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The soil CO_2-lake is a key for understanding global climate change

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Abstract:

In addition to the widely recognized increase in atmospheric CO_2 concentration, are there other factors that will have an important impact on global warming? In this study, a concept of “soil CO_2-lake” was introduced, and the pivotal roles of soil CO_2-lake in carbon cycling and related climate changes were illustrated. We demonstrated that the soil CO_2-lake can link the aboveground and underground carbon processes, the organic-inorganic carbon conversion, and the carbon transfer between terrestrial and aquatic system, as well as directly change soil heat balance. The coupling of “soil CO_2-H_2O-mineral matter (MM)” may provide a new dimension for understanding the mechanism of global warming. While, the effects of soil CO_2-related processes on global climate changes may be concealed by that of atmospheric CO_2. The relationship between soil CO_2-lake dynamics and the major carbon cycle processes since the industrial revolution needs to be explored, and field manipulation experiments and monitoring platforms may be useful to determine the connections between soil CO_2-lake and climate changes during vegetation degradation and restoration. Although direct evidence of soil CO_2-lake in regulating global climate change is still to be obtained, we proposed to incorporate soil CO_2-lake into the global change model which may be helpful to comprehensively understand the carbon cycle and related climate changes.

Keywords: CO_2-lake, soil CO_2-H_2O coupling, soil heat balance, greenhouse effect.

The rise of atmospheric CO_2 is considered as the main driving force of global warming since the industrial revolution (Anderson et al., 2016). Much attention has also been paid to soil CO_2 since it may increase CO_2 emission into the atmosphere (Lei et al., 2021). It was found that soil and soil CO_2 can regulate the surface heat balance by enhancing heat retention (Zhang et al., 2020). We considered that soil CO_2 may potentially play a pivotal role in terrestrial carbon cycle. Paying attention to both the atmospheric CO_2 and soil CO_2 can not only reflect the heat absorption in the atmosphere, but also reflect the heat retention within soil, which is of great significance to comprehensively understand the carbon cycle and related climate changes.

In this study, we estimated the standing amount of soil CO_2 pool and its turnover rate in terrestrial lands. Then, a concept of "soil CO_2-lake" was introduced, and the pivot roles of soil CO_2-lake in carbon cycling and related climate changes were illustrated. Finally, how the "soil CO_2-lake" conception could contribute to global change studies was discussed.

1. The characteristics of soil CO_2 pool

Given that soil CO_2 concentration was usually in range of 0-50,000 ppm (Hashimoto et al., 2007) and responsive to temperate and precipitation (Ray et al., 2020; Lei et al., 2021), the soil CO_2 pool looks like a variable lake of CO_2, which turnover rapidly with large flow of input and output. The estimated standing amount of soil CO_2-lake in global terrestrial soil profile (1m deep), with average CO_2 concentration of 20,000 ppm, was 0.01 Pg C and 0.0054 Pg C when 50% and 25% of soil porosity was assumed, respectively (Fig.1a).

In addition, the soil CO_2-lake seemed active and changeable. As for the same 1 m soil profile with average CO_2 concentration of 20,000 ppm, if the total soil CO_2 emission of 1000 g C m^{-2} $year^{-1}$ was observed, the estimated turnover rate of soil CO_2 was 0.9 times $hour^{-1}$ and 1.9 times $hour^{-1}$ when 50% and 25% of soil porosity was assumed, respectively (Fig. 1b).

2. The pivot roles of soil CO_2-lake in carbon cycling and related climate changes

It is well known that soil CO_2-lake could be a major driver of aboveground carbon cycling. There was around 98 Pg C $year^{-1}$ of CO_2 emission from soil into atmosphere (Bond-Lamberty and Thomson, 2010; Lei et al., 2021). The emitted soil CO_2 may significantly influence vegetation photosynthesis when it was quickly re-fixed by understory plants (Brooks et al., 1997) or exert an effect of CO_2 fertilization (Huang et al., 2018). Then the soil CO_2 remaining in the atmosphere was supposed to make the greenhouse effect stronger.

