Prediction of the vertical scaling of soil organic carbon in temperate forest soils using percolation theory

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Abstract. Forest soil stores a large portion of soil organic carbon (SOC), making it one of the essential components of global carbon cycling. There is apparent spatial variability of SOC in forest soils, but the mechanism that regulates the vertical pattern of SOC is still not clear. Understanding the vertical distribution as well as the transport process of SOC can be of

10   importance in developing comprehensive SOC models in forest soils, as well as in better estimating terrestrial carbon cycling. We propose a theoretical scaling derived from percolation theory to predict the vertical scaling of SOC with soil depth in temperate forest soils, with the hypothesis that the content of SOC along soil profile is limited by the transport of solute. The powers of the vertical scaling of 5 published datasets across different regions of the world are -0.920, -1.097, -1.196, - 1.062, and -1.038, comparing with the theoretical value of -1.149. Field data from Changbai Mountain region, Jilin, China, with

15   spatial variation of SOC correlating strongly to temperature, precipitation, and sampling slope is constrained well by theoretical boundaries predicted from percolation theory, indicating that the vertical transport so as the content of SOC along soil profile is limited by solute transport, which can be described by percolation theory in both small and large scales. Prediction of SOC content in Changbai Mountain region based on an estimated SOC content at 0.15 m from available data demonstrates a good agreement with field observation, suggesting the potential of collaborating the presented model with

20   other surface soil models to predict SOC storage and carbon cycling in temperate forest soils.

1 Introduction

Soil is the largest reservoir of terrestrial organic carbon, storing more carbon than is present in plant bodies and the atmosphere combined (Schlesinger, 1997). A large portion of soil organic carbon (SOC) comes from forest soils (accounts for about 73% as estimated by Sedjio (1993)), making the SOC in forest soils a vital component of global carbon cycling.

25   SOC content in forest soils depends on the budget between the organic matter input from plant remains and the output through carbon decomposition by soil microbes (Jenny, 1941; Schlesinger, 1977). There is apparent spatial variability of SOC in forest soils. The magnitude of SOC links to many factors including precipitation, temperature, soil properties (i.e. mineral content and mineral assemblage, Feller and Beare, 1997; Torn, 1997; Rasmussen and Southard, 2005), forest stands (Wang et al., 2015), and land use (Hao et al., 2015). Temperature mainly controls the decomposition of SOC through

30   affecting microbial activity (Jobbágy and Jackson, 2000), and generally negatively correlates to SOC content, while precipitation affects the production of plants as well as the decomposing process of plant litter into SOC, and has a positive correlation to SOC (Jobbágy and Jackson, 2000; Wang et al., 2002, Yang et al., 2007, Liu et al., 2016). The vertical distribution of SOC usually shows a strong gradient. In general, most SOC is retained in top-soils (~20 cm) (Fröberg et al., 2007, 2009; Kramer et al., 2010; Tate et al., 2011), and SOC content declines as soil depth goes deeper. Comparison of SOC

35   content at various climatic conditions and forest stands along the soil profile have revealed how the vertical distribution of SOC is affected by those relevant factors, but the mechanism that regulates the vertical pattern of SOC through soil profile is still not clear (Jobbágy and Jackson, 2000, Rumpel and Kögel-Knabner, 2011; Ota et al., 2013). Several models (Braakhekke et al., 2011; Ota et al., 2013) have been developed to predict SOC or soil organic matter contents in forest soils, with adopting different approaches describing the vertical transport process of SOC. Thus, understanding the dynamics of vertical

40   pattern of SOC in forest soils can be one of the key factors for developing comprehensive SOC models, which is of great

importance for predicting terrestrial carbon cycling both in short and long time scales, as well as for improving predictions of the response of soil carbon cycle to climate change and human activities.

