Title: Soil and soil CO\textsubscript{2} magnify greenhouse effect

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ABSTRACT

Soil has been recognized as an indirect driver of global warming by regulating atmospheric greenhouse gases. However, in view of the higher heat capacity and CO\textsubscript{2} concentration in soil than those in atmosphere, the direct contributions of soil to greenhouse effect may be non-ignorable. Through field manipulation of CO\textsubscript{2} concentration both in soil and atmosphere, we demonstrated that the soil-retained heat and its slow transmission process within soil may cause slower heat leaking from the earth. Furthermore, soil air temperature was non-linearly affected by soil CO\textsubscript{2} concentration with the highest value under 7500 ppm CO\textsubscript{2}. This study indicates that the soil and soil CO\textsubscript{2} together with atmospheric CO\textsubscript{2}, play indispensable roles in fueling the greenhouse effect. We proposed that anthropogenic changes in soils should be focused in understanding drivers of the globe warming.
Keywords: soil CO₂ concentration, soil temperature, atmosphere temperature, soil heat loop, earth heat balance

INTRODUCTION

CO₂ is one of the major greenhouse gases and the change in atmospheric CO₂ concentration has been considered as the most important driver of global warming [1-3]. The low heat capacity of atmospheric air and the strong convection processes in the troposphere make it difficult to effectively retain heat energy within atmospheric air. The magnitude of greenhouse effect would be much limited if the atmospheric CO₂-absorbed surface radiation could not be largely retained within the earth. Previously, the role of soil (including soil water and gases) in the greenhouse effect has been recognized as sources and/or sinks of atmospheric greenhouse gases [4-8]. However, is it possible that soil and CO₂ in soil directly contribute to the greenhouse effect? There are several characteristics of soil that may facilitate soil to play essential roles in global warming. Firstly, surface soil (e.g., 0-20 cm) was likely to access heat energy either from solar radiation or from the surface downward longwave radiation. In view of the higher heat capacity and slower heat loss in soil than those in atmosphere [9], soil may act as one of the more efficient heat storages. The observed 31% greater increase of soil surface temperature than increase of air temperature in China (1962-2011) [10] may imply that the heat is more readily retained in soil than in atmosphere. The energy flux from soil can affect the land-atmosphere interactions and potentially regulate weather and climate [9,11]. Secondly, although the total volume of CO₂ in soil air is less than the volume of atmospheric CO₂, the concentrations of CO₂ in soil were usually 5-100 fold higher than that of the concentration of atmospheric CO₂ [12]. This highly-enriched CO₂ in soil may further alter the heat balance in surface lands. However, no studies
have tried to evaluate the potential direct contributions of soil and soil CO₂ to greenhouse effect. We considered that the greenhouse effect would rely on both the roles of atmospheric CO₂ in absorbing heat radiation and the roles of soil and soil CO₂ in retaining heat. We hypothesized that an increase of CO₂ concentration in soils would enhance the process of heat trapping within soils, and, thus, regulate the greenhouse effect on the earth.

Here, we performed a field mesocosm study in which CO₂ concentration was manipulated at five levels (i.e., L300 ppm, L480 ppm, L3200 ppm, L7500 ppm and L16900 ppm) and air temperature in mesocosms that standing in atmosphere (simulated AT atm) or being buried under 10 cm of surface soil layer (simulated AT soil) were monitored for six days.

RESULTS

Temporal change pattern of air temperatures in atmosphere and soil

To show the potential roles of atmospheric air and soil in heat balance, the daily amplitudes and temporal change pattern of air temperatures both in atmosphere and soil were examined. The simulated AT atm fluctuated from 15.95°C to -3.70°C during the six experimental days (Fig. 1). For a given day, the changes of simulated AT atm can be separated into four periods (Atom-P1 to Atom-P4) (see Methods; Fig. 1); the simulated AT atm started to increase during 9:11 – 9:51, occasionally at 11:21 (day 6), and reach the highest temperature during 12:31 – 13:21. While, the simulated AT soil only fluctuated from 5.42°C to 1.22°C (Fig. 2). For a given day, the changes of simulated AT soil can also be separated into four periods (Soil-P1 to Soil-P4) (see Methods; Fig. 2); but the simulated AT soil started to increase during 11:51 – 15:21, and reach the highest temperature during 18:41 – 21:01.
The temporal change pattern of temperature in the real atmospheric air was as similar as that in the simulated atmospheric air with CO₂ concentration of L300 but lower than that with CO₂ concentration of L480 during periods with higher heat radiation (Atom-P2 and Atom-P3); in contrast, temperatures in the real atmospheric air were consistently higher than those in both the two types of simulated atmospheric air during periods with lower heat radiation (Atom-P1 and Atom-P4) (Fig. S1). In general, the temperatures of simulated soil air could be as high as those of bulk soil during the short warmest periods in soil in the day, furthermore, the temperatures of simulated soil air with CO₂ concentration of L7500 could be higher than those of bulk soil on days when the total heat radiation was much higher; in addition, the temperatures of simulated soil air fluctuated with larger amplitudes and mostly were lower than those of the bulk soil (Fig. S2).

