Arctic Soil Governs Whether Climate Change Drives Global Losses or Gains in Soil Carbon

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Abstract Key uncertainties in terrestrial carbon cycle projections revolve around the timing, direction, and magnitude of the carbon cycle feedback to climate change. This is especially true in carbon-rich Arctic ecosystems, where permafrost soils contain roughly one third of the world's soil carbon stocks, which are likely vulnerable to loss. Using an ensemble of soil biogeochemical models that reflect recent changes in the conceptual understanding of factors responsible for soil carbon persistence, we quantify potential soil carbon responses under two representative climate change scenarios. Our results illustrate that models disagree on the sign and magnitude of global soil changes through 2100, with disagreements primarily driven by divergent responses of Arctic systems. These results largely reflect different assumptions about the nature of soil carbon persistence and vulnerabilities, underscoring the challenges associated with setting allowable greenhouse gas emission targets that will limit global warming to 1.5°C.

Plain Language Summary Soils store carbon, lots of carbon. Because of these large carbon stocks, exchanges of carbon dioxide between soils and the atmosphere are large, and the potential responses of soil carbon stocks and fluxes to projected changes in climate are uncertain. The understanding of factors responsible for the persistence of these vast soil carbon stores has changed dramatically, and models need to widely implement these new ideas. Here we evaluate three models that make different assumptions about factors responsible for persistence of carbon in soils. Our results show that although the different model formulations produce similar estimates for initial soil carbon stocks, they show large spread in the fate of soil carbon under projected changes in soil temperature, moisture, and plant growth through the end of this century. These results highlight that greater attention is needed to develop and test model formulations that are consistent with observations and understanding—especially in the Arctic which has large soil carbon stores that are likely to experience rapid change in upcoming decades.

1. Introduction

Uncertainties in the terrestrial carbon (C) cycle feedback to projected climate change make it challenging to set emission reduction targets that are consistent with thresholds to limit climate warming (Friedlingstein et al., 2014; Jones et al., 2013). Soils contain the largest actively cycling terrestrial C pool on Earth, with approximately one third of the world's soil C stock in permafrost soils of the Arctic, which are likely vulnerable to projected warming through the end of this century (Hugelius et al., 2014; Schuur et al., 2015; Slater & Lawrence, 2013). Globally, a diversity of factors contributes to the persistence of this vast, heterogeneous C pool, including, its biochemical quality; environmental conditions, like permafrost or inundation; and physicochemical protection, on mineral surfaces or in aggregates (Lehmann & Kleber, 2015; Schmidt et al., 2011). Models are being built with new ways of representing the effect of these factors on soil C persistence and transformations (Abramoff et al., 2018; Ahrens et al., 2015; Sulman et al., 2018; Wieder et al., 2013), affording opportunities to assess structural uncertainties related to the most appropriate way to represent biogeochemical understanding and scale-up limited observations.

Emerging theories of soil organic matter (SOM) persistence emphasize the production of microbial products and their stabilization on mineral surfaces and within aggregates (Cotrufo et al., 2013; Grandy & Neff, 2008; Kallenbach et al., 2016; Miltner et al., 2012; Six et al., 2006). Accordingly, soil C persistence results from

limited microbial access to otherwise decomposable substrate, and not biochemical recalcitrance (Dungait et al., 2012; Kleber et al., 2011; Lehmann & Kleber, 2015; Schimel & Schaeffer, 2012). While some models reflect these insights, they are not commonly represented in large-scale model ensembles. Instead, soil models often share common structural assumptions that are predicated on biochemical recalcitrance (Bradford & Fierer, 2012; Schimel, 2001; Todd-Brown et al., 2013). Ensemble projections with these models typically suggest a weak soil C feedback under global change (Koven, Chambers, et al., 2015; McGuire et al., 2018; Todd-Brown et al., 2014). Troublingly, these studies overlook contemporary understanding into how environmental conditions and soil physicochemical properties limit microbial access to otherwise decomposable substrates. As such, they do not provide insight into the mechanisms by which microbial activity and soil physical properties may interact to influence soil C persistence or vulnerabilities under global change.

