Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation

Forrest M. Hoffman

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2024 EESM PI Meeting
Rockville, Maryland, USA

RUBISCO

EESM-RGMA RUBISCO Science Focus Area (SFA)

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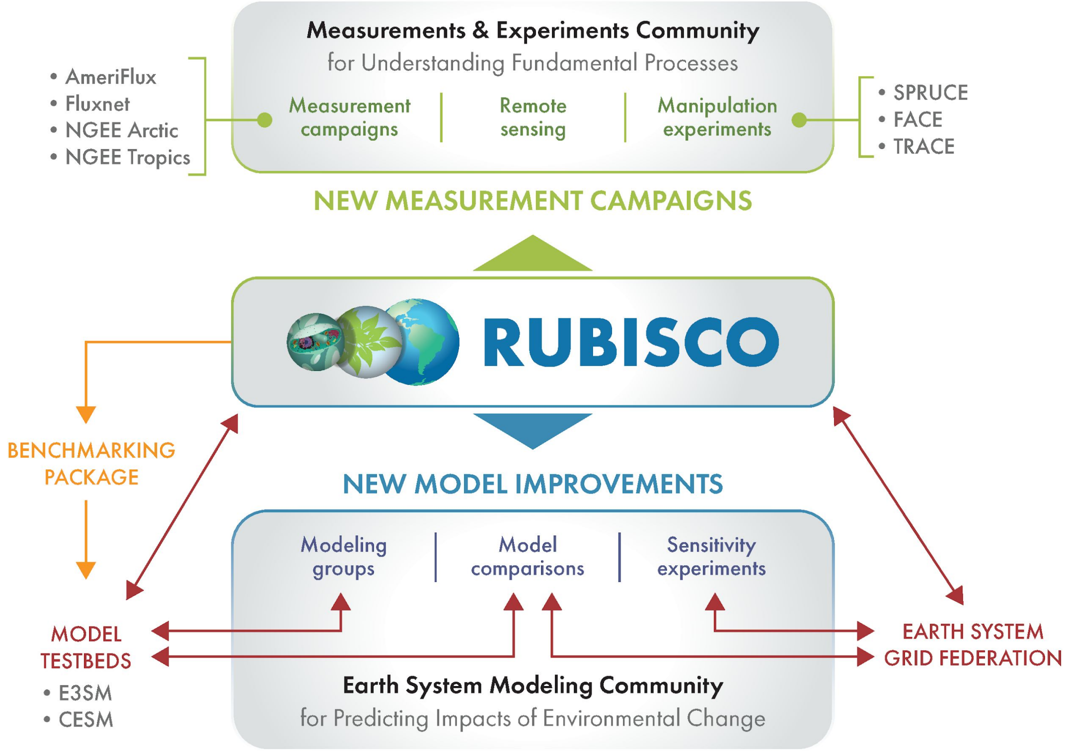
RUBISCO Research Goals

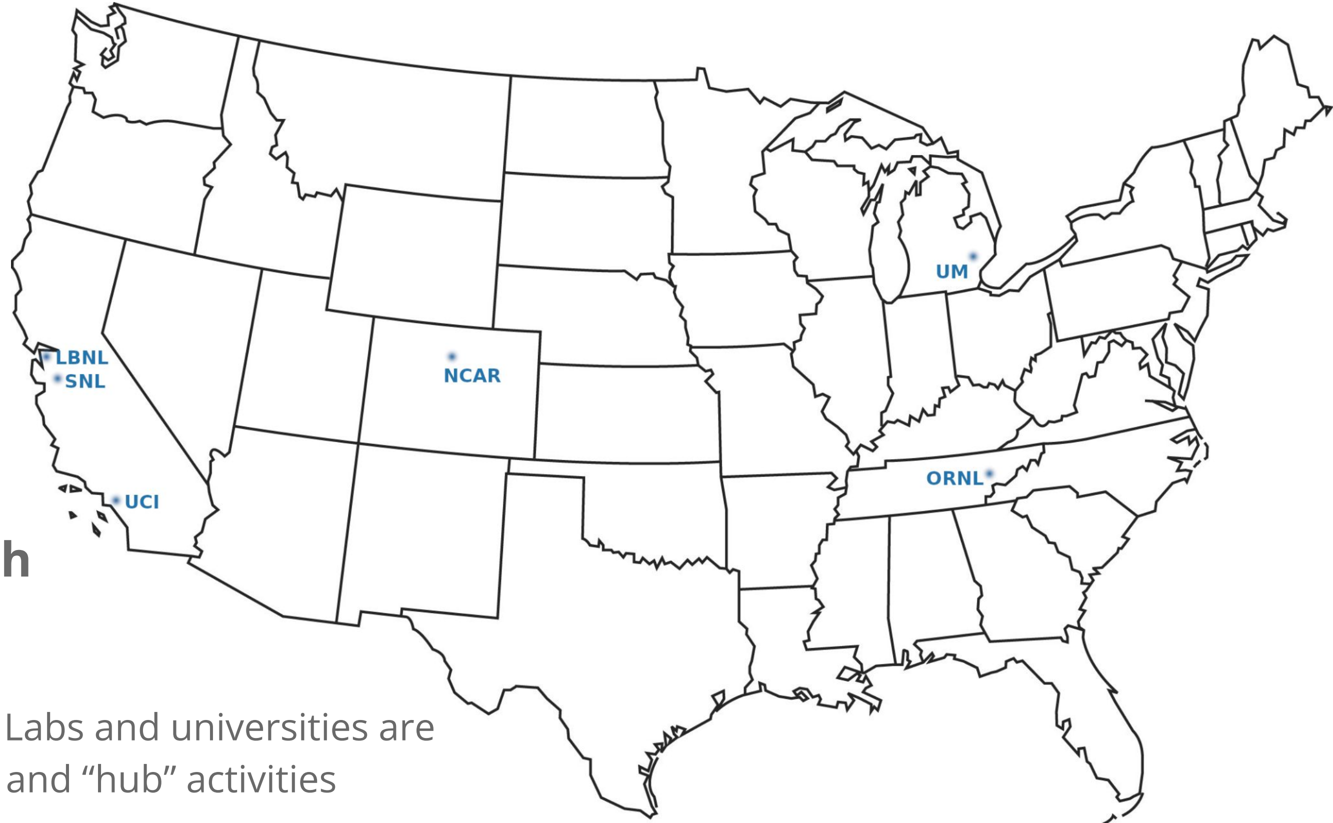
- Identify and quantify interactions between biogeochemical cycles and the Earth system
- Quantify and reduce uncertainties in Earth system models (ESMs) associated with interactions

