Reconciling Uncertainties in Biogeochemical Interactions through Synthesis and Computation

Forrest M. Hoffman

U.S. DEPARTMENT of ENERGY

June 11, 2026

E3SM All Hands Meeting

Bethesda, Maryland, USA

RUBISCO

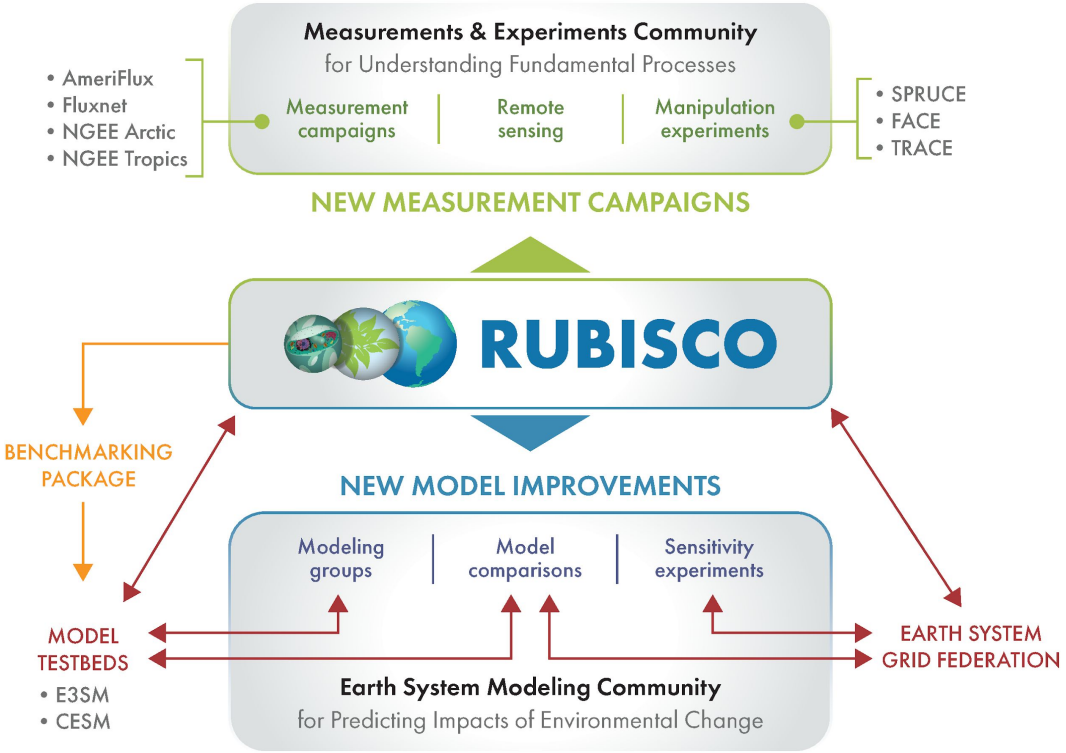
EESM-RGMA RUBISCO Science Focus Area (SFA)

Forrest M. Hoffman (Laboratory Research Manager), Charles D. Koven (Science Co-Lead), and James T. Randerson (Chief Scientist)