However, the influences of soil CO_2-lake on belowground carbon cycling were not fully illustrated. Soil CO_2-lake could be closely related with other major carbon processes as well as directly change soil heat balance (Fig. 3). The soil CO_2-lake made a bridge between organic matter decomposition, inorganic matter weathering, and soil heat balance. On the one hand, soil CO_2-lake links organic realm to inorganic realm. Soil CO_2 may accumulate with the mineralization of litter and root-derived carbon during autotrophic (Ra) and heterotrophic respiration (Rh). The activities of soil fauna and/or microbiota enhance soil CO_2 production and then accelerate both the chemical weathering (Regnier et al., 2013; Yan et al.., 2014; Deng et al., 2022) and biogenic calcification (Briones et al., 2008). As a result, organic carbon was converted into inorganic carbon and transferred to aquatic system, which further regulated global carbon cycle by forging nexus between the continents, ocean and atmosphere. (Regnier et al., 2013; Battin et al., 2023). On the other hand, soil CO_2-lake could directly change soil heat balance. Soil CO_2, especially when its concentration reached around 7500 ppm, has been found to increase soil air temperature significantly and potentially contribute to the greenhouse effect (Zhang et al., 2020). Furthermore, such a non-severe increase of soil temperature will stimulate belowground biological activities (Wang et al., 2021) and enhancing silicate weathering (Deng et al., 2022). Finally, the activities of soil biota and root may improve soil aggregate structure with greater soil porosity (Lehmann et al., 2017), and, thus, increase soil water retention capacity and the volume of soil air. The soil aggregate and associated porosity function as ‘biogeochemical reactors’ (Battin et al., 2023) where organic matter, O_2, CO_2, H_2O and mineral-matter (MM) interact and coupling. As a result, both the size of soil CO_2-lake and the amount of inorganic carbon that transfers into aquatic system may be increased.

3. What could be added to global change studies by focusing on soil CO_2-lake?

Paying more attention on the soil CO_2 pool would be helpful in getting a full map of the mechanism for understanding of global change. Firstly, a holistic view of global carbon cycling could be obtained because the above- and belowground systems of terrestrial lands, as well as the terrestrial and aquatic systems, were fully connected through the soil CO_2-lake.

Secondly, the unstable and changing soil CO_2-lake may appear to be a huge uncertainty, but in fact it may provide a new dimension for explaining global climate change. In comparison to atmospheric CO_2, the spatial-temporal heterogeneity of soil CO_2 was much greater. Only when the relatively uniform atmospheric CO_2 is combined with the heterogeneous hydrothermal conditions can the climate and environmental changes in different regions of the earth be fully explained. The coupling of soil CO_2-H_2O-MM, together with the coupling of CO_2-H_2O in atmosphere (Held and Soden, 2000), is an important potential driving force of surface hydrothermal conditions, so it is necessary to combine the two (i.e., atmospheric CO_2 and soil CO_2) to interpret the CO_2-mediated global changes.

Thirdly, there is a possibility that the change of soil CO_2 and its related processes is the other main driving force of global warming since the industrial revolution, rather than the generally recognized increase of atmospheric CO_2 concentration. When the atmospheric CO_2 concentration was increased with industrial revolution, the intense land use change such as deforestation occurred simultaneously, and may alter soil CO_2-lake. Hence, the effects of soil CO_2–related processes on global climate changes might be concealed by that of atmospheric CO_2.

Finally, there are large opportunities for human being in regulating soil CO_2-lake and its ecological functions. Human activities such as afforestation, ecosystem restoration, no-tillage farming, and sponge-city construction may improve the formation of natural soil aggregate structure. The coupling of CO_2-H_2O-MM within soil may maintain a more stable and livable ecosystem. The well-developed vegetation and soil, with better soil aggregate structure and greater porosity, may facilitate the coupling of CO_2-H_2O-MM within soil. Thus, the protection of natural vegetation and soil is not only conducive to the protection of biodiversity (Newbold et al., 2016; Luby et al., 2022), but also crucial to alleviating global warming and maintaining the livable environment of the earth. The natural climate solutions (NCS), the strategies for increasing carbon storage (Lu et al., 2022), would also contribute more to climate change mitigation.

