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

Fang Yu¹, Jinping Zheng¹, Qiang Liu¹, Chunnan Fan¹.

¹ College of Forestry, Beihua University, Jilin, 132013, China

Correspondence to: Chunnan Fan (cn_fan@163.com)

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 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 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 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. 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 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 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 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.

Major sources of SOC in the surface layer of forest soil are leaf litter and plant debris, 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 coarse 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 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 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 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

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, \( t \), 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 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 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 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,

\[
t \propto h^{-0.87},
\]

(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, 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,

\[
C_{soc} \propto h^{-0.87}, \quad \text{or} \quad h \propto C_{soc}^{-1.149},
\]

(3)

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

\[
\frac{h}{h_s} = \left( \frac{C_{soc}}{C_s} \right)^{-1.149},
\]

(4)

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 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

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 pictum*Thunb. ex Murray, *Betula costate*, and *Tilia amurensis*. Each site includes two 30m \( \times \) 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  |                 |                              |                      |                  |           |
| CS-P1  | 43°28’N 126°48’E| broad-leaved deciduous forest| 0.75                | 3.7              | 14        |
| CS-P2  |                 |                              |                      |                  |           |
| TS-P1  | 43°22’N 126°55’E| broad-leaved deciduous forest| 0.75                | 3.7              | 12        |
| TS-P2  |                 |                              |                      |                  |           |
| LX-P1  | 43°3’N 129°3’E  | broad-leaved deciduous forest| 0.6                 | 3.6              | 14        |
| LX-P2  |                 |                              |                      |                  |           |
| HS-P1  | 42°24’N 128°28’E| mixed broadleaf-conifer forest| 0.67               | 2.2              | 13        |
| HS-P2  |                 |                              |                      |                  |           |
| HG-P1  | 43°19’N 130°23’E| broad-leaved deciduous forest| 0.57               | 4.9              | 5         |
| HG-P2  |                 |                              |                      |                  |           |

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-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

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). 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°4’36’N 10°27.12’E            | 0.8                    | 7.8              | Braakhekke et al., 2011 |
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 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).

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

| Soil Depth (m) | Site   | SOC (%) | Slope (%) |
|---------------|--------|---------|-----------|
|               |        | 0.05    | 0.15      | 0.25      | 0.4       | 0.75      | 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     | 0.22      | 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     | 1.3       | 13        |
|               | HS-P2  | 6.625   | 4.053     | 2.273     | 1.821     | 1.8       | 18        |
|               | HG-P1  | 5.872   | 3.704     | 1.522     | 1.106     | 5         |           |
|               | HG-P2  | 7.477   | 3.306     | 1.196     | 1.485     | 5         |           |

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 $C_{\text{max}} = 12.78\%$, $C_{\text{min}} = 0.49\%$, and $h_s = 0.1485$ m. 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 0.1485 m, and took this value as the corresponding $h_s$ for A layer.
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 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).

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 -1.062 is quite convincing for it include a total of 183 soil profiles in temperate 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 prediction from percolation theory with averaged SOC content across 6 study sites in Changbai Mountain region. Dash line represents 1:1 ratio.

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...
Cs = 3.233 % and hs = 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-P1 is 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 stays with what is described by percolation theory, since the distribution 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.

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 Cs 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 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.

Competing Interests
The authors declare that they have no conflict of interest.

