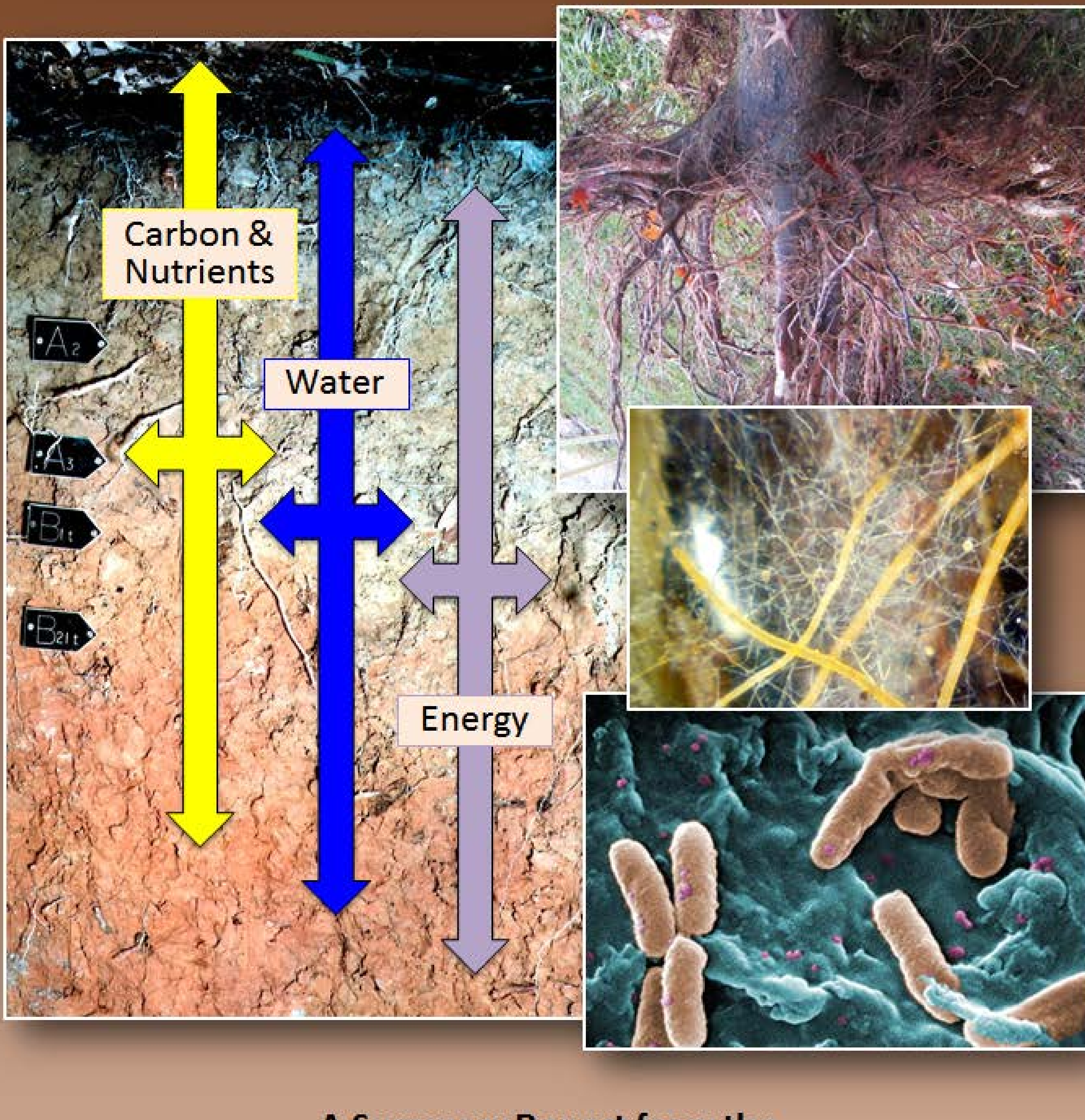
Data-Model Needs for Belowground Ecology



A Summary Report from the
Terrestrial Ecosystem Science (TES) Mini-Workshop
May 8, 2014

Front Cover Images: The dynamics of carbon, nutrients, energy, and water are essential aspects of the belowground processes that are critical to whole-ecosystem function. Vertical profiles of soil characteristics, processes, and interactions across the landscape are important for understanding and modeling belowground systems. Images at the right highlight the integrated nature of biotic components of belowground ecosystems, including plants roots, plant-microbe interactions in the rhizosphere, and microbially mediated transformations of soil organic matter and nutrients.

Back Cover Images: Montage depicting belowground research activities and schematic example of a model used to study belowground processes.

All front and back cover images were contributed by the authors except for the image of bacteria, which was obtained from the Centers for Disease Control and Prevention Public Health Image Library (photo credit: Janice Haney Carr) http://phil.cdc.gov/phil/details.asp.

Data-Model Needs for Belowground Ecology

A Summary Report from the
Terrestrial Ecosystem Science (TES) Mini-Workshop
May 8, 2014

Report Date: December 4, 2014

Organizing Committee

Vanessa Bailey[4], Paul J. Hanson[3], Julie Jastrow[1], Margaret Torn[2] and Daniel Stover[5]

National Laboratory Participants

Ben Bond-Lamberty[4], Eoin Brodie[2], Dipankar Dwivedi[2], Zhaosheng Fan[1], Yilin Fang[4], Bardan Ghimire[2], Nancy Hess[4], Roser Matamala[1], Melanie Mayes[3], Umakant Mishra[1], Lee Ann McCue[4], Peter Nico[2], Sarah O'Brien[1], Caitlin Hicks Pries[2], Chris Schadt[3], Jeff Warren[3], and Xiaojuan Yang[3]

Invited External Speakers

Yiqi Luo[6] and Will Wieder[7]

Participating Organizations

[1]Argonne National Laboratory
[2]Lawrence Berkeley National Laboratory
[3]Oak Ridge National Laboratory
[4]Pacific Northwest National Laboratory
[5]U.S. Department of Energy, Office of Science
[6]University of Oklahoma
[7]National Center for Atmospheric Research, Earth System Laboratory

This page left blank.

Table of Contents

This page left blank.

Executive Summary

Terrestrial life on Earth depends on belowground cycling and storage of a significant portion of the planet's biologically-active carbon. The interplay among organic inputs by primary producers, soil organic matter stabilization, and assimilation and mineralization by soil organisms drives belowground ecology. Understanding belowground carbon dynamics, including the stability and vulnerability of soil organic carbon stocks, is necessary to project the responses and feedbacks of terrestrial ecosystems to a changing climate. Although conceptually understood, belowground hydrobiogeochemical systems are not well characterized with quantitative and mechanistic representations of critical functions. As a result, these systems are inadequately represented in modeling efforts, limiting our ability to understand and project terrestrial carbon source/sink relationships at various temporal and spatial scales. The belowground science community lacks robust databases and data libraries against which model sensitivities and performance can be tested and enhanced. Improved understanding of belowground ecosystems, including biotic and abiotic interactions, is needed to ensure that model structures include and provide adequate representations of critical belowground processes, functions, and dynamics.

A one-day workshop brought together experimental and modeling representatives from the four Department of Energy (DOE) National Laboratories where the Office of Biological and Environmental Research (BER) Terrestrial Ecosystem Science (TES) program has investments in belowground ecology. The group focused on identifying and characterizing (1) critical experimental and observational datasets for testing and developing existing and future belowground-process models and land models; (2) the limitations and needs for modeling belowground processes within ecosystem models; and (3) key areas for leveraging current research activities across the National Laboratories and BER-funded projects. Discussion results are organized in this report as: (I) over-arching data requirements for advancing understanding of belowground ecology; (II) efforts that could rapidly improve understanding and model representations of belowground components of terrestrial ecosystems; and (III) longer-term research needs that would benefit from greater and more sustained support.

Ecosystem models, while not perfect, represent a reasonable expression of scientific understanding of integrated ecosystem and belowground processes. We can use models, and the reduction of model error and uncertainty, as an organizing theme for future belowground research. Investments should be aimed where rapid improvements of belowground representation are possible. Uncertainty and sensitivity analyses can guide prioritization of parameter improvements while new structures may be needed to represent previously ignored mechanisms. Data synthesis should be considered a near-term priority, addressing the results of uncertainty analyses and the need for structural improvements. Long-term research plots and studies that can serve as model benchmarking sites should be supported and augmented. Selected new sites should be added in association with key observational and experimental efforts. Spatial and temporal scaling are pervasive challenges, motivating a research-community concept for producing belowground information at scales relevant for addressing regional to global questions. In summary, a rigorous understanding of belowground systems — linking the scales at which key processes occur to the scales at which we measure and model them — is needed to accurately predict the responses and feedbacks of terrestrial ecosystems to a changing climate.

This page left blank.

Introduction

Belowground components of terrestrial ecosystems cycle and store a significant portion of Earth's biologically-active carbon. Climate change is expected to increase global temperatures and alter patterns of precipitation and drought. Resulting changes in soil moisture and temperature strongly influence belowground biogeochemical processes. Thus, understanding belowground carbon dynamics and stocks, including their stability and vulnerability, is necessary to project the responses and feedbacks of terrestrial ecosystems to a changing climate. Within soils, physical and chemical processes interact with plants, microbes and the soil matrix to regulate the turnover, accumulation, stabilization, and vulnerability of carbon with respect to global cycles of the greenhouse gases, carbon dioxide (CO_2) and methane (CH_4). Further, many belowground processes are critical regulators of the health and function of aboveground components of terrestrial ecosystems. But belowground hydrobiogeochemical processes are not well understood as a functional system. As a result, they are inadequately represented in modeling efforts, limiting our ability to understand and project the carbon source/sink relationship of terrestrial ecosystems at various temporal and spatial scales. While the Department of Energy (DOE), Office of Biological and Environmental Research (BER), Terrestrial Ecosystem Science (TES) program and initiatives in other agencies are making significant efforts to improve the representation of these processes in models, the community lacks robust databases and data libraries against which model sensitivities and performance can be tested. Further, improved understanding of belowground ecosystems is needed to ensure that model structures include and provide adequate representations of critical belowground processes, functions, and dynamics.

A one-day workshop brought together experimental and modeling representatives from the four DOE National Laboratories where TES has investments in belowground ecology. Within the context of their terrestrial research, this small group focused on identifying and characterizing: (1) critical experimental and observational datasets for testing and developing existing and future belowground-process models and land models; (2) the limitations and needs for modeling belowground processes within ecosystem models; and (3) key areas for leveraging current research activities across the National Laboratories and BER-funded projects. The key outcomes are organized into: (I) over-arching data requirements for advancing understanding of belowground ecology; (II) efforts that could rapidly improve understanding and model representations of belowground components of terrestrial ecosystems; and (III) longer-term research needs that would benefit from greater and more sustained support.

I. Data-model requirements for advancing understanding of belowground ecology

Observational and experimental data play a central role in improving land models and their ability to predict ecosystem-climate feedbacks. In turn, models help us to integrate and interpret experimental data, scale observations across space and time, identify critical knowledge gaps, and inform research priorities. Workshop participants considered data-model needs, as summarized in Table 1 and Sections II and III, in the context of four types of data-model applications:

- Model evaluation and uncertainty quantification
- Model initialization and boundary conditions
- Development and improvement of model structures and parameter estimates
- Scaling and integration of observational data and experimental results

To fulfill these objectives, datasets are needed for steady-state and dynamic conditions, and for processes operating over multiple time scales, under multiple environmental conditions, and coupled with targeted database functionalities. A brief assessment of belowground data needs in the context of available datasets (examples listed in Appendix B) is summarized below.