4. Conclusion remarks

Overall, soil CO_2-lake is likely to link the biological components (photosynthesis and organic matter decomposition), physical processes (heat exchange within soil and between soil and surface atmosphere) and chemical processes (carbonate and silicate weathering) together, which may provide a new dimension for understanding the mechanism and uncertainties of global climate change.

Although direct evidence of soil CO_2-lake in regulating global climate change is still to be obtained, it is timely to incorporate soil CO_2-lake into the global change model. We need firstly to find a way to estimate the change pattern of soil CO_2-lake since the industrial revolution. In addition, field manipulation experiments and monitoring platforms should be established to quantify the relationship between soil CO_2-lake dynamics and the key carbon cycle processes, and evaluate the impacts of soil CO_2-lake on the climate and environmental changes in ecosystems at different stages of vegetation degradation or restoration.

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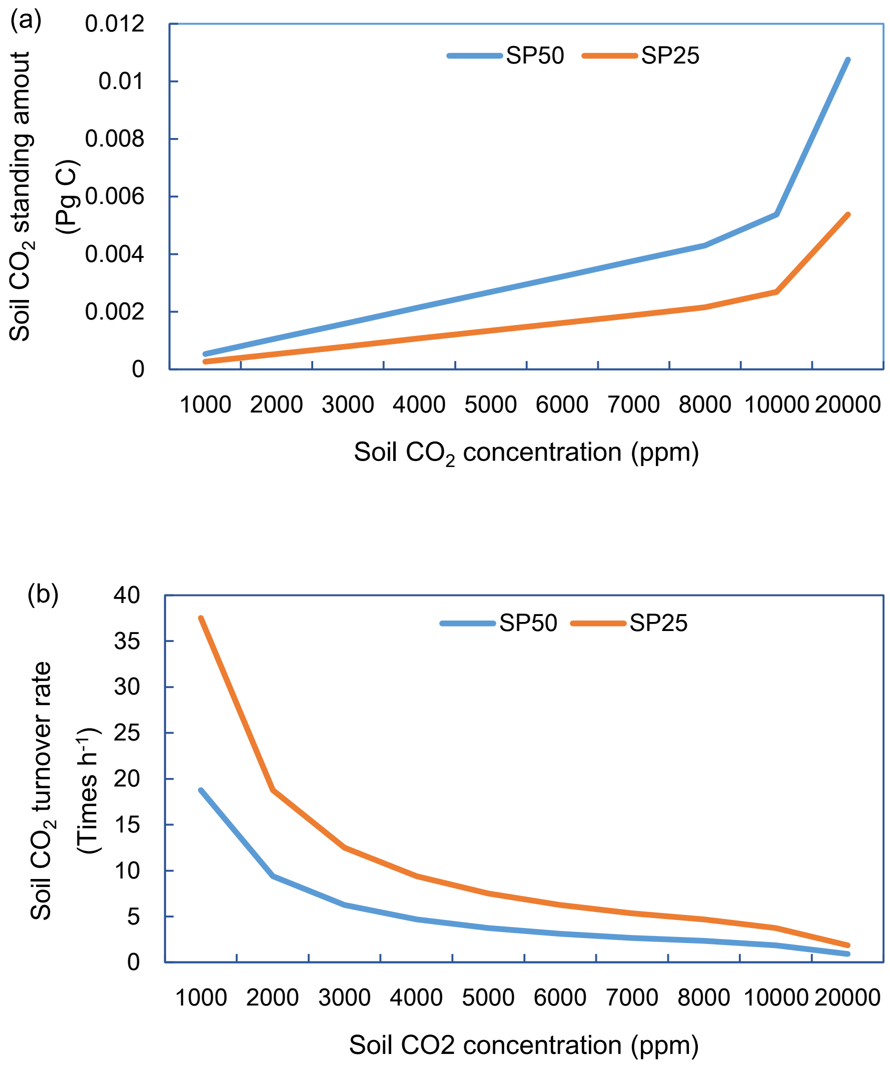

Figure 1. The estimated global amount of standing soil CO_2 (Pg C) (a) and turnover rate (times $hour^{-1}$) (b) in the 0-1 m soil profile. SP50 and SP25 refers to 50% and 25% of soil porosity was assumed, respectively. Data of areas in different types of land cover was from literature (Houghton and Nassikas, 2017), but to obtain a conservative estimation, only areas of global forest, cropland and pasture were included. When estimating soil CO_2 turnover rate, an annual soil CO_2 emission of 1000 g C m^{-2} was assumed which was approximately the average soil respiration in subtropical and temperate regions during 1987-2016 (Lei et al., 2021), and all soil CO_2 produced in soil was considered to emit into atmosphere without any obstacles.

