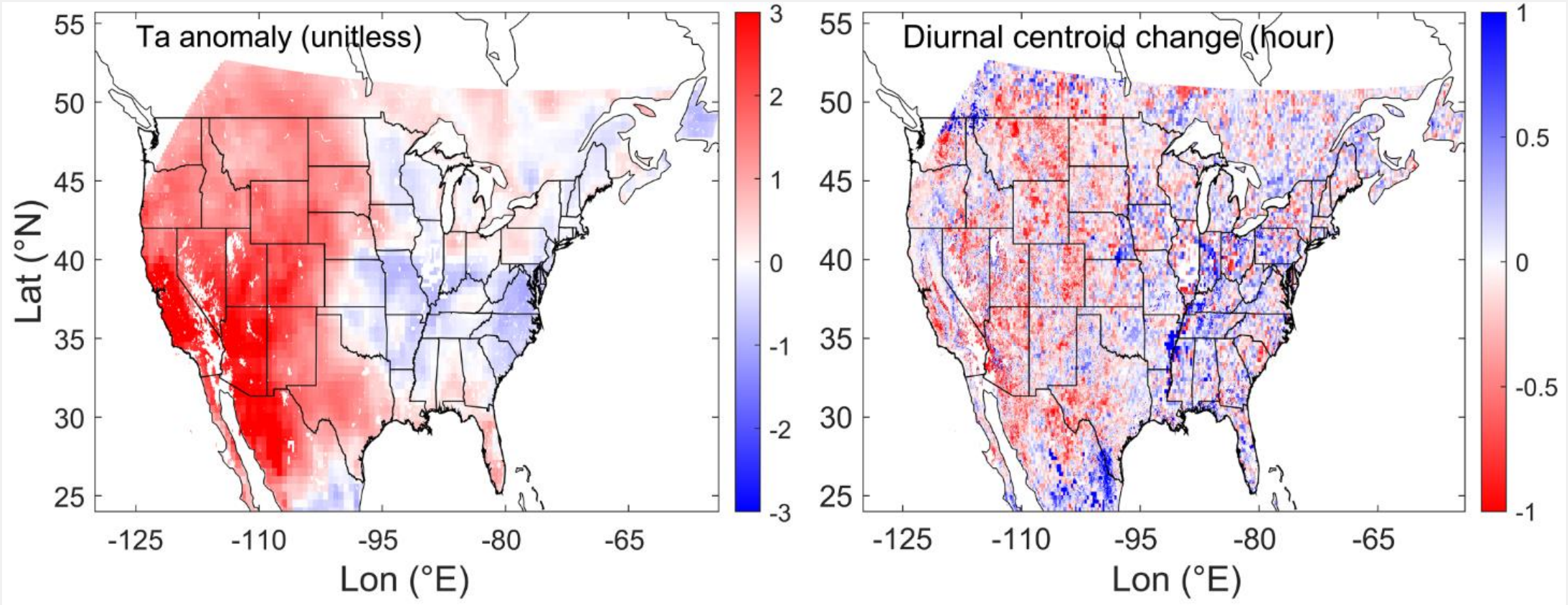
Geostationary satellite detects midday depression in dryland photosynthesis



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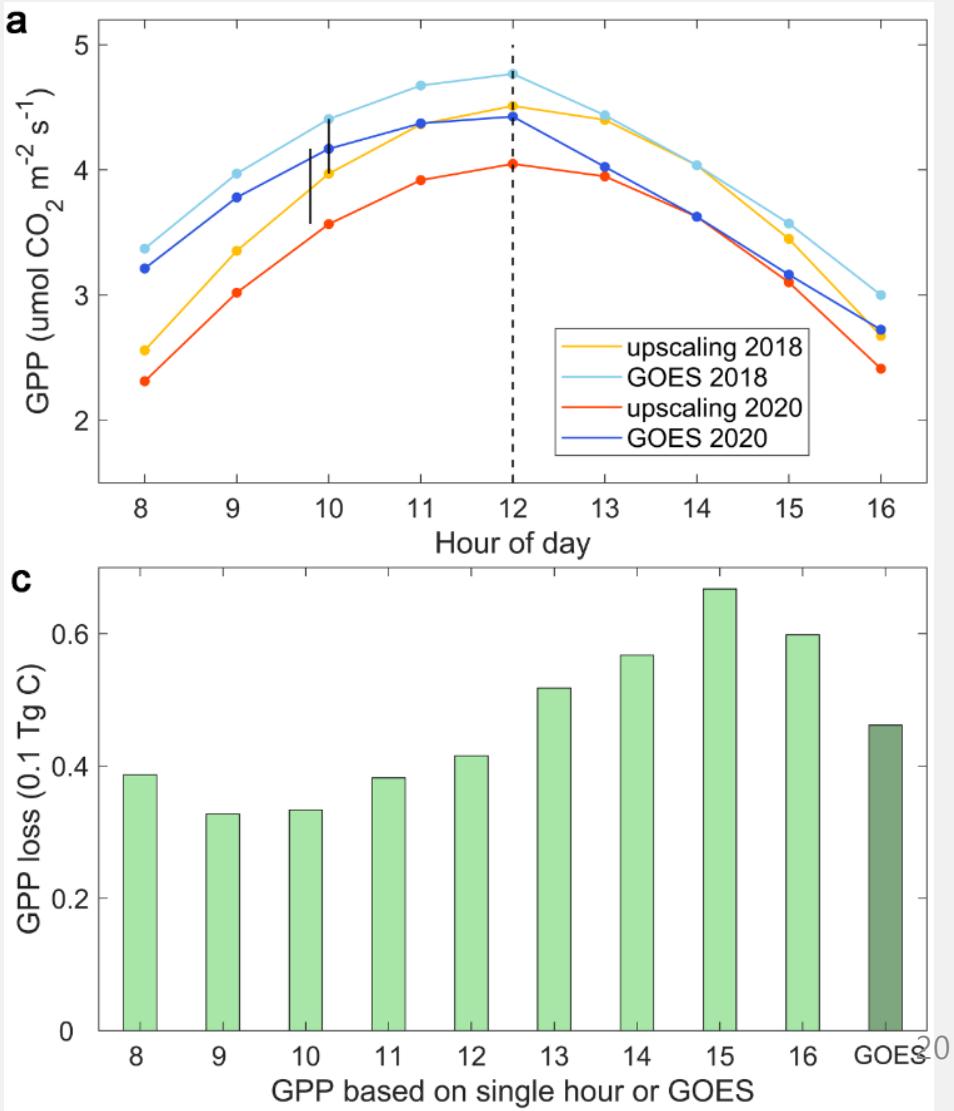
Li et al., (2023) Science Advances

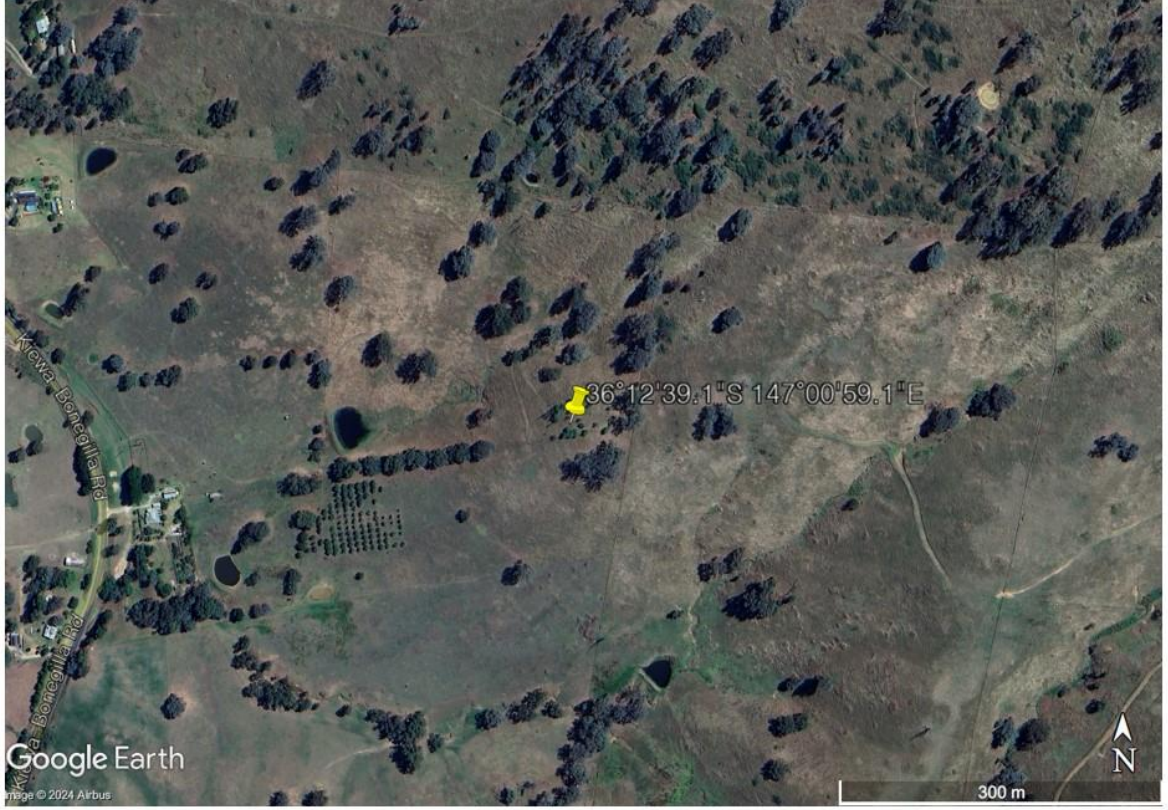
Temporal upscaling from snapshot leads biases in daily sum estimates

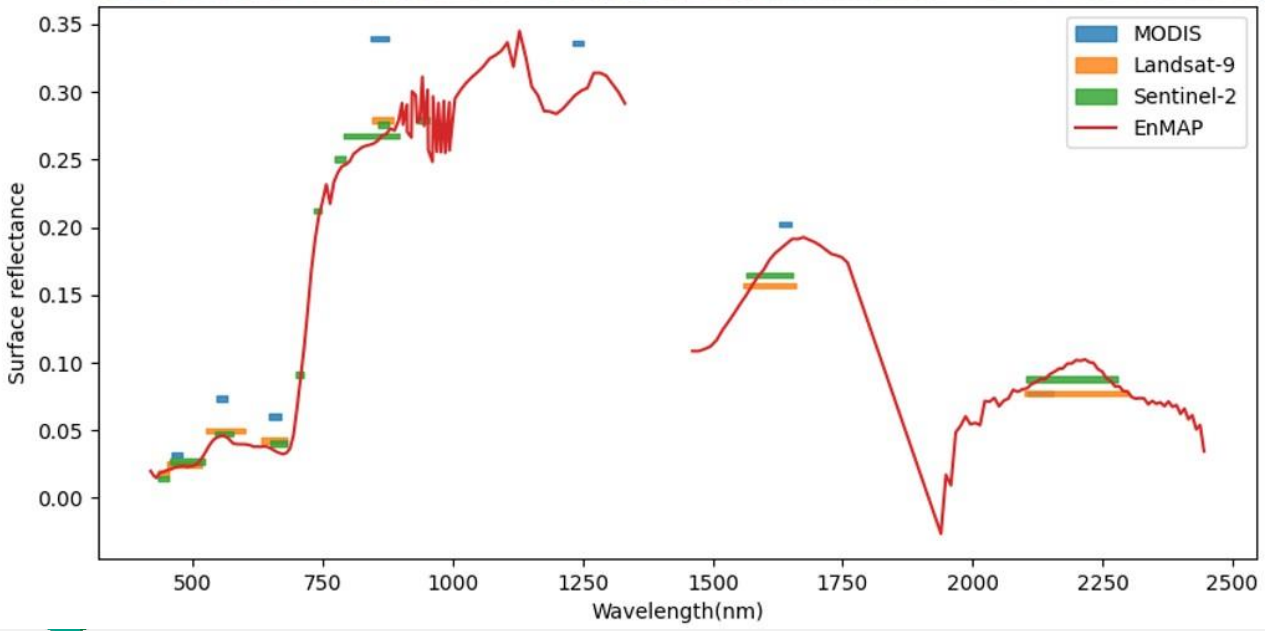
- 2020 Western US heatwave induced strong diurnal asymmetry of photosynthesis in dryland
- Diurnal monitoring of photosynthesis from geostationary satellite could minimize the bias in daily sum estimates



Li et al., (2023) Science Advances

SPECTRUM

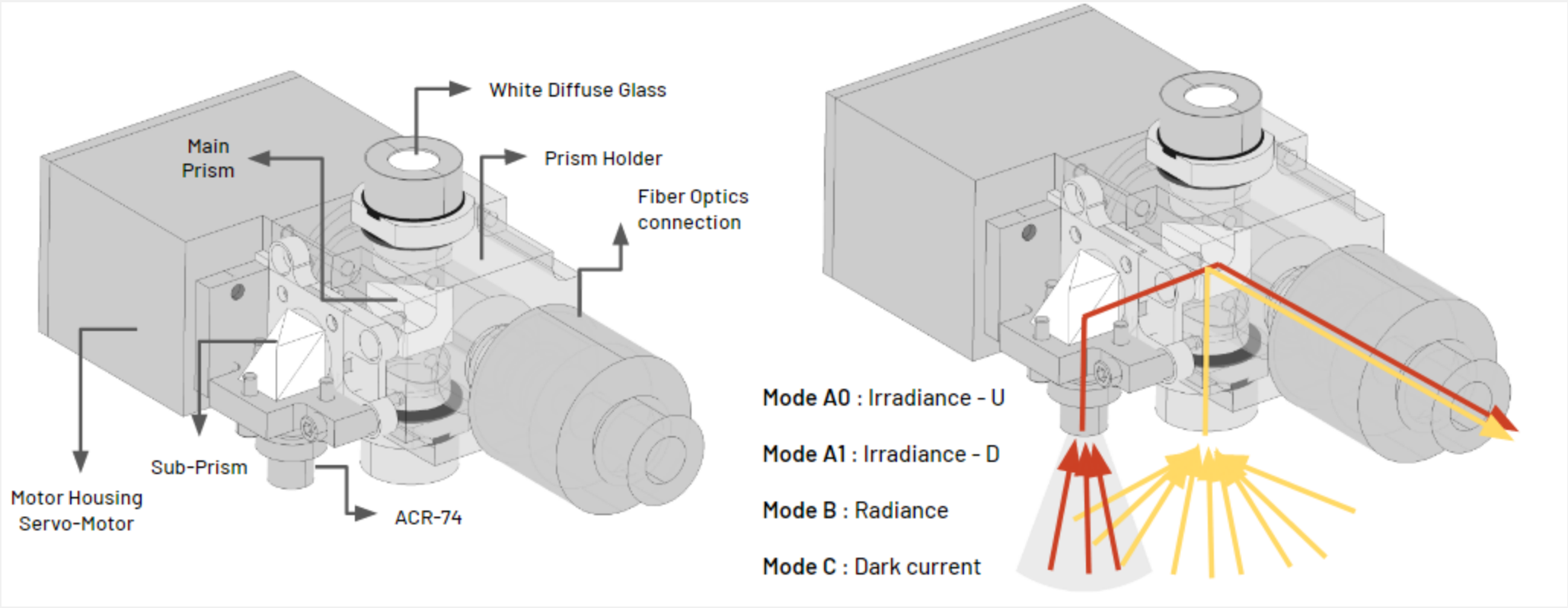




- Heterogeneous
  - Landscape
  - Spectral bands
  - Spectral resolutions
  - Spatial resolution
  - Temporal revisit frequency
- Tower based hyperspectral network is much needed

