

June 15, 2015

Dear Editor,

Attached please find the Author's Response for manuscript Soil 2-133-2015, A call for international soil experiment networks by Torn et al. Per your instructions, it includes (1) a point-by-point response to the reviews and a list of all relevant changes made in the manuscript, and (2) a marked-up manuscript version (combined in one *.pdf file).

I have summarized (listed) all the relevant changes below. In my interactive replies to the two reviews, I detailed my response to reviews. Per the instructions to submit all documentation in one combined PDF, I am also including those two replies in this file.

Also included in this file is the marked-up, revised manuscript showing all changes using the Adobe Acrobat comment tools. Please note that this the same manuscript file that I uploaded as the "Manuscript (pdf)" with the title "soild-2-133-2015_Torn Revised 20150517 r2.pdf"

Yours,
Margaret Torn.

Summary list of changes:

1. Citations added for climate interactions (Williams)
2. Noted that experiments have artifacts and limitations, and citation (Hanson)
3. Added mention of possibility of nesting experimental manipulations within Critical Zone Observatory, and citation. (Banwart)
4. Added citation for early proponent of soil experiment networks (Paustian)
5. Added citation for spatial variation in radiocarbon and soil carbon turnover times.
6. Changed PI to participants or investigators, and corrected typos in spelling.
7. Corrected the other typos

1 Reply to:

2 Interactive comment on “**A call for international soil experiment networks for studying, predicting,**
3 **and managing global change impacts**” by M. S. Torn et al.

4 **B. Jason (Referee)**

5 jason.beringer@uwa.edu.au

6 Received and published: 12 March 2015

7
8 We thank the reviewer for his comments and suggestions, and are glad that the main thrust of our
9 argument—for whole-soil manipulations and networks of such experiments—had some resonance.
10 We address the comments in the order they were presented.

11
12 1. Narrow focus on soils. It is correct that in this effort we are focusing on the effects of climate change
13 on soil ecosystem services, with an emphasis on soil biogeochemistry. However, while SOM cycling and
14 nutrient provision are two critical ecosystem services that depend on climate, there are many others and
15 we hope that our mention of soil ecosystem services conjures up a broader list for the reader.
16 We agree that a strong case could be made for networks for other purposes, and hope that the SOIL
17 Forum hosts a lively exchange of such cases.

18
19 2. Relationship to existing networks. We agree that existing networks offer valuable resources and
20 potential partnerships for a network of experiments. The experimental network would not be redundant,
21 because most soil, critical zone, and ecosystem networks are observational, rather than experimental (with
22 respect to climate change experiments), such as CZO and NEON. The ISCN is not a network of sites, but
23 rather is a carbon-focused database. Nevertheless, we are glad it was mentioned because it is also a good
24 resource: in fact, the iSEN proposes to build upon ISCN data templates to accommodate manipulative
25 treatments. Due to word limits, we had to reduce mention of non-experimental networks like CZO.
26 However, CZO sites could be good locations for manipulative experiments; the kinds of research and
27 observations conducted at CZOs are highly synergistic. We have now added mention of critical zone
28 observatories and the example of nesting manipulations within a CZO network (citing Banwart et al.).

29
30 We included a table of soil manipulative experiment networks (mostly international). We welcome further
31 suggestions via the interactive discussion about (1) networks of global-change soil-manipulation
32 experiments, or (2) observational networks like CZO that could potentially host experiments.

33
34 3. References. Thanks for the recommendations of good papers. We have added citation to Paustian
35 (1995) as an early proponent of this idea, and cite Banwart (2012) for developing the concept of using
36 CZOs (see Banwart (2012) for an example of nesting manipulations within a CZO network).
37 There are many other excellent papers about soil monitoring networks as well, but given our word limit
38 will thought these were especially relevant.

39
40 4. Limitations of Manipulative experiments. We agree that manipulative experiments have limitations,
41 and that we should augment this in the paper. Typical artifacts include a step change in conditions (e.g, a
42 step change of 4oC); relatively short duration; small islands of manipulation; manipulation of only some
43 system components. We have added a citation to Hanson et al. 2008 on this point.

44
45 5. Relationship between experiments and gradients. We agree and intended to promote the view that a
46 combination of approaches is best. The integration of manipulations and natural gradients could be
47 particularly powerful. We had to cut some of the original text on the relationship among gradients,
48 experiments, and laboratory studies because of space limitations.

49
50 6. Were we trying to guide others’ research on nutrient dynamics? The comment on page 7 about *nutrient*
51 *dynamics* was specifically in reference to the fact that some iSEN participants are prioritizing nutrient

dynamics at their sites. No greater implication was intended.

7. “Engaging the community through larger networks and meetings of scientific unions for example AGU and EGU (for example) is a must and piggybacking off developed networks will be important to access the relevant communities and have their engagement.”

We are glad to hear that this call for action resonates and that the reviewer thinks it is mature enough to now engage other networks and communities. Earlier meetings at AGU and EGU were used to develop the basic scientific principles, and it is good to have the encouragement to expand the community at this time. That was one goal of the Forum article!

8. “The critical zone Observatory has a focus that is synergistic with this proposed network and provides a larger framework. The most value to be gained by a soil experimental network will be gained by linking disciplines as part of a larger picture [for example the CZOs].”

We agree there is large potential synergy. It would be wonderful if a group would like to develop manipulative experiments in partnership with the CZOs. At the same time, other PIs are partnering with some of the other networks and field stations mentioned by the reviewer, and others with, for example, agricultural research networks

9. Create a system of intensive manipulative sites with observational sites. It is an excellent suggestion to consider a hierarchical approach, where some manipulation experiments are performed at a number of key intensive sites, and coordinated with simpler observations that are made at more sites across a wider range of conditions. This is a nice expansion on the idea that it would be effective to nest manipulations within gradients or matrices of, for example, different soil types, climate, and vegetation zones.

10. Consider opportunities posed by AmeriFlux and FLUXNET.

Although we did not have space in the Forum to spell out connections with observational networks, the writing team includes the lead of the AmeriFlux Management Project, a founding member of the ISCN, the director of two large European networks, and other strong network connections.

We agree that there are benefits to nesting experiments in sites for which ecosystem fluxes are being measured (there is a soil warming experiment in the footprint of Harvard Forest AmeriFlux site, for example). However, if the goal were to use eddy flux to measure the treatment response, a soil warming treatment that matched the footprint of a flux tower would require each manipulated plot to be $>10^4 \text{ m}^2$, and even if smaller than that, a large manipulative experiment could be a large perturbation to other studies in the tower footprint.