References
Braakhekke, M. C., Beer, C., Hoosbeek, M. R., Kruijt, B., Schrumpf, M., and Kabat, P.: SOMPROF: a vertically explicit soil organic matter model. Ecol. Modell., 222(10), 1712-1730, doi: 10.1016/j.ecolmodel.2011.02.015, 2011.
Baisden, W. T. and Parfitt, R. L.: Bomb 14C enrichment indicates decadal C pool in deep soil? Biogeochemistry, 85, 59–68, doi: 10.1007/s10533-007-9101-7, 2007.
Cushman, J. H. and O’Malley, D.: Fickian dispersion is anomalous. J. Hydro., doi:10.1016/j.jhydrol.2015.06.036, 2015.
Dai, W., Huang, Y., Wu, L. and Y, J.: The relationship between SOC and pH of zonal soils in China (in Chinese). Acta pedologica snica. 46, 851–860, 2009.
Elzein, A. and Balesdent, J.: Mechanistic simulation of vertical distribution of carbon concentrations and residence times in soils. Soil Sci. Soc. Am. J., 59, 1328–1335, 1995.
Egli, M., Dahms, D. and Norton, K.: Soil formation rates on silicate parent material in alpine environments: Different approaches–different results. Geoderma, 213, 320–333, doi: 10.1016/j.geoderma.2013.08.016, 2014.
Feller, C. and Beare, M. H.: Physical control of soil organic matter dynamics in the Tropics. Geoderma, 79, 69-116, doi: 10.1016/S0016-7061(97)00039-6, 1997.
Friend, J. A.: Achieving soil sustainability. J. Soil Water Conserv., 47, 156–157,1992.
Fröberg, M., Hanson, P. J., Trumbore, S. E., Swanston, C. W. and Todd, D. E.: Flux of carbon from 14C-enriched leaf litter throughout a forest soil mesocosm. Geoderma, 149, 181–188, doi: 10.1016/j.geoderma.2008.11.029, 2009.
Fröberg, M., Jardine, P. M., Hanson, P. J., Swanston, C. W., Todd, D. E., Tarver, J. R. and Garten Jr, C. T.: Low dissolved organic carbon input from fresh litter to deep mineral soils. Soil Sci. Soc. Am. J., 71, 347–354, doi: 10.2136/sssaj2006.0188, 2007.
Gill, R. A. and Jackson, R. B.: Global patterns of root turnover for terrestrial ecosystems. New Phytol., 147, 13–31, doi: 10.1046/j.1469-8137.2000.00681.x, 2000.
Gunnell, Y.: Radiometric ages of laterites and constraints on long-term denudation rates in West Africa. Geology. 31, 131–134, doi: 10.1130/0091-7613, 2003.
Hunt, A. G.: Soil depth and soil production. Complexity, doi: 10.1002/cplx.21664, 2015a.
Hunt, A. G.: Predicting rates of weathering rind formation. Vadose Zone J., doi: 10.2136/vzj2014.09.0123, 2015b.

Hunt, A. G. and Ghanbarian, B.: Percolation theory for solute transport in porous media: Geochemistry, geomorphology, and carbon cycling. Water Resour. Res., 52, 7444–7459, doi: 10.1002/2016WR019289, 2016.

Hunt, A. G. and Skinner, T. E.: Longitudinal dispersion of solutes in porous media solely by advection. Philos. Mag., 88, 2921–2944, 2008.

Hao, X., Han, X., Li, L., Zou, W., Lu, X. and Qiao, Y.: Profile distribution and storage of soil organic carbon in a black soil as affected by land use types. (in Chinese). Chinese Journal of Applied Ecology, 26 (4), 965–972, doi: 10.13287/J.1001-9332.2015.0010, 2015.

Jobbágy, E. G. and Jackson, R. B.: The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl., 10(2), 423–436, 2000.

Jenny, H.: Factors of Soil Formation: A System of Quantitative Pedology. New York: McGraw-Hill Book Company, Inc, 1941.

Joslin, J. D., Gaudinski, J. B., Torn, M. S., Riley, W. J. and Hanson, P. J.: Fine-root turnover patterns and their relationship to root diameter and soil depth in a C-labeled hardwood forest, New Phytol., 172, 523–535, doi: 10.1111/j.1469-8137.2006.01847.x, 2006.

Kramer, C., Trumbore, S., Fröberg, M., Dozal, L. M. C., Zhang, D., Xu, X., Santos, G. M. and Hanson, P. J.: Recent (<4 year old) leaf litter is not a major source of microbial carbon in a temperate forest mineral soil. Soil Biol. Biochem., 42, 1028–1037, doi: 10.1016/j.soilbio.2010.02.021, 2010.

Keith, H., Mackey, B. G. and Lindenmayer, D. B.: Re-evaluation of forest biomass carbon stocks and lessons from the world’s most carbon-dense forests. PNAS, 106, 28, 11635–11640, doi: 10.1073/pnas.0901970106, 2009.

Leifeld, J. and Kogel-Knabner, I.: Organic carbon and nitrogen in fine soil fractions after treatment with hydrogen peroxide. Soil Biol. Biochem., 33, 2155-2158, doi: 10.1016/j.soilbio.2010.02.021, 2001.

Liu, Y., Li, S., Sun, X. and Yu, X.: Variations of forest soil organic carbon and its influencing factors in east China. China. Ann. For. Sci., 73, 501–511, doi: 10.1007/s13595-016-0543-8, 2016.

LY/T 1237-1999: Determination of organic matter in forest soil and calculation carbon-nitrogen ratio. China Academy of Forestry Research Institute of Forestry forest soil, 1999.