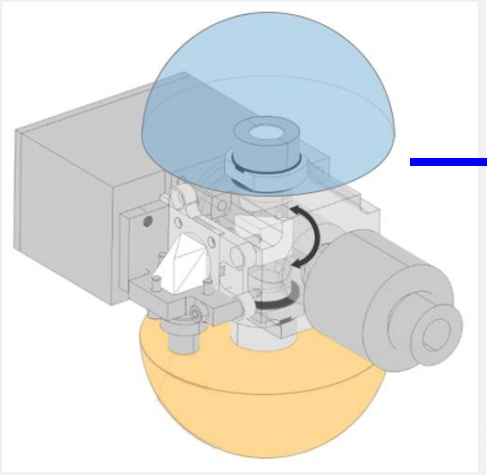
Ryu (in review) JGR-B

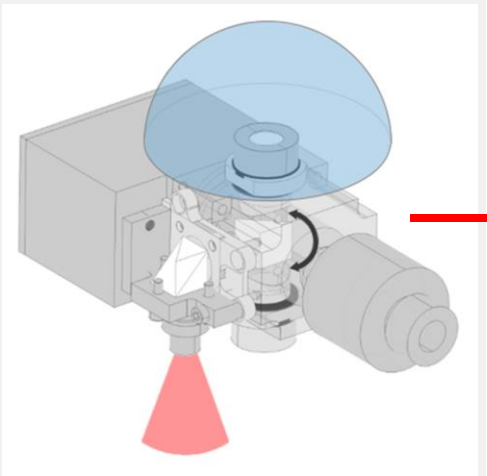
Upgraded rotaprism system that integrates BHR and BRF in VNIR, SIF and SWIR

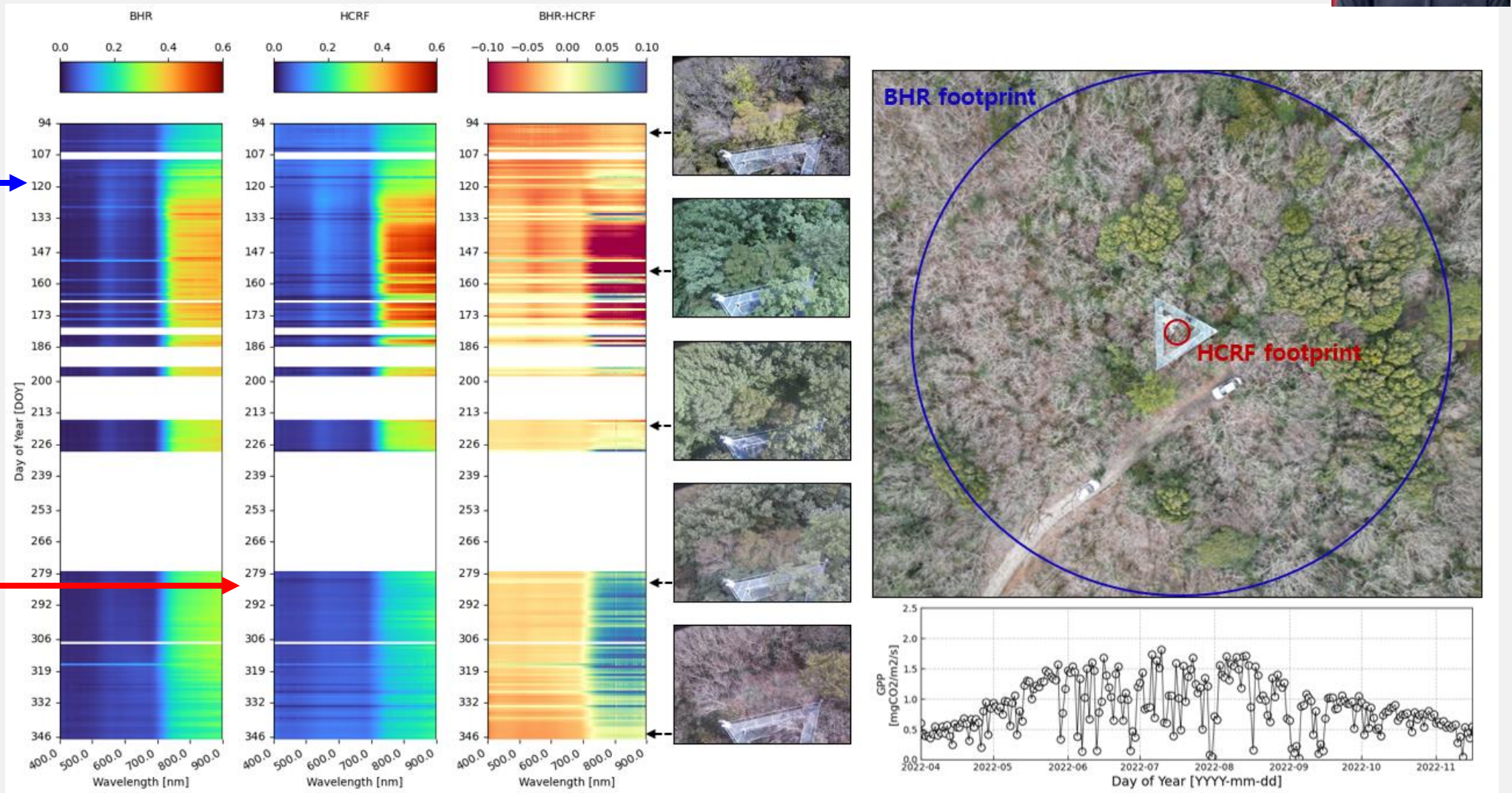


Lee et al (to be submitted)

Different view geometries







Lee et al (to be submitted)

Hyperspectral systems in six flux towers

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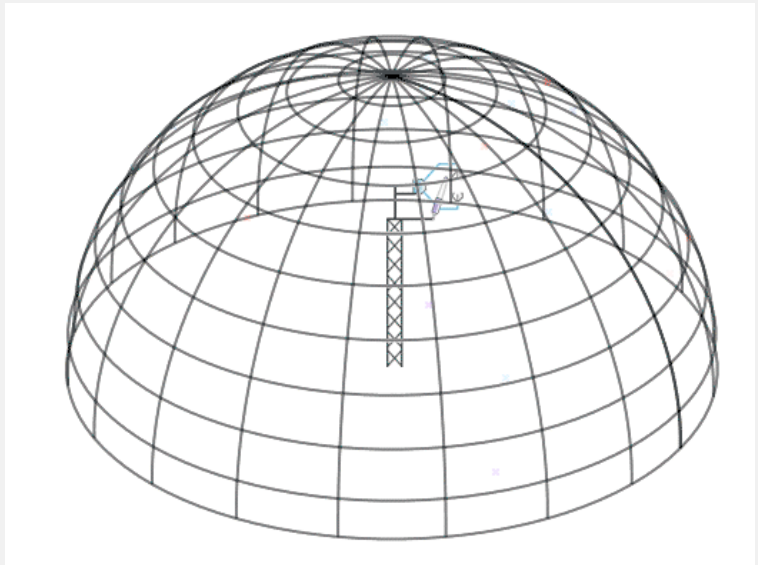
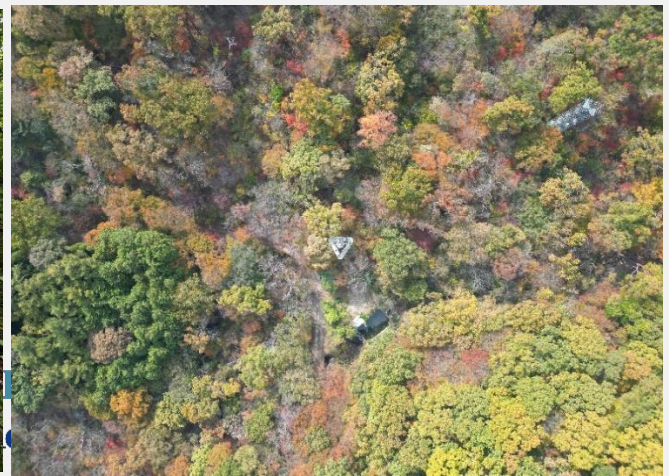
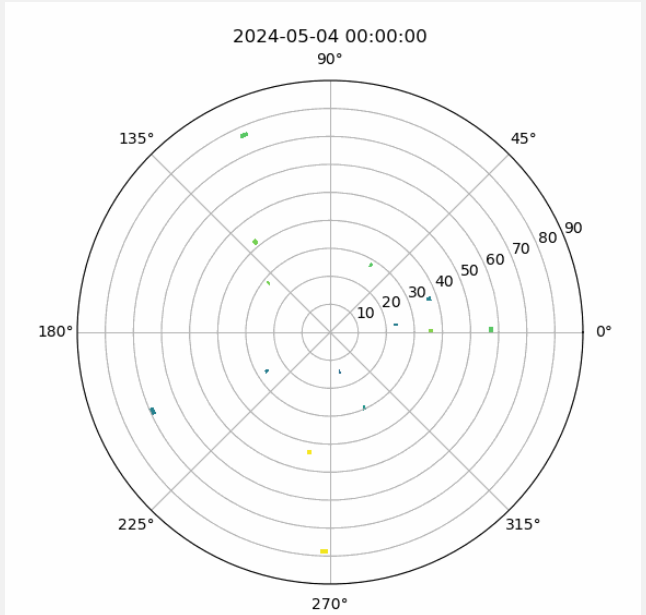
GNSS-based L-VOD