Changing environmental conditions could reshuffle the factors that drive persistence in existing SOM pools. This may be especially important following permafrost thaw, where increases in temperature and liquid water availability may accelerate the decomposition of SOM that was previously persistent due to frozen conditions. Nevertheless, we have high confidence that soil thermal and hydraulic changes will occur in the Arctic (Slater & Lawrence, 2013) and that these abiotic changes will disrupt the primary mechanism (freezing) for SOM persistence in this C-rich region (Ping et al., 2015; Schuur et al., 2015). However, it remains uncertain to what extent the subsequent physicochemical protection of organic matter on mineral surfaces may attenuate the extent and rate of permafrost SOM decomposition following thaw (Gentsch et al., 2018; Ping et al., 2015). The timing and magnitude of potential permafrost C feedbacks remains unclear, but given their common structural assumptions, we suspect that previous model ensembles do not capture the true uncertainty associated with soil C dynamics in a warming Arctic.

Structural differences in models reflect incomplete understanding of how to represent critical features related to microbial-mineral interactions in models that make global-scale C cycle projections. In the physical climate system, model developments aimed at making more complete representation of atmospheric processes may not reduce model ensemble spread. However, by considering a broader range of plausible mechanisms, they increase confidence that projected climate outcomes might occur (Knutti & Sedlacek, 2013). Similarly, ensembles of soil biogeochemical models that integrate new process knowledge should more broadly represent the range of potential C-cycle outcomes (Bradford et al., 2016). This integration builds confidence in future soil C projections because the true state of scientific knowledge is represented in the ensemble, even if it increases projection uncertainty (i.e., model-ensemble spread). Given shifts in understanding of factors controlling SOM persistence and potential vulnerabilities, here we use an ensemble of soil biogeochemical models that more broadly captures structural uncertainties in factors affecting soil C decomposition and persistence to quantify potential soil C responses under two representative climate change scenarios.

2. Methods

We developed a soil biogeochemical testbed, which forces its soil biogeochemical models with identical biotic and abiotic conditions (Wieder et al., 2018; Figure S1 in the supporting information). Three models currently included in our testbed are (a) the Carnegie-Ames-Stanford Approach (CASA-CNP) model (Potter et al., 1993; Randerson et al., 1996; Wang et al., 2010), a first-order linear model that implicitly represents microbial activity (similar to previous ensembles), and two models that explicitly represent microbial activity and reflect emerging theoretical understanding: (b) the MIcrobial-MIneral Carbon Stabilization (MIMICS) model (Wieder et al., 2014; Wieder et al., 2015) and (c) the Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment (CORPSE) model (Sulman et al., 2014; Sulman et al., 2017). By providing consistent biotic and abiotic forcings, our biogeochemical testbed removes idiosyncratic differences in climate and vegetation dynamics among land models that potentially confound interpretation of divergent soil biogeochemical projections (Todd-Brown et al., 2014). Our testbed, therefore, provides a numerical platform to evaluate theories related to SOM decomposition and persistence.

Structural uncertainties among models in our testbed more broadly reflect—when compared with previous model ensembles—the breadth of theories regarding the importance of factors controlling the long-term persistence of SOM and its potential vulnerabilities to environmental change. One of the most notable differences among models is the implicit (CASA-CNP) vs. explicit (MIMICS and CORPSE) representation of

Table 1
Mean of Area Weighted Ecosystem Characteristics and Soil C Stocks Simulated by Each Model Globally (Top Rows), and for Grid Cells > 50°N Latitude (bottom rows)

| | Soil temperature | Soil moisture | Frozen soil water | NPP | Veg C | CASA-CNP | Soil C stocks | |
							MIMICS	CORPSE
	°C	% Saturation	% Saturation	Pg C/year	Pg C	Pg C	Pg C	Pg C
Global mean								
1900	14.1	45.9	9.9	47.8	401	1,365	1,409	1,717
Hist.	+1.0	+0.3	−0.9	+7.1	+36	+18	+11	+1
RCP4.5	+1.8	+1.2	−1.0	+13.6	+101	+60	+18	−30
RCP8.5	+3.4	+1.8	−1.9	+24.1	+150	+69	+4	−58
>50°N latitude								
1900	−1.6	36.6	30.4	11.7	171	847	729	1,291
Hist.	+1.1	+1.4	−2.4	+2.0	+13	+5	−6	−13
RCP4.5	+2.0	+2.6	−2.4	+3.8	+42	+23	−27	−78
RCP8.5	+3.8	+4.1	−5.0	+6.6	+60	+21	−53	−122

