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Effects of biochar on soil respiration mediated by rainfall events: evidence from one-year field experiment in an urban forest

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Abstract

Background Biochar is widely recognized for its capacity to capture and store carbon in soil attributed to its stable structure. However, in most field studies examining the effects of biochar application on soil respiration, the impact of rainfall events on the experimental outcomes has not been taken into account. To address the existing gap in this research field, we conducted a one-year study on soil respiration in an urban camphor forest and collected the data of soil respiration, soil temperature, soil moisture, and the rainfall events closest to the soil respiration monitoring time. We specifically examined how different stages of rainfall events influenced soil respiration in relation to biochar application.

Results This study found that the annual average soil respiration rate increased with the doses of biochar application, and the soil respiration rate under the biochar application at the dose of 45 t/ha showed a significant rise. The stages of rainfall events, rainfall amount, and the interaction effect of the two, and biochar doses significantly affected soil respiration. The parameters in the regression model for soil respiration, soil temperature and moisture varied with the different stages of rainfall events and the doses of biochar application. The biochar application eliminated the significant effect of soil moisture on soil respiration during one day after rainfall events. The significant correlation between soil moisture and the temperature sensitivity of soil respiration (Q_{10}) was eliminated by biochar application, both during one day after rainfall events and more than eight days after rainfall events.

Conclusions Our findings indicated that the rice straw biochar application has a short-term positive effect on soil respiration in urban camphor forests. The rainfall events affect the field soil respiration monitored in the biochar applications, possibly by affecting the soil respiration response to soil temperature and moisture under different doses of biochar application. The impact of rainfall events on soil respiration in biochar application experiments should be considered in future forest monitoring management and practice.

Keywords Biochar, Rainfall, Soil respiration, Wet-dry cycle, Soil temperature, Soil moisture

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Introduction

Biochar is a carbon-rich porous material produced by pyrolysis or hydrothermal carbonization of biomass generated by thermal decomposition of plant, animal, manure, and other raw materials (Chen et al. 2019; Yazdani et al. 2019). Amid growing concerns about resource and environmental issues, biochar is increasingly recognized as an exceptional soil amendment (Lehmann et al. 2021; Shen and Yuan 2023) due to its high availability, high commercial benefits, and important role in the circular economy (Tian et al. 2022; Seo et al. 2022). Extensive studies have elucidated that biochar has remarkable porosity and an alkaline pH (Singh et al. 2022), which can effectively improve nutrient absorption (Hossain et al. 2020), improve moisture holding capacity (Basso et al. 2013) and increase crop yield (Ye et al. 2020), playing an essential role in nutrient and carbon cycling in soil. At the same time, biochar is highly structurally stable and remarkably resistant to decomposition (Wang et al. 2016), which has led scientists to become increasingly optimistic about its ability to reduce soil carbon dioxide emissions (Schmidt and Noack 2000; Woolf et al. 2010). Soil respiration (Rs) usually refers to the release of carbon dioxide from the soil to the atmosphere (Hashimoto et al. 2023) and soil respiration is the second largest land-based carbon flux after photosynthesis (Xu and Shang 2016). Numerous studies have shown that biochar application can increase soil organic matter storage and affect Rs (Yang et al. 2022; Afshar and Mofatteh 2024). However, the evidence for the effects of biochar on Rs is inconclusive, and extensive studies have indicated that biochar can either enhance (Hui et al. 2018), reduce (Zhou et al. 2017), or have no significant impact on Rs (Liu et al. 2016b). As the research progressed, the wide range of results emphasized the complexity inherent in the mechanisms by which biochar affects Rs (Li et al. 2018; Singh et al. 2022; Dewi et al. 2024), which highlighted the necessity for additional research to clarify the underlying mechanisms responsible for these contrasting impacts (Liu et al. 2016b; Bekchanova et al. 2024).

Extreme rainfall caused by climate change has been widely reported in recent years (Myhre et al. 2019; Fowler et al. 2021; Robinson et al. 2021). Global warming has significantly changed the frequency of heavy rainfall events in the northwestern Pacific region (Utsumi and Kim 2022), and rainfall events have gradually evolved into ecological factors that are now important considerations in ecosystem processes. Rainfall events could potentially alter the dissolution fraction (Smebye et al. 2016) and ageing of biochar applied to the soil (Wang et al. 2020), affecting the environmental stability and carbon sequestration capacity of biochar. At the same time, rainfall events typically cause rapid fluctuations in Rs (Niu et al. 2019) through altering soil temperature and moisture (Phillips et al. 2009), and disrupting the association between Rs, soil temperature and moisture over a brief time scale (Han et al. 2018). Additionally, Rs was also influenced by the classic Birch effect of rainfall events—the frequent rainfall pulses generated by rainfall (Birch 1958a). These pulses can moisten the soil surface, accumulate unstable carbon and microbial biomass used for microbial decomposition on the soil surface, causing substantial carbon dioxide emissions (Williams et al. 2009).

While the significance of rainfall events on ecological system carbon cycling is widely recognized, there remains a notable gap in our understanding of the hidden responses of Rs to rainfall events following biochar application. Studies have shown that during rainfall events, biochar with different properties may undergo different molecular transformations at the molecular level, including oxidation, dissolution and fragmentation (Wang et al. 2020; Ge et al. 2024), which can explain how the carbon stock of biochar and its role in soil carbon cycling will change. In terms of the measurement, in situ manual measurements of Rs in the field still account for the majority of Rs literature (Bond-Lamberty et al. 2024). Due to accessibility and experimental arrangements, researchers in situ manual measurements of Rs usually measure once a month (Cueva et al. 2017; Jian et al. 2018), which makes it lack of measurement on a more complete time scale (Vargas and Le 2023) and may not be able to capture the Rs pulses driven by rainfall pressure (Savage et al. 2014; Leon et al. 2014). The prevalent empirical models that link Rs to soil temperature and moisture have yet to fully encapsulate the intricate dynamics of the rainfall process (Liu et al. 2016a), which limits their predictive ability (Yan et al. 2019). Drawing attention to the influence of rainfall events on biochar application experiments can enhance our comprehension of the dynamic processes of Rs affected by biochar application and rainfall events, thereby more precise predictions regarding the impact of biochar application on Rs.

Urban forests, as integral parts of cities that provide key urban ecological services, are pivotal in the urban carbon cycle (Livesley et al. 2016; Salmond et al. 2016). Studies have reported that human interference (Steenberg et al. 2017), soil compaction, and nutrient deficiencies in urban areas currently restrict the growth of urban forest trees (Pavao-Zuckerman 2008). Recently, biochar has been applied for reducing drought stress in urban plans (Somerville et al. 2020; Yoo et al. 2020), improving the soil environment for plant growth (Manea et al. 2023) and sequestering soil carbon (Lo Piccolo et al. 2022). The camphor tree (*Cinnamomum camphora* (L.) J. Presl.), as a crucial part in the subtropical urban forests, has been designated as the official tree of 36 cities in China, with an approximate population of 172.81 million people residing in places where camphor trees are common (Zhou and Yan 2016). Camphor forests play a crucial role in urban carbon flux. This study conducted a one-year in situ monitoring of Rs in an urban camphor forest in Changsha City, following the multiple doses of biochar application. We aimed to examine the impacts of various biochar doses on Rs in urban camphor forests and to analyze how different stages of rainfall events affected the response of Rs to biochar doses, soil temperature, and soil moisture. We hypothesize that the response of Rs to rainfall will change with the stages of rainfall, and that the aging of biochar will increase with the time since biochar application and the duration of the rainfall events.

Materials and methods

Description of the site and experimental materials

The field study was performed in an artificial camphor forest in the Urban Forest Ecology Research Station of Central South Forestry and Technology University (112°48’E, 28°03’N). The camphor forest was artificially constructed in 1958, covering an area of 777.6 m^2 (21.6 m × 36 m). The experimental area had an annual average temperature of 16.5 °C and an average yearly rainfall of 1435.8 mm, mainly concentrated between June and August, with subtropical humid monsoon climate (Fig. 1). Prior to the biochar application, the soil type was krasnozem with pH of 4.41, organic carbon of 16.56 g kg^{-1}, and total nitrogen of 1.42 g kg^{-1}, total phosphorus of 5.62 g kg^{-1} at 0–20 cm depth.

Rice straw has a wide range of sources and rich biomass in Hunan Province. Considering its importance for the resource management of agricultural waste in Hunan Province, the biochar employed in this study was formed by decomposing rice straw at temperature of 600 °C in an oxygen-limited condition. Biochar was obtained from Jiangsu Huafeng Agricultural Biotechnology Co., Ltd in China and had pH of 10.53, organic matter of 15.12 g kg^{-1}, total nitrogen of 9.82 g kg^{-1}, total phosphorus of 9.63 g kg^{-1}, total potassium of 29.31 g kg^{-1}, and specific surface area of 75.35 m^2 g^{-1}.

Experimental design and sampling

This field study established a fixed area measuring 400 m^2 (20 m × 20 m) in October 2021. A random block design was adopted, with four levels of biochar application: the control group with 0 t/ha biochar application (CK), treatment groups with 15 t/ha (B15), 30 t/ha (B30), and 45 t/ha biochar application (B45) (Fig. 2a). The biochar application level of the B15 group was based on the carbon storage of forest in Changsha during 2022, and the biochar application levels of the B30 and B45 groups consistently exceeded the local carbon storage in order to research the impacts of excessive biochar application. Each treatment consisted of four replicates, resulting in a total of sixteen plots, each measuring 1 m^2 (1 m × 1 m). The plots were spaced at least 1 m apart, and a 10 cm high trench was constructed around each plot to minimize mutual influence between plots. In December 2021, a polyvinyl chloride soil collar (Φ 20 cm × H 10 cm) was embedded at the center of the diagonal in eachplot for in-situ monitoring with the LI-8100 equipment. The soil collars were embedded into the soil in depth of 4–5 cm, leaving about 3 cm of upper edge visible above the surface (Fig. 2b). In March 2022, biochar was spread evenly on the soil surface. We assumed that biochar could fully infiltrate and decompose through natural activities such as rainfall and soil microbial decomposition.

