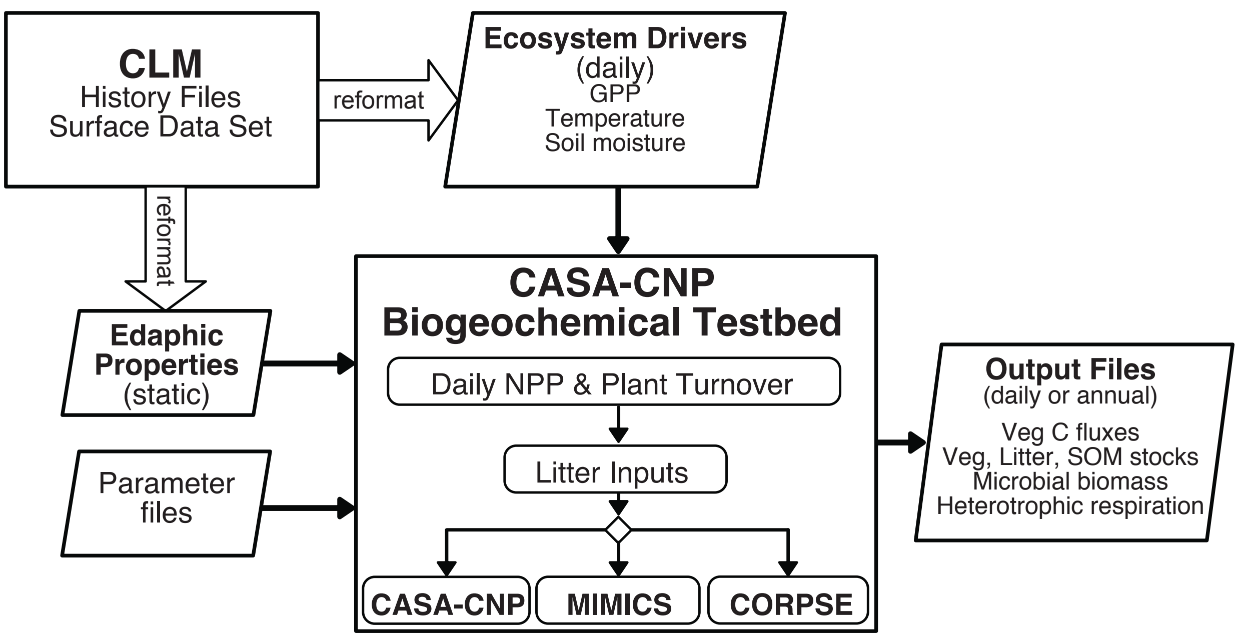
Project Summary

Award #: DE-SC0014374
Title: Benchmarking and Improving Microbial-explicit Soil Biogeochemistry Models
PI: Wieder, William
Project Period: 08/01/2015 - 07/31/2018

Summary:

Soils represent the largest terrestrial carbon pool on Earth. Yet emerging theories regarding stabilization of soil organic matter remain poorly represented in global-scale models; thus, underestimating the true uncertainty associated with potential terrestrial carbon cycle – climate feedbacks. With this project we created a testbed to compare and evaluate soil biogeochemical models (W. Wieder at the Univ. of CO, Boulder), data synthesis (R. Phillips, Indiana Univ.) and parameter estimation (S Allison, Univ. CA Irvine) to quantify uncertainty associated with potential soil C changes. This project resulted in 14 Presentations, 14 Publications and helped support the training of three graduate students. A significant accomplishment with this work was the creation of a soil biogeochemical testbed, which forces three soil carbon models (CASA, MIMICS, and CORPSE) with common environmental drivers. This code base is publicly available on PI Wieder's github page [https://github.com/wwieder/biogeochem_testbed_1.1].

The figure below shows a schematic diagram of the soil biogeochemical testbed. Work to date uses input data generated by simulations from the Community Land Model over the historical period (1901–2010), and under RCP4.5 and RCP8.5 (2011-2100). Outputs from the testbed include daily and annually averaged vegetation carbon fluxes, carbon stocks in vegetation, litter, microbial biomass, and soil organic matter pools as well as heterotrophic respiration fluxes.



