FORUM

Digging Into the World Beneath Our Feet: Bridging Across Scales in the Age of Global Change

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Climate change, land use practices, and other consequences of a growing human population affect soil sustainability. Unfortunately, scientists studying belowground processes have traditionally been limited to data and models that capture intermediate spatial and temporal scales, failing to accurately characterize soil phenomena at societally relevant scales, including the larger spatial scales at which many policy decisions are made.

However, traditional approaches are now changing rapidly due to the ever-increasing availability of data that span from nanometers to megameters and from seconds to millennia. Informational advances present an opportunity for new collaborations—particularly between belowground observational scientists and Earth system modelers—to link knowledge across scales to better understand the world beneath our feet.

Limited Scales of Observation

Important soil biogeochemical processes are typically measured at centimeter to meter scales but are influenced by factors at finer and coarser scales (Figure 1). At the finer end, carbon and other substrates are enzymatically released from within soil colloids at the nanometer scale. Scaling up, representation of dominant controls on biogeochemical processes requires data on microbial community composition and oxygen content (micrometer scale), soil structural features and plant community composition (meter scale), hydrology (kilometer scale), and land use and climate (megameter scale). Our limited ability to make direct observations of nutrient transformations and interacting drivers at multiple spatial scales often renders predictions outside the meter scale uncertain and makes it difficult to predict phenomena at larger scales.

Field-based studies of soil biogeochemical cycles typically occur at intermediate (weeks to months) time scales. However, significant nutrient transformations can occur during brief events (spanning minutes to hours) when substrate availability, soil moisture, temperature, and microbial populations align. Although recent advances in automated measurements of dynamic processes, such as trace gas fluxes, are becoming widespread, intermittent behaviors remain difficult to predict accurately in ecosystem models. Comparable problems plague our understanding of the temporal variability of belowground phenomena at longer (decadal) time scales; few studies capture interannual shifts in soil processes or their drivers.

New Resources for an Outstanding Problem

The importance of temporal and spatial scaling was recognized early in soil science's history. *Waksman* [1932] commented that soil colloids (nanometer) exert effects on soil microbial processes (micrometer), which influence plant growth (meter) and field soil fertility. Nevertheless, a statement made by *Ojima* [1992, p. 2] more than 20 years ago still rings true today: "We are still in the early stages of dynamically linking the components of the earth system in our models…In many cases, the observations necessary to validate the [models]…do not exist."

We are now in a unique position to overcome disparities between measurement resolutions and desired scales of prediction. New technology and network science are increasing our ability to explore both ends of Figure 1. Metagenomic approaches can determine how functional attributes of soil microbial communities change across biomes or in response to climate. Thus, study of microbiology now informs scales at which we can probe ecologically significant processes. New publicly available megameter-scale data sets of soil properties are emerging, such as the Harmonized World Soil Database of the United Nations' Food and Agriculture Organization and those built through the Critical Zone Observatory network, the National Ecological Observatory Network, the Natural Resources Conservation Service's U.S. General Soil Map (STATSGO), and the U.S. Geological Survey's Geochemical and Mineralogical Data for Soils program.