**CO₂ concentration effects on air temperatures in atmosphere and soil**

The effects of CO₂ concentration on air temperatures both in the atmospheric air and soil air were examined. In general, the simulated ATₐₐm increased with CO₂ concentration significantly at periods of Atom-P2 and Atom-P3 especially during day 1 – day 5 when the sun-derived radiation was relatively higher (Table S1). A decline of the simulated ATₐₐm in response to the increase of CO₂ concentration at periods of Atom-P2 and/or Atom-P3 was observed when compared with the temperatures in the treatment with L7500 to that with L16900 during day 1- day 3 (Table S1). Furthermore, a decline of the simulated ATₐₐm in response to the increase of CO₂ concentration at periods of Atom-P1 and Atom-P4 occurred when comparing the temperature in the treatment with low CO₂ concentration (i.e., L300 or L480) to that with high concentration (i.e., L3200 or L7500 or L19600) (Table S1; Fig. S3). In brief, the simulated ATₐₐm at periods of Atom-P1 and
Atom-P4 was the highest in treatment with L480, which was significantly higher than that in treatment with L7500 and/or L19600.

The influences of soil CO\textsubscript{2} concentration on air temperature in soil were more complex than those in atmosphere. In general, the simulated AT\textsubscript{soil} increased with CO\textsubscript{2} concentration significantly at periods of Soil-P2 and/or Soil-P3 during day 1 – day 5 when the sun-derived radiation was relatively higher (Table S2). A decline of the simulated AT\textsubscript{soil} in response to the increase of CO\textsubscript{2} concentration at periods of Soil-P2 and/or Soil-P3 was also observed when compared the temperature in treatment with L7500 to that with L16900 during day 1- day 5 (Table S2). In brief, the simulated AT\textsubscript{soil} in treatment with L7500 was the highest, which was usually significantly higher than that with L480 and/or with L16900 at periods of Soil-P2 and/or Soil-P3 during day 1-day 5. In addition, the simulated AT\textsubscript{soil} in treatment with L7500 was only significantly higher than that with L3200 for stage of Soil-P2 at day 1, but was significantly higher than that in all other treatments of CO\textsubscript{2} concentration for stage of Soil-P2 at Day 3. On the contrary, we did not observe significant decline of the simulated AT\textsubscript{soil} in response to the increase of CO\textsubscript{2} concentration at periods of Soil-P1 and Soil-P4 when compared the temperature in the treatment with low CO\textsubscript{2} concentration (i.e., L300 or L480) to that with high concentration (i.e., L3200 or L7500 or L19600).

**DISCUSSION**

**The complimentary roles of atmospheric air and soil in greenhouse effect**

In our study, the temperatures of both the real and simulated atmospheric air exerted great amplitudes indicating that the heat in the atmosphere was readily lost into outer space of the earth. We considered that the atmospheric CO\textsubscript{2} plays a role as “racket” that catches the “ball of
surface radiation” and beats it out in all directions. Thus, a certain proportion of heat would escape to outer space for each round of CO₂-based radiation absorption and re-emission. In other words, if only the role of atmospheric CO₂ was considered, for example, when the surface lands were totally covered by bare rocks, the heat amount that the earth could retain would be much limited (Fig. 3A).

In contrast, one of the most distinct characteristics of soil is the slower heat transmission compared to that in atmosphere [13]. The temperatures of both the bulk soil and simulated soil air exerted smaller amplitudes than those in atmosphere indicating that the soil may possess higher heat capacity and hold heat more efficiently than atmospheric air. For instance, a simulation study using desert soils reported that 35% of the net radiation may be transferred into soil [14]; in addition, soil heat flux was found to result in 7.6% of the net radiation being stored in soil at daytime, and acted as a heat source to outer soil layers at night-time accounting for more than 50% of the net night-time radiation at an Antarctic area during warmer months [15]. Also, soil temperature was found to be generally higher than surface air temperature in the Tibetan Plateau during 1983-2013 [16]. Therefore, either the solar radiation or the “ball of surface radiation” that was kicked back to the surface soil by the atmospheric CO₂ could be partly retained in soil and thus potentially form a cache of heat (Fig. 3B). This heat storage in soil would contribute to the greenhouse effect on the earth.

Furthermore, it was notable that in this study soil air temperature reached the highest values 403 ± 24 min later than that of atmospheric air. The complex heat transfer either through conduction or convection among the soil solid phase, liquid water and soil gases [9] may cause such lagging warming in soil. Importantly, it retained heat within soil for a longer period of time. A recent study suggested that the cooling in the deep Pacific may offset more than one-fourth of
the heat gain above 2000 m [17]. Here, however, the lagging warming of soil would reduce the possibility of heat loss into outer space during a given period and potentially provide an opportunity of transferring heat from soil to surface air during colder periods (Fig. 3B). Hence, other than ground radiation, soil heat flux would be an essential heat source to surface atmospheric air especially at night-time and early morning, which may increase the level of the daily minimum temperature in surface atmosphere.