Products of DOE award (University of Colorado award)

Presentations (all by PI W. Wieder)

1. NREL Colloquium at Colorado State University "*Ecosystem to Earth system modeling: The next 50 years?"* Nov. 2018, Invited
2. British Royal Society "*Knowledge-model integration: Soil, models, and the terrestrial C cycle*" Oct 2018, Invited
3. Ecological Society of America annual meeting "*Chloroflexi to Climate: Microbial services at regional-to-global scales*" Aug 2017, Invited
4. University of Bergen *"Ecological insights in the Earth system: Facilitating knowledge-model integration"* June 2017
5. Cornell University "*Ecological insights in the Earth system*", seminar for the Crop and Soil Sciences Department April 2017, Invited
6. US Department of Energy "*Knowledge-model integration*", Ignite style talk at the annual PI meeting April 2017, Invited
7. AGU Fall Meeting "*Thresholds of understanding: exploring assumptions in biogeochemical models*" Oral presentation Dec 2016

Publications:

1. **Wieder WR**, MD Hartman, **B Sulman**, CD Koven, MA Bradford. *In Review*. Arctic systems could drive global losses or gains in soil carbon under climate change. *Nature Climate Change*.
2. **Wieder WR**, MD Hartman, **B Sulman**, YP Wang, CD Koven, GB Bonan (2018). Carbon cycle confidence and uncertainty: exploring variation among soil biogeochemical models. *Global Change Biology*, 24, 1563-1579 doi:10.1111/gcb.13979.
3. Rasmussen C, K Heckman, **WR Wieder**, et al. (2018). Beyond clay: towards an improved set of variables for predicting soil organic matter content. *Biogeochemistry*, 137, 297 doi:10.1007/s10533-018-0424-3.
4. Koven CD, G Hugelius, DM Lawrence, **WR Wieder** (2017). Climatological temperature sensitivity of soil carbon is higher in cold than warm climates. *Nature Climate Change*, 7, 817-822 doi:10.1038/nclimate3421.
5. Buchkowski RW, MA Bradford, **AS Grandy**, OJ Schmitz, **WR Wieder** (2017). Applying population and community ecology theory to advance understanding of belowground biogeochemistry. *Ecology Letters*, 20(2), 231-245, doi:10.1111/ele.12712
6. Crowther TW, KEO Todd-Brown, CW Rowe, **WR Wieder**, et al. (2016). Quantifying global soil carbon losses in response to warming. *Nature*, 540(7631): 104-108, doi:10.1038/nature20150.
7. **Grandy, AS, WR Wieder**, K Wickings, and E Kyker-Snowman (2016). Beyond microbes: Are fauna the next frontier in soil biogeochemical models? *Soil Biology and Biochemistry*, 102: 40-44, doi:10.1016/j.soilbio.2016.08.008

8. Bradford MA, **WR Wieder**, GB Bonan, N Fierer, PA Raymond, TW Crowther (2016). Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change* 6: 751-758, doi:10.1038/nclimate3071
9. **Wieder WR**, **SD Allison**, et al. (2015). Explicitly representing soil microbial processes in Earth system models. *Global Biogeochemical Cycles*. 29: 1782–1800 doi:10.1002/2015GB005188.

Relevant Service

- Reviewer, LBL Belowground Biogeochemistry SFA, May 2018
- Reviewer, DOE Office of Science Graduate Student Research (SCGSR) Program, Jan 2018
- Chapter co-author, BERAC Grand Challenges II workshop this is developing recommendations for the next 20 years of research priorities for the DOE. March 2017
- Contributor for the U.S. Department of Energy Offices of Advanced Scientific Computing Research (ASCR) workshop 2016.

