RESEARCH ARTICLE

An ignored key link in greenhouse effect: Soil and soil CO₂ slow heat loss

Weixin Zhang^{1,†}, Chengde Yu^{2,†}, Zhifeng Shen¹, Shu Liu¹, Suli Li¹, Yuanhu Shao¹, Shenglei Fu^{1,*}

*1 Key Laboratory of Geospatial Technology for the Middle and Lower Yellow River Regions, Ministry of Education;
College of Environment and Planning, Henan University, Kaifeng 475004, China*

2 School of Life Sciences, Henan University, Kaifeng 475004, China

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ABSTRACT

The ever-increasing atmospheric CO₂ concentration is a key driver of modern global warming. However, the low heat capacity of atmosphere and strong convection processes in the troposphere both limit heat retention. Given the higher heat capacity and CO₂ concentration in soil compared to the atmosphere, the direct contributions of soil to the greenhouse effect may be significant. By experimentally manipulating CO₂ concentrations both in the soil and the atmosphere, we demonstrated that the soil-retained heat and the slower soil heat transmission decrease the amount of heat energy leaking from the earth. Furthermore, the soil air temperature was affected by soil CO₂ concentration, with the highest value recorded at 7500 ppm CO₂. This study indicates that soil and soil CO₂, together with atmospheric CO₂, play a crucial role in the greenhouse effect. The spatial and temporal heterogeneity of soils and soil CO₂ should be further investigated, given their potentially significant influence on global climate change.

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1 Introduction

Carbon dioxide is one of the major greenhouse gases and the change in atmospheric CO₂ concentration has been considered as the most important drivers of current global warming (Lacis et al., 2010; Feldman et al., 2015; Anderson et al., 2016). Under normal conditions, the low heat capacity of atmosphere and strong convection in the troposphere make it difficult to effectively retain heat energy within the atmosphere. Any greenhouse effect would be limited if atmospheric CO₂-absorbed surface radiation was not largely retained within the earth. Previously, soils (including soil water and gases) have been recognized as sources and/or sinks of atmospheric greenhouse gases, potentially contributing to the

greenhouse effect (Bouwman, 1989; Jenkinson et al., 1991; Lal, 2003; Smith et al., 2003; Oertel et al., 2016). Several soil characteristics suggest this: first, surface soil (0–20 cm) retains heat energy from either solar radiation or surface downward longwave radiation. Given the higher heat capacity and slower heat loss in soil compared to the atmosphere (Di, 2009), it may be a more efficient heat storage. The observed 31% greater increase in soil surface temperature compared to that of air temperature in China (1962–2011) also implies that heat is more readily retained in soil than in the atmosphere (Zhang et al., 2016). The energy flux from soils can affect land-atmosphere interactions and potentially influence the regulation of weather and climate (Tang et al., 1982; Di, 2009). Secondly, although the total volume of CO₂ in soil air (pores) is lower than that of the atmosphere, the CO₂ concentration in soil is 5- to 100-fold higher than in the atmosphere (Wang et al., 2019). This highly-enriched soil CO₂ may further alter the heat balance of surface soils. However, research is yet to evaluate the potential direct contribution of soils and soil CO₂

* Corresponding author

E-mail address: fsl@henu.edu.cn (S. Fu)

[†]These authors contributed equally to this work.

to the greenhouse effect. We assumed that both atmospheric CO₂, as well as soils and soil CO₂, would play a determinant role in this greenhouse warming effect, by absorbing radiation and retaining heat, respectively. We hypothesized that an increase in soil CO₂ concentration would enhance soil heat retention and thus regulate the greenhouse effect.

Here, we performed a field mesocosm study, in which five different CO₂ concentrations were used (L300, L480, L3200, L7500, and L16900 ppm) and air temperatures in mesocosms standing in the atmosphere (simulated AT_{atm}) or buried under 10 cm of surface soil layer (simulated AT_{soil}) were monitored for six days.

2 Materials and methods

2.1 Experimental design

Eight subplots were chosen on the campus farmland of Henan University (114°18' E, 34°48' N), in Kaifeng, China. The fluvo-aquic soil within each subplot was removed to form a rectangular pit (100 cm × 80 cm × 27 cm), at 50-cm intervals between each adjacent subplot (Fig. 1). To reduce the potential heat energy exchange, each pit was covered with a polyethylene woven sheet with inner polyethylene lining film. Subsequently, five transparent polypropylene containers (16.5 cm height × 10.5 cm diameter) with different levels of CO₂ concentration were set on the plastic sheet in a straight line, with 3 cm separating adjacent containers. Each subplot was considered as a block; each container was considered as a mesocosm. Four of the eight subplots were randomly chosen, then filled back with soil, with approximately 10 cm soil added over the top of polypropylene containers. Thus, 20 containers were left in the atmosphere and not buried in soils (atmospheric treatment) and the remaining 20 containers were buried in soils.