Neff, J. C. and Asner G. P.: Dissolved organic carbon in terrestrial ecosystems: Synthesis and a model. Ecosystems, 4, 29–48, doi: 0.1007/s100210000058, 2001.

Ota, M., Nagai, H. and Koarashi, J.: Root and dissolved organic carbon controls on subsurface soil carbon dynamics: A model approach. Journal of Geophysical Research: Biogeosciences, 118, 1646–1659, doi: 10.1002/2013JG002379, 2013.

Rumpel, C. and Kögel-Knabner, I.: Deep soil organic matter– A key but poorly understood component of terrestrial C cycle. Plant Soil, 338, 143–158, doi: 10.1007/s11104-010-0391-5, 2011.

Rasmussen, C. and Southard, R. J.: Mineral assemblage and aggregates control carbon dynamics in California conifer forest. Soil Sci. Soc. Am. J., 69, 1711–1721, doi: 10.2136/sssaj2005.0040, 2005.

Sheppard, A. P., Knackstedt, M.A., Pinczewski, W. V. and Sahimi, M.: Invasion percolation: new algorithms and universality classes. J Phys A Math., 32, L521–L529, doi: 10.1088/0305-4470/32/49/101, 1999.
Sedjo, R. A.: The carbon cycle and global forest ecosystem. Water Air Soil Pollutant., 70, 295–307, doi: 10.1007/BF01105003, 1993.

Schlesinger, W. H.: Carbon balance in terrestrial detritus. Annu. Rev. Ecol. Syst., 8, 51–81, doi: 0.1146/annurev.es.08.110177.000411, 1977.

Schlesinger, W. H.: Biogeochemistry, an analysis of global change. San Diego, California: Academic Press. doi: 10.1093/obo/9780199830601, 1997.

Sun, X., Tang, Z., Ryan, M. G., You, Y. and Sun, O. J.: Changes in soil organic carbon contents and fractionations of forests along a climatic gradient in China. For. Ecosyst., 1, 1–12, doi: 0.1186/s40663-019-0161-7, 2019.

Tate, K. R., Lambie, S. M., Ross, D. J. and Dando, J.: Carbon transfer from 14C-labeled needles to mineral soil and 14C- CO2 production, in a young Pinus radiate Don Stand. Eur. J. Soil Sci., 62, 127–133, doi: 10.1111/j.1365-2389.2010.01316.x, 2011.

Torn, M. S., Trumbore, S. E., Chadwick, O. A., Vitousekm P. M. and Hendricks, D. M.: Mineral control of soil organic carbon storage and turnover. Nature, 389, 170–173, doi: 10.1038/38260, 1997.

White, A. F. and Brantley, S. L.: The effect of time on the weathering rates of silicate minerals: Why do weathering rates differ in the lab and in the field? Chem. Geol., 202, 479–506, doi: 10.1016/j.chemgeo.2003.03.001, 2003.

Wang, D., Geng, Z., She, D., He, W. and Hou, L.: Soil organic carbon storage and vertical distribution of carbon and nitrogen across different forest types in the Qinling Mountains. (in Chinese). Acta Ecologica Sinica, 35(16), 5421–5429, doi: 10.5846/stxb201311032655, 2015.

Wang, S., Zhou, G., Lu, Y. and Zhou, J.: Distribution of soil carbon, nitrogen and phosphorus along Northeast China Transect (NECT), and their relationship with climatic factors. Acta Phytoecol Sin., 26, 513–517, doi: 10.1007/s11769-002-0041-9, 2002.

Yu, F. and Hunt, A.G.: An examination of the steady-state assumption in certain landscape evolution models. Earth Surf. Process Landf., 42, 2599–2610, doi: 10.1002/esp.4209, 2017.

Yu, F., Faybishenko, B., Hunt, A.G. and Ghanbarian, B.: A simple model of the variability of soil depths. Water, 9 (7), 460, doi: 10.3390/w9070460, 2017.

Yu, F. and Hunt, A.G.: Predicting soil formation on the basis of transport-limited chemical weathering. Geomorphology, 301, 21–27, doi: 10.1016/j.geomorph.2017.10.027, 2018.

Yang, Y., Mohammam, A., Zhou, R. and Feng, J.: Storage, pattern and environmental controls of soil organic carbon in China. Biogeochemistry, 84, 131, doi: 10.1007/s10533-007-9109-z, 2007.