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The effect of the feedback cycle between the soil organic carbon and the soil hydrologic and thermal dynamics

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ABSTRACT

Biogeochemical feedback processes between soil organic carbon (SOC) in high-latitude organic soils and climate change is of great concern for projecting future climate. More accurate models of the SOC stock and its dynamics in organic soil are of increasing importance. As a first step toward creating a soil model that accurately represents SOC dynamics, we have created the Physical and Biogeochemical Soil Dynamics Model (PB-SDM) that couples a land surface model with a SOC dynamics model to simulate the feedback cycle of SOC accumulation and thermal hydrological dynamics of high-latitude soils. The model successfully simulated soil temperatures for observed data from a boreal forest near Fairbanks, and 2000 year simulations indicated that the effect of the feedback cycle of SOC accumulation on soil thickness would result in a significant differences in the amount of SOC.

Keywords: Soil Organic Carbon; High-Latitude Soil; Soil Hydrology; Soil Thermal Regime; Land Surface Model; Organic Carbon Decomposition Model; Feedback Cycle

1. INTRODUCTION

Large amounts of soil organic carbon (SOC) are stored in high-latitude soils. Cold temperatures and a highly moist environment create a large stock of SOC. The total amount of SOC in soils around the globe has been estimated to be 419 - 455 Pg [1,2], 1672 Pg [3], and 2376 - 2456 Pg [4]. These values account for a third to half the total carbon stock of global terrestrial ecosystems and equivalent to more than half of the total atmospheric carbon [3,5].

In high-latitude organic soils, the accumulation of SOC increases the water holding capacity of the soil and raises the water table, creating anoxic conditions. Insulation by SOC keeps the soil temperature relatively low in summer and raises the permafrost, creating an impermeable surface that in turn raises the water table further. These effects of SOC accumulation slow down decomposition and lead to further accumulation of SOC. This positive feedback process, known as paludification, maintains high-latitude soils as net carbon sinks and creates a large SOC stock [6].

However, any positive feedback process is inherently destabilizing [6]. As the climate warms, the cold and anoxic conditions that slow down the decomposition could be lost. Faster decomposition would reduce the SOC layer, which would in turn reduce the insulation of deeper soil and lower the water table, allowing further decomposition and release of carbon into the atmosphere. The resulting release of large amounts of carbon into the atmosphere could warm the climate further, driving even more SOC decomposition. This positive feedback in response to a warming atmosphere has the potential to severely augment global climate change. With the heightened concern about global climate change, the ability to accurately model the SOC stock and its dynamics in high-latitude organic soils is of increasing importance.

Reflecting this concern, there have been numerous studies on the physics and biogeochemical processes of organic soils. Several studies have observed the effect of changing climate on SOC in high-latitude organic soils [5,7,8]. Studies such as Ise *et al.* [6] have modeled the dynamics of SOC under a changing climate. Other studies have modeled the soil thermal regime and hydrology that account for the insulating effect of SOC [9-12].

However, to the best of our knowledge, no study has modeled the effect of the mutual feedbacks between soil thermal and hydrological processes and SOC biogeochemical processes. This feedback cycle is a key process that has led to the accumulation of SOC in the past, and could greatly influence the response of SOC to atmospheric warming.

As a first step toward creating a soil model that accurately represents the SOC feedback cycle, we created the Physical and Biogeochemical Soil Dynamics Model (PB-SDM). This model couples a land surface model (LSM) that simulates thermal and hydrological dynamics of soils with a SOC model that simulates the accumulation and decomposition of SOC. The SOC model includes a feedback cycle of changing SOC thickness that influences soil temperature and moisture, which in turn influences SOC decomposition. To assess the effect of the feedback cycle, we compared the results of PB-SDM to a model that does not account for feedback.

2. MODEL DESCRIPTION

The PB-SDM couples the 1-D Noah Land Surface Model (LSM) [13; version 3.3] with a SOC dynamics model (SDM) developed by Ise *et al.* [6; ED2.0-peat] to simulate the feedback cycle of SOC and the thermal and hydrological dynamics of the soil (**Figure 1**).