45 Major sources of SOC in the surface layer of forest soil are leaf litter and plant debirs, while down further in the subsurface layer, the carbon delivered from plant remains above plays a minor role, and might be neglected (Fröberg et al., 2007, 2009). The input of SOC in the subsurface layer mainly comes from the downward movement of soil carbon in the form of dissolved organic carbon (DOC), and from root litter along the soil profile (Neff & Asner, 2001; Baisden and Parfitt, 2007; Leifeld and Kögel-Knabner, 2001). Given the long lifespans of course roots (>2 mm in diameter), and the dramatically decreasing trend of fine root litter production with soil depth (Trumbore et al., 2006), carbon input from root litter likely to

50 contributes a very small part of total SOC in the subsurface layer of soil (Gill and Jackson, 2000; Joslin et al., 2006). Meanwhile, SOC from the displacement and deformation of the soil matrix can be extremely slow (Elzein and Balesdent, 1995). Many studies have found a deeper SOC profile than that of living roots, suggesting that the downward transport of DOC along the soil profile is the potential driver of the redistribution of carbon in the soil (Jobbágy and Jackson, 2000; Neff & Asner, 2001; Baisden and Parfitt, 2007, Ota et al., 2013). Therefore, the vertical pattern of SOC along soil profile is

55 strongly related to the transport of DOC by percolating water in forest soils.

Given the vital role of the percolating water as an active agent that transports and redistributes the SOC in forest soils, here we propose to apply percolation theory to explain and predict the vertical scaling of SOC content in temperate forest soils. We hypothesize that in temperate forest soils, water percolating downward along soil profile is the key factor that controls

60 the distribution of SOC, while the effect from the carbon input from roots and soil matrix can be neglected, such that the scaling of SOC content with soil depth is constrained by the vertical transport of the percolating water, which can be described by percolation theory. The proposed theoretical scaling is evaluated by published data of SOC in temperate forest soils across the world, as well as our field data from temperate forests soils in Changbai Mountain region, China.

2 Materials and Methods

65 ### 2.1 Theoretical framework of percolation theory

Percolation theory is one of the theories describing non-Gaussian transport, which has been recognized as a norm in natural porous media (e.g. Cushman & O'Malley, 2015). Within the theoretical framework of percolation theory, Hunt and Skinner (2008) developed a solute transport theory, and generated a function of solute arrival time distribution with transport distance in porous media. From the theory, the transport of solute slows down as it travels, such that the solute transport time,

70 t, does not increase linearly with transport distance, x. Instead, t increases with x to the power of D_b (Lee et al., 1999), with D_b as the fractal dimensionality of percolation backbone that is described by percolation theory. This power-law formulation has been observed and confirmed in the time dependence of chemical weathering rates and soil production rates in several studies (Friend, 1992; Gunnell, 2003; White and Brantley, 2003; Egli et al., 2014), where solute transport controls the rate of chemical weathering. Models derived from the theory have also been successfully developed to predict soil formation (Yu

75 and Hunt, 2017; 2018; Yu et al., 2017) and the depth of calcic horizon (Hunt and Ghanbarian, 2016).

The relevance of percolation theory to the vertical scaling of SOC content with soil depth is that the downward movement of SOC from the surface layer of soil can be a key factor that redistributes and controls the vertical pattern of SOC, and that the infiltration of SOC, mainly in the form of DOC along the soil profile ultimately traces back to the vertical transport of solute

80 in the soil. As described in percolation theory, the solute transport time t scales with transport distance, x, in the form of $t \propto x^{D_b}$, and the value of D_b is a given value in percolation theory that only depends on the moisture condition and the dimension of flow in the medium, regardless of other properties of the medium. For the application here, we consider the

transport of SOC in temperate forest soils as 3D saturated conditions, where D_b = 1.87 (Sheppard et al., 1999), since the percolation of SOC in soil is a wetting process. There also could be possibilities of 2D condition, for example, if along a

85 fracture plane, which might be less common in forest soils. Table 1 summarizes the values of D_b in different scenarios.

