Empirical estimates to reduce modeling uncertainties of soil organic carbon in permafrost regions: a review of recent progress and remaining challenges

U Mishra, J D Jastrow, R Matamala, G Hugelius, C D Koven, J W Harden, C L Ping, G J Michaelson, Z Fan, R M Miller, A D McGuire, C Tarnocai, P Kuhry, W J Riley, K Schaefer, E A G Schuur, M T Jorgenson, and L D Hinzman

1 Environmental Science Division, Argonne National Laboratory, Argonne, IL 60439, USA
2 Biosciences Division, Argonne National Laboratory, Argonne, IL 60439, USA
3 Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden
4 Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
5 US Geological Survey, 345 Middlefield Road MS 962, Menlo Park, CA 94025, USA
6 Palmer Research Center, School of Natural Resources and Agricultural Sciences, University of Alaska Fairbanks, Palmer, AK 99675, USA
7 US Geological Survey, Alaska Cooperative Fish and Wildlife Research Unit, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
8 Research Branch, Agriculture and Agri-Food Canada, Ottawa, ON, K1A 0C6, Canada
9 National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309, USA
10 Department of Biology, University of Florida, Gainesville, FL 32611, USA
11 Alaska Ecoscience, 2332 Cordes Way, Fairbanks, AK 99709, USA
12 International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775, USA

E-mail: umishra@anl.gov

Received 5 April 2013
Accepted for publication 2 July 2013
Published 18 July 2013
Online at stacks.iop.org/ERL/8/035020

Abstract

The vast amount of organic carbon (OC) stored in soils of the northern circumpolar permafrost region is a potentially vulnerable component of the global carbon cycle. However, estimates of the quantity, decomposability, and combustibility of OC contained in permafrost-region soils remain highly uncertain, thereby limiting our ability to predict the release of greenhouse gases due to permafrost thawing. Substantial differences exist between empirical and modeling estimates of the quantity and distribution of permafrost-region soil OC, which contribute to large uncertainties in predictions of carbon–climate feedbacks under future warming. Here, we identify research challenges that constrain current assessments of the distribution and potential decomposability of soil OC stocks in the northern permafrost region and suggest priorities for future empirical and modeling studies to address these challenges.

Keywords: soil organic carbon, Earth system models, uncertainty, carbon–climate feedbacks, permafrost, cryoturbation

Online supplementary data available from stacks.iop.org/ERL/8/035020/mmedia

1. Introduction

Perennially frozen soils of the northern circumpolar region (19 million km² or 16% of the global soil area; Tarnocai...
et al 2009) store one of the largest reservoirs of organic carbon (OC) in the terrestrial biosphere (1672 Pg). Several unique processes of organic matter accrual—including peat accumulation (Gorham 1991), intermittent burial by windblown and waterborne sediments (Schuur et al 2008), and cryoturbation (Michaelson et al 1996, Bockheim 2007)—coupled with the low temperatures of the high latitudes have sequestered OC in circumpolar soils for millennia. Cryoturbation is a process that dominates soil genesis in northern circumpolar regions, and it results in the displacement and mixing of soil materials due to frost churning (Washburn 1980), and differential frost heaving actions (Van Vliet-Lanoë 1991). Thus, the amounts of OC contained in permafrost-region soils cannot be predicted by the carbon dynamics expected from current rates of primary production and organic matter turnover in the region. Anticipated changes in climate are likely to cause widespread permafrost thaw, leading to mineralization of this previously frozen carbon (Schuur and Abbott 2011). As a consequence, potentially large releases of greenhouse gases (GHGs) could cause a positive feedback to global climate change, resulting in further warming (Zhuang et al 2006, Koven et al 2011, Schaefer et al 2011, Burke et al 2012, MacDougall et al 2012, Schneider von Deimling et al 2012). At present, a potential discrepancy exists between observation-based estimates of soil OC (SOC) stocks in the circumpolar permafrost region and the baseline SOC stock estimates simulated by Earth system models (ESMs) to enable predictions of future carbon–climate feedbacks (figure 1). These inconsistencies are primarily due to differing environmental controls of SOC considered both in observations and ESMs (Todd-Brown et al 2013). Recent assessments using ESMs predict very large ranges in SOC losses from permafrost (17–508 Pg C by 2100) under higher end GHGs emission scenarios (Special Report on Emissions Scenarios A2 climate change scenario and representative concentration pathway 8.5), which demonstrates the large uncertainty for current predictions of carbon–climate feedbacks from climate warming in permafrost regions (Zhuang et al 2006, Koven et al 2011, Burke et al 2012, MacDougall et al 2012). Projections of permafrost degradation, and associated estimates of the permafrost carbon feedback, vary widely due to differences in how models represent the effects of soil organic matter and snow on surface thermal conductivity (Koven et al 2013). The median of available estimates (11 model ensemble) of cumulative emissions by 2100 from thawing permafrost is 100 Pg C (Schaefer et al 2012). Based on the standard deviation of the model ensemble, the uncertainty range is 56% or ±53 Pg C. Major sources of uncertainties in above estimates include; unknown quantity of permafrost carbon, mobility of dissolved organic matter into lakes and oceans, potential enhanced peat growth, and the development of thermokarst features (Camill et al 2001, Schaefer et al 2012, Koven et al 2013). A sensitivity analysis has revealed that after the climate model scenario itself, the second greatest source of this uncertainty was the distribution of SOC stocks (Burke et al 2012), which highlights the critical need for resolving the differences illustrated in figure 1.

Although recent efforts have greatly improved estimates of the quantity, decomposability, combustibility, and distribution of permafrost-region SOC stocks (e.g., Zimov et al 2006, Ping et al 2008a, 2010, Schuur et al 2008, McGuire et al 2009, Tarnocai et al 2009, Harden et al 2012, Hugelius et al 2012), these estimates are still poorly constrained because of logistical difficulties limiting widespread sampling efforts in this remote environment (Schuur et al 2009, Kuhry et al 2010). Consequently, these empirical estimates are still large sources of uncertainty in efforts to predict and validate carbon–climate feedbacks (e.g., Schaefer et al 2011, Koven et al 2011, Burke et al 2012, Schneider von Deimling et al 2012). Thus, improved fine-resolution, three-dimensional observational estimates of
the distributions of permafrost-region SOC stocks and their potential decomposability would be important resources for development and testing of ESMs. In this study, we identify and synthesize several research challenges for improving empirical estimates of permafrost-region SOC stocks and, where possible, suggest pathways or recommendations for effectively addressing them.

2. Improving the number and robustness of observations

Advances in the understanding of circumpolar region SOC stocks have come through the efforts of a large number of scientists and international collaborations. For example, the Northern Circumpolar Soil Carbon Database (NCSCD), developed as a collaborative effort by scientists from Canada, the United States, Russia, and Europe, holds data for 1778 pedons or profiles (the basic soil unit used for the classification and sampling of soils) containing information on soil C content across the entire permafrost region (Tarnocai et al. 2009, Hugelius et al. 2013). Yet the amount of data is small relative to temperate or other regions of the world primarily due to logistical difficulties, extreme working conditions, and the cost involved with accessing remote areas. The soils in permafrost regions are undersampled, both spatially and vertically, especially below the active layer (Ping et al. 2008a, 2010, Kuhry et al. 2010, Johnson et al. 2011). Existing databases vary considerably in terms of sampling depth and protocols, analytical methods, and the overall reliability of the data (Hugelius and Kuhry 2009, Hugelius et al. 2013). Therefore, significant risks for biased conclusions exist due to inadequate and uneven distributions of SOC profile observations in permafrost regions. The samples were taken at varying depth intervals, and, in some cases, without regard to genetic soil horizons. For instance, the depth of soil samples ranges from 10 to 300 cm in the Alaska soil characterization database (NSSL 2010), even though deeper soil carbon stores are known to exist due to the preservation of ancient organic deposits (Tarnocai et al. 2009). Importantly, spatial distributions are unbalanced, leaving vast, often remote, areas of the region completely unrepresented in existing databases (e.g., NSSL 2010).

A recent compilation of pedons with data available at depths >100 cm (figure 2) demonstrates the scarcity of data available to accurately describe SOC stocks stored below a depth of 1 m. Similarly, very few observations exist from deeper alluvial deposits and ice-rich Pleistocene (yedoma) deposits that store immense amounts of SOC in portions of the Arctic landscape (Tarnocai et al. 2009). Without samples that adequately represent these areas, many uncertainties in deep C stocks and their distribution will remain.

The NCSCD has quantified SOC stocks to 3 m depths for the northern circumpolar permafrost region; see Hugelius et al. (2013) for a full technical description. This database links digitized regional soil maps to mean SOC stock values derived from 1778 pedons. The permafrost regions of Alaska and Canada are represented by 131 and 1038 pedons, respectively, but the database contains only 609 pedons from the Eurasian permafrost region, all in Russia. For the Eurasian sector, additional data from Batjes (1996) were used for those soil orders that were not represented in the available pedon database. Using the NCSCD, Tarnocai et al. (2009) estimated SOC stocks for the upper 100 cm of the entire northern circumpolar permafrost region with an average data density of one sample per ∼10500 km² (1778 pedons for a 181000 km² land area). Even with comparatively higher sample densities available for Alaska (one sample per ∼2500 km²), Mishra and Riley (2012) found that the overall density and uneven distribution of available samples were insufficient to fully characterize SOC dependence on climate, edaphic factors, and land cover types. Johnson et al. (2011) also reported the need for additional observations from permafrost horizons and wetlands of Alaska and recommended increased sampling along longitudinal gradients that might be more representative of climate regimes in Alaska.

Future sampling activity should capture the spatial variability of environmental soil-forming factors (i.e., climate, vegetation, topographic relief, parent material, and age of soils) at scales needed to facilitate geospatial extrapolations across large expanses of remote landscapes. In addition to these factors, the cryogenic processes such as differential frost heaving that result in patterned ground and cryoturbated soils (high- and low-centered polygons, frost boils, hummocks, pingos, etc) are an integral part of northern permafrost regions (Michaelson et al. 1996, Bockheim and Tarnocai 1998, Vandenberghe 1988, Bockheim 2007, Ping et al. 2008b, 2013, Tarnocai and Bockheim 2011). Using the NCSCD database, we approximated 19% of the soil area (3.6 million km²) to be cryoturbated. The impact of these features on the heterogeneity of SOC stocks needs to be considered when upscaling to regional scale databases. Future sampling efforts targeted at reducing the variability and error propagations associated with the heterogeneity created by these cryogenic processes could help to reduce the uncertainties associated
with regional carbon accounting (Hugelius 2012). Moreover, additional samples are needed below a depth of 1 m, especially from areas with deep carbon stocks (such as yedoma and deltaic deposits). Future sampling efforts should seek to capture the variability in topographic features (both macro- and microtopography), age of soils, land cover types (e.g., wetlands, forest, and tundra), and fire history, to enhance upscaling efforts.

Although many studies demonstrate the value of detailed ancillary information for optimization of soil sampling (Minasny and McBratney 2006, Simbahan and Dobermann 2006), for large parts of the northern circumpolar permafrost region such detailed information is not available. Therefore, additional replicates that are critical for reliable estimates of SOC in permafrost terrain should be taken following a recommended work order and sampling protocol: (1) identification of geographic regions that are currently undersampled, with special regard to regional-scale factors such as bioclimatic zones or gradients and landscape age (including late quaternary glaciation history); (2) consideration and evaluation of the uncertainties associated with existing data for a particular region (Hugelius 2012); (3) implementation of stratified random sampling approaches that account for relevant combinations of local-scale soil-forming factors such as parent material, topographic relief, cryogenic processes, land cover or soil chronosequences (Hugelius et al 2011); (4) collection of soil samples in the context of the depth distributions of genetic horizons throughout the entire soil profile; and (5) measurement of organic and inorganic carbon and nitrogen concentrations, bulk density, coarse fragments, and ice content on specific soil horizons. Ideally, pedons should be described and sampled following suggested sampling protocols (Ping et al 2013), but in those cases where logistical constraints or lack of cryo-pedological expertise hampers exhaustive sampling and description of pedons, sampling should be carried out by following the general guidelines laid out in field sampling forms presented in the supplementary material (available at stacks.iop.org/ERL/8/035020/mmedia).

3. Predicting spatial and vertical distributions of SOC stocks

Frequently used global estimates of SOC stocks (Post et al 1982, Batjes 1996, Jobbagy and Jackson 2000) have been shown to substantially underestimate northern circumpolar SOC stocks (Ping et al 2008a, Tarnocai et al 2009). Earlier global estimates were limited to the upper 1 m of the soil profile and/or generally assumed SOC depth distributions comparable to those of more temperate regions and reflective of existing vegetation. These studies did not account for the considerable amount of carbon stored at depth due to cryoturbation and buried frozen deposits that developed in unglaciated areas of North America and Eurasia during the late Pleistocene (Höfe and Ping 1996, Tarnocai et al 2009, Schirrmieister et al 2011). Focusing specifically on the northern circumpolar permafrost region, Tarnocai et al (2009) estimated that the soils of this region store 1672 Pg of carbon—an amount more than twice the carbon in the atmosphere and comparable to accepted global estimates for the surface meter of soils (Post et al 1982, Batjes 1996, Jobbagy and Jackson 2000). Yet this and other recent estimates of carbon stocks in permafrost-region soils (Ping et al 2008a, 2010, Bliss and Maursetter 2010, Johnson et al 2011) were made by stratifying the study area (by using soil mapping units, ecoregions, or landscape units), averaging point observations of SOC stocks within each stratum, and multiplying by the areal extent of that stratum. Outside of permafrost areas, this approach has been associated with high estimation errors because the SOC estimates generated by this approach may not represent the soil and environmental heterogeneity that exists within the considered strata (Meersmans et al 2008, Sanchez et al 2009).

To address these concerns McBratney et al (2003), proposed a framework for predicting the spatial distribution of soil classes or specific soil attributes by using spatially referenced soil-forming factors (Jenny 1941) or ‘scorpan’ factors (other soil properties, climate, organisms, relief, parent material, age, and spatial coordinates) and spatially autocorrelated residuals. Several subsequent studies have demonstrated that this approach can produce more accurate representations of spatial variability of soil properties and reduce prediction errors (Rasmussen 2006, Meersmans et al 2008). In permafrost regions, the capability to more accurately represent natural variability is a critical issue, particularly for soils with cryogenic features, including uneven, interrupted, and cryoturbated soil horizons. Mishra and Riley (2012) used a geographically weighted regression approach to predict the spatial and vertical distributions of SOC in Alaska. Though this study reported associated prediction errors, the extent to which the impact of complex cryogenic processes on SOC storage can be accurately described using geospatial approaches remains unknown, particularly for areas with low data availability. Upscaling approaches specific to permafrost regions are needed to more reliably account for the spatial variation of environmental factors and cryogenic processes affecting circumpolar soils, improve spatial extrapolations, and generate better estimates of regional SOC stocks.

The magnitude of carbon–climate feedback associated with different scenarios of future warming in permafrost regions will depend on the depth distribution of vulnerable OC in the active and permafrost layers of the soil profile (Grosse et al 2011). However, efforts to synthesize information on the vertical distributions of SOC stocks for the northern permafrost region in a manner that can be used to inform predictions of the vulnerability of SOC stocks to combustion, hydrologic change, and warming scenarios are only beginning (Harden et al 2012). Such efforts to represent the vertical distributions of SOC stocks at landscape and regional scales are challenged even more than the accounting of total stocks because (1) the number of samples from permafrost horizons are more limited below a depth of 1 m (figure 2) due to logistical constraints, and (2) the genetic horizons of cryoturbated soils can be warped and can have pockets of highly organic soil intermixed with mineral soil or parent material (figure 3) (Pettapiece 1974, Tarnocai and
Figure 3. Soil profiles at two study sites in Alaska showing absence (a) and presence (b) of cryoturbation. Soil classification following Soil Taxonomy (Soil Survey Staff 2010).

Zoltai 1978). Thus, efforts to apply consensus sampling protocols as discussed above, need to ensure that generated samples and data can be used to model the vertical distribution of SOC stocks throughout the entire soil profile/strata and predict this distribution across the landscape. This will require that samples collected in the context of genetic horizons include a clear accounting and characterization of their depth distributions, including an accurate estimation of the actual effective thickness of cryoturbated or disrupted horizons (Michaelson et al 2001, Ping et al 2013).

4. Characterizing carbon forms and predicting their fate

The spatial heterogeneity of environmental factors and their controls on SOC dynamics exert a dominant influence on terrestrial carbon storage and turnover, creating one of the major uncertainties in model predictions of carbon–climate feedbacks (Schmidt et al 2011). In addition to the substantial uncertainties surrounding current estimates of SOC stocks, even less is known about the potential decomposability of the carbon stored in permafrost-region soils and how soil carbon forms and chemistry vary across land cover classes or soil types within different ecoregions (Kuhry et al 2010). Upon thawing, the innate initial decomposability of previously frozen SOC pools depends on the origin and chemistry of the organic matter, organomineral associations, and the extent of mineralization that occurred before these materials were incorporated into permafrost (Dai et al 2002a, 2002b, Kuhry et al 2009, Xu et al 2009). In general, most organic matter stored in permafrost underwent some level of decay before its incorporation in perennially frozen horizons (Hugelius et al 2012). But in syngenetic permafrost deposits (such as yedoma), relatively undecomposed organic materials were sometimes rapidly buried and frozen. Upon thawing, however, the actual rate of decomposition depends on the interactions of numerous controlling factors (such as temperature, aeration, water and nutrient availability, and associations of organic materials with soil minerals) that affect the integrated activities of the microbial community as well as the physical access of decomposers and their enzymes to thawed carbon pools (Davidson and Janssens 2006, Schmidt et al 2011). Ultimately, process-based models will be required to predict the integrated responses of these interactions. The parameterization, calibration, and validation of these models across different soil types and their inclusion into regional models and ESMs will benefit significantly from the identification of biogeochemical indicators that can be used to characterize the lability or decomposability of SOC stocks across the permafrost region (Kuhry et al 2010, Hugelius et al 2012, Burke et al 2012). Efforts to identify indicators of potential decomposability and assess their utility will require measurements coupled to experiments (e.g., laboratory incubations, manipulative field studies) and field observations spanning bioclimatic zones, permafrost degradation, and disturbance gradients.

5. Using observation-based SOC estimates to inform models

Several recent studies have improved the representation of high-latitude SOC dynamics in global-scale models (e.g., Lawrence et al 2008, Schaefer et al 2011, Koven et al 2011). However, substantial differences remain between SOC estimates simulated by models and those derived from observations (figure 1). These differences largely occur because of uncertainties in observation-based SOC estimates caused by extrapolating limited observations, both spatially and vertically, and several limitations of ESM modeling approaches. These limitations include (1) a need
to introduce vertical resolution for SOC stocks in models that have typically not considered vertical profiles in SOC dynamics; (2) the highly nonlinear environmental controls on SOC turnover at high latitudes, including freezing/thawing, saturated and/or anoxic conditions, which require high fidelity in modeling the soil physical environment; (3) theoretical and practical difficulties in the methods for initializing the SOC component of ESMs that—as discussed below—are particularly acute at high latitudes; (4) a lack of representation of spatial heterogeneity of soil properties; and (5) a lack of cryogenic processes typical of high-latitude environments, such as cryogenic aggregation and cryoturbation.

The theoretical and practical difficulties in initializing SOC stocks in ESMs arise from a simplifying assumption common to ESMs: that model SOC stocks can be initialized by allowing the model to be forced by repeating cycles typical of past climate conditions until SOC stocks have built up to the point that heterotrophic respiration is balanced by net primary productivity and the model is at an initial SOC equilibrium. This assumption, while likely untrue everywhere (Schmidt et al 2011), is violated particularly strongly at high latitudes because the long timescale for SOC turnover means that SOC in permafrost persists from prior climates, for example, with the formation of Pleistocene loess or Holocene peat deposits. Different permafrost carbon models have taken different approaches for overcoming some, but not all, of these problems. For example, in some cases, active layer carbon stocks were allowed to be in equilibrium with the current climate while permafrost carbon stocks were initialized to map-based estimates (e.g., Schaefer et al 2011, MacDougall et al 2012). In another approach, a slow transport term was defined to allow carbon to migrate from the active layer to permafrost during the model equilibration period to enable shallow permafrost carbon stocks to also equilibrate with active layer stocks (Koven et al 2009), with perhaps a lower boundary to these shallow permafrost processes below which yedoma carbon is initialized (Koven et al 2011).

If observation-based SOC maps are to be used as model validation data, then the reliability of model simulations can be assessed by comparing the SOC stocks predicted by models, which have included different mechanistic processes, to the observed SOC maps. For example, Koven et al (2011) showed that model simulation of initial equilibrium SOC stocks in permafrost regions can vary substantially depending on whether various freeze/thaw and permafrost processes are included in the model. The accuracy of alternative model simulations of baseline estimates (and the processes used to generate them) can only be evaluated against high-quality observational data and reliable three-dimensional geospatial extrapolations of these data.

Alternatively, if permafrost SOC maps are to be used as model initialization states, then the three-dimensional structure of SOC stocks and a clear observation-based boundary between active layer and permafrost SOC are needed. In addition, carbon associated with organic and mineral soils needs to be separated, both geographically and by soil horizons, so that models correctly partition the SOC by the appropriate controls on SOC turnover. An estimate of combustibility, decomposability, or vulnerability to degradation is needed to inform the further partitioning of SOC into labile versus slow turnover pools of soil models. Lastly, the uncertainty associated with empirical SOC estimates is needed if this uncertainty is to be effectively propagated through the models to estimate its impact on emissions.

6. Quantifying uncertainties in predictions

Addressing uncertainty in both observation-based and modeled estimates of SOC stocks is a critical challenge for reliable predictions of carbon–climate feedbacks. The databases currently available for permafrost regions, for example, the NCSCD (Hugelius et al 2013) and the pedons hosted by the International Soil Carbon Network (www.fluxdata.org/nscn/SitePages/ISCN.aspx) are composed of a number of input datasets of variable depths and details. As a result, many sources of uncertainty and variability exist in current SOC estimates for permafrost regions, including disproportionate numbers of available pedons for certain geographic areas, insufficient data for cryoturbated soil horizons and organic soils, limited bulk density measurements for many pedons, and the large polygon sizes used for upscaling (Kuhry et al 2010, Johnson et al 2011, Hugelius 2012). Likewise, different predictive factors used for upscaling to regional estimates of SOC stocks come with their own inherent errors. To date, quantitative estimates of uncertainties associated with permafrost SOC stocks are only available from one local/regional study from the western Russian Arctic (Hugelius 2012). Therefore, uncertainty quantification should be included with any efforts to update SOC stock estimates for the entire northern circumpolar permafrost region.

Sensitivity analysis can be used to identify the most important predictive factors for estimating and extrapolating the distributions of SOC stocks in permafrost regions (Ogle et al 2003, VandenBygaart et al 2004, Mishra et al 2012). Spatial analysis can be used to optimize the choice of additional sampling sites by identifying which soil types, land cover types, landscape positions, and bioclimatic zones have adequate representations versus those that require more samples to reduce uncertainty (Minasny and McBratney 2006, Hugelius et al 2012).

Similarly, uncertainty also exists in predicting carbon–climate feedbacks due to permafrost thawing and future warming using ESMs. In a modeling study of the impact of permafrost carbon release on global mean temperatures by 2100, Burke et al (2012) found that (1) uncertainty in climate model warming scenarios caused about half of the spread in predicted global warming, (2) uncertainties in the distribution (mainly vertical) of SOC contributed roughly one quarter, and (3) uncertainties in the potential decomposability of SOC and decomposition processes together accounted for the other quarter. Although the land models that are used at global scales lack accurate representation of many of the necessary mechanisms to represent SOC dynamics (Schmidt et al 2011), we conclude that uncertainty in predicting carbon–climate...
feedback could be reduced if high-resolution maps of SOC stocks that delineate the active and permafrost layers of the entire soil profile were available at a resolution similar to those of other environmental attributes (e.g., bioclimatic zones, geomorphology, hydrology, fire regime, and land use). Additionally, initial analyses suggest that the coupling of such geospatial delineations with indicators of the inherent decomposability of the SOC subjected to thawing would further contribute to reducing the uncertainties of carbon–climate feedback predictions (Burke et al 2012, Hugelius et al 2012).

7. Conclusions and future directions

Over the last two decades, substantial progress has been made in estimating carbon stored in soils of northern circumpolar permafrost regions. Still, the magnitude of the carbon pool at risk and its potential interactions with the Earth’s climate warrants further research to improve characterization of the three-dimensional distributions and potential vulnerability of the region’s SOC stocks. The challenges to achieving this goal are not independent and are logically linked, such that iterative research efforts can help reduce the uncertainties associated with SOC estimates in permafrost regions and predictions of their role in carbon–climate feedbacks (figure 4). A coordinated effort among North American and Eurasian research programs will be essential to the further advancement of circumpolar estimates. If possible, pedons should be sampled and described following established soil sampling protocols and a soil classification system adapted to the specific requirements of cold-region soils. Reaching a global consensus toward this might need a comprehensive workshop focused on developing sampling protocols and analytical standards. Since soil properties, including carbon concentration and bulk density, vary vertically on the basis of soil horizons, it would be ideal if SOC stocks can be quantified vertically by genetic horizons. Methods for assessing and coping with fine-scale heterogeneity and its implications for sampling and upscaling are also needed. Although regional estimates of SOC stocks are all grounded on the application of pedogenic process understanding at some scale, development and application of alternative approaches for geospatial extrapolations based on the increasing availability of high-resolution geospatial representations of multiple soil predictive factors can be helpful in reducing prediction errors.

Predictions of the potential for SOC losses in response to permafrost thaw or disturbance can be enhanced by mapping biogeochemical indicators of SOC quality or potential decomposability in addition to SOC stocks (Hugelius et al 2012, Schaedel et al 2012). Statistical uncertainty analyses are needed to evaluate extrapolation procedures and predictions and to inform additional sampling needs and efficiency. Lastly, further steps should be taken to incorporate cryogenic processes specific to high-latitude conditions into models for reliable prediction of permafrost SOC climate feedbacks. However, the validation of process representations and testing of model simulations require investment in the efforts outlined here to reduce the uncertainties associated with observational data. We see these challenges as opportunities for the permafrost research community to organize, prioritize, and coordinate the allocation of efforts and resources.

Acknowledgments

This paper originated as the result of the presentations and discussions at two workshops organized by Argonne National Laboratory at the request of the US Department of Energy, Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division to discuss the state of current knowledge and research needs for characterizing and modeling soil carbon in permafrost regions and its potential vulnerability to changing climate. The formulation of the ideas and concepts presented here have also benefited from discussions facilitated by the Vulnerability of Permafrost Carbon Research Collaboration Network (www.biology.ufl.edu/permafrostcarbon/) sponsored by the National Science Foundation. This study was supported by the US Department of Energy, Office of Science under contract No. DE-AC02-06CH11357 to Argonne National Laboratory.

References

Batjes N H 1996 Total carbon and nitrogen in the soils of the world Eur. J. Soil Sci. 47 151–63
Bliss N B and Maursetter J 2010 Soil organic carbon stocks in Alaska estimated with spatial and pedon data Soil Sci. Soc. Am. J. 74 565–79
Bockheim J G 2007 Importance of cryoturbation in redistributing organic carbon in permafrost-affected soils Soil Sci. Soc. Am. J. 71 1335–42
Bockheim J G and Tarnocai C 1998 Recognition of cryoturbation for classifying permafrost-affected soils Geoderma 81 281–93
Brown J, Ferrians O J, Heginbottom J A Jr and Melnikov E S 2001 *Circumpolar Arctic Map of Permafrost and Ground-Ice Conditions Version 2* (Boulder, CO: National Snow and Ice Data Center)  
Burke E J, Hartley I P and Jones C D 2012 Uncertainties in the global temperature change caused by carbon release from ‘permafrost thawing’ *Cryosphere* 6 1063–76  
Camill P, Lynch J A, Adams J D and Jordan B 2001 Changes in biomass, aboveground net primary production, and peat accumulation following permafrost thaw in the boreal peatlands of Manitoba, Canada *Ecosystems* 4 461–78  
Dai X Y, Ping C L and Michaelson G J 2002a Characterizing soil organic matter in Arctic tundra soils by different analytical approaches *Org. Geochem.* 33 407–19  
Dai X Y, White D and Ping C L 2002b Comparing bioavailability in five Arctic soils by pyrolysis-gas chromatography/mass spectrometry *J. Anal. Appl. Pyrol.* 62 249–58  
Davidson E A and Janssens I A 2006 Temperature sensitivity of soil carbon decomposition and feedbacks to climate change *Nature* 440 165–73  
Gottham E 1991 Northern peatlands: role in the carbon cycle and probable responses to climatic warming *Ecol. Appl.* 1 182–95  
Grosse G et al 2011 Vulnerability of high-latitude soil organic carbon to permafrost degradation to soil column depth and representation of soil organic matter *J. Geophys. Res.* 117 G00K06  
Harden J W et al 2012 Field information links permafrost carbon to physical vulnerabilities of thawing *Geophys. Res. Lett.* 39 L15704  
Höfte C M and Ping C L 1996 Properties and soil development of late-Pleistocene paleosols from Seward Peninsula, northwest Alaska *Geomicrobiol. J.* 12 251–64  
Hugelius G 2012 Spatial upscaling using thematic maps: an analysis of uncertainties in permafrost soil carbon estimates *Glob. Biogeochim. Cycle* 26 GB2026  
Hugelius G and Kuhry P 2009 Landscape partitioning and permafrost environment *Glob. Biogeochim. Cycle* 23 GB3006  
Hugelius G, Routh J, Kuhry P and Crill P 2012 Mapping the degree of decomposition and thaw remobilization potential of soil organic matter in discontinuous permafrost terrain *J. Geol. Res.* 117 G02030  
Hugelius G, Tarnocai C, Broll G, Canadell J G, Kuhry P and Swanson D K 2013 The northern circumpolar soil carbon database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions *Earth Syst. Sci. Data* 5 3–13  
Hugelius G, Virtanen T, Kaverin A, Pastukhov A, Rivkin F, Marchenko S, Romanovsky V and Kuhry P 2011 High resolution mapping of ecosystem carbon storage and potential effects of permafrost thaw in periglacial terrain, European Russian Arctic *J. Geol. Res.* 116 G03024  
Jenny H 1941 *Factors of Soil Formation* (New York: McGraw-Hill) p 281  
Jobbagy E G and Jackson R B 2000 The vertical distribution of soil organic carbon and its relation to climate and vegetation *Ecol. Appl.* 10 423–36  
Johnson K D et al 2011 Soil carbon distribution in Alaska in relation to soil-forming factors *Geomicrobiol. J.* 107/108 71–84  
Koven C D, Friedlingstein P, Ciais P, Khorostyanov D, Krinner G and Tarnocai C 2009 On the formation of high-latitude soil carbon stocks: the effects of cryoturbation and insulation by organic matter in a land surface model *Geophys. Res. Lett.* 36 L21501  
Koven C D, Riley W J and Stern A 2013 Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth system models *J. Clim.* 26 1877–900  
Koven C D, Ringeval B, Friedlingstein P, Ciais P, Cadule P, Khorostyanov D, Krinner G and Tarnocai C 2011 Permafrost carbon-climate feedbacks accelerate global warming *Proc. Natl. Acad. Sci. USA* 108 14769–74  
Kuhry P, Dorrepaal E, Hugelius G, Schuur E A G and Tarnocai C 2010 Potential remobilization of belowground permafrost carbon under future global warming *Permafrost Periglac.* 21 208–14  
Kuhry P, Ping C L, Schuur E A G, Tarnocai C and Zimov S 2009 Report from the International Permafrost Association: carbon pools in permafrost regions *Permafrost Periglac.* 20 229–34  
Lawrence D M, Slater A G, Romanovsky V E and Nicolosky D J 2008 Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter *J. Geophys. Res.* 113 F02011  
MacDougall A H, Avis C A and Weaver A J 2012 Significant existing commitment to warming from the permafrost carbon feedback *Nature Geosci.* 5 719–21  
McBratney A B, Mendoza-Santos M L and Minasny B 2003 On digital soil mapping *Geoderma* 117 3–52  
McGuire A D, Anderson L G, Christensen T R, Dallimore S, Guo L, Hayes J D, Heimann M, Lorenson T D, Macdonald R W and Roulet N 2009 Sensitivity of the carbon cycle in the Arctic to climate change *Ecol. Monograph.* 79 523–55  
Meersmans J, De Ridder F, Canter F, De Baets S and Van Molle M 2008 A multiple regression approach to assess the spatial distribution of soil organic carbon (SOC) at the regional scale (Flanders, Belgium) *Geoderma* 143 1–13  
Michaelson G J, Ping C L and Kibble M J 1996 Carbon storage and distribution in tundra soils of arctic Alaska, USA *Arctic Alpine Res.* 28 414–24  
Michaelson G J, Ping C L and Kibble M J 2001 Effects of soil morphological and physical properties on estimation of carbon storage in arctic soils *Assessment Methods for Soil Carbon ed R Lal, J M Kibble, R F Follett and B A Stewart (Boca Raton, FL: Lewis Publishers) pp 339–47  
Minasny B and McBratney A B 2006 A conditioned Latin hypercube method for sampling in the presence of ancillary information *Comput. Geosci.* 32 1378–88  
Mishra U and Riley W J 2012 Alaskan soil carbon stocks: spatial variability and dependence on environmental factors *Biogeoosciences* 9 3637–45  
Mishra U, Torn M S, Ogle S and Masanet E 2012 Improving regional soil carbon inventories: combining IPCC carbon inventory method with regression kriging *Geoderma* 189/190 288–95  
NSSL (National Soil Survey Laboratory) 2010 *Soil Characterization Database* (available at http://ssldata.nrcs.usda.gov/, accessed 6 March 2010)  
NCSCD (Northern Circumpolar Soil Carbon Database) 2012 *Soil Characterization Database* (available at http://dev1.geo.usda.gov/mbcc/dev/ncscd/, accessed 10 October 2012)  
Ogle S M, Breidt F J, Eve M D and Paustian K 2003 Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and 1997 *Glob. Change Biol.* 9 1521–42  
Pettapiece W W 1974 A hummocky permafrost soil from the subarctic of northwestern Canada and some influence of fire *Can. J. Soil Sci.* 54 343–55  
Ping C L, Michaelson G J, Jorgenson M T, Kibble J M, Epstein H, Romanovsky V E and Walker D A 2008a High stocks of soil organic carbon in the North American arctic region *Nature Geosci.* 1 615–9  
Ping C L, Clark M H, Kibble J M, Michaelson G J, Shur Y and Stiles C A 2013 Sampling protocols for permafrost-affected soils *Soil Horizons* 54 13–9  
Ping C L, Michaelson G J, Kane E S, Packe E C, Stiles C A, Swanson D K and Zaman N D 2010 Carbon stores and biogeochemical properties of soils under black spruce forest, Alaska *Soil Sci. Soc. Am. J.* 74 969–78
Ping C L, Michaelson G J, Kimble J M, Romanovsky V E, Shur Y L, Swanson D K and Walker D A 2008b Cryogenesis and soil formation along a bioclimate gradient in Arctic North America J. Geophys. Res. 113 G03S12

Post W M, Emanuel W R, Zinke P J and Stangenberger A G 1982 Soil carbon pools and world life zones Nature 298 156–9

Rasmussen C 2006 Distribution of soil organic and inorganic carbon pools by biome and soil taxa in Arizona Soil Sci. Soc. Am. J. 70 256–65

Sanchez P A et al 2009 Digital soil map of the world Science 325 680–1

Schaefer C et al 2012 Pan-arctic permafrost C quality and vulnerability over time: a synthesis of long-term incubation studies Presented at 2012 Fall Meeting, AGU (San Francisco, CA, Dec.) Abstract B13H-02

Schaefer K, Lantuit H, Romanovsky V E and Schuur E A G 2012 Policy Implications of Warming Permafrost (Nairobi: United Nations Environment Programme)

Schaefer K, Zhang T, Bruhwiler L and Barrett A P 2011 Amount and timing of permafrost carbon release in response to climate warming Tellus B 63 165–80

Schirrmeister L, Grosse G, Wetterich S, Overduin P P, Strauss J, Schuur E A G and Hubberten H W 2011 Fossil organic matter characteristics in permafrost deposits of the northeast Siberian Arctic J. Geophys. Res. 116 G00M02

Schneider von Deimling T, Meinshausen M, Levermann A, Huber V, Frieler K, Lawrence D M and Bovkin V 2012 Estimating the near-surface permafrost-carbon feedback on global warming Biogeosciences 9 649–65

Schmidt M W I et al 2011 Persistence of soil organic matter as an ecosystem property Nature 478 49–56

Schuur E A G et al 2008 Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle BioScience 58 701–14

Schuur E A G and Abbott B 2011 Permafrost carbon network 2011 climate change: high risk of permafrost thaw Nature 480 32–3

Schuur E A G, Vogel J G, Crummer K G, Lee H, Sickman J O and Osterkamp T E 2009 The effect of permafrost thaw on old carbon release and net carbon exchange from tundra Nature 459 556–9

Simbahan G C and Dobermann A 2006 Sampling optimization based on secondary information and its utilization in soil organic mapping Geoderma 133 345–62

Soil Survey Staff 2010 Keys to Soil Taxonomy 11th edn (Washington, DC: USDA—Natural Resources Conservation Service)

Tarnocai C and Bockheim J G 2011 Cryosolic soils of Canada: genesis, distribution, and classification Can. J. Soil Sci. 91 749–62

Tarnocai C, Canadell J P, Schuur E A G, Kuhry P, Mazhitova G and Zimov S 2009 Soil organic carbon pools in the north circumpolar permafrost region Glob. Biogeochem. Cycle 23 GB203

Tarnocai C and Zoltai S C 1978 Earth hummocks of the Canadian arctic and subarctic Arctic Alpine Res. 10 581–94

Todd-Brown K E O, Randerson J T, Post W M, Hoffman F M, Tarnocai C, Schuur E A G and Allison S D 2013 Causes of variation in soil carbon predictions from CMIP5 Earth system models and comparison with observations Biogeosciences 10 1717–36

VandenBygaart A J, Gregorich E G, Angers D A and Stoklas U F 2004 Uncertainty analysis of soil organic carbon stock change in Canadian cropland from 1991 to 2001 Glob. Change Biol. 10 983–94

Vandenbergh J 1988 Cryoturbations. Advances in Periglacial Geomorphology ed M J Clark (Chichester: Wiley) pp 179–98

Van Vliet-Lanoë B 1991 Differential frost heave, load casting and convection: converging mechanisms; a discussion of the origin of cryoturbations Permafrost Periglac. 2 123–39

Washburn A L 1980 Geocryology (New York: Wiley)

Xu C, Guo L, Ping C L and White D M 2009 Chemical and isotopic characterization of size-fractionated organic matter from cryoturbated tundra soils, northern Alaska J. Geophys. Res. 114 G03002

Zimov S A, Schuur E A G and Chapin F S III 2006 Permafrost and the global carbon budget Science 312 1612–3

Zhuang Q et al 2006 CO2 and CH4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century Geophys. Res. Lett. 33 L17403