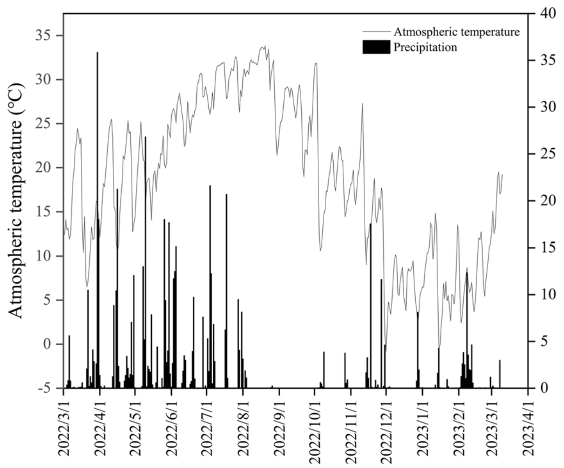

Fig. 1 Atmospheric temperature (line plot) and rainfall (bar) in the experimental area

Measurement of Rs, soil temperature and moisture

This study conducted a one-year in-situ monitoring experiment on Rs in the camphor forest using LI- 8100 from March 2022 to March 2023. We measured Rs rate starting 24 h after the biochar application, and then continued measurements every 3–4 days. The measurement time was from 9:00 am to 11:00 am suggested by Jian et al. (2018). For each measurement, the LI- 8100 chamber was placed on the collar and the Rs rate was calculated through linear regression of the increase in carbon dioxide consumption within 3–5 min after chamber equilibrium. Each soil collar was measured for 3 min, with a front and rear emptying time of 90 s. We did not remove soil surface litter before monitoring measure to preserve the original state of the experimental plot to the greatest extent possible, which made Rs data measured represent the sum of root respiration and microbial

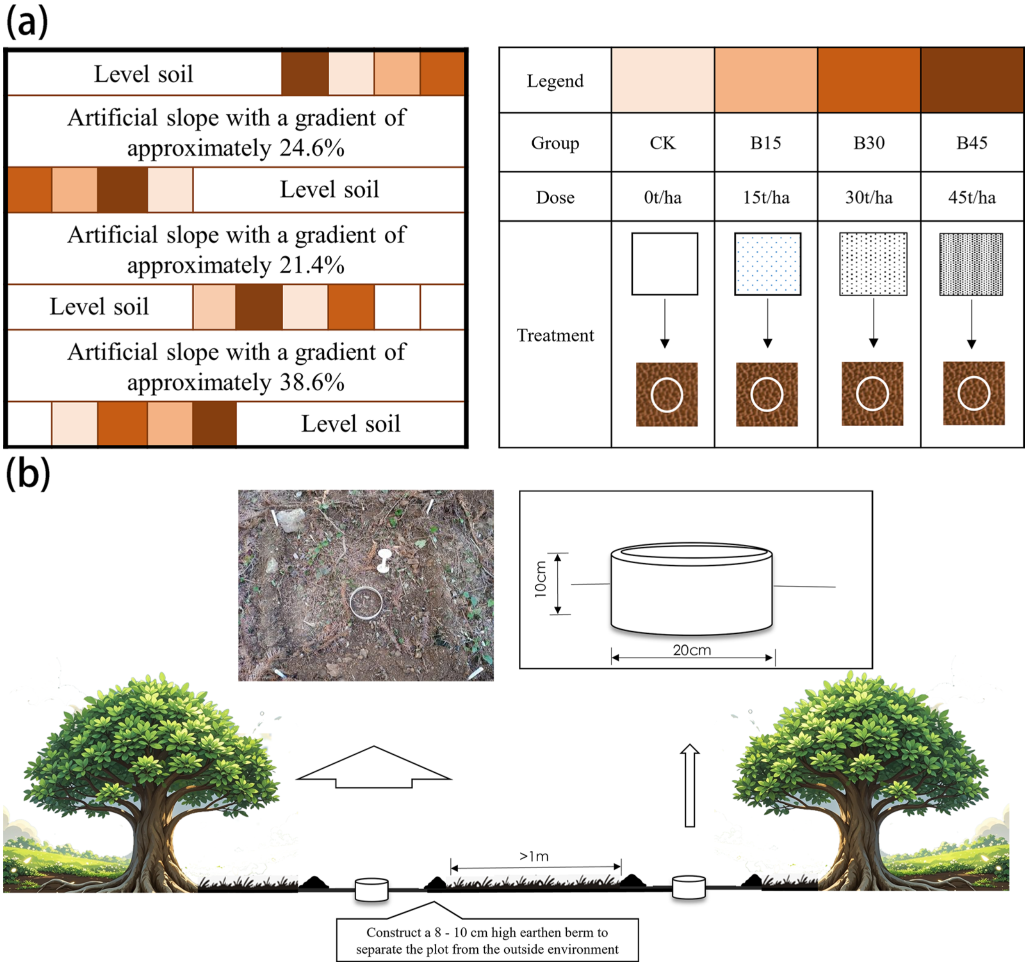

Fig. 2 Schematic map of experimental design (**a**) and layout of sample plots (**b**). In (**a**), The areas on the same row represent the same state of the area (level soil or artificial slope). CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application Dynamics of mean soil respiration (**a**) and annual average soil respiration (**b**) under different treatments

respiration under natural conditions. The average Rs rate for each treatment was calculated based on the average of the 4 chamber measurements obtained during a single measuring event.

In order to achieve long-term and continuous monitoring of soil temperature and moisture, this study inserted a TMS-4 data logger at a depth of 5 cm in each sample plot. The devices were used to measure soil temperature and moisture at a depth of 5 cm in real-time. We set parameters such as measurement frequency and read the data through the company's software Lolly Manager in an external computer. The soil temperature and moisture data were recorded every 15 min in this study.

Statistical analysis

Based on average net ecosystem productivity (NEP) levels in Changsha City, the growing season is delineated as extending from March to October each year in this study, as suggested by Richardson et al. (2010). According to the intensity and frequency of rainfall in Changsha City, rainfall events were categorized into three levels based on the cumulative rainfall of a single event: LR (less than 10 mm) ,MR(10-100 mm), and HR(more than 100 mm). The Rs data were categorized into four rainfall stages based on the interval between each monitoring event and the most recent prior rainfall event: IR (monitoring conducted during the rainfall event), OAR (monitored one day after rainfall), TEAR (monitored 2–8 days after rainfall), and EAR (monitored more than 8 days after rainfall). We divided soil temperature and moisture into distinct ranges suggested by Gu et al. (2016) and the relevant studies on soil temperature and moisture in Changsha, Hunan Province (Yu et al. 2019; Luo et al. 2020), to examine the significance of soil temperature and moisture conditions on Rs. To evaluate the influence of rainfall events on soil moisture and soil temperature,

Table 1 Three-way ANOVA results to tests the impact of biochar dose, rainfall amount, and rainfall stage on soil respiration (Rs)

EXP		**Rs (μmol m^{-2} s^{-1})**		
Three-way ANOVA		***F***	***df***	***P***
Factor				
	Biochar dose	25.456	3	**0.001**
	Rainfall stage	33.833	3	**0.001**
	Rainfall amount	48.468	23	**0.001**
	Biochar dose × Rainfall stage	0.912	9	0.514
	Biochar dose × Rainfall amount	0.876	69	0.751
	Rainfall stage × Rainfall amount	7.849	9	**0.001**
	Biochar dose × Rainfall Stage × Rainfall amount	0.359	27	0.999

$R^2 = 0.700$ Bold numbers are statistically significant ($P < 0.05$)

we calculated the changes in soil temperature and moisture before and after the occurrence of rainfall, denoted as ΔTS and ΔSM.

The effect of soil temperature on the Rs rate was modeled using the following equation, as suggested by Rey et al. (2002):

$$R_s = ae^{bT} \tag{1}$$

where Rs is the rate of respiration, T is the soil temperature at a depth of 5 cm, a and b are the fitted parameters. The soil at a depth of 0–10 cm is recognized as the most bioactive region, containing a significant quantity of roots and microbial activity (Makita et al. 2011), which are instrumental in facilitating the majority of Rs (Kuzyakov and Gavrichkova 2010). The statistical analyses have also revealed that the soil temperature at a depth of 5 cm has the greatest potential to explain the fluctuations in Rs (Pavelka et al. 2007).

The temperature sensitivity coefficient (Q_{10}) was calculated using the following equation, as suggested by Luan et al. (2011):

$$Q_{10} = e^{10b} \tag{2}$$

where b is the fitted parameter of Eq. (1).

The effect of soil moisture on Rs rate was modeled using the linear equation, as suggested by Ma et al. (2019):

$$Rs = aM + b \tag{3}$$

where Rs is the respiration rate, M is the soil moisture at a depth of 5 cm, a and b are the fitted parameters.

Prior to conducting statistical analysis, data were subjected to tests for normality. We used one-way ANOVA to analyze the differences in Rs and Q_{10} across the IR, OAR, TEAR, and EAR stages, as well as the differences in Rs under different rainfall conditions during the IR and OAR stages. Post-hoc testing was undertaken using Tukey's HSD when significant differences were detected ($P < 0.05$). We used multiple regression analysis and the three-way ANOVA to analyze the impact of biochar dose, time interval of rainfall events, and rainfall amount on Rs. We analyzed the response of Rs to soil temperature and moisture at different rainfall stages using regression analysis and Pearson correlation analysis. The relationship between soil moisture and Q_{10} was analyzed using Pearson correlation analysis.

SPSS 26.0 was used to conduct the statistical analysis. The significance level was $P < 0.05$. Origin 2023 was used to draw the dot line chart, bar chart and fitting diagram. Adobe Photoshop 2023 was used to draw the schematic map.