Table 1. Values of fractal dimensionality of percolation backbone (D_b) (from Hunt, 2015a)

Dimension and saturated conditions	D_b
2-D Saturated (random)	1.64
3-D Saturated or wetting (random)	1.87
2-D Unsaturated (invasion)	1.22
3-D Unsaturated or drying (invasion)	1.46

Thus, in the context of the transport of SOC in temperate forest soil, we have,

90 $$t \propto h^{1.87},$$ (1)

where t is the transport time of solute, and h is soil depth. By taking the time derivative of h, one can obtain the vertical scaling of delivery rate of SOC, $R_{soc,}$ with soil depth,

$$\frac{dh}{dt} = R_{soc} \propto h^{-0.87},$$ (2)

If we only consider the downward delivery of SOC from the soil surface as the source of SOC input to the subsurface layer,

95 and neglect the input of carbon from roots and the deformation of the soil matrix, one can derive the scaling of SOC, C_{soc} with soil depth h as,

$$C_{soc} \propto h^{-0.87}, \quad or \quad h \propto C_{soc}^{-1.149},$$ (3)

Eq. (3) can be rewritten in a more useful form for predicting SOC at any given h,

$$\frac{h}{h_s} = \left(\frac{C_{SOC(h)}}{C_s}\right)^{-1.149},$$ (4)

100 with C_s as a known SOC content (in most cases, the SOC content in the surface layer of soil), and h_s as the corresponding soil depth. Since SOC in the surface soil depends on the balance between carbon input and output, C_s can be different across sites.

Theoretical scaling of SOC with soil depth from Eq. (3) and (4) were compared with our field data as well as data from

105 published papers, to evaluate the application of percolation theory in predicting the vertical pattern of SOC in temperate forest soils in small and large scales. Field data were sampled from 6 temperate forests in Changbai Mountain region, Jilin, China, and published data were referenced from 5 datasets collected from temperate forest soils across different regions in the world.

2.2 Soil sampling and analysis

110 Soil samples were collected from 6 temperate forest soils (labelled as JL, CS, TS, LX, HS, and HG) in Changbai Mountain region, within Jilin Province, northeast of China, and all sites are barely disturbed by human activities. Changbai Mountain region is part of the northeast forest region in China. Except HG, which is the mixed-broadleaf conifer forest, the rest 5 sites are all broad-leaved deciduous forests. Dominant vegetation include *Fraxinus rhynchophylla Hance , Juglans mandshurica Maxim , Quercus mongolica Fisch. ex Ledeb , Acer pictumThunb. ex Murray , Betula costate,* and *Tilia amurensis.* Each site

115 includes two 30m × 30m plots (labelled as P1 and P2) with different sampling slope. Details of the 12 subsites are summarized in Table 2.

Table 2. Site information of the 6 temperate forests in Changbai Mountain region, Jilin, China

Site	Location	Forest Type	Precipitation (m/yr)	Temperature (°C)	Slope (°)
JL-P1	43°37"N 126°2'E	broad-leaved deciduous forest	0.65-0.7	4.9	12
JL-P2					18
CS-P1	43°28"N 126°48'E	broad-leaved deciduous forest	0.75	3.7	14
CS-P2					12
TS-P1	43°22'N 126°55'E	broad-leaved deciduous forest	0.75	3.7	24
TS-P2					22
LX-P1	43°3'N 129°3'E	broad-leaved deciduous forest	0.6	3.6	14
LX-P2					17
HS-P1	42°24'N 128°28'E	mixed broadleaf-conifer forest	0.67	2.2	13
HS-P2					18
HG-P1	43°19'N 130°23'E	broad-leaved deciduous forest	0.57	4.9	5
HG-P2					5

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Five sampling points were randomly set at each plot. Soil samples were collected using a stainless steel corer down to 1m or to C layer (if C layer is shallower than 1m), which were further divided into 5 soil intervals, 0-0.1 m, 0.1-0.2 m, 0.2-0.3 m, 0.3-0.5 m, and 0.5-1 m. Samples at the same soil layer from the 5 sampling points in each plot were mixed as one, and naturally air-dried with any plant residue removed before analyzing. Dry samples were then milled and sieved through 10-

125 mesh screen. SOC of each soil layer was determined using potassium dichromate oxidation method with external heating following the standard procedure (LY/T 1237-1999). The average depth of each soil interval was taken as the corresponding soil depth.