Table 1. Near-term and longer-term opportunities for meeting data-model needs in belowground ecology.

Near-term opportunities for rapid improvement

- Augment or create databases for existing data
- Conduct data synthesis, meta-analysis, and geospatial interpolations using existing datasets
- Create model benchmarking datasets for evaluating models
- Perform data assimilation for model parameter improvement and uncertainty quantification
- Develop functional testing platforms for assessing belowground processes in models

Longer-term opportunities

- Develop new process understanding needed for ecosystem projections (see Table 2)
- Determine the level of complexity in process representation needed for exploring belowground feedbacks to climatic change
- Address cross-cutting issues, including:
  - Model structures
  - Scaling and spatial heterogeneity
  - Depth distributions and temporal dynamics
  - Nutrient cycling and water availability
  - Plant-microbe-soil interactions

Soil data-model needs: Soils data are available for some state variables, such as soil carbon stocks, soil properties (e.g., bulk density, texture), and soil order (Appendix B), but the quality of coverage across the globe is variable. Fewer databases exist for fluxes and other process data. For both state variables and process-level data, data limitations exist for surface soils, but they are especially severe for the soil subsurface (often defined as > 20 cm depth). Field sampling strategies and models vary in how they represent the vertical soil profile. Some databases (e.g., the Harmonized World Soil Database) aggregate over vertical resolution, and most are limited to the top meter. The AmeriFlux and International Soil Carbon Network (ISCN) databases, however, allow soil layers defined by depth increments or soil horizon to be cross-referenced to accommodate different data sources. As an additional challenge, models often employ variable depth intervals, with finer vertical resolution near the soil surface and differences in the maximum depth of simulation.

Plant data-model needs: Regional to global datasets are available for root distribution and mass (e.g., Global Distribution of Root Profiles, http://www.daac.ornl.gov), but these data do not adequately capture the complexity and variability of root growth, turnover, morphology, and function among ecosystem types or plant species. For example, no multi-site database exists for root functional characteristics, such as nutrient uptake or water transport. The transfer of biomass carbon from roots to soils may be estimated from data on root turnover (which is not well constrained by existing datasets), but the transfer of carbon to soil via mycorrhizal fungi, root exudation, and rhizodeposition (plus the role of microbial communities in such processes) is not so readily inferred.

Microbial data-model needs: Microbial mineralization and transformations of soil organic matter are central processes in the global carbon cycle. Despite recent advances in measurement capabilities and data generation, additional research is needed to translate these data in ways that can better represent microbial community structure and function. A high priority need is to determine what resolution of microbial community and functional understanding is needed in predictive models (e.g., from the coarse level of relative fungal:bacterial ratios to the resolution derived from metagenomic sequencing), and if necessary, ascertain how to use knowledge gained through contemporary ’omic research in models.

Gaps and limitations: Notwithstanding the existence of a number of datasets and databases, empirical and modeling communities alike recognize significant gaps and limitations in data available for model-data applications. Intensive and extensive multi-site measurements with a belowground focus, coordinated across disciplines, space, and time are needed (Figure 1).

The need for generalizable approaches to bridging spatial and temporal scales is a particularly acute knowledge gap. More effort is needed to characterize belowground conditions throughout the soil profile (e.g., carbon stocks, available nutrients, mineralogy, water-holding capacity, rooting depths), and to provide temporal and spatial data for important ecosystem processes. For example, CO_2, CH_4, and nitrous oxide (N_2O) fluxes, litter decomposition, microbial community dynamics, and enzyme production are likely to vary spatially and temporally, as are important process drivers such as soil moisture and temperature.

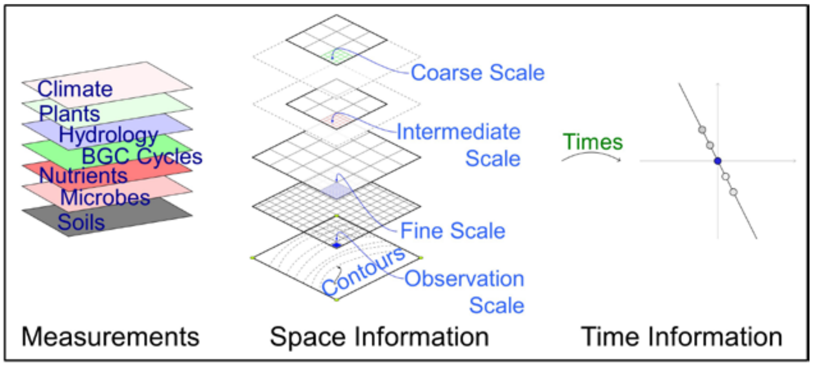


Figure 1. Spatial and temporal coordination of comprehensive measurements is crucial for long-term advances in belowground ecology. The left side of the figure represents one snapshot of measurements by different research disciplines. Measurement schemes must be designed and conducted to be integrated, scaled, and interpreted in space (middle) and over time (right).

Further, improved understanding of plant-microbe-soil interactions is needed, not only for analysis of climate feedbacks but also for microbe-to-biome and sustainable bioenergy initiatives. A multi-disciplinary approach is required to make connections between different research areas and different model compartments. Fulfilling such needs might help models capture emergent processes (e.g., priming effects or soil carbon residence time) without needing to rely upon specific parameterizations, which could vary for different ecosystems.

Improving the value of new and existing datasets: Developing new datasets should be done with defined hypotheses and model needs in mind and include gold-standard metrics for data quality, methods documentation, measurement units, and uncertainty characterization. For model benchmarking, databases are needed that organize and harmonize the full breadth of input and output values for fine-scale and grid-scale models. This means not just soil and root carbon stocks, but also soil conditions that regulate biogeochemical processes, root and microbial community traits and their functions, and the relevant driver data. Metadata and data access should be assured via data management plans coupled with the development of a common metadata search capability. Where appropriate (e.g., soils, tissues), samples represented in databases should ideally be archived (using best current practices) for future reference or analysis.

To facilitate model-data comparisons, objective methods and visualization tools are needed for aggregating and scaling point data to model grid scales, while distinguishing observations from interpolated data to preserve the variability and uncertainty information in the measurements. The DOE-supported AmeriFlux database and the TRY database of plant traits (www.try-db.org/) provide possible examples of how belowground-focused databases might be organized. Realization of the importance and value of past and future investments in data generation and synthesis has never been greater. Justification for increased emphasis on data management and preservation efforts is provided in Appendix A and demonstrated by the application of archived data to recent experiment-model inter-comparisons (e.g., Walker et al., 2014).

II. Near-term opportunities for rapid improvement

Workshop participants identified several opportunities for near-term advances in belowground research that take advantage of existing data and databases, as summarized in Table 1 and discussed here.

Augment or create databases for existing data. Many opportunities exist for creating or improving relational databases by compiling and organizing data from existing sources to make them more useful for synthesis and model applications. For example, harmonizing of variable units, time steps, and depth increments is often necessary. Further, value-added products can often be generated from the original data — such as calculation of soil carbon stocks from reported data on carbon concentration, bulk density, and depth increments. In addition to initial investments in these activities, in many cases there is a need for active curation and updating as new data become available. For example, carbon turnover times are a sensitive diagnostic for soil models. The only direct tracer for turnover time in undisturbed ecosystems is radiocarbon (^{14}C). Although design of a ^{14}C database has been completed (under TES support), additional effort is needed to input existing data, which span all major continents and soil orders. Similarly, a root trait database is being compiled (also under TES support) in collaboration with TRY. Further, the ISCN database could be augmented by gathering and inputting soil carbon data generated by past DOE-supported activities. More generally, a system for linking belowground databases — envisioned as a community-driven, agency-supported belowground clearinghouse that, for example, allows flexible metadata searching and structured data queries — would create many opportunities for improving comprehensive understanding of belowground systems.

Data synthesis, meta-analysis, and geospatial interpolations. Some poorly constrained, key belowground parameters could be improved through synthesis of the literature (e.g., recent TES-supported reviews on tundra root distribution and dynamics and the representation of root function in terrestrial biosphere models; Iversen et al., 2014 and Warren et al., 2014, respectively). Surveys of microbial community structure and function across ecosystems, and their responses to climate manipulations, are being published — presenting another opportunity for gaining new insight through synthesis. Similarly, compilation and meta-analysis of published data on the responses of soil respiration and nutrient cycling in soil warming studies could identify general response patterns needed to parameterize and evaluate belowground temperature functions in Earth system models. Geospatial analysis and interpolation (e.g., Mishra and Riley, 2012; Yang et al., 2013) can be used to synthesize and extrapolate point data to scales useful for land models, identify important environmental drivers, and help identify the need for and prioritize investments in additional observations.

Create model benchmarking datasets for evaluating models. Quite a few studies have invested in comprehensive, well-defined belowground measurements, such as selected AmeriFlux sites and experimental manipulations (e.g., Free Air CO_2 Enrichment [FACE] experiments, the Detritus Input and Removal Transfer [DIRT] experiments, isotopic studies). These studies create near-term model benchmarking opportunities. Benchmarking exercises could be carried out using these sites to gain confidence in model projections and to enable development of process-resolving benchmarked models (e.g., Walker et al., 2014). Databases could be integrated into the International Land Model Benchmarking (ILAMB) framework (supported by the DOE BER Regional and Global Climate Modeling [RGCM] program) to facilitate model testing. Taking advantage of multiple sites or regional-scale databases, geospatial modeling and statistics can also provide spatially resolved datasets for validation, benchmarking, and uncertainty evaluations of model outputs (e.g., Drewniak et al., 2014; Mishra and Riley, 2014).

Data assimilation for model parameter improvement and uncertainty quantification. Long-term field studies, AmeriFlux sites, and manipulative experiment sites (e.g., warming studies) with large amounts of belowground data should be leveraged to enable data assimilation activities to improve model parameterization. For example, simulation of organic matter decomposition with depth in boreal forests was informed by data assimilation from three sites (Fan et al., 2008), and data from the Alaska Peatland Experiment (APEX) were used to model the impact of anaerobic zones in unsaturated peatland soils on CO_2 and CH_4 emissions (Fan et al., 2014). Such data assimilation activities can facilitate interactive learning mediated by both measurements and the feedbacks from model projections. For instance, ecological models are often hypersensitive to projected rainfall deficits, and a model improvement exercise targeting available interannual drought data should go a long way toward adjusting ecosystem model drought responsiveness. Such an exercise could take advantage of under-utilized information on interannual variation in rainfall and soil moisture embedded in long-term observational and experimental data. These data could provide important reference information for defining the sensitivity of vegetation and ecosystem processes to limiting moisture levels. Development of such data assimilation exercises, employing data from multiple sites (e.g., Hararuk et al., 2014) and taking advantage of the databases and benchmarking approaches described above, would be a powerful method of improving many model parameters and evaluating uncertainties for belowground processes.