Results

Rs and biochar application, rainfall events

The ANOVA results showed that biochar dose, rainfall stage and rainfall amount significantly affected Rs

Table 2 Multiple regression analysis showing the dependence of soil respiration on biochar dose, rainfall amount, and time interval since last rainfall event

Variable	**Regression coefficient**	**Standard error**	**Standardized regression coefficient**	***t***	***P***
Constant	2.964	0.135		21.933	< 0.001
Biochar dose	0.020	0.004	0.153	4.990	< 0.001
Rainfall amount	0.001	0.000	0.148	4.641	< 0.001
Time interval since last rainfall event	− 0.119	0.010	− 0.378	− 11.871	< 0.001

$F = 76.585$, $P < 0.001$; $R^2 = 0.217$, Adjusted $R^2 = 0.214$. Group: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application during the experimental period ($P < 0.05$), and Rs was significantly affected by the interaction between stage and rainfall amount (Table 1). The multiple linear regression analysis showed that the inclusion of biochar dose, time interval of rainfall events and rainfall amount in the regression equation for Rs was statistically significant ($P < 0.001$) and could explain 21.4% of the variation in Rs (Table 2).

Rs response to biochar application

The Rs rate across different treatment groups exhibited significant fluctuations throughout the year, with an increase in spring, peaking in summer, and a gradual decline in autumn (Fig. 3). The Rs rate in the B45 group was significantly higher than that in other treatment groups ($P < 0.05$) (Fig. 3b), which could be attributed to the marked increase in Rs in the B45 group beginning in April 2022 and disappearing in September 2022 (Figs. 3b, 4a).

Based on the monthly average soil respiration data, the soil respiration rate in the biochar-applied groups exceeded that of the control group in most months (Fig. 4b). The increase in Rs rate of the biochar-applied groups was most substantial during the first two months of biochar application and then gradually declined until October 2022, at which point Rs rate began to rise again. From August to September 2022, the biochar-applied groups exhibited an opposite inhibitory effect on Rs rate, and the B30 group demonstrated the most substantial inhibition of Rs rate during this period.

Rs and rainfall events

The trend of Rs and soil temperature in different treatment groups was similar, showing substantial seasonal effects. In contrast, this trend diverged from that observed in soil moisture (Fig. 5). It is worth noting that during major and long-term rainfall events, Rs rate exhibited many abnormally large values (Fig. 3b). Furthermore, soil moisture exhibited distinct fluctuations coincident with rainfall events, with the increase in soil moisture becoming increasingly substantial as rainfall intensifies (Fig. 5c). Rainfall in the experimental area was predominantly concentrated from March to August 2022, which significantly contributed to the annual total rainfall (Fig. 1). This seasonal rainfall coincided with a collective increase in Rs rate observed in biochar-applied groups (B15, B30 and B45), with the B45 treatment group exhibiting a particularly notable surge in Rs rate (Fig. 5a). The observed increase in Rs rate did not correlate directly with the doses of biochar applied, since the results suggested that the B15 group was more effective in enhancing Rs rate compared to the B30 group during this period (Fig. 4b).

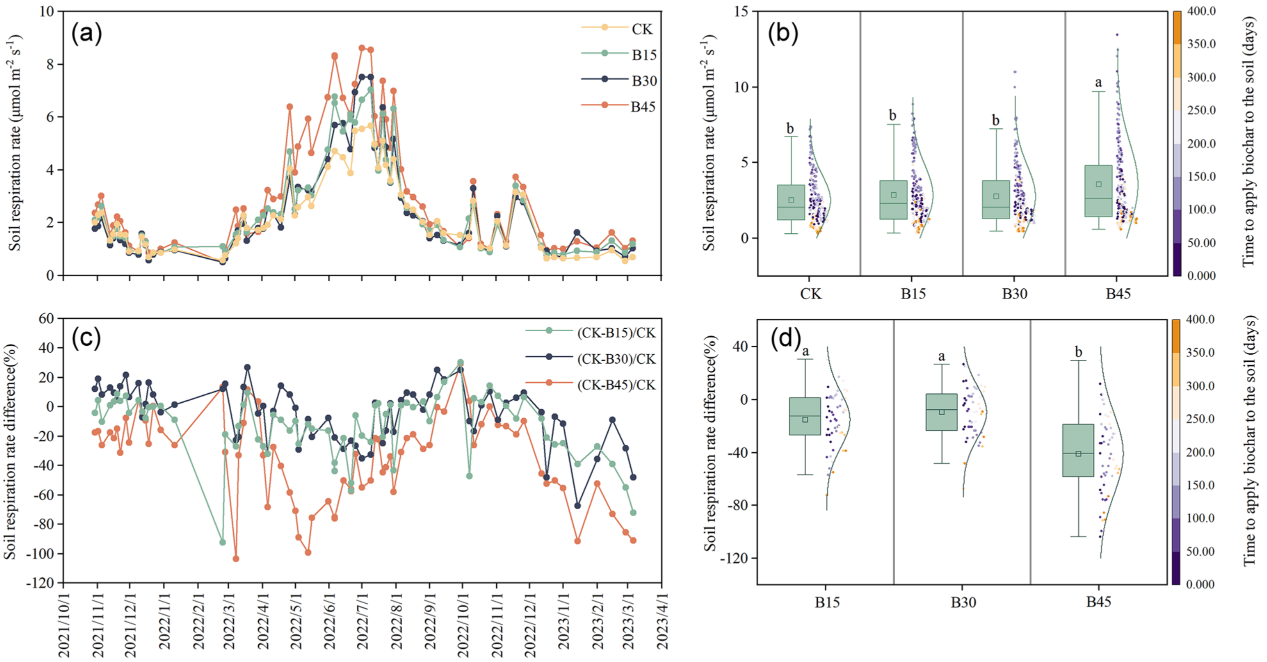

Fig. 3 Dynamics of mean soil respiration deviation (**c**) and annual average soil respiration deviation (**d**) in each treatment group compared to the control group (mean, $n = 4$). The color mapping in figures (**b**) and (**d**) indicates the applied time of biochar. In (**c**) and (**d**), the *y*-axis shows the mean percentage different in soil respiration rate between the biochar-applied treatment and the control treatment. CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application

We found that the B45 treatment group exhibited a significant increase in Rs rate during the first three rainfall stages (IR, OAR, and TEAR) in the growing season ($P < 0.05$), while showing no significant difference compared to the CK group during the EAR stage ($P > 0.05$) (Fig. 6a). In contrast, the other treatment groups did not show significant difference in Rs rate compared to the CK group during any rainfall stage ($P > 0.05$). In the non-growing season, we observed that only the Rs rate in the B45 group significantly increased compared to the CK group during the EAR stage ($P < 0.05$), while the Rs rate in other biochar-applied groups did not show significant changes ($P > 0.05$). Rs rate in different treatment groups differed across the total range of rainfall events during the IR period. In both LR and MR rainfall events during the OAR and IR periods, the Rs rate in the B45 group was significantly higher than that in the CK group ($P < 0.05$), and there were different increases in the Rs rate in the B15 and B30 groups (Fig. 6c, d).

The response of Rs to soil temperature and moisture under rainfall events

The Rs rate of the B45 group was significantly higher than that of the CK group ($P < 0.05$) across all soil temperature ranges investigated in this study. It is noteworthy that the Rs rate of the B15 group rose significantly compared to the B30 group during the soil temperature range of 10–20 °C, while this situation flipped when soil temperature reached 20 °C (Fig. 7a). In contrast, different soil moisture ranges did not exhibit the similar situation. The B15 group had a higher Rs rate under low soil moisture conditions (0–20%) compared to other treatment groups, but as soil moisture increased, the B45 group was more capable of stimulating a higher degree of Rs release (Fig. 7b).

We found that rainfall events during the experiment had an immediate effect on soil temperature and moisture (Fig. 8) and soil temperature and moisture were important controlling factors for Rs in the study (Fig. 9, Table 3). The results showed that soil temperature explained more of the variation in Rs than soil moisture. The fitted model demonstrated that the influence of soil temperature on Rs diminished as the doses of biochar application increased. The Rs was significantly related to soil moisture in a linear regression ($P < 0.001$), with soil moisture accounting for 11.7–28.2% of the variability of Rs (Fig. 9).

The study showed that the response of Rs to soil temperature and moisture differed across distinct stages of rainfall events, since the different stages of rainfall significantly altered the slope of the exponential regression curve and the explanatory power of the regression model (Figs. 10, 11). Nevertheless, the biochar application reduced the prominent impact of soil temperature during the IR stage, and in the B45 group, soil temperature did not significantly affect Rs ($P > 0.05$). The model

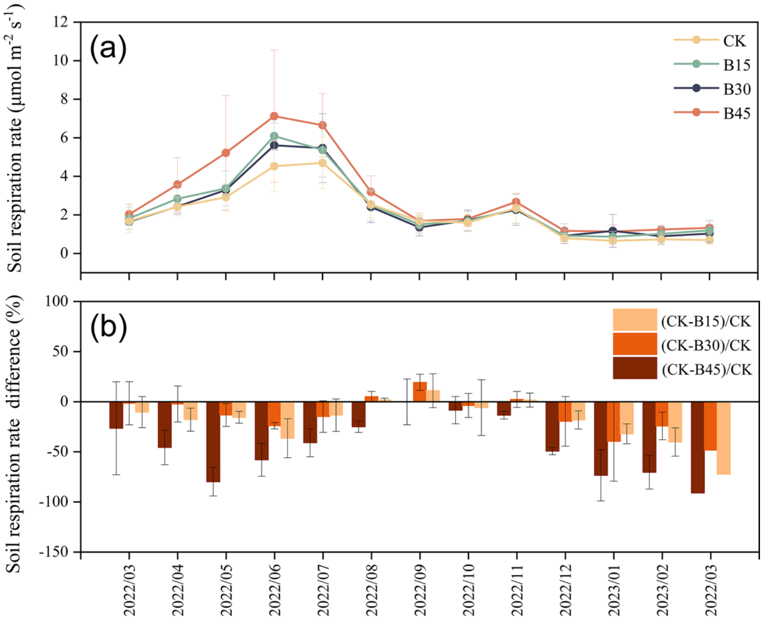

Fig. 4 Monthly mean soil respiration under different treatments (**a**). Monthly mean soil respiration deviation in each treatment group compared to the control group (**b**) (mean, $n = 4$). In (**b**), the *y*-axis shows the monthly average percentage difference in soil respiration rate between the biochar-applied group and the control group. Error bars are the standard deviation. CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application