A Way Forward

We suggest three parallel efforts to leverage new data and build a comprehensive

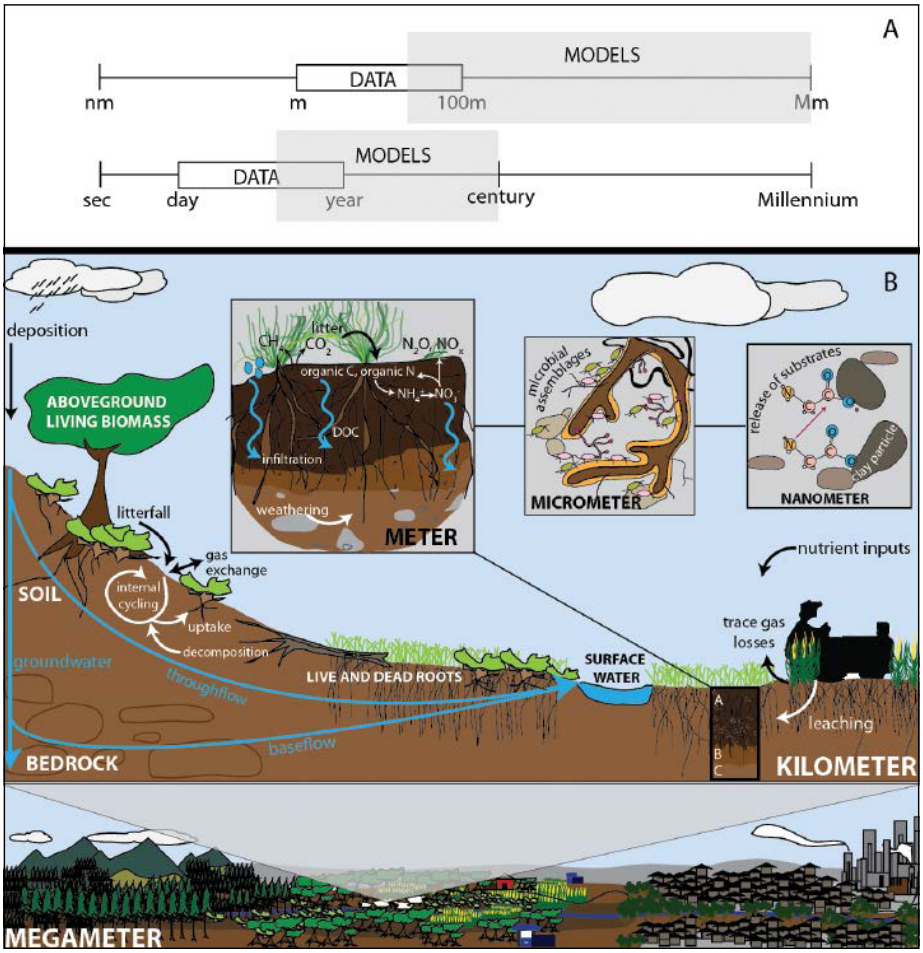

Fig. 1. (a) Scales over which most belowground data and models representing soil biogeochemical processes exist, from nanometers (nm) through meters (m) to megameters (Mm) and from seconds through centuries to millennia. (b) Nested scales of belowground biogeochemical processes. Modified from Paul *[2014].*

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understanding of belowground processes. First, we need to strengthen commitments to collect and curate publicly available data—data sets that are not accessible are not valuable. This push must come from science networks as well as individual researchers.

In particular, we need data on abiotic and biotic features across scales to better resolve mechanisms underlying soil biogeochemical processes, drivers, and feedbacks.

Second, we need models that provide a numerical representation of contemporary soil biogeochemical theory and are applicable across scales and ecosystems [e.g., *Schmidt et al.,* 2011; *Wieder et al.,* 2013]. Moving forward, we envision interdisciplinary teams of hypothesis-testing scientists creating and evaluating models that apply to the full range of spatial and temporal scales.

Finally, both efforts will require interdisciplinary collaboration, likely driven by scientists currently in training. They must have access to academic programs that provide appropriate quantitative skills to query and analyze large data sets, along with broad understanding of global issues affecting soils. We emphasize that collaborative efforts must work toward producing process-based scaling functions that incorporate biology, chemistry, and physics to understand controls on soil biogeochemical processes.

Although daunting, similar approaches have been applied aboveground. The biogeochemical and biogeophysical effects of vegetation have been explored by integrating species-specific leaf gas exchange measurements, eddy flux data, remote sensing, and Earth system models [e.g., *Bonan et al.,* 2012]. Comparable approaches belowground would improve future research efforts and link scientists interested in phenomena across scales and disciplines.

Cross-scale understanding and improved predictive capacity of belowground processes are critical to determine how we sustain soil health and function. This is one of the grand challenges of our time. We recognize that meeting this challenge is a tall order, but as we expand our ability to see belowground, we are positioned to produce unique data sets and build new knowledge across scales through cooperative action.

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