2.2 CO₂ concentration manipulation

The LI840A (Licor, USA) equipped with gas pump (0.5 L min⁻¹) was used to manipulate CO₂ concentration in the containers at normal atmospheric pressure. First, a helium-oxygen mixture (21% O₂) was used to replace the air in each container. Then, when the CO₂ concentration in the container dropped below 100 ppm, pure CO₂ was used to prepare CO₂ treatments of different concentrations. The five levels of CO₂ concentration used in this study were: 309±13 ppm (L300), 486±38 ppm (L480), 3203±257 ppm (L3200), 7576±676 ppm (L7500), and 16 913±551 ppm (L16900). While it would be not relevant to examine the effect of extremely high CO₂ concentrations on air temperature in the atmosphere, soil CO₂ concentration can be as high as 20 000 ppm (Hirano et al., 2003; Wang et al., 2011; Sheng et al., 2012), hence our chosen range of CO₂ levels was deemed appropriate. The same range of CO₂ levels was set both in the soil and atmosphere to allow a direct comparison of the role of CO₂ in regulating heat balance between these contrasting environments.

2.3 Temperature monitoring

The mean air temperature in each container was recorded every 10 min using a temperature sensor (iButton DS1922L, Dallas, USA) hung at the center of the container (Fig. 1). Air temperature changes around six days (daytime: 6:01–17:51, nighttime: 18:01–5:51) were continuously monitored. To assess the bias in temperature measurement caused by the polypropylene container, the atmospheric air temperature outside the container at the center of each block was also monitored simultaneously. To examine the temperature difference between the bulk soil and the simulated soil air, the soil temperature outside the container at the center of each block was also monitored. All the temperature sensors were hung at the same height.

2.4 Data analysis

According to the air temperature variations within soils and the atmosphere, data were grouped into four time periods with a distinct status of heat radiation for a given day-night cycle. These periods were: early morning typically characterized by lower heat radiation (Atom-P1); daytime with higher and increasing heat radiation (Atom-P2); daytime with higher and decreasing heat radiation (Atom-P3); and nighttime with lower heat radiation (Atom-P4). This grouping aimed to examine the effects of CO₂ concentration on the changes of simulated AT_{atm}, while periods of morning and early afternoon with lower soil air temperature (Soil-P1), daytime and early nighttime with higher and increasing soil air temperature (Soil-P2), nighttime with higher and decreasing soil air temperature (Soil-P3), and nighttime with lower soil air temperature (Soil-P4) were focused to examine the effects of CO₂ concentration on the changes of simulated AT_{soil}.

A repeat-measure ANOVA was then performed to explore the effects of CO₂ concentration on air temperature in mesocosms either standing in the atmosphere or covered by 10 cm of topsoil for each period during the six experimental days. To assess the biases of temperature measurement derived from the use of polypropylene containers, temporal variations of surrounding atmospheric temperatures and those within containers with a similar CO₂ concentration (e.g., surface-atmosphere: L300 and L480) were compared. To investigate the hypothesized heat exchange between soil air and soil particles, temperature variations in the bulk soil and the simulated soil air with five levels of CO₂ concentration were also compared. All statistical analyses were performed using SPSS 19.0 (IBM).

3 Results

3.1 Temporal change pattern of air temperatures in atmosphere and soil

To show the potential roles of atmospheric air and soil in regulating heat balance, the daily amplitudes and temporal

Fig. 1 Field experimental design (A) and section view showing the setup of mesocosms (B). In panel A, the four white blocks are subplots in which mesocosms were not buried with soils; the four gray blocks are subplots in which mesocosms were buried with soils; each open circle is a mesocosm; each dot within or outside of the open circle is a temperature sensor; L300, L480, L3200, L7500, and L16900 represented the five levels of CO₂ concentration used in this study. In panel B, the sub-panels above and below referred to each sub-system with mesocosms standing in the atmosphere and being buried in soils, respectively.

change pattern of air temperatures both in atmosphere and soil were examined.