The RUBISCO SFA works with the measurements and the modeling communities to use best-available data to evaluate the fidelity of ESMs. RUBISCO identifies model gaps and weaknesses, informs new model development efforts, and suggests new measurements and field campaigns.



RUBISCO Consists of Six Partner Institutions

- **3 DOE National Labs**
  - Lawrence Berkeley (LBNL)
  - Oak Ridge (ORNL)
  - Sandia (SNL)
- **2 Universities**
  - U. California Irvine (UCI)
  - U. Michigan (UM)
- **National Center for Atmospheric Research (NCAR)**



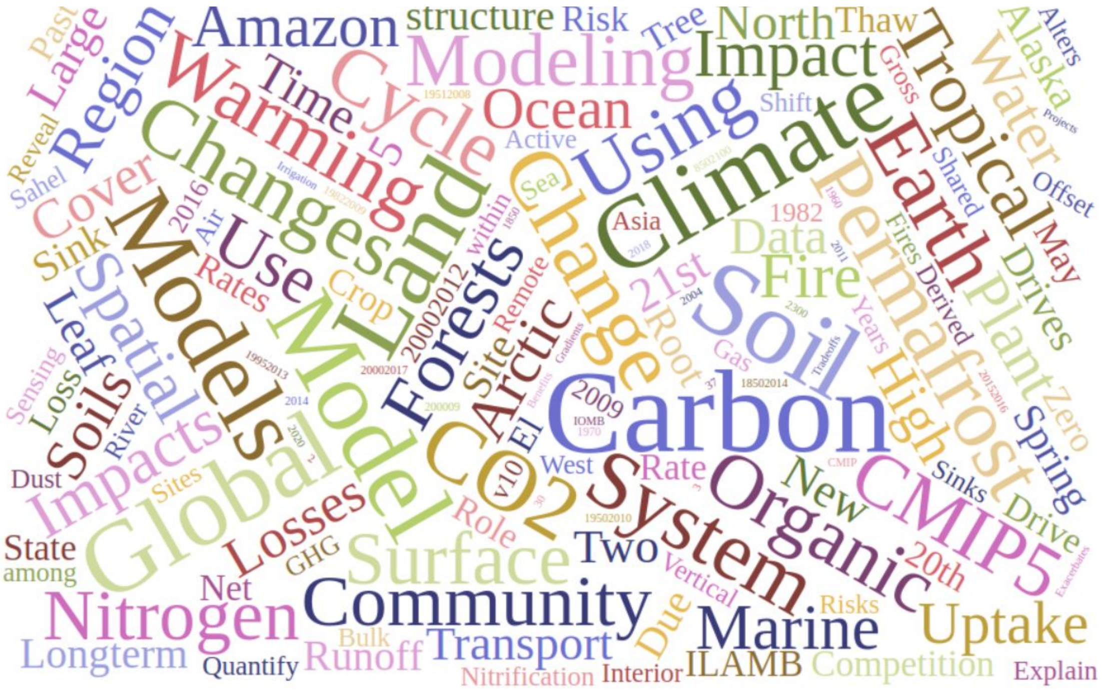
Collaborations at other National Labs and universities are fostered by our Working Groups and “hub” activities


RUBISCO
International Land Model Benchmarking (ILAMB) Workshop
May 16-18, 2016, Washington, DC, USA
U.S. DEPARTMENT OF
ENERGY
Office of Science
BGC Feedbacks SFA
Celebrations ARE BETTER AT BUCA
1. Benchmarking SOC change predictions
AGU 100
Our tools are improving, we can explore deep future time with fully coupled Earth System Models
The International Land Model Benchmarking (ILAMB) System
CMIP6 models perform better than CMIP5 models against many data streams
Hoffman, Collier, ILAMB team (in prep)
2018 RUBISCO Carbon Dynamics Working Group Meeting
Oak Ridge National Laboratory, Clinch River Cabin
Oak Ridge, Tennessee, USA October 3-5, 2018
RUBISCO-AmeriFlux Working Group Meeting
UC Berkeley Botanical Garden * October 13-17, 2019

RUBISCO is at the forefront of understanding how climate change will affect ecosystems and biogeochemical cycles at regional-to-global scales