RUBISCO Research Goals

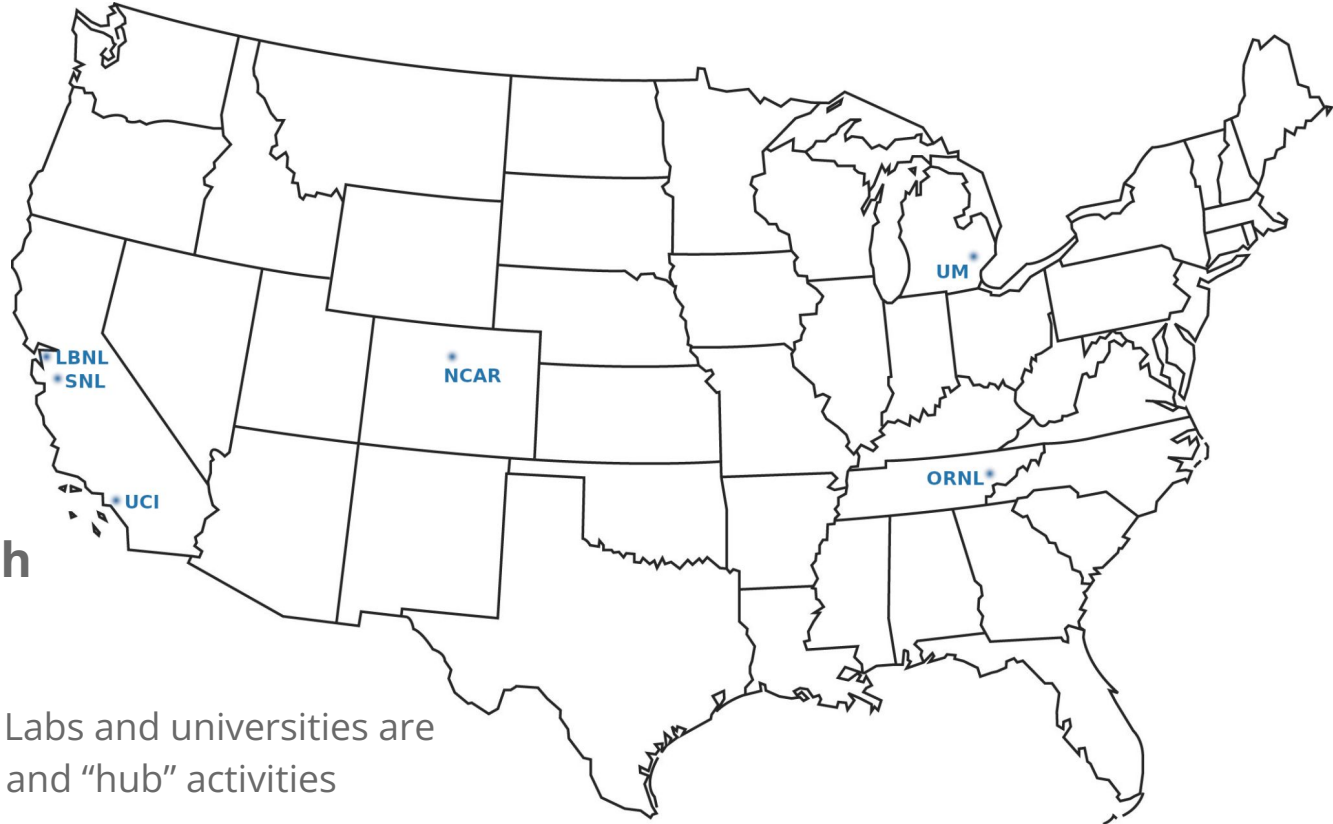
- Identify and quantify interactions between biogeochemical cycles and the Earth system
- Quantify and reconcile uncertainties in Earth system models (ESMs) associated with those interactions

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 Phase 3 Research & Development Objectives

1. Pursue **hypothesis-driven research** to quantify uncertainties related to estimates of contemporary terrestrial and ocean processes
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 **biogeochemical interactions** on Earth system variability
4. Explore **ecological & hydrological interactions** through simulation, analysis, & benchmarking using the 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 **ensemble and parameter perturbation simulations** to quantify uncertainty and understand interactions and feedbacks

Science Questions Span Temporal and Spatial Scales

Science Questions

1. How can observational constraints and models be used to identify and quantify uncertainties in terrestrial and oceanic processes?
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 biogeochemical interactions to future Earth system variability on seasonal, interannual, and decadal timescales?
4. What are the key pathways and strengths of multiscale ecological and hydrological interactions and teleconnections?

Community Resource Objectives

1. Develop ILAMB & IOMB and deploy in REF
2. Manage SOM, AmeriFlux, Soil Moisture, and Biomass Working Groups
3. Biogeochemical-water cycle simulations

The Weak Land Carbon Sink Hypothesis

Objective

Develop a global carbon budget that simultaneously reconciles key constraints offered by satellite-derived vegetation biomass, atmospheric O_2, and the north-south atmospheric CO_2 gradient.

Approach

- We combined satellite vegetation carbon time series with additional information on detrital pools to estimate the net land carbon flux directly from 2000–2019 (green line, Figure 1A).
- We developed a 2-box atmospheric inversion model to estimate the northern land sink using atm. data from 1959–2022 (black line, Figure 1B).

Results/Impacts

- At a global scale, our estimate of the net land carbon sink from the satellite data is 0.8 ± 0.7 Pg C/y from 2000–2019, nearly a factor of two lower than the Global Carbon Project (GCP) and IPCC estimates (Figure 1A).
- With concurrent adjustments to ocean (+8%) and fossil fuel (−6%) fluxes (Table 1), we developed a budget that reconciles key constraints provided by vegetation carbon, the north-south CO_2 gradient, and O_2 trends.

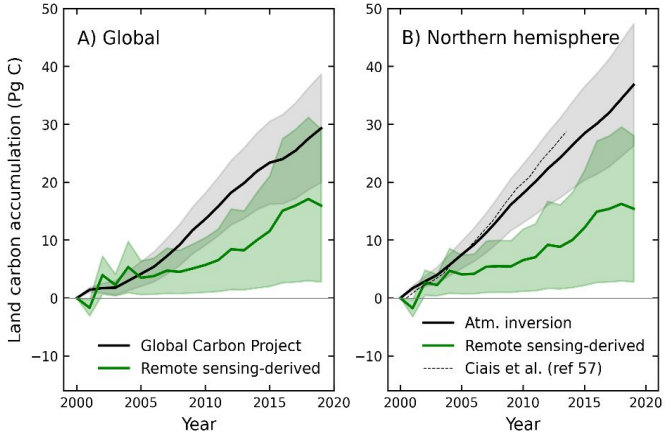


Figure 1. Satellite-derived estimates of land carbon accumulation (green) compared to other approaches.