Therefore, we considered that the greenhouse effect resulted from three closely related processes: surface heat radiation absorption in atmospheric air, heat storage within soil and heat re-transfer from soil to atmospheric air. The latter two soil processes, although were well-documented in meteorological studies [9,11,18-19], have not been acknowledged to play direct roles in fueling greenhouse effect.

**CO₂ concentration-mediated greenhouse effect in atmosphere and soil**

The increased atmospheric air temperatures with CO₂ concentration (ranging from 300 ppm to 7500 ppm) at daytime with higher radiation were understandable. Unexpectedly, the magnitude of temperature increase of atmospheric air in mesocosms with 16900 ppm CO₂ declined significantly compared to that with 7500 ppm CO₂ at daytime with higher radiation. In addition, the temperatures of atmospheric air in mesocosms with substantially higher CO₂ concentration (ranging from 3200 ppm to 16900 ppm) were lower than that with the lower CO₂ concentration (480 ppm) at early morning and/or nighttime with lower heat radiation. These results emphasized that the molecules of CO₂ not only absorb the infrared radiation but also re-emit it to the surrounding space (20). Thus an increase of CO₂ concentration in atmospheric air may result in either an increase or decrease of the air temperature in the atmosphere, depending on the balance of heat gain and loss. In other words, CO₂ with substantially higher concentration may enhance
the net heat loss to colder surrounding interfaces when the heat absorption capacity of CO\textsubscript{2} was saturated or heat input was much limited.

As in atmosphere, both a positive and a negative effect of soil CO\textsubscript{2} concentration on air temperature in soil were observed. Furthermore, the air temperatures in soil were non-linearly affected by soil CO\textsubscript{2} concentration. On one hand, at daytime and early nighttime with higher temperature in soil air, soil air temperature with CO\textsubscript{2} concentration of 7500 ppm was higher than that with lower CO\textsubscript{2} concentrations. This suggested that an increased CO\textsubscript{2} concentration to a limited extent would enhance heat trapping in soil air. On the other hand, the significant decrease of soil air temperature in mesocosms with CO\textsubscript{2} concentration of 16900 ppm indicated that soil with substantially higher CO\textsubscript{2} concentration may cool the soil probably by transferring more heat to surrounding space during colder periods when the temperature difference between soil and surface atmospheric air became larger. The realistic significance of these findings was greater than those in the atmosphere because CO\textsubscript{2} concentration in soil air was often in the range of 1,000 ppm – 20,000 ppm [21-23]. Hence, the variation of soil CO\textsubscript{2} concentration may regulate the balance of heat gain and loss in soil which determines the contribution of soil to surface warming of the earth.

The using of polypropylene container has induced some uncertainties in measuring the effects of CO\textsubscript{2} concentration on temperature. The temperatures in the simulated air were lower than those in both the real atmosphere and the bulk soil during colder periods such as late night and early morning. These results implied that using of polypropylene container may cause underestimation of the effects of CO\textsubscript{2} concentration on air temperature in both the atmosphere and soil when the total heat input into the system was limited. However, this simple mesocosm
approach effectively illustrated that the changes of CO₂ concentration both in atmosphere and soil may alter the heat balance within respective system.

**Changes in soil and soil CO₂ may cause changes in global warming**

Besides the indirect influence of soil on global warming via regulating atmospheric CO₂ [24], this study indicates that soil and soil CO₂ could contribute directly to the greenhouse effect. In previous studies, soil warming has been recognized as one of consequences or reflections of the atmospheric CO₂-induced greenhouse effect [16,19]. Both the average temperature of 10 cm soils and 100 cm soils were increased by 0.31 °C decade⁻¹ during 1967 - 2002 in the United States [25-26]. However, our results indicated that soil warming, together with the role of atmospheric CO₂ in heat radiation trapping, may act as a direct driver of greenhouse effect. If so, the observed increasing soil warming may imply that the warming effect of soils on surface air would be gradually increased. The observed closely positive correlation between surface atmospheric air temperature and soil temperature in the Eurasian continent [18] may also partly reflect such warming effect of soils on surface atmospheric air. In addition, the contribution of soil to greenhouse effect may be manifested in the soil-mediated changes in hydrothermal condition at small spatial scale. For instance, the warming effect of soil on land surface could cause significant difference of microclimate. We have observed that at the foot of a hill, a cement floor was icy but no ice was formed on the adjacent soils. These phenomena implied that, as we postulated in the conceptual model (Fig. 3A), the heat flow from soils which were obstructed by solid surfaces such as cement floor could profoundly change the temperature of land surface.

Given that soil heterogeneity was far greater than that of CO₂ distribution in atmosphere, soil heterogeneity-mediated natural greenhouse effect may partly explain the variation of local weather (e.g., large diurnal temperature difference in arid regions) across the earth. In
considering that 42% - 68% of the terrestrial land surface had been disturbed during the period 1700 – 2000 [27], we postulated that the anthropogenic changes in soils may be the other important drivers of the globe warming.