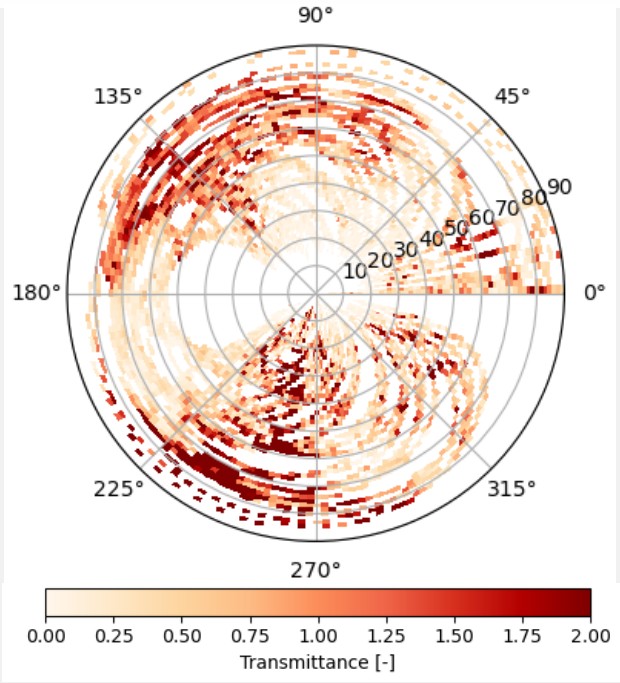
2024-05-04 00:00:00

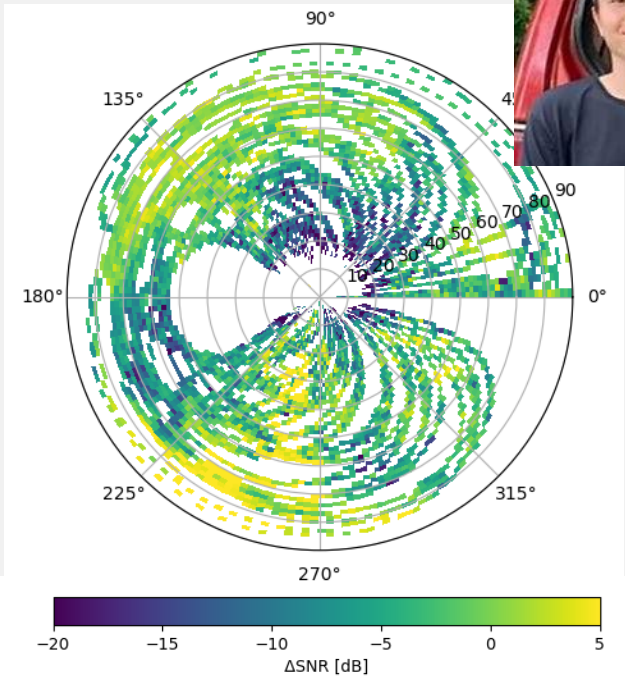
Satellite Num: 21

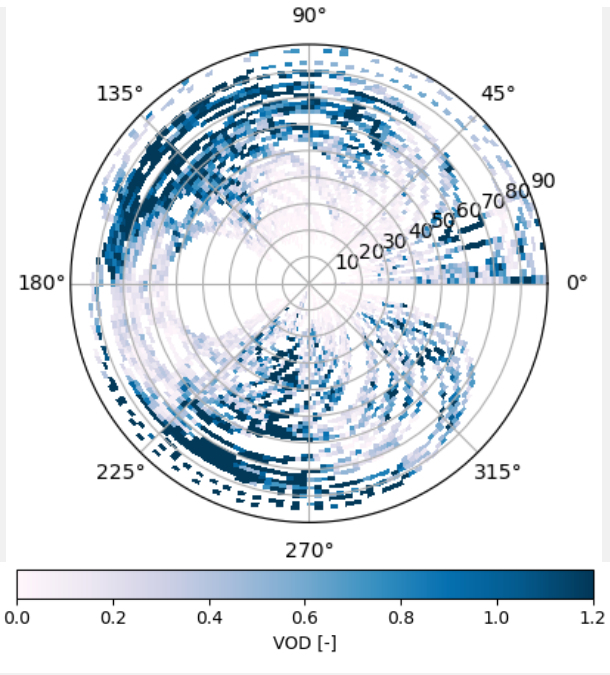






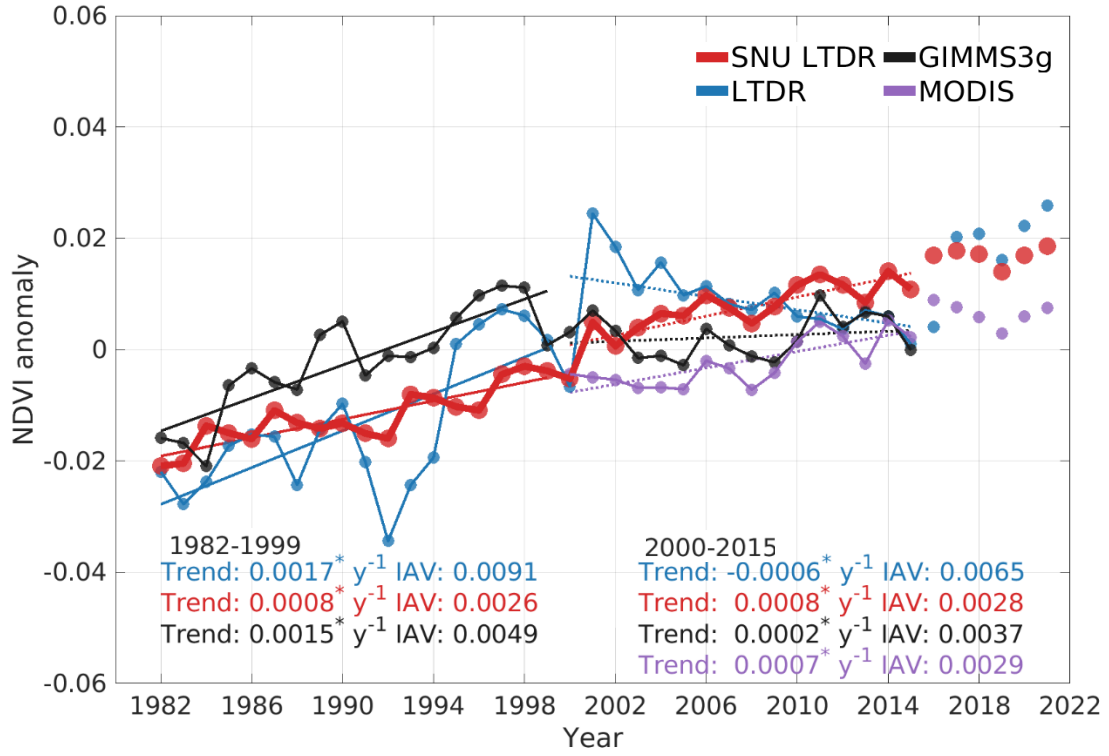


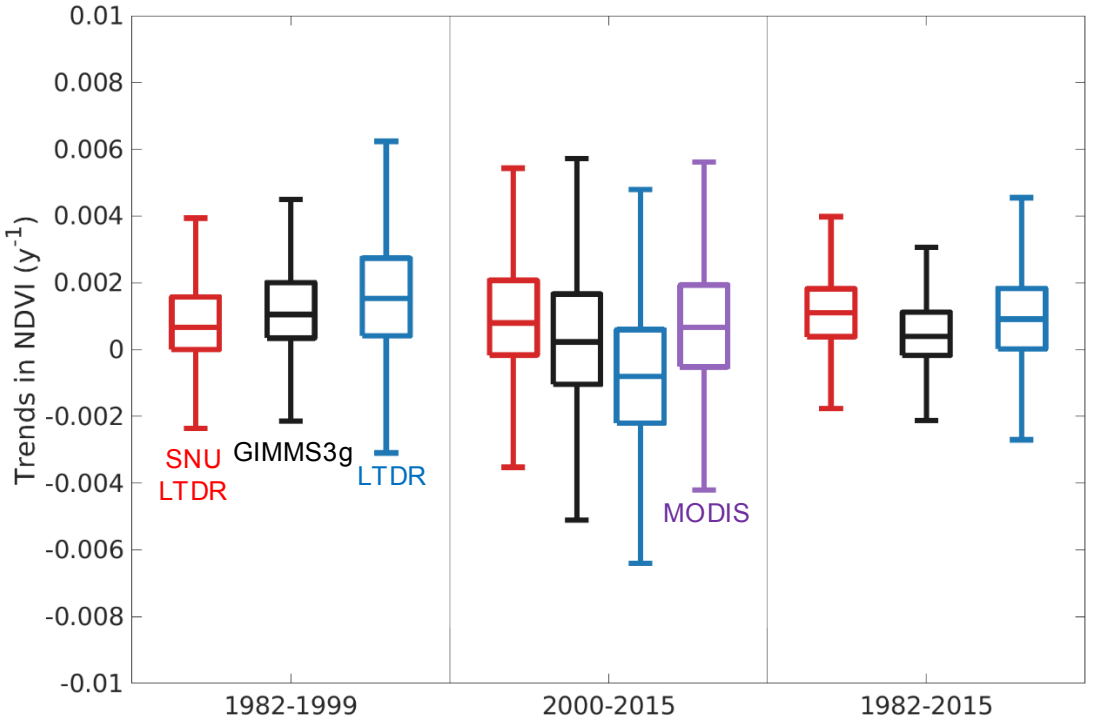




We really need long-term spec data

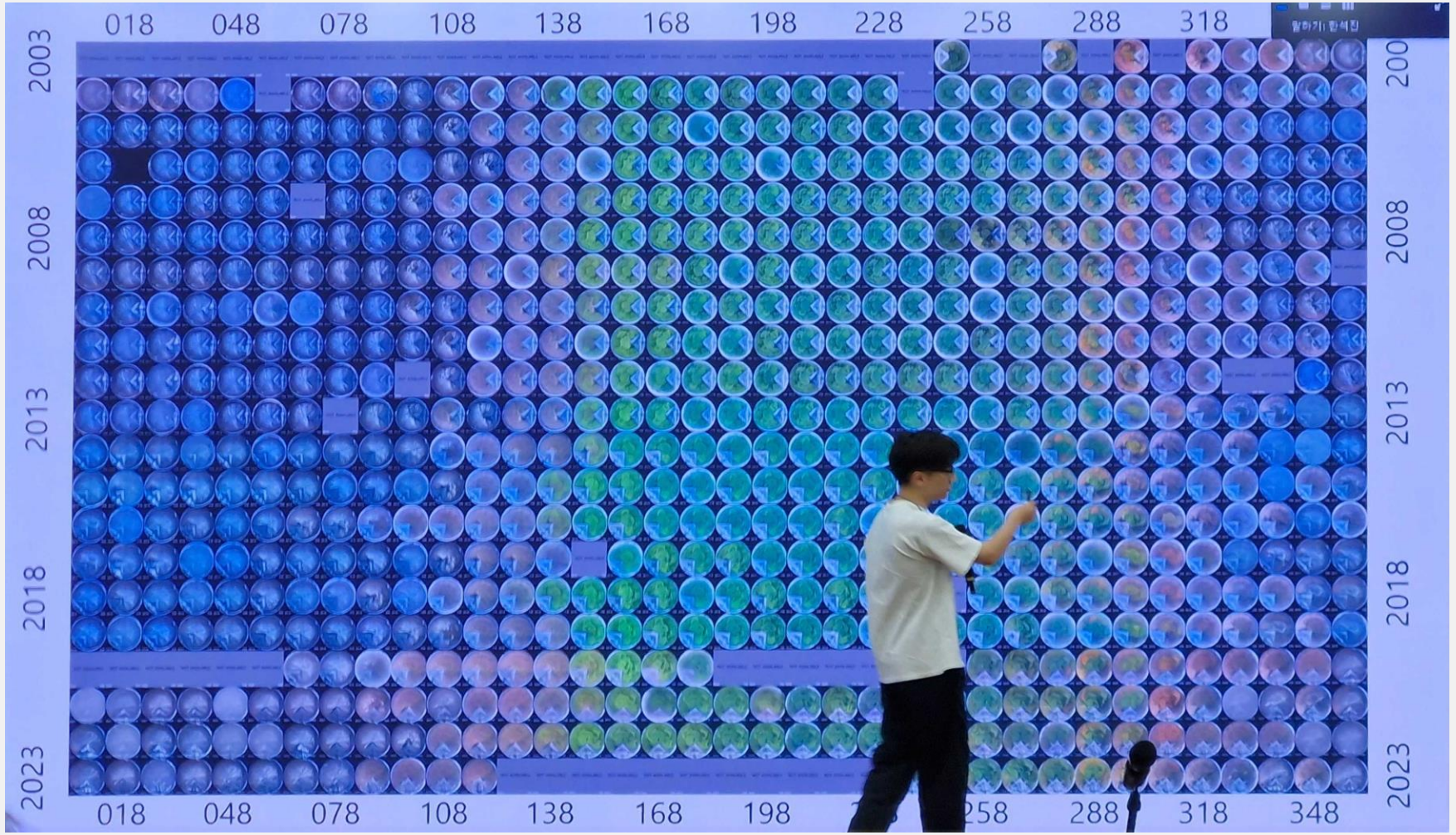
- Many papers reported saturation of CO2 effects/WUE/… after 2000, but it depends on the long-term VI data
- We found a persistent greening over the four decades

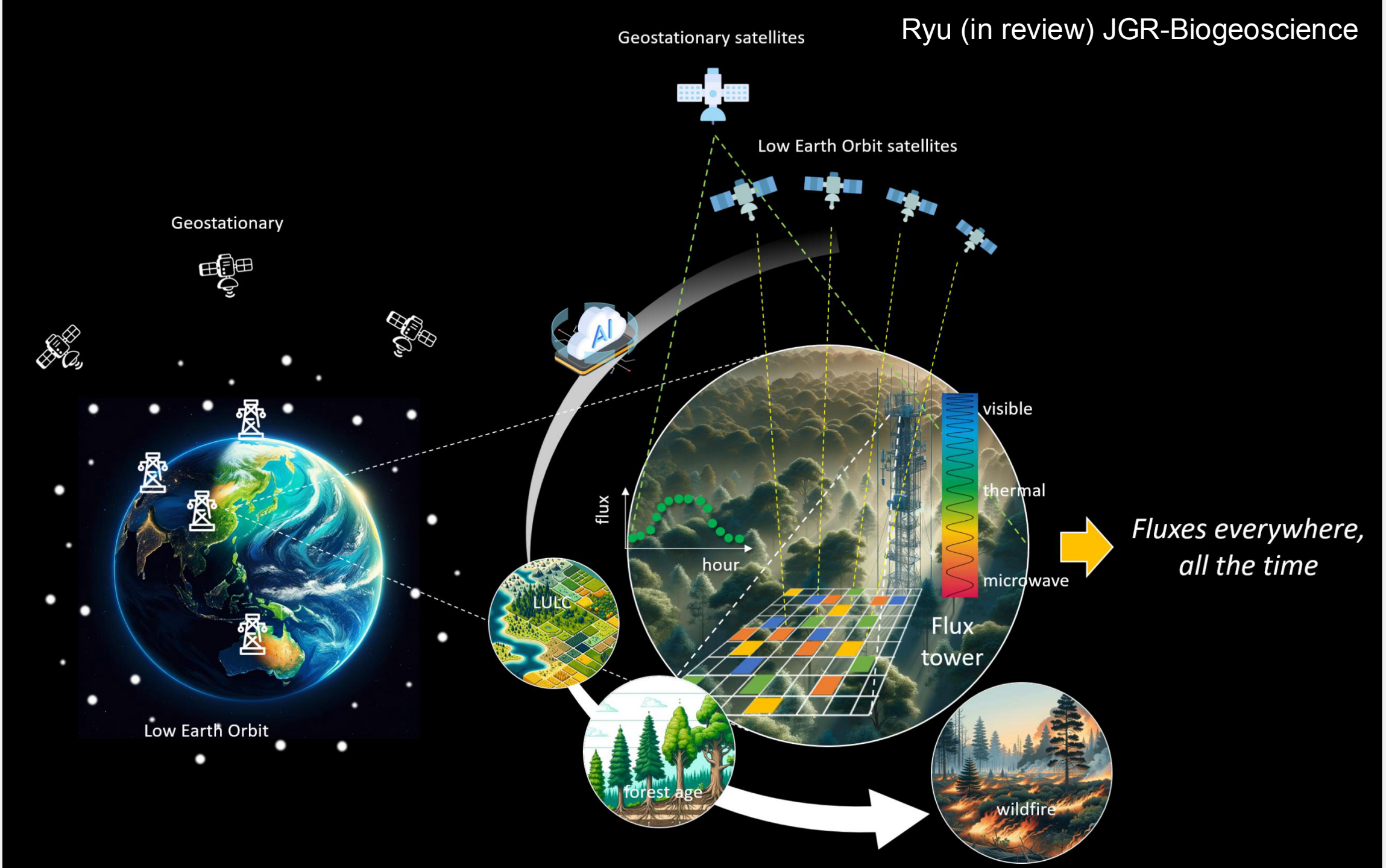




Amazing example: 20 years PEN records

-Kenlo Nishida Nasahara and Taiga Sasagawa from U Tsukuba-




Ryu (in review) JGR-Biogeoscience
Geostationary satellites
Low Earth Orbit satellites
Geostationary
AI
visible
thermal
microwave
flux
hour
LULC
Flux tower
forest age
wildfire
Low Earth Orbit
Fluxes everywhere, all the time

Take home message

- Strengthen collaborations between flux and remote sensing communities
- Install hyperspectral systems in flux towers
- Build long-term records of spectral observations
  - Shared protocols
  - Calibration, calibration, calibration….

AtmoFacts

Quantify emissions. Visualize impacts.