Noah LSM is a land surface scheme for numerical weather and climate prediction models created by the National Center for Environmental Prediction of the U.S. National Weather Service [13]. The LSM uses air temperature, precipitation, and solar radiation to calculate vertical heat fluxes and the transfer of moisture through the soil at 15 minutes interval. Details of the model can be found in Koren *et al.* [14] and Mitchell [15]. Noah LSM calculates soil temperatures and moistures from climate data, which worked well for coupling the model with the SDM and will allow future application of the model to a wide range of locations and climate scenarios. In addition, Noah LSM has extensive calculations for thaw and refreeze of snow cover, snow albedo changes due to aging of the snowpack [13], and distinguishes between frozen and liquid soil moisture. These characteristics are essential for simulating high-latitude land surfaces where the ground is covered by snow for much of the year and permafrost greatly influences soil hydrology [11].

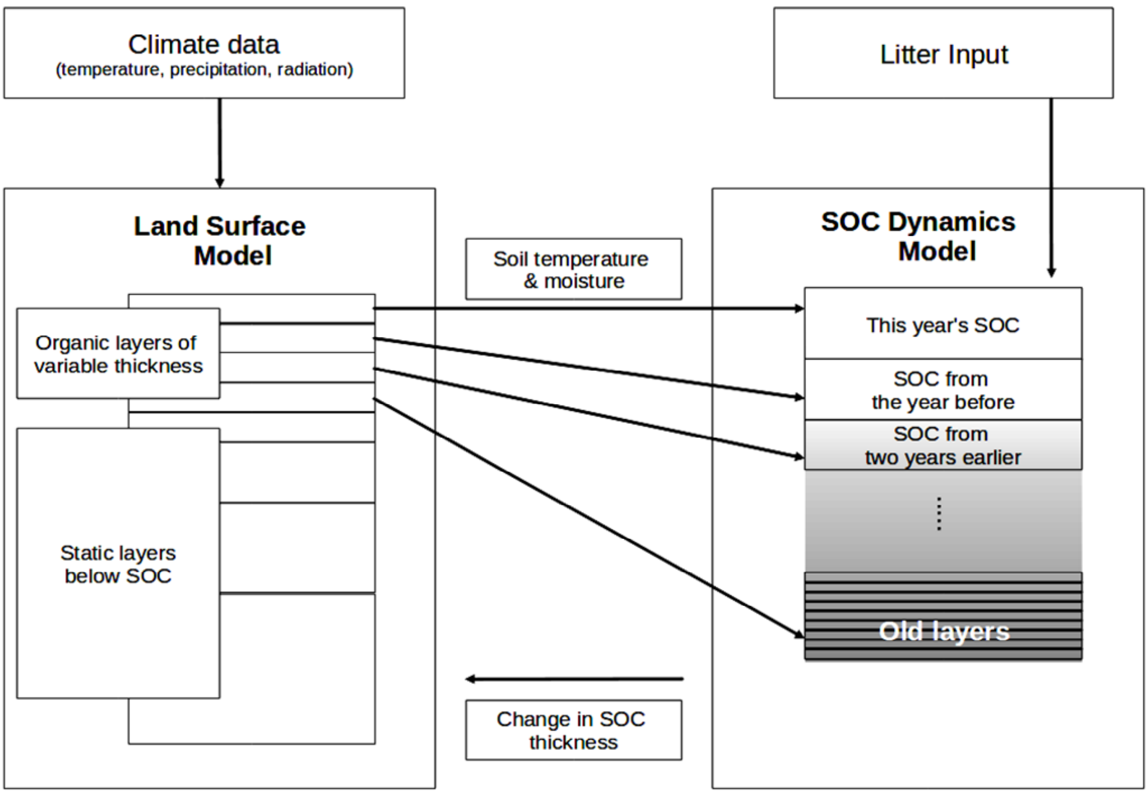

Figure 1. The structure of the Physical and Biogeochemical Soil Dynamics Model (PB-SDM). The SDM uses the soil temperature and moisture from the Noah Land Surface Model (LSM) to calculate the decomposition of soil organic carbon (SOC), while the LSM incorporates the change in SOC thickness from the SDM. Note that the LSM and SDM each has its own set of layers. The color gradation in the SDM indicates changing soil quality as litter decomposes into humus.