Overall, we considered that soil and soil CO$_2$, together with atmospheric CO$_2$, play indispensable roles in fueling the greenhouse effect on the earth. We proposed that anthropogenic changes in soils should be focused in understanding drivers of the globe warming. Further studies are needed to unravel how the human-induced land use changes (e.g., deforestation, farming and cement floor expanding) affect the heat loop among the soil solid phase, water and soil air, and, thus regulate the greenhouse effect.

METHODS

Experimental design

Eight subplots were chosen at a campus farmland in Henan University (114°18′ E, 34°48′ N), Kaifeng, China, and the Fluvo-aquic soils from each subplot were removed to form a rectangular pit (length 100 cm × width 80 cm × height 27 cm), with 50 cm distance between any two adjacent subplots. To reduce the potential energy exchange, each of the pits was covered by a polyethylene woven sheet with lining. Then five transparent polypropylene containers (16.5 cm in height, 10.5 cm in diameter) with different levels of CO$_2$ concentration were put on the plastic sheet in a straight line with 3 cm distance between any two adjacent containers. Each of such subplot was regarded as a block; each of such container was regarded as a mesocosm. Half of the eight subplots were randomly chosen and then filled back with the soils, with approximately 10 cm soil covered over the top of the polypropylene containers. Thus, 20 containers were left in the atmosphere of the pits and other 20 containers were buried in soils.
**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. In brief, the Helium-oxygen mixture (with 21% O₂) was used to replace air in each container at the beginning, and when the CO₂ concentration in the container was less than 100 ppm, the pure CO₂ was used to prepare CO₂ with different concentrations. The five manipulated levels of CO₂ concentration were 309 ± 13 ppm (L300), 486 ± 38 ppm (L480), 3203 ± 257 ppm (L3200), 7576 ± 676 ppm (L7500) and 16913 ± 551 ppm (L16900), respectively.

**Temperature monitoring**

The mean air temperature in each container was recorded every ten minutes by temperature sensor of iButton DS1922L (DALLAS, USA) which was hung at the center of the container. Air temperature changes around six days (daytime: 06:01 – 17:51, nighttime: 18:01 – 05:51) were continuously monitored. To assess the bias of temperature measurement derived from the using of polypropylene container, the atmospheric air temperature outside the container at the center of each block were also monitored. 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 were also monitored. All the temperature sensors of iButton DS1922L were hung at the same height.

**Data analysis**

According to the pattern of changes in air temperature in atmosphere and soils, data were separated into four different periods for a given day. In brief, periods of early morning with 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) were included for the changes of simulated AT\textsubscript{atm}; 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), daytime and early nighttime with higher and decreasing soil air temperature (Soil-P3), and nighttime with lower soil air temperature (Soil-P4) were included for the changes of simulated AT\textsubscript{soil}.

The repeated measure ANOVA was then performed to explore CO\textsubscript{2} concentration effects on the air temperature in mesocosms that were either standing in the atmosphere or covered by 10 cm layer of soils at each period for each of the six experimental days. To assess the biases of temperature measurement derived from the using of polypropylene containers, the temporal change patterns of air temperatures in atmosphere and within containers with similar CO\textsubscript{2} concentrations as in surface atmosphere (L300 and L480) were compared; to show the potential heat exchange between soil air and soil particles, the temperature change patterns in the bulk soil and the simulated soil air with five levels of CO\textsubscript{2} concentrations were also compared. All statistical analyses were performed with SPSS 19.0 (IBM).

**SUPPLEMENTARY DATA**

Supplementary data are available.

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AUTHOR CONTRIBUTIONS

W.Z., C.Y., and S.F. initiated the collaborative study and designed the experiment; C.Y., W.Z., Z.S., S.L. and S.L.L. conducted the lab and field work; W.Z. and C.Y. performed data analysis; W.Z., C.Y., Y.S. and S.F. discussed the data and prepared the manuscript.

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COMPETING INTERESTS

The authors declare no competing interests.

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**Fig. 1.** The effects of CO$_2$ concentration on the temperatures in simulated atmospheric air during the six experimental days. AT$_{atm}$: air temperature in atmosphere.
Fig. 2. The effects of CO₂ concentration on the temperatures in simulated soil air (covered by 10 cm surface soil) during the six experimental days. AT_{soil}: air temperature in soil.
Fig. 3. A conceptual model showing how soil contribute to greenhouse effect. Panel (A) assuming only the bare rock remained on the surface of the terrestrial lands. Panel (B) showing
natural lands with soils. “×” means the heat flux disappeared. The “heat loop” represents the potential heat transfer among the three major components of soil, i.e., soil solid phase, soil air and soil water. The short white-yellow arrows refer to heat flow being transferred into soil or out to the surface atmospheric air. The $n$ and $n'$ refers to the total number of CO$_2$-mediated heat absorption-release round 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 atmosphere.
Supplementary Materials for

Soil and soil CO₂ magnify greenhouse effect

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This file includes:

Figs. S1 to S3

Tables S1 to S2
**Fig. S1.** The comparisons of change patterns of temperatures in the real atmospheric air (AT$_{atm}$) at block center and in the simulated atmospheric air with CO$_2$ concentration of 300 ppm and 480 ppm during the six experimental days.
**Fig. S2.** The comparisons of change pattern of temperatures in bulk soil (T$_{soil}$) at block center and in the simulated soil air (AT$_{soil}$) with five levels of CO$_2$ concentration (300 ppm – 16900 ppm) during the six experimental days.
Fig. S3. The negative effect of increased CO$_2$ concentration on temperature in the simulated atmospheric air at nighttime and early morning during which the environmental temperature was lower than 2°C.
Table S1. The repeated measure ANOVA results of CO$_2$ concentration effects on the temperature in the simulated atmospheric air during the six experimental days. NA: data not available; †noted that the air temperature in mesocosms with treatment of L480 was likely to be higher than that of L7500 and L16900 ($P = 0.051$ and $P = 0.079$, respectively); ‡noted that the air temperature in mesocosms with treatment of L480 was likely to be higher than that of L300 ($P = 0.072$); ¶ noted that the air temperature in mesocosms with treatment of L300 was likely to be lower than that of L3200 and L7500 ($P = 0.079$ and $P = 0.079$, respectively); § noted that the air temperature in mesocosms with treatment of L300 was likely to be lower than that of L3200 and L7500 ($P = 0.058$ and $P = 0.074$, respectively); ‖ noted that the air temperature in mesocosms with treatment of L300 was likely to be lower than that of L480 ($P = 0.051$). The upward and downward arrows indicated that some of the treatments with higher CO$_2$ concentration may cause increased and decreased air temperature in the mesocosms, respectively; the arrow with dashed line indicated that the CO$_2$ concentration effect on air temperature in mesocosms was not significant but deserved to be noticed ($0.05 < P < 0.1$). The difference letter indicated significant effect of CO$_2$ concentration on air temperature ($P < 0.05$).

| Days | Periods | Time (h: m) | Air temperature in mesocosms ($^\circ$C, Mean ± SE) | F and $P$ value |
|------|---------|------------|--------------------------------------------------|----------------|
|      |         |            | Levels of CO$_2$ concentration in mesocosms (ppm) |                 |
|      |         |            | L300     | L480     | L3200    | L7500    | L16900   |                 |
| Day 1| Atom-P1: Early morning with lower heat radiation | NA        | NA       | NA       | NA       | NA       | NA       | NA       |


| Time Period | Condition | Mean ± SE | Reaction | Time Period | Condition | Mean ± SE | Reaction | Time Period | Condition | Mean ± SE | Reaction |
|-------------|-----------|-----------|----------|-------------|-----------|-----------|----------|-------------|-----------|-----------|----------|
| 12:01-13:11 | Daytime with higher and increasing heat radiation | 7.06 ± 0.18c | 0.18c | 26.06 ± 0.18c | 0.18c | 10.49 ± 0.22b | 0.22b | 12.77 ± 0.27a | 0.27a | 10.95 ± 0.31b | 0.31b |
| 12:01-13:11 | Daytime with higher and increasing heat radiation | 6.56 ± 0.26c | 0.26c | 11.93 ± 0.26c | 0.26c | 7.73 ± 0.41b | 0.41b | 8.97 ± 0.59a | 0.59a | 8.54 ± 0.51ab | 0.51ab |
| 13:31-16:31 | Daytime with higher and decreasing heat radiation | 7.40 ± 0.28d | 0.28d | 8.32 ± 0.28d | 0.28d | 8.34 ± 0.28d | 0.28d | 8.47 ± 0.28d | 0.28d | 8.82 ± 0.28d | 0.28d |
| 0:01-5:51  | Nighttime with lower heat radiation | 1.22 ± 0.07ab | 0.07ab | 1.16 ± 0.07ab | 0.07ab | 1.31 ± 0.07a | 0.07a | 1.15 ± 0.07b | 0.07b | 1.14 ± 0.07bc | 0.07bc |
| 6:01-8:01  | Early morning with lower heat radiation | -2.57 ± 0.09ab | 0.09ab | -2.53 ± 0.09ab | 0.09ab | -2.78 ± 0.10b | 0.10b | -2.60 ± 0.09ab | 0.09ab | -2.60 ± 0.10b | 0.10b |
| 9:31-13:21 | Daytime with higher and increasing heat radiation | 6.03 ± 0.44c | 0.44c | 9.12 ± 0.44c | 0.44c | 7.58 ± 0.57b | 0.57b | 8.14 ± 0.60b | 0.60b | 8.27 ± 0.68a | 0.68a |
| 13:31-16:31| Daytime with higher and decreasing heat radiation | 7.40 ± 0.28d | 0.28d | 8.32 ± 0.28d | 0.28d | 8.34 ± 0.28d | 0.28d | 8.47 ± 0.28d | 0.28d | 8.82 ± 0.28d | 0.28d |
| 0:01-5:51  | Nighttime with lower heat radiation | 1.22 ± 0.07ab | 0.07ab | 1.16 ± 0.07ab | 0.07ab | 1.31 ± 0.07a | 0.07a | 1.15 ± 0.07b | 0.07b | 1.14 ± 0.07bc | 0.07bc |
| 6:01-8:01  | Early morning with lower heat radiation | -2.57 ± 0.09ab | 0.09ab | -2.53 ± 0.09ab | 0.09ab | -2.78 ± 0.10b | 0.10b | -2.60 ± 0.09ab | 0.09ab | -2.60 ± 0.10b | 0.10b |