Table 1. Global Carbon Project and proposed global carbon budgets.

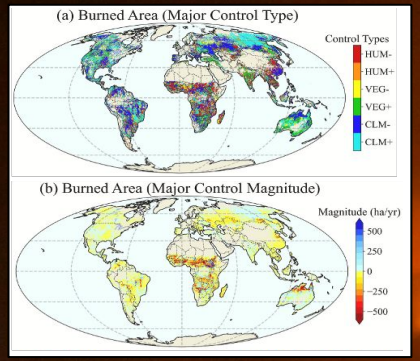
Flux component: Units: Pg C/y	Global Carbon Project: mean	Global Carbon Project: 1 σ	Weak Land Sink Hypothesis: mean	Weak Land Sink Hypothesis: 1 σ	Percent difference
Fossil fuel emissions	8.6	± 0.4	8.1	± 0.9	-6
Atmospheric growth rate	4.6	± 0.1	4.6	± 0.1	0
Ocean sink	2.5	± 0.4	2.7	± 0.5	8
Land sink	1.6	± 0.6	0.8	± 0.7	-46

Randerson, James T., **Yui Li**, **Weiwei Fu**, **François Primeau**, **Jinhyuk E. Kim**, **Mingquan Mu**, **Forrest M. Hoffman**, A. T. Trugman, L. Yang, C. Wu, J. A. Wang, W. R. L. Anderegg, A. Baccini, M. A. Friedl, S. Saatchi, A. S. Denning, and M. L. Goulden (2025), The Weak Land Carbon Sink Hypothesis, *Sci. Adv.*, 11(37), eadr5489, doi:10.1126/sciadv.adr5489.