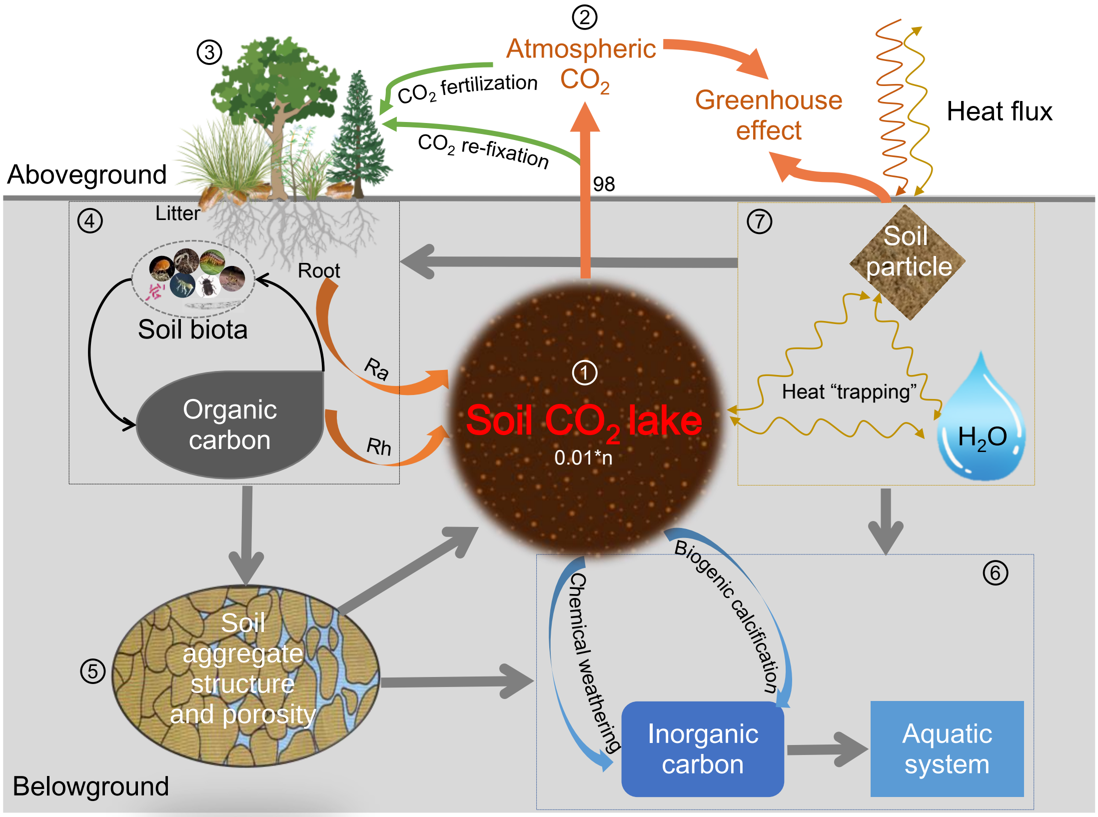

Figure 2. The soil CO_2 pool and its connections with major carbon processes and greenhouse effect. ①Soil CO_2-lake, which was estimated as 0.01*n Pg C year^{-1}, **n** refers to the turnover times per year; ②Atmospheric CO_2 pool; ③CO_2 fixation by vegetation; ④Soil food webs-regulated carbon decomposition and transformation; ⑤ Soil porosity characteristics; ⑥Inorganic carbon pool; ⑦Heat balance regulated by the interaction between soil CO_2 and soil particles. Ra and Rh refers to autotrophic respiration and heterotrophic respiration, respectively. The unit of carbon pool is Pg C year^{-1}.