Possible effect of soil organic carbon on its own turnover: A negative feedback

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ABSTRACT

Soil carbon (C) sequestration plays an important role in mitigating climate change; therefore, it is essential to understand the mechanisms underlying soil organic carbon (SOC) turnover and dynamics. The humification coefficient of input organic materials (h) and the SOC decomposition rate (k) together control the SOC turnover, and they have been well known to be affected by factors including climatic factors, organic material qualities, soil characteristics, and anthropogenic activities. However, the SOC content changes over time, and thus far, whether the SOC content is an inherent factor has not been understood clearly. By using a new mathematical method, we found that SOC is possibly able to regulate its own turnover through a negative feedback: h decreases and k increases simultaneously with an increase in the SOC content. This feedback is caused by a series of chemical, biological, and physical mechanisms. We suggest that the response of the SOC pool to climate change is a function of the C input level to soil, temperature, and negative feedback of the SOC turnover; in addition, organic materials should be applied in priority to soils with low SOC content to enhance the soil C sequestration.

1. Introduction

The global soil organic carbon (SOC) pool is approximately twice the size of the atmospheric pool and approximately thrice the size of the biotic pool (Lal, 2004); hence, a small change in the C loss from soils exerts a significant influence on the carbon dioxide (CO_2) concentrations in the atmosphere (Smith et al., 2008a). Soil C sequestration plays an important role in mitigating climate change (Lal, 2004; Smith et al., 2008b); therefore, it is essential to understand the mechanisms underlying SOC turnover and dynamics.

The first-order kinetic model (Eq. (1)) and its solution (Eq. (2)) have been widely used for studying the SOC turnover and dynamics (Jenkinson et al., 1994; Jenny, 1941).

$$dC/dt = I_m h - Ck \quad (1)$$

$$C = I_m h/k - (I_m h/k - C_0)\exp(-kt) \quad (2)$$

where C denotes the SOC content (g kg^{-1}); C_0, the initial SOC content at the beginning of a long-term experiment; t, time (yr); I_m, the C input level per soil mass (g kg^{-1} yr^{-1}); h, the proportion of input C incorporating into SOC (i.e., humification coefficient, no unit); and k, the SOC decomposition rate (yr^{-1}). When $dC/dt = 0$, $E = I_m h/k$, where E is the SOC equilibrium level (g kg^{-1}).

It is believed that h and k are affected by several factors such as climatic factors (e.g., temperature and moisture), soil characteristics (e.g., texture), input organic material qualities (e.g., C/nitrogen ratio and lignin content), and anthropogenic activities (e.g., tillage) (Falloon and Smith, 2009; Prescott, 2010). These two coefficients are considered to be constant for a given set of the above factors. As a result, the SOC equilibrium level increases linearly with an increase in the C input level (Paustian et al., 1997) (Fig. 1b). However, it has recently been shown that SOC can be saturated (Six et al., 2002), suggesting that the SOC equilibrium level does not increase linearly without any limit with an increase in the C input level. Stewart et al. (2007) proposed a saturation-based SOC

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dynamics pattern: not only does the SOC content change asymptotically with time (Fig. 1a), but the SOC equilibrium level also increases asymptotically with an increase in the C input level, and the maximum equilibrium value is the SOC saturation (S) (Fig. 1c). They suggested that a decreasing h with increasing SOC content (i.e., $h = 1 - C/S$) is responsible for this asymptotic relationship. However, they considered that k remained unchanged irrespective of the SOC content.

Some previous studies have reported that k increases with an increase in the SOC content. Estimations with long-term experiments based on the first-order kinetics (Eq. (1)) show an increase in k with an increase in the SOC content (Cai and Qin, 2006; Huggins et al., 1998; Li et al., 2010). Radiocarbon (δ^{14}C) dating (Janzen et al., 1998) and laboratory incubation (Wang et al., 2012) of soil from long-term agroecological experiments show high k in the case of a high SOC content. Moreover, the enrichment of SOC improves soil aggregation (Blanco-Canqui and Lal, 2004; Bronick and Lal, 2005), that is to say, the proportion of macroaggregate increases with the increase in SOC content; meanwhile, seven studies using the δ^{13}C natural abundance technique show a higher k in macroaggregates than in microaggregates (Six and Jastrow, 2002), indicating indirectly an increase in k in the case of a relatively high SOC content.

Thus, confusion regarding the following remains for a given set of the abovementioned factors: (1) what the relationship between SOC equilibrium level and C input level is and (2) how h and k change with a change in the SOC content, or whether the SOC content affects h and k? It is likely that SOC saturation exists, and SOC influences its own turnover by simultaneously decreasing h and increasing k as it accumulates. Thus far, this hypothesis has not been tested conclusively.