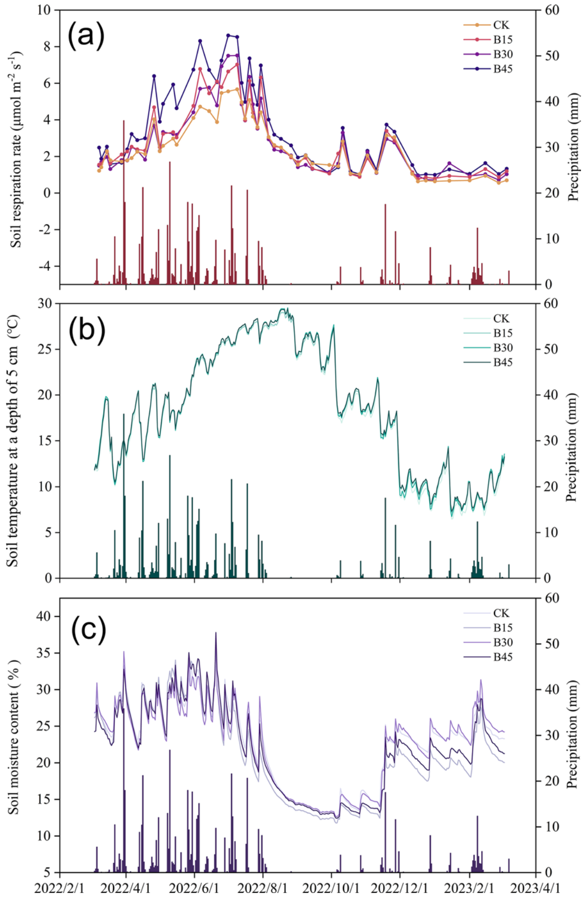

Fig. 5 Dynamics of mean soil respiration (**a**), mean soil temperature (**b**), mean soil moisture (**c**) under different treatments. The bar chart represents the daily mean rainfall in the experimental area. CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application

between Rs and soil temperature was highly explanatory in all treatment groups during the OAR stage, with soil temperature accounting for more than 50% of the variability in Rs of the CK and B15 groups.

We observed that during the OAR stage, soil moisture significantly affected Rs in the CK group ($P<0.05$), whereas no statistically significant linear relationship was found between soil moisture and Rs in the biochar-applied group ($P>0.05$) (Fig. 11). In addition, the fitting equations of Rs to soil moisture had negative slopes during the EAR stage.

Temperature sensitivity coefficient Q_{10}

There was no significant difference in Q_{10} among the treatment groups ($P<0.05$). However, Q_{10} varied significantly across different stages of the rainfall event ($P<0.05$). The Q_{10} for each treatment reached their maximum during the OAR stage, while the minimum Q_{10} were observed during the IR stage. The Q_{10} in the B30 and B45 groups was significantly lower than that in the CK group during the EAR stage ($P<0.05$), but there was no significant difference in Q_{10} between the treatment groups during other stages ($P>0.05$) (Fig. 12).

The results of the correlation analysis showed that soil moisture showed a significant correlation with Q_{10} in the CK group during the OAR and EAR stages ($P<0.05$), and the correlation coefficients reached 0.989 and 0.973, respectively (Table 4). There was no significant correlation between soil moisture and Q_{10} in the biochar-applied groups ($P>0.05$), while Q_{10} was significant correlated with soil moisture in the CK group ($P<0.05$) (Table 4).

Discussion

Response of Rs to different doses of biochar application

Our study showed that the application of different doses of rice straw biochar increased Rs rate to varying degrees during a one-year research, and that biochar application at the dose of 45 t/ha had a significant effect on increasing Rs rate ($P<0.05$) (Fig. 3b). This variation may be attributed to the application dose and the aging of the biochar, as this study investigated the effect of excess biochar application on Rs compared to the local soil organic carbon. Previous studies have indicated that a large dose of biochar application may promote Rs, which may be closely related to the stimulating effect of biochar application on organic carbon decomposition (Kerré et al. 2016). This effect is primarily attributed to the provision of temporarily labile carbon by biochar to soil microorganisms post-application, which can then be assimilated and utilized by these microorganisms (Smith et al. 2010). Sagrilo et al. (2015) found that soils with C content ≤ 10 g kg^{-1} showed a significantly increased carbon dioxide emission after the application of different doses of biochar. Besides, the experimental period of this study was one year, aimed at exploring the short-term effects of biochar application on Rs. This made it possible that the applied time and biochar ageing also affected the experimental results. Ding et al. (2018) showed that the applied time was the most important determinant of the induction of carbon-stimulation by biochar, and that positive priming only occurred during the first 775 days after biochar application, after which it turned negative. After biochar was applied to the soil, it was affected by various natural processes, including the wet and dry cycles and temperature changes (Fu et al. 2019; Meng et al. 2020), which led to significant changes in its properties, thereby enhancing or impairing its performance in terms of field application and long-term carbon storage (Wang et al. 2020). Further long-term field experiments are essential

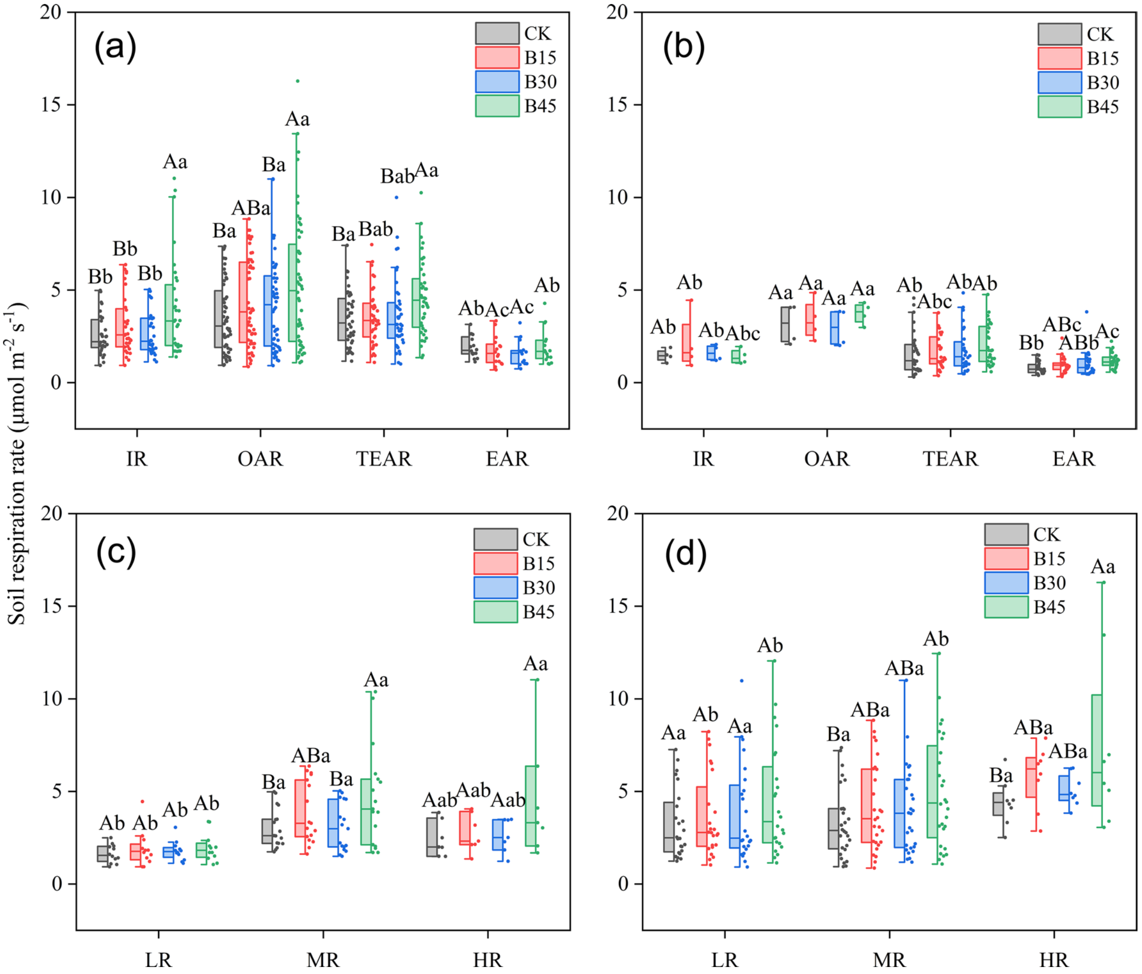

Fig. 6 Averaged soil respiration under different treatments in different stages of rainfall events during the growing season (**a**) and non-growing season (**b**). Averaged soil respiration under different treatments in different cumulative rainfall levels during the stage of monitoring conducted during the rainfall event (IR) (**c**) and monitored one day after rainfall (OAR) (**d**). Error bars are the standard deviation. Capital letters represent significant difference between treatment groups in the same stage ($P < 0.05$), whereas lowercase letters represent significant difference between different stages in the same group ($P < 0.05$). Treatment: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. Stage: IR, monitoring conducted during the rainfall event; OAR, monitored one day after rainfall; TEAR, monitored 2–8 days after rainfall; EAR, monitored more than 8 days after rainfall. Cumulative rainfall levels: LR (less than 10 mm), MR (10–100 mm), and HR (more than 100 mm)

to evaluate the sustained effects of biochar on Rs. These studies will enhance our comprehensive understanding of biochar's impacts, particularly its behavior under diverse environmental conditions.