More generally, we imagine that there are many more opportunities for good sites (and good network partners) than we could find or describe. We encourage other suggestions and contributions through this discussion forum. We also leave it to scientists who would like to develop a participating experiment to find the site or sites that meet their research interests, logistics needs, and funding opportunities. In parallel, it is worth developing a set/map of potential sites (or site criteria) in hopes of achieving a distribution of experiments that covers a useful combination of environmental conditions. This would be a worthwhile scoping project, and could take into account information from many of the networks mentioned in this review, models, and other sources.

11. In response to this theme of the review (i.e., “a discussion on the consideration of linking with larger scale networks.”), we agree that collaborating with existing networks and specific network sites has great benefit. At the same time, it does not seem wise to choose only certain networks for partnership, nor warranted to require self-funded, international PIs to locate where we dictate. To the extent that an existing network is interested in expanding their scope to include experiments, however, this would be a

great opportunity.

12. Title suggests management of global change. The title is meant to say that this is research for managing “global change impacts,” rather than managing global change. Does that help? It is a rather long title, but one of the research goals is development of approaches to managing impacts, for example in agricultural contexts.

13. Important to engage modelers. Excellent point. Using information from modeling studies and having buy-in from modelers is important. Indeed, modeling studies and data-requests from modelers directly shaped the SPRUCE, California, and Puerto Rico projects, and the SPRUCE and California experiments employ full time modelers as part of those studies. We will make sure that the point is stated in the article.

14. Figure 2 relevance. The reviewer wonders if this is relevant enough for inclusion. We thought an illustration of a deep soil warming experiment would be useful, and leave it to the editor to advise us. We could remove the upper-left and upper-right panels to simplify the graphic.

1 Reply to:

2 Interactive comment on “A call for international soil experiment networks for studying,
3 predicting, and managing global change impacts”

4 by M. S. Torn et al.

5 **Anonymous Referee #2**

6 Received and published: 16 April 2015

7
8
9 We thank the reviewer for their comments and suggestions.

10
11 We agree that climate and atmospheric change will affect plant growth in many ways. To keep this Forum
12 focused on soils, we used examples of relatively direct influence of plants on soils, namely changes in the
13 amount, timing, depth, and chemistry of plant inputs to soil. Participants in the network could expand the
14 scope at their sites to include plant manipulations, or other biological considerations.

15
16 The reviewer suggests that having additional detail on experimental design would allow the proposal to
17 be more widely considered. We omitted such detail from the Forum in part because it was intended to be
18 a more general thought piece, but since we do offer one specific network as an example, the international
19 Soil Experiment Network (iSEN). The iSEN will be posting experimental designs on the website very
20 soon. If space were available, we would be happy to add more detail of our vision for possible
21 experimental designs. The initial proposal for manipulations is that warming and isotopically labeled litter
22 are highest priority, followed by nitrogen additions and/or water manipulations depending on the site and
23 research context. Some research in iSEN will be aimed at agricultural systems, for example. For similar
24 reasons the needed replication also depends on site specific heterogeneity and history.

25
26 Manipulation levels could be chosen to match modeled climate scenarios (as was the case for the
27 California sites) or to develop a response curve using many manipulation levels (as was the case for
28 SPRUCE). We submit that having at least one treatment level in common among sites will facilitate
29 synthesis.

30
31 The review raises an important point about the importance of linking with “biological and ecosystem
32 research programs more generally.” It makes sense to nest soil experiments within larger ecosystem (or
33 critical zone) studies where conditions permit, as well as to look for opportunities to create new joint
34 initiatives with other programs.

35
36 Regarding approaches to handling unmonitored factors and variation among sites, in iSEN we propose to
37 employ two approaches: (1) facilitating synthesis so that site differences are more easily interpreted and
38 (2) process-rich modeling that includes monitored and unmonitored factors and can be used to simulate
39 different histories of land use, climate, and disturbance. A critical component of network success will be
40 having a data management system for primary data and metadata that allows intelligent interpretation and
41 synthesis. For ancillary data, AmeriFlux and FLUXNET have detailed reporting templates for
42 disturbances, land use and management, and vegetation and soil properties that can be modified for the
43 iSEN. As the reviewer is raising basic questions of experimental and network design, there are probably
44 many other productive ways to address these questions. We solicit community input on them and
45 especially on how site history and disturbance should be documented.

46
47 We thank the reviewers for pointing out places that need references and the spelling mistake. We have
48 added the citations requested. We substituted the term “participant” for PI except where we specifically
49 meant Principal Investigator; in some cases PI is preferred to ‘collaborator’ because it reinforces the
50 concept of a network of autonomous PIs.

This discussion paper is/is has been under review for the journal SOIL. Please refer to the corresponding final paper in SOIL if available.

A call for international soil experiment networks for studying, predicting, and managing global change impacts

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1 Introduction

The soil profile encompasses a remarkably large range of biogeochemical conditions, processes, and fluxes. For example, in most soils the turnover time of soil organic carbon (SOC) varies more between the soil surface and 1 m deep than between surface soils in the tropics versus the Arctic. Radiocarbon observations in different soil types show that SOC decomposition rates decrease with depth, with residence times of years-to-decades at the soil surface to over 10 000 years at 1 m deep (e.g., Torn et al., 2002). There are many competing hypotheses for this steep decline in SOC turnover with depth. They can be grouped loosely into physical-chemical accessibility, energetic limits to microbial activity, microclimate and pH, and physical disconnect between decomposers and substrate. While all of these mechanisms control deep SOC cycling, data are lacking to unravel their relative importance in different soils under different environmental conditions. This is, however, critical knowledge for predicting soil responses to global change, because fairly rapid loss (or gain) of old and/or deep SOC stocks is possible and more than 80 % of the world's SOC is found below 20 cm depth (Jobbagy and Jackson, 2000). Currently, the soil modules within Earth System Models are parameterized for surface soil and lack mechanisms important for stabilization and losses of deep SOC. Hence, we suggest that a critical challenge is to achieve process-level understanding at the global level and the ability to predict whether, and how, the large stores of deep, old SOC are stabilized and lost under global change scenarios.