The simulated AT_{atm} fluctuated from -3.70 to 15.95°C throughout the experimental period (Fig. 2). For any given day, variations in simulated AT_{atm} were grouped into four periods (Atom-P1 to -P4; Fig. 2); the simulated AT_{atm} started to increase during 9:11–9:51, occasionally at 11:21 (day 6), reaching peak temperatures between 12:31–13:21. Meanwhile, the simulated AT_{soil} only fluctuated from 5.42 to 1.22°C (Fig. 3). For a given day, variations in simulated AT_{soil} were

also grouped into four periods (Soil-P1 to -P4; Fig. 3); but the simulated AT_{soil} started to increase during 11:51–15:21, reaching peak temperatures between 18:41–21:01.

The temperature variations in the atmospheric air were similar to those in the simulated atmospheric air at L300 but lower than those at L480 during periods of higher heat radiation (Atom-P2 and -P3). By contrast, temperatures in the surrounding atmosphere were consistently higher than those of the two types of simulated atmospheric air during periods of lower heat radiation (Atom-P1 and -P4; Fig. S1). Generally,

Fig. 2 The effects of CO₂ concentration on the temperature in simulated atmospheric air throughout the experiment. AT_{atm}: air temperature in the surrounding atmosphere. Standard errors (SE) are not shown to enable a clearer illustration of the variations in air temperature between mesocosms treated with five levels of CO₂ concentration. The detailed data of mean ± SE and statistical analysis are shown in Table S1.

simulated soil air temperatures could be as high as those of bulk soil during the short warmest periods in the daytime. Additionally, the temperatures of simulated soil air at L7500 were higher than those of bulk soil on days when total heat radiation was much higher (e.g., day 3), and fluctuations in simulated soil air temperatures were much larger than those of bulk soil, although average temperatures were lower (Fig. S2).

3.2 Effects of CO₂ concentration on atmospheric and soil temperatures

The effects of CO₂ concentration on air temperatures in the soil and atmosphere were examined. Generally, the simulated AT_{atm} significantly increased with CO₂ concentration during Atom-P2 and -P3, particularly on days 1 to 5 when the amount of sun-derived radiation was relatively higher (Table S1). A decline in simulated AT_{atm} in response to an increase in CO₂ concentration during Atom-P2 and/or -P3 was observed when comparing the air temperature in the mesocosm at L7500 to that at L16900 on days 1 to 3 (Table S1). Furthermore, a similar decline occurred during Atom-P1 and -P4 when comparing air temperatures in mesocosms under low CO₂ concentrations (i.e., L300 or L480) to those under high concentrations (i.e., L3200, L7500 or L16900; Table S1, Fig. S3). In essence, simulated AT_{atm} during Atom-P1 and -P4

was the highest in the mesocosm treated with L480, which was significantly higher than that treated with L7500 and/or L16900.

The effects of soil CO₂ concentration on soil air temperature were more complex than in the atmosphere. Simulated AT_{soil} significantly increased with CO₂ concentration during Soil-P2 and/or -P3 on days 1 to 5, when the sun-derived radiation was relatively higher (Table S2). A decline in simulated AT_{soil} in response to increasing CO₂ concentrations during Soil-P2 and/or -P3 was also observed when comparing the air temperature in the mesocosm treated with L7500 to that treated with L16900 on days 1 to 5 (Table S2). The simulated AT_{soil} was the highest in mesocosms treated with L7500 and usually significantly higher than those treated with L480 and/or with L16900 during Soil-P2 and/or -P3 on days 1 to 5. Furthermore, the simulated AT_{soil} in mesocosms treated with L7500 was significantly higher than that treated with L3200 during Soil-P2 on day 1 and with all other levels of CO₂ concentration during Soil-P2 on day 3. Contrastingly, we did not observe a significant decline in simulated AT_{soil} in response to increasing CO₂ concentration during Soil-P1 and -P4 when comparing the air temperature in mesocosms treated with low CO₂ concentrations (i.e., L300 or L480) to those treated with high concentration (i.e., L3200, L7500 or L16900).

Fig. 3 The effects of CO₂ concentration on the temperatures in simulated soil air (covered by 10 cm surface soil) throughout the experimental period. AT_{soil}: air temperature in the soil. Standard errors (SE) are not shown to enable a clearer illustration of the variations in air temperature between mesocosms treated with five levels of CO₂ concentration. The detailed data of mean±SE and statistical analysis are shown in Table S2.