Seasonal variation of the relationship between Rs and rainfall

In our study, Rs rate under different biochar treatments showed significant differences during various stages of rainfall events (Fig. 3a), with these differences being more pronounced during the growing season compared to the non-growing season (Fig. 4). Previous studies have demonstrated that Rs, triggered by rainfall during the growing season and particularly during heavy rainfall events (Peng et al. 2013), can account for nearly 50% of the carbon dioxide released from the soil (Brito et al. 2013). The influence of rainfall events on Rs was particularly pronounced throughout the entire incubation period, as the study site experienced more frequent precipitation in summer and autumn compared to winter and spring (Fig. 1). A significant portion of the annual precipitation is attributed to rainfall during the growing season (Shi et al. 2011). The rewetting of dry soil frequently leads to a rapid emission of carbon dioxide (Birch 1958b), which has been proved in laboratory (Kieft et al. 1987) and field studies (Yan

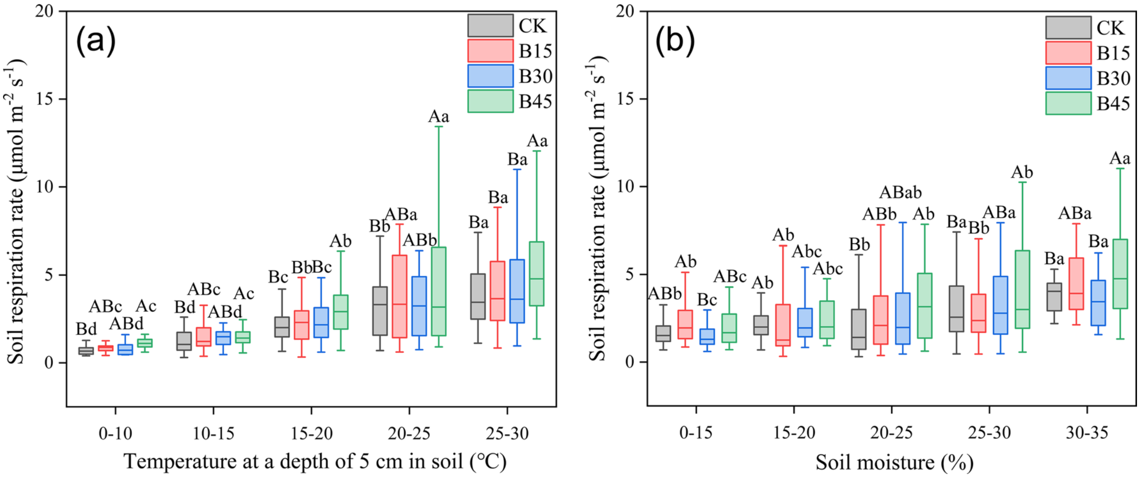

Fig. 7 Averaged soil respiration under different treatments in different soil temperature (**a**) and soil moisture levels (**b**). Error bars are the standard deviation. Capital letters represent significant difference between treatment groups in the same stage ($P < 0.05$), whereas lowercase letters represent significant difference between different stages in the same group ($P < 0.05$). CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application

et al. 2014). In addition, the reduced frequency of rainfall during winter leads to an accumulation of carbon dioxide in the soil micropores. Subsequently, during the growing season, rainfall events can lead to the replacement of this carbon dioxide by soil moisture, thereby enhancing the emission of carbon dioxide from the soil (Huxman et al. 2004). Furthermore, the recovery of sprouting of roots in spring is extremely responsive to the levels of soil moisture (Schwinning et al. 2005). Rainfall events in this study frequently resulted in rapid increases in soil moisture levels (Fig. 8), which may subsequently trigger a prompt acceleration in root development and an enhancement in Rs rates (Liu et al. 2019). However, it is crucial to acknowledge that rainfall events during the non-growing season are relatively infrequent and occur at longer intervals (Figs. 1, 8). The scale and frequency of these events throughout the non-growing season may not be sufficient to replenish soil moisture, thereby reducing the statistical significance of these events compared to those in the growing season (Fig. 6).

We observed that Q_{10} values peaked during the OAR stage, while they were comparatively low during the IR stage (Fig. 12). This can be attributed to the condition that during rainfall events, when soil pore space is saturated, the subsequent increase in soil moisture can block the pores, leading to anoxia stress. This stress inhibits the respiration of aerobic microorganisms and the aerobic respiration of the root system (Lado-Monserrat et al. 2014; Singh et al. 2017). Later, in the OAR stage, as the plant roots adsorb from the surface to the deeper layers of soil (Liu et al. 2020), the water availability of the dry surface soil will help maintain the activity of the microbial communities and fine roots near the soil surface (Bauerle et al. 2008), resulting in a larger Q_{10} in the OAR stage.

Response of Rs to rainfall treated with different doses of biochar

The results of this study showed that Rs during the experiment was significantly affected by the biochar dose, time interval of rainfall events and rainfall amount ($P < 0.05$) (Tables 1, 2). Throughout the growing season, Rs rates in the biochar-applied groups were higher compared to the control group, and this difference was particularly pronounced in the B45 group, which resulted in the most substantial increase in Rs (Figs. 3c, 4a). This trend coincided with the timing of large-scale, continuous rainfall events in the experimental area (Fig. 5a), indicating that rainfall events may play an essential role in amplifying the stimulating impact of biochar on Rs. Research has demonstrated that the biochar application greatly influences the response of Rs to abrupt fluctuations in soil moisture levels caused by rainfall events (Lado-Monserrat et al.

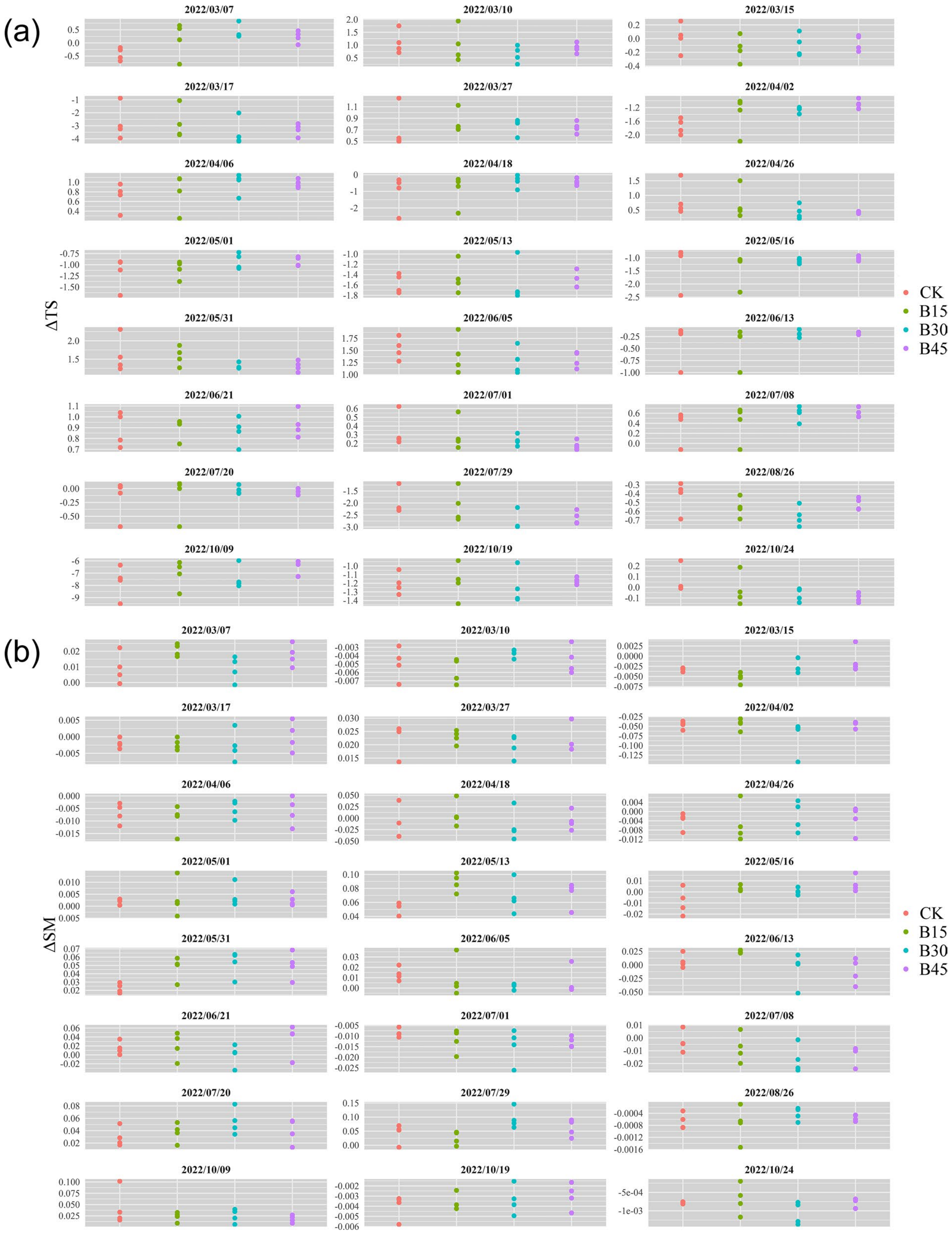

Fig. 8 ΔTS (**a**) and ΔSM (**b**) under different treatments during rainfall events at the closest time prior to the measurement experiments. ΔTS and ΔSM are calculated by the changes in soil temperature and moisture before and after the occurrence of rainfall events. CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application

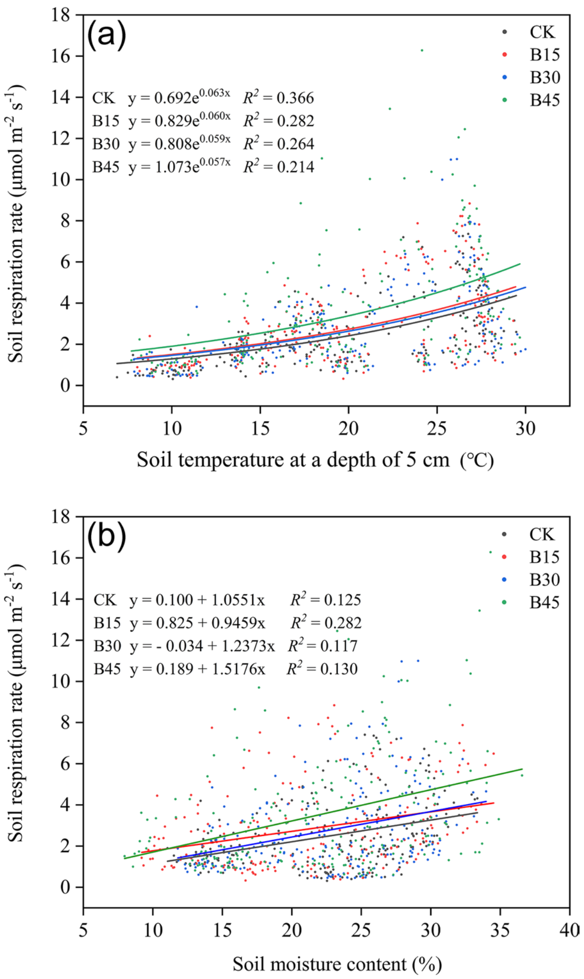

Fig. 9 Regression relationships between soil respiration and soil temperature (**a**), soil respiration and soil moisture (**b**) under different treatments. CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. R^2 values and regression equations are provided