*Day 2*
| Time                  | Activity                           | Values                          | Statistical Test | P-value   |
|-----------------------|------------------------------------|---------------------------------|------------------|-----------|
| Day 4                 | **Atom-P2: Daytime with higher**   | 9:21-12:31                      | 9.66 ± 11.32 ±   | 12.00 ± 13.30 ± 12.02 ± | $F_{4,15} = 11.63$; $P < 0.001$; ↑↓ |
|                       | and increasing heat radiation      |                                 | 0.69c 0.86b 0.93b 1.05a 0.96b |           |           |
|                       | **Atom-P3: Daytime with higher**   | 12:41-15:21                     | 12.07 ± 14.33 ± 15.02 ± 15.95 ± 15.15 ± | $F_{4,15} = 9.44$; | $P = 0.001$; ↑ |
|                       | and decreasing heat radiation      |                                 | 0.15c 0.26b 0.30ab 0.42a 0.34ab |           |           |
|                       | **Atom-P4: Nighttime with lower**  | 0:00-5:51                       | -3.26 ± -3.17 ± -3.48 ± -3.70 ± -3.53 ± | $F_{4,15} = 1.77$; |           |
|                       | heat radiation                     |                                 | 0.08ab 0.07a 0.07ab 0.07b 0.07ab | $P = 0.188$; ↓ |           |
| Day 5                 | **Atom-P1: Early morning with**    | 6:01-8:31                       | -3.50 ± -3.31 ± -3.66 ± -3.77 ± -3.72 ± | $F_{4,15} = 1.49$; |           |
|                       | lower heat radiation               |                                 | 0.28a 0.28a 0.28a 0.30a 0.27a | $P = 0.254$↑↓; |           |
|                       | **Atom-P2: Daytime with higher**   | 9:11-13:11                      | 7.11 ± 9.01 ±   | 9.56 ± 10.40 ± 9.62 ± | $F_{4,15} = 7.68$; |           |
|                       | and increasing heat radiation      |                                 | 0.53c 0.75b 0.81ab 0.90a 0.83ab | $P = 0.001$; ↑ |           |
|                       | **Atom-P3: Daytime with higher**   | 13:21-17:01                     | 8.90 ± 10.74 ± 11.25 ± 11.79 ± 11.25 ± | $F_{4,15} = 9.30$; |           |
|                       | and decreasing heat radiation      |                                 | 0.37c 0.56ab 0.62a 0.68a 0.66a | $P = 0.001$; ↑ |           |
|                       | **Atom-P4: Nighttime with lower**  | 0:01-5:51                       | -2.18 ± -2.23 ± -2.44 ± -2.52 ± -2.46 ± | $F_{4,15} = 0.367$; |           |
|                       | heat radiation                     |                                 | 0.08a 0.08a 0.08a 0.07a 0.08a | $P =0.828$ |           |
| Day 5                 | **Atom-P1: Early morning with**    | 6:01-8:41                       | -2.82 ± -2.41 ± -2.60 ± -2.69 ± -2.65 ± | $F_{4,15} = 0.327$; |           |
|                       | lower heat radiation               |                                 | 0.23a 0.21a 0.22a 0.23a 0.21a | $P =0.856$ |           |
| Time Period                  | Mean ± SEM | Heat Radiation |
|-----------------------------|------------|----------------|
| **Day 6**                   |            |                |
| **Atom-P1:** Early morning with lower heat radiation | 1.10 ± 0.02 | 1.25 ± 0.02 |
| **Atom-P2:** Daytime with higher and increasing heat radiation | 9:51-13:11 | 7.96 ± 0.65b |
| **Atom-P3:** Daytime with higher and decreasing heat radiation | 13:21-16:21 | 10.08 ± 0.35b |
| **Atom-P4:** Nighttime with lower heat radiation | 0:01-5:51 | 1.25 ± 0.04a |
| **Atom-P2:** Daytime with higher and increasing heat radiation | 11:21-13:01 | 4.60 ± 0.19a |
| **Atom-P3:** Daytime with higher and decreasing heat radiation | 13:11-14:51 | 5.14 ± 0.09a |
| **Atom-P4:** Nighttime with lower heat radiation | 0:01-5:51 | 0.92 ± 0.05ab |

**ANOVA Results:**
- $F_{4,15} = 2.80$ for Atom-P2: Daytime with higher and increasing heat radiation, $P = 0.064$.
- $F_{4,15} = 2.26$ for Atom-P3: Daytime with higher and decreasing heat radiation, $P = 0.112$.
- $F_{4,15} = 1.81$ for Atom-P4: Nighttime with lower heat radiation, $P = 0.181$. 