Note. Values show the global initial state (mean of 1901–1910), change by the end of the historical period (mean of 2001–2010), and their change under RCP4.5 and 8.5 (mean of 2091–2100).
Abbreviations: CASA-CNP: Carnegie-Ames-Stanford Approach; CORPSE: Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment; MIMICS: MIcrobial-MIneral Carbon Stabilization; NPP: net primary production; RCP: Representative Concentration Pathway.

microbial activity (Schimel, 2001). Additional differences are reflected in the model structures (Figure S2 and Table S1 in the supporting information) and parameterizations. Here we focus our analysis on the spatial distribution and temporal changes of bulk soil C and the physicochemically protected soil C pool (s), with the latter illustrating key uncertainties among models. Models in our testbed assume that protected C pools are either inherently resistant to decomposition (e.g., long turnover times for passive C in CASA-CNP) or physically isolated from microbial decomposition (as in MIMICS and CORPSE). MIMICS and CORPSE also differ in how they represent factors controlling the formation and turnover of physicochemically protected C (Text S1 in the supporting information). Despite these differences, models in our testbed all use clay content as a proxy to determine the capacity of soils to physicochemically protect soil C (Bailey et al., 2018). Although generalizability of this assumption is being questioned (Rasmussen et al., 2018; Rowley et al., 2018), the protected soil C simulated here broadly corresponds to mineral associated organic matter (MAOM) that could be isolated by particle size or density fractionation (Sohi et al., 2001). This MAOM typically has older radiocarbon ages, consistent with longer turnover times and greater persistence of mineral-associated organic C (Trumbore, 2009), which corresponds to the passive, physicochemically protected, and protected soil C pools simulated by CASA, MIMICS, and CORPSE, respectively (Text S1). Thus, despite differences in the models' structure and parameterization (Figure S2 and Table S1), we assume that these protected soil C pools are functionally equivalent to each other.

This study used the global scale, C-only implementation of the CASA-CNP vegetation model to prescribe identical litterfall and soil conditions for each soil model. The models were spun up to steady-state using conditions simulated at the start of the twentieth century. We then simulated transient changes in plant productivity, soil moisture, and soil temperature through 2100 under Representative Concentration Pathways (RCPs) 4.5 and 8.5. Our analysis focused on quantifying initial C pools simulated by each model and characterizing model structural uncertainty versus the forcing uncertainty associated with soil C projections through the end of this century.

3. Results

3.1. Initial Soil C Stocks

The global sums of initial soil C pools were similar among models (Table 1), albeit with distinct spatial distributions (Figures S3 and S4). The models show large variation in high-latitude C stocks, ranging from 730 to 1,290 Pg C, but large variation is also reflected in observationally derived estimates of soil C stocks (Figure S5 and Table 1). All of the models show a higher temperature sensitivity of soil C turnover in cold-domain ecosystems (<0°C mean annual temperature) compared to temperate and tropical
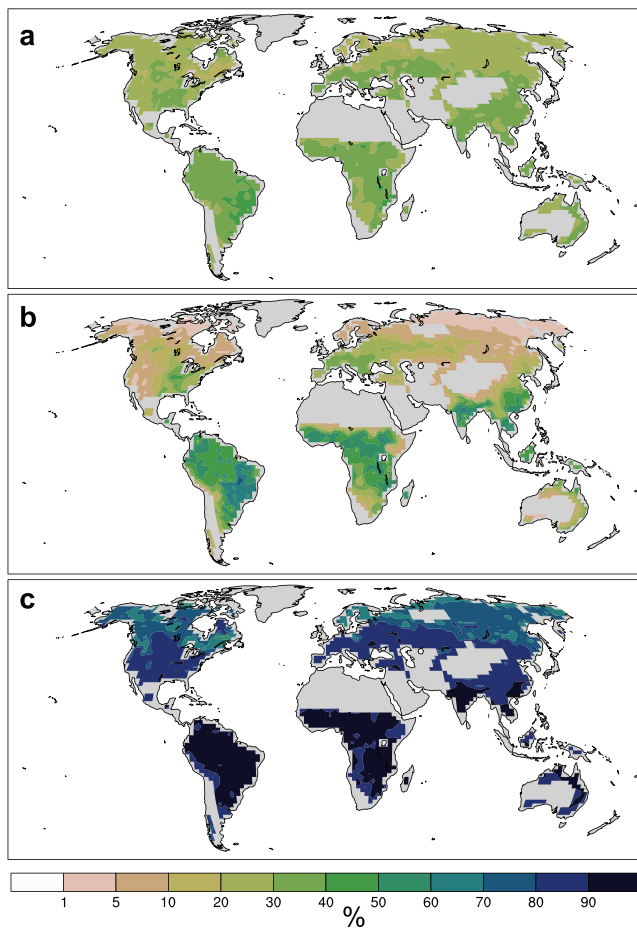
Figure 1. Percentage of total soil carbon in the passive pool in (a) Carnegie-Ames-Stanford Approach (CASA-CNP), and in the protected pools simulated by (b) MIcrobial-MIneral Carbon Stabilization (MIMICS), and (c) Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment (CORPSE) at the start of the simulation (1901–1910). All of the models use soil clay content as a proxy to determine the capacity of soils to physicochemically protect soil C, resulting in a latitudinal gradient in the percent of soil C considered protected from microbial decomposition.