We modified the LSM to account for feedback of changing SOC depth. LSM originally included four layers of soil, with thicknesses of 0.1, 0.3, 0.6, and 1 m, and a single layer of vegetation canopy. We added four more soil layers on top, each starting at 0.025 m. Each of the four layers can expand to 0.1 m according to the total accumulation of SOC in the SDM. We tried to avoid having a thicker soil layer on top of a thinner layer by adjusting the layers from the bottom first and by keeping the maximum thickness of 0.1 m. A minimum thickness of 0.025 m was set to avoid errors and inaccuracies that might result from values being too small.

The SDM is based on the model by Ise *et al.* [6]. SOC is pooled into fibrous litters and decomposed humus. New litter inputs are added to the fibrous litter pool. As the litter decomposes, part of the decomposed litter turns into humus. To account for the changing depth and accumulation of new organic material, SOC is pooled into annual layers. Each year, a new layer is created on top of the older SOC layers. At each time step, decomposition of litter and humus is calculated for each layer, while litter inputs are added only to the most recent layer. The thickness of each layer of SOC is then calculated. Soil temperature and moisture values used for calculating the decomposition rate of each SOC layer are taken from the soil layers of the LSM, as opposed to the SDM annual layers, according to its depth.

We used data measured at the flux tower site of the University of Alaska Fairbanks (UAF) to calibrate our parameters. The site is located 65˚07'24.4"N and 147˚29'15.2"W and is dominated by black spruce (*Picea mariana*) forest with tree heights up to 6.5 m. The forest floor is covered with sphagnum moss (*Sphagnum* spp.) [16]. Model parameters were adjusted to roughly fit the record of soil temperatures during the snow-free season of 2009, because most SOC decomposition occurs at temperatures above freezing. We also adjusted the model to fit the recorded depth of permafrost, and the amount of SOC taken from the site in September, 2009. We assumed that the record of active layer thickness taken at the time was roughly equal to the maximum active layer thickness. The litter input for the SDM was assumed to be constant at the rate of 0.358 kg $C \cdot m^{-2} \cdot y^{-1}$, a value estimated by the SEIB-DGVM model [17]. The model was ran for 2000 years by repeating the 2003 climate data from the same site.

To assess the impact of dynamic soil depth, we conducted an experiment with two models with static soil depth. In the first static model (Static 1), we replaced the four layers of SOC in LSM with a single static layer of 0.1 m thickness, from which all of the soil temperature and moisture data used to calculate SOC decomposition were taken, effectively turning the SDM into a single-layer model. In the second model (Static 2), the top two soil layers in the LSM were fixed at 0.1 and 0.2 m, generally matching the observed 0.3 m of SOC in the active layer at the UAF site. Soil temperatures and moistures for calculating litter decomposition were taken from the top 0.1 m of soil, while the calculation for humus used the second 0.2 m layer, effectively turning the SDM into a two-layer model. We ran these static models for 2000 years with the climate data from 2003 to compare the trajectory and equilibrium value of SOC.