| Time Period                  | Mean ± SEM | Heat Radiation |
|-----------------------------|------------|----------------|
| **Day 6**                   |            |                |
| **Atom-P1:** Early morning with lower heat radiation | 1.10 ± 0.02 | 1.25 ± 0.02 |
| **Atom-P2:** Daytime with higher and increasing heat radiation | 9:51-13:11 | 7.96 ± 0.65b |
| **Atom-P3:** Daytime with higher and decreasing heat radiation | 13:21-16:21 | 10.08 ± 0.35b |
| **Atom-P4:** Nighttime with lower heat radiation | 0:01-5:51 | 1.25 ± 0.04a |
| **Atom-P2:** Daytime with higher and increasing heat radiation | 11:21-13:01 | 4.60 ± 0.19a |
| **Atom-P3:** Daytime with higher and decreasing heat radiation | 13:11-14:51 | 5.14 ± 0.09a |
| **Atom-P4:** Nighttime with lower heat radiation | 0:01-5:51 | 0.92 ± 0.05ab |

**ANOVA Results:**
- $F_{4,15} = 2.80$ for Atom-P2: Daytime with higher and increasing heat radiation, $P = 0.064$.
- $F_{4,15} = 2.26$ for Atom-P3: Daytime with higher and decreasing heat radiation, $P = 0.112$.
- $F_{4,15} = 1.81$ for Atom-P4: Nighttime with lower heat radiation, $P = 0.181$. 

**Note:**
- The table includes the time periods and mean ± SEM values for each condition, along with the results of the ANOVA tests.
Table S2. The repeated measure ANOVA results of CO$_2$ concentration effects on the air temperature of the simulated soil air in mesocosms covered by 10 cm layer of soil during the six experimental days. †noted that the air temperature in mesocosms with treatment of L7500 was likely to be higher than that of L300 ($P = 0.06$); ‡noted that the air temperature in mesocosms with treatment of L7500 was likely to be higher than that of L3200 ($P = 0.073$). NA: data not available. The upward and downward arrows indicated that some of the treatments with higher CO$_2$ concentration may cause increased and decreased air temperature in the mesocosms, respectively. The difference letter indicated significant effect of CO$_2$ concentration on air temperature ($P < 0.05$).

| Days | Periods                     | Time (h: m) | Air temperature in mesocosms (°C, Mean ± SE) | F and P value |
|------|-----------------------------|-------------|-----------------------------------------------|---------------|
|      |                             |             | Levels of CO$_2$ concentration in mesocosms (ppm) |               |
|      |                             |             | L300  | L480  | L3200 | L7500 | L16900 |               |
| Day 1| Soil-P1: Morning and early afternoon | NA          | NA    | NA    | NA    | NA    | NA    | NA           |
|      | with lower soil air temperature |             |       |       |       |       |       |              |
|      | Soil-P2: Daytime and early nighttime | 14:01-18:41| 2.86 ± | 2.85 ± | 2.54 ± | 3.22 ± | 2.78 ± | $F_{4,15} = 1.56$; $P = 0.236$; ↑ |
|      | with higher and increasing soil air temperature |             | 0.06ab| 0.11ab| 0.08b | 0.06a | 0.04ab |              |
| Time                  | Soil-P1: Morning and early afternoon | Soil-P2: Daytime and early nighttime | Soil-P3: Daytime and early nighttime | Soil-P4: Nighttime with lower soil air | F<sub>4,15</sub>  |
|-----------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|------------------|
| 6:01-12:01            | 2.58 ± 0.03a                         | 3.29 ± 0.04ab                        | 3.55 ± 0.05a                         | 3.45 ± 0.05a                         | 0.89;           |
|                       | with lower soil air temperature      | with higher and increasing soil air   | with higher and decreasing soil air   | with lower soil air                   | P = 0.493       |
|                       | 2.28 ± 0.04a                         | 3.11 ± 0.06a                         | 3.40 ± 0.06a                         | 3.24 ± 0.04a                         | P = 0.40        |
|                       | 2.46 ± 0.05a                         | 3.30 ± 0.06a                         | 3.59 ± 0.06a                         | 3.47 ± 0.07a                         | P = 0.116       |
|                       | 2.41 ± 0.06a                         | 3.44 ± 0.07a                         | 3.63 ± 0.06a                         | 3.44 ± 0.06a                         | P = 0.531       |
|                       | 2.29 ± 0.06a                         | 3.16 ± 0.07a                         | 3.40 ± 0.06a                         | 3.26 ± 0.06a                         | P = 0.604       |
| Day | Soil \(\text{P}_1\): Morning and early afternoon | Time | Temperature (°C) | ANOVA Results |
|-----|----------------------------------|------|---------------|----------------|
| 3   | with lower soil air temperature | 6:01-10:31 | 3.26 ± 0.04a, 3.03 ± 0.07a, 3.22 ± 0.06a, 3.16 ± 0.04a | \(F_{4,15} = 0.63; P = 0.649\) |
| 3   | Soil \(\text{P}_2\): Daytime and early nighttime | 12:11-18:41 | 4.33 ± 0.02b, 4.28 ± 0.04b, 4.23 ± 0.02b, 4.56 ± 0.02a, 4.18 ± 0.03b | \(F_{4,15} = 4.17; P = 0.018; \uparrow\downarrow\) |
| 3   | with higher and increasing soil air temperature | 18:51-22:11 | 5.21 ± 0.03ab, 5.19 ± 0.05b, 5.24 ± 0.04ab, 5.42 ± 0.03a, 5.07 ± 0.02b | \(F_{4,15} = 3.04; P = 0.051; \uparrow\downarrow\) |
| 3   | Soil \(\text{P}_4\): Nighttime with lower soil air temperature | 0:01-5:51 | 4.08 ± 0.04a, 3.91 ± 0.04a, 4.10 ± 0.07a, 3.96 ± 0.06a, 3.85 ± 0.05a | \(F_{4,15} = 0.47; P = 0.758\) |

