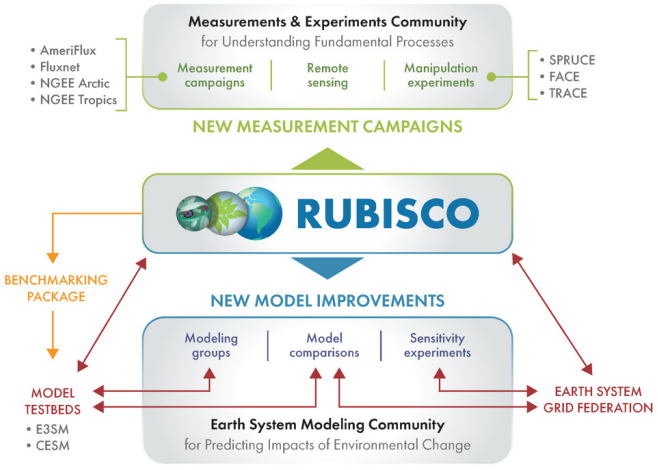
REDUCING UNCERTAINTIES IN BIOGEOCHEMICAL INTERACTIONS THROUGH SYNTHESIS AND COMPUTATION (RUBISCO)

As earth system models (ESMs) become increasingly complex, there is a growing need for comprehensive and multi-faceted evaluation, analysis, and diagnosis of model results. The relevance of model predictions to the U.S. Department of Energy's (DOE's) energy-related mission hinges in part on the assessment and reduction of uncertainty in predicted biogeochemical and hydrological cycles, which requires repeatable and automated analysis methods, as well as new observational and experimental data.

This Scientific Focus Area (SFA) pioneered the development and application of new hypothesis-driven diagnostic approaches for evaluating ESM representations of biogeochemical and hydrological processes at site, regional, and global scales.

To advance understanding of terrestrial and marine biogeochemical processes and their interactions with the global earth system, researchers are developing new analysis methods that use observations to test and constrain model



The RUBISCO SFA works with the measurements and 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.

predictions, inform model development, and identify needed measurements and field experiments.

In an effort sponsored by the DOE's Office of Science through the Regional and Global Model Analysis program, a diverse team from Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, Argonne National Laboratory, Brookhaven National Laboratory, the University of California at Irvine, and the University of Michigan is developing new diagnostic approaches to evaluate ESM biogeochemical process representations. Their research and development efforts have produced the International Land Model Benchmarking (ILAMB) Package, an open source model evaluation system that leverages a growing collection of laboratory, field, and remote sensing observations. This benchmarking system has been extended to include marine biogeochemistry, and is called the International Ocean Model Benchmarking (IOMB) Package when run in that mode.

ILAMB has been instrumental in guiding the development and calibration of land models, including DOE's Energy Exascale Earth System Model (E3SM) Land Model (ELM), and it has been used to assess multi-model performance by the international Global Carbon Project. Both ILAMB and IOMB are now being used to evaluate models participating in phase 6 of the Coupled Model Intercomparison Project (CMIP6). RUBISCO researchers employ these and other model evaluation tools to engage experimentalists, including those in DOE's Terrestrial Ecosystem Science Program, in identifying model weaknesses and needed measurements and field experiments.

SCIENTIFIC FOCUS

The overarching goals of RUBISCO are to identify and quantify interactions between biogeochemical and hydrological cycles and the earth system, and to quantify and reduce uncertainties in ESMs associated with those interactions. Researchers are achieving these goals by conducting hypothesis-driven multi-model analyses and comparisons with observational data. In recognition of DOE science priorities for understanding the structure and function of ecosystems, RUBISCO is focused on biogeochemical and hydrological interactions associated with changes on interannual to decadal timescales, including ecological impacts of changes in disturbance regimes and extremes, and on long-term trends.

An important part of current RUBISCO research is on CMIP6 simulations and analyses—especially for land and ocean carbon cycle and hydrological model projections, aimed at documenting how the predictive capacity of ESMs has potentially improved over the past decade.