The following characteristics of RUBISCO science set it apart from other BER SFAs and DOE Office of Science investments:

1. *A focus on the carbon cycle and ecosystems at regional-to-global scales*
2. *Use, analysis, and benchmarking c Earth system models*
3. *Connecting measurements to models*
4. *Using Earth system models to test hypotheses regarding ecosystem responses to climate change*



Generated from 335 RUBISCO journal article titles

RUBISCO Phase 3 Research & Development Objectives

1. Pursue **hypothesis-driven research** to reduce uncertainties related to estimates of contemporary terrestrial and ocean carbon sinks
2. Apply new advances in the field of **artificial intelligence (AI) and machine learning (ML)** to improve prediction and simulation of biospheric processes
3. Assess the impact of **carbon–climate feedbacks** on future climate variability
4. Explore **ecological teleconnections** through simulation, analysis, and benchmarking using DOE's Energy Exascale Earth System Model (E3SM) & CESM
5. Develop & apply our open source **ILAMB and IOMB benchmarking software** tools for evaluation of ESM biogeochemical & hydrological processes
6. Manage **Working Groups** that engage community researchers and RUBISCO scientists in data synthesis, multi-model analysis, and benchmarking
7. Conduct **large ensemble and parameter simulations** to explore feedbacks

Why Are Feedbacks Important? Which Feedbacks?

- **Feedbacks are important** because they can exacerbate or moderate climate change; their interactions are complex and poorly quantified
- **Reducing uncertainties** is an aspirational aim of the project, though we often uncover and reconcile feedback uncertainties
- **Examples of feedbacks** we have addressed:
  - Negative carbon cycle feedbacks from CO_2 fertilization and positive feedbacks from warming/drought impacts on NPP, respiration, fire, and permafrost thaw
  - Carbon cycle feedbacks from solubility, stratification, and biological pump changes in the ocean
  - Soil moisture, precipitation, and energy-driven feedbacks from stomatal closure under rising atm. CO_2
  - Albedo and energy feedbacks from land use & land cover change, disturbance, changes in phenology, and climate variability (e.g., ENSO)

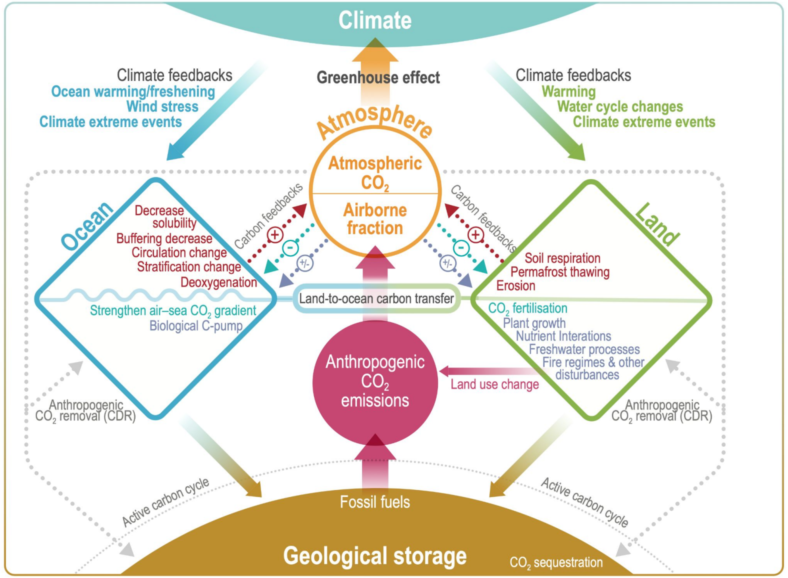


Figure 5.2, IPCC AR6 WG1

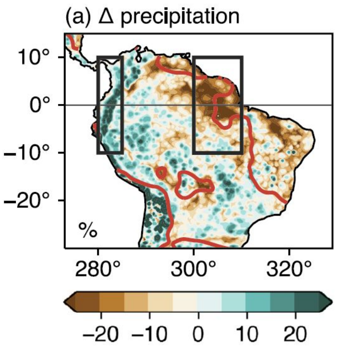
Science Questions Span Many Spatial and Temporal Scales

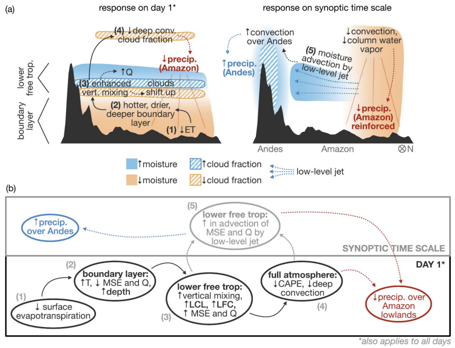
Overarching Phase 3 Science Questions

1. How can observational constraints and models be used to identify and reduce uncertainties in terrestrial and oceanic carbon sinks?
2. How can advances in machine learning be leveraged to improve understanding of biospheric processes and their representation in Earth System Models?
3. What is the contribution of the carbon–climate feedback to future climate and biospheric variability on interannual to multi-decadal timescales?
4. What are the key pathways and strengths of global ecological teleconnections?