4 Discussion

4.1 The complementary roles of atmospheric air and soil in the greenhouse effect

In our study, the temperatures of both actual and simulated atmospheric air showed large fluctuations, indicating that atmospheric heat was readily lost into the upper layers of the atmosphere. We represent this using the following analogy: the atmospheric CO₂ acts as a “racket” that catches the “ball” of surface radiation and deflects it in all directions. Thus, a certain proportion of heat escapes to outer space for each round of CO₂-based radiation absorption and re-emission. If we only considered the role of atmospheric CO₂, for instance, in the case that surface lands were completely covered with bare rocks, the earth’s heat retention capacity would be very limited (Fig. 4A).

By contrast, one of the most distinct characteristics of soil is its low heat transmission (and conversely, high heat retention) compared to the atmosphere (Zhao et al., 2013). The temperatures of both the bulk soil and simulated soil air showed small fluctuations compared to those of the surrounding atmosphere, confirming that soils have a higher heat retention capacity compared to atmospheric air. Another

simulation study using desert soils reported that 35% of net solar radiation may be transferred into soils (Niu et al., 1997). Additionally, soil heat flux was found to result in 7.6% of the net radiation being stored within soils during the day, acting as a heat source to the surface soil layers at night, accounting for more than 50% of the net nighttime radiation in the Antarctic during warmer months (Alves and Soares, 2016). Furthermore, long-term temperature monitoring in the Tibetan Plateau (1983–2013), revealed that soil temperatures were generally higher than surface air temperatures (Zhu et al., 2018). Therefore, either the solar radiation or the “ball of surface radiation” that was kicked back to the surface soil by the atmospheric CO₂ (i.e., the downward long-wave radiation) could be partly retained in the soil and thus potentially form a cache of heat (Fig. 4B). This soil heat storage enhanced heat retention capacity of surface lands and, thus, can contribute to the greenhouse effect on the earth.

A notable result in this study was that soil air temperatures peaked 403±24 min later than those in the atmosphere. Complex patterns of heat transfer regulated by conduction and convection among the soil solid phase, liquid water, and soil gases (Di, 2009) may be the reason behind such a lag in soil warming. Most importantly, soils retained heat significantly longer than the atmosphere. A recent study suggested that

Fig. 4 Conceptual model showing how soils contribute to the greenhouse effect. In panel A, the assumption is that the terrestrial surface is covered by bare rock, while in panel B, the model includes the presence of natural lands and soils. “X” means the heat flux disappeared. The “heat loop” represents potential heat transfer between the three major components of soil (i.e., soil solid phase, soil air, and soil water). The n and n' refer to the total number of CO₂-mediated heat absorption-release rounds per day in terrestrial lands covered with bare rock and soils, respectively; at daily scale, $n' < n$ due to the slower heat transmission process within soil compared to that in the atmosphere.

cooling in the deep Pacific may offset more than one-fourth of the heat gain above 2000 m (Gebbie and Huybers, 2019). However, this study suggests that the delayed soil warming would reduce the heat lost into outer space and potentially transfer heat from the soil to the surface air during cooler periods (Fig. 4B). Therefore, other than ground radiation, soil heat flux is an essential source of heat to surface atmospheric air, particularly during the night and in the early morning, which

may increase the daily minimum temperatures of the surface atmosphere.

The greenhouse effect results from three closely-related processes: surface heat radiation absorption into the atmosphere, heat storage within the soil, and heat re-transfer from the soil into atmospheric air. The latter two, although were well-documented in meteorological studies (Tang et al., 1982; Hu and Feng, 2005; García-Suárez and Butler, 2006;

Di, 2009), have not been confirmed to play direct roles in the greenhouse effect.

4.2 CO₂ concentration-mediated greenhouse effect in the soil and atmosphere

As was predicted, atmospheric air temperature increased with increasing CO₂ concentration during days with higher radiation. However, the magnitude of this increase in mesocosms treated with 16 900 ppm CO₂ was significantly lower than that under 7500 ppm CO₂ during days with higher radiation. Furthermore, atmospheric air temperatures in mesocosms with high CO₂ concentration (3200 to 16 900 ppm) were lower than those with lower CO₂ concentration (480 ppm) during the early morning and/or nighttime with lower heat radiation. These results suggest that CO₂ molecules absorb infrared radiation and re-emit it into the surrounding space (Shia, 2010). Therefore, an increase in CO₂ concentration in the atmospheric air may result in either an increase or a decrease in air atmospheric temperature, depending on the balance of heat gain and loss. In other words, high CO₂ concentrations may enhance net heat loss to colder surrounding interfaces when the heat absorption capacity of CO₂ is saturated or the heat input is limited.