2.3 Sources of external data from published papers

130 Sources of the published data (Table 3) include 3 global databases of soil profile in temperate forest soils (National Soil Characterization Database produced by the U.S. Department of Agriculture, World Inventory of Soil Emission Potential Database, and the Canadian Forest Service) summarized in Jobbágy and Jackson (2000), which cover 60 samples for the temperate deciduous forest, and 123 for the temperate evergreen forest across the world, and 3 field studies done in Hailun, China (Hao et al., 2015), Qinling Mountains, China (Wang et al., 2015), and Hainich, Germany, (Braakhekke et al., 2011).

135 Soil depths were taken as the averaged depth of each soil interval, and the unit of SOC was converted from g kg^{-1} to g 100g^{-1}, except data from Jobbágy and Jackson (2000), which was presented in relative proportion content throughout the first meter of soil in the original article.

Table 3. Site information of referenced data from published papers

Site	Location	Precipitation (m yr^{-1})	Temperature (°C)	Reference
3 Global databases	NA	NA	NA	Jobbágy and Jackson, 2000
Hailun	47°26'N, 126°38'E	0.5-0.6	1.5	Hao et al., 2015
Qinling Mountains 1	34°04'-34°35'N 106°54'-107°11'E	0.6-0.9	11	Wang et al., 2015
Qinling Mountains 2	34°10'-34°20'N 106°28'-106°38'E	0.9	7.6	Wang et al., 2015
Hainich, Germany	51°4.76'N 10°27.12'E	0.8	7-8	Braakhekke et al., 2011

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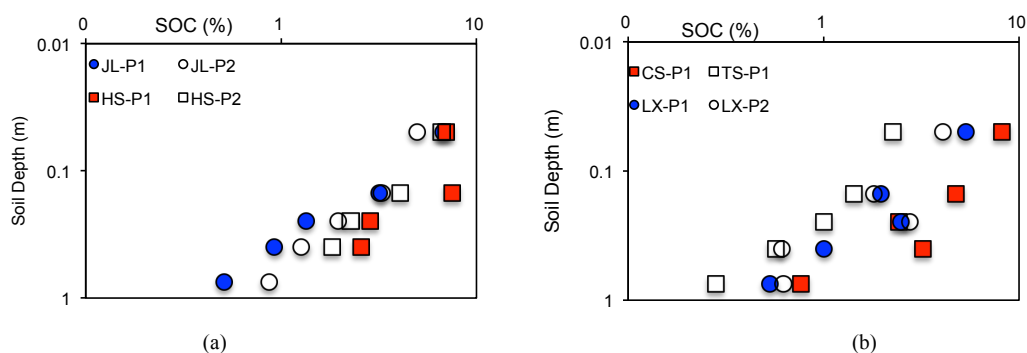
3 Results

Sampling results from 6 temperate forest soils in Changbai Mountain region is summarized in Table 4, with surface SOC ranging from 2% to 8%. The SOC content demonstrates spatial variability that strongly correlates to temperature, precipitation, and slope (Fig. 1 and 2). In general, cooler sites retained more SOC than warmer ones (JL-P1 vs. HS-P1 and

145 JL-P2 vs. HS-P2 in Fig. 1(a)), and precipitation favours the production of SOC (CS-P1 vs. LX-P1 in Fig.1(b)). Effects of temperature and precipitation on SOC are in accordance with previous studies (e.g. Jenny, 1941; Jobbágy and Jackson, 2000; Wang et al., 2002; Liu et al., 2016). We examined the effect of slope, and sites with identical climatic conditions but steeper slopes show lower SOC contents (JL-P1 vs. JL-P2, HS-P1 vs. HS-P2, CS-P1 vs. TS-P1, and LX-P1 vs. LX-P2, in Fig. 1).

150      **Table 4**. SOC (%) in the 6 temperate forest soils (12 subsites) in Changbai region, Jilin, China

	Soil Depth (m)					
	0.05	**0.15**	**0.25**	**0.4**	**0.75**	
Site	SOC (%)					**Slope (°)**
JL-P1	6.745	3.191	1.345	0.926	0.511	12
JL-P2	4.944	3.277	1.955	1.272	0.868	18
CS-P1	8.160	4.763	2.431	3.215	0.766	14
CS-P2	8.354	4.580	2.726	2.220	0.766	12
TS-P1	2.264	1.427	0.999	0.568	0.281	24
TS-P2	2.976	3.671	1.707	0.933		22
LX-P1	5.319	1.966	2.485	1.006	0.532	14
LX-P2	4.081	1.813	2.762	0.615	0.624	17
HS-P1	7.028	7.498	2.860	2.564		13
HS-P2	6.625	4.053	2.273	1.821		18
HG-P1	5.872	3.704	1.522	1.106		5
HG-P2	7.477	3.306	1.196	1.485		5

(a)                    (b)

155  **Figure 1:** Effects of temperature, precipitation and slope on SOC content.