Examples of High Impact Science

The influence of CO_2 physiology on projected changes in rainfall, runoff, and land surface temperature



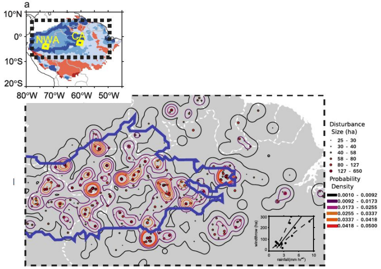


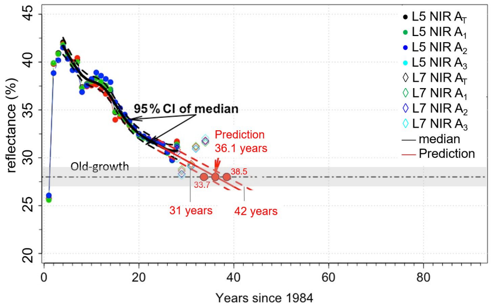
Langenbrunner et al., 2019, *Earth's Future*

New insight about mechanisms by which stomatal responses to rising atmospheric CO_2 influence future changes in precipitation, soil moisture, streamflow, & temperature in CMIP models

Papers: Kooperman et al. 2018a, 2018b; Fowler et al. 2019; Langenbrunner et al. 2019; Zhou et al. 2021; Zarakas et al; 2021; Zhou et al., 2022

Disturbance impacts on carbon cycling, ecosystem composition, and climate



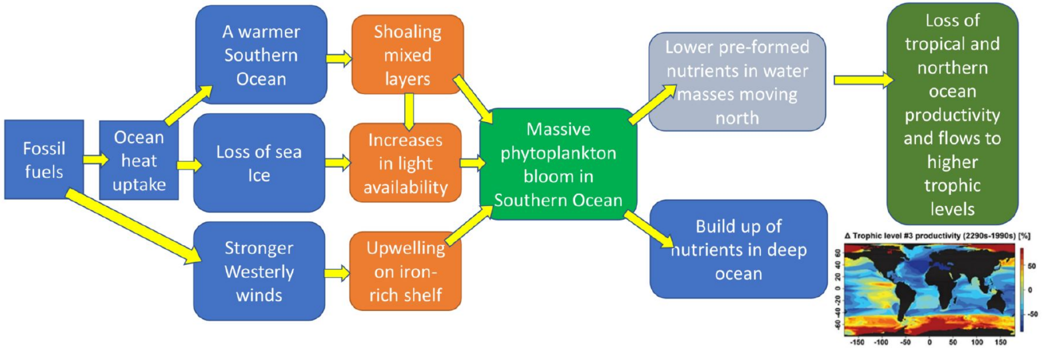


We used Landsat to identify disturbances and the recovery times from windthrows, clearing, and fire across the Amazon. We also found good comparisons with ELM-FATES predictions for these tropical disturbances

Papers: Negron-Juarez et al. 2018, 2020; Yuan et al., 2021; Wang et al., 2021, 2022; Urquiza Muñoz et al., 2021; Xu et al. 2021; Li et al., 2020, 2021; Xu et al., 2020; Turetsky et al., 2020; Cai et al., 2019; Parazoo et al., 2018

Examples of High Impact Science

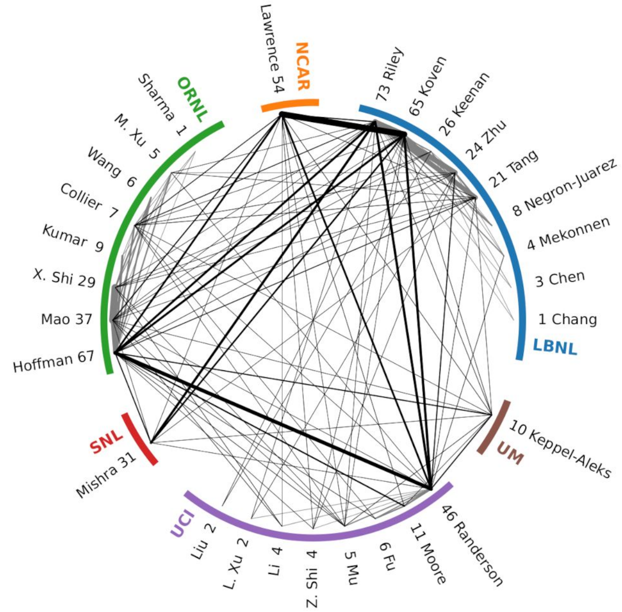
Identification and quantification of long-range ecosystem teleconnections



We define an ecological teleconnection as a perturbation to a local ecosystem that, in turn, modifies the functioning of a remote ecosystem. We examined ecological teleconnections driven by changes in vegetation cover, physiology, fire aerosols, deforestation, and climate-driven changes in net export production in ocean ecosystems

Papers: Moore et al. 2018; Fu et al. 2018; Langenbrunner et al., 2019; Fu et al., 2020; Xu et al., 2021; Li et al., 2020, Li et al., 2021

RUBISCO research promotes strong collaboration across institutions and team members