Similarly, we observed both positive and negative effects of soil CO₂ concentration on soil air temperature. The soil air temperature had a nonlinear relationship with soil CO₂ concentration. During the daytime and early night, soil air temperature in mesocosms treated with a CO₂ concentration of 7500 ppm was usually higher than that treated with lower CO₂ concentrations, particularly on days with strong heat radiation. This suggests that an increase in CO₂ concentration would, to a certain extent, enhance heat-trapping in the soil air. However, the significant decrease in soil air temperature in mesocosms treated with a CO₂ concentration of 16 900 ppm showed that soil with significantly higher CO₂ concentration may reduce soil temperature, possibly by transferring more heat to the surrounding air space during colder periods, when the temperature difference between the soil and surface air was larger. The significance of these findings was greater than for those in the atmosphere, as CO₂ concentration in soil air was often in the range of 1000 ppm–20 000 ppm (Hirano et al., 2003; Wang et al., 2011; Sheng et al., 2012). Therefore, variations in soil CO₂ concentration may regulate the balance of soil heat gain and loss, which determines the contribution of soil to surface warming and, ultimately, the greenhouse effect and global warming.

Our decision to use polypropylene containers introduced some uncertainties in measuring the effects of CO₂ concentration on air temperature. Simulated air temperatures were lower than those in both the surrounding atmosphere and bulk soil during colder periods (e.g., late nights and early mornings). These results imply that using polypropylene containers may lead researchers to underestimate the influence of CO₂ concentration on air temperature, both in the atmosphere and in soils, when the total heat input into the

system is limited (e.g., late night and early morning). However, our approach effectively showed that variations in atmospheric and soil CO₂ concentration may alter the heat balance within each respective system.

4.3 Changes in soil and soil CO₂ may contribute to global warming

Other than the indirect influence of soil on global warming through the regulation of atmospheric CO₂ (Zhou et al., 2019), this study indicates that soils and soil CO₂ contribute directly to the greenhouse effect. Previous studies also identified soil warming as one of the consequences of atmospheric CO₂-induced greenhouse effect (García-Suárez and Butler, 2006; Zhu et al., 2018). In a 1967–2002 study of US soils, researchers found that the average temperature of 10- and 100-cm deep soils increased by 0.31°C per decade (Hu and Feng, 2003; Hicks Pries et al., 2018). However, our results indicate that soil warming, together with the role of atmospheric CO₂ in heat radiation absorption, is possibly a direct driver of the greenhouse effect. If so, the observed increase in soil warming might imply that the warming effect of soils on surface air would increase gradually. The observed strong positive correlation between surface atmospheric air temperature and soil temperature in Eurasia (Hu and Feng, 2005) also partly reflects this soil-warming effect on the surface atmospheric air. Furthermore, the contribution of soils to the greenhouse effect is mediated through changes in hydrothermal conditions over small spatial scales. For instance, the warming effect of soil on the land surface could cause a significant change in microclimate. We have ever observed that a cement floor was icy but no ice was formed on the adjacent soils (unpublished observation). These phenomena may imply that, as shown in the conceptual model (Fig. 4A), the heat flow from soils obstructed by solid surfaces (e.g., a cement floor) could profoundly change the temperature of the land surface.

Given that the spatial and temporal heterogeneity of soils and soil CO₂ was far greater than that of CO₂ concentration in the atmosphere, soil heterogeneity-mediated natural greenhouse effect may partly explain variations in local weather patterns across the earth (e.g., large diurnal temperature difference in arid regions). If we consider that 42%–68% of the terrestrial land surface had been disturbed from 1700 to 2000 (Hurt et al., 2006), it is reasonable to expect that anthropogenic changes in soils are important drivers of global warming.

Overall, we conclude that soils and soil CO₂, together with atmospheric CO₂, play a key role in the greenhouse effect. We propose that anthropogenic disturbances in soils can help us to understand the drivers of global warming, suggesting that soils influence the development of human civilization in more complex ways than originally considered, given their direct and indirect impact on the regulation of global warming processes. Future research should focus on describing the effects of human-induced changes in land use

(e.g., deforestation, farming, cement floor expansion) and soil biota-mediated organic matter decomposition on the regulation of greenhouse gas concentration and the greenhouse effect.

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Author contributions

W. Zhang, C. Yu, and S. Fu initiated the collaborative study and designed the experiment; C. Yu, W. Zhang, Z. Shen, S. Liu and S. L. Li conducted the laboratory and field work; W. Zhang and C. Yu performed data analysis; W. Zhang, C. Yu, Y. Shao and S. Fu dischanguessed the data and prepared the manuscript.

Electronic supplementary material

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