3. RESULTS

The PB-SDM successfully reproduced the soil temperature, permafrost depth, and SOC amount of the UAF site. Comparison of the observed soil temperatures to the simulated soil temperatures showed a good estimate of spring and summer soil temperatures at a depth of 0.05 m, and the timing of spring thawing also matched the observations (**Figure 2**). There were, however, consistent

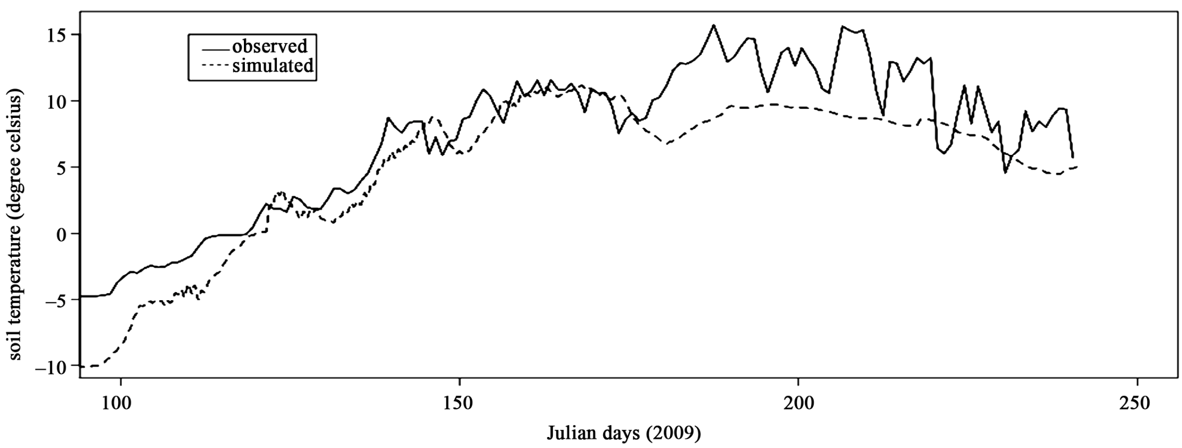

Figure 2. Comparison of the simulated soil temperature to observed soil temperatures in the spring-summer of 2009 at the boreal forest near Fairbanks. The observations were at 0.05 m depth, and the simulation data are from 0.059 m. The observed temperature is the daily average.

underestimates of soil temperatures during snow-covered periods, and a slight underestimate in late summer. The simulated total amount of carbon in the soil was 28.470 kg C·m^{-2} with the thickness of 0.294 m, compared to the observed 25.060 kg C·m^{-2} in the top 0.290 m of soil. The LSM layers deeper than 0.294 m remained below freezing throughout the year, compared to the observed permafrost depth of 0.290 m.

Comparison of the dynamic layered SOC model with static models showed significant differences in the amount of SOC (**Figure 3**). Litter for both static models was 1.578 kg C·m^{-2} at the end of the simulation as expected, since both models set the litter at top 0.1 m of the soil, while the dynamic model had 2.843 kg C·m^{-2} of litter. Litter in the static models was only 55.5% of the amount predicted by the dynamic model at the end of 2000 years. The humus at the end of the simulation using the Static 1 model was 14.768 kg C·m^{-2}, the Static 2 model had 31.820 kg C·m^{-2}, and the dynamic model had 26.054 kg C·m^{-2}. The humus predicted in Static 1 was 56.7% of that using the dynamic model, while Static 2 was 122.1% of the dynamic model. The total amount of SOC in the static model was 16.346 kg C·m^{-2} for the Static 1, 33.398 kg C·m^{-2} for the Static 2, and 28.897 kg C·m^{-2} for the dynamic model. The predicted SOC was 56.56% using Static 1 and 115.57% using Static 2, relative to the dynamic model. The amount of litter was at an equilibrium after 2000 years of simulation. In the dynamic model, the amount of litter initially increased past the equilibrium value and then gradually subsided. Equilibrium was not reached by 2000 years for the amount of humus in the dynamic model or the Static 2 model. Humus in the Static 1 model had either reached an equilibrium or the increase was too small to detect. The increase in the amount of humus was faster for both static models than the dynamic models in early years.