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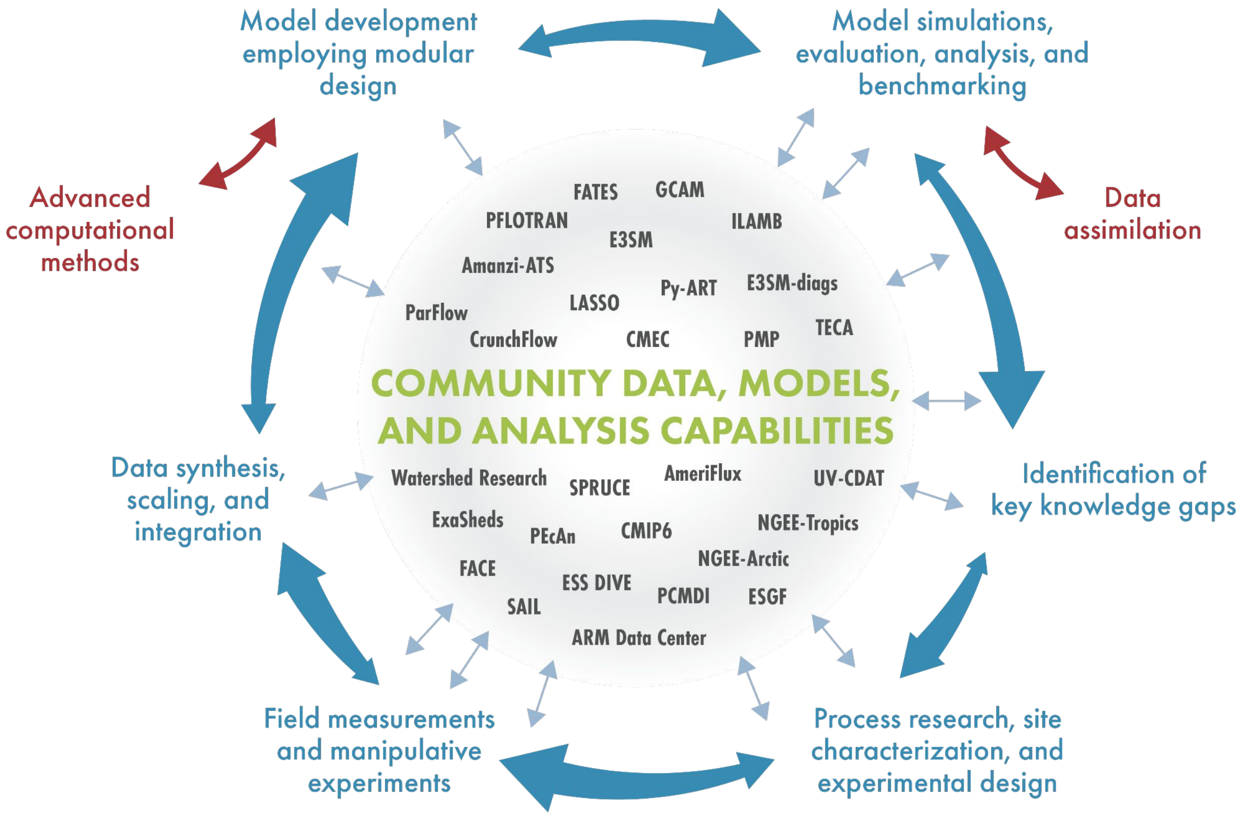
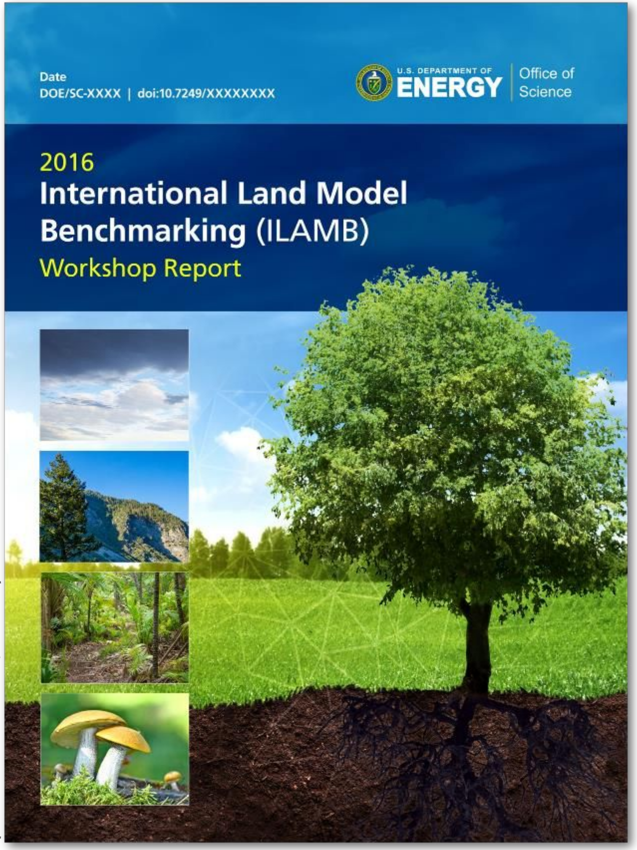
DOE's Model-Data-Experiment Enterprise (aka MODEX)





(Hoffman et al., 2017)

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Model Benchmarking with ILAMB & IOMB

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RUBISCO leads the development of the International Land Model Benchmarking (ILAMB) and International Ocean Model Benchmarking (IOMB) packages for community multi-model evaluation.

We used ILAMB and IOMB to compare CMIP5 vs. CMIP6 models (IPCC AR6).