ecosystems, consistent with observationally derived estimates presented by Koven et al. (2017); Figure S6). Collectively, the model ensemble results agree with observed global soil C stocks and turnover time-temperature relationships as well or better than previous ensembles (Table S2; Koven et al., 2017; Todd-Brown et al., 2013). But despite this agreement, each model makes distinct assumptions about the size and dynamics of protected pools of C that are largely inaccessible to soil microbes (or which decompose very slowly).

The fraction of soil C considered protected from microbial decomposition varies greatly among models (Figure 1), with protected soil C pools totaling 329, 214, and 1,297 Pg C in CASA-CNP, MIMICS, and CORPSE, respectively. These differences reflect theoretical uncertainties about how to measure and conceptualize organic matter dynamics in soils. The actual amount of protected C in any location is difficult to quantify empirically, much less define globally. Recent observational work emphasizes the importance of climate thresholds determined by ecosystem water balance, which influences mineral weathering and mechanisms of organic matter stabilization (Kramer & Chadwick, 2018; Rasmussen et al., 2018). Roughly one quarter of global soil C stocks are bound to reactive minerals in subsurface soils (Kramer & Chadwick, 2018), with a spatial distribution that is distinct from the protected C fractions simulated by models in our testbed (Figure S7). To our knowledge, these spatial distributions are not well represented in any global-scale model, including those in our testbed, and improving these representations should be considered a high priority if we are to confidently extrapolate emerging mechanistic insights for C cycle projections.

3.2. Transient Response to Environmental Change

Figure 2 illustrates how differences in the underlying model assumptions have divergent consequences for the persistence and vulnerability of soil C pools. Under the combined effects of climate change and increases in plant productivity, models in our testbed show global soil C accumulation (CASA-CNP), negligible changes (MIMICS), and large losses (CORPSE; Table 1 and Figures S8 and S9). The scenario uncertainty represented by RCP4.5 and 8.5 characterizes two very different trajectories for changes in atmospheric CO_2 concentrations, with global temperatures warming by 1.8 to 3.4° and productivity increasing by 28 to 50%, respectively.

Despite pronounced differences in the forcing scenarios, model uncertainty accounted for 95% of the total uncertainty in soil C changes (Figure 2). Because all models in our testbed received identical forcing inputs, differences in projections reflect underlying structural and parametric uncertainties among the models.

Differences in the conceptualization of protected soil C pools among models in our testbed help to explain transient soil C projections (Figures 3, S10, and S11). The lack of liquid water in frozen soils prevents microbial decomposition in all the models, but upon thaw conceptualizations of bioavailability vary greatly among models. In CASA-CNP, the accelerated decomposition associated with soil thaw is largely limited to pools with faster historical turnover times and is more than offset by increases in productivity and litter inputs, resulting in high latitude soil C gains totaling 23 and 21 Pg C under RCP4.5 and 8.5, respectively (Table 1). The inherently slow turnover times applied to the passive C pools in CASA-CNP result in negligible changes in protected soil C (Figures 3a and 3b).