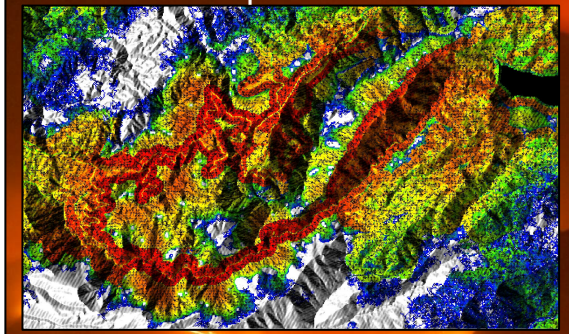
Wildfire Research

RUBISCO

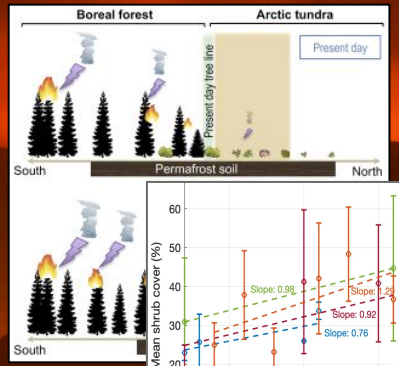
Drivers of Fire Risk

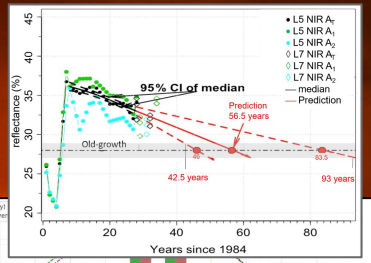


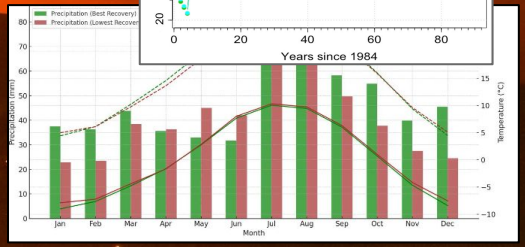
Fuel Connectivity & Fire Exposure/Risk



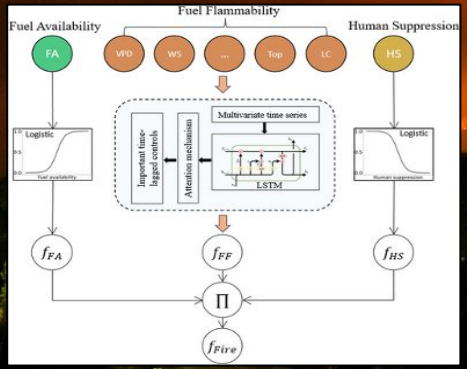
Vegetation Responses to Wildfire



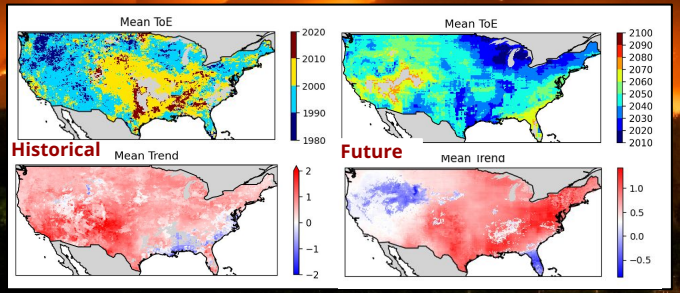




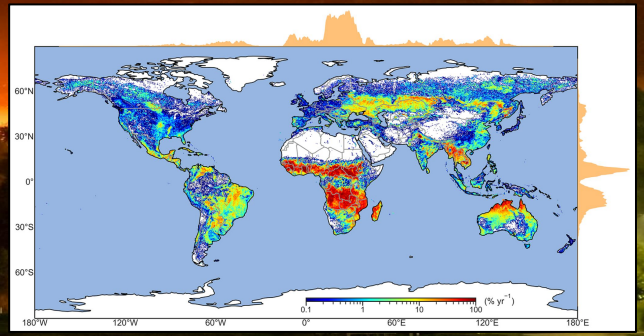
Vegetation Regrowth & Recovery



AI/ML Wildfire Prediction



Changing Fire Weather



Satellite Wildfire Fluxes & Extent

Berkeley Lab

NCAR
National Center for Atmospheric Research

Oak Ridge National Laboratory

Sandia National Laboratories

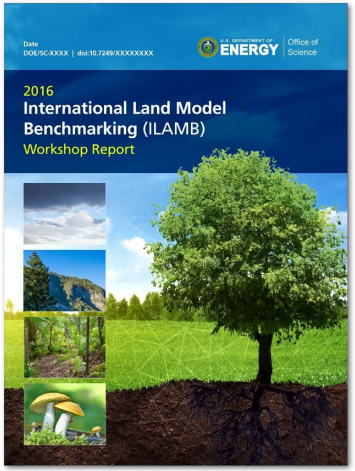
University of California Irvine

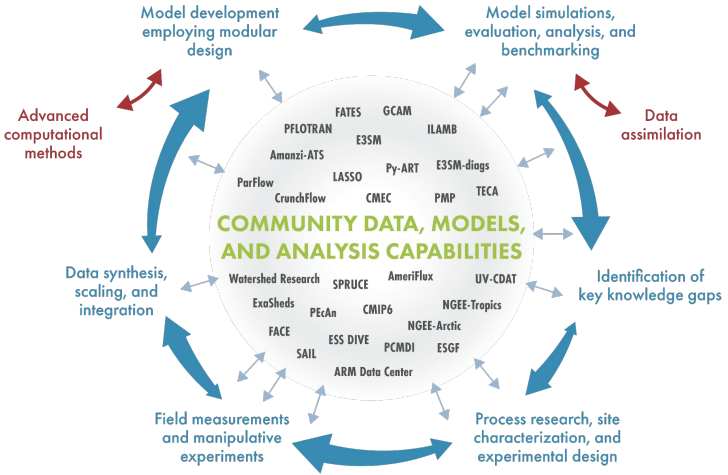
University of Michigan

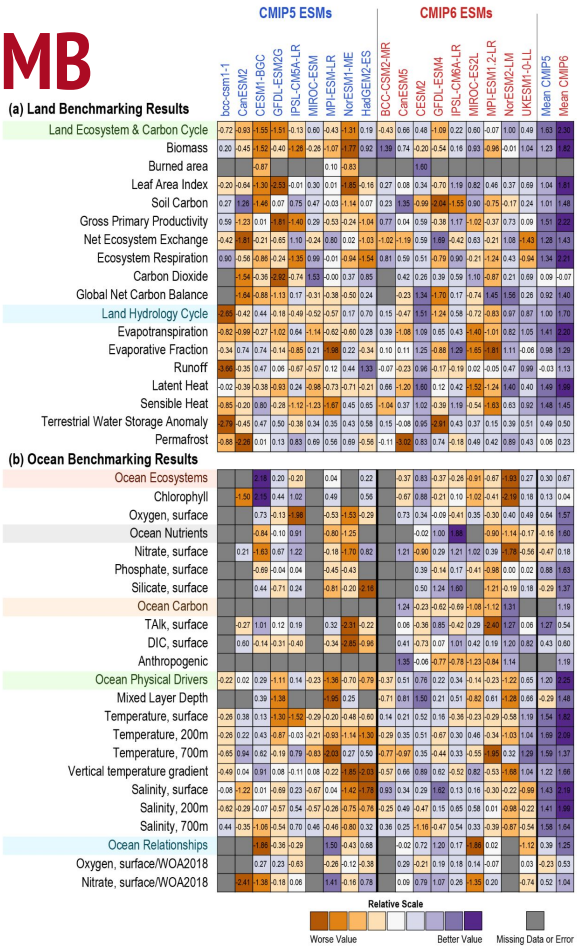
Model Benchmarking with ILAMB & IOMB

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 evaluate multiple generations of Earth system models