 (a) Effects of temperature (JL-P1 vs. HS-P1, JL-P2 vs. HS-P2) on SOC.

 (b) Effects of precipitation (CS-P1 vs. LX-P1) on SOC.

 (a) and (b) Effects of slope (JL-P1 vs. JL-P2, HS-P1 vs.HS-P2, CS-P1 vs. TS-P1, and LX-P1 vs. LX-P2) on SOC.

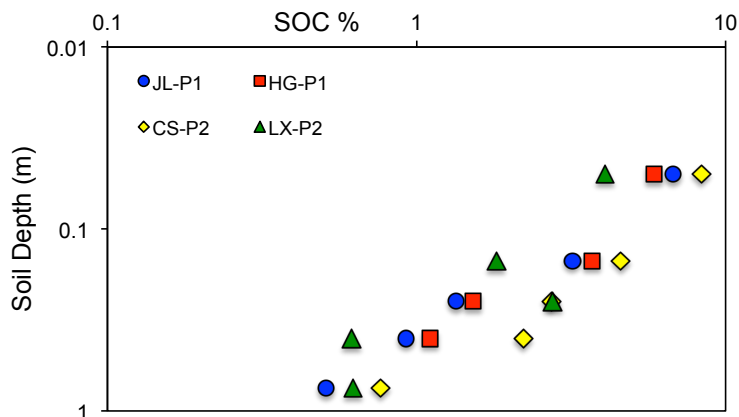



Figure 2: Combined effect of slope plus precipitation (CS-P2 vs. LX-P2, and JL-P1 vs. HG-P1), and slope plus temperature (LX-P2 vs. HG-P1) on SOC.

Figure 2 shows the effects of temperature and precipitation on SOC when coupled with slope. Temperature in CS-P2 and LX-P2 are close, but the higher precipitation and lower slope in CS-P2 tend to retain more water, resulting in higher SOC. One the contrary, JL-P1 has similar temperature with HG-P1, but it is wetter and steeper. The SOC contents in these two subsites are close, indicating that the feedbacks from higher precipitation and steeper slope seem to be neutralized here. When precipitation is close, SOC in LX-P2 is lower than that in HG-P1. Cooler climate in LX-P2 favours the accumulation of SOC, however, the much more steeper (17 degrees vs. 5 degrees) topography has a more negative effect such that SOC is lower in LX-P2.

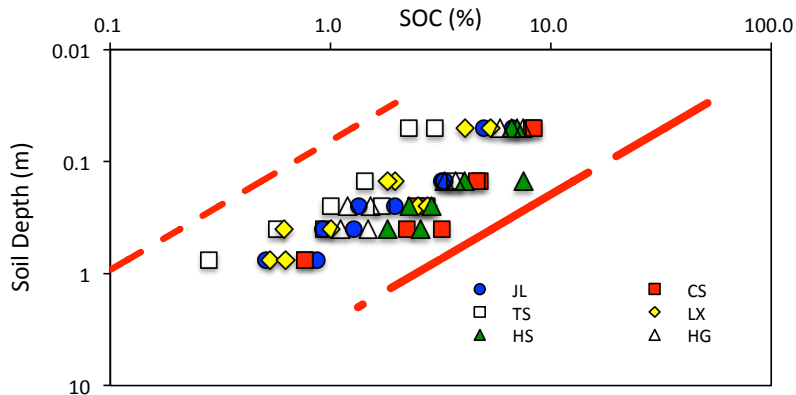



Figure 3: Comparison of theoretical scaling of SOC proposed by percolation theory with observed data from temperate forest soils in Changbai Mountain region.