2014). In terms of different stages of rainfall events, the Rs of the B45 group significantly increased in comparison to other groups during the IR, OAR and TEAR stage ($P<0.05$) (Fig. 6), contributing to the majority of the difference in Rs of B45 group. Rainfall and wet-dry cycles are an important but often overlooked mechanism for biochar aging and are also the main causes of physical breakdown and decomposition of biochar in field in situ experiments (Wang et al. 2020). Biochar absorbs water during rainfall, leading to the expansion of graphite flakes and structural distortion. This expansion increases the susceptibility of biochar to fracture under mechanical stress, resulting in fragmentation (Spokas et al. 2014). The process contributes to the formation of dissolved black carbon and create a new and more functional soil structure, which can increase transport pores and play a crucial role in plant root and soil animal growth (Sun et al. 2018). Additionally, research has indicated that biochar application elevates soil pH, which positively correlates with the stimulation of Rs due to wet-dry cycles (Singh Yadav et al. 2023). Low pH can restrict soil microbial activity, thus impeding the decomposition of soil organic matter by microorganisms (Andersson and Nilsson 2001). Conversely, an increase in pH can reduce the binding strength of soil organic matter to mineral surfaces, this reduction allows microorganisms greater access to previously protected soil organic matter (Newcomb et al. 2017).

Rainfall events affect the response of Rs to soil temperature and moisture under different treatments

This study showed that Rs exhibited distinct responses to soil temperature and moisture during the various stages of rainfall events (Figs. 10, 11). Laboratory and field experiments have demonstrated the significance of soil temperature and moisture as key environmental factors influencing the temporal variability of Rs (Miao et al. 2013). Our study demonstrated that varying doses of biochar application mitigated the impact of soil temperature on Rs (Fig. 10). Some studies have shown that the activated carbon in biochar can potentially mitigating the impact of soil temperature on Rs by adsorbing and sequestering carbon dioxide (Bruun et al. 2014). In addition, the extensive surface area of biochar helps shield indigenous root remnants and organic carbon from undergoing mineralization (Junna et al. 2014), which may cause a reduction in the fitting degree of the

(See figure on next page.)

Fig. 10 Regression relationships between soil respiration and soil temperature under different treatments during distinct stages of rainfall events (**a**, **c**, **e**, **g**) and total stage (**b**, **d**, **f**, **h**). Figures of each treatment group are positioned consecutively, with the figure showing distinct stages of rainfall events positioned above the figure showing the total stage. The color of the points in (**b**, **d**, **f**, **h**) represents different stages of rainfall events. Group: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. Stage: IR, monitoring conducted during the rainfall event; OAR, monitored one day after rainfall; TEAR, monitored 2–8 days after rainfall; EAR, monitored more than 8 days after rainfall

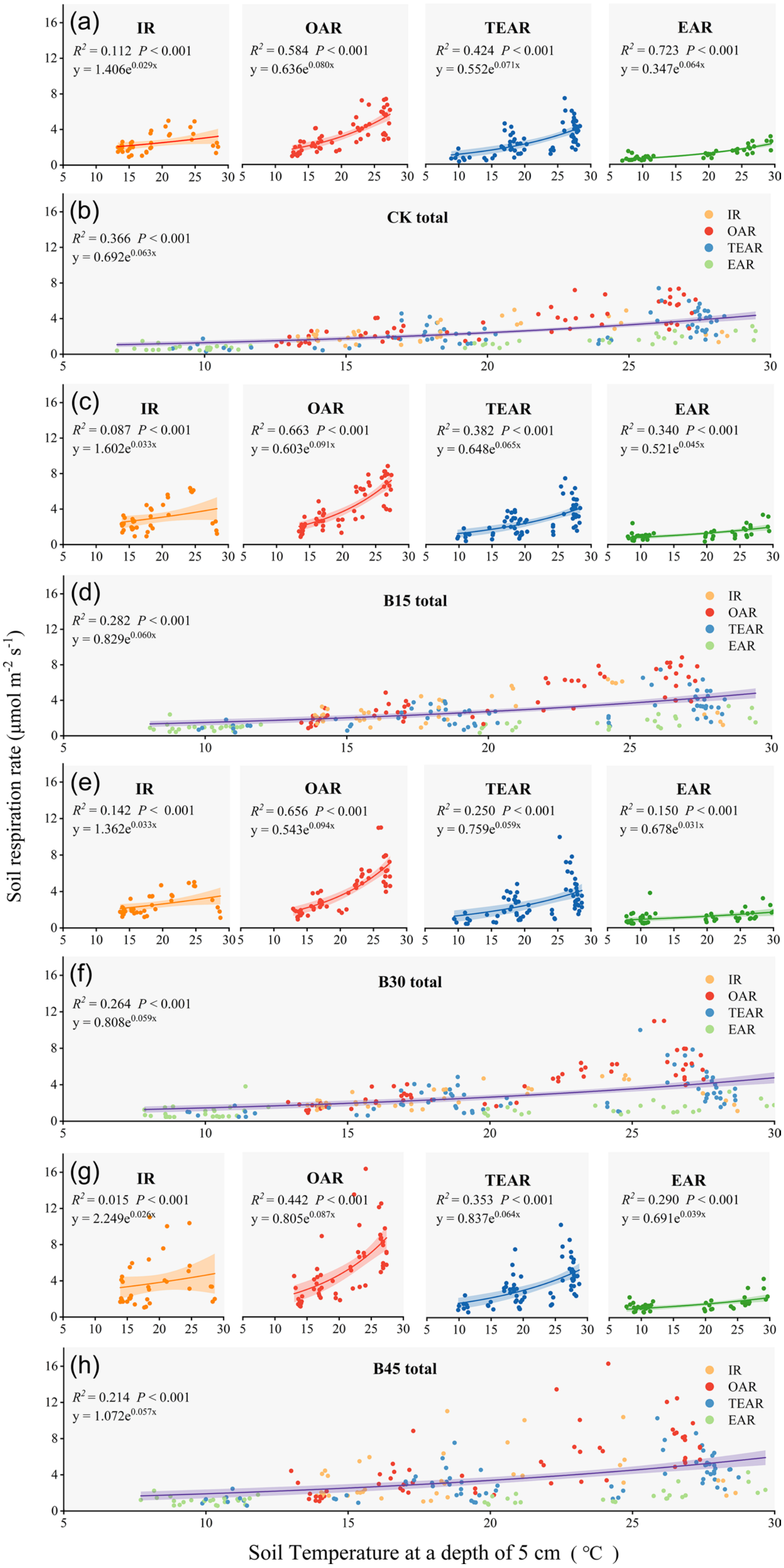

Fig. 10 (See legend on previous page.)

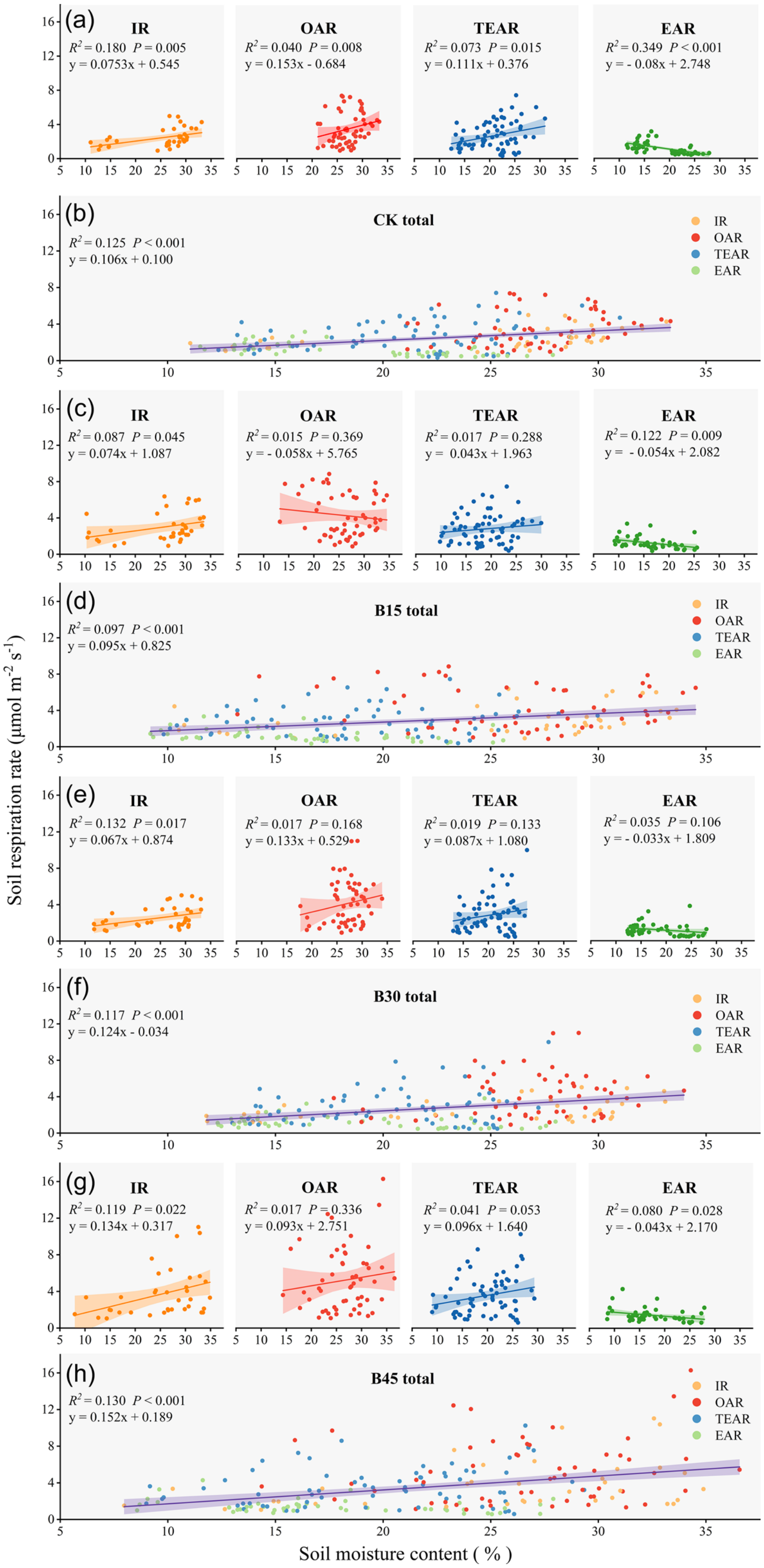

Fig. 11 (See legend on next page.)