ILAMB 2025

Meeting Goals

- Highlight new techniques for model evaluation to reconcile uncertainties
- Enable coordination among community model intercomparison projects
- Increase awareness of new data streams available model benchmarking
- Increase use and sharing of information and community tools, including ILAMB
- Design new metrics and evaluation approaches for next generation ILAMB

Meeting Outcomes

- Released ILAMBv3.0 to community
- Prioritized integration of new data sets, removal of deprecated data, development of new community metrics
- Developing meeting report that charts course for future development of ILAMB

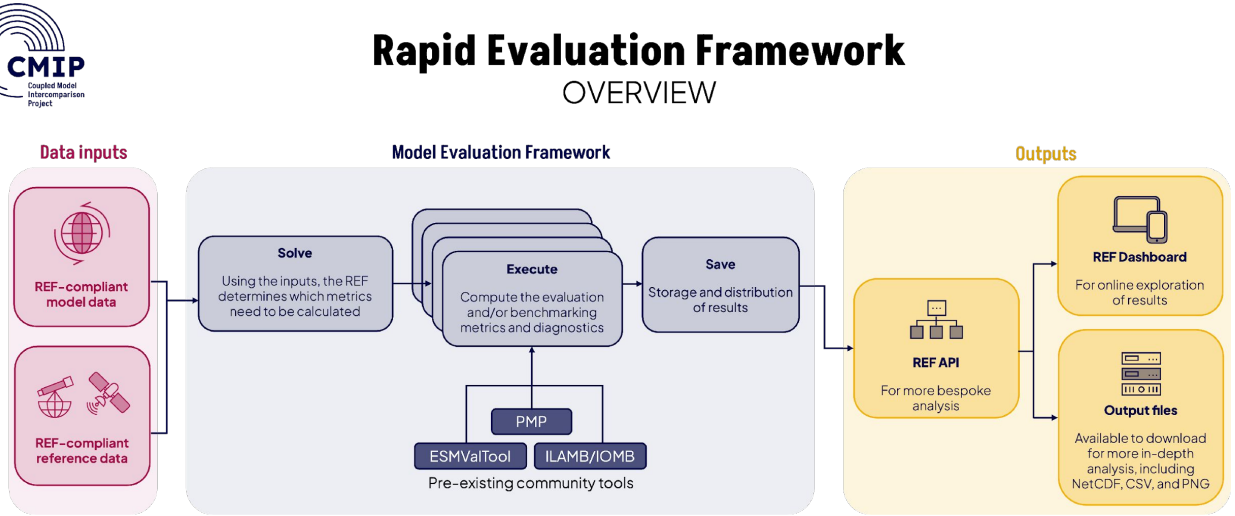
2025 International Land Model Benchmarking (ILAMB) Hybrid Meeting

December 11–13, 2025, in New Orleans, Louisiana, USA

- About 60 in-person participants and 10–20 virtual attendees from US, UK, Germany, France, Japan, and Australia
- Included plenary presentations, breakout sessions, & poster sessions
- Followed by RUBISCO Working Groups and All Hands Meetings on Sunday, December 14, 2025

Rapid Evaluation Framework (REF)

- The REF orchestrates execution of community model diagnostics in a consistent, traceable way for publishing the resulting metrics, figures, and provenance for analysts
- The REF is extensible to support different requirements and community diagnostics and packages



https://www.climate-ref.org/

https://doi.org/10.5281/zenodo.20053946

- The REF enables integration of community evaluation tools into workflows
- Diagnostics are executed and published as data are published on Earth System Grid Federation (ESGF)

Hoffman, Forrest M., Birgit Hassler, Ranjini Swaminathan, Jared Lewis, et al. 2026. “Rapid Evaluation Framework for the CMIP7 Assessment Fast Track.” *Geosci. Model Dev.*, in revision.