In Fig. 3, we plot our field observations from the 6 study sites comparing with theoretical scalings predicted from Eq. (4). Minimum and maximum predictions were calculated with setting $C_{s(max)}$ = 12.78%, $C_{s(min)}$ = 0.49%, and h_s = 0.1485m. Dai et al. (2009) summarized SOC in A layer of 199 soil profiles in northeast forest region in China, with 0.49% as the lowest value and 12.78% as the highest. We averaged the depth of A layers of 594 soil profiles within Changbai region, resulting an averaged depth of 0.1485m, and took this value as the corresponding h_s for A layer.

180   As shown in Fig. 3, all observed data are within the predicted boundaries from percolation theory, with variation of SOC in
the same soil depth among sites, which is affected by climate and topography. Variation of the environmental conditions
causes the spatial variability of SOC in the surface layer of soil (Fig.1 and 2, and the intercept on y-axis), but has no
significant effect on the vertical scaling of SOC (shown as the slopes on the log-log plot), indicating that the vertical
distribution of SOC is limited by the vertical transport of solute in temperate forest soils regardless of the carbon input from

185   soil surface.

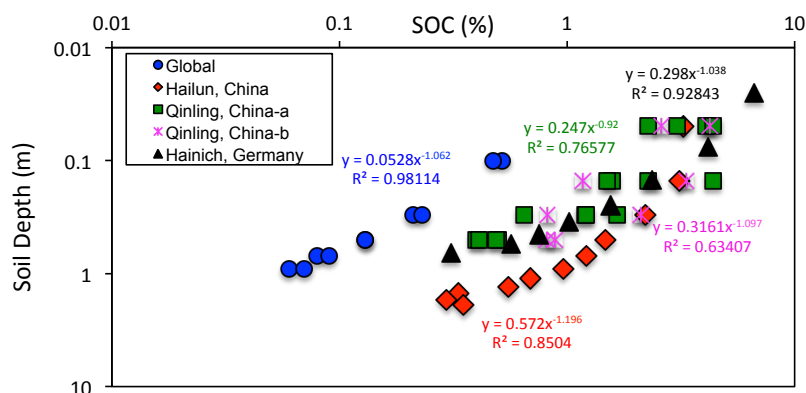



Figure 4: Vertical scaling of SOC content from 5 published datasets including a global dataset referenced from Jobbágy and
Jackson (2000), and 3 field studies done in Hailun (Hao et al., 2015), and Qinling Mountains, China (Wang et al., 2015), and
Hainich, Germany, (Braakhekke et al., 2011)

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Figure 4 demonstrates the vertical scaling of SOC content with soil depth from published data (Wang et al., 2015, Hao et al.,
2015, Jobbágy & Jackson, 2000, and Braakhekke et al., 2011). The scaling powers are -0.920, -1.097, -1.196, - 1.062, and -
1.038 from the 5 datasets (average is -1.063), comparing with the theoretical scaling, -1.149 in Eq. (3), demonstrating a good
agreement between prediction and observation. Data referenced from Jobbágy and Jackson (2000) with scaling power of -

195   1.062 is quite convincing for it include a total of 183 soil profiles in temperature forest soils across different regions of the
world, indicating that the presented theoretical scaling can be applied in large-scale of prediction.
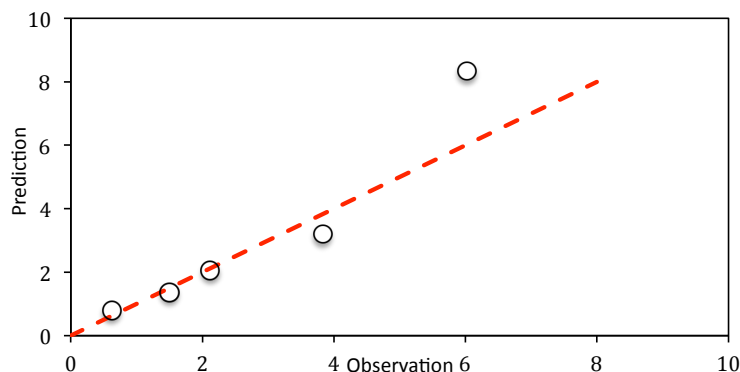
Figure 5: Comparison of predication from percolation theory with averaged SOC content across 6 study sites in Changbai
Mountai region. Dash line represents 1:1 ratio.