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Fig. 11 Regression relationships between soil respiration and soil moisture under different treatments during distinct stages of rainfall events **(a**, **c**, **e**, **g)** and total stage (**b**, **d**, **f**, **h**). Figures of each treatment group are positioned consecutively, with the figure showing distinct stages of rainfall events positioned above the figure showing the total stage. The color of the points in (**b**, **d**, **f**, **h**) represents different stages of rainfall events. Group: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. Stage: IR, monitoring conducted during the rainfall event; OAR, monitored one day after rainfall; TEAR, monitored 2–8 days after rainfall; EAR, monitored more than 8 days after rainfall

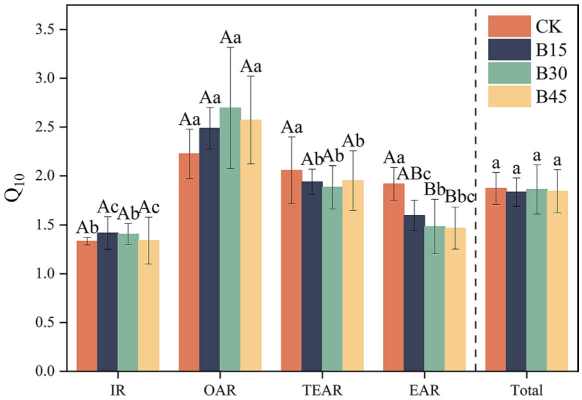

Fig. 12 Q_{10} under different treatments in different stages of rainfall events. Error bars are the standard deviation. Capital letters represent significant difference between treatment groups in the same stage ($P < 0.05$), whereas lowercase letters represent significant difference between different stages in the same group ($P < 0.05$). Group: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. Stage: IR, monitoring conducted during the rainfall event; OAR, monitored one day after rainfall; TEAR, monitored 2–8 days after rainfall; EAR, monitored more than 8 days after rainfall

Rs and soil temperature equations (Fig. 10b, d, f, h). Different treatments in the exponential fitting model of Rs and soil temperature only showed good predictive performance in the OAR stage, indicating that soil moisture did not constitute a limiting factor for Rs in this stage. At the same time, we found that in the EAR stage, the fitting curve of Rs and soil temperature was quite flat, and soil temperature can account for over 70% of the variation in Rs of the CK group (Fig. 10a), indicating that soil moisture is very likely to be a limiting factor for Rs in the EAR stage. However, we observed that the negative impact of extremely low soil moisture conditions on Rs seems to be modified by the biochar application (Fig. 7). In the biochar-applied groups, the exponential fitting curve in this stage is relatively steeper than that in the CK group, and the degree of explanation is less (Fig. 10c, e, g). Research indicated that the biochar application can decrease fluctuations in soil temperature and alleviate extreme soil temperature levels (Zhang et al. 2013), which may be due to the ability of biochar to improve soil water retention by reducing soil bulk density through the dilution effect resulting from low biochar bulk density, and the direct introduction of new pore space (Atkinson et al. 2010).

Research on Rs under various soil moisture conditions has been extensively conducted across different ecological systems (Fissore et al. 2009; Drake et al. 2014). Increasing studies have shown that the responses of Rs to soil moisture at various stages of rainfall events are influenced by several factors such as water potential, dry and wet conditions, and the length of dry periods (Reichstein et al. 2002). In our study, soil moisture significantly affected Rs in all treatment groups during the IR stage (Fig. 11a, c, e, g, Table 3). Insufficient soil moisture can directly impede microbial activity and root respiration in soil (Almagro et al. 2009). Consequently, as the soil transitions from dry to wet, the rise in soil moisture following rainstorm events might stimulate Rs by enhancing substrates to diffuse (Lado-Monserrat et al. 2014).

Table 4 Pearson correlations between Q_{10} and soil moisture (SM) under different treatments in different rainfall stage

Q_{10}	**CK**				**B15**			
	IR	**OAR**	**TEAR**	**EAR**	**IR**	**OAR**	**TEAR**	**EAR**
SM	0.888	0.989*	0.864	0.973*	0.093	− 0.676	0.131	− 0.274
Q_{10}	**B30**				**B45**			
	IR	**OAR**	**TEAR**	**EAR**	**IR**	**OAR**	**TEAR**	**EAR**
SM	0.341	0.548	− 0.084	0.301	0.912	− 0.387	− 0.288	− 0.802

*indicates significant differences ($P < 0.05$). Group: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. Stage: IR, monitoring conducted during the rainfall event; OAR, monitored one day after rainfall; TEAR, monitored 2–8 days after rainfall; EAR, monitored more than 8 days after rainfall

Table 3 Pearson correlations between soil respiration (Rs), soil temperature (TS) and soil moisture (SM) under different treatments during different rainfall stages

Rs	**CK**				**B15**			
	IR	**OAR**	**TEAR**	**EAR**	**IR**	**OAR**	**TEAR**	**EAR**
SM	0.451^{**}	0.240	0.294^{*}	-0.602^{**}	0.336^{*}	-0.122	0.131	-0.375^{**}
TS	0.402^{*}	0.776^{**}	0.663^{**}	0.818^{**}	0.373^{*}	0.827^{**}	0.637^{**}	0.560^{**}
Rs	**B30**				**B45**			
	IR	**OAR**	**TEAR**	**EAR**	**IR**	**OAR**	**TEAR**	**EAR**
SM	0.396^{*}	0.187	0.184	-0.236	0.380^{**}	0.131	0.236	-0.316^{**}
TS	0.448^{**}	0.824^{**}	0.528^{**}	0.398^{**}	0.231	0.688^{**}	0.690^{**}	0.513^{**}

*indicates significant differences ($P < 0.05$). Group: CK, control; B15, 15 t/ha biochar application; B30, 30 t/ha biochar application; B45, 45 t/ha biochar application. Stage: IR, monitoring conducted during the rainfall event; OAR, monitored one day after rainfall; TEAR, monitored 2–8 days after rainfall; EAR, monitored more than 8 days after rainfall

We observed that the variability of this relationship between soil moisture and Rs became more pronounced as the doses of biochar application increased during the OAR stage (Fig. 11). A similar pattern was observed for the correlation between Q_{10} and soil moisture during the OAR stage (Table 4). The lack of significance can be attributed to the unique structure of biochar, which is highlighted by its high porosity and surface area. This arrangement generates supplementary pores in the soil, facilitating a more advantageous habitat for the proliferation of soil microorganisms and plant roots. Therefore, this environment may play a vital part in decreasing the reliance of Rs on soil moisture in the biochar treatment groups.

Conclusion

Existing models that simulate and predict the effects of biochar application on Rs largely rely on frequent observations of soil temperature and moisture, often neglecting the response of Rs to rainfall events. This oversight is significant, as rainfall exerts a substantial influence on the uncertainty of carbon calculations associated with biochar application across ecological systems, particularly in the water-rich southern regions during the rainy season. This study demonstrated that rainfall events significantly influenced soil respiration rates and the impacts of biochar on soil respiration in a one-year field monitoring experiment. Therefore, incorporating the distribution of rainfall events and establishing a temporal framework based on these occurrences is essential for accurately assessing the impact of biochar on Rs. The effectiveness of the rainfall-event-based approach proposed in this study requires validation across a broader spatial scale and in diverse locations. This study provides data support for the application of biochar in urban forests and the impact of biochar on Rs in urban forests, as well as considerations for field monitoring of Rs under biochar application, especially for artificial monitoring, which includes how should we consider the impact of rain events on our monitoring behavior and Rs when planning artificial field monitoring experiments on Rs. Rationally selecting the monitoring time of Rs will help with the processing of Rs data in the later stage and the prediction of future Rs, and more accurately assess the impact of biochar application on urban forest carbon fluxes.

Abbreviations

Rs	Soil respiration
TS	Soil temperature
SM	Soil moisture
IR	Monitoring conducted during the rainfall event
OAR	Monitored one day after rainfall
TEAR	Monitored 2–8 days after rainfall
EAR	Monitored more than 8 days after rainfall
LR	The cumulative precipitation of a single rainfall event is less than 10 mm
MR	The cumulative precipitation of a single rainfall event is between 10 and 100 mm
HR	The cumulative precipitation of a single rainfall event is larger than 100 mm

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Author contributions

HRZ: Project administration, Formal analysis, Data collection, Writing-Original Draft; ZJD: Formal analysis, Project administration; XL: Formal analysis; JYL: Formal analysis; YC: Formal analysis; XW: Formal analysis; XCL: Project administration; XZ: Project administration, editing, Material preparation; WDY: Project administration.