By contrast, with warming in the Arctic, microbes in MIMICS and CORPSE gain access to previously frozen, potentially decomposable soil C pools, causing rapid decomposition and soil C losses. Much of the high-latitude soil C simulated by MIMICS is not protected (Figure 1) and, therefore, vulnerable to microbial decomposition with warming—resulting in Arctic soil C losses totaling 27 to 53 Pg C by 2100. At the same time, the enhanced microbial turnover directly contributes to the formation of soil C that is considered
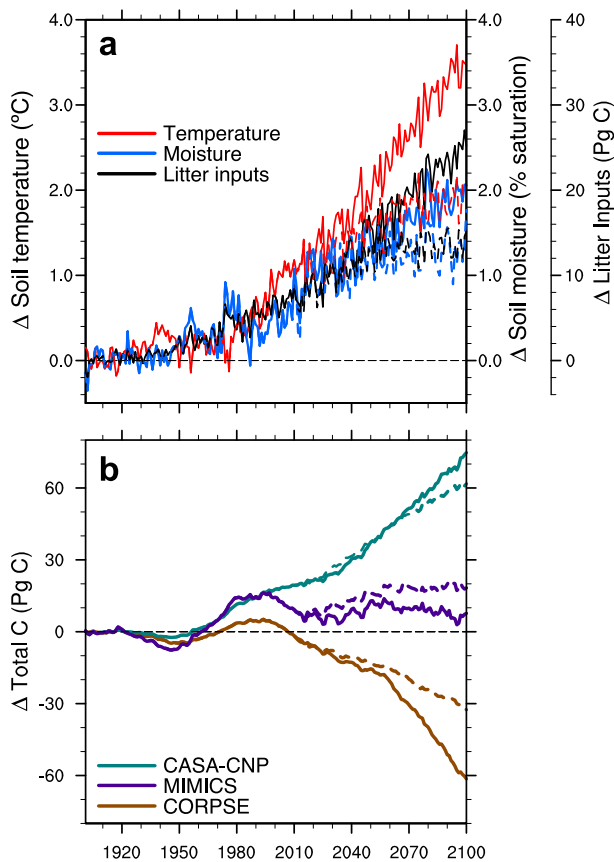
Figure 2. Globally averaged changes in (a) forcing data and (b) soil C stocks under Representative Concentration Pathways (RCP) 4.5 and 8.5 (dashed and solid lines, respectively), relative to a 1901–1910 baseline. Forcing data (a) show changes in soil temperature (°C), soil moisture (% saturation), and litter inputs (red, blue, and black lines, respectively). Changes in soil C stocks (b) are simulated by Carnegie-Ames-Stanford Approach (CASA-CNP), MIcrobial-MIneral Carbon Stabilization (MIMICS), and Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment (CORPSE; green, purple, and brown lines, respectively). Despite the large differences in scenario uncertainty represented in (a), 95% of the variation in (b) is attributed to model uncertainty.

physicochemically protected. Thus, despite net losses of soil C, future scenarios increase microbial activity and turnover, resulting in physicochemical stabilization and modest increases in Arctic protected soil C pools (11 to 18 Pg C under RCP 4.5 and 8.5, respectively; Figures 3c and 3d).

Finally, CORPSE assumes a higher initial fraction of protected soil C in high latitudes (Figure 1), but that exchanges between protected and unprotected soil C pools occur on decadal time scales (section 2 and Text S1). In CORPSE, mineral surfaces compete with microbial biomass for unprotected C; thus, increases in temperature that accelerate soil C decomposition can decrease protected C formation because more C is decomposed before it can be protected. These dynamics result in large losses in the Arctic of total soil C (78 to 121 Pg C), as well as protected soil C (21 to 34 Pg C; Figures 3e and 3f). The ensemble spread in model projections underscores fundamental uncertainties in protected soil C responses to perturbations and highlights that soil C projections under global change scenarios may be more uncertain than prior ensembles suggest, especially in the Arctic.

4. Discussion

Soil models used in our testbed generate initial global soil C stocks and turnover times that are broadly consistent with observational estimates (Tables 1 and S2 and Figures S3–S6), marking an improvement relative to previous model ensembles (Koven et al., 2017; Tian et al., 2015; Todd-Brown et al., 2013). Although initial conditions are important for determining the magnitude of projected soil C stocks, large uncertainties in observationally derived soil C estimates persist that are larger than the differences among models presented here (Table 1 and Figures S3–S5; Tifafi et al., 2018). And while closer agreement in initial soil C stocks may be helpful, other studies indicate that size of initial soil C pools is not a good predictor of potential soil C gains or losses with environmental change (Tian et al., 2015; Wieder et al., 2014). Despite improvements in estimates of global soil C stocks and their inferred turnover times, relative to previous ensemble, models in our testbed make very different estimates of the amount of soil C that may be considered "protected" from microbial decomposition (Figure 1). Although theory emphasizes that the physical isolation of organic matter from soil microbes protects soil C from decomposition (Conant et al., 2011; Dungait et al., 2012), the extent to which these protected soil C pools may be vulnerable to environmental change remains uncertain. This uncertainty is reflected in projections of soil C change simulated by our testbed.