| Day | Soil \(\text{P}_1\): Morning and early afternoon | Time | Temperature (°C) | ANOVA Results |
|-----|----------------------------------|------|---------------|----------------|
| 4   | with lower soil air temperature | 6:01-12:51 | 3.24 ± 0.04a, 2.94 ± 0.05a, 3.08 ± 0.06a, 2.98 ± 0.06a, 2.91 ± 0.06a | \(F_{4,15} = 0.71; P = 0.599\) |
| 4   | Soil \(\text{P}_2\): Daytime and early nighttime | 14:41-19:21 | 3.92 ± 0.02b, 3.82 ± 0.04b, 3.89 ± 0.04ab, 4.11 ± 0.04a, 3.78 ± 0.01b | \(F_{4,15} = 2.50; P = 0.087; \uparrow\downarrow\) |
| Time Period                          | Temperature       | Soil-P3: Daytime and early nighttime | Soil-P4: Nighttime with lower soil air |
|-------------------------------------|-------------------|--------------------------------------|----------------------------------------|
| 19:31-22:31                         | 2.44 ± 0.63a      | 2.49 ± 0.60a                          | 2.47 ± 0.65a                           |
| with higher and decreasing          |                   | 2.55 ± 0.66a                          | 2.22 ± 0.65a                           |
| soil air temperature                |                   |                                      |                                        |
| 0:01-5:51                           | 1.49 ± 0.49a      | 1.46 ± 0.46a                          | 1.45 ± 0.48a                           |
| Soil-P1: Morning and early afternoon|                   | 1.52 ± 0.50a                          | 1.22 ± 0.49a                           |
| 6:01-13:11                          | 3.02 ± 0.03a      | 2.71 ± 0.04a                          | 2.86 ± 0.05a                           |
| with lower soil air temperature     |                   | 2.78 ± 0.06a                          | 2.70 ± 0.05a                           |
| Soil-P2: Daytime and early nighttime|                   |                                       |                                        |
| 14:41-20:01                         | 3.81 ± 0.03ab     | 3.71 ± 0.02b                          | 3.77 ± 0.04ab                          |
| with higher and increasing soil air |                   | 3.99 ± 0.04a                          | 3.66 ± 0.01b                           |
| temperature                         |                   |                                        |                                        |
| Soil-P3: Daytime and early nighttime|                   |                                       |                                        |
| 20:11-23:31                         | 4.09 ± 0.06a      | 4.01 ± 0.04a                          | 4.17 ± 0.07a                           |
| with higher and decreasing soil air |                   | 4.21 ± 0.06a                          | 3.96 ± 0.04a                           |
| temperature                         |                   |                                        |                                        |
| Soil-P4: Nighttime with lower soil air|                  |                                        |                                        |
| 0:01-5:51                           | 3.66 ± 0.05a      | 3.49 ± 0.04a                          | 3.68 ± 0.06a                           |
| temperature                         |                   | 3.62 ± 0.06a                          | 3.48 ± 0.06a                           |
| Day 6 | Soil-P1: Morning and early afternoon | 6:01-11:41 | 3.44 ± 0.05a | 3.24 ± 0.04a | 3.43 ± 0.06a | 3.40 ± 0.05a | 3.23 ± 0.05a | $F_{4,15} = 0.49$; $P = 0.741$
|       | with lower soil air temperature      |           |              |              |              |              |              |                          |
|       | Soil-P2: Daytime and early nighttime | 11:51-21:01 | 3.77 ± 0.03a | 3.67 ± 0.03a | 3.77 ± 0.03a | 3.81 ± 0.03a | 3.63 ± 0.03a | $F_{4,15} = 0.48$; $P = 0.750$
|       | with higher and increasing soil air  |           |              |              |              |              |              |                          |
|       | Soil-P3: Daytime and early nighttime | 21:11-23:51 | 3.92 ± 0.06a | 3.84 ± 0.06a | 3.95 ± 0.07a | 3.93 ± 0.06a | 3.78 ± 0.06a | $F_{4,15} = 0.34$; $P = 0.850$
|       | with higher and decreasing soil air  |           |              |              |              |              |              |                          |
|       | Soil-P4: Nighttime with lower soil air | 0:01-5:51 | 3.78 ± 0.04a | 3.64 ± 0.05a | 3.79 ± 0.05a | 3.71 ± 0.05a | 3.59 ± 0.04a | $F_{4,15} = 0.36$; $P = 0.830$ |