AgenticILAMB: Toward autonomous bias diagnosis and attribution for Earth System Models

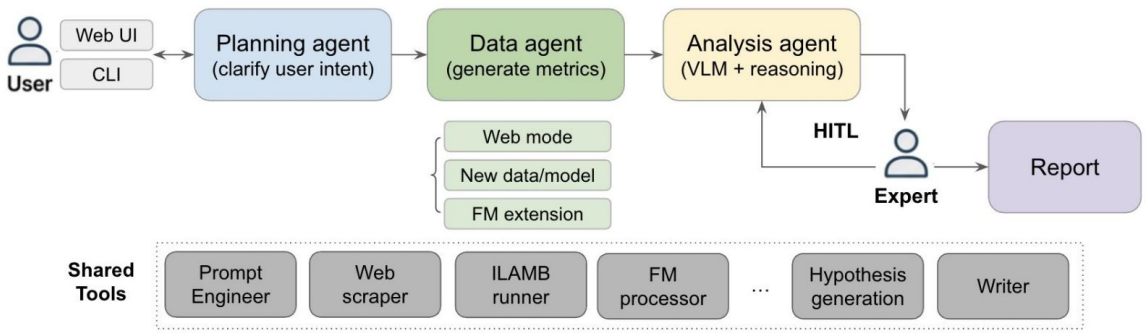
Under development by Huiqi Wang (UC Berkeley) and Qing Zhu (LBNL)

Goal:
Build a multi-agent system for autonomous bias diagnosis and attribution in ESMs, and explore a human-in-the-loop workflow.

Current status:
Successfully tested on biomass evaluation, with extended capability to integrate Foundation Model biomass estimates across western CONUS.

Next steps:

- Define evaluation metrics for the agent system
- Improve the VLM model
- Encode expert knowledge to constrain agent reasoning



Open questions:

- How do we evaluate a non-deterministic process?
- Can the system find what we cannot?

Call for feedback from RUBISCO & E3SM communities:

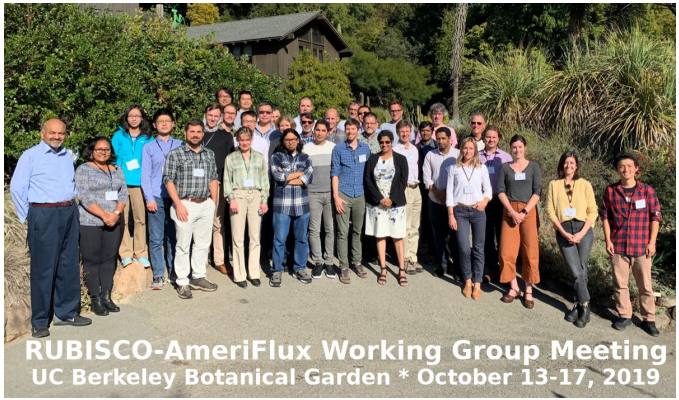
- As our target users, what functionalities would make your work easier and more efficient?

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

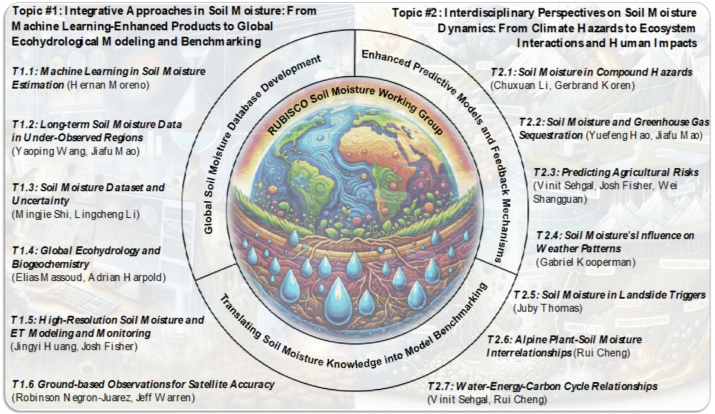
★ Partnership with NASA



RUBISCO Soil Organic Matter Working Group

- Synthesizing SOM 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 variability
- Developing metrics for model evaluation and constraints

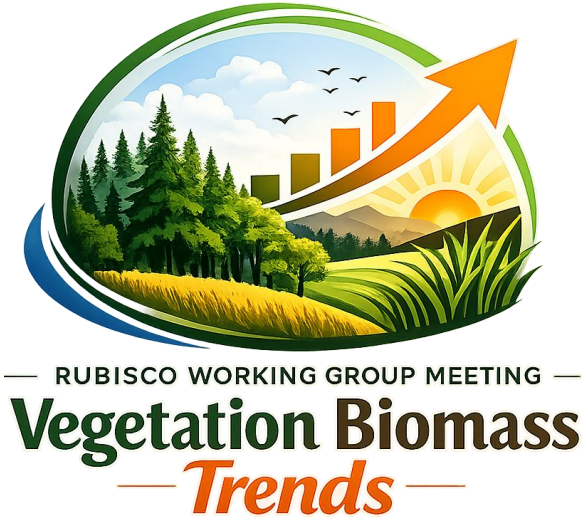
★ Partnership with AmeriFlux Project

BERKELEY LAB · NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH · OAK RIDGE National Laboratory · Sandia National Laboratories · UNIVERSITY OF CALIFORNIA IRVINE · MICHIGAN