Products of DOE award (Indiana University subaward)

Presentations

1. Sulman, B.N., Moore, J.A., Keller, A.B., Craig, M.E., and A.T. Classen. "Incorporating microbe-mineral interactions into biogeochemical models". Ecological Society of America Annual Meeting, New Orleans, Louisiana, August, 2018.
2. Phillips, R.P. Terrer, C., Craig, M.E. and B.N. Sulman. "Plant-microbe mediation of ecosystem responses to elevated CO_2: New understanding through synthesis and modeling". Ecological Society of America Annual Meeting, New Orleans, Louisiana, August, 2018.
3. Craig, M.E., Geyer, K.M., Brzostek, E.R., and R.P. Phillips. "Linking mycorrhizal associations with microbial growth and soil organic matter properties across temperate forests. Ecological Society of America Annual Meeting, New Orleans, Louisiana, August, 2018.
4. Phillips, R.P. Terrer, C., Craig, M.E. and B.N. Sulman. "Plant-microbe-mineral mediation of ecosystem responses to elevated CO_2: New understanding through synthesis and modeling. Geological Society of America; Indianapolis, Indiana, November, 2018.
5. Phillips, R.P., Craig, M.E., Beidler, K., Keller, A.B., Brzostek, E.R., and J.B. Fisher "Are mycorrhizal fungi "trait integrators" or active agents of change of SOM dynamics in forests?" Energy Institute at the University of Michigan (co-sponsored by the Beyond Carbon Neutral Program); Ann Arbor, MI, May, 2018
6. Phillips, R.P. "Belowground processes in models: How much realism is enough?" DOE Office of Biological & Environmental Research "Long-term Vision" Workshop; Washington, DC, March, 2017.

Manuscripts

1. **Craig, M.E., Keller, A.B**. (co-first-authors), **Sulman, B.N., Wieder, W.R., Allison, S.D.,** Grandy, A.S., Tiemann, L., and **R.P. Phillips**. *In prep*. "Litter and climate controls on forest soil carbon-to-nitrogen ratios at the global scale". *Anticipated submission date: December, 2018*

Abstract: While the ratio of carbon-to-nitrogen (C:N) in soil is often used as a proxy for rates of carbon and nutrient cycling in ecosystems, our incomplete understanding of what controls C:N ratios at global scale has limited their representation in Earth system models. We compiled a data set of *ca.* 400 plot-level, spatially coordinated measurements of litter chemistry and soil C:N to investigate the nature of their global relationship. Then, we determined how well a soil C and N model (CORPSE-N) matched observations, and used the model to investigate mechanisms linking litter chemistry to soil C:N. We observed a strong, but context-dependent relationship between litter and soil C:N at the global scale (R^2 = 0.39). This relationship was weak at latitudinal extremes and strongest at mid-latitudes. CORPSE-N matched our observations reasonably well and demonstrated that indirect effects of litter chemistry on soil C:N – mediated by dynamic microbial production and turnover – are more important than the direct effects of substrate origin. In conclusion, we find evidence that litter input quality is an important control over soil C:N at the global scale. These findings emphasize the need to consider how changes to litter inputs mediate global change effects on the many ecosystem processes regulated by soil organic matter stoichiometry.

2) Keller, A.B., and **R.P. Phillips.** *In Revision*. Leaf litter decay rates differ between mycorrhizal groups yet show contrasting patterns in temperate vs. tropical forests. New Phytologist

Abstract: While the primary controls on litter decomposition are well established, we lack a framework for predicting interspecific differences in litter decay within and across ecosystems.

Given previous research linking tree mycorrhizal association with carbon and nutrient dynamics, we hypothesized that the two dominant mycorrhizal groups in forests – arbuscular mycorrhizal (AM) and ectomycorrhizal (ECM) fungi – differ in litter decomposition rates. We compiled leaf litter chemistry and decay data for AM- and ECM-associating angiosperms and gymnosperms (> 200 species) from temperate and sub/tropical forests, and investigated relationships between decay rates, mycorrhizal association, phylogeny and climate. In temperate forests, AM litters decayed faster than ECM litters, with litter nitrogen and phylogeny best explaining variation in litter decay. In sub/tropical forests, we found no significant difference in litter decay rate between mycorrhizal groups, and variation in decay rates was best explained by litter phosphorus. Our results suggest that knowledge of tree mycorrhizal association may improve predictions of species effects on ecosystem processes, particularly in temperate forests where AM and ECM species commonly co-occur, providing a predictive framework for linking litter quality, organic matter dynamics and nutrient acquisition in forests.