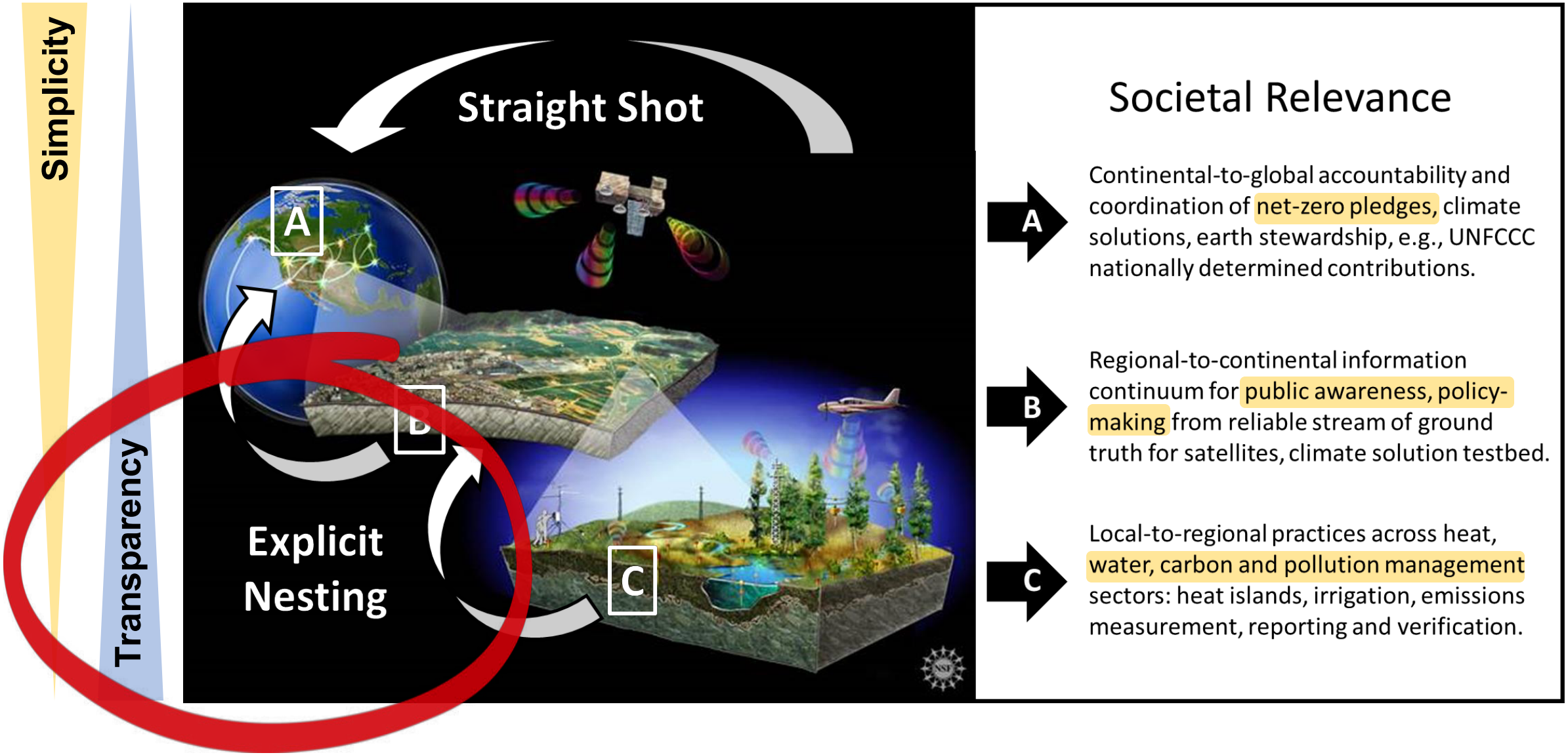
Linking Realms from Ground to Orbit

Matching Fluxes *x* States Across Scales

Stefan Metzger, Ph.D.
smetzger@atmofacts.com

Acknowledgement: NSF Award Number: 2313772 “Closing the energy balance gap at scale”

What are we scaling for?



Societal Relevance

A Continental-to-global accountability and coordination of net-zero pledges, climate solutions, earth stewardship, e.g., UNFCCC nationally determined contributions.

B Regional-to-continental information continuum for public awareness, policy-making from reliable stream of ground truth for satellites, climate solution testbed.

C Local-to-regional practices across heat, water, carbon and pollution management sectors: heat islands, irrigation, emissions measurement, reporting and verification.

Eddy-covariance (EC) in the Measurement, Reporting, Verification feature set

Feature	Spatialized EC	Classical EC	Slow EC	Atmospheric inversion	RS + model proxies	In-situ proxies, manual	Activity-based
Quantifies individual sources and sinks					✓	✓	✓
Spatial acuity and representativeness					✓		
Measures >95% emissions / removals (e.g., LCFS*)				✓			
Measures >80% emissions / removals				✓			
Measures atmospheric emissions and removals				✓			
Continuous, real time				✓			
Economic <$1K km^{-2} y^{-2}				✓	✓	✓	✓
All climate forcers				✓			

* LCFS = California Air Resources Board Low Carbon Fuel Standard

Eddy-covariance (EC) in the Measurement, Reporting, Verification feature set

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Measures >80% emissions / removals		✓		✓			
Measures atmospheric emissions and removals		✓	✓	✓			
Continuous, real time		✓	✓	✓			
Economic <$1K km^{-2} y^{-2}			✓	✓	✓	✓	✓
All climate forcers		✓	✓	✓			

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Quantifies individual sources and sinks	✓				✓	✓	✓
Spatial acuity and representativeness	✓				✓		
Measures >95% emissions / removals (e.g., LCFS*)	✓			✓			
Measures >80% emissions / removals	✓	✓		✓			
Measures atmospheric emissions and removals	✓	✓	✓	✓			
Continuous, real time	✓	✓	✓	✓			
Economic <$1K km^{-2} y^{-2}	✓		✓	✓	✓	✓	✓
All climate forcers	✓	✓	✓	✓			

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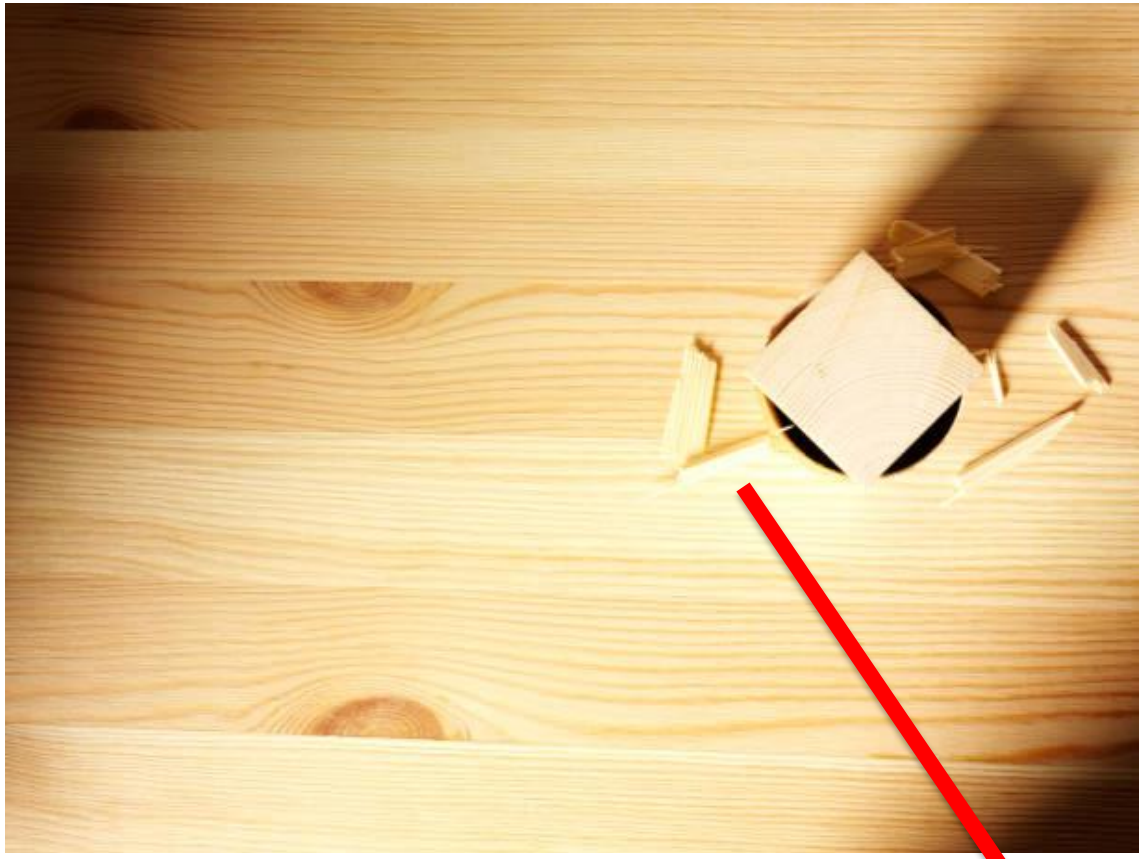
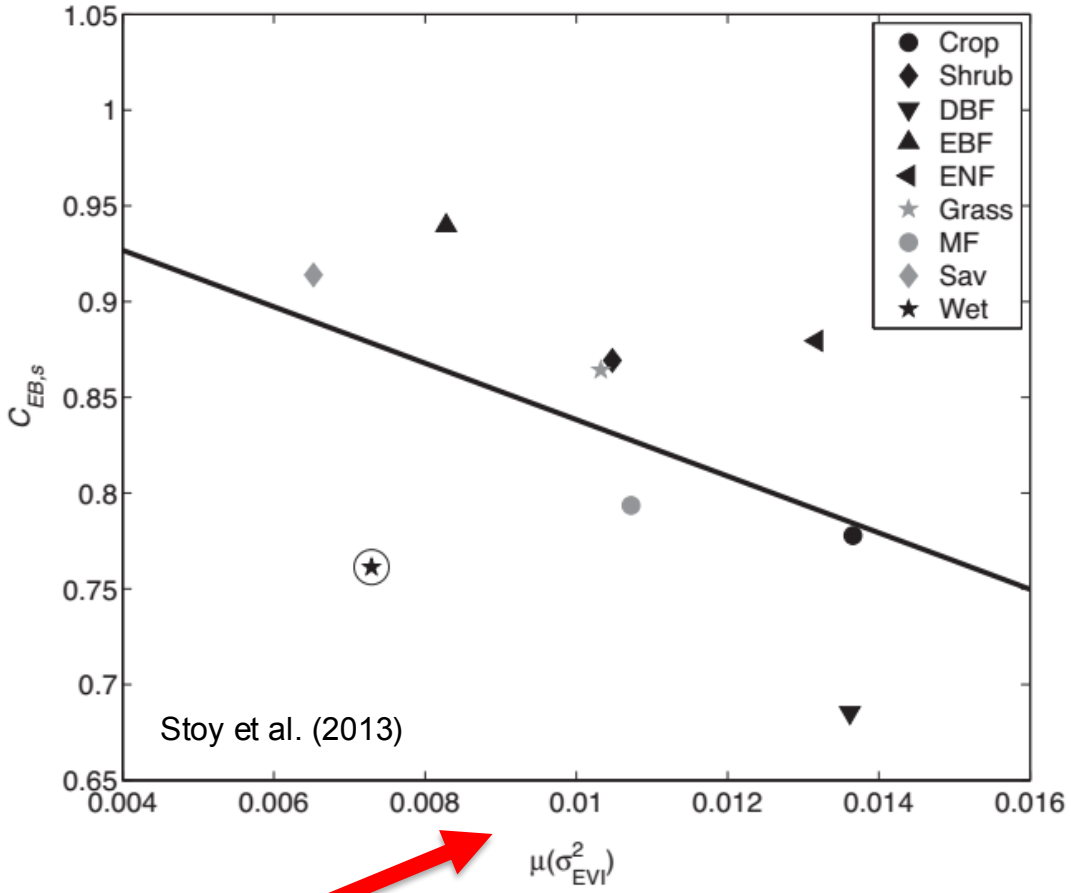
Eddy-covariance (EC) in the Measurement, Reporting, Verification feature set

Feature	Spatialized EC	Classical EC	Slow EC	Atmospheric inversion	RS + model proxies	In-situ proxies, manual	Activity-based
Quantifies individual sources and sinks	✓				✓	✓	✓
Spatial acuity and representativeness	✓				✓		
Measures >95% emissions / removals (e.g., LCFS*)	✓			✓			
Measures >80% emissions / removals	✓	✓		✓			
Measures atmospheric emissions and removals	✓	✓	✓	✓			
Continuous, real time	✓	✓	✓	✓			
Economic <$1K km^{-2} y^{-2}	✓		✓	✓	✓	✓	✓
All climate forcers	✓	✓	✓	✓			

* LCFS = California Air Resources Board Low Carbon Fuel Standard

Account for missing fluxes by satisfying the micrometeorology

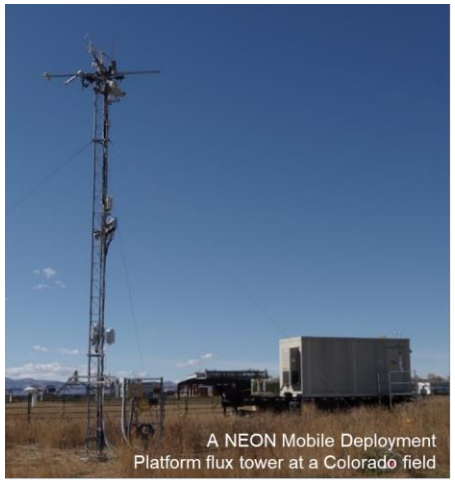




20% - 40% missing flux

AtmoFacts

From observational puzzle to continuity of energy and mass

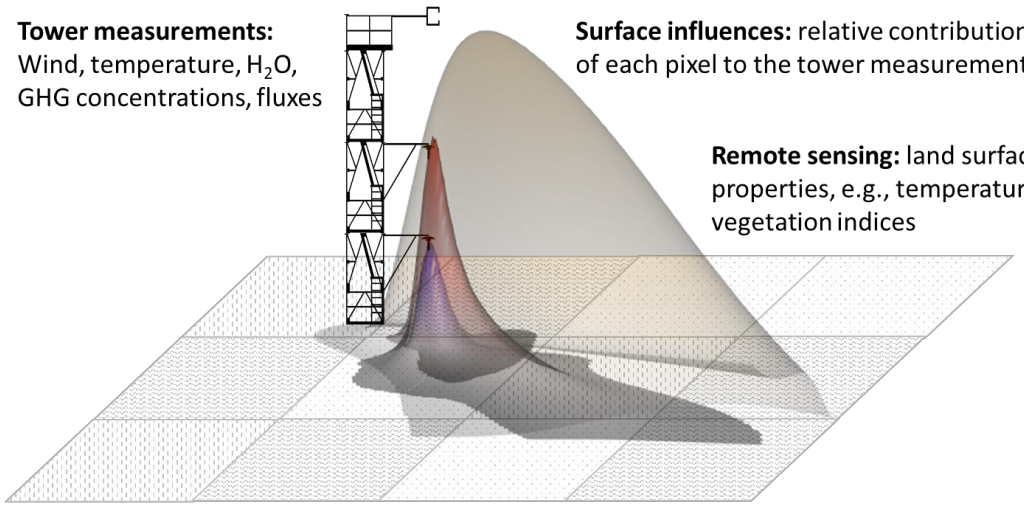


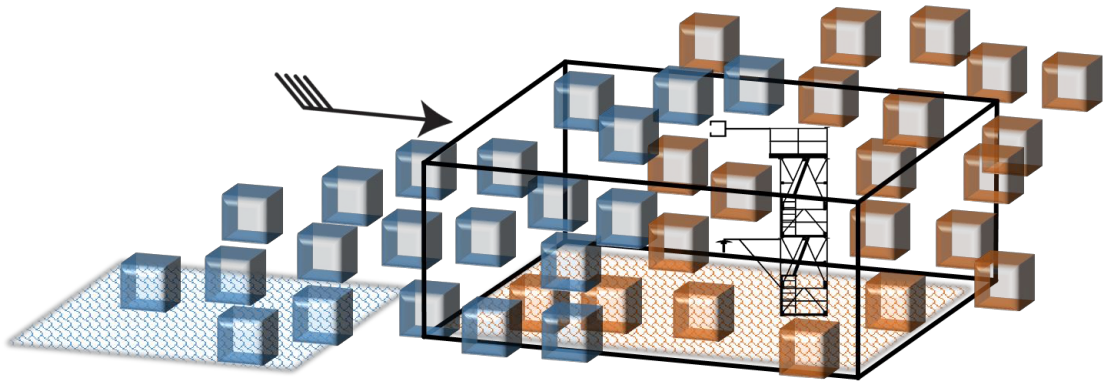
Classical EC

Tower measurements:
Wind, temperature, H_2O,
GHG concentrations, fluxes

Surface influences: relative contribution of each pixel to the tower measurements