Develop functional testing platforms for assessing belowground processes in models. The community needs a relatively rapid means for testing mechanisms or key processes in higher-order models such as the various versions of the Community Land Model (CLM-CESM or CLM-ACME). Platforms are needed to allow exploration of different approaches to process representations and to support uncertainty quantification — particularly for structural uncertainty, where simple parameter sensitivity analyses are not sufficient. Such platforms would allow exploration of belowground representations and parameters within higher-order models to assess the impact of different belowground processes on model outputs (e.g., net primary production and soil respiration). Moreover, conventional parameter-based sensitivity analyses could be conducted with limited investment. For example, a functional-unit testing framework is currently being used to develop a root module in CLM 4.5 (supported by TES) that leverages data from the Oak Ridge National Laboratory FACE experiment to improve model representation of root structure and function and better understand uncertainty (Wang et al., 2014a). Recently published reaction-network models make modeled processes more transparent, which facilitates inclusion and evaluation of new mechanisms in CLM (Fang et al., 2013; Riley et al., 2014). These platforms will allow comparisons of ecosystem biogeochemical cycles using different conceptual models within the same modeling framework.

III. Longer-term research opportunities

Many data-model needs will require a larger or more sustained investment. The workshop identified numerous belowground knowledge and data gaps that currently limit model improvement (Table 2). For many of these, making advances would require new data, from observational and experimental studies, in addition to the progress recommended in Section II. Identifying priorities for specific investments of this type was beyond the scope of a one-day workshop. Yet, these priorities must be defined, and this could be accomplished through inter-Laboratory working groups and/or a broader community workshop. Such follow-on activities could prioritize the list of topics as well as articulate the specifications for a belowground database (or clearinghouse) to address these knowledge gaps.

Table 2. Gaps in belowground data and understanding that limit model improvement. The cross-cutting issues are applicable to most microbial, root, and soil topics. The order of topics within each column does not imply research priorities.

Microbes	Roots	Soils	Cross-cutting issues
• Biomass, growth & mortality • Activity & C decomposition • Functional traits (e.g., enzyme production) • Biomass turnover (residue inputs to SOM) • Community composition & diversity • Utilizing 'omics data	• Species-specific biomass, production & mortality • Morphology, C:N, chemical composition, storage pools • Functional traits (e.g., water & nutrient uptake) • Biomass turnover (decomposition inputs to SOM) • Non-structural C (exudates, rhizodeposits) • Symbiotic associations (mycorrhizae, N fixers)	• SOM stocks, composition, and distribution through the soil • SOM stabilization/vulnerability (organo-mineral interactions, aggregation, other mechanisms) • Soil structural controls on habitat (spatial accessibility, constraints on air/water & roots/microbes) • Production, fate, & transport of DOC (& nutrients) • Biogeochemical interactions (redox, weathering, nutrients) • Parent material (mineralogy) & landscape controls	• Scaling • Spatial heterogeneity • Depth distributions • Temporal dynamics • Nutrient cycling • Water availability • Root-microbe-soil interactions • Belowground-aboveground interactions • Model structures
C = carbon; SOM = soil organic matter; N = nitrogen; DOC = dissolved organic carbon.			

However, several overarching longer-term needs and issues were identified during the workshop, and these are applicable to most, if not all, of the topical belowground data and knowledge gaps listed in Table 2. These longer-term needs and issues are briefly discussed below.

Develop new process understanding needed for ecosystem projections. The data needs for developing better understanding of belowground ecosystem function are substantial because of the difficulties of observing: (1) the relatively inaccessible soil matrix without disturbing it, (2) a highly-interconnected system, and (3) the very fast timescales of some processes (e.g., enzyme activities) and very slow timescales of others (e.g., weathering). Understanding and quantifying the complex interactions among belowground ecosystem components as well as between belowground and aboveground components are particularly challenging. Nevertheless, improving understanding of belowground ecosystem function is a priority because many current model representations are coarse approximations, and it is difficult to even test sensitivities (or assess structural uncertainty) for processes or mechanisms that are not in a model.

Determine the level of complexity in process representation needed for exploring belowground feedbacks to climatic change. A disconnect exists between measured belowground data and the manner in which models at all scales treat belowground processes. A set of benchmarking studies should be developed that would allow direct coupling of experiments and models. These coupling exercises should demonstrate which data are needed to constrain different parameters, and whether improving the resolution of these data improves the predictive power of models. However, the lack of representation of some processes in models must also be considered because structural gaps cannot be identified with parameter uncertainty or sensitivity analyses. A useful example of the potential for closely coupling belowground measurements with model treatment is the Partitioning in Trees and Soils (PiTS) framework supported by TES (Warren et al., 2012).

The fundamental issue of determining the level of complexity required in models arises for many different system components and processes, such as plant root functions, symbiotic relationships, and soil organic matter stabilization processes. In the next paragraph, microbes are highlighted as an example of the types of issues that must be addressed to determine the appropriate level of complexity needed for model improvement because of the uniquely pivotal role of microbes in the cycling of soil organic matter and the large DOE investment in microbial genomic research.

The ecological modeling community is moving away from first-order decomposition kinetics toward microbially-enabled models, such as those supported by the Accelerated Climate Model for Energy (ACME) and the Next Generation Ecosystem Experiments (NGEE). Reaction-based and microbially-enabled versions of CLM and other process models (e.g., Fang et al., 2014; Riley et al., 2014; Tang and Riley, 2014; Wang et al., 2014a,b; Xu et al., 2014) are being supported by BER, but many of the required parameters are poorly documented or known only for specific sites. Implementing these models will require solid understanding of major microbial functional groups and their roles in mediating carbon/nutrient dynamics, as well as detailed datasets for model testing and initialization. In order for genomic information to be used to represent microorganisms and their activities in models, this information must be transformed into functionally useful, globally relevant knowledge. Multi-omic approaches promise new insights, but significant effort will be required to determine how to best use high-resolution data to quantify functions in ways that support conceptual and predictive models — for example, translating sequence data into microbial functional traits (to complement plant functional types/traits).

For all knowledge gaps described here, spatially and temporally resolved data from intensive study sites and experiments representing multiple biomes are needed for parameter estimation and testing, for structural development, and for evaluating the level of complexity required to represent key processes in models.

Address cross-cutting issues. Cross-cutting issues add to the challenge of understanding belowground functions and the feedbacks among soil, plants, and atmosphere. Major cross-cutting issues for belowground systems are identified in Table 2. One of these issues — the need to evaluate and modify model structures — has been discussed previously. Others are highlighted here to illustrate the importance of cross-cutting issues for data-model integration. ***(1) Scaling and spatial heterogeneity.*** Applications of data are hindered by the disparate scales of observations and by native heterogeneity versus model resolution. Geospatial modeling and statistical techniques could be helpful, as could some of the hierarchical and reduced-order modeling approaches being developed by NGEE-Arctic and other DOE projects. ***(2) Depth distributions and temporal dynamics.*** The practice of placing belowground phenomenon into black boxes that average across depth is a known modeling problem. Depth-resolved data are available for roots and some environmental variables, but depth characterization needs to be emphasized for all belowground processes. Further, the fact that the distribution of processes throughout the soil profile change in a dynamic way through time deserves further consideration, both in observations and in model representations. ***(3) Nutrient cycling.*** Nutrient cycling processes are well conceptualized, but not well characterized by direct empirical measurements. Plant uptake of nutrients presents a measurable end point but does not capture dynamic constraints that influence growth and productivity. ***(4) Plant-microbe-soil interactions.*** Plant-microbe-soil interactions are recognized as critical controls on belowground carbon and nutrient flows, but barriers in observation methods have limited data collection efforts. New isotopic and ’omics approaches combined with clever experimental designs could be used to promote process understanding that can be incorporated into model frameworks. Coordinated measurements and experiments at multiple sites are needed to elucidate the key interactions regulating belowground carbon dynamics, aboveground interactions, and responses/feedbacks to changing climatic conditions.

Concluding Message

Biogeochemical simulation models at different scales, while not perfect, represent a reasonable expression of our understanding of integrated ecosystem and belowground processes at those scales. We can use models, and the opportunities for reducing model error and uncertainty, as an organizing theme for our efforts. Investments should be directed at rapid improvement of the representation of belowground processes in terrestrial biogeochemical models, such as CLM. Uncertainty and sensitivity analyses can guide prioritization of parameter improvements while new structures may be needed to include previously ignored mechanisms.

Data synthesis should be considered a near-term priority, particularly for addressing the results of uncertainty analyses and the need for new structural improvements. Synthesis will require better management of existing data as well as new archiving. It is timely for the research community to develop standard policies for archiving samples and data, and to set minimum information and metadata standards for inventories and other databases representing belowground ecosystem components and processes across different biomes.

Long-term research plots and studies that can serve as benchmark sites should be supported and augmented, and some new sites may be needed in association with key observational and experimental efforts. Such sites would be designed to allow thorough characterization of microorganisms and their activity, soil biogeochemical characteristics, root distributions and dynamics, and carbon turnover and flow through the system. At such sites, researchers would focus on a process across multiple scales: the mechanisms driving the process, how these mechanisms are affected by changes in local environmental conditions, and how to translate this information into metrics of higher order ecosystem function (i.e., growth, carbon exchange, water cycling).

Spatial and temporal scaling are challenges that cross-cut many of the data needs outlined during the workshop. Most, if not all, belowground traits exhibit spatial heterogeneities, both laterally and with depth, as well as temporal variation. A research-community concept for gathering belowground information at scales relevant for addressing regional- to global-scale questions is needed.

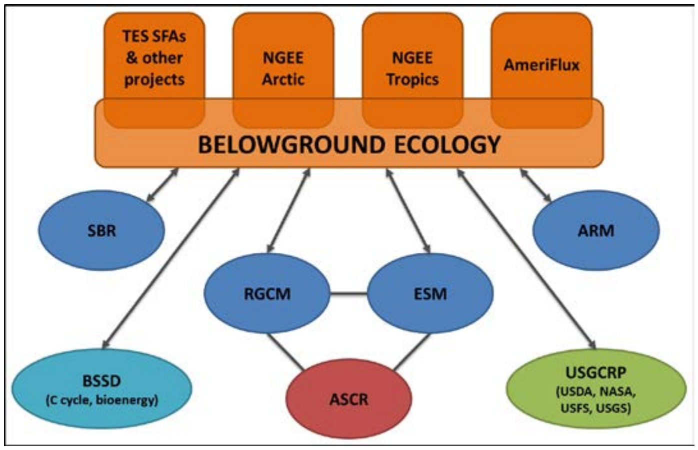


Figure 2. Greater understanding of belowground systems is essential to TES research goals and can both benefit from and contribute to research programs across BER, in Advanced Scientific Computing Research (ASCR), and at other federal agencies contributing to the U.S. Global Change Research Program (USGCRP). For a complete explanation of acronyms, see list inside back cover.

In summary, a rigorous understanding of belowground systems — linking the scales at which key processes occur to the scales at which we measure and model them — is needed to accurately predict the responses and feedbacks of terrestrial ecosystems to a changing climate. DOE BER research (Figure 2) and National Laboratory capabilities are well poised to address many of these challenges.

Priorities, gaps, and science needs:

As a result of discussions held during this one-day workshop, several recommendations for both near-term and longer-term activities were developed — including suggestions for activities geared towards more specific identification and prioritization of belowground research needs. These priorities, gaps, and science needs are outlined below.