3. **Sulman, B.N**., Shevliakova, E., Brzostek, E.R., Kivlin, S.N., Malyshev, S., Menge, D.N.L., and X. Xhang, *In Revision.* “Diverse mycorrhizal associations enhance terrestrial C storage in a global model”. Global Biogeochemical Cycles

Abstract: Accurate projections of the terrestrial carbon (C) sink are critical to understanding the future of the global C cycle and for setting goals for anthropogenic CO_2 emission reductions. The extent to which this C sequestration capacity will be limited in the future by nitrogen (N) availability remains a critical uncertainty. While plants use a diverse set of nutrient acquisition strategies to mitigate N limitation under elevated CO_2, current earth system models (ESMs) and dynamic global vegetation models (DGVMs) largely omit these mechanisms. Current models with coupled C-N cycles project that N limitation will severely reduce future terrestrial C sequestration. Using a novel model of N-acquiring plant-microbe symbioses incorporated into a DGVM, we show that increases in N acquisition via soil organic matter (SOM) decomposition and atmospheric N_2 fixation can support long-term enhancement of terrestrial C sequestration at global scales under elevated CO_2. Under a global 100 ppm increase in CO_2 concentrations, shifts in N acquisition pathways facilitated 200 Pg C of terrestrial C sequestration over 100 years compared to 50 Pg C over 100 years for a scenario in which N acquisition pathways could not change. Our results suggest that a diversity of N acquisition strategies is an important determinant of terrestrial C sequestration potential under elevated CO_2, and that DGVMs with coupled terrestrial C-N cycles that omit these N acquisition mechanisms underestimate the potential for future terrestrial C uptake.

3. **Sulman BN**, J. A. M. Moore, R. Z. Abramoff, C. Averill, S. N. Kivlin, K. Georgiou, B. Sridhar, M. Hartman, G. Wang, **W. R. Wieder**, M. A. Bradford, Y. Luo, M. Mayes, E. Morrison, W. J. Riley, A. Salazar, J. P. Schimel, J. Tang, and A. T. Classen. “Multiple models and experiments underscore large uncertainty in soil carbon dynamics”. Biogeochemistry Letters. doi:10.1007/s10533-018-0509-z.

Abstract: Soils contain more carbon than plants or the atmosphere, and sensitivities of soil organic carbon (SOC) stocks to changing climate and plant productivity are a major uncertainty in global carbon cycle projections. Despite a consensus that microbial degradation and mineral stabilization processes control SOC cycling, no systematic synthesis of long-term warming and litter addition experiments has been used to test process-based microbe-mineral SOC models. We explored SOC responses to warming and increased carbon inputs using a synthesis of 147 field manipulation experiments and five SOC models with different representations of microbial

and mineral processes. Model projections diverged but encompassed a similar range of variability as the experimental results. Experimental measurements were insufficient to eliminate or validate individual model outcomes. While all models projected that CO_2 efflux would increase and SOC stocks would decline under warming, nearly one third of experiments observed decreases in CO_2 flux and nearly half of experiments observed increases in SOC stocks under warming. Long-term measurements of C inputs to soil and their changes under warming are needed to reconcile modeled and observed patterns. Measurements separating the responses of mineral-protected and unprotected SOC fractions in manipulation experiments are needed to address key uncertainties in microbial degradation and mineral stabilization mechanisms. Integrating models with experimental design will allow targeting of these uncertainties and help to reconcile divergence among models to produce more confident projections of SOC responses to global changes.