4. DISCUSSIONS

The dynamic PB-SDM model successfully reproduced the physical and biogeochemical conditions of high-latitude organic soil. The simulated soil temperature during spring and summer, the period when most SOC decomposition occurs, was a good match to observations. The permafrost depth and the amount and thickness of SOC in the simulation was close to observations. One main concern with our simulation is that we lack continuous observations of soil moisture data. Because the model's simulation of soil moisture fluctuated widely in response to precipitation, a single measurement of soil moisture at any one time could not be used to fit the model. However, we are confident in our model's performance for temperature, and any effect of the divergence of soil moisture on SOC dynamics was accounted for by adjusting the decomposition rate.

Comparison of the dynamic PB-SDM model and the static models showed that feedback of SOC dynamics and soil thermal and hydrological dynamics have significant effects on the calculation of the amount of SOC. While the depth of SOC layers in the static models was arbitrary, the SOC thickness of 0.3 m in the Static 2 model (0.1 m litter, 0.2 m humus) is not far from the predicted SOC thickness of the dynamic model of 0.2935 m. Yet even though the total depth of SOC was approximately the same, the total amount of SOC differed by more than 15%. It is interesting to note that the dynamic

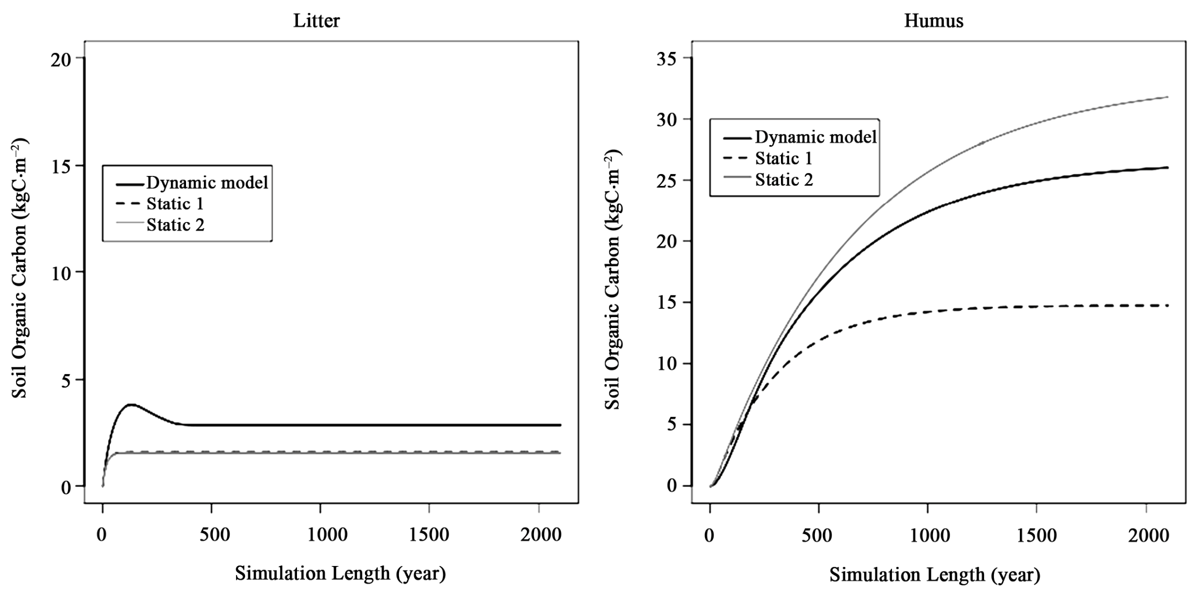

Figure 3. Comparison of the dynamic SOC model to the static models. Note the litter amount in the dynamic model increases rapidly at first, then subsides, suggesting a delayed reaction to the dynamics of soil thickness.

model and the Static 2 model differ not only in the rate and trajectory of approaching the equilibrium, but in the final values as well. These results suggest that a typical model with a predetermined thickness of SOC layers assuming a state of equilibrium could be significantly biased.