Remote sensing: land surface properties, e.g., temperature, vegetation indices

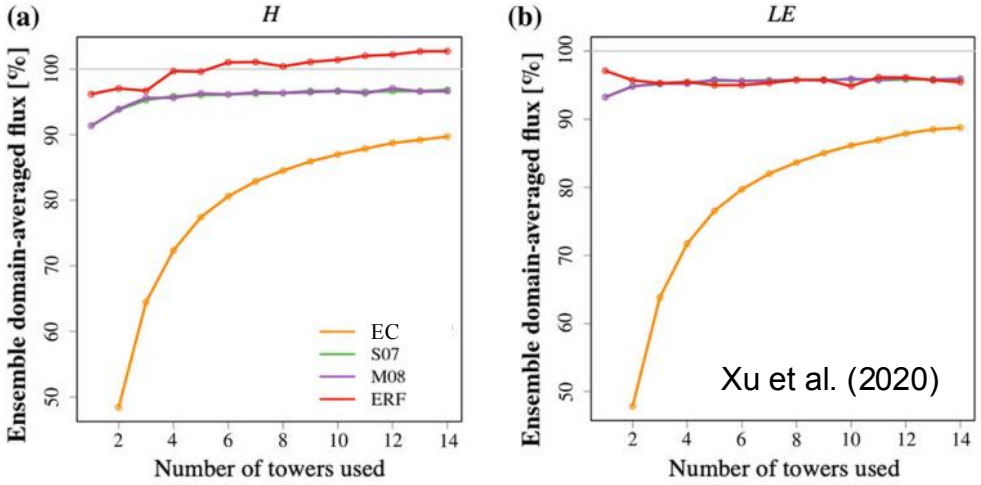




Adopted from: Metzger (2018)

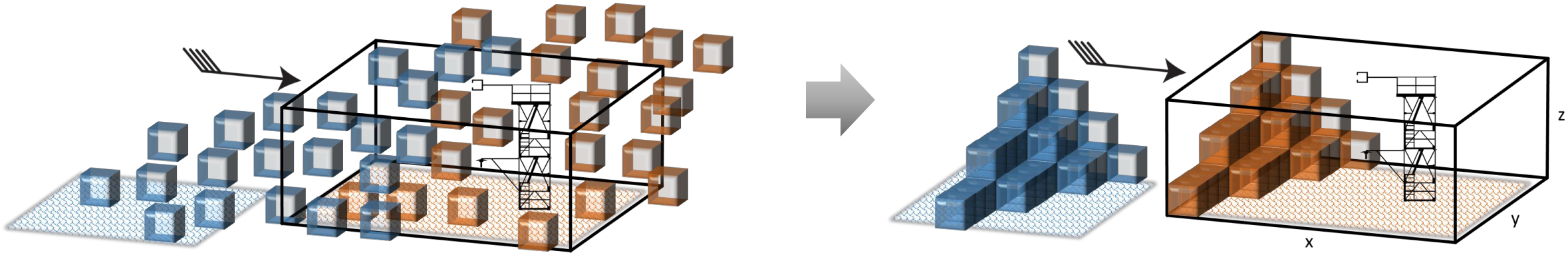
AtmoFacts

From observational puzzle to continuity of energy and mass



Classical EC

Spatialized EC



Adopted from: Metzger (2018)

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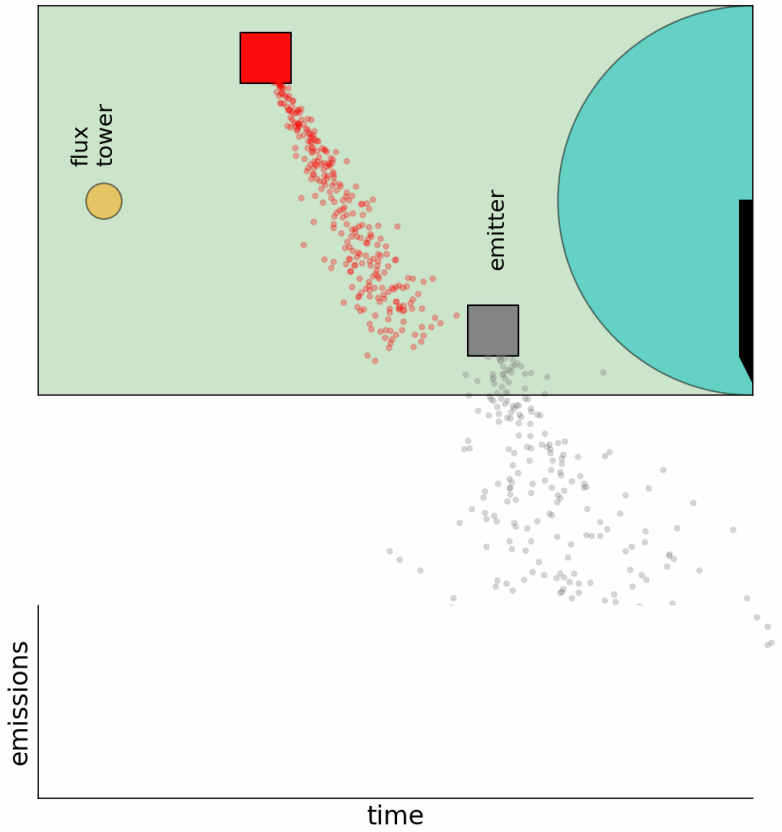
Eddy-covariance (EC) in the Measurement, Reporting, Verification feature set

Feature	Spatialized EC	Classical EC	Slow EC	Atmospheric inversion	RS + model proxies	In-situ proxies, manual	Activity-based
Quantifies individual sources and sinks	✓				✓	✓	✓
Spatial acuity and representativeness	✓				✓		
Measures >95% emissions / removals (e.g., LCFS*)	✓			✓			
Measures >80% emissions / removals	✓	✓		✓			
Measures atmospheric emissions and removals	✓	✓	✓	✓			
Continuous, real time	✓	✓	✓	✓			
Economic <$1K km^{-2} y^{-2}	✓		✓	✓	✓	✓	✓
All climate forcers	✓	✓	✓	✓			

* LCFS = California Air Resources Board Low Carbon Fuel Standard

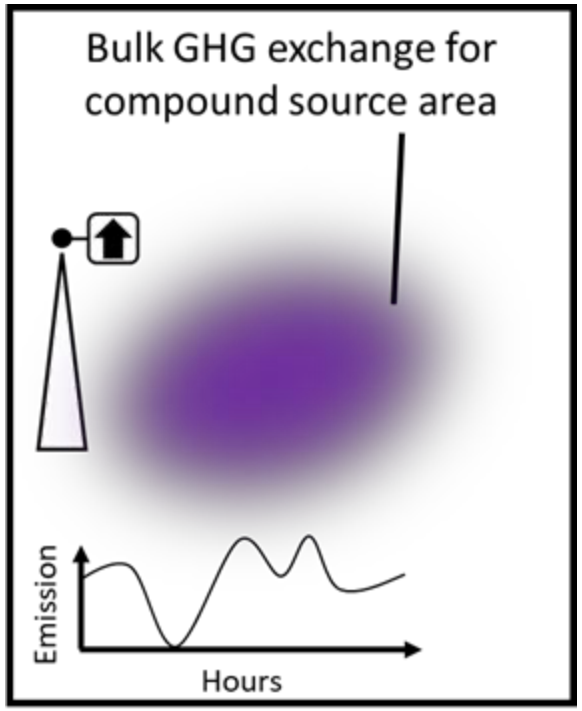
Quantify individual sources and sinks

Classical 30-min mixing



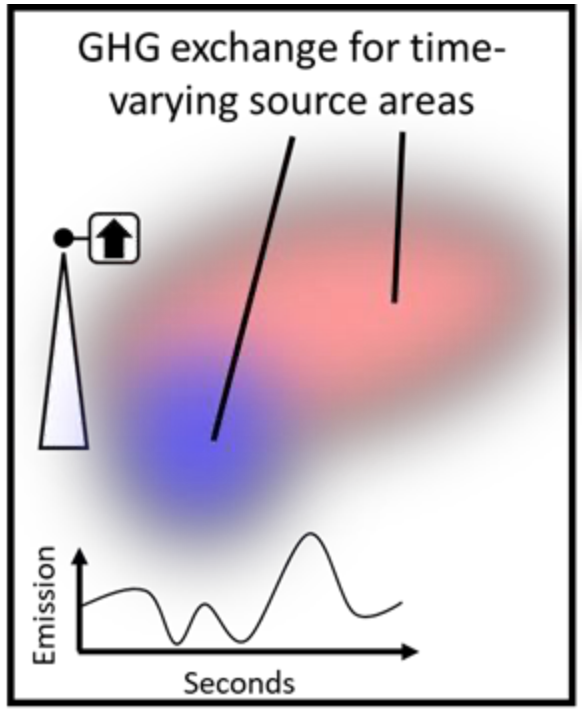
Spatialized EC runs high-resolution fluxes backwards on the wind

Classical 30-min mixing



- 1 x 30-min data point
- 7+ decades tradition
- Information averaging
- Ambiguous attribution

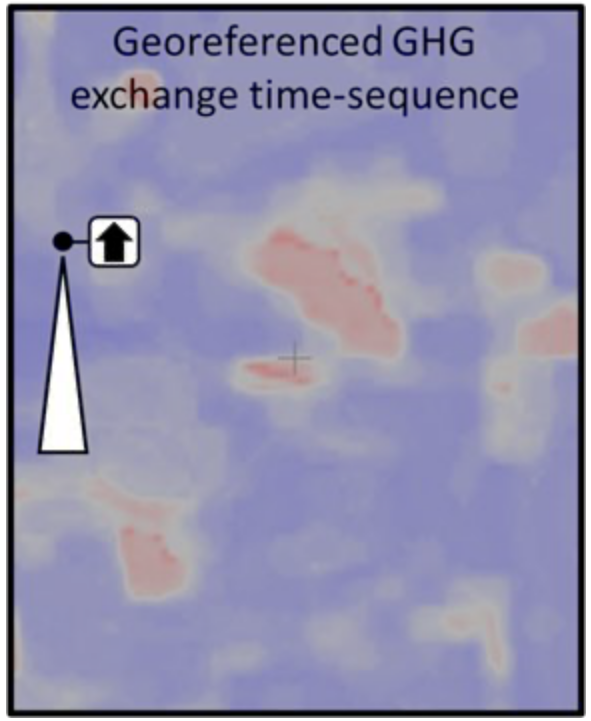
Flux tower 20 Hz data



- 10,000s x 20 Hz points in time

7+ decades innovation: time-frequency decomposition, dispersion modeling, physics-guided AI;
10 - 100 X statistical power

Spatialized EC 30-min un-mixing



- 10,000s x 30-min pixels in space
- NKOTB, dozens applications
- Information transcription
- **Unambiguous attribution**

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Eddy-covariance (EC) in the Measurement, Reporting, Verification feature set

Feature	Spatialized EC	Classical EC	Slow EC	Atmospheric inversion	RS + model proxies	In-situ proxies, manual	Activity-based
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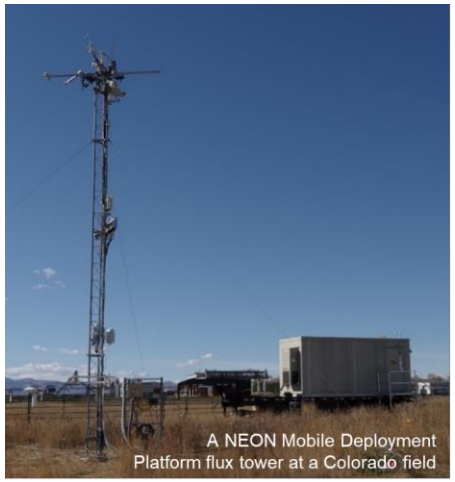
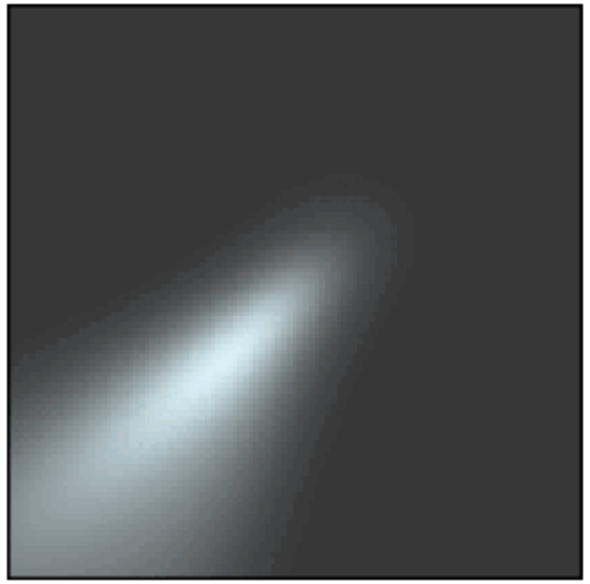
Measures atmospheric emissions and removals	✓	✓	✓	✓			
Continuous, real time	✓	✓	✓	✓			
Economic <$1K km^{-2} y^{-2}	✓		✓	✓	✓	✓	✓
All climate forcers	✓	✓	✓	✓			

