Scaling soil processes with data from above and below: Using space-based and local observations to project carbon cycle-climate feedbacks

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Summary: Committed investment is needed to link mechanistic understanding of soil processes, predictive models, and space-based data. Specific objectives should aim to: represent emerging belowground understanding in models; evaluate the resulting simulations with global-scale observations; and build confidence in greenhouse gas budgets and projections.

1 Key challenges for Earth System Science in the coming decade:

Advancing our understanding and representation of belowground processes in the face of environmental change is a key challenge facing Earth System Science. Addressing this challenge requires mechanistic insight be applied in process-based models that are validated with large-scale and space-based observations. Although remote sensing platforms currently have limited capabilities to directly observe belowground processes, they can observe large-scale state factors that influence subsurface activity (e.g., climate, topography, vegetation, and land use) and the emergent properties of those drivers on belowground processes (e.g., production of greenhouse gasses) (Fig. 1). Thus, over the next decade we need financial and intellectual commitments to link process-based understanding with models and large-scale observations in order to assess regional and global biogeochemical responses on a changing planet.

Despite advancements in conceptual and numerical representations of climate system, there remains considerable uncertainty and very low confidence in the projected magnitude and sign of terrestrial carbon (C) cycle–climate feedbacks[1-5]. Improving confidence in projected feedbacks is critical to inform decisions regarding allowable carbon dioxide (CO_2) emissions that are compatible with particular climate trajectories[6,7]. High uncertainty in terrestrial biogeochemical projections reflects the incomplete understanding of how best to represent biologically driven processes at global scales[8,9]. The theoretical underpinnings and C stocks simulated in Earth System Models (ESMs) are notably poor[10,11]. These shortcomings that have direct impacts on projections of atmospheric CO_2 and climate. They must be addressed with empirical research that improves our mechanistic understanding of terrestrial processes, which is translated into the next generation of models that are parameterized, and validated with appropriate large-scale data sets. These advancements especially needed in the representation of soils – the largest terrestrial C pool on Earth – which provide a multitude of ecosystem services critical to supporting life on our planet[12].

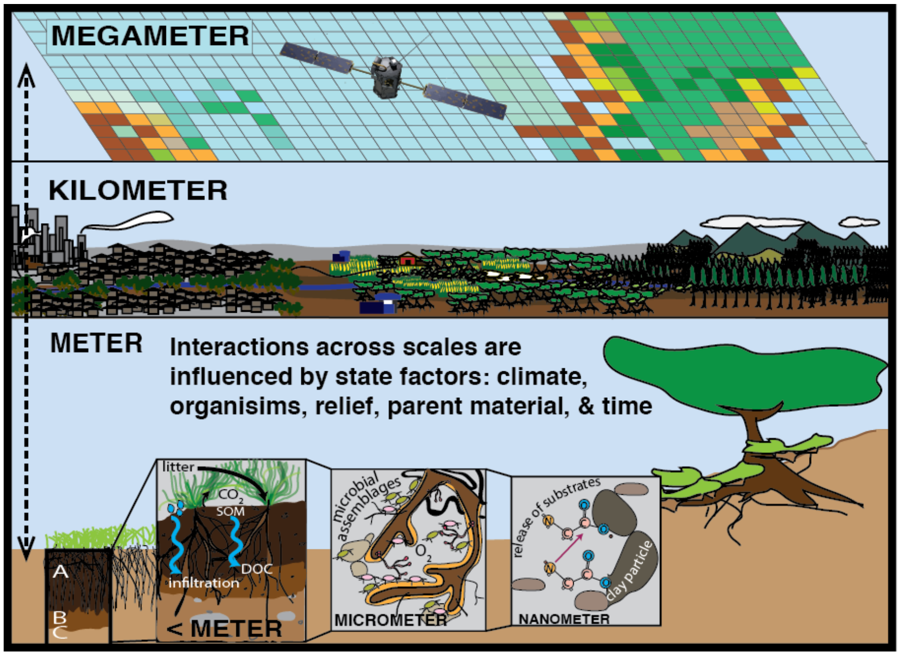

Fig. 1 | Controls over soil biogeochemical processes at various spatial scales. At fine scales (nm, μm, and m), biological and soil physiochemical factors control soil biogeochemical processes. At larger scales (> m), factors like relief and climate interact with fine scale factors to mediate soil biogeochemical dynamics and responses to perturbations. Data are needed across scales and disciplines to improve our understanding and projections of ecosystem responses to change (e.g., soil C response to warming; modified from ref. 13).

2 Addressing these challenges:

Models generally use broad-scale variation in factors such as plant communities, land use, and vegetation to predict soil-atmosphere exchange of C. However, empirical and theoretical advances emphasize that soil C cycling is strongly regulated by microbial communities and their interactions with minerals[14-17]. Microbes are not just decomposers, but are also the proximate source of organic matter that persists in soils. Indeed, other known controls of C cycling, including those represented in most models, may serve primarily as indirect controls over C cycling through their effects on microbe-mineral interactions. Models based on these new theories show that explicitly considering microbial soil organic matter formation improves steady-state estimates of global soil C stocks and, more importantly, changes the magnitude of projected terrestrial C storage responses to global environmental change [18-22].