1. Enhance efforts to preserve, organize, and access federally-supported belowground data, by developing:
    a. guidelines for metadata and archiving formats specific to belowground data;
    b. requirements and support for archiving all BER-generated belowground data in publically searchable and accessible data repositories, with a fair-use policy; and
    c. a relational database for belowground data, and in particular DOE-supported data, with linkage to other databases and data networks, such as the Earth System Grid.

2. Compile and synthesize existing data to create preliminary benchmark datasets for model evaluations. This activity could leverage or contribute to ongoing model-evaluation efforts, e.g., the RGCM-supported ILAMB framework. Fulfill known modeling-community priorities, such as:
    a. testing model representations of soil organic carbon turnover times by ingesting existing ^{14}C data to build a radiocarbon database, using the existing BER-supported database template;
    b. synthesize and create geospatial products from existing datasets on root depth distributions, root carbon and nitrogen stocks, and root turnover for model testing;
    c. synthesize and develop spatial and temporal interpolations of existing soil respiration datasets for model testing;
    d. conduct modeling assessments to inform future belowground research and data priorities.
3. Foster collaborative opportunities to support multi-Lab, multi-Scientific Focus Area (SFA) projects — engaging both experimentalists and modelers — that take advantage of potential synergies among the National Labs, their SFAs and other projects.
    a. Specifically, develop cross-Lab, multi-program topical working groups to identify and prioritize potential synergistic opportunities that can take advantage of ongoing experiments, long-term field sites, and the wealth of archived data at the Labs (and elsewhere) to improve model representations of belowground processes.
    b. Integrated cross-Lab initiatives could tackle high priority items emerging from the working group discussions and activities, including (but not limited to) those identified in this report and by future workshops. Such efforts would reduce data and knowledge limitations, and would support the development of a process-rich, fine-scale carbon/ecosystem model that (a) underpins next-generation belowground models and (b) stimulates new hypotheses about terrestrial responses to global change.
    c. Such research initiatives could leverage existing expertise and User Facilities — such as the Environmental Molecular Sciences Laboratory, the Joint Genome Institute, the Atmospheric Radiation Measurement (ARM) Climate Research Facility, and others.
4. Conduct community workshops structured to enable intensive interactions between modelers and empiricists to uncover key knowledge gaps, data deficiencies, model parameterizations, and model structures that are limiting predictive understanding of carbon and nutrients flows through belowground ecosystems. Workshops could be structured to address microbial, plant, and soil topics individually or in a combined manner, but should address these belowground components in the context of the cross-cutting issues identified in Table 2. The workshops would help to:
    a. facilitate greater communication between the empirical research and modeling communities and reduce disconnects that slow progress;
    b. identify and prioritize key areas for integrated model-data development and investment; and
    c. define database functionalities required to enable identified model-data activities.

5. Additional investments might include Early Career opportunities or targeted Funding Opportunity Announcements (FOAs) by the Climate and Environmental Sciences Division (CESD) and the Biological Systems Science Division (BSSD). There may also be opportunities that bridge Environmental System Science (ESS) and BSSD projects or capabilities. These bridging opportunities could include themes such as:
    a. conduct research on belowground carbon transformations, fate, and transport in the context of the cross-cutting issues identified in Table 2; this research should be conducted in parallel with multi-scale ecosystem modeling;
    b. provide mechanistic knowledge for trait-based representation of plant roots and microorganisms in belowground models through experiments designed to link trait-based information to function.

Cited References

Drewniak BA, Mishra U, Song J, Prell J, Kotamarthi VR (2014) Modeling the impact of agriculture land use and management on U.S. carbon budget. *Biogeosciences Discussion* 11: 13675-13698.

Fan Z, Neff JC, Harden JW, Wickland KP (2008) Boreal soil carbon dynamics under a changing climate: A model inversion approach. *Journal of Geophysical Research: Biogeosciences (2005-2012)* 113: G04016. doi:10.1029/2008JG000723.

Fan Z, Neff JC, Waldrop MP, Ballantyne AP, Turetsky MR (2014) Transport of oxygen in soil pore-water systems: implications for modeling emissions of carbon dioxide and methane from peatlands. *Biogeochemistry* doi:10.1007/s10533-014-0012-0.

Fang Y, Huang M, Liu C, Li H, Leung LR (2013) A generic biogeochemical module for Earth system models: Next Generation BioGeoChemical Module (NGBGC), version 1.0. Geoscientific Model Development 6: 1977-1988. doi:10.5194/gmd-6-1977-2013

Hararuk, O, Xia J, Luo Y (2014) Evaluation and improvement of a global land model against soil carbon data using a Bayesian Markov chain Monte Carlo method. *Journal of Geophysical Research: Biogeosciences* 119: 403-417.

Iversen CM, Sloan VL, Sullivan PF, Euskirchen ES, McGuire AD, Norby RJ, Walker AP, Warren JM, Wullschleger SD (2014) The unseen iceberg: Plant roots in arctic tundra (Tansley Review). *New Phytologist* doi:10.1111/nph.13003.

Mishra U, Riley WJ (2012) Alaskan soil carbon stocks: spatial variability and dependence on environmental factors. *Biogeosciences* 9: 3637-3645.

Mishra U, Riley WJ (2014). Active-layer thickness across Alaska: Comparing observation-based estimates with CMIP5 Earth system model predictions. *Soil Science Society of America Journal* 8: 894-902. doi:10.2136/sssaj2013.11.0484.

Riley WJ, Maggi FM, Kleber M, Torn MS, Tang JY, Dwivedi D, Guerry N (2014) Long residence times of rapidly decomposable soil organic matter: application of a multi-phase, multi-component, and vertically-resolved model (TOUGHREACTv1) to soil carbon dynamics. *Geoscientific Model Development Discussions* 7: 815-870.

Tang JY, Riley WJ (2013) A total quasi-steady-state formulation of substrate uptake kinetics in complex networks and an example application to microbial litter decomposition. *Biogeosciences* 10: 8329-8351.

Walker AP, Hanson PJ, De Kauwe MG, Medlyn BE, Zaehle S, Asao S, Dietze M, Hickler T, Huntingford C, Iversen CM, Jain A, Lomas M, Luo YQ, McCarthy H, Parton WJ, Prentice IC, Thornton PE, Wang SS, Wang YP, Warlind D, Weng ES, Warren, JM, Woodward FI, Oren R, Norby RJ (2014) Comprehensive ecosystem model-data synthesis using multiple data sets at two temperate forest free-air CO_2 enrichment experiments: Model performance at ambient CO_2 concentration. *Journal of Geophysical Research: Biogeosciences* 119: 937-964.

Wang D, Xu Y, Thornton P, King A, Steed C, Gu L, Shuchart J. (2014a) A functional test platform for the Community Land Model. *Environmental Modelling & Software* 55: 25-31.

Wang G, Jagadamma S, Mayes MA, Schadt CW, Steinweg JM, Gu L *et al* (2014b) Microbial dormancy improves development and experimental validation of ecosystem model. *The ISME Journal* doi:10.1038/ismej.2014.120.

Warren JM, Iversen CM, Garten CT, Norby RJ, Childs J, Brice DJ, Evans RM, Gu L, Thornton PE, Weston DJ (2012) Timing and magnitude of carbon partitioning through a young loblolly pine (*Pinus taeda* L.) stand using ^{13}C labeling and shade treatments. *Tree Physiology* 32: 799-813.

Warren JM, Hanson PJ, Iversen CM, Kumar J, Walker AP, Wullschleger SD (2014) Root structural and functional dynamics in terrestrial biosphere models – evaluation and recommendations. *New Phytologist* doi:10.1111/nph.13034.

Xu X, Schimel JP, Thornton PE, Song X, Yuan F, Goswami S (2014) Substrate and environmental controls on microbial assimilation of soil organic carbon: a framework for Earth system models. *Ecology Letters* 17: 547-555. doi:10.1111/ele.12254.

Yang X, Post WM, Thornton PE, Jain A (2013) The distribution of soil phosphorus for global biogeochemical modeling. *Biogeosciences* 10: 2525-2537.

This page left blank.

APPENDIX A: DATA PRESERVATION

Data preservation is a serious problem for science in general because of the relatively few extant data, especially for belowground studies. Recently Vines et al. (2014) surveyed a wide range of studies over the last 22 years and found that the odds of a dataset being reported as available (assuming the authors could be contacted) fell by 17% per year and author availability dropped by an *additional* 7% yr^{-1}. This infers that after two decades, only about one-third of the data from publicly-funded research is still available for future meta-analyses, model validation, reuse, etc. The authors concluded that, regardless of good intentions, data cannot be reliably preserved by individual researchers (Vines et al., 2014).

Other problems, arguably less critical but still serious, exist as well. For example, the 'file drawer effect', named (Rosenthal, 1979) for the tendency of researchers to publish statistically significant but not insignificant results, is a serious enough problem to warrant formal statistical consideration in meta-analyses (Møller et al., 2001). The resulting bias has been shown to exist in soil respiration studies (Dieleman and Janssens, 2010).

Governments, funding agencies, and journals are increasingly enacting policies to ensure that research data are available on public archives and are supported by comprehensive metadata to facilitate future reuse. We encourage DOE TES to support this movement, specifically with respect to belowground studies and data, by:

- Requiring all funded projects to deposit data in public archives (not researcher web pages) for every publication.
- Requiring funded projects to budget for data management, preservation, and archiving.
- Encouraging data products to be made available via data sharing and archival sites such as figshare (http://figshare.com) and Dryad (http://datadryad.org), which provide data DOIs that will be referenced in all publications.
- Encouraging the use of best practices by researchers for both data and model code (e.g., tabular data archived in nonproprietary file formats; spatial data encoded in well-documented open formats such as NetCDF; metadata compliant with Ecological Metadata Language; computer models and their results archived following best community practices; Thornton et al., 2005).

These goals may be addressed by engaging existing data center experts (e.g., the Carbon Dioxide Information and Analysis Center [CDIAC]) to address the curation of archived data, and the development of expanded repositories for TES (and other ecosystem)-related research.

Cited References

Dieleman WIJ, Janssens IA (2010) Can publication bias affect ecological research? A case study on soil respiration under elevated CO_2. *New Phytologist* 190: 517-521.

Møller AP, Jennions MD (2001) Testing and adjusting for publication bias. *Trends in Ecology and Evolution* 16: 580-586.

Rosenthal R (1979) The file drawer problem and tolerance for null results. *Psychological Bulletin* 86: 638-641.

Thornton PE, Cook RB, Braswell BH, Law BE, Post WM, Shugart HH, Rhyne BT, Hook LA (2005) Archiving numerical models of biogeochemical dynamics. *Eos* 86: 431-432.

Vines TH, Albert AYK, Andrew RL, Débarre F, Bock DG, Franklin MT, Gilbert KJ, Moore J-S, Renaut S, Rennison DJ (2014) The availability of research data declines rapidly with article age. *Current Biology* 24: 94-97.

APPENDIX B: LIST OF BELOWGROUND DATA SOURCES COMPILED BEFORE THE WORKSHOP

1. ROOT CHARACTERISTICS

1.1 Global Distribution of Root Profiles in Terrestrial Ecosystems

Schenk, H. J., and R. B. Jackson. 2003. Global Distribution of Root Profiles in Terrestrial Ecosystems. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/660.

1.2 Global Distribution of Fine Root Biomass in Terrestrial Ecosystems

Jackson, R. B., H. A. Mooney, and E.-D. Schulze. 2003. Global Distribution of Fine Root Biomass in Terrestrial Ecosystems. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/658.