2. Methods

2.1. Proposal of the integrated model

In this present study, we built a new model—the integrated model including two equations (Eqs. (3) and (4))—to describe the saturation-based SOC dynamics pattern.
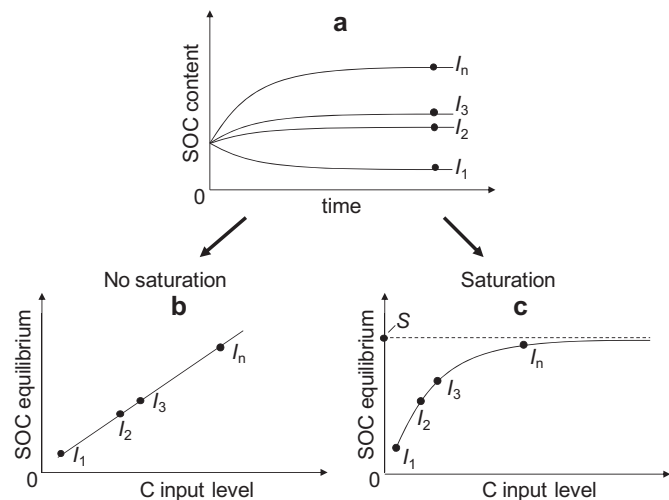
$$dC/dt = Ir(1 - C/E) \tag{3}$$

Fig. 1. SOC dynamics patterns. (a), SOC content changes asymptotically to equilibrium over time; (b), SOC equilibrium level increases linearly with a higher C input level assuming that there is no SOC saturation; and (c), SOC equilibrium level increases asymptotically with a higher C input level assuming that there is SOC saturation. Dots denote the SOC equilibrium levels (Modified from Stewart et al. (2007)).

$$dE/dI = R(1 - E/S) \tag{4}$$

where r denotes a constant reflecting the potential maximum SOC accumulation rate (g ha kg^{-2}) when the SOC content is 0 g kg^{-1} (Fig. 2). There is a specific r for each C input level per unit area (I, kg ha^{-1} yr^{-1}). R denotes a constant reflecting the potential maximum soil C sequestration efficiency (g ha yr kg^{-2}) (Fig. 2).

The solutions of these two equations are as follows:

$$C = E - (E - C_0)\exp\left(\frac{-Ir}{E}t\right) \tag{5}$$

and

$$E = S - (S - E_0)\exp\left(\frac{-R}{S}I\right) \tag{6}$$

where E_0 denotes the SOC equilibrium value when the C input level is zero. E_0 is an infinitesimal value to zero in theory but is usually $E_0 > 0$ according to the available data. This is possible not only because of the uncertainty of data (i.e., errors in the SOC content dynamics, C input level estimation, and regression) but also because of the fact that most soils contain a recalcitrant SOC fraction which can endure for hundreds to thousands of years. Eq. (5) explaining the SOC dynamics over time (C vs. t relationship) is called the "dynamics equation," and Eq. (6) depicting the relationship between the equilibrium level and the C input level (E vs. I relationship) is called the "equilibrium equation."

2.2. Method of analyzing the h vs. C and k vs. C relationships

The h vs. C and k vs. C relationships reflect the effect of the SOC content on h and k. It should be noted that when calculating these two relationships, the unit of the C input level must be set consistently with that of the SOC content in Eq. (1). Setting the total C input level that determines the SOC equilibrium level as I (C input level per field unit area, kg ha^{-1} yr^{-1}), and the C input level that is used for expressing the h vs. C and k vs. C relationships as I_m (C input level per soil mass, g kg^{-1} yr^{-1}), leads to the following:

$$I_m = \frac{I}{100DB} \tag{7}$$

where D denotes the thickness of the topsoil layer (cm) and B represents the bulk soil density (g cm^{-3}). The bulk soil density may
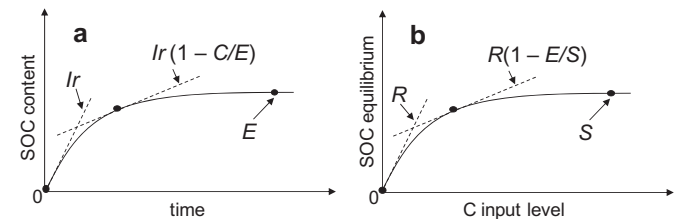

Fig. 2. Concepts of the potential maximum SOC accumulation rate and the potential maximum SOC sequestration efficiency. Assuming that the SOC content is 0 g kg^{-1}, C from organic material is added to soil at level I (kg ha^{-1} yr^{-1}). One year later, (a), the SOC content increases to C_1 for one year of input C, and r is defined as $(C_1 - 0)/(I * 1 \text{ yr})$; hence, the SOC content increase in unit time for the C input level is Ir. However, it becomes increasingly difficult for the soil to stabilize C as the SOC content increases to equilibrium (E, g kg^{-1}) over time. Alternatively, (a), the instantaneous practical SOC accumulation rate ($\Delta C/(I * 1 \text{ yr})$) decreases as $r(1 - C/E)$; hence, the instantaneous SOC content increase per unit time is $Ir(1 - C/E)$. A certain C input level leads to an equilibrium value. (b), Setting $I = nI_i$ ($n = 1, 2, 3...$), I_i as the unit C input level that is infinitesimal, and E_i as the relevant SOC equilibrium level, we obtain $R = E_i/I_i$. Further, the equilibrium increase per unit input level ($\Delta E/I_i$) decreases as $R(1 - E/S)$ when SOC equilibrium increases to saturation.