* LCFS = California Air Resources Board Low Carbon Fuel Standard

High-resolution attribution and scale extension for direct flux towers



Classical Flux Tower



Credit: US-PFa tower data (desai@aos.wisc.edu), Flux Mapper (smetzger@atmofacts.com)

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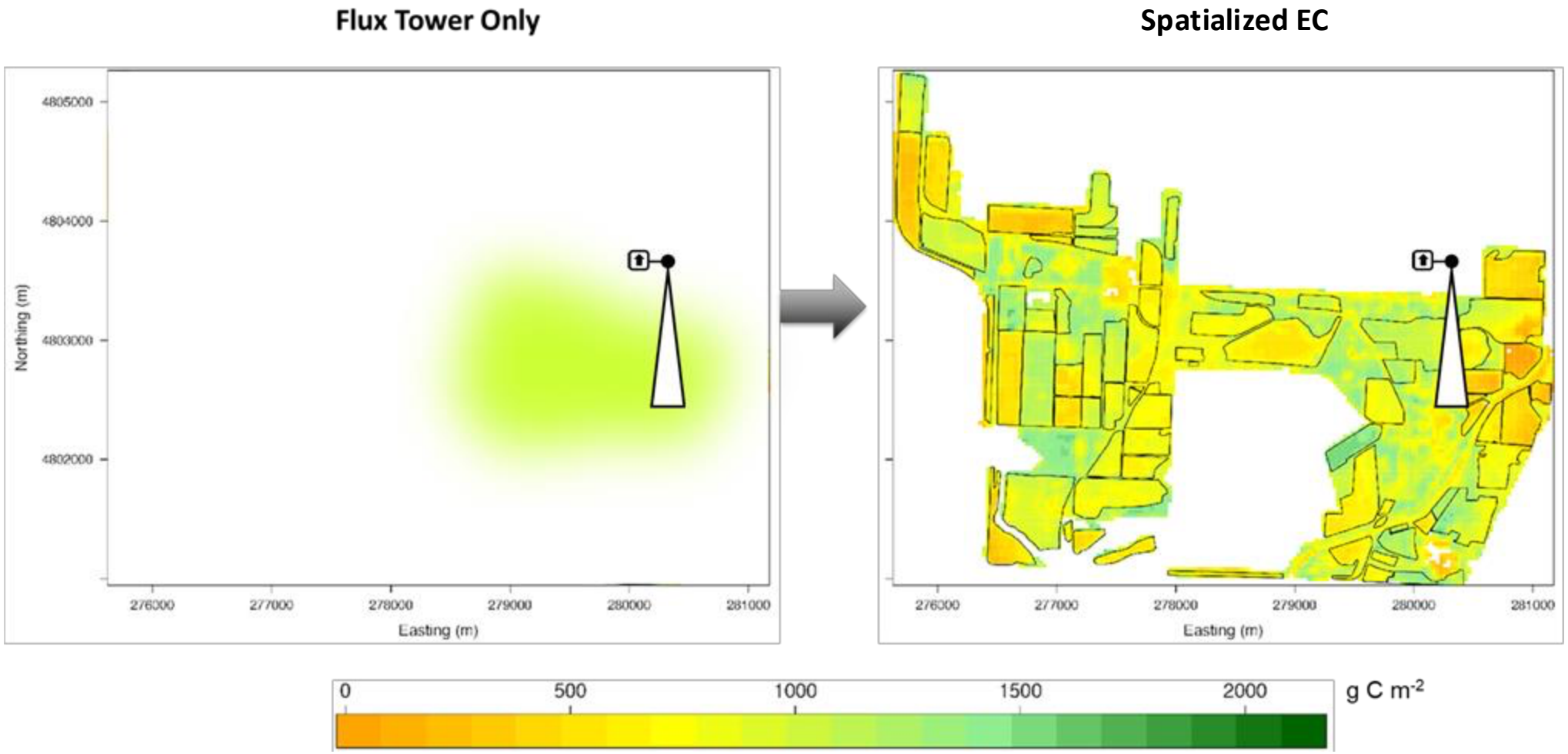
Real-world case study – dairy farm flux tower



Adopted from: Wiesner et al. (2022)

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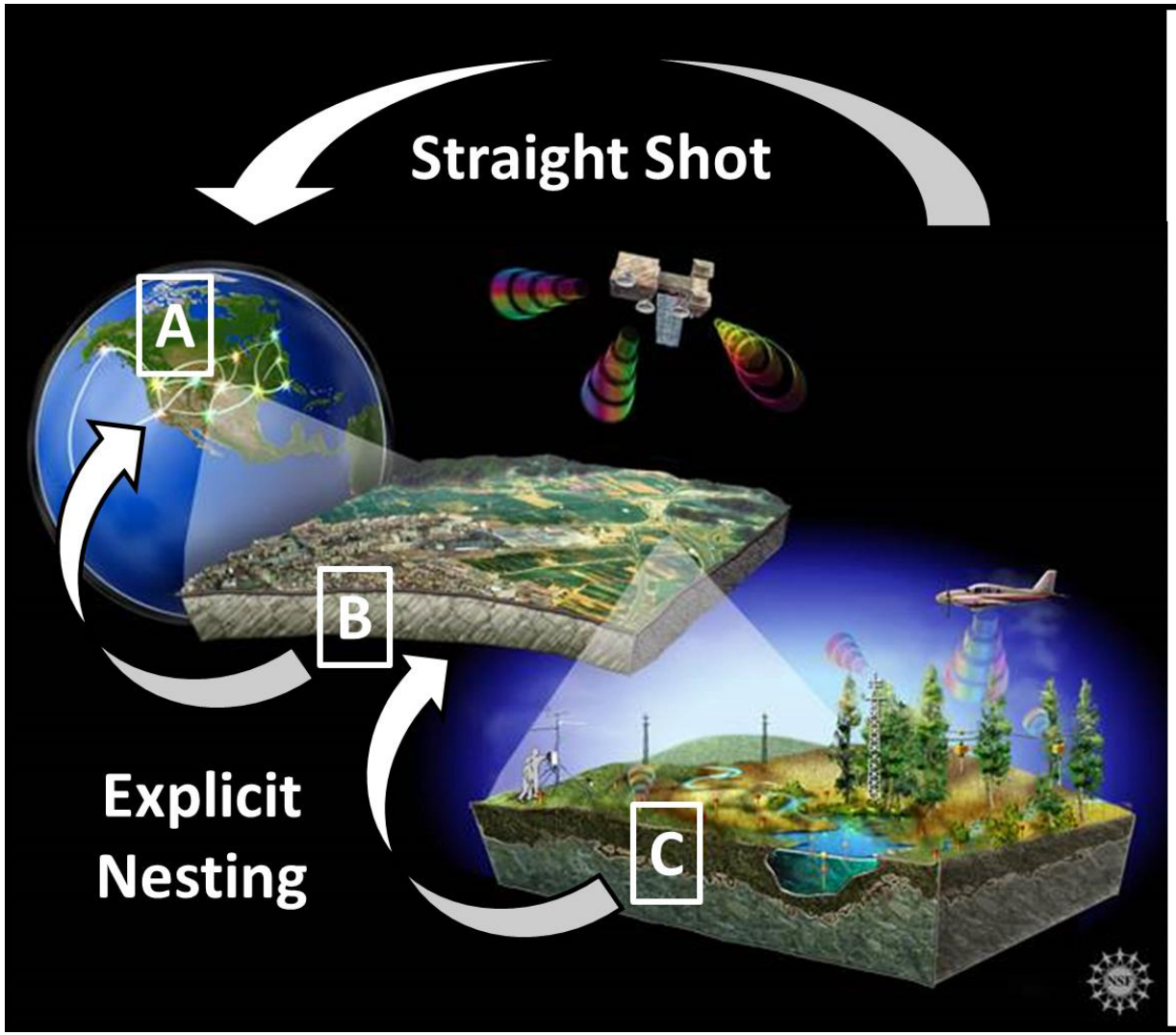
“Right-scaling” recipe

Simplicity

Transparency



“Recipe”

- Sensible choice among “straight shot” and “explicit nesting” to meet the demands of the task at hand.
- “Straight shot” affords simplicity but struggles with scale-emergent properties such as continuity of energy and mass.
- “Explicit nesting” propagates spatial and temporal controls separately, makes data intuitive to use and serves as “Flux Tower Multiplier”.

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Quantify emissions. Visualize impacts.

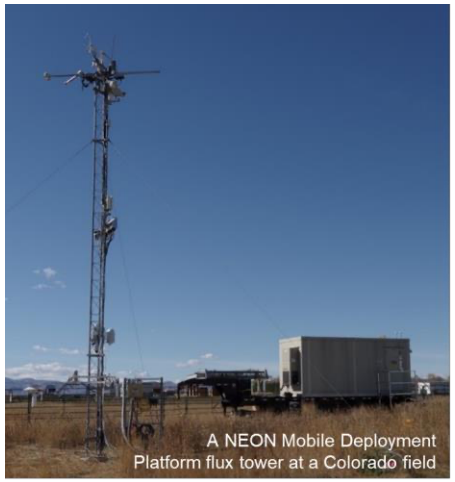
Linking Realms from Ground to Orbit

Matching Fluxes *x* States Across Scales

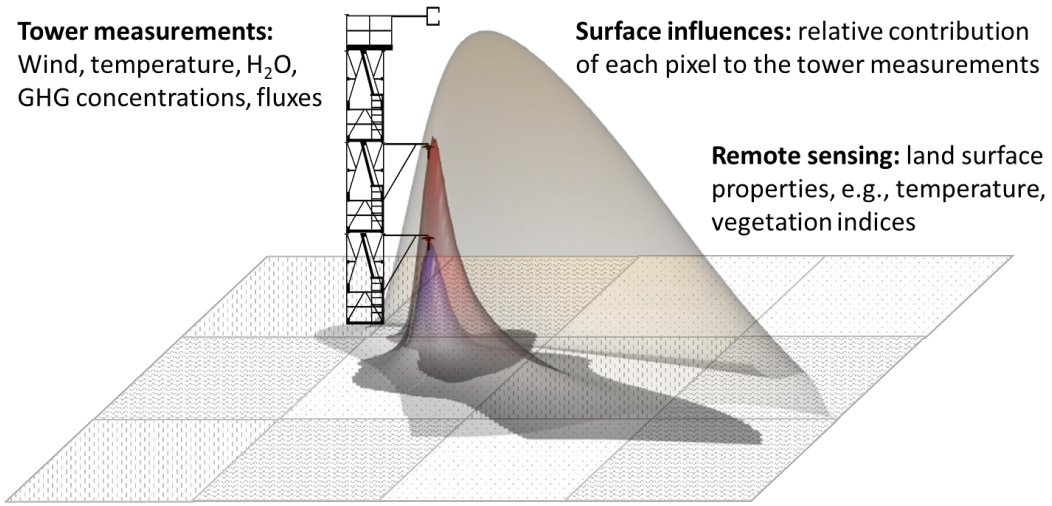
Stefan Metzger, Ph.D.
smetzger@atmofacts.com

Acknowledgement: NSF Award Number: 2313772 “Closing the energy balance gap at scale”

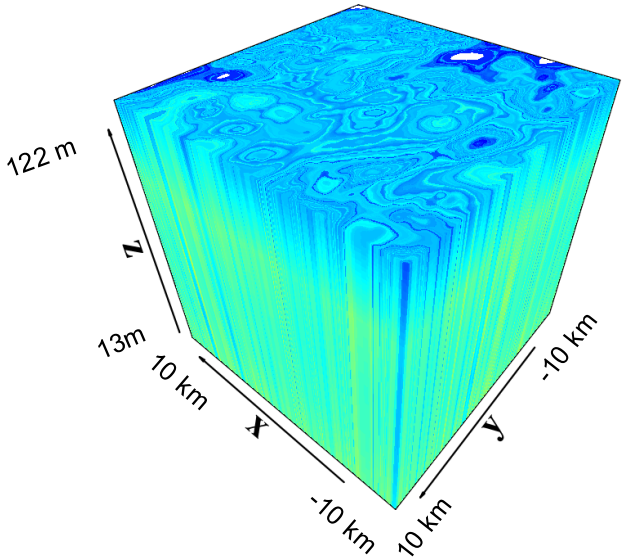
From observational puzzle to continuity of energy and mass



Classical EC



Spatialized EC



Adopted from: Metzger (2018)