New RUBISCO Community Working Group

RUBISCO Biomass Working Group

- Synthesizing above- and belowground vegetation live biomass from remote sensing and in situ measurements and applying machine learning to produce gridded data
- Assessing trends in live biomass for understanding wildfire and disturbance (whiplash) risks and constraining carbon budgets
- Developing metrics for evaluating vegetation models

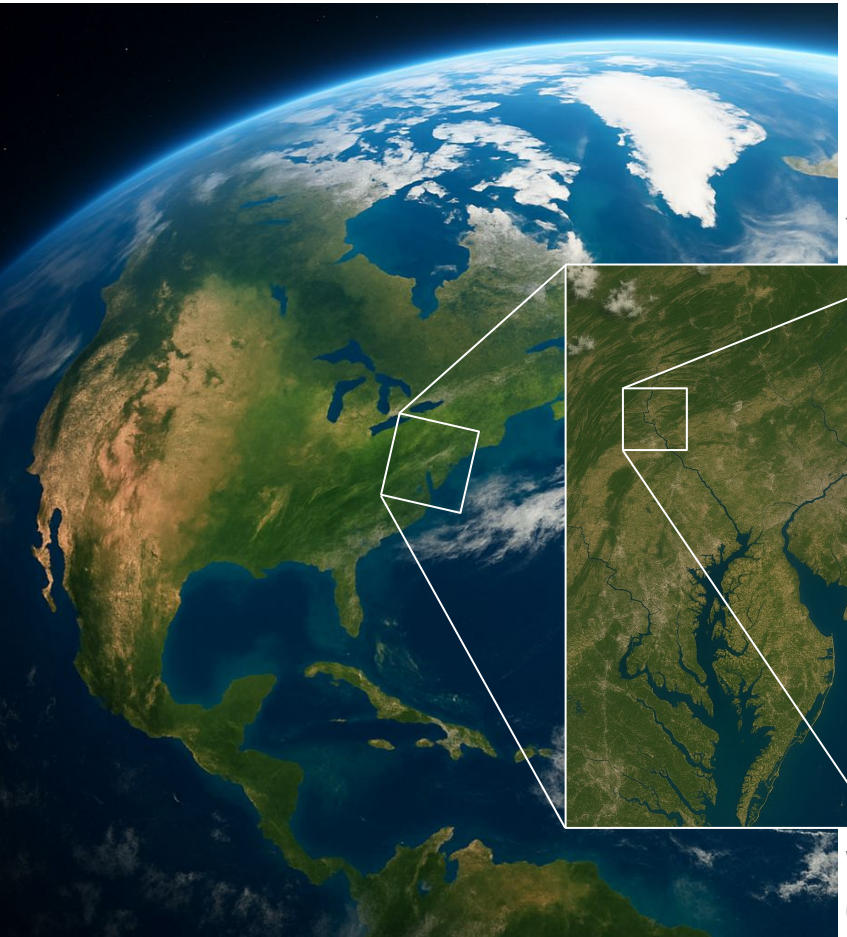


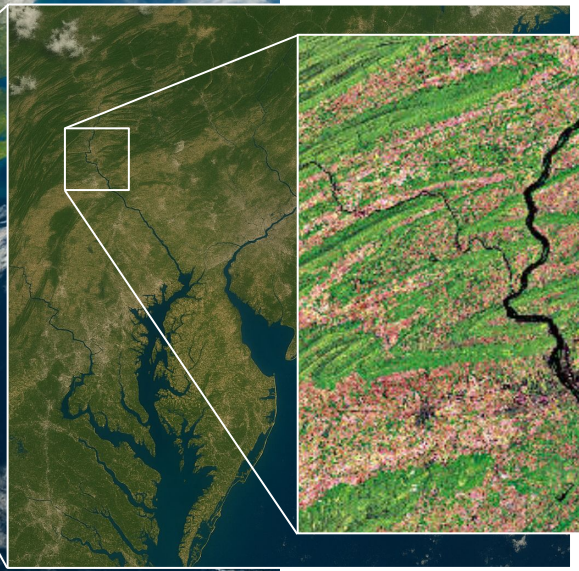
- Planning for an **international meeting** to address vegetation biomass trends focused on North America
- Engaging US and European space agencies and large scale ecological projects
- Likely in Southern California in October 2026

Test Bed for Terrestrial Biogeochemical & Water Cycles

Continental-scale test bed utilizes E3SM and performs top-down scaling to the watershed level

Framework adds representation of vegetation & biogeochemistry absent in traditional hydrological models