SIX RESEARCH OBJECTIVES

1. Develop hypothesis-driven approaches for evaluation of ESM biogeochemical and hydrological process representations at site, regional, and global scales;
2. Investigate the degree to which contemporary observations can be used to reduce uncertainties in future scenarios, including the use of an "emergent constraint" approach that draws up an ensemble of models;
3. Build upon the open source ILAMB/IOMB benchmarking software tools to leverage the growing collection of laboratory, field, and remote sensing data sets for systematic evaluation of ESM processes;
4. Evaluate the performance of process representations and their interactions with the Earth system in ESMs using ILAMB/IOMB;
5. Conduct CMIP6 experiments using state-of-the-science ESMs; and
6. Provide international leadership for biogeochemistry model evaluation and benchmarking.

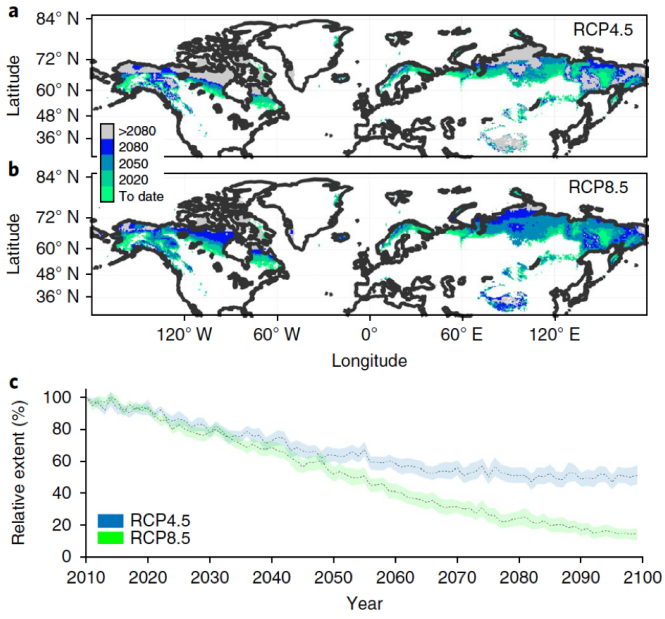
RUBISCO is investigating the applicability of emergent constraint approaches in various ESM analyses and performing synthesis studies that will improve the ability to constrain future projections. Researchers are integrating ILAMB with the Predictive Ecosystem Analyzer (PEcAn) package as a means for automating uncertainty quantification analyses and delivering new kinds of diagnostics of model fidelity.

Based on the latest ILAMB Workshop, RUBISCO has organized two key synthesis activities aimed at developing improved datasets and evaluation metrics. The Soil Carbon Dynamics Working Group meets regularly to assess how to best use disparate databases of soil carbon, respiration, and age data to initialize and constrain soil decomposition models. The Carbon-Water-Energy Fluxes Working Group organizes synthesis activities for measurements from eddy covariance flux tower networks, like AmeriFlux and FLUXNET, to develop datasets for evaluating ecosystem process models.

ACCOMPLISHMENTS

Over the past eight years, RUBISCO and its predecessor projects have pioneered the development and application of new diagnostic approaches for understanding the carbon cycle and ecosystem processes and their representations in models, resulting in more than 180 peer-reviewed publications. Several of these focused on benchmarking and analysis of biogeochemistry and land surface processes in the suite of phase 5 of the Coupled Model Intercomparison Project (CMIP5) models and, more recently, CMIP6 models.

The RUBISCO team has contributed significantly to the development and systematic evaluation of E3SM and the



Satellite observations from 1982–2010 were combined with CMIP5 ESM projections to analyze the functional responses of vegetation cover changes in the world's cold regions. Observations indicated a greening of high-latitude ecosystems over the past 3–4 decades related to warming. Keenan and Riley (2018) showed a projected decline in the temperature limitation of vegetation cover in cold regions, and suggested that temperature-limited ecosystems are expected to be primarily limited by other factors as soon as the latter half of this century. Figure adapted from Keenan and Riley (2018).

Community Earth System Model (CESM), focusing on areas of critical uncertainties associated with tropical forest nutrient dynamics, trajectories of disturbance and enhanced growth, the state and fate of permafrost carbon, the strength of carbon cycle feedbacks on land and in the ocean, and the evolution of ocean carbon and oxygen and marine biogeochemical cycles.

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RUBISCO SFA Website
https://www.bgc-feedbacks.org/

International Land Model Benchmarking Website
https://www.ilamb.org/