High model uncertainty in our soil C projections (Figure 2b) is consistent with evidence that model uncertainty dominates terrestrial C cycle projections (Hewitt et al., 2016; Lovenduski & Bonan, 2017). However, projection uncertainties in previous model ensembles were not the result of different structural assumptions, but instead were driven, in part, by differences among models in the simulated changes in climate and plant productivity. The strength of our approach is that we eliminated such idiosyncratic differences by ensuring all models in our testbed received identical forcing inputs, thus enabling a closer look at how differences in model assumptions related to projected soil C sensitivities to global change. Below we discuss how uncertainties in future soil C projections are related to model assumptions and implementations and specifically how they relate to potential soil C vulnerabilities in the Arctic.

4.1. Protected Soil C

Measurement and theory suggest that the association of organic matter with mineral surfaces confers persistence to otherwise decomposable substrates (Cotrufo et al., 2013; Dungait et al., 2012; Kleber et al., 2011; Mikutta et al., 2006). To our knowledge, results presented by Kramer and Chadwick (2018) are the first
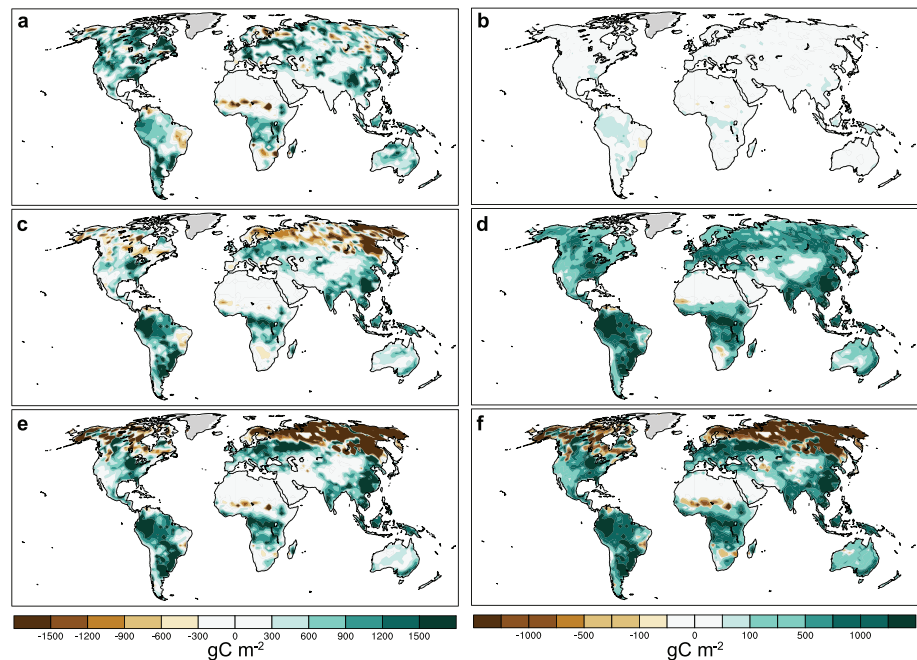
Figure 3. Changes in (left column) total and (right column) protected soil carbon under Representative Concentration Pathway (RCP) 8.5 simulated by (a and b) Carnegie-Ames-Stanford Approach (CASA-CNP), (c and d) MIcrobial-MIneral Carbon Stabilization (MIMICS), and (e and f) Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment (CORPSE). CASA-CNP shows total C accumulation in the Arctic, whereas MIMICS and CORPSE both show net soil C losses. Negligible changes in protected C for CASA-CNP projections reflect the slow turnover of passive soil C, whereas MIMICS shows large gains of protected soil C in the Arctic and CORPSE shows large protected C losses. All values show changes in soil C stocks at the end of the simulation (2091–2100), relative to initial values (1901–1910; g C/m^2).

attempt to estimate global stocks of MAOM (Figure S7) that may be comparable to protected C stocks represented in our testbed (Figure 1). The differences in protected stocks among the models presented here, and the observationally derived estimates of Kramer and Chadwick (2018), exemplify uncertainties arising as our understanding develops about the mechanisms that confer persistence of organic matter in soils. They highlight the need to develop, apply, and evaluate model formulations that seek to test and advance these new theories emerging from empirical data.