1.3 ISLSCP II Ecosystem Rooting Depths

Schenk, H.J., and R.B. Jackson. 2009. ISLSCP II Ecosystem Rooting Depths. In Hall, Forrest G., G. Collatz, B. Meeson, S. Los, E. Brown de Colstoun, and D. Landis (eds.). ISLSCP Initiative II Collection. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/929

Ichii, K., H.Hashimoto, , M. A White. C. Potter, L. R. Hutyra, A. R. Huete, R. B. Myneni, R. R. Nemani. (2007), Constraining rooting depths in tropical rainforests using satellite data and ecosystem modeling for accurate simulation of gross primary production seasonality. *Global Change Biolog*y, 13: 67–77. doi: 10.1111/j.1365-2486.2006.01277.x

Schenk, H.J. and R.B. Jackson. 2002. The global biogeography of roots. *Ecol Monog* 72, 311-328.

Schenk, H. J. and R. B. Jackson. 2005. Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma*. Vol: 126(1-2). Pages 129-140.

1.4 Global Distribution of Root Turnover in Terrestrial Ecosystems

Gill, R., and R. B. Jackson. 2003. Global Distribution of Root Turnover in Terrestrial Ecosystems. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/661.

Gill, R.A., and R.B. Jackson. 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytologist* 147, 13-31.

McCormack, M.L, D.M. Eissenstat, A.M. Prasad, E.A.H. Smithwick. (2013) Regional scale patterns of fine root lifespan and turnover under current and future climate. *Global Change Biology*, 19: 1697-1708.

Yuan, Z. Y. and H. Y. H. Chen, (2010) Fine root biomass, production, turnover rates, and nutrient contents in boreal forest ecosystems in relation to species, climate, fertility, and stand age: literature review and meta-analyses, *Crit. Rev. Plant Sci.*, 29, 204–221, 2010.

1.5 Root:shoot ratio

Mokany K., J. R. Raison, and A. S. Prokushkin. 2006 Critical analysis of root:shoot ratios in terrestrial biomes *Glob. Change Biol.* 12 84-96

1.6 Global Distribution of Root Nutrient Concentrations in Terrestrial Ecosystems

Gordon, W. S., and R. B. Jackson. 2003. Global Distribution of Root Nutrient Concentrations in Terrestrial Ecosystems. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/659.

Gordon, W. and R, B. Jackson. 2000. Nutrient concentrations in fine roots. *Ecology*. Vol: 81. Pages 275-280.

Jackson, R. B., H. A. Mooney, E. D. Schulze. 1997. A global budget for fine root biomass, surface area, and nutrient contents. *Proceedings of the National Academy of Sciences*. Vol: 94. Pages 7362-7366

1.7 Plant Trait Database (TRY)

http://www.try-db.org/TryWeb/Home.php This database does not currently include extensive belowground data for roots, but it is expected that it will in the future.

1.8 BROT: Plant trait database for Mediterranean Basin species

http://www.uv.es/jgpausas/brot.htm Database includes data on rooting depth and shoot:root ratio

2. SOIL CHARACTERISTICS

2.1 A Global Database of Gas Fluxes from Soils after Rewetting or Thawing, Version 1.0 (2012.04.16)

Kim, D.-G., R. Vargas, B. Bond-Lamberty, and M. R. Turetsky. 2012. A Global Database of Gas Fluxes from Soils after Rewetting or Thawing, Version 1.0. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1078

2.2 A Global Database of Soil Respiration Data, Version 1.0 (2010.05.28)

Bond-Lamberty, B.P. and A.M. Thomson. 2010. A Global Database of Soil Respiration Data, Version 1.0. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/984

2.3 A Global Database of Soil Respiration Data, Version 2.0 (2012.03.13)

Bond-Lamberty, B.P. and A.M. Thomson. 2012. A Global Database of Soil Respiration Data, Version 2.0. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1070

2.4 A Global Database of Soil Respiration Data, 3.0 (2014.08.04)

Bond-Lamberty, B.P. and A.M. Thomson. 2014. A Global Database of Soil Respiration Data, Version 3.0. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1235

2.5 Global Annual Soil Respiration Data (Raich and Schlesinger 1992) (2001.12.06)

Raich, J. W. and W. H. Schlesinger. 2001. Global Annual Soil Respiration Data (Raich and Schlesinger 1992). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/622.

Interannual Variability in Global Soil Respiration on a 0.5 Degree Grid Cell Basis (1980-1994) (2003), NDP-081

Global Patterns of Carbon Dioxide emissions from Soils on a 0.5 Degree Grid Cell Basis (1996), DB1015

2.6 Global Data Set of Derived Soil Properties, 0.5-Degree Grid (ISRIC-WISE) (2000.09.05)

Batjes, N. H. (ed.). 2000. Global Data Set of Derived Soil Properties, 0.5-Degree Grid (ISRIC-WISE). [Global Data Set of Derived Soil Properties, 0.5-Degree Grid (International Soil Reference and Information Centre - World Inventory of Soil Emission Potentials)]. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/546.

2.7 Global Soil Profile Data (ISRIC-WISE) (2000.09.05)

Batjes, N. H. (ed.). 2000. Global Soil Profile Data (ISRIC-WISE). [Global Soil Profile Data (International Soil Reference and Information Centre - World Inventory of Soil Emission Potentials)]. Data set. Available on-line [http://www.daac.ornl.gov] from ORNL Distributed Active Archive Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/547.

2.8 Global Distribution of Plant-Extractable Water Capacity of Soil (Dunne) (2000.08.18

Dunne, K. A., and C. J. Willmott. 2000. Global Distribution of Plant-Extractable Water Capacity of Soil (Dunne). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/545.

2.9 Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS) (2000.12.20)

Global Soil Data Task Group. 2000. Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS). [Global Gridded Surfaces of Selected Soil Characteristics (International Geosphere-Biosphere Programme - Data and Information System)]. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/569.

2.10 Global Organic Soil Carbon and Nitrogen (Zinke et al.) (1998.11.10)

Zinke, P. J., A. G. Stangenberger, W. M. Post, W. R. Emanuel, and J. S. Olson. 1998. Global Organic Soil Carbon and Nitrogen (Zinke et al.). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. Previously published in Worldwide Organic Soil Carbon and Nitrogen Data, CDIAC NDP-018, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A., 1986. doi:10.3334/ORNLDAAC/221.

2.11 Global Soil Texture and Derived Water-Holding Capacities (Webb et al.) (2000.09.05)

Webb, R. W., C. E. Rosenzweig, and E. R. Levine. 2000. Global Soil Texture and Derived Water-Holding Capacities (Webb et al.). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/548.

2.12 Global Soil Types, 0.5-Degree Grid (Modified Zobler) (2000.05.19)

Post, W. M., and L. Zobler. 2000. Global Soil Types, 0.5-Degree Grid (Modified Zobler). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/540.

2.13 Global Soil Types, 1-Degree Grid (Zobler) (1999.05.05)

Zobler, L. 1999. Global Soil Types, 1-Degree Grid (Zobler). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/418.

2.14 Northern and Mid-Latitude Soil Database, Version 1 (2004.05.26)

Cryosol Working Group. 2004. Northern and Mid-Latitude Soil Database, Version 1. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/705.

NACP Model Driver Data: North America 0.25-degree HWSD derived soil data
http://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=20039

2.15 Regridded Harmonized World Soil Database v1.2

Wieder, W.R., J. Boehnert, G.B. Bonan, and M. Langseth. 2014. Regridded Harmonized World Soil Database v1.2. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1247.

2.16 International Soil Carbon Network

http://www.fluxdata.org/NSCN/SitePages/ISCN.aspx

2.17 USDA/NRCS National Cooperative Soil Survey Soil Characterization Data

http://ncsslabdatamart.sc.egov.usda.gov/

2.18 USDA/NRCS SSURGO and STATSGO2 Databases

SSURGO http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053627
STATSGO2 http://datagateway.nrcs.usda.gov/Catalog/ProductDescription/GSMCLIP.html

2.19 USDA/NRCS Rapid Assessment of U.S. Soil Carbon (RaCA)

https://prod.nrcs.usda.gov/wps/portal/nrcs/detail/soils/research/?cid=nrcs142p2_054164

2.20 USDA/NRCS Soil Geochemistry Spatial Database

http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/home/?cid=nrcs142p2_053632

2.21 Agriculture Agrifood Canada National Soil DataBase (NSDB)

http://sis.agr.gc.ca/cansis/nsdb/index.html

2.22 CSIRO Australian Soil Resource Information System

http://www.asris.csiro.au/methods.html

2.23 Joint Research Centre European Soil Portal

http://eusoils.jrc.ec.europa.eu/library/esdac/esdac_access2.cfm

2.24 Northern Circumpolar Soil Carbon Database; Bolin Center Stockholm University.

http://bolin.su.se/data/ncscd/

2.25 CDIAC Terrestrial Carbon Management Data Sets and Analyses (mostly soil C data)

http://cdiac.ornl.gov/carbonmanagement/

2.26 molTERdb Online computational database for soil molecular data (European Science Foundation)

Global SOM repository including NMR (Mahieu et al. 1999) and ^{14}C datasets (Mills et al. 2013)

http://molterdb.irstea.fr/publi/

2.27 Other Literature References Containing Distributed Soil Data

Global Soil Data Task. 2014. Global Soil Data Products CD-ROM Contents (IGBP-DIS). Data Set. Available online [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/565.

Journet, E., Balkanski, Y., & Harrison, S. P. (2014). A new data set of soil mineralogy for dust-cycle modeling. *Atmospheric Chemistry and Physics*, *14*(8), 3801-3816.

Kirkby C.A., J.A. Kirkegaard, A.E. Richardson, L.J. Wade, C. Blanchard, G. Batten (2011) Stable organic matter: a comparison of C:N:P:S ratios in Australian and other world soils Geoderma, 163:197–208.

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and soil*, *241*(2), 155-176.

Tian H., G. Chen, C. Zhang, J.M. Melillo, C.A.S. Hall *(*2009*)* Pattern and variation of C : N : P ratios in China's soils*: a synthesis of observational data*. Biogeochemistry*, doi: DOI:* 10.1007/s10533-009-9382-0.

West, T. O. 2014. Soil Carbon Estimates in 20-cm Layers to 1-m Depth for the Conterminous US, 1970-1993. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1238

Yang X., W. M.Post (2011) Phosphorus transformations as a function of pedogenesis: a synthesis of soil phosphorus data using Hedley fractionation method. *Biogeosciences* 8: 2907-2916.

Yang, X., W. M. Post, P. E. Thornton, and A. Jain. 2014. A Global Database of Soil Phosphorus Compiled from Studies Using Hedley Fractionation. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1230

Yang, X., W. M. Post, P. E. Thornton, and A. Jain. 2014. Global Gridded Soil Phosphorus Distribution Maps at 0.5-degree Resolution. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1223

3. MICROBIAL AND ENZYME PARAMETERS, AND SOIL INCUBATION EXPERIMENTS

3.1 Microbial communities

Fierer, N., M. S.Strickland, D. Liptzin, M. A. Bradford, and C. C. Cleveland. (2009), Global patterns in belowground communities. Ecology Letters, 12:1238–1249. doi:10.1111/j.1461-0248.2009.01360.

Sinsabaugh, R. L., C. L., Lauber, M. N. Weintraub, B. Ahmed, , S. D., Allison, C. Crenshaw, , A. R. Contosta, D. Cusack, , S. Frey, M. E Gallo,., T. B. Gartner, S. E. Hobbie, K. Holland, , B. L.Keeler, J. S. Powers, , M. Stursova,, C. Takacs-Vesbach, M. P. Waldrop, M. D. Wallenstein, D. R. Zak, and L. H. Zeglin. (2008). Stoichiometry of soil enzyme activity at global scale. Ecology Letters, 11:1252–1264. doi: 10.1111/j.1461-0248.2008.01245.x

3.2 C:N:P Ratios

Cleveland, C. C. and D. Liptzin. (2007) C:N:P stoichiometry in soil: is there a ''Redfield ratio'' for the microbial biomass? *Biogeochemistry* 85:235–252 DOI 10.1007/s10533-007-9132-0

3.2 Microbial biomass

Hartman, WH; Richardson, CJ, (2013) Differential nutrient limitation of soil microbial biomass and metabolic quotients (qCO_2): is there a biological stoichiometry of soil microbes?, *PLoS One*, 8(3):e57127. DOI: 10.1371/journal.pone.0057127

Holden, S. R and K. K. Treseder. 2013. A meta-analysis of soil microbial responses to forest disturbances. *Frontiers in Microbiology* 4: 163.

Sinsabaugh, R. L., S. Manzoni, and D. L. Moorhead. 2013. Carbon use efficiency of microbial communities: stoichiometry, methodology and modelling. *Ecology Letters* 16: 7,930–939. DOI: 10.1111/ele.12113

Treseder, K. K. 2008. Nitrogen additions and microbial biomass: a meta-analysis of ecosystem studies. Ecology Letters, 11: 1111–1120 doi: 10.1111/j.1461-0248.2008.01230.x

Xu, X., P. E. Thornton, and W. M. Post (2013), A global analysis of soil microbial biomass carbon, nitrogen, and phosphorus in terrestrial ecosystems, *Global Ecology and Biogeography*, *22*:737-749.

3.3 Enzymes

Hui, D., M. A.Mayes, G. Wang, and W. M. Post. 2013. Kinetic parameters of phosphatase: A quantitative synthesis. *Soil Biology and Biochemistry* 65:105-113.

Sinsabaugh, R. L. and J. J. Follstad Shah.2012. Ecoenzymatic Stoichiometry and Ecological Theory. *Annu. Rev. Ecol. Evol. Syst.* 43:313-343.

Sinsabaugh, R. L., B. H. Hill, J. J. Follstad. 2009. Ecoenzymatic stoichiometry of microbial organic nutrient acquisition in soil and sediment. *Nature* 462, 795-798,

Sinsabaugh, R.L., C. L. Lauber, M. N. Weintraub, et al. 2008. Stoichiometry of soil enzyme activity at global scale. *Ecology Letters*,11: 1252–1264 doi: 10.1111 /j.1461-0248.2008.01245.x

Wang, G., W. M.Post, , M. A. Mayes, J. Frerichs , and S. Jagadamma2012. Parameter estimation for models of ligninolytic and cellulolytic enzyme kinetics. *Soil Biology & Biochemistry* 48:28-38, doi 10.1016/j.soilbio.2012.01.011.

3.4 Sorption of dissolved organic carbon

Mayes, M.A., K. Heal, , C. Brandt, J. R. Phillips, and P. M.Jardine. 2012. Relation between soil order and Langmuir parameters for sorption of dissolved organic carbon. *Soil Science Society of America Journal* 76:1027-1037, doi:10.2136/sssaj2011.0340.

3.5 Lab-scale incubation experiments

Hamdi, S., F. Moyano, S. Sall, M. Bernoux, and T. Chevallier. 2013. Synthesis analysis of the temperature sensitivity of soil respiration from laboratory studies in relation to incubation methods and soil conditions. *Soil Biology & Biochemistry* 58: 115-126. DOI: 10.1016/j.soilbio.2012.11.012

Schädel, C. et al 2014. Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. Global Change Biology 20: 641-652. DOI: 10.1111/gcb.12417

Zhang, W.D., X. Wang, and S. Wang. 2013. Addition of External Organic Carbon and Native Soil Organic Carbon Decomposition: A Meta-Analysis. *Plos One* 8: e54779 DOI: 10.1371/journal.pone.0054779

3.6 Modeling SOC decomposition – testing databases

Cerri, C. E. P., M. Easter, K. Paustian, et al. 2007. Simulating SOC changes in 11 land use change chronosequences from the Brazilian Amazon with RothC and Century models. *Agriculture, Ecosystems and Environment* 122:1, 46–57.

Franko, U., H. Kolbe, E. Thiel, E. Ließ. .2011 Multi-site validation of a soil organic matter model for arable fields based on generally available input data *Geoderma*, 166: 1, 119-134 DOI: 10.1016/j.geoderma.2011.07.019

Franko, U., G. Schramm, V. Rodionova, M. Korschens, P. Smith, K. Coleman, V. Romanenkov, and L. Shevtsova. 2002. EuroSOMNET — a database for long-term experiments on soil organic matter in Europe. *Computers and Electronics in Agriculture* 33 33:3, 233 – 239, **DOI:** 10.1016/S0168-1699(02)00009-1.

Moyano, F. E., N. Vasilyeva, L. Bouckaert, et al. 2012. The moisture response of soil heterotrophic respiration: interaction with soil properties. *Biogeosciences*, 9:3, 1173–1182, **DOI:** 10.5194/bg-9-1173-2012

Powlson, D. S., P. Smith, K. Coleman, J. U. Smith, M. J. Glendining, M. Körschens, U. Franko. .1998. A European network of long-term sites for studies on soil organic matter *Soil and Tillage Research*, *.47:3–4, 263-274*, DOI: 10.1016/S0167-1987(98)00115-9

Smith, P., J.U. Smith, D. S. Powlson, et al. 1997 A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma*.81:1-2, 153-225.

4.0 METAGENOMICS DATABASES

MG-RAST the Metagenomes database from Argonne Lab http://metagenomics.anl.gov/

Mycocosm the fungal genomic program (database) from JGI: http://genome.jgi.doe.gov/programs/fungi/index.jsf

The 1000 Fungal Genomes program (database) from JGI: http://genome.jgi.doe.gov/programs/fungi/1000fungalgenomes.jsf

The Metagenomics program (database) from JGI: exploration of microbial communities: http://genome.jgi.doe.gov/programs/metagenomes/genome-releases.jsf

The Microbial Genomics program (database) from JGI: exploration of the microbial diversity: http://genome.jgi.doe.gov/programs/bacteria-archaea/genome-releases.jsf

Earth Microbiome Project: http://www.earthmicrobiome.org/

The Earth Microbiome Project is a proposed massively multidisciplinary effort to analyze microbial communities across the globe. The general premise is to examine microbial communities from their own perspective. Hence we propose to characterize the Earth by environmental parameter space into different biomes and then explore these using samples currently available from researchers across the globe. We will analyze 200,000 samples from these communities using metagenomics, metatranscriptomics and amplicon sequencing to produce a global Gene Atlas describing protein space, environmental metabolic models for each biome, approximately 500,000 reconstructed microbial genomes, a global metabolic model, and a data-analysis portal for visualization of all information.

5.0 OBSERVATIONAL STUDIES AND MANIPULATION EXPERIMENTS

5.1 Observational or manipulated C stock studies

CIDET Moore T. R., J.A. Trofymow, C. Prescott, , J. Fyles, , B. Titus, , and CIDET Working Group. 2006. Patterns of carbon, nitrogen and phosphorus release from decomposing foliar litter in Canadian forests. *Ecosystems* 189:46-62.) https://cfs.nrcan.gc.ca/projects/76

LIDET – Long-term Intersite Decomposition Experiment Team (LIDET). 1995. Meeting the challenge of long-term, broad-scale ecological experiments. Publication No. 19. US. LTER Network Office: Seattle, WA, USA. 23 p. http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm

ROTHC database at http://www.rothamsted.ac.uk/aen/eusomnet/

AmeriFlux - Terrestrial Carbon Dioxide, Water Vapor, and Energy Balance Measurements •
Data from various flux towers in N and S. America (especially N. America)
Data include CO_2 and Water vapor, but many sites have a variety of detailed soil, vegetation and meteorological data available
A component of the worldwide network of towers (FLUXNET):

http://fluxnet.ornl.gov/
http://ameriflux.lbl.gov/Pages/default.aspx
http://ameriflux.ornl.gov/

Geographical Distribution of Biomass Carbon in Tropical Southeast Asian Forests: A Database, (2001) NDP-068

Historic Land Use and Carbon Estimates for South and Southeast Asia: 1880-1980 (1994), NDP-046

Tropical Africa: Land Use, Biomass, and Carbon Estimates for 1980 (1996), NDP-055

Geographical Distribution of Woody Biomass Carbon in Tropical Africa: An Updated Database for 2000 (2007), NDP-055b

Olson's Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: An Updated Database Using the GLC2000 Land Cover Product (2007), NDP-017b

Major World Ecosystem Complexes Ranked by Carbon in Live Vegetation: A Database (1985), NDP-017

Walker Branch - Long-Term Hydrology, Stream Ecology, Forest Characterization & Biogeochemistry Data;
Various data files including vegetation, watershed discharge, water chemistry

http://walkerbranch.ornl.gov/index.shtml
Walker Branch Throughfall Displacement Experiment Data Report: Site Characterization, System Performance, Weather, Species Composition, and Growth (2001), NDP-078A

Worldwide Organic Soil Carbon and Nitrogen Data (1986), NDP-018

Next Generation Ecosystem Experiments – Arctic (NGEE-Arctic) data sets

Observational studies of vegetation and soils in the Arctic; Data include physical and chemical characteristics of soil by layer, C:N, microbes, roots, vegetation, climate, hydrology, etc… http://ngee-arctic.ornl.gov/

5.2 Warming studies

Bai, E., S. L. Li, W. H. Xu, W. Li, W. W. Dai, P. Jiang. 2013. A meta-analysis of experimental warming effects on terrestrial nitrogen pools and dynamics. *New Phytologist* 199:2, 441-451. doi : 10.1111/nph.12252

Rustad, L. E., J. L. Campbell, G. M. Marion, R. J. Norby, M. J. Mitchell, A. E. Hartley, J. H. C. Cornelissen, and J. Gurevitch.2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* 126:4, 543–562. DOI 10.1007/s004420000544

5.3 Elevated CO_2 and priming effects

Free–Air Carbon Dioxide Enrichment studies (FACE) data sets

Aspen, Duke, Nevada Desert and ORNL FACE sites

Data include vegetation, soil physical and chemical characteristics, respiration, root production, water use, plant physiology, etc… http://public.ornl.gov/face/

Cheng, W. X., W. J. Parton, M. A. Gonzalez-Meler, R. Phillips, s. Asao, G. g. McNickle, e. Brzostek, J. D. Jastrow. 2014. Synthesis and modeling perspectives of rhizosphere priming. *New Phytologist* 201:1, 31–44, **DOI:** 10.1111/nph.12440.

de Graaff, M. A., K. J. van Groenigen, J. Six, B. Hungate, C. Van Kessel. 2006. Interactions between plant growth and soil nutrient cycling under elevated CO_2: a meta-analysis. *Global Change Biology* 12:11, 2077–2091, doi: 10.1111/j.1365-2486.2006.01240.

Hungate, B. A., K.-J. van Groenigen, J. Six, J. D. Jastrow, Y. Q. Luo, M.-A. de Graaff, C. van Kessel, and C. W. Osenberg. 2009. Assessing the effect of elevated carbon dioxide on soil carbon: a comparison of four meta-analyses. *Global Change Biology* 15:2020-2034.

Jastrow, J. D., R. M. Miller, R. Matamala, R. J. Norby, T. W. Boutton, C. W. Rice, and C. E. Owensby. 2005. Elevated atmospheric carbon dioxide increases soil carbon. *Global Change Biology* 11:12, 2057-2064, DOI: 10.1111/j.1365-2486.2005.01077.x.

Luo Y. Q. D. F. Hui and D. Q. Zhang 2006 Elevated CO_2 stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis. *Ecology*87:1 53-63, **DOI:** 10.1890/04-1724

van Groenigen, K. J., X. Qi, C. W. Osenberg, Y. Q. Luo, B. A. Hungate. 2014. Faster Decomposition Under Increased Atmospheric CO_2 Limits Soil Carbon Storage. *Science.* 344:6183, 508-509. DOI: 10.1126/science.1249534 .

Van Groenigen K. J., J. Six, B.A. Hungate, C. van Kessel, M.A. de Graaff, N. van Breemen .2006. Element interactions limit soil carbon storage. *Proceedings of the National Academy of Sciences of the United States of America*, 103:17, 6571-6574, DOI: 10.1073/pnas.0509038103

5.4 Other manipulations

Throughfall Displacement Experiment (TDE)

Various data files including species composition, water use, organic and mineral soil elements.
http://tde.ornl.gov/tdedata.html
TDE Model Intercomparison Project Data Archive

Partitioning in Trees and Soils (PiTS) — PiTS-1: Carbon Partitioning in Loblolly Pine after ^{13}C Labeling and Shade Treatments

Various data files including: N, ^{12}C and ^{13}C in soil and roots, root biomass and production, plant physiology, soil water extraction, soil texture and BD, soil respiration, water use
http://tes-sfa.ornl.gov/sites/default/files/PiTS_1_Users_Guide_20130423.pdf
http://tes-sfa.ornl.gov/sites/default/files/PiTS_1_data_files.zip

SPRUCE (Spruce and Peatland Responses Under Climatic and Environmental Change)

Various data files including: environmental, climate, soils, vegetation, microbial data.
http://mnspruce.ornl.gov/content/public-data-download

5.5 Regionally Specific Belowground Datasets

BOREAS Data Sets

http://daac.ornl.gov/cgi-bin/dataset_lister_new.pl?p=2

ISLSCP Project Data

ISLSCP II Total Plant-Available Soil Water Storage Capacity of the Rooting Zone

Kleidon, A., 2011. ISLSCP II Total Plant-Available Soil Water Storage Capacity of the Rooting Zone. In Hall, Forrest G., G. Collatz, B. Meeson, S. Los, E. Brown de Colstoun, and D. Landis (eds.). ISLSCP Initiative II Collection. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/1006

ISLSCP II Ecosystem Rooting Depths

Schenk, H.J., and R.B. Jackson. 2009. ISLSCP II Ecosystem Rooting Depths. In Hall, Forrest G., G. Collatz, B. Meeson, S. Los, E. Brown de Colstoun, and D. Landis (eds.). ISLSCP Initiative II Collection. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/929

ISLSCP II Global Gridded Soil Characteristics

Scholes, R. J., and E. Brown de Colstoun. 2011. ISLSCP II Global Gridded Soil Characteristics. In Hall, Forrest G., G. Collatz, B. Meeson, S. Los, E. Brown de Colstoun, and D. Landis (eds.). ISLSCP Initiative II Collection. Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/1004

FIFE Project Data

FIFE Root Biomass Data Set
http://daac.ornl.gov/FIFE/guides/Root_Biomass_Data.html

FIFE Soil CO_2 Efflux Data Set
http://daac.ornl.gov/FIFE/guides/Soil_CO2_Flux_Data.html

FIFE Soil Moisture Data: Peck (FIFE)
http://daac.ornl.gov/FIFE/guides/Peck_Soil_Moisture_Data.html

FIFE Soil Moisture Gravimetric Data
http://daac.ornl.gov/FIFE/guides/Soil_Moisture_Gravimetric_Data.html

Soil Bulk Density Data (FIFE
http://daac.ornl.gov/FIFE/guides/Soil_Bulk_Density_Data.html

Soil Hydraulic Conductivity Data (FIFE)
http://daac.ornl.gov/FIFE/guides/Soil_Hydraulic_Conductivity_Data.html

Soil Moisture Release Data (FIFE)
http://daac.ornl.gov/FIFE/guides/Soil_Moisture_Release_Data.html

Soil Survey Reference (FIFE)
http://daac.ornl.gov/FIFE/guides/Soil_Survey_Ref.html

Soil Thermal Conductivity Data (FIFE)
http://daac.ornl.gov/FIFE/guides/Soil_Thermal_Cond_Data.html

Soil Water Properties Derived Data (FIFE)
http://daac.ornl.gov/FIFE/guides/Soil_Water_Prop_Derv_Data.html

<u>LBA Data Sets</u>

LBA-ECO CD-04 Soil Moisture Data, km 83 Tower Site, Tapajos National Forest, Brazil
Goulden, M.L. S.D. Miller and H.R. da Rocha. 2010. LBA-ECO CD-04 Soil Moisture Data, km 83 Tower Site, Tapajos National Forest, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/979

LBA-ECO CD-04 Soil Respiration, km 83 Tower Site, Tapajos National Forest, Brazil
Goulden, M.L., H.R. da Rocha, S.D. Miller and H.C. de Freitas. 2011. LBA-ECO CD-04 Soil Respiration, km 83 Tower Site, Tapajos National Forest, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1039

LBA-ECO CD-05 Soil VWC and Meteorology, Rainfall Exclusion, Tapajos National Forest
Nepstad, D.C., P.R. Moutinho, and P. Brando. 2013. LBA-ECO CD-05 Soil VWC and Meteorology, Rainfall Exclusion, Tapajos National Forest. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA http://dx.doi.org/10.3334/ORNLDAAC/1169

LBA-ECO CD-08 Carbon Isotopes in Belowground Carbon Pools, Amazonas and Para, Brazil
Telles E.D.C., P.B. de Camargo, L.A. Martinelli, S.E. Trumbore, E.S. da Costa, J. Santos, N. Higuchi, R.C. Oliveira and D. Markewitz. 2011. LBA-ECO CD-08 Carbon Isotopes in Belowground Carbon Pools, Amazonas and Para, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1025

LBA-ECO CD-09 Soil and Vegetation Characteristics, Tapajos National Forest, Brazil
Williams, M., Y.E. Shimabokuro and E.B. Rastetter. 2012. LBA-ECO CD-09 Soil and Vegetation Characteristics, Tapajos National Forest, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1104

LBA-ECO CD-10 Forest Litter Data for km 67 Tower Site, Tapajos National Forest
Rice, A.H., E. P. Hammond, S. R. Saleska, L. Hutyra, M. Palace, M. Keller, P. B. de Carmargo, K. Portilho, D. Marques and S. C. Wofsy. 2008. LBA-ECO CD-10 Forest Litter Data for km 67 Tower Site, Tapajos National Forest. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/862

LBA Regional Derived Soil Properties, 0.5-Deg (ISRIC-WISE)
Batjes, N. H. 2003. LBA Regional Derived Soil Properties, 0.5-Deg (ISRIC-WISE). Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/701.

LBA Regional Organic Soil Carbon and Nitrogen Data (Zinke et al.)
Zinke, P. J., A. G. Stangenberger, W. M. Post, W. R. Emanuel, and J. S. Olson. 2003. LBA Regional Organic Soil Carbon and Nitrogen Data (Zinke et al.). Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/683.

LBA-ECO ND-02 Cation Leaching from Forest and Pasture Soils, Para, Brazil
Markewitz, D., E.A. Davidson, R.D.O. Figueiredo, P.R. Moutinho and D.C. Nepstad. 2012. LBA-ECO ND-02 Cation Leaching from Forest and Pasture Soils, Para, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1074

LBA-ECO ND-02 CO_2 Flux from Soils in Forests and Pastures, Acre, Brazil: 1999-2001
Salimon, C.I., E.A. Davidson, R.L. Victoria, and A.W.F. Melo. 2012. LBA-ECO ND-02 CO_2 Flux from Soils in Forests and Pastures, Acre, Brazil: 1999-2001. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1066

LBA-ECO ND-02 Soil Gas and Water Content, Rainfall Exclusion, Tapajos National Forest
Davidson, E.A., C.J.R. de Carvalho, R.O. Figueiredo. 2012.LBA-ECO ND-02 Soil Gas and Water Content, Rainfall Exclusion, Tapajos National Forest: 1999-2002. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1117

LBA-ECO ND-02 Soil Gas Flux, Rainfall Exclusion, km 67, Tapajos National Forest
Davidson, E.A., C.J.R. de Carvalho, R.O. Figueiredo. 2009. LBA-ECO ND-02 Soil Gas Flux, Rainfall Exclusion, km 67, Tapajos National Forest. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi: 10.3334/ORNLDAAC/955

LBA-ECO ND-02 Soil Trace Gas Fluxes in Eastern Amazonia, Para, Brazil: 1999-2003
Davidson, E.A., C.J.R. de Carvalho, and R.O. Figueiredo. 2009. LBA-ECO ND-02 Soil Trace Gas Fluxes in Eastern Amazonia, Para, Brazil: 1999-2003. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi: 10.3334/ORNLDAAC/953

LBA-ECO ND-02 Soil Volumetric Water Content, Tapajos National Forest, Brazil
Belk, E.L., D. Markewitz, T. Rasmussen, E.J.M. Carvalho, D.C. Nepstad, and E.A. Davidson. 2012. LBA-ECO ND-02 Soil Volumetric Water Content, Tapajos National Forest, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1061

LBA-ECO ND-02 Trace Gas Flux from Forest Soil, Para, Brazil : 1999-2001
Davidson, E.A., C.J.R. de Carvalho, I.C.G. Vieira, R.O. Figueiredo. 2009. LBA-ECO ND-02 Trace Gas Flux from Forest Soil, Para, Brazil : 1999-2001. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi: 10.3334/ORNLDAAC/954

LBA-ECO ND-03 Stream and Soil Water Data, Fazenda Nova Vida, Rondonia: 1994-2001
Deegan, L.A., C. Neill, S.M. Thomas, A.V. Krusche, M.V.R. Ballester, R.L. Victoria. 2012. LBA-ECO ND-03 Stream and Soil Water Data, Fazenda Nova Vida, Rondonia: 1994-2001. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1113

LBA-ECO ND-04 Secondary Forest Carbon and Nutrient Stocks, Central Amazonia, Brazil
Feldpausch, T.R., M.A. Rondon, E.C.M. Fernandes, S.J. Riha. and E. Wandelli. 2012. LBA-ECO ND-04 Secondary Forest Vegetation and Soil Carbon and Nutrient Stocks, Brazil. Data set. Available on-line (http://daac.ornl.gov) from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1069

LBA-ECO ND-07 Microbial Biomass in Cerrado Soils, Brasilia, Brazil
Viana, L.T., M. Molina, M.M.C. Bustamante, A.S. Pinto, K. Kisselle, R.G. Zepp, and R.A. Burke. 2011. LBA-ECO ND-07 Microbial Biomass in Cerrado Soils, Brasilia, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1017

LBA-ECO ND-07 Nitric Oxide Flux from Cerrado Soils, Brasilia, Brazil: 2004
Kozovits, A.R., L.T. Viana, D.M. Sousa, A.S. Pinto, M.M.C. Bustamante, and R.G. Zepp. 2012. LBA-ECO ND-07 Nitric Oxide Flux from Cerrado Soils, Brasilia, Brazil: 2004 . Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/ORNLDAAC/1124

LBA-ECO ND-10 Soil Properties of Pasture Chronosequences, Para, Brazil: 1997

Asner, G.P., A.R. Townsend, and M.M.C. Bustamante. 2013. LBA-ECO ND-10 Soil Properties of Pasture Chronosequences, Para, Brazil: 1997. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1171

LBA-ECO ND-11 Forest Soil Structure and Nitrate, NW Mato Grosso, Brazil: 2004-2005

Feldpausch, T.R., E.G. Couto, J. Lehmann, S.J. Riha. 2010. LBA-ECO ND-11 Forest Soil Structure and Nitrate, NW Mato Grosso, Brazil: 2004-2005. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/976

LBA-ECO ND-11 Litter Decomposition, Carbon, and Nitrogen Dynamics in Agroforestry

Schwendener, C.M., J. Lehmann, P.B. de Camargo, R.C.C. Luizao, and E.C.M. Fernandes. 2009. LBA-ECO ND-11 Litter Decomposition, Carbon, and Nitrogen Dynamics in Agroforestry. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/915.

LBA-ECO ND-11 Soil Properties of Forested Headwater Catchments, Mato Grosso, Brazil

Novaes Filho, J.P., E.C. Selva ,E.G. Couto, J. Lehmann, M.S. Johnson, and S.J. Riha. 2009. LBA-ECO ND-11 Soil Properties of Forested Headwater Catchments, Mato Grosso, Brazil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/914

LBA-ECO ND-11 Soil Water Pressure and Flow Measurements under Tree Crops

Renck, A. and J. Lehmann. 2007. LBA-ECO ND-11 Soil Water Pressure and Flow Measurements under Tree Crops. Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/851.

SAFARI Project Databases

SAFARI 2000 Annual CO_2 Emissions from Soil, 0.5 Deg-Grid (Raich and Potter)

http://daac.ornl.gov//S2K/guides/raich_potter_grid_co2.html

SAFARI 2000 Vegetation and Soils, 1-Deg (Wilson and Henderson-Sellers)

Wilson, M. F., and A. Henderson-Sellers. 2002. SAFARI 2000 Vegetation and Soils, 1-Deg (Wilson and Henderson-Sellers). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/642.

SAFARI 2000 Wetlands Data Set, 1-Deg (Matthews and Fung)

Matthews, E., and I. Fung. 2002. SAFARI 2000 Wetlands Data Set, 1-Deg (Matthews and Fung). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/632.

SAFARI 2000 Annual CO_2 Emissions from Soil, 0.5 Deg-Grid (Raich and Potter)

Raich, J. W., and C. S. Potter. 2002. SAFARI 2000 Annual CO_2 Emissions from Soil, 0.5 Deg-Grid (Raich and Potter). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/644.

SAFARI 2000 Annual Soil Respiration Data (Raich and Schlesinger 1992)

Raich, J. W., and W. H. Schlesinger. 2002. SAFARI 2000 Annual Soil Respiration Data (Raich and Schlesinger 1992). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/645.

SAFARI 2000 Derived Soil Properties, 0.5-Deg (ISRIC-WISE)

Batjes, N. H. 2002. SAFARI 2000 Derived Soil Properties, 0.5-Deg (ISRIC-WISE). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/634.

SAFARI 2000 Organic Soil Carbon and Nitrogen Data (Zinke et al.)

Zinke, P. J., A. G. Stangenberger, W. M. Post, W. R. Emanuel, and J. S. Olson. 2002. SAFARI 2000 Organic Soil Carbon and Nitrogen Data (Zinke et al.). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/638.

SAFARI 2000 Selected Soil Characteristics, 10-km Grid (IGBP-DIS)

Global Soil Data Task. 2002. SAFARI 2000 Selected Soil Characteristics, 10-km Grid (IGBP-DIS). [SAFARI 2000 Selected Soil Characteristics, 10-km Grid (International Geosphere-Biosphere Programme - Data and Information Services)]. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/647.

SAFARI 2000 Soil Profile Data (ISRIC-WISE)

Batjes, N. H. (ed). 2002. SAFARI 2000 Soil Profile Data (ISRIC-WISE). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/648.

SAFARI 2000 Soil Types, 0.5-Deg Grid (Modified Zobler)

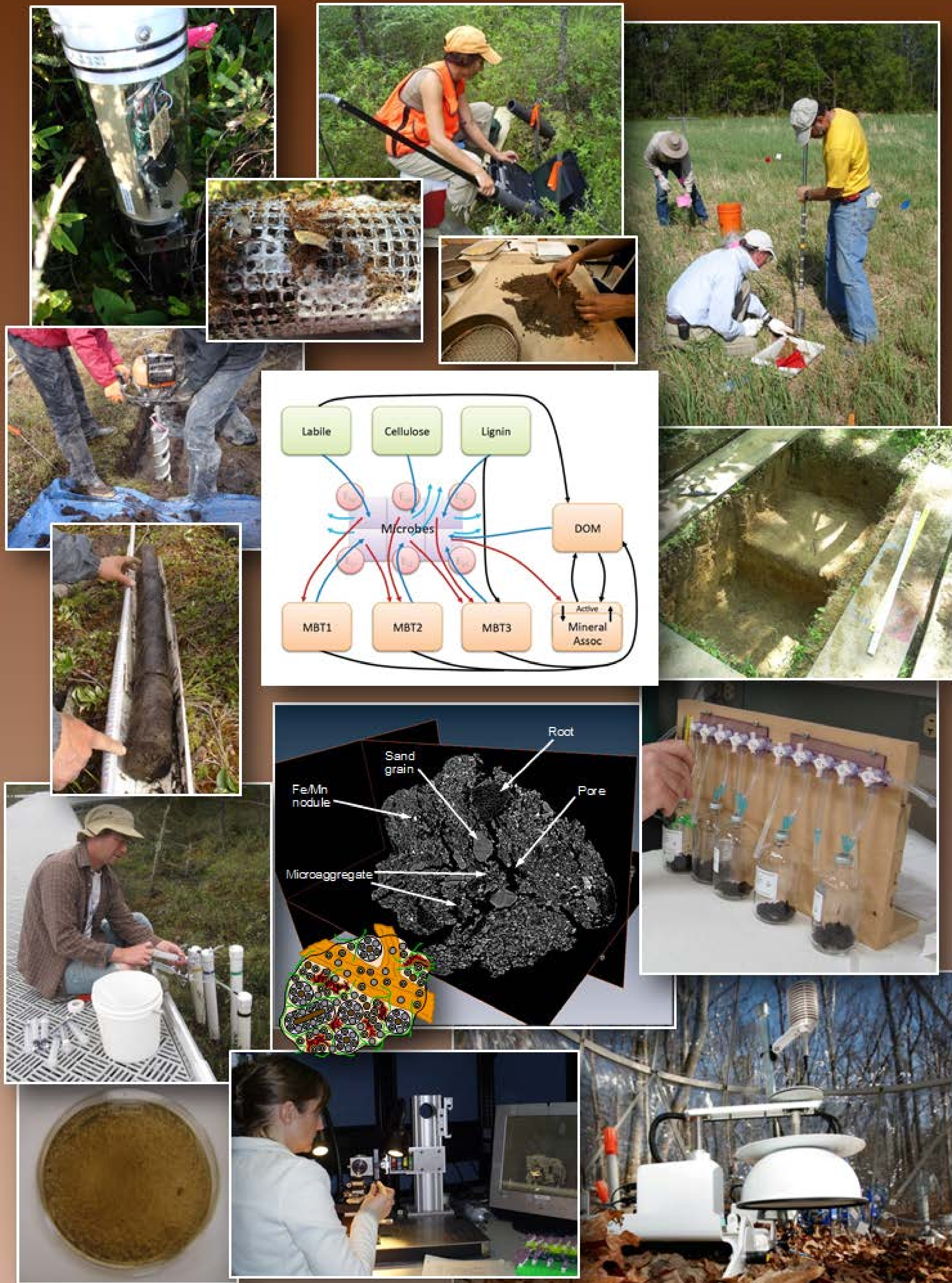
Post, W. M., and L. Zobler. 2002. SAFARI 2000 Soil Types, 0.5-Deg Grid (Modified Zobler). Data set. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/649.

VEMAP 1: U.S. Soil (1998.11.10)

Kittel, T. G. F., N. A. Rosenbloom, T. H. Painter, D. S. Schimel, H. H. Fisher, A. Grimsdell, VEMAP Participants, C. Daly, and E. R. Hunt, Jr. 2002. VEMAP 1: U.S. Soil. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/227.

Acronyms and Abbreviations

^{14}C	radiocarbon
ACME	Accelerated Climate Model for Energy
AmeriFlux	Consortium of eddy covariance sites for measuring landscape-scale fluxes of energy, carbon dioxide, and water — many of which are supported by DOE
APEX	Alaska Peatland Experiment
ARM	Atmospheric Radiation Measurement
ASCR	DOE Office of Advanced Scientific Computing Research
BER	DOE Office of Biological and Environmental Research
BSSD	DOE BER Biological Systems Science Division
C	carbon
CDIAC	Carbon Dioxide Information and Analysis Center
CESD	DOE BER Climate and Environmental Sciences Division
CH_4	methane
CLM-4.5	Community Land Model, Version 4.5
CLM-CESM	CLM embedded within the Community Earth System Model
CLM-ACME	CLM being prepared for application to ACME
CO_2	carbon dioxide
DIRT	Detritus Input and Removal Transfer experiments
DOC	dissolved organic carbon
DOE	United States Department of Energy
DOI	distinct object identifier (a specific web location code used to identify a data products)
ESM	DOE BER Earth System Modeling program
ESS	DOE BER Environmental System Science activity
FACE	Free Air CO_2 Enrichment experiments
ILAMB	International Land Model Benchmarking project
ISCN	International Soil Carbon Network
N	nitrogen
N_2O	nitrous oxide
NASA	National Aeronautics and Space Administration
NetCDF	a set of software libraries and self-describing, machine-independent data formats
NGEE	Next Generation Ecosystem Experiment
PiTS	Partitioning in Trees and Soil experiment
RGCM	DOE BER Regional and Global Climate Modeling program
SBR	DOE BER Subsurface Biogeochemical Research program
SFA	Scientific Focus Area
SOC	soil organic carbon
SOM	soil organic matter
TES	DOE BER Terrestrial Ecosystem Science program
TRY	a global plant trait database
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey



Labile
Cellulose
Lignin
Microbes
DOM
MBT1
MBT2
MBT3
Active
Mineral
Assoc
Root
Sand
grain
Fe/Mn
nodule
Pore
Microaggregate