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Figure 5 shows the prediction of SOC (%) along soil profile in Changbai Mountain region, comparing with the averaged
values of our field data in the 6 temperate forest soils. Theoretical values were predicted from Eq. (4) with setting

C_s = 3.233 % and h_s = 0.1485 m. The values were estimated from the average values of SOC and soil depth of A layer from 594 sampling sites in Changbai region. Except the data point at 0.05 m, all values are almost on the 1 to 1 line, demonstrating a good agreement between prediction and field data.

4 Discussions

In accordance with previous studies (e.g. Jenny 1941; Jobbágy and Jackson, 2000; Liu et al., 2016), our field data shows spatial variability of SOC strongly correlates to temperature and precipitation across sites, with a possible linear relationship. SOC in HS-P1 is about 1.5 times higher than JL-P1 in average, if we take the ratio of SOC across the two subsites at each layer, while the temperature is 1.5 times cooler. SOC in CS-P1 is about 1.60 times of that in LX-P1, and precipitation in CS-P1is 1.25 times higher. Sampling slope also affects the content of SOC since it affects the ability of soil to retain water. We haven't found a clear function of slope and SOC based on the available data. The effect of forest type was not considered. A study (Sun et al., 2019) conducted across 3 forest types, conifer, mixed, and broadleaf forests show that there is no significant difference of SOC across these forest types. The dominant forest type of our study is broadleaved deciduous forest, with an exception of HG, which is dominated by conifer-broadleaf forest.

Figure 3 and 4 demonstrates good agreement between theory and observation from both published data and our sampling results. Regardless of the variation of SOC across sites at the same soil layer, the scaling power of the vertical scaling of SOC with soil depth agrees well with the prediction, and our field data is constrained well by the theoretical boundaries. The results suggest that the transport of solute in soil dominates the vertical transport so as the vertical distribution of SOC in temperate forest soils, such that the vertical scaling of SOC follows the scaling of solute transport proposed by percolation theory, and it can be predicted by the presented scaling in this paper.

The prediction of SOC content through soil profile using Eq. (4) with available site information shows fairly good agreement with field data, except the SOC at 0.05m. Shallow soil is more vulnerable to external disturbance, thus SOC at 0.05 m might be not as stable and reliable as SOC down further. To apply Eq. (4) for SOC prediction, there is an absent value of C_s in Eq. (4), which needs to be obtained either from field sampling or from other surface SOC models, such as GIS technology. Rough estimation of SOC might be accomplished, given the clear correlation between precipitation, temperature and SOC, if C_s and the corresponding depth h_s are known for a referenced site with similar slope.

5 Conclusions

The vertical pattern of SOC concentration in temperate forest soils in both small and large scales agrees well with the theoretical scaling proposed by percolation theory, suggesting the downward movement of SOC transported by the percolating water may be the dominant source of SOC in the subsurface layer, and the redistribution of SOC is mainly limited by the vertical transport of solute. Percolation theory is capable to describe and predict the downward transport as well as the vertical scaling of SOC in temperate forest soils.

With the spatial variation of SOC at same soil depth across sites, the vertical scaling of SOC with soil depth stays with what is described by percolation theory, since the distribution of SOC is controlled by solute transport. The prediction of SOC using estimated average C_s from available data agrees well with the averaged field values, suggesting the potential of adopting the presented method to other surface SOC models in developing comprehensive SOC models to predict SOC storage, and better understand and estimate carbon cycling in temperate forest soils.

Author Contributions

Fang Yu, led the conceptualization, investigation, and the methodology of the study, and contributed to data analysis and wrote the manuscript.

Jinping Zheng, contributed to data sampling, funding acquisition, and supported the conceptualization, data analysis and
250 manuscript editing.

Qiang Liu, supported the data analysis, funding acquisition, the investigation and methodology of the study, as well as the manuscript editing.

Chunnan Fan, led the project administration, contributed to the funding acquisition, supported the data sampling and the manuscript editing.

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Competing Interests

The authors declare that they have no conflict of interest.

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