4. Bailey, V.L., Bond-Lamberty, B., DeAngelis, K., **Grandy, A.S.,** Hawkes, C.V., Heckman, K., Lajtha, K., **Phillips, R.P., Sulman, B.N**., Todd-Brown, K., and M.D. Wallenstein. 2017. Soil carbon cycling proxies: Understanding their critical role in predicting climate change feedbacks. Global Change Biology, 24: 895-905. DOI: 10.1111/gcb.13926

Abstract: The complexity of processes and interactions that drive soil C dynamics necessitate the use of proxy variables to represent soil characteristics that cannot be directly measured (correlative proxies), or that aggregate information about multiple soil characteristics into one variable (integrative proxies). These proxies have proven useful for understanding the soil C cycle, which is highly variable in both space and time, and are now being used to make predictions of the fate and persistence of C under future climate scenarios. However, the C pools and processes that proxies represent must be thoughtfully considered in order to minimize uncertainties in empirical understanding. This is necessary to capture the full value of a proxy in model parameters and in model outcomes. Here, we provide specific examples of proxy variables that could improve decision-making, and modeling skill, while also encouraging continued work on their mechanistic underpinnings. We explore the use of three common soil proxies used to study soil C cycling: metabolic quotient, clay content, and physical fractionation. We also consider how emerging data types, such as genome-sequence data, can serve as proxies for microbial community activities. By examining some broad assumptions in soil C cycling with the proxies already in use, we can develop new hypotheses and specify criteria for new and needed proxies.

Products of DOE award (UC Irvine subaward)

Presentations:

Conference: Global Soil Biology Conference 2, October 15th - 18th, 2017
Title: Bayesian Evaluation of Dynamical Soil Carbon Models Using Soil Carbon Flux Data
Authors: HW Xie, A Romero-Olivares, M Guindani, SD Allison
Abstract: 2016 was Earth's hottest year in the modern temperature record and the third consecutive record-breaking year. As the planet continues to warm, temperature-induced changes in respiration rates of soil microbes could reduce the amount of carbon sequestered in the soil organic carbon (SOC) pool, one of the largest terrestrial stores of carbon. This would accelerate temperature increases. In order to predict the future size of the SOC pool, mathematical soil carbon models (SCMs) describing interactions between the biosphere and atmosphere are needed. SCMs must be validated before they can be employed for predictive purposes. In this study, we consider two SCMs, CON and AWB, and assess their adequacy to describe observed data patterns using established Bayesian model selection criteria, which have been proposed in the literature to maximize the predictive accuracy of a model based on information from available data. More specifically, we compare the models using the Widely Applicable Information Criterion (WAIC), the Leave-One-Out Information Criterion (LOOIC), and the LPML (log pseudo marginal likelihood).

Conference: AGU Fall Meeting, December 11th - 15th, 2017
Title: Bayesian Evaluation of Dynamical Soil Carbon Models Using Soil Carbon Flux Data
Authors: HW Xie, A Romero-Olivares, M Guindani, SD Allison
Abstract: 2016 was Earth's hottest year in the modern temperature record and the third consecutive record-breaking year. As the planet continues to warm, temperature-induced changes in respiration rates of soil microbes could reduce the amount of carbon sequestered in the soil organic carbon (SOC) pool, one of the largest terrestrial stores of carbon. This would accelerate temperature increases. In order to predict the future size of the SOC pool, mathematical soil carbon models (SCMs) describing interactions between the biosphere and atmosphere are needed. SCMs must be validated before they can be chosen for predictive use. In this study, we check two SCMs called CON and AWB for consistency with observed data using Bayesian goodness of fit testing that can be used in the future to compare other models. The CON and AWB models are used for their computational tractability, but differ in that CON consists of a first-order linear system of equations, while AWB is non-linear in its SOC pool equation. We compare the fit of the models to longitudinal soil respiration data from a meta-analysis of soil heating experiments using a family of Bayesian goodness of fit metrics called information criteria, including the Widely Applicable Information Criterion (WAIC), the Leave-One-Out Information Criterion (LOOIC), and the Log Pseudo Marginal Likelihood (LPML). These information criteria take the entire posterior distribution into account, rather than just one outputted model fit line. Lower WAIC and LOOIC and larger LPML indicate a better-fitting model.