As historical pressures and dependence on soils for food and fuel production continue, the coming century brings new, global changes as well. Two of the most widespread impacts of anthropogenic activities on soils in this century will be warmer temperatures (Fig. 1) and altered plant allocation belowground due to elevated atmospheric CO₂ concentrations (Luo et al., 2006) and deposition of reactive nitrogen (Janssens et al., 2010). The resulting effects on SOC cycling are less certain: warming may increase microbial activity and therefore accelerate SOC turnover (Davidson and Janssens 2006; Conant et al., 2011), while more plant allocation belowground may

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increase stocks due to additional inputs or decrease stocks through priming effects (Kuz'yakov, 2010; Cheng et al., 2014). Climate-change impacts will be compounded with growing levels of nitrogen deposition, ozone pollution, and land use and land cover change. Societal reliance on soil ecosystem services, and the threat of large positive climate feedbacks, demands that we understand surface and deep soil responses to global change and how to enhance the resilience of soil systems across the whole soil profile.

2 The need for deep soil manipulation experiments

To achieve generalizable understanding of soil response to global change, and to test management solutions in real-world conditions, we need controlled experiments that are carried out in situ, consider the whole soil profile, and are at locations spanning a range of conditions.

Field manipulation experiments fill a critical niche as complements to natural gradient studies and laboratory incubations. While laboratory studies have been useful to explore relative responses to different factors, such as temperature, moisture, and nutrients (e.g., Fang et al., 2005; Fierer and Schimel, 2002; Reichstein et al., 2005), they have substantial artifacts – such as a lack of plants, disrupted soil structure, and fairly constant temperature and moisture – and hence cannot represent the complex interactions occurring in situ that we seek to understand.

Natural gradients can provide insights into the influence of different environmental factors on soil biogeochemistry, but they have their own limitations for global change research. For example, most spatial climate gradients are in quasi-steady state, whereas global change impacts are largely a question of transient responses (conversely, experimental manipulations by themselves are often too short to reveal long-term responses). Often, factors of interest co-vary, making it difficult to isolate mechanisms or quantify response functions. For example, seasonally warmer temperatures often

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co-vary with plant leaf area and root exudation, and heat waves often coincide with drought.

Field manipulation experiments overcome many of the limitations of laboratory and gradient studies. Controlled manipulations allow key variables to be held relatively constant while others are changed, providing methods to test cause-and-effect and isolate direct response functions within real ecosystems. Moreover, anthropogenic activity is creating unprecedented conditions, such as hyper-tropical temperatures (Meehl et al., 2012), that cannot be found in natural gradients. While manipulations involve significant infrastructure and ~~operational costs and efforts~~, they represent an essential approach for understanding soil dynamics.

3 Opportunities for forming a global soil experiment network

Networks of replicated experiments are essential to reveal broad-scale mechanisms underlying ecosystem responses to global change because the response of SOC cycling to global change factors depends on environmental conditions that vary spatially as well as with soil depth (e.g., Sanaullah et al., 2012; Gillabel et al., 2010; Plante et al., 2009; Mellilo et al., 2011). These controls are not well understood, making it difficult to extrapolate results from isolated experiments (Janssens et al., 2010; Davidson and Janssens, 2006). Moreover, long-term soil warming experiments, for example, show transient increases and decreases in soil respiration and SOC stocks over time, attributed to SOC depletion, changes in plant input chemistry, and microbial acclimation (e.g., Hartley et al., 2007; Bradford et al., 2008; Saleska et al., 2002; Frey et al., 2013). In general, it is difficult to extrapolate results from one experiment to other locations, and from short- to long-term responses, without much greater understanding of how ecosystem properties shape the responses.

Soil experiments have been conducted in various ecosystems, and some have been coordinated in networks (Table 1). Nevertheless, meta-analyses of the environmental factors influencing the response of SOC storage and turnover have been hampered

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by differences in treatments. For example, sites differ in the soil depths manipulated, magnitude of manipulation (even with consistent treatment design, the magnitude of manipulation can be site-dependent), manipulation duration, co-variables manipulated, and measurements made (Bai et al., 2013). Thus, enhanced support for coordination at the initiation of experiments would be beneficial.

There is a need to integrate experiments in different places to achieve more global coverage for the study of soil responses to global change, such as warming and altered precipitation, extreme climate events, elevated tropospheric ozone concentration, and nitrogen deposition. The integration of manipulation studies would create new research opportunities to study whole-soil responses – opportunities that would be amplified by effective exchange of data and expertise. Moreover, the implementation of a network of coordinated experimental facilities would allow the productive sharing of knowledge as well as skills in service of maintaining complex experiments.

Hence, global change research calls for an international network of coordinated ecosystem experiments representing the most important soil regions of the world, spanning a range of soil types, climate, and vegetation zones (Fraser et al., 2013). As much as possible, these should include global change experiments arrayed along environmental or land-use gradients to disentangle effects of the various factors affecting responses in real-world ecosystems.

4 The benefits of a global network of soil manipulation experiments

A network of relatively standardized and integrated manipulation experiments would have benefits for multi-site synthesis activities, model development and testing, generating generalizable knowledge, and education and mentoring. Once sites are established that provide the desired commonalities and contrasts, and operating in a consistent manner, the comparability of measurements and treatments would accelerate our understanding far beyond the current state-of-the-art. This is currently not the case in ad hoc networks. An example is found in the lack of standardization of soil mois-

ture measurements, which was recently reported to hamper a synthesis of ecosystem drought manipulation experiments (Vicca et al., 2012). Comparability of manipulation infrastructure, treatment levels, and measurements would make samples and results readily comparable. Syntheses of more standardized experiments would enable strong tests of Earth System models, and more precise knowledge of how key processes and parameters vary globally.

Collaboration among the network's PIs may also provide financial and intellectual bonuses. For example, if only one group could produce isotopically labeled litter or conduct a high cost or specialized analysis for the entire network, each team could focus their resources to make unique contributions. In addition, the learning experience from existing sites reduces the risks involved in starting up a new site. Science teams can take advantage of support for high level networking (e.g., EU COST and U.S. NSF RCN programs), transnational access (e.g., INTERACT), and shared education (e.g., GREENCYCLES, and PIRE). Thus, a well-established network may enhance funding opportunities, through recognition, leverage, and risk-sharing.

Having closely related experiments also allows students and staff trained at one site to transfer their knowledge to new staff at other experiments. This not only provides a pool of expertise that is less volatile than that of single-site experiments, but also allows easier transfer of capabilities to less-developed institutions or countries. Wonderful opportunities for students arise when they have access to multiple sites and facilities because they can interact with multiple PIs and be trained by different groups within the network who excel in different aspects of the network's research. One of the most important outcomes is that the multi-disciplinary nature of the network is likely to train a new generation of students that can integrate knowledge at a much higher level than currently possible.

Well-designed networks are also invaluable to outside collaborators who give added value to the network by conducting novel measurements, testing new methods, and promoting evolution of the network to new and ever-relevant applications.

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5 Site selection for an international network of soil manipulation experiments

Site selection is a critical step in developing a network focused on determining SOC dynamics throughout the soil profile. The history, chemical characterization, and setting (climatic, hydrological and geological) of sites have to be considered within the framework of the questions the experiments are designed to address. Criteria must be established to define the context and the contrasts desired for experiments, for example how sites differ in soil structure, chemistry, macroelements like C, N, and P, as well as biologically important trace elements. In addition, a set of selected soil profiles, that are representative of important soil types, well-characterized, and span environmental gradients should be established to serve as benchmarks.

Certain land uses or areas of the globe may be high priority, depending on the soil ecosystem services in question. Peatland and permafrost ecosystems contain large carbon stocks that are potentially very vulnerable to global change; arable land is the logical focus for food security research.

Field experiments become even more effective if they can be nested within environmental gradients (Jenny, 1941), to allow interaction among factors, space-for-factor substitution, and analysis at different timescales of response.

Soil experiment networks could take advantage of existing observational networks and experimental facilities to find locations with good site characterization, infrastructure, and access to resources. Examples of international field networks having a range of land management and cover, long-term support, and mandates compatible with hosting global change manipulations include: the European infrastructure for analysis and experimentation on ecosystems (AnaEE www.anaee.com/); Critical Zone Observatories, the Long-Term Ecological Research network; and experiments listed in Table 1. Field experiments could be linked to facilities like ecotrons and lysimeters (e.g., www.ecotron.cnrs.fr/index.php/en/) for more control over precipitation-inputs, soil moisture, and air temperature. We also urge taking advantage of opportunities for whole ecosystem experiments (Fig. 2).

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Manipulative experiments have fairly substantial logistical and infrastructure requirements, such as requiring line power for soil warming, that will also drive site selection. Thus, in practice, a balance will be struck between selecting sites that leverage existing facilities, that create clean environmental gradients, and that are conducive for obtaining funding.

6 Critical ingredients for network success

Cooperation, transparency, collaboration, and support are the basic elements of a successful network. The concept of the network needs to be well defined but not prescriptive, in other words, goals should be well defined but flexible enough to respond effectively to technological advances and shifting scientific issues and questions. For networks to have their greatest impact, we recommend:

- Shared data: open data access with fair data use policies.
- Shared opportunities: building trust and collaboration among partners, such as early invitations to collaborate and to contribute to student advising in the network.
- Shared research: scientists working across sites from the very beginning, such as post-docs supported to lay the ground work for synthesis before and as data are generated.
- Shared successes: every network team needs early success, the more established groups can mentor less experienced groups.
- Shared resources and facilities: engineering designs, protocols, databases, analytical facilities, technical coordination, and protocols for meta-analyses.

Networks need multidisciplinary research teams, consisting of scientists as well as engineers, technicians, and data managers. The complex interactions among ecosys-

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tem components require the involvement of researchers from many different disciplines. Modeling is important within the network for planning, experimental design, and data management. Modeling conducted before the experiments are implemented can evaluate and improve the sensitivity of the experiments to detect ecosystem changes, including changes in replication and duration (Luo et al., 2011). Furthermore, model predictions can generate hypotheses to be tested by the network experiments and hence identify needed measurements. Network observations and findings should lead to improvements in model structure and parameters.

Technical support is critical to achieving the high scientific potential of an experimental network, to attend to the design, building, day-to-day operation, and maintenance of experiments. A network coordinator ensures that network projects use resources efficiently, avoid duplication of efforts yet make the essential measurements, and share data and information. Funding for resources that would be shared internationally, like coordination and database management, can be difficult to sustain but is essential for long-term success.

7 The international soil experiment network for deep soil warming

As one example of how such a network might operate: we are establishing a new network of soil experiments called iSEN (international Soil Experiment Network; (Fig. 1), guided by the question: what are the effects of global warming on whole soil profile ecosystem services? The structure of iSEN is similar to a franchised business. The network develops the framework of core measurements and manipulations, provides the “recipes” – the protocols for experimental manipulations, basic measurements, and data formats – and the structure for shared resources such as databases. The principle investigator (PI) for each site obtains their own funding and may add experimental manipulations and measurements onto the core framework. The proposed network will define a minimum standard for the protocols and treatments needed to qualify to participate in the network, while allowing individual sites to add treatments reflecting their

context. A key benefit of the network is that the data will be comparable across sites, allowing for robust synthesis and meta-analysis.

Currently, the proposed core manipulations are warming and addition of $^{13}\text{C} / ^{15}\text{N}$ labeled litter with optional water and nitrogen manipulations. Another feature that sets this network apart from other soil experiments (or networks) is that measurements and manipulations will not be limited to only surface soil; our goal is to study responses across the entire soil profile or at least to 1 m. The initial focus is on SOC cycling, but many teams will also examine nutrient dynamics, and other questions related to ecosystem services that soils provide. As a network of independent PI's, we envision the network will evolve in membership, protocols, experimental manipulations, and priorities, shaped by new environmental problems and new opportunities.

We envision a network of global scale. Applying the same experimental setup and analytical protocols to various sites will allow identification of general patterns in the response of SOC storage and turnover to soil warming and definition of controlling environmental and soil variables. These response functions will facilitate upscaling of experimental and observational results to larger spatial scales. Improvement in mechanistic understanding of soil processes will be used to improve local soil-profile and Earth System models.

8 Conclusions

Fluxes of soil carbon to the atmosphere occur globally but are the product of locally controlled processes, and are thus governed by different mechanisms in different ecosystems, with different histories and local conditions. No single super-site, or gradient, can give us the generalizable knowledge that global prediction requires. Instead, networks of experimental manipulations that investigate the whole soil profile, nested in natural environmental gradients, provide the most promising approach to studying global change effects on soil ecosystem services. There are numerous opportunities to leverage existing observational networks to create such gradients.

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In general, networks should be based on coordinated long-term experiments, process studies within these experiments, and modeling to underpin and extrapolate results from the experiments. The resulting reduced uncertainty regarding the role of soils as positive or negative feedbacks to global change will improve future climate projections. Finally, with the knowledge gained from such a global network, science-based mitigation strategies, as well as solutions for current and future ecological and agricultural challenges, could be developed and tested at the network's experimental facilities. As such, soil networks like those proposed here have a unique and important role in advancing soil science for global challenges.

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Table 1. Soil experiment networks. These are some of the existing soil experiment networks. Most manipulate the litter layer and topsoil, except the iSEN which is focused on the whole soil profile.

Network	Description	Years active	Reference, URL
LIDET	Long-term Inter-site Decomposition Experiment Team: effect of substrate quality and macroclimate on litter decomposition and nutrient dynamics	1990–2000	Parton et al. (2007) http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm
DIRT	Detritus Input and Removal Treatments: impact of rates and sources of plant inputs on the accumulation and dynamics of SOM and nutrients in forest soils	1990–present	Nadelhoffer et al. (2006) http://dirt.oregonstate.edu
ITEX	International Tundra Experiment: impact of warming (air and surface soil) on tundra ecosystems	1992–present	Elmendorf et al. (2012) http://ibis.geog.ubc.ca/itex/
LTSE	Long-Term Soil Experiments: management control over soil carbon and nutrient cycling	2004–present	Richter et al. (2007) http://nicholas.duke.edu/ltse/
SOERE-ACBB	Systems of Observation and Experimentation in Environmental Research in Agroecosystems, Biochemical cycles and Biodiversity. Long term field experiments.	2005–present	Klump et al. (2011); Senapati et al. (2014) http://www.soere-acbb.com/
NutNet	Nutrient Network: impact of nutrients and herbivores on grassland diversity and productivity	2006–present	Borer et al. (2014) http://nutnet.umn.edu/
INTERFACE	An Integrated Network for Terrestrial Ecosystem Research on Feedbacks to the Atmosphere and Climate: Linking experimentalists, ecosystem modelers, and Earth system modelers.	2010–present	https://www.bio.purdue.edu/INTERFACE/
RhizoNet	Linking roots, the rhizosphere and soil science with aboveground ecosystem ecology: A network of sites monitoring rhizosphere processes.	2013–present	http://www.rhizonetscience.com/
Drought-Net	A global network to assess terrestrial ecosystem response to drought: International Drought Experiment	2014–present	http://wp.natsci.colostate.edu/droughtnet/
iSEN	International Soil Experiment Network: Deep soil warming and addition of isotopically labeled litter in soil profile.	2014–present	http://soilexperimentnetwork.org

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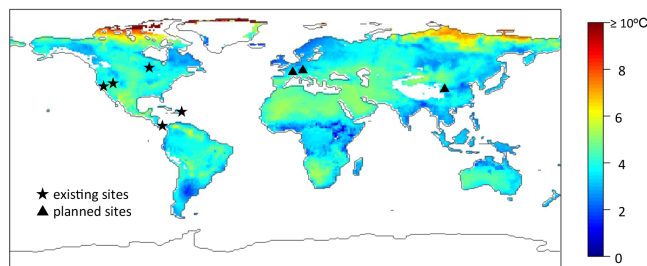


Figure 1. Predicted soil warming and the locations of existing and planned sites in the International Soil Experiment Network (iSEN). Warming is the mean 2080–2100 temperature relative to a 1986–2005 baseline, at 0.01 m soil depth, based on CESM RCP 8.5 (Meehl et al., 2012; map of soil warming from Phillips and Torn, in preparation). The symbols indicate iSEN sites that are operational, under construction, or in the planning phase. Any team that is prepared to follow the network principles is invited to join the Network. Existing sites (operational, under construction) (1) US SPRUCE (boreal peatland, Histosol), 47°30' N, 93°29' W (see Fig. 2). (2) US Hopland (annual grassland, Mollisol), 39°00' N, 123°04' W. (3) US Blodgett (coniferous forest, Alfisol), 38°53' N, 120°38' W. (4) Puerto Rico (tropical forest, Ultisol), 18°18' N, 65°50' W. (5) Panama (tropical forest, Soil order has not been determined), 9°09' N, 79°51' W. Planned sites: (6) Switzerland Lägeren (temperate broadleaf forest, Cambisol), 47°29' N, 8°22' E. (7) France Lusignan (grassland and cropland, Cambisol), 46°25' N, 0°07' E. (8) China Haibei (alpine grassland, Cambisol), 37°30' N, 101°12' E.

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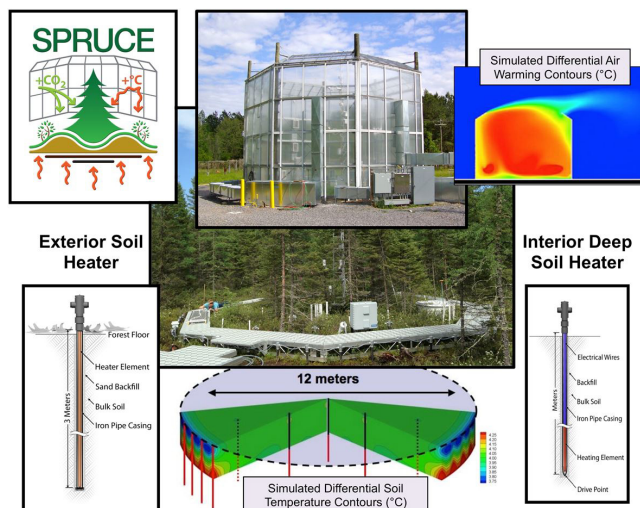


Figure 2. The experiment on Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) is designed to expose a boreal forest to whole-ecosystem warming including deep soil warming combined with elevated CO_2 exposure (<http://mnspruce.ornl.gov>). A warmed air space above active deep-soil warming maintain temperature differentials from ambient conditions while retaining annual, seasonal, and diurnal variations. The presence of enclosure walls for air warming makes warming the vertical air space affordable. Elevated CO_2 can be added to this enclosed air space to achieve a two-way experimental treatment.

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A call for international soil experiment networks for studying, predicting, and managing global change impacts

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1 Introduction

The soil profile encompasses a remarkably large range of biogeochemical conditions, processes, and fluxes. For example, in most soils the turnover time of soil organic carbon (SOC) varies more between the soil surface and 1 m deep than between surface soils in the tropics versus the Arctic. Radiocarbon observations in different soil types show that SOC decomposition rates decrease with depth, with residence times of years-to-decades at the soil surface to over 10 000 years at 1 m deep (e.g., Torn et al., 2002). There are many competing hypotheses for this steep decline in SOC turnover with depth. They can be grouped loosely into physical-chemical accessibility, energetic limits to microbial activity, microclimate and pH, and physical disconnect between decomposers and substrate. While all of these mechanisms control deep SOC cycling, data are lacking to unravel their relative importance in different soils under different environmental conditions. This is, however, critical knowledge for predicting soil responses to global change, because fairly rapid loss (or gain) of old and/or deep SOC stocks is possible and more than 80 % of the world's SOC is found below 20 cm depth (Jobbagg and Jackson, 2000). Currently, the soil modules within Earth System Models are parameterized for surface soil and lack mechanisms important for stabilization and losses of deep SOC. Hence, we suggest that a critical challenge is to achieve process-level understanding at the global level and the ability to predict whether, and how, the large stores of deep, old SOC are stabilized and lost under global change scenarios.

As historical pressures and dependence on soils for food and fuel production continue, the coming century brings new, global changes as well. Two of the most widespread impacts of anthropogenic activities on soils in this century will be warmer temperatures (Fig. 1) and altered plant allocation belowground due to elevated atmospheric CO₂ concentrations (Luo et al., 2006) and deposition of reactive nitrogen (Janssens et al., 2010). The resulting effects on SOC cycling are less certain: warming may increase microbial activity and therefore accelerate SOC turnover (Davidson and Janssens 2006; Conant et al., 2011), while more plant allocation belowground may

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increase stocks due to additional inputs or decrease stocks through priming effects (Kuz'yakov, 2010; Cheng et al., 2014). Climate-change impacts will be compounded with growing levels of nitrogen deposition, ozone pollution, and land use and land cover change. Societal reliance on soil ecosystem services, and the threat of large positive climate feedbacks, demands that we understand surface and deep soil responses to global change and how to enhance the resilience of soil systems across the whole soil profile.

2 The need for deep soil manipulation experiments

To achieve generalizable understanding of soil response to global change, and to test management solutions in real-world conditions, we need controlled experiments that are carried out in situ, consider the whole soil profile, and are at locations spanning a range of conditions.

Field manipulation experiments fill a critical niche as complements to natural gradient studies and laboratory incubations. While laboratory studies have been useful to explore relative responses to different factors, such as temperature, moisture, and nutrients (e.g., Fang et al., 2005; Fierer and Schimel, 2002; Reichstein et al., 2005), they have substantial artifacts – such as a lack of plants, disrupted soil structure, and fairly constant temperature and moisture – and hence cannot represent the complex interactions occurring in situ that we seek to understand.

Natural gradients can provide insights into the influence of different environmental factors on soil biogeochemistry, but they have their own limitations for global change research. For example, most spatial climate gradients are in quasi-steady state, whereas global change impacts are largely a question of transient responses (conversely, experimental manipulations by themselves are often too short to reveal long-term responses). Often, factors of interest co-vary, making it difficult to isolate mechanisms or quantify response functions. For example, seasonally warmer temperatures often

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co-vary with plant leaf area and root exudation, and heat waves often coincide with drought.

Field manipulation experiments overcome many of the limitations of laboratory and gradient studies. Controlled manipulations allow key variables to be held relatively constant while others are changed, providing methods to test cause-and-effect and isolate direct response functions within real ecosystems. Moreover, anthropogenic activity is creating unprecedented conditions, such as hyper-tropical temperatures (Meehl et al., 2012), that cannot be found in natural gradients. While manipulations involve significant infrastructure and ~~operational costs and efforts~~, they represent an essential approach for understanding soil dynamics.

3 Opportunities for forming a global soil experiment network

Networks of replicated experiments are essential to reveal broad-scale mechanisms underlying ecosystem responses to global change because the response of SOC cycling to global change factors depends on environmental conditions that vary spatially as well as with soil depth (e.g., Sanaullah et al., 2012; Gillabel et al., 2010; Plante et al., 2009; Mellilo et al., 2011). These controls are not well understood, making it difficult to extrapolate results from isolated experiments (Janssens et al., 2010; Davidson and Janssens, 2006). Moreover, long-term soil warming experiments, for example, show transient increases and decreases in soil respiration and SOC stocks over time, attributed to SOC depletion, changes in plant input chemistry, and microbial acclimation (e.g., Hartley et al., 2007; Bradford et al., 2008; Saleska et al., 2002; Frey et al., 2013). In general, it is difficult to extrapolate results from one experiment to other locations, and from short- to long-term responses, without much greater understanding of how ecosystem properties shape the responses.

Soil experiments have been conducted in various ecosystems, and some have been coordinated in networks (Table 1). Nevertheless, meta-analyses of the environmental factors influencing the response of SOC storage and turnover have been hampered

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by differences in treatments. For example, sites differ in the soil depths manipulated, magnitude of manipulation (even with consistent treatment design, the magnitude of manipulation can be site-dependent), manipulation duration, co-variables manipulated, and measurements made (Bai et al., 2013). Thus, enhanced support for coordination at the initiation of experiments would be beneficial.

There is a need to integrate experiments in different places to achieve more global coverage for the study of soil responses to global change, such as warming and altered precipitation, extreme climate events, elevated tropospheric ozone concentration, and nitrogen deposition. The integration of manipulation studies would create new research opportunities to study whole-soil responses – opportunities that would be amplified by effective exchange of data and expertise. Moreover, the implementation of a network of coordinated experimental facilities would allow the productive sharing of knowledge as well as skills in service of maintaining complex experiments.

Hence, global change research calls for an international network of coordinated ecosystem experiments representing the most important soil regions of the world, spanning a range of soil types, climate, and vegetation zones (Fraser et al., 2013). As much as possible, these should include global change experiments arrayed along environmental or land-use gradients to disentangle effects of the various factors affecting responses in real-world ecosystems.

4 The benefits of a global network of soil manipulation experiments

A network of relatively standardized and integrated manipulation experiments would have benefits for multi-site synthesis activities, model development and testing, generating generalizable knowledge, and education and mentoring. Once sites are established that provide the desired commonalities and contrasts, and operating in a consistent manner, the comparability of measurements and treatments would accelerate our understanding far beyond the current state-of-the-art. This is currently not the case in ad hoc networks. An example is found in the lack of standardization of soil mois-

ture measurements, which was recently reported to hamper a synthesis of ecosystem drought manipulation experiments (Vicca et al., 2012). Comparability of manipulation infrastructure, treatment levels, and measurements would make samples and results readily comparable. Syntheses of more standardized experiments would enable strong tests of Earth System models, and more precise knowledge of how key processes and parameters vary globally.

Collaboration among the network's PIs may also provide financial and intellectual bonuses. For example, if only one group could produce isotopically labeled litter or conduct a high cost or specialized analysis for the entire network, each team could focus their resources to make unique contributions. In addition, the learning experience from existing sites reduces the risks involved in starting up a new site. Science teams can take advantage of support for high level networking (e.g., EU COST and U.S. NSF RCN programs), transnational access (e.g., INTERACT), and shared education (e.g., GREENCYCLES, and PIRE). Thus, a well-established network may enhance funding opportunities, through recognition, leverage, and risk-sharing.

Having closely related experiments also allows students and staff trained at one site to transfer their knowledge to new staff at other experiments. This not only provides a pool of expertise that is less volatile than that of single-site experiments, but also allows easier transfer of capabilities to less-developed institutions or countries. Wonderful opportunities for students arise when they have access to multiple sites and facilities because they can interact with multiple PIs and be trained by different groups within the network who excel in different aspects of the network's research. One of the most important outcomes is that the multi-disciplinary nature of the network is likely to train a new generation of students that can integrate knowledge at a much higher level than currently possible.

Well-designed networks are also invaluable to outside collaborators who give added value to the network by conducting novel measurements, testing new methods, and promoting evolution of the network to new and ever-relevant applications.

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5 Site selection for an international network of soil manipulation experiments

Site selection is a critical step in developing a network focused on determining SOC dynamics throughout the soil profile. The history, chemical characterization, and setting (climatic, hydrological and geological) of sites have to be considered within the framework of the questions the experiments are designed to address. Criteria must be established to define the context and the contrasts desired for experiments, for example how sites differ in soil structure, chemistry, macroelements like C, N, and P, as well as biologically important trace elements. In addition, a set of selected soil profiles, that are representative of important soil types, well-characterized, and span environmental gradients should be established to serve as benchmarks.

Certain land uses or areas of the globe may be high priority, depending on the soil ecosystem services in question. Peatland and permafrost ecosystems contain large carbon stocks that are potentially very vulnerable to global change; arable land is the logical focus for food security research.

Field experiments become even more effective if they can be nested within environmental gradients (Jenny, 1941), to allow interaction among factors, space-for-factor substitution, and analysis at different timescales of response.

Soil experiment networks could take advantage of existing observational networks and experimental facilities to find locations with good site characterization, infrastructure, and access to resources. Examples of international field networks having a range of land management and cover, long-term support, and mandates compatible with hosting global change manipulations include: the European infrastructure for analysis and experimentation on ecosystems (AnaEE www.anaee.com/); Critical Zone Observatories, the Long-Term Ecological Research network; and experiments listed in Table 1. Field experiments could be linked to facilities like ecotrons and lysimeters (e.g., www.ecotron.cnrs.fr/index.php/en/) for more control over precipitation-inputs, soil moisture, and air temperature. We also urge taking advantage of opportunities for whole ecosystem experiments (Fig. 2).

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Manipulative experiments have fairly substantial logistical and infrastructure requirements, such as requiring line power for soil warming, that will also drive site selection. Thus, in practice, a balance will be struck between selecting sites that leverage existing facilities, that create clean environmental gradients, and that are conducive for obtaining funding.

6 Critical ingredients for network success

Cooperation, transparency, collaboration, and support are the basic elements of a successful network. The concept of the network needs to be well defined but not prescriptive, in other words, goals should be well defined but flexible enough to respond effectively to technological advances and shifting scientific issues and questions. For networks to have their greatest impact, we recommend:

- Shared data: open data access with fair data use policies.
- Shared opportunities: building trust and collaboration among partners, such as early invitations to collaborate and to contribute to student advising in the network.
- Shared research: scientists working across sites from the very beginning, such as post-docs supported to lay the ground work for synthesis before and as data are generated.
- Shared successes: every network team needs early success, the more established groups can mentor less experienced groups.
- Shared resources and facilities: engineering designs, protocols, databases, analytical facilities, technical coordination, and protocols for meta-analyses.

Networks need multidisciplinary research teams, consisting of scientists as well as engineers, technicians, and data managers. The complex interactions among ecosys-

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tem components require the involvement of researchers from many different disciplines. Modeling is important within the network for planning, experimental design, and data management. Modeling conducted before the experiments are implemented can evaluate and improve the sensitivity of the experiments to detect ecosystem changes, including changes in replication and duration (Luo et al., 2011). Furthermore, model predictions can generate hypotheses to be tested by the network experiments and hence identify needed measurements. Network observations and findings should lead to improvements in model structure and parameters.

Technical support is critical to achieving the high scientific potential of an experimental network, to attend to the design, building, day-to-day operation, and maintenance of experiments. A network coordinator ensures that network projects use resources efficiently, avoid duplication of efforts yet make the essential measurements, and share data and information. Funding for resources that would be shared internationally, like coordination and database management, can be difficult to sustain but is essential for long-term success.

7 The international soil experiment network for deep soil warming

As one example of how such a network might operate: we are establishing a new network of soil experiments called iSEN (international Soil Experiment Network; (Fig. 1), guided by the question: what are the effects of global warming on whole soil profile ecosystem services? The structure of iSEN is similar to a franchised business. The network develops the framework of core measurements and manipulations, provides the “recipes” – the protocols for experimental manipulations, basic measurements, and data formats – and the structure for shared resources such as databases. The principle investigator (PI) for each site obtains their own funding and may add experimental manipulations and measurements onto the core framework. The proposed network will define a minimum standard for the protocols and treatments needed to qualify to participate in the network, while allowing individual sites to add treatments reflecting their

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context. A key benefit of the network is that the data will be comparable across sites, allowing for robust synthesis and meta-analysis.

Currently, the proposed core manipulations are warming and addition of $^{13}\text{C} / ^{15}\text{N}$ labeled litter with optional water and nitrogen manipulations. Another feature that sets this network apart from other soil experiments (or networks) is that measurements and manipulations will not be limited to only surface soil; our goal is to study responses across the entire soil profile or at least to 1 m. The initial focus is on SOC cycling, but many teams will also examine nutrient dynamics, and other questions related to ecosystem services that soils provide. As a network of independent PI's, we envision the network will evolve in membership, protocols, experimental manipulations, and priorities, shaped by new environmental problems and new opportunities.

We envision a network of global scale. Applying the same experimental setup and analytical protocols to various sites will allow identification of general patterns in the response of SOC storage and turnover to soil warming and definition of controlling environmental and soil variables. These response functions will facilitate upscaling of experimental and observational results to larger spatial scales. Improvement in mechanistic understanding of soil processes will be used to improve local soil-profile and Earth System models.

8 Conclusions

Fluxes of soil carbon to the atmosphere occur globally but are the product of locally controlled processes, and are thus governed by different mechanisms in different ecosystems, with different histories and local conditions. No single super-site, or gradient, can give us the generalizable knowledge that global prediction requires. Instead, networks of experimental manipulations that investigate the whole soil profile, nested in natural environmental gradients, provide the most promising approach to studying global change effects on soil ecosystem services. There are numerous opportunities to leverage existing observational networks to create such gradients.

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In general, networks should be based on coordinated long-term experiments, process studies within these experiments, and modeling to underpin and extrapolate results from the experiments. The resulting reduced uncertainty regarding the role of soils as positive or negative feedbacks to global change will improve future climate projections. Finally, with the knowledge gained from such a global network, science-based mitigation strategies, as well as solutions for current and future ecological and agricultural challenges, could be developed and tested at the network's experimental facilities. As such, soil networks like those proposed here have a unique and important role in advancing soil science for global challenges.

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Table 1. Soil experiment networks. These are some of the existing soil experiment networks. Most manipulate the litter layer and topsoil, except the iSEN which is focused on the whole soil profile.

Network	Description	Years active	Reference, URL
LIDET	Long-term Inter-site Decomposition Experiment Team: effect of substrate quality and macroclimate on litter decomposition and nutrient dynamics	1990–2000	Parton et al. (2007) http://andrewsforest.oregonstate.edu/research/intersite/lidet.htm
DIRT	Detritus Input and Removal Treatments: impact of rates and sources of plant inputs on the accumulation and dynamics of SOM and nutrients in forest soils	1990–present	Nadelhoffer et al. (2006) http://dirt.oregonstate.edu
ITEX	International Tundra Experiment: impact of warming (air and surface soil) on tundra ecosystems	1992–present	Elmendorf et al. (2012) http://ibis.geog.ubc.ca/itex/
LTSE	Long-Term Soil Experiments: management control over soil carbon and nutrient cycling	2004–present	Richter et al. (2007) http://nicholas.duke.edu/ltse/
SOERE-ACBB	Systems of Observation and Experimentation in Environmental Research in Agroecosystems, Biochemical cycles and Biodiversity. Long term field experiments.	2005–present	Klump et al. (2011); Senapati et al. (2014) http://www.soere-acbb.com/
NutNet	Nutrient Network: impact of nutrients and herbivores on grassland diversity and productivity	2006–present	Borer et al. (2014) http://nutnet.umn.edu/
INTERFACE	An Integrated Network for Terrestrial Ecosystem Research on Feedbacks to the Atmosphere and Climate: Linking experimentalists, ecosystem modelers, and Earth system modelers.	2010–present	https://www.bio.purdue.edu/INTERFACE/
RhizoNet	Linking roots, the rhizosphere and soil science with aboveground ecosystem ecology: A network of sites monitoring rhizosphere processes.	2013–present	http://www.rhizonetscience.com/
Drought-Net	A global network to assess terrestrial ecosystem response to drought: International Drought Experiment	2014–present	http://wp.natsci.colostate.edu/droughtnet/
iSEN	International Soil Experiment Network: Deep soil warming and addition of isotopically labeled litter in soil profile.	2014–present	http://soilexperimentnetwork.org

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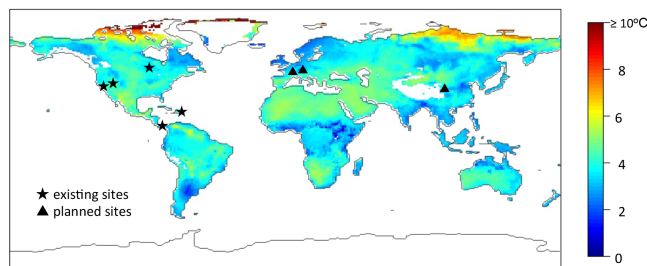


Figure 1. Predicted soil warming and the locations of existing and planned sites in the International Soil Experiment Network (iSEN). Warming is the mean 2080–2100 temperature relative to a 1986–2005 baseline, at 0.01 m soil depth, based on CESM RCP 8.5 (Meehl et al., 2012; map of soil warming from Phillips and Torn, in preparation). The symbols indicate iSEN sites that are operational, under construction, or in the planning phase. Any team that is prepared to follow the network principles is invited to join the Network. Existing sites (operational, under construction) (1) US SPRUCE (boreal peatland, Histosol), 47°30' N, 93°29' W (see Fig. 2). (2) US Hopland (annual grassland, Mollisol), 39°00' N, 123°04' W. (3) US Blodgett (coniferous forest, Alfisol), 38°53' N, 120°38' W. (4) Puerto Rico (tropical forest, Ultisol), 18°18' N, 65°50' W. (5) Panama (tropical forest, Soil order has not been determined), 9°09' N, 79°51' W. Planned sites: (6) Switzerland Lägeren (temperate broadleaf forest, Cambisol), 47°29' N, 8°22' E. (7) France Lusignan (grassland and cropland, Cambisol), 46°25' N, 0°07' E. (8) China Haibei (alpine grassland, Cambisol), 37°30' N, 101°12' E.

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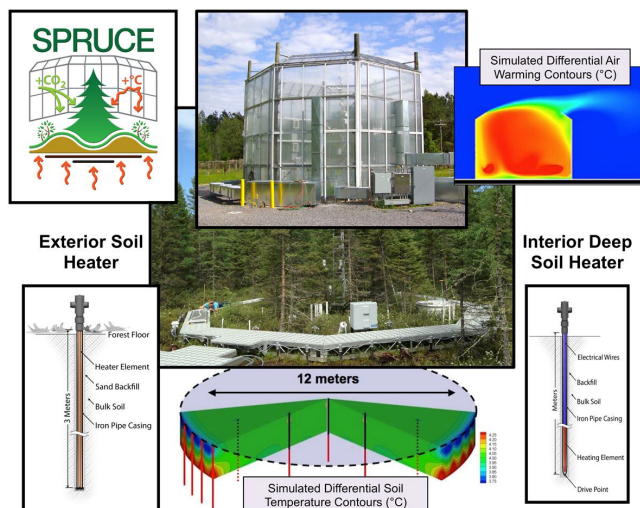


Figure 2. The experiment on Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) is designed to expose a boreal forest to whole-ecosystem warming including deep soil warming combined with elevated CO_2 exposure (<http://mnspruce.ornl.gov>). A warmed air space above active deep-soil warming maintain temperature differentials from ambient conditions while retaining annual, seasonal, and diurnal variations. The presence of enclosure walls for air warming makes warming the vertical air space affordable. Elevated CO_2 can be added to this enclosed air space to achieve a two-way experimental treatment.

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