The dynamic model also showed differences in the trajectory of SOC amount. The rapid increase in litter and slow increase in humus in the dynamic model indicate that litter decomposition was slow at first, and accelerated later as a result of the increase in SOC thickness. We believe that the litter increased as SOC thickness increased, but eventually the surface soil dried as SOC thickness increased and moisture drained into deeper layers. Decomposition in humus, meanwhile, continued to slow down as SOC accumulated. The lack of such a pattern in the results of the static models could lead to significant bias in predicting the rate of change, especially under climate change scenarios.

The layered, dynamic structure also has the potential to capture the phenomenon of syngenetic permafrost aggradation, where lower layers of SOC get locked in permafrost as new SOC accumulates on top, leading to continuous accumulation of SOC in the soil [8]. To do so, however, probably requires further development of the model, such as finer and more flexible SOC layers in the LSM. Another potential benefit of the dynamic model is that it can calculate an expected pattern of C-14 distribution in the SOC layer. Discrepancies in C-14 distribution between the model result and observations would provide clues for past events at the observation site, such as wildfire, climatic changes, or influence of cryoturbation and other forms of vertical mixing of the soil.

Although our model shows promise, there are several areas in which it could be improved. The LSM uses the same set of soil parameters for the entire soil column. While our model accounts for changing soil depth due to SOC, the soil parameters remain the same regardless of the amount of SOC or the proportion of litter/humus for all layers. However, numerous studies have shown the importance of incorporating the highly porous near-surface SOC layers and a surface moss layer with less porous mineral soil layer underneath in modeling the soil thermal and hydrological dynamics of high-latitude peat soil [9-11,18-19]. The use of a single parameter for the entire soil column, however, also means that the effect of SOC dynamics in our model was most likely a conservative estimate.

The SDM can be improved by taking the vertical mixing of soil into account, such as cryoturbation. Koven *et al.* [9] showed that the effects of cryoturbation can be significant in calculating SOC, as it permits SOC into deeper layers. Also, the current structure of the model cannot simulate SOC that would accumulate at more than 0.4 m. SOC is observed below 0.4 m in significant amounts [3]. For the purpose of our study, the maximum of 0.4 m depth for SOC accumulation was a reasonable assumption because the active layers where SOC biochemical processes occur are well within 0.4 m of the soil surface. However, for further study of changing climate and degrading permafrost, SOC in deeper soil should be taken into account.

There is also an issue of the computation time and data set size. The layering of SOC by year means that for a 2000-year simulation, the model kept track of 2000 layers of SOC. Both the computational time and data set size was still within an acceptable level for our study, but as the years of simulation increase so does the computation time for each time step. For simulations of longer time periods, simplification of the SDM may be necessary.

Improvements of our model should include, first and foremost, incorporation of more realistic soil parameters with SOC amount and the litter/humus ratio. By incurporating SOC properties into LSM, we expect a more significant effect from the feedback from SOC accumulation. Once that is in place, the effects of vertical mixing of soil by cryoturbation similar to that of Koven *et al.* [9] could be added.

Another important improvement, particularly as we move on to experiments with changing climate, is the feedback of SOC litter input in response to changing soil conditions. Currently the model assumes constant input of litter, but as climate and soil conditions change, so would the vegetation. A warmer climate would promote faster decomposition, and also promote plant photosynthesis and increase litter input. Some studies have shown that the amount of SOC is determined more by soil conditions, which determine the decomposition process, than by vegetation cover, which determines SOC input [20]. Another study suggested that greater production of organic material is part of the cause of SOC accumulation in poorly drained organic soils, even though those areas have faster decomposition near the surface [21]. Some studies have indicated that increased photosynthesis would make up for carbon lost through increased decomposition [11], but other studies have shown a net release of carbon into the atmosphere with a warming climate [8].

Although it is still under development, the PB-SDM showed the significance of one of the feedback processes in high-latitude organic soil dynamics. Further development of the model has the potential to provide more insights into organic soil feedbacks in response to climate change.

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