Conference: AGU Fall Meeting, December 10th - 14th, 2018
Title: A Bayesian Approach to Soil Biogeochemical Model Comparison
Authors: HW Xie, A Romero-Olivares, M Guindani, SD Allison
Abstract: A quantitative approach for sorting soil biogeochemical carbon models (SBMs) by predictive accuracy and goodness-of-fit present empirical data has yet to be strictly defined. In this study, we present a Bayesian approach to SBM comparison, whose steps can be incorporated into a statistical model selection framework. We compared the fit of two SBMs called the conventional (CON) and Allison-Wallenstein-Bradford (AWB) models to data of

microbial soil CO2 flux from a meta-analysis of 25 soil warming experiments (Romero-Olivares et al., 2017). We used the widely applicable information criterion (WAIC), leave-one-out cross validation (LOO), log pseudo-marginal likelihood cross validation (LPML), and R-squared metrics to quantify the goodness-of-fit of CON and AWB to the dataset. WAIC and LOO both account for overfitting by penalizing for greater model parameter count (Vehtari and Gelman, 2014). We examined the feasibility of truncating prior distribution supports and fixing pre-warming steady states to constrain fitting to biologically realistic parameter space. Normal and informative priors were used. We found that prior truncation resulted in posterior density deformity at more extreme pre-warming microbial(MIC)-to-SOC ratios for both models. For less extreme ratios, posterior densities were not deformed, indicating priors were reasonably established. These results indicate that prior truncation and fixing of initialized steady states are attemptable techniques for constraining fitting to biologically realistic parameter space with the use of non-extreme steady state ratios. We demonstrate that WAIC and LOO can be used in conjunction with other goodness-of-fit metrics to inform SBM selection. Decreasing pre-warming steady state SOC relative to MIC generally improved LOO, WAIC, LPML, and R-squared for CON and AWB, but increased effective parameter count and overfitting in AWB's case. CON generally outperformed AWB in LOO and WAIC because of its reduced overfitting burden.

Conference: 2018 American Geophysical Union Fall Meeting, Washington DC
Title: Reverse Michaelis-Menten kinetics derived from scaling forward kinetics
Authors: Wang, B., and S.D. Allison.
Abstract: Plant residues and soil organic matter are predominantly decomposed by exo-enzymes. Many soil carbon models now represent enzymatic decomposition, but the mathematical formulation of this process has been debated over the last 15 years. Some models apply the Michaelis-Menten equation to represent enzyme kinetics whereas other apply the “reverse” Michaelis-Menten equation, which assumes that kinetic rates saturate at high enzyme concentrations. The application of reverse Michaelis-Menten kinetics has been difficult to verify experimentally because of methodological limitations. Therefore, the overarching goal of our study was to validate application of the reverse equation using model-based evidence. We used a spatially explicit, individual- and trait-based microbial model, DEMENT, to examine the relationship between substrate decay rate and enzyme concentration at microbial to ecosystem scales. Manipulation of enzyme concentration was achieved by changing the microbial enzyme production rate. Across different substrates, we found a consistent saturating relationship between reaction rates and enzyme concentrations that fit the reverse Michaelis-Menten equation very well. This mathematical relationship emerges from the spatialtemporal heterogeneity of substrates and enzymes in our model system. Our results illustrate how traditional Michaelis-Menten kinetics at the microbial scale are compatible with reverse kinetics at the ecosystem scale. This scaling exercise validates the application of the reverse Michaelis-Menten equation in soil biogeochemical models.

Manuscript:
He, Y., S. E. Trumbore, M. S. Torn, J. W. Harden, L. J. S. Vaughn, S. D. Allison, and J. T. Randerson. 2016. Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century. Science 353: 1419-1424.

Other accomplishments:

- Zheng Shi and our team have been collaborating to develop ISRaD, the International Soil Radiocarbon Database. This work developed out of the He et al. 2016 paper, and we are using the database to analyze the drivers of carbon ages and turnover times by depth and with different environmental drivers.

- Sasha Hararuk and I have been collaborating with Emma Sayer to parameterize MIMICS with a dataset from Panama. The dataset includes respiration, microbial, and soil carbon responses to litter addition and removal. The results so far show that including a moisture sensitivity function in the model improves the fit to data and that only a single microbial biomass pool is required for the most parsimonious model.