Attend Breakout Session
1: Metrics, Benchmarks and Credibility of Model Output
today at 1:00 pm in the Forest Glen Room
to learn more about ILAMB

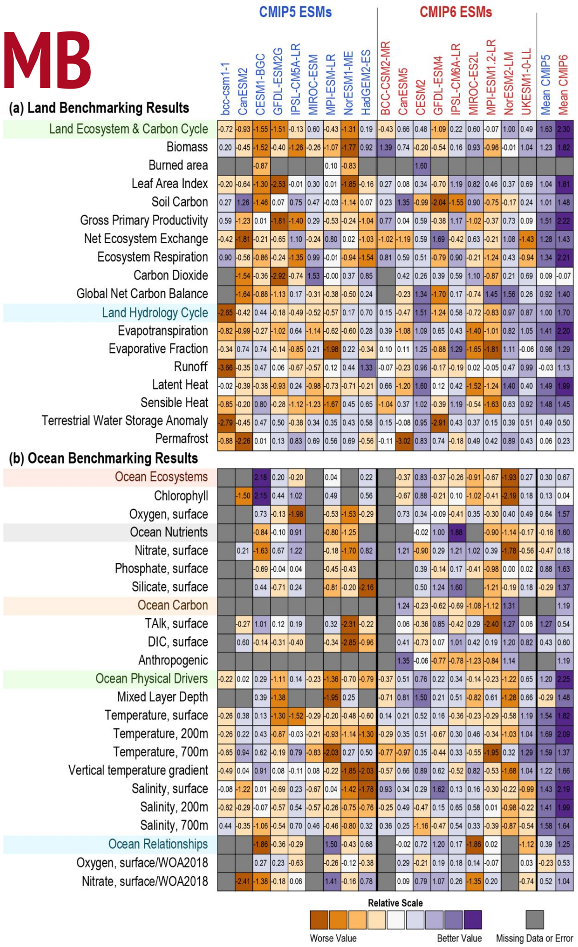

Figure 5.22, IPCC AR6 WGI

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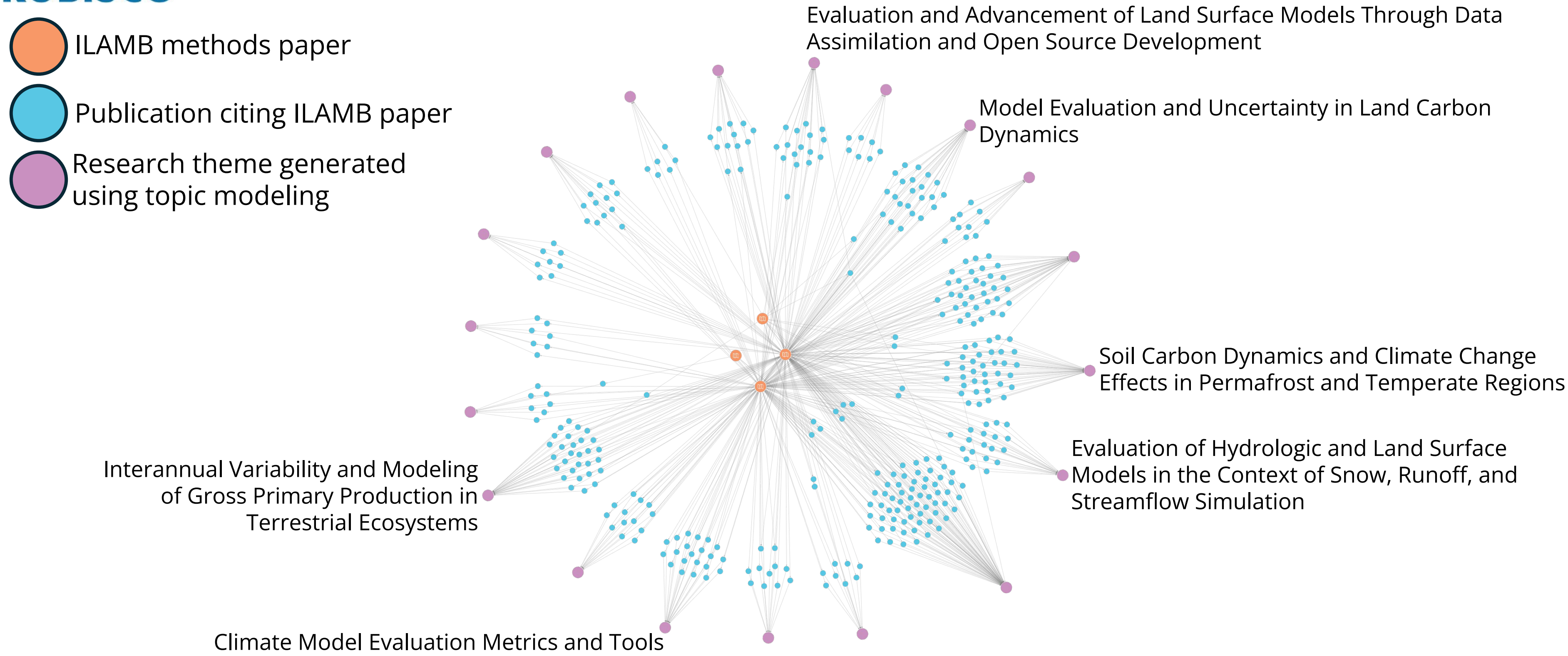
Research Themes Citing ILAMB Methods Papers