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Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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References

Afshar M, Mofatteh S (2024) Biochar for a sustainable future: environmentally friendly production and diverse applications. Results Eng 23:102433. https://doi.org/10.1016/j.rineng.2024.102433

Almagro M, López J, Querejeta JI, Martínez-Mena M (2009) Temperature dependence of soil CO$_2$ efflux is strongly modulated by seasonal patterns of moisture availability in a Mediterranean ecosystem. Soil Biol Biochem 41:594–605. https://doi.org/10.1016/j.soilbio.2008.12.021

Andersson S, Nilsson SI (2001) Influence of pH and temperature on microbial activity, substrate availability of soil-solution bacteria and leaching of dissolved organic carbon in a mor humus. Soil Biol Biochem 33:1181–1191. https://doi.org/10.1016/S0038-0717(01)00022-0

Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337:1–18. https://doi.org/10.1007/s11104-010-0464-5

Basso AS, Miguez FE, Laird DA et al (2013) Assessing potential of biochar for increasing water-holding capacity of sandy soils. GCB Bioenergy 5:132–143. https://doi.org/10.1111/gcbb.12026

Bauerle TL, Richards JH, Smart DR, Eissenstat DM (2008) Importance of internal hydraulic redistribution for prolonging the lifespan of roots in dry soil. Plant Cell Environ 31:177–186. https://doi.org/10.1111/j.1365-3040.2007.01749.x

Bekchanova M, Kuppens T, Cuypers A et al (2024) Biochar's effect on the soil carbon cycle: a rapid review and meta-analysis. Biochar 6:88. https://doi.org/10.1007/s42773-024-00381-8

Birch HF (1958a) The effect of soil drying on humus decomposition and nitrogen availability. Plant Soil 10:9–31. https://doi.org/10.1007/BF01343734

Birch HF (1958b) Pattern of humus decomposition in East African soils. Nature 181:788–788. https://doi.org/10.1038/181788a0

Bond-Lamberty B, Ballantyne A, Berryman E et al (2024) Twenty years of progress, challenges, and opportunities in measuring and understanding soil respiration. J Geophys Res Biogeosci 129:e2023JG007637. https://doi.org/10.1029/2023JG007637

Brito P, Trujillo JL, Morales D et al (2013) Response of soil CO$_2$ efflux to simulated precipitation pulses in a canary island pine forest at treeline. Arid Land Res Manag 27:178–187. https://doi.org/10.1080/15324982.2012.755716

Bruun S, Clauson-Kaas S, Bobuľská L, Thomsen IK (2014) Carbon dioxide emissions from biochar in soil: role of clay, microorganisms and carbonates. Eur J Soil Sci 65:52–59. https://doi.org/10.1111/ejss.12073

Chen W, Meng J, Han X et al (2019) Past, present, and future of biochar. Biochar 1:75–87. https://doi.org/10.1007/s42773-019-00008-3

Cueva A, Bullock SH, López-Reyes E, Vargas R (2017) Potential bias of daily soil CO$_2$ efflux estimates due to sampling time. Sci Rep 7:11925. https://doi.org/10.1038/s41598-017-11849-y

Dewi RK, Gong Y, Huang Q et al (2024) Addition of biochar decreased soil respiration in a permanent no-till cover crop system for organic soybean production. Soil Tillage Res 237:105977. https://doi.org/10.1016/j.still.2023.105977

Ding F, Van Zwieten L, Zhang W et al (2018) A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. J Soils Sediments 18:1507–1517. https://doi.org/10.1007/s11368-017-1899-6

Drake PL, McCormick CA, Smith MJ (2014) Controls of soil respiration in a salinity-affected ephemeral wetland. Geoderma 221–222:96–102. https://doi.org/10.1016/j.geoderma.2014.01.010

Fissore C, Giardina CP, Kolka RK, Trettin CC (2009) Soil organic carbon quality in forested mineral wetlands at different mean annual temperature. Soil Biol Biochem 41:458–466. https://doi.org/10.1016/j.soilbio.2008.11.004

Fowler HJ, Lenderink G, Prein AF et al (2021) Anthropogenic intensification of short-duration rainfall extremes. Nat Rev Earth Environ 2:107–122. https://doi.org/10.1038/s43017-020-00128-6

Fu Q, Zhao H, Li T et al (2019) Effects of biochar addition on soil hydraulic properties before and after freezing-thawing. Catena 176:112–124. https://doi.org/10.1016/j.catena.2019.01.008

Ge M, Wang B, Chen B et al (2024) Hydrochar and its dissolved organic matter aged in a 30-month rice-wheat rotation system: do primary aging factors alter at different stages? Environ Sci Technol 58:3019–3030. https://doi.org/10.1021/acs.est.3c08044

Gu L, Pallardy SG, Yang B et al (2016) Testing a land model in ecosystem functional space via a comparison of observed and modeled ecosystem flux responses to precipitation regimes and associated stresses in a Central U.S. forest. J Geophys Res Biogeosci 121:1884–1902. https://doi.org/10.1002/2015JG003302

Han G, Sun B, Chu X et al (2018) Precipitation events reduce soil respiration in a coastal wetland based on four-year continuous field measurements. Agric For Meteorol 256–257:292–303. https://doi.org/10.1016/j.agrformet.2018.03.018

Hashimoto S, Ito A, Nishina K (2023) Divergent data-driven estimates of global soil respiration. Commun Earth Environ 4:460. https://doi.org/10.1038/s43247-023-01136-2

Hossain MZ, Bahar MM, Sarkar B et al (2020) Biochar and its importance on nutrient dynamics in soil and plant. Biochar 2:379–420. https://doi.org/10.1007/s42773-020-00065-z

Hui D, Yu C-L, Deng Q et al (2018) Weak effects of biochar and nitrogen fertilization on switchgrass photosynthesis, biomass, and soil respiration. Agriculture 8:143. https://doi.org/10.3390/agriculture8090143

Huxman TE, Snyder KA, Tissue D et al (2004) Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia 141:254–268. https://doi.org/10.1007/s00442-004-1682-4

Jian J, Steele MK, Day SD et al (2018) Measurement strategies to account for soil respiration temporal heterogeneity across diverse regions. Soil Biol Biochem 125:167–177. https://doi.org/10.1016/j.soilbio.2018.07.003

Junna S, Bingchen W, Gang X, Hongbo S (2014) Effects of wheat straw biochar on carbon mineralization and guidance for large-scale soil quality improvement in the coastal wetland. Ecol Eng 62:43–47. https://doi.org/10.1016/j.ecoleng.2013.10.014

Yu K, Ouyang NX, Zhang YZ et al (2019) Study on estimation method of annual average soil temperature in soil taxonomy of Hunan Province. Hunan Agric Sci (12):30–37.

Kerré B, Hernandez-Soriano MC, Smolders E (2016) Partitioning of carbon sources among functional pools to investigate short-term priming effects of biochar in soil: a ^{13}C study. Sci Total Environ 547:30–38. https://doi.org/10.1016/j.scitotenv.2015.12.107

Kieft TL, Soroker E, Firestone MK (1987) Microbial biomass response to a rapid increase in water potential when dry soil is wetted. Soil Biol Biochem 19:119–126. https://doi.org/10.1016/0038-0717(87)90070-8

Kuzyakov Y, Gavrichkova O (2010) REVIEW: Time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls. Glob Change Biol 16:3386–3406. https://doi.org/10.1111/j.1365-2486.2010.02179.x

Lado-Monserrat L, Lull C, Bautista I et al (2014) Soil moisture increment as a controlling variable of the "Birch effect". Interactions with the pre-wetting soil moisture and litter addition. Plant Soil 379:21–34. https://doi.org/10.1007/s11104-014-2037-5

Lehmann J, Cowie A, Masiello CA et al (2021) Biochar in climate change mitigation. Nat Geosci 14:883–892. https://doi.org/10.1038/s41561-021-00852-8

Leon E, Vargas R, Bullock S et al (2014) Hot spots, hot moments, and spatio-temporal controls on soil CO_2 efflux in a water-limited ecosystem. Soil Biol Biochem 77:12–21. https://doi.org/10.1016/j.soilbio.2014.05.029

Li Y, Li Y, Chang SX et al (2018) Biochar reduces soil heterotrophic respiration in a subtropical plantation through increasing soil organic carbon recalcitrancy and decreasing carbon-degrading microbial activity. Soil Biol Biochem 122:173–185. https://doi.org/10.1016/j.soilbio.2018.04.019

Liu L, Wang X, Lajeunesse MJ et al (2016a) A cross-biome synthesis of soil respiration and its determinants under simulated precipitation changes. Glob Change Biol 22:1394–1405. https://doi.org/10.1111/gcb.13156

Liu X, Zheng J, Zhang D et al (2016b) Biochar has no effect on soil respiration across Chinese agricultural soils. Sci Total Environ 554–555:259–265. https://doi.org/10.1016/j.scitotenv.2016.02.179

Liu Y, Liu S, Miao R et al (2019) Seasonal variations in the response of soil CO_2 efflux to precipitation pulse under mild drought in a temperate oak (*Quercus variabilis*) forest. Agric For Meteorol 271:240–250. https://doi.org/10.1016/j.agrformet.2019.03.009

Liu Z, Jia G, Yu X (2020) Variation of water uptake in degradation agroforestry shelterbelts on the North China Plain. Agric Ecosyst Environ 287:106697. https://doi.org/10.1016/j.agee.2019.106697

Livesley SJ, McPherson EG, Calfapietra C (2016) The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. J Environ Qual 45:119–124. https://doi.org/10.2134/jeq2015.11.0567

Lo Piccolo E, Becagli M, Lauria G et al (2022) Biochar as a soil amendment in the tree establishment phase: what are the consequences for tree physiology, soil quality and carbon sequestration? Sci Total Environ 844:157175. https://doi.org/10.1016/j.scitotenv.2022.157175

Luan J, Liu S, Wang J et al (2011) Rhizospheric and heterotrophic respiration of a warm-temperate oak chronosequence in China. Soil Biol Biochem 43:503–512. https://doi.org/10.1016/j.soilbio.2010.11.010

Ma M, Zang Z, Xie Z et al (2019) Soil respiration of four forests along elevation gradient in northern subtropical China. Ecol Evol 9:12846–12857. https://doi.org/10.1002/ece3.5762

Makita N, Hirano Y, Mizoguchi T et al (2011) Very fine roots respond to soil depth: biomass allocation, morphology, and physiology in a broad-leaved temperate forest. Ecol Res 26:95–104. https://doi.org/10.1007/s11284-010-0764-5

Luo Y, Luo M, Fan J, Luo L, Duan S (2020) Precision evaluation of FY-3B MWRI based soil moisture product in Hunan Province. Guizhou Agric Sci 48:113–118

Manea A, Tabassum S, Lambert M et al (2023) Biochar