Developing the models that link theory and observations across multiple scales remains limited because: (a) we do not have the requisite empirical data and understanding to represent the mechanisms we think are important; (b) we lack relationships that allow us to use remotely-sensed data over large scales to estimate ecosystem function, and link these processes to mechanisms; and (c) we are unsure what key biotic and abiotic processes are necessary to represent in global-scale models. By putting soil microbes into models we are beginning to represent critical organisms that directly control soil C cycling, but to do this effectively we need to better understand microbial physiological traits and how they affect biogeochemical dynamics in soils.

Observations provided by new technologies and experimental approaches are rapidly expanding the spatial and temporal scales over which measurements are made. Such advancements reshape and refine the understanding of belowground processes[23] and provide an opportunity to meet fundamental scientific challenges. However, linking insight provided by these disparate data streams, which span orders of magnitude in spatial and temporal scale, to the global C cycle is needed to address societally and policy relevant issues over the next decade. To address this challenge we need a greater investment, integration and communication among empiricists and modelers. These collaborations should cross disciplinary boundaries (from biology, geology, atmospheric science, and remote sensing) to apply theory, generate hypotheses, collect data, and refine understanding through an iterative exchange of ideas and information.

This area of research should aim to improve confidence in belowground projections by identifying and representing key mechanisms such as microbial activity and physicochemical stabilization of soil organic matter under different environmental conditions. We suggest focusing in the near-term on improving confidence in model projections, as opposed to reducing uncertainty, because with better process-based representation, we can be confident that gains in certainty are actually meaningful.

3 Space-based observations are fundamental to addressing these challenges:

We may not be able to see soil microbes from space, but we can observe state factors that drive soil processes at larger scales (Fig. 1). By linking mechanistic insight into soil microbial-mineral interactions with the next generation of process-based ESMs and space-based observations we expect to:

1. *Represent* emerging belowground understanding in models;
2. *Evaluate* the resulting biogeochemical simulations from the top-down; and
3. *Increase confidence* in greenhouse gas budgets and projections.

Space-based observations will be critical for linking mechanistic understanding with advanced models to improve confidence in the representation of biogeochemical processes and projections.

Earth system models must *represent* emerging understanding of belowground processes. This can be accomplished by linking microbial traits with broad-scale variation in state factors. Space-based observations have exceptional potential to inform scaling relationships between local measurements and global models. Remote sensing is now used to: classify soil type[24,25]; monitor changes in vegetation over time (e.g., Landsat and MODIS); and provide real time information on the seasonal cycle, interannual variability, and effects of extreme events on global climate and surface soil moisture conditions (e.g., GCOM-W1 and SMAP). These global measurements should be paired with rigorous point based quantification of microbial physiological traits, soil C, and their responses to state factors. With proper investment and engagement we can reach the point where linking broad differences in state factors with functional variation in microbial communities and activity is achievable. Space-based observations can provide data that are fundamental to upscaling local observations to regional and global scales, and this information can then be used to inform the structure and parameterization of ESMs.

Space-based data will also be critical to *evaluating* simulated greenhouse gas fluxes from the next generation of ESMs. Previously, ground-based observations from eddy-flux tower measurements were used to evaluate fluxes of C, energy and water from ESMs[26-28]. With increasing fidelity, however, observation platforms provide excellent top-down constraints on the concentration and distribution of greenhouse gasses in the atmosphere (e.g., OCO-2, GOSAT, and TCCON). The Orbiting Carbon Observatory 2 (OCO-2) provides globally gridded information with high temporal resolution that can be used to inform, parameterize, and evaluate ESMs. With high enough spatial and temporal measurements, an inverse modeling approach could suggest places/biomes we need to understand better. Specifically, we envision this satellite-based data will provide top-down constraints on the location, magnitude and timing of terrestrial greenhouse gas fluxes, and that these data will be critical to develop and validate the next generation of ESMs.

We expect to *increase confidence* in model projections by simultaneously improving the small-scale process representation and large-scale patterns of greenhouse gas budgets and fluxes. This objective points to the interplay between ESMs and spaced-based data, whereby process-based models are used to interpret satellite observations as we monitor planetary change from above. For example, surface CO_2 measurements show the amplitude of the Northern Hemisphere seasonal CO_2 cycle is increasing[29], but offer relatively little insight into the mechanisms responsible for this observation. Although several hypotheses exist for contributors to this[29-31], the spatial and temporal resolution provided by satellites like OCO-2 and Soil Moisture Active Passive (SMAP) will provide greater insight into the timing and location of systems that may be responsible for this observation. Interpreting these space-based observations with ESMs that are based on the theoretical underpinnings described above will increase the value of satellite data, and concurrently improve the accuracy and confidence in model simulations. A key test of ESMs will be reproducing both the current day seasonal CO_2 cycle magnitude and its change over the past 60 years, and getting soil processes right will be an important step to achieving this.

Earth system models provide a powerful tool for merging insights provided from field- and lab-based observations with space-based data products in ways that will provide a deeper understanding of the factors regulating soil biogeochemical processes across scales. Developing these capacities is critical to advance basic and applied research in soil, agricultural, ecosystem, and Earth System Science. Building these interdisciplinary connections will expand scientific opportunities and address societal needs to more accurately project belowground responses and feedbacks to environmental perturbations.

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