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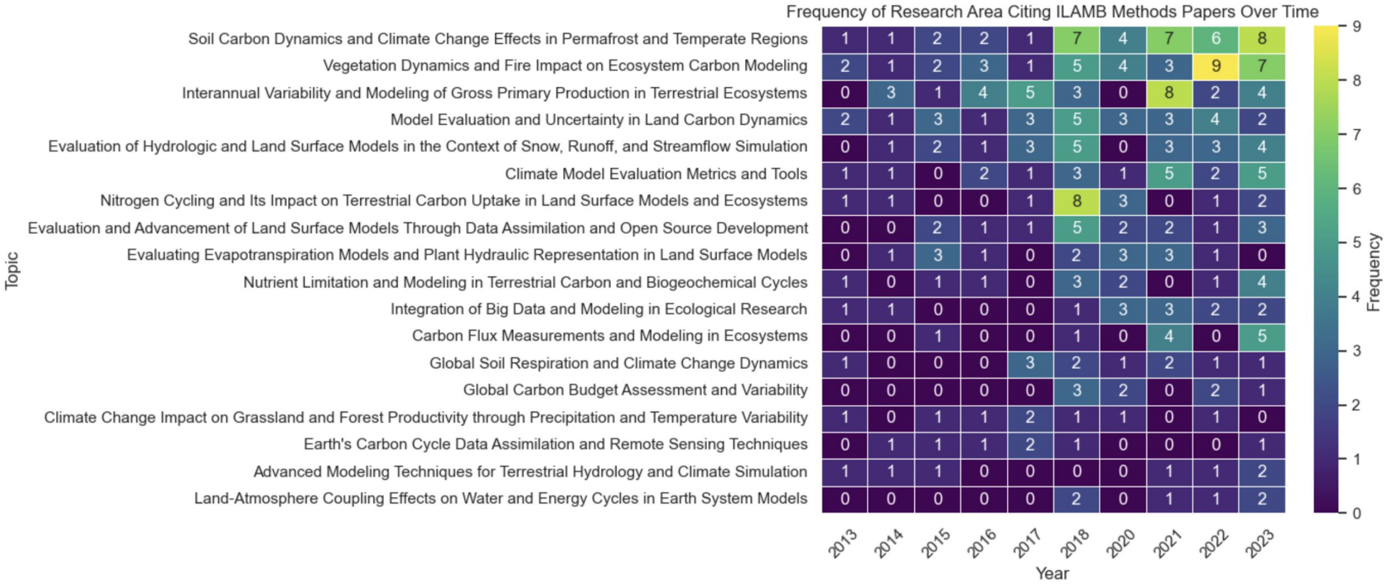

Thanks to Chris Vernon (PNNL) for this preliminary analysis

ILAMB Methods Papers

- **2012**: A Framework for Benchmarking Land Models
- **2016**: International Land Model Benchmarking (ILAMB) Workshop Report
- **2018**: Evaluating Uncertainties in Marine Biogeochemical Models: Benchmarking Aerosol Precursors
- **2018**: The International Land Model Benchmarking (ILAMB) System: Design, Theory, and Implementation

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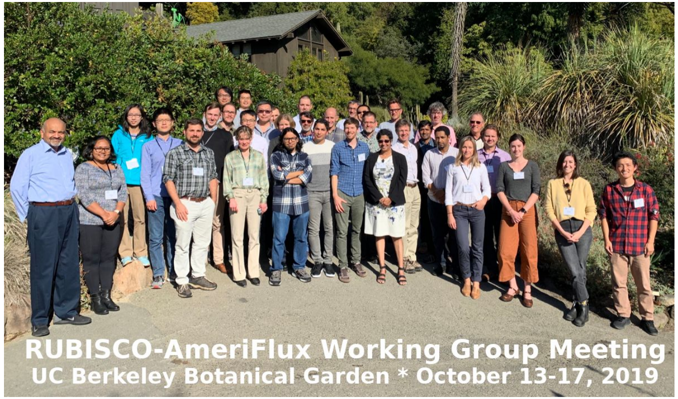
RUBISCO Leadership of Community Working Groups

RUBISCO Soil Moisture Working Group

- Synthesizing global soil moisture data from in situ and remote sensing
- Developing metrics for model evaluation of vertical distribution of moisture

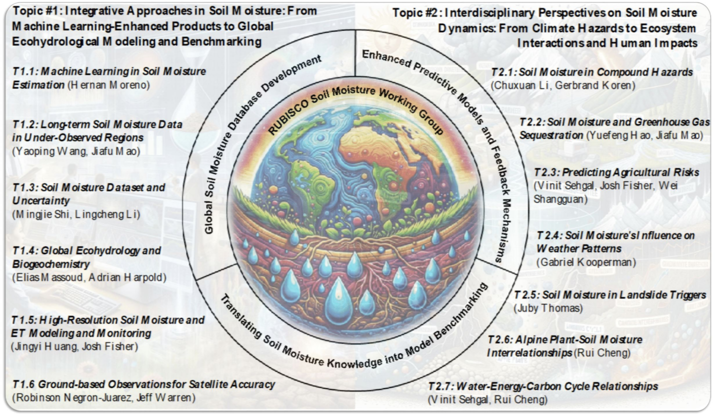
★ Partnership with NASA



RUBISCO Soil Carbon Dynamics Working Group

- Synthesizing soil carbon measurements and applying machine learning to produce gridded data
- Developing metrics and evaluating microbially explicit decomposition models

★ Partnership with ESS projects and potentially BSSD projects



RUBISCO-AmeriFlux Working Group

- Synthesizing eddy covariance data to provide observational data
- Analyzing responses to disturbance and climate extremes
- Developing metrics for model evaluation and constraints