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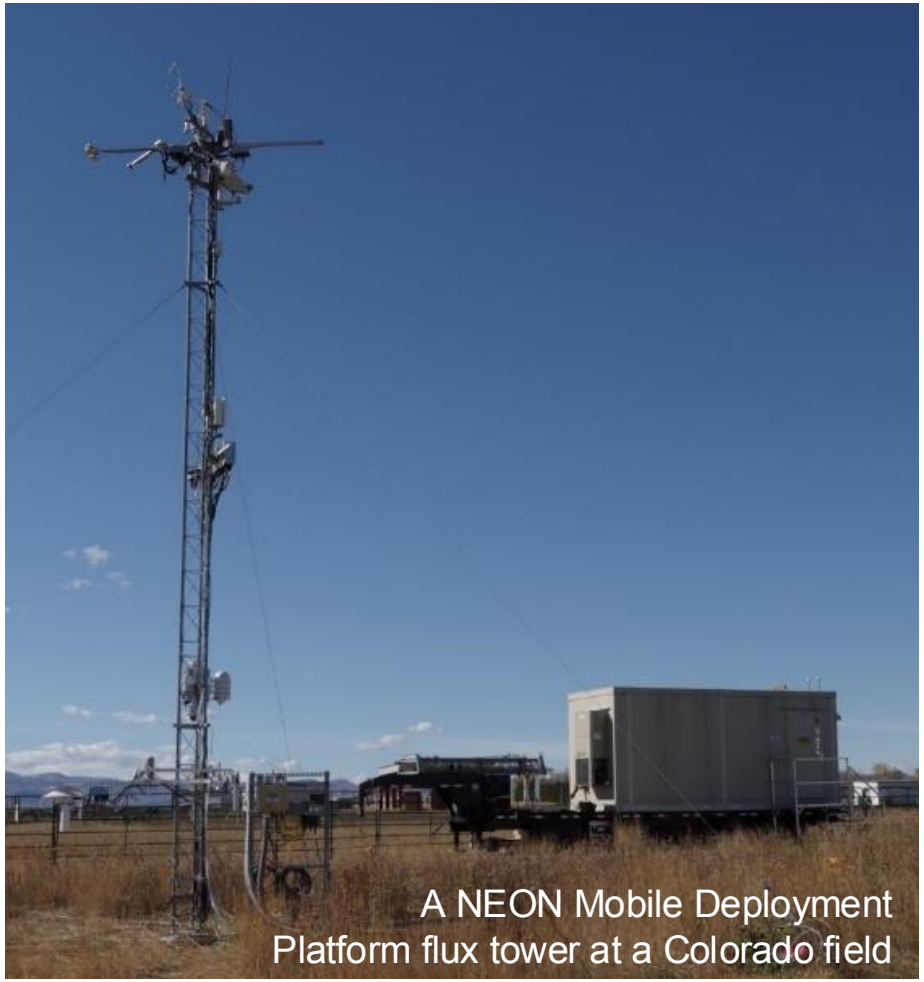
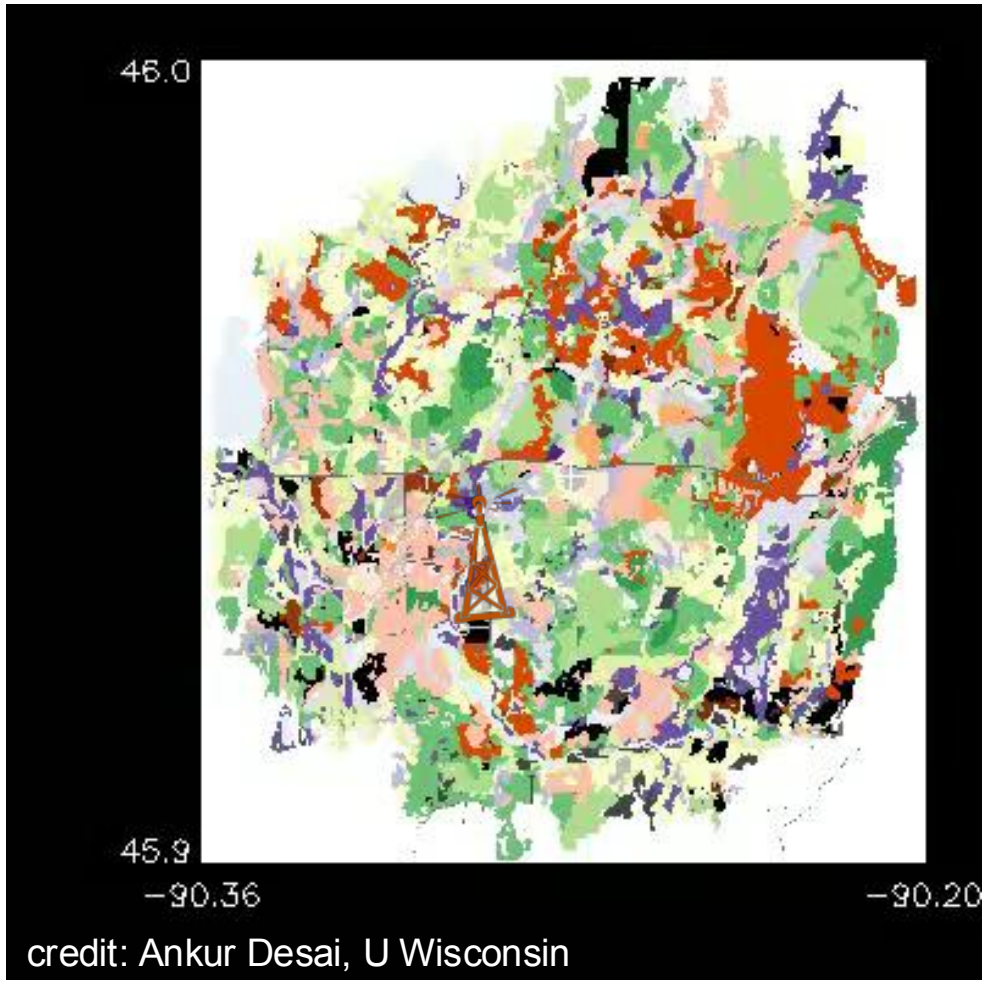
Quantify individual sources and sinks



A NEON Mobile Deployment Platform flux tower at a Colorado field



credit: Ankur Desai, U Wisconsin

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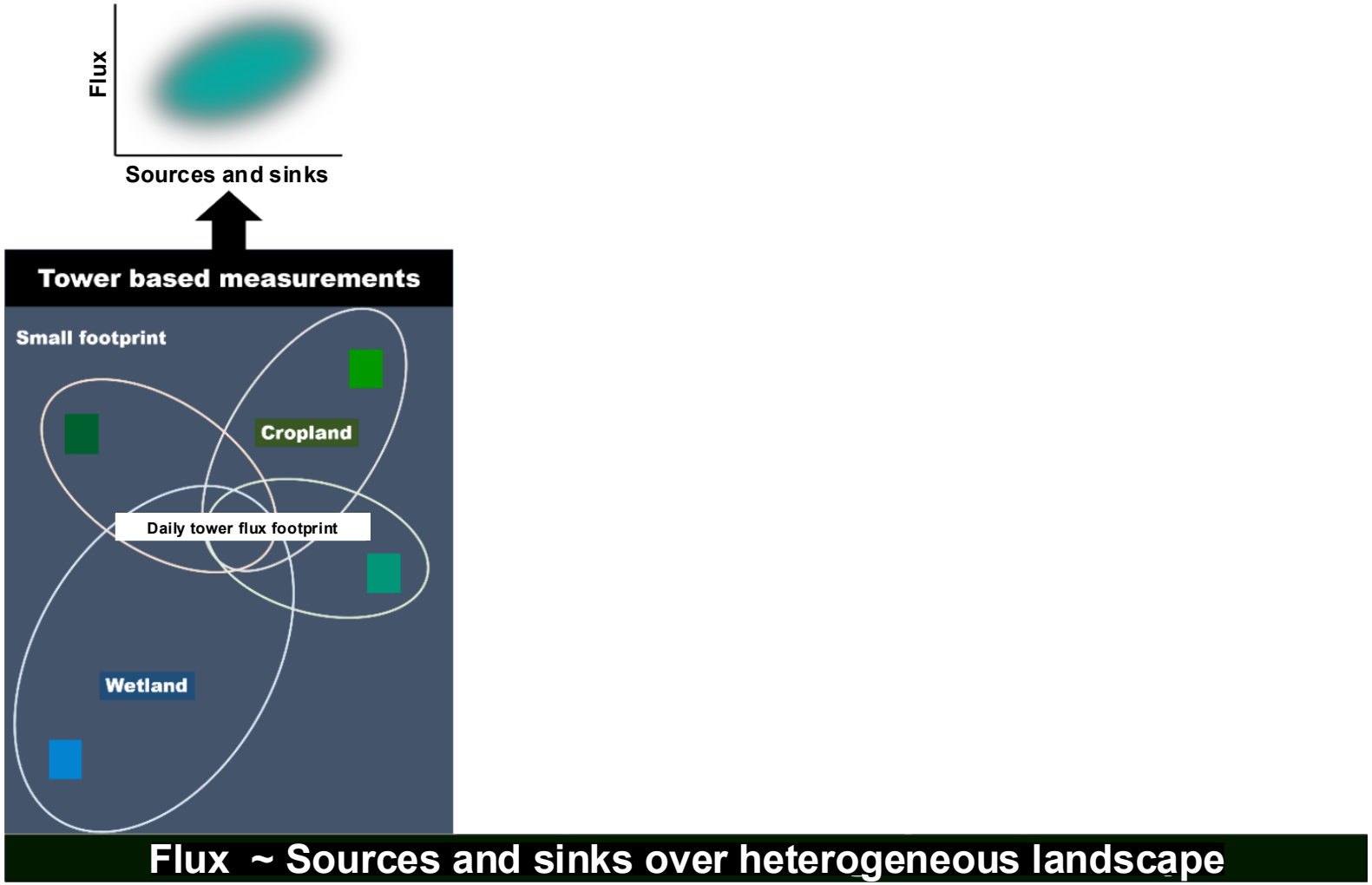
Spatialized EC runs high-resolution fluxes backwards on the wind

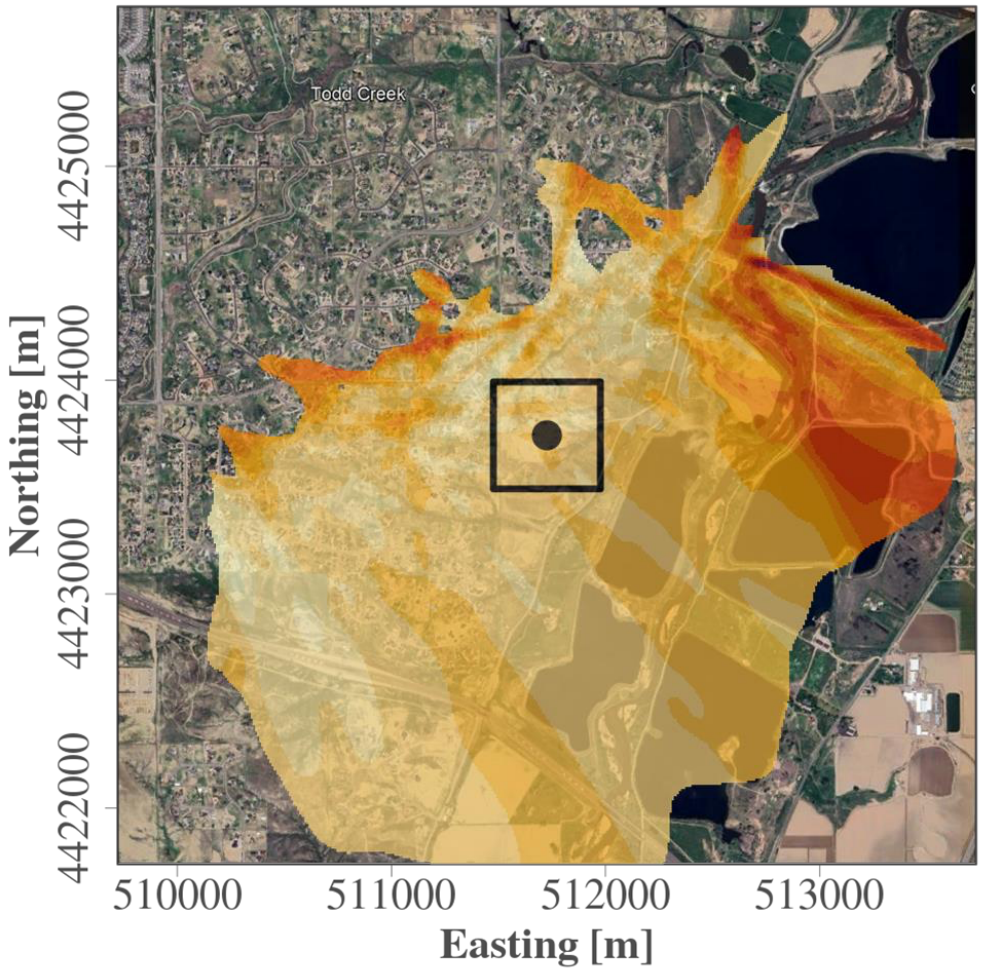
High spatiotemporal resolution quantifies individual sources and sinks through time



Adopted from: Kong et al. (2022)

Real-world case study – Oil and Gas unmanned methane flux aircraft

In partnership with Black Swift TECHNOLOGIES



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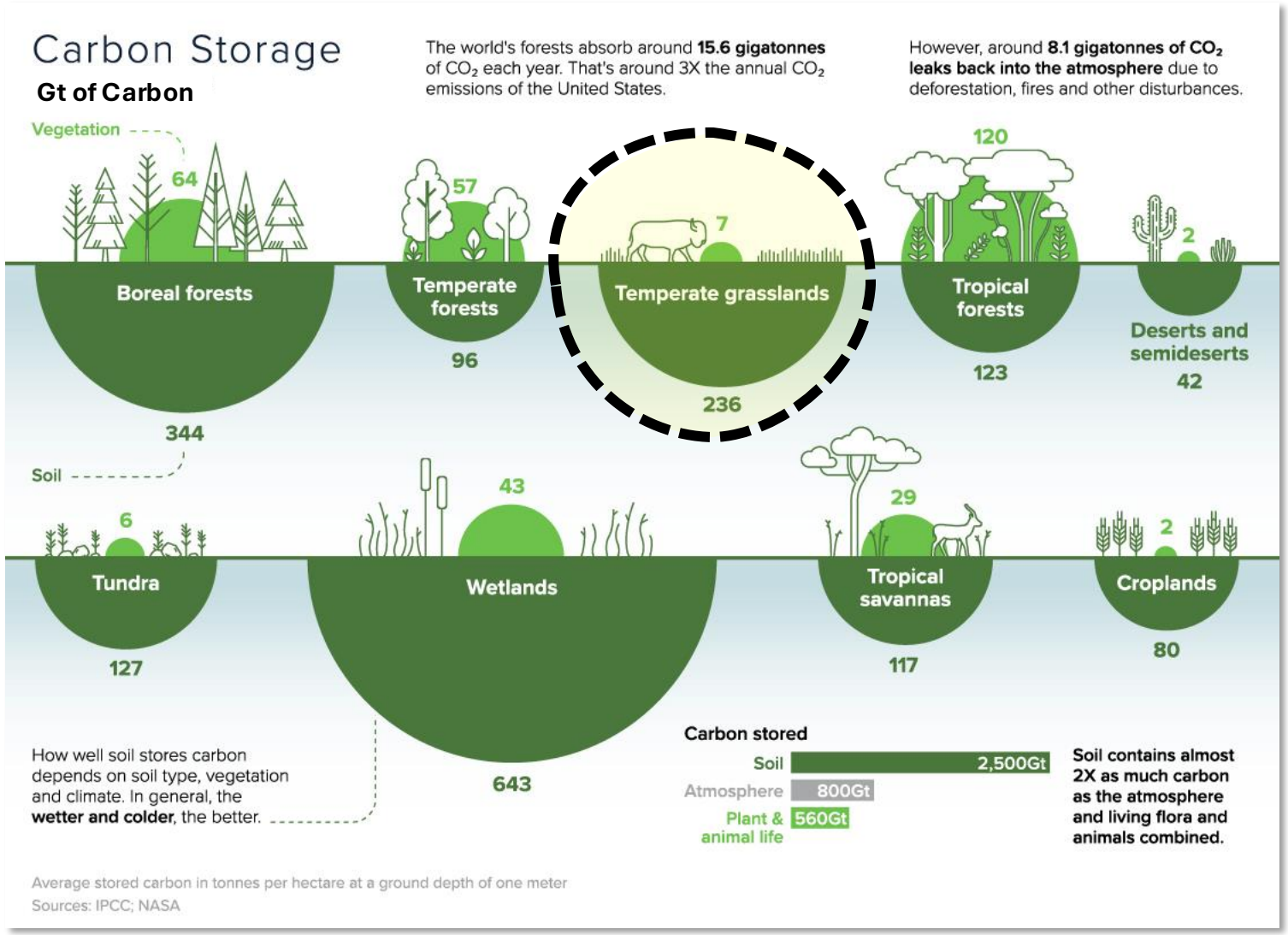
Bridging the gap between science and social benefit: Eddy flux for measurement, reporting and verification of grassland carbon sequestration

Kevin Tu, Kateri Environmental

AmeriFlux Workshop: Remote Sensing and Fluxes Upscaling for Real-world Impact, July 9-10, 2024, LBNL

Why Focus on Grasslands?

Sustainable land management and conservation of terrestrial ecosystems are crucial for achieving Sustainable Development Goals (SDGs) → including **climate change mitigation** and **reducing biodiversity loss**, **social/community benefits**



https://www.visualcapitalist.com/sp/visualizing-carbon-storage-in-earths-ecosystems/

- Grazing lands (mostly grasslands) occupy about half of the planets land surface[1]
- Within US, grazing lands cover ~28% of the land area (655M acres)[2]
- About 20% of the worlds soil organic carbon (1500 Gt) resides in grazing lands[2]
- The large soil carbon 'debt' due to human activity has potential to be restored[3]

1-World Wildlife Fund (www.worldwildlife.org);
2-Noble Research Institute (www.noble.org/3m);
3-Sanderman et al. (2017: Soil carbon debt of 12,000 years of human land use, PNAS, 114(36): 9575-9580)

1. There is a massive increase in offset and inset credit purchasing – especially in nature based markets

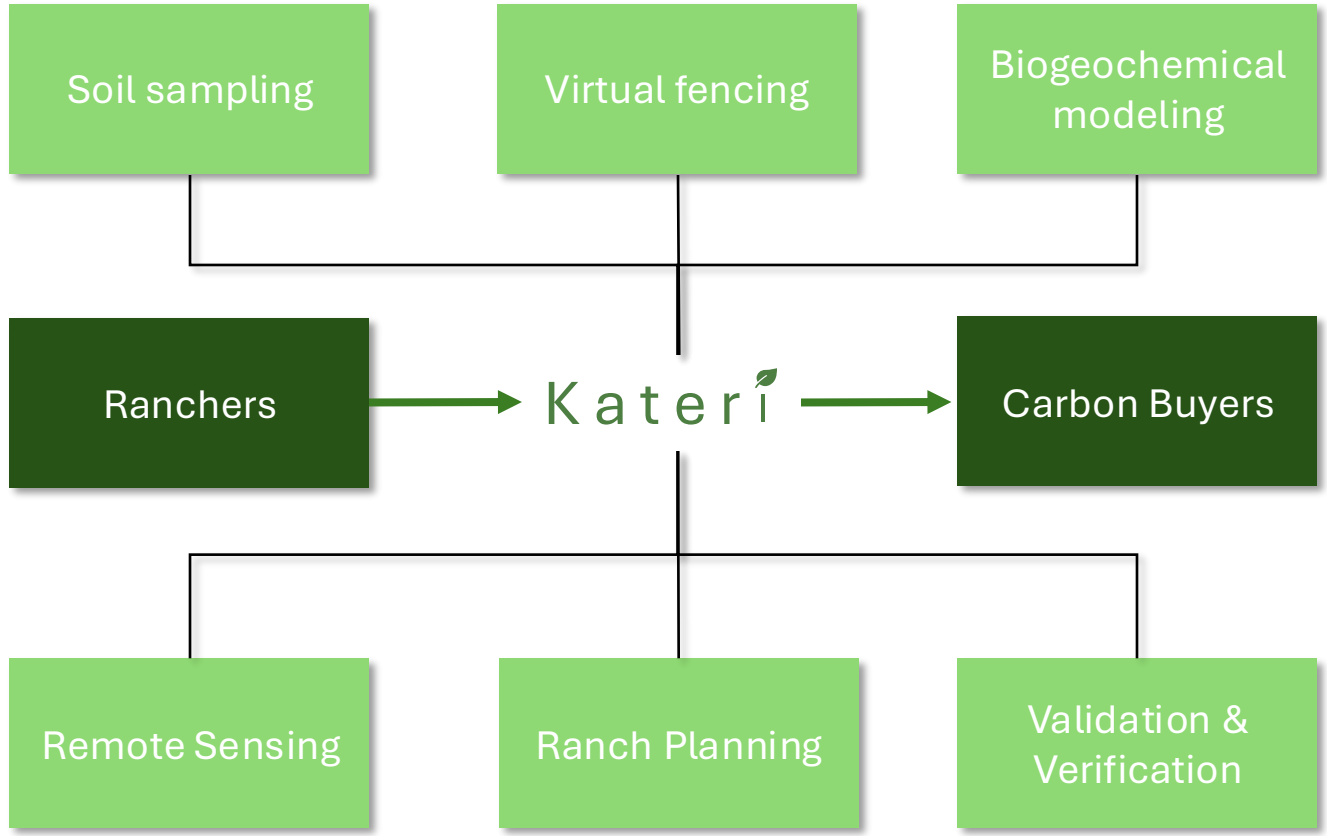
2. Grasslands are an underutilized carbon sink and ranching has historically lacked the technology to scale regenerative methods

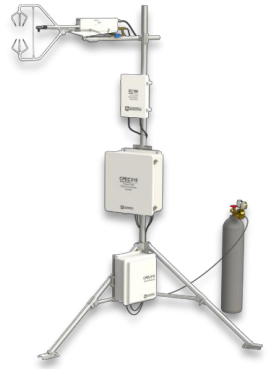
3. Governments around the world are dedicating huge funds to spur more climate friendly agriculture

Significant opportunity for nature-based solutions in one of the world's largest ecosystems

Kateri is a tech-enabled carbon developer combining biogeochemical modeling, virtual fencing, and advancements in soil measurements to unlock the carbon sequestration potential of grasslands through rotational grazing

***Kateri** provides end-to-end services for ranchers to capture the potential of their natural capital*

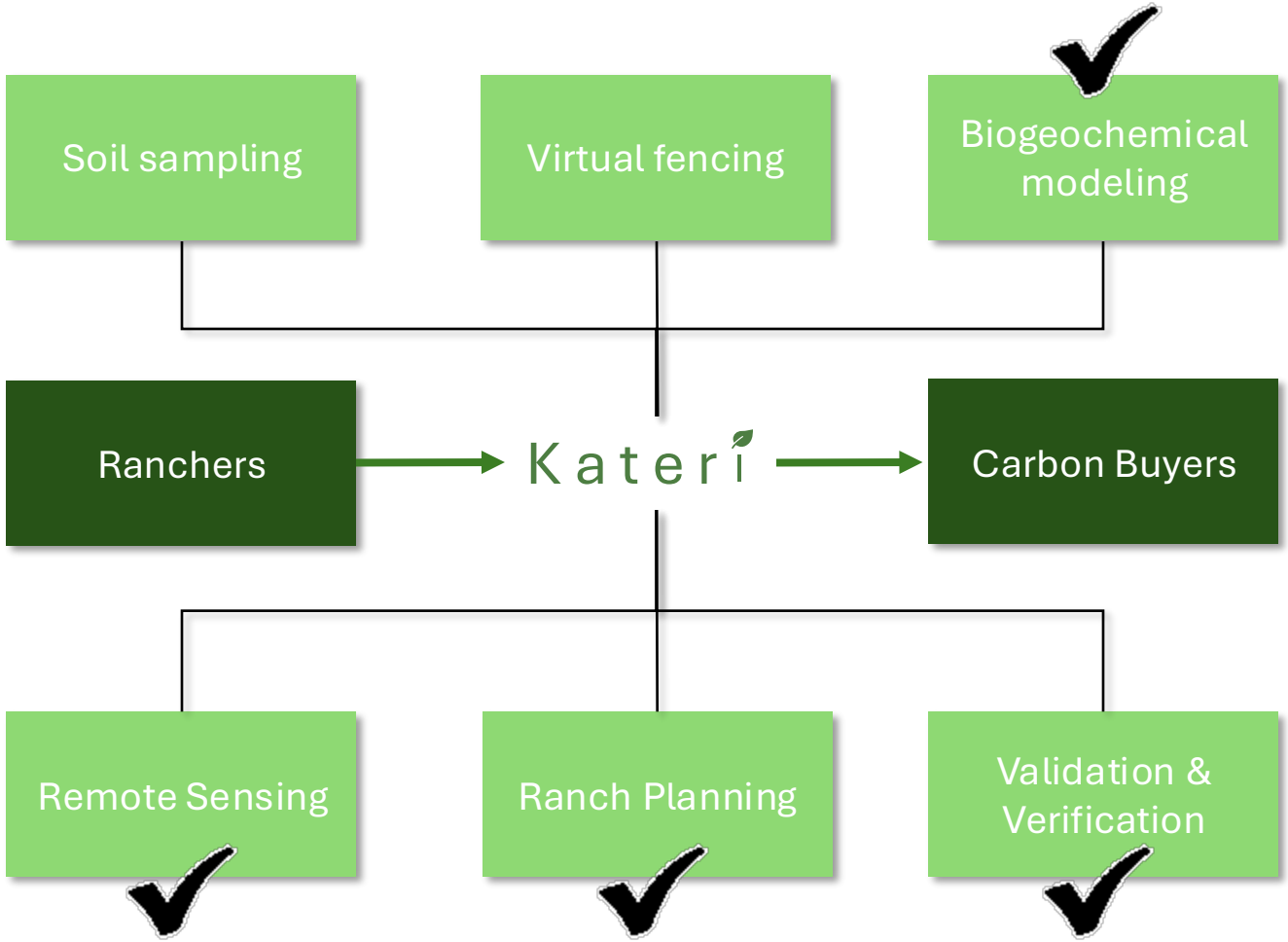




Flux data enables

- biogeochemical model cal/val
- upscaling with remote sensing to project level
- real-time monitoring of management decisions impacts
- verification and validation

Where do flux towers fit in?

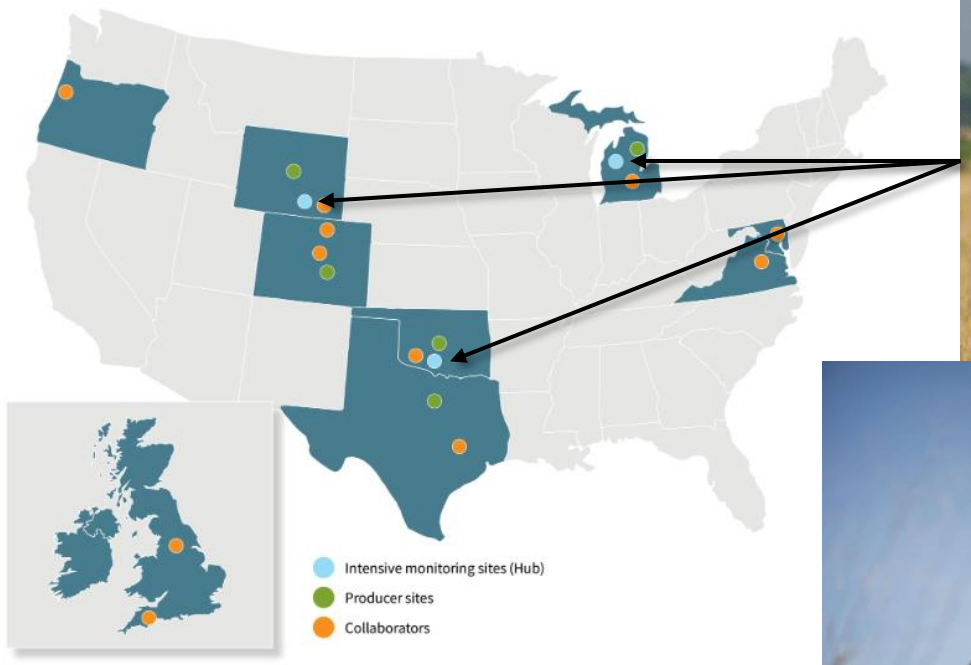


Eddy Flux as the de facto Method for Rangeland Research

1. Rangeland Carbon Tracking and Management (RCTM) system – data from 61 AmeriFlux and NEON sites

2. Metrics, Management, and Monitoring (3M) project – 30 new low-cost flux towers deployed

Researchers from 11 nonprofit organizations, private research organizations and public universities in the United States and the United Kingdom.



- 30 LC flux towers deployed in first year
- 58 LC total towers planned
- SOC stock measurements
- Remote sensing
- Ecosystem biogeochemical modeling

Noble Research Institute (www.noble.org/3m)

Pilot Implementation of Low-cost Eddy Flux for Project Development

Quanterra (https://www.quanterrasystems.com/)

Deploying low-cost Quanterra systems in four rangeland carbon projects

- Prior studies establish low-cost systems as potential alternatives to conventional eddy covariance (Cunliffe et al. 2022, van Ramshorst et al. 2024, Callejas-Rodelas et al. 2024)
- Site locations span a range of climate, soil, vegetation conditions
- Data to be used for **calibration and validation of rangeland carbon flux models** (e.g. MEMS, SNAPGRAZE, RCTM) in combination with SOC stocks

Additional low-cost flux systems to consider

- Licor low-cost eddy flux (still in development)
- Variance Bowen Ratio
- Surface Renewal

Challenges for Eddy Flux with Grassland NbS Projects

https://www.bovinevetonline.com/

Cost – Conventional eddy covariance systems are too expensive (for credit prices & sequestration rates)

Accuracy – Eddy flux historically used to inform functional relationships but NbS requires a shift in focus to **defensible cumulative NEE** – *How do we minimize uncertainty and ensure accuracy and precision?*

Strong **topographic variation** in typical rangeland landscapes limits tower placement

Low fluxes typify low productivity rangeland systems, near uncertainty limits of conventional EC

Standards – eddy covariance currently not permitted by registries for grassland CO2 sequestration or model cal/val *– We need guidelines and protocols to facilitate its wider and proper use*

Next Steps

- **System of systems** – Combining eddy flux with soil SOC stock measurements, animal GPS tracking, remote sensing and modeling
- **Measure-measure** rather than measure-model – Use ‘control towers’ on conventionally and/or ungrazed pastures for baseline or reference scenarios
- **Flux Mapping** – monitor different pastures with a single tower for real-time grazing management: