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, other elements, 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 elements and organic matter.

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.
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May 8, 2014

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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 ecosystems; (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.
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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 (CO2) and methane (CH4). 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 ecosystems; (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 soil vertical 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 are 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, CO2, CH4, and nitrous oxide (N2O) 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.

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 databases 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 and 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 intercomparisons (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, timesteps, 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 CO₂ 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 CO₂ and CH₄ 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 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.

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

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.

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.

Recommendations:

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 recommendations are outlined below.

1. Enhance efforts to preserve, organize, and access federally supported (including BER-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.  

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). See list on p. ii for a complete explanation of acronyms.
2. Conduct a community workshop, engaging modelers and empiricists, to:
   a. prioritize knowledge and data gaps for improvement of process understanding;
   b. prioritize investments for generating new observational and experimental data to
      address model gaps, based on model assessment and expert input; and
   c. define database functionalities required to enable identified model-data activities.

3. Target investments toward addressing high priority gaps in data and knowledge that are
   limiting model improvements for representation of belowground ecology, for example via an
   Early Career opportunity. Using BER as an example, Funding Opportunity Announcements
   (FOAs) by the Climate and Environmental Sciences Division (CESD) and the Biological
   Systems Science Division (BSSD) could provide opportunities, and there could be
   opportunities that bridge Environmental System Science (ESS) and BSSD projects or
   capabilities.

4. Create preliminary benchmark datasets for model evaluation by leveraging the RGCM-
   supported ILAMB framework and existing TES data. Potential examples include:
   a. fulfill a top model-community priority for testing soil organic carbon turnover times
      by supporting ingest of existing $^{14}$C data to build a radiocarbon database, using the
      existing BER-supported database template; and
   b. conduct a model assessment using ILAMB to inform research and data priorities.

5. Develop a new collaborative opportunity to support multi-Lab, multi-Scientific Focus Area)
   projects, engaging both experimentalists and modelers, which take advantage of potential
   synergies among the National Labs and SFAs. Such integrated research initiatives should
   leverage existing expertise and User Facilities — such as the Environmental Molecular
   Sciences Laboratory, the Joint Genome Institute, Atmospheric Radiation Measurement
   (ARM) Climate Research Facility, and others. These initiatives would reduce data and
   knowledge limits to model testing and development and would support the development of a
   process-rich, fine-scale carbon/ecosystem model that (a) underpins next-generation
   belowground models (by serving as a benchmark model, as a modular model test bed, and/or
   as a basis for reduced-order or reduced-complexity representations), and (b) stimulates new
   hypotheses about terrestrial responses to global change.
Cited References


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., CDIAC) to address the curation of archived data, and the development of expanded repositories for TES (and other ecosystem)-related research.
Cited References


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

1. ROOT CHARACTERISTICS

1.1 Global Distribution of Root Profiles in Terrestrial Ecosystems

1.2 Global Distribution of Fine Root Biomass in Terrestrial Ecosystems

1.3 ISLSCP II Ecosystem Rooting Depths

1.4 Global Distribution of Root Turnover in Terrestrial Ecosystems

1.5 Root:shoot ratio
1.6 Global Distribution of Root Nutrient Concentrations in Terrestrial Ecosystems


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)

http://dx.doi.org/10.3334/ORNLDAAC/1078

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


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


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

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

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

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

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

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

2.11 Global Soil Texture and Derived Water-Holding Capacities (Webb et al.) (2000.09.05)
2.12 Global Soil Types, 0.5-Degree Grid (Modified Zobler) (2000.05.19)

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

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

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

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)
2.22 CSIRO Australian Soil Resource Information System

2.23 Joint Research Centre European Soil Portal

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 14C datasets (Mills et al. 2013)
http://molterdb.irstea.fr/publi/

2.27 Other Literature References Containing Distributed Soil Data


3. MICROBIAL AND ENZYME PARAMETERS, AND SOIL INCUBATION EXPERIMENTS

3.1 Microbial communities


3.2 C:N:P Ratios

3.2 Microbial biomass


3.3 Enzymes


3.4 Sorption of dissolved organic carbon


3.5 Lab-scale incubation experiments


3.6 Modeling SOC decomposition – testing databases


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


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 CO2 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/

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


5.3 Elevated CO2 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/


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 13C Labeling and Shade Treatments
Various data files including: N, 12C and 13C 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_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

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5.5 Regionally Specific Belowground Datasets

**BORreas 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

ISLSCP II Ecosystem Rooting Depths

ISLSCP II Global Gridded Soil Characteristics

**FIFE Project Data**

FIFE Root Biomass Data Set

FIFE Soil CO2 Efflux Data Set

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

FIFE Soil Moisture Gravimetric Data

Soil Bulk Density Data (FIFE)

Soil Hydraulic Conductivity Data (FIFE)

Soil Moisture Release Data (FIFE)

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

Soil Thermal Conductivity Data (FIFE)

Soil Water Properties Derived Data (FIFE)
LBA Data Sets

LBA-ECO CD-04 Soil Moisture Data, km 83 Tower Site, Tapajos National Forest, Brazil

LBA-ECO CD-04 Soil Respiration, km 83 Tower Site, Tapajos National Forest, Brazil

LBA-ECO CD-05 Soil VWC and Meteorology, Rainfall Exclusion, Tapajos National Forest

LBA-ECO CD-08 Carbon Isotopes in Belowground Carbon Pools, Amazonas and Para, Brazil

LBA-ECO CD-09 Soil and Vegetation Characteristics, Tapajos National Forest, Brazil

LBA-ECO CD-10 Forest Litter Data for km 67 Tower Site, Tapajos National Forest

LBA Regional Derived Soil Properties, 0.5-Deg (ISRIC-WISE)

LBA Regional Organic Soil Carbon and Nitrogen Data (Zinke et al.)

LBA-ECO ND-02 Cation Leaching from Forest and Pasture Soils, Para, Brazil
LBA-ECO ND-02 CO2 Flux from Soils in Forests and Pastures, Acre, Brazil: 1999-2001

LBA-ECO ND-02 Soil Gas and Water Content, Rainfall Exclusion, Tapajos National Forest

LBA-ECO ND-02 Soil Gas Flux, Rainfall Exclusion, km 67, Tapajos National Forest


LBA-ECO ND-02 Soil Volumetric Water Content, Tapajos National Forest, Brazil

LBA-ECO ND-02 Trace Gas Flux from Forest Soil, Para, Brazil: 1999-2001


LBA-ECO ND-04 Secondary Forest Carbon and Nutrient Stocks, Central Amazonia, Brazil

LBA-ECO ND-07 Microbial Biomass in Cerrado Soils, Brasilia, Brazil

LBA-ECO ND-07 Nitric Oxide Flux from Cerrado Soils, Brasilia, Brazil: 2004
LBA-ECO ND-10 Soil Properties of Pasture Chronosequences, Para, Brazil: 1997

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

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

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

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

SAFARI Project Databases

SAFARI 2000 Annual CO2 Emissions from Soil, 0.5 Deg-Grid (Raich and Potter)

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

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

SAFARI 2000 Annual CO2 Emissions from Soil, 0.5 Deg-Grid (Raich and Potter)

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

SAFARI 2000 Derived Soil Properties, 0.5-Deg (ISRIC-WISE)
SAFARI 2000 Organic Soil Carbon and Nitrogen Data (Zinke et al.)

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

SAFARI 2000 Soil Profile Data (ISRIC-WISE)

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

VEMAP 1: U.S. Soil (1998.11.10)
### Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>$^{14}$C</td>
<td>radiocarbon</td>
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<tr>
<td>ACME</td>
<td>Accelerated Climate Model for Energy</td>
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<tr>
<td>AmeriFlux</td>
<td>Consortium of eddy covariance sites for measuring landscape-scale fluxes of energy, carbon dioxide, and water — many of which are supported by DOE</td>
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<tr>
<td>APEX</td>
<td>Alaska Peatland Experiment</td>
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<tr>
<td>ARM</td>
<td>Atmospheric Radiation Measurement</td>
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<td>ASCR</td>
<td>DOE Office of Advanced Scientific Computing Research</td>
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<tr>
<td>BER</td>
<td>DOE Office of Biological and Environmental Research</td>
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<tr>
<td>BSSD</td>
<td>DOE BER Biological Systems Science Division</td>
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<tr>
<td>C</td>
<td>carbon</td>
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<tr>
<td>CDIAC</td>
<td>Carbon Dioxide Information and Analysis Center</td>
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<td>CESD</td>
<td>DOE BER Climate and Environmental Sciences Division</td>
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<tr>
<td>CH$_4$</td>
<td>methane</td>
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<td>CLM-4.5</td>
<td>Community Land Model, Version 4.5</td>
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<tr>
<td>CLM-CESM</td>
<td>CLM embedded within the Community Earth System Model</td>
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<tr>
<td>CLM-ACME</td>
<td>CLM being prepared for application to ACME</td>
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<td>CO$_2$</td>
<td>carbon dioxide</td>
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<td>DIRT</td>
<td>Detritus Input and Removal Transfer experiments</td>
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<td>DOC</td>
<td>dissolved organic carbon</td>
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<td>DOE</td>
<td>United States Department of Energy</td>
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<td>DOI</td>
<td>distinct object identifier (a specific web location code used to identify a data products)</td>
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<tr>
<td>ESM</td>
<td>DOE BER Earth System Modeling program</td>
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<td>ESS</td>
<td>DOE BER Environmental System Science activity</td>
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<td>FACE</td>
<td>Free Air CO$_2$ Enrichment experiments</td>
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<td>ILAMB</td>
<td>International Land Model Benchmarking project</td>
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<td>ISCN</td>
<td>International Soil Carbon Network</td>
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<tr>
<td>N</td>
<td>nitrogen</td>
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<td>N$_2$O</td>
<td>nitrous oxide</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NetCDF</td>
<td>a set of software libraries and self-describing, machine-independent data formats</td>
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<td>NGEE</td>
<td>Next Generation Ecosystem Experiment</td>
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<td>PiTS</td>
<td>Partitioning in Trees and Soil experiment</td>
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<td>RGCM</td>
<td>DOE BER Regional and Global Climate Modeling program</td>
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<td>SBR</td>
<td>DOE BER Subsurface Biogeochemical Research program</td>
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<tr>
<td>SFA</td>
<td>Scientific Focus Area</td>
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<td>SOC</td>
<td>soil organic carbon</td>
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<td>SOM</td>
<td>soil organic matter</td>
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<td>TES</td>
<td>DOE BER Terrestrial Ecosystem Science program</td>
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<td>TRY</td>
<td>a global plant trait database</td>
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<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
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<td>USFS</td>
<td>United States Forest Service</td>
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<tr>
<td>USGCRP</td>
<td>United States Global Change Research Program</td>
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<td>USGS</td>
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