★ Partnership with AmeriFlux Project

Additional EESM, EESSD, and BER Collaborations

- **RGMA University Projects:** *Nathan Collier, Forrest Hoffman, Charlie Koven, David Lawrence, and Jim Randerson* – model simulation, evaluation, and metrics development
- **E3SM:** *Qing Zhu and Xiaojuan Yang* – ELM model development, nutrient dynamics
- **InteRFACE:** *Jitu Kumar* – Land model evaluation
- **NGEE Arctic:** *Forrest Hoffman, Charlie Koven, Jitu Kumar, Zelalem Mekonnen, Jing Tao, and Chonggang Xu* – co-leading Data Synthesis & Evaluation Cross-cut and Dynamics & Disturbance Cross-cut, remote sensing data synthesis
- **NGEE Tropics:** *Charlie Koven, Chonggang Xu, and Xiaojuan Yang* – Project and modeling leadership, simulation and analysis
- **AmeriFlux:** *Trevor Keenan* – Science applications of eddy covariance data
- **ESGF2-US:** *Forrest Hoffman, Jitu Kumar, Nathan Collier, Elias Massoud, and Min Xu* – Project leadership, software infrastructure, and data management
- **Joint BioEnergy Institute (JBEI):** *Umakant Mishra* – Agroecosystem modeling

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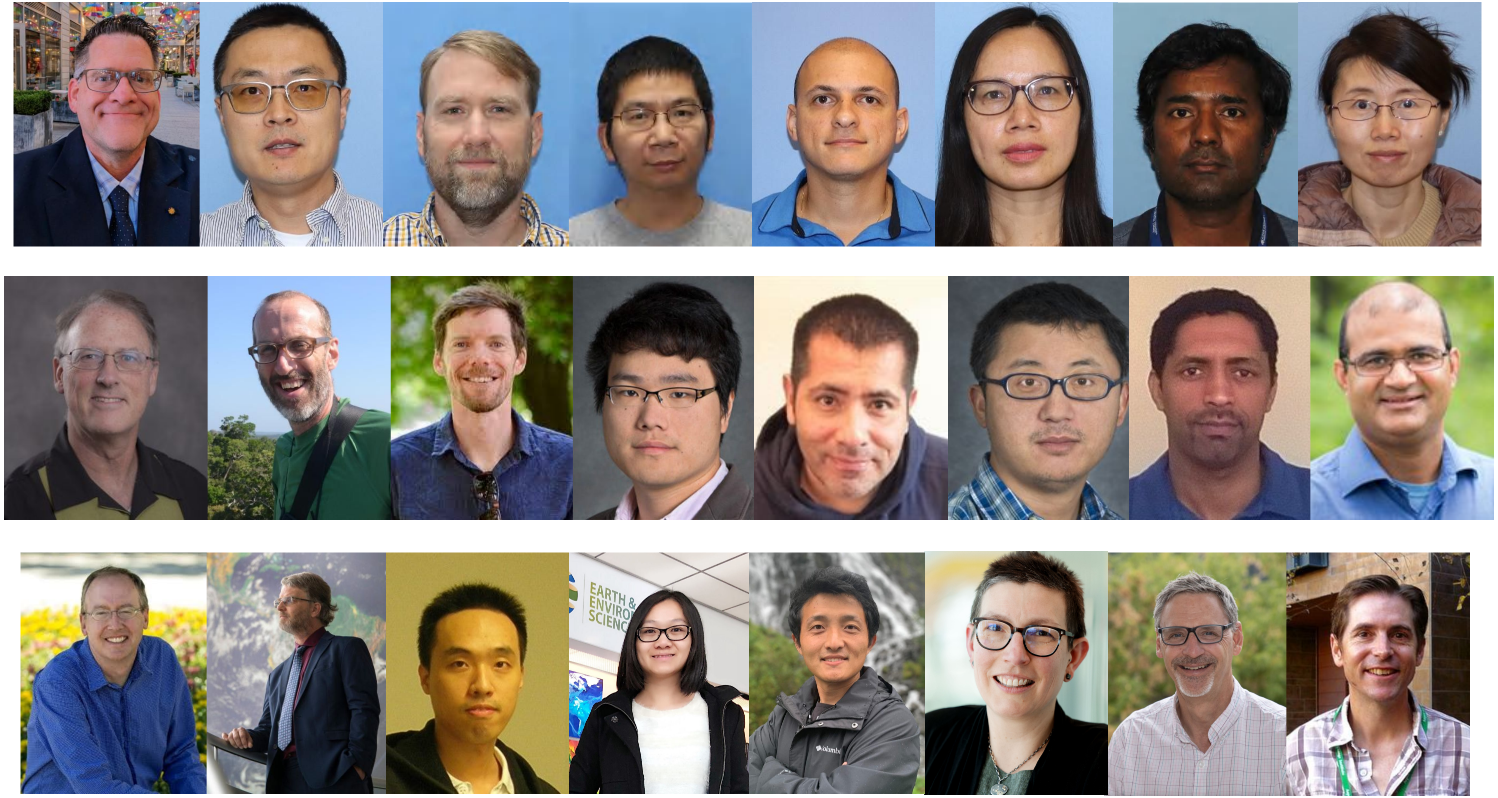
Project Personnel Across Institutions



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