Simulates vegetation, soil health, and water

Represents disturbances

Predicts impacts on energy systems and urban areas

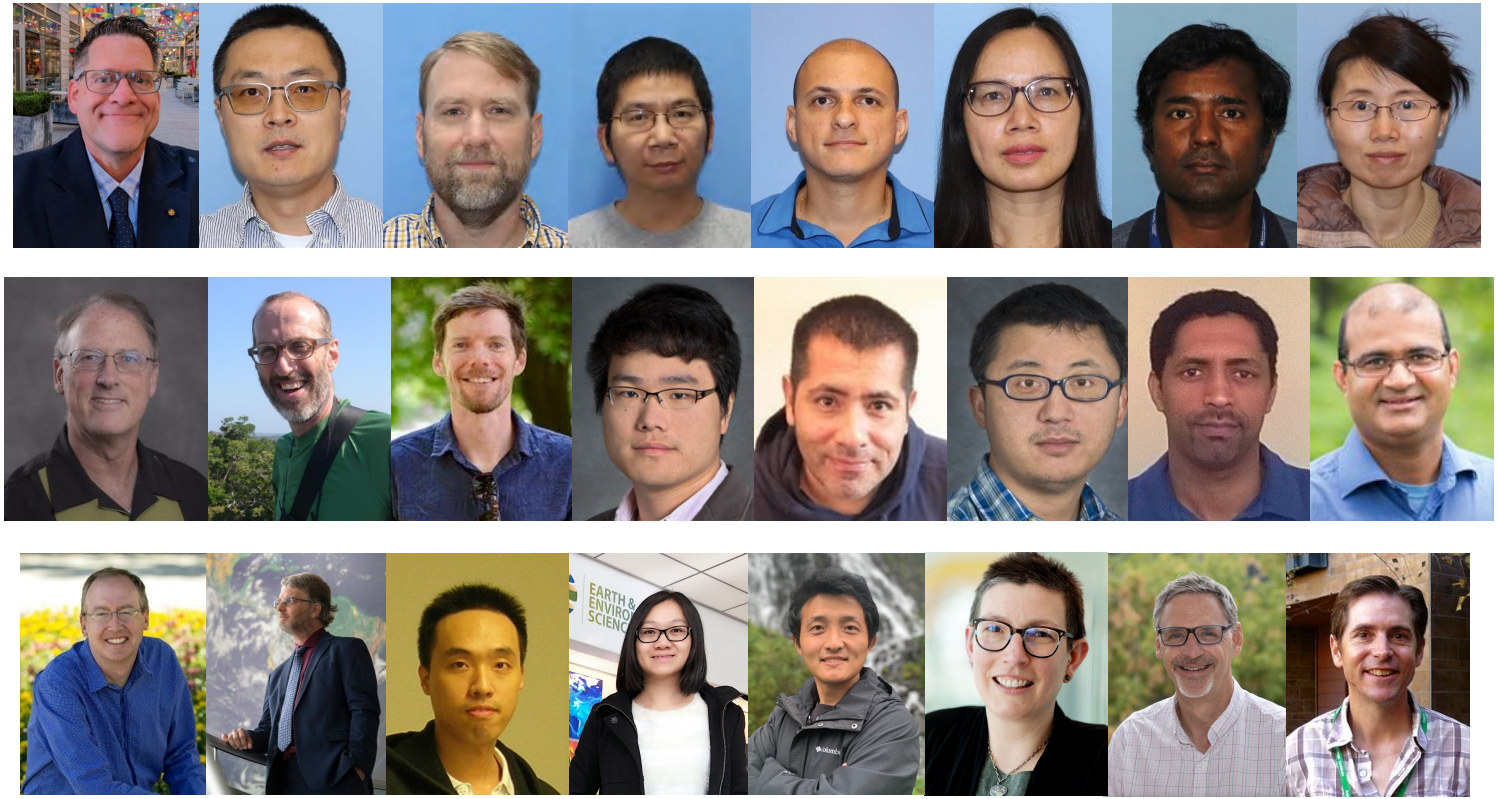
Watershed level uses watershed models (ATS, PFLOTRAN) as a calibration at the finest scale

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, wildfire, nutrient dynamics
- **NGEE Arctic:** *Forrest Hoffman, Charlie Koven, Jitu Kumar, Zelalem Mekonnen, Jing Tao, Elias Massoud, and Morgan Steckler* – co-leading Data Synthesis & Evaluation Cross-cut and Dynamics & Disturbance Cross-cut, remote sensing & site data synthesis, model evaluation
- **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, Min Xu, and Morgan Steckler* – Project leadership, software infrastructure, and data management
- **Joint BioEnergy Institute (JBEI):** *Umakant Mishra* – Agroecosystem modeling

Seeking new engagement on coordinated simulation and analysis with E3SM

Project Personnel Across Institutions



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