Models in our testbed all use clay content as a proxy for mineralogical controls on potential physicochemical protection of soil C. This common assumption (Bailey et al., 2018; Rasmussen et al., 2018) produces latitudinal gradients in protected soil C in all three of the soil models evaluated here (Figure 1), but recent work highlights shortcomings of this assumption, with pH and weathering thresholds that allow either calcium or iron- and aluminum-oxides to stabilize organic matter in soils. (Kramer & Chadwick, 2018; Rasmussen et al., 2018; Rowley et al., 2018). Both the use of clay and chemical extractions simplify the diversity of chemical and physical mechanisms by which soil C may be stabilized (Chadwick & Chorover, 2001). Collectively, this uncertainty highlights opportunities to refine model representations of factors (e.g., soil mineralogy) that control SOM persistence in large scale models.

Turnover times of the protected (passive) pool in CASA-CNP range from roughly 20 to 2,000 years, which are further modified by environmental scalars for soil temperature and moisture, yielding effective turnover times for passive soil C in the arctic of 10^3–10^4 years. Given their inherently slow turnover times, these pools are relatively inert on centennial timescales (Figure 3). As a result, in CASA-CNP high latitude increases in primary productivity and litter inputs more than compensate for accelerated decomposition associated with warming. By contrast, both microbial-explicit models assume that the higher surface area of clay-rich soils physically protects microbial residues that are inherently decomposable and that microbial residues build SOM. MIMICS and CORPSE represent physicochemically "protected" soil C as pools that soil microbes cannot access or decompose, but which turn over (back into unprotected soil C pools that microbes can access)

on decadal time scales (Figure S2 and Text S1). Thus, protected pools in MIMICS and CORPSE can change more rapidly than those in CASA-CNP (Figure 3). The turnover time of protected C is a function of soil texture (MIMICS) or is fixed (in CORPSE; Text S1). Furthermore, there is no respiration flux associated with movement from protected to available pools in either model. As such, fluxes into and out of their respective protected soil C pools are not influenced directly by changes in environmental conditions (temperature or soil moisture), but indirectly by changes in the size and activity of microbial biomass pools.

Although MAOM generally has high persistence, under certain conditions this protected pool of C may ultimately be vulnerable to microbial decomposition. For example, organic acids produced by root exudates may liberate mineral-bound soil C so that it can be decomposed (Keiluweit et al., 2015). Such mechanisms may have important implications for ecosystem nutrient cycling if plants and microbes can exploit this potential vulnerability of mineral-associated (or protected) organic matter (Jilling et al., 2018). To date, these insights are poorly implemented in global-scale models. Thus, additional efforts are needed to refine estimates of "protected" soil C stocks, describe mathematical functions that represent these mechanisms of persistence, and clarify potential vulnerabilities of protected soil C to environmental change.

4.2. Arctic Soil C Vulnerabilities

Several model intercomparison projects suggest that with warming and elevated concentrations of CO_2 in the atmosphere, high-latitude ecosystems will sequester additional C through the end of this century because increases in plant productivity offset accelerated decomposition rates (Koven, Chambers, et al., 2015; McGuire et al., 2018; Todd-Brown et al., 2014). These results are mirrored in our CASA-CNP simulations (Figures 2 and 3) and are consistent with theories of biochemical recalcitrance that underpin first-order models. By contrast, MIMICS and CORPSE simulations show greater Arctic soil C vulnerabilities—results that are consistent with experimental evidence, albeit contested (Crowther et al., 2016; van Gestel et al., 2018), for accelerated decomposition and soil C losses with warming of permafrost soil regions (Commane et al., 2017; Hicks Pries et al., 2016). These stark discrepancies highlight knowledge gaps and the need to experimentally evaluate the individual and combined effects of warming and elevated CO_2 on the persistence of soil C in a region containing roughly one third of the world's soil C stocks.

As permafrost thaws, vast stores of previously frozen soil C will be exposed to microbial decomposition (Schuur et al., 2015; Slater & Lawrence, 2013). The potential transition from unprotected to mineral-protected soil C pools under warming (Gentsch et al., 2018) was simulated by MIMICS, but it still led to a net loss of Arctic soil C (Figure 3). Although our model ensemble is more inclusive of contemporary understanding of controls on soil C persistence than previous intercomparisons, some potentially important processes are still omitted. None of the three models we evaluated represent the potential for root exudates to liberate MAOM, which might be expected to accentuate total and protected soil C losses. Other important processes include the role of iron- and aluminum-oxides in stabilizing SOM in sites with deeper active layers (Evgrafova et al., 2018), as well as in nonpermafrost soils (Rasmussen et al., 2018). Even with improved process representation, the timescales over which decomposition of previously frozen soil C will cause the release of greenhouse gases to the atmosphere remain uncertain, as does the degree to which mineral stabilization mechanisms may subsequently protect soil C. This wider view of factors responsible for soil C persistence highlights shortcomings of all three model projections and helps generate testable hypotheses that can guide further investigation into what the likely outcomes of environmental change will be on soil C stocks.

High uncertainties in soil C projections, combined with new theoretical understanding of SOM persistence (and vulnerability), underscore the need to revise and improve global-scale soil biogeochemical models. Mounting observational and experimental evidence suggests the potential for high permafrost C losses with warming (Schuur et al., 2015). Extensive and rapid thermal and hydrologic changes are likely over the Arctic, yet the collection of models used in prior ensembles do not project significant permafrost soil C losses during this century (McGuire et al., 2018). We contend that by better capturing model structural uncertainty associated with the nature of SOM persistence, our results help represent how this crucial uncertainty could feasibly translate to the timing and magnitude of potential soil C-climate feedbacks. In particular, different conceptualizations of soil C persistence and vulnerability to decomposition generate a wide ensemble spread, highlighting the need to test the contrasting process assumptions with experimental data, especially in Arctic systems.

Future work should also consider how vertically resolved models, which explicitly represent microbial-mineral interactions at multiple depths in the soil profile, affect nutrient mediated plant-soil feedbacks and associated changes in plant productivity (Koven et al., 2013; Koven, Lawrence, et al., 2015). Additionally, models likely underestimate the sensitivity of ecosystem turnover times to precipitation and potential changes in the hydrological cycle (Carvalhais et al., 2014), emphasizing the importance of improving the parameterizations of soil moisture effects on soil C turnover and respiration (Yan et al., 2018). These dynamics are especially important in the Arctic, where efforts to understand and project the effects of permafrost thaw are complicated by high subsurface heterogeneity in soil hydrology (Walvoord & Kurylyk, 2016), heterotrophic activity that occurs in liquid water films in sub-zero soils (Mikan et al., 2002; Rivkina et al., 2000), and potentially high rates of dissolved organic matter losses that are subsequently susceptible to decomposition (Cory et al., 2013; Plaza et al., 2019). None of these dynamics are typically captured in models, including those presented here, and highlight productive avenues for future research. Indeed, linking these biophysical dynamics to biogeochemical responses remains a challenge to reliable assessments of the magnitude of terrestrial C cycle-climate feedbacks (Grosse et al., 2016). Addressing these knowledge gaps in model intercomparisons, which include multiple model structures, will facilitate estimates of the true range of projection uncertainty based on current knowledge regarding soil C persistence. Such modeling efforts will help to build confidence that C cycle-climate feedback projections are inclusive of contemporary scientific understanding. Such inclusivity provides to policymakers a credible scientific basis upon which to consider how best to deal with the influence of these feedbacks when negotiating greenhouse gas emission targets to limit climate change.

Author Contributions

W.R.W., B.N.S., and M.D.H. designed the study. M.D.H led the development of the testbed model code. W.R. W. coordinated the experiments and wrote the manuscript. All authors contributed significantly to the final analysis and revisions of the manuscript.

Competing Interests

The authors declare no competing financial interests.

Code and Data Availability

Model code and analysis scripts are available at W.R.W.'s GitHub account https://github.com/wwieder/biogeochem_testbed_1.1. The datasets generated for and/or analyzed during the current study are available on the Climate Data Gateway https://doi.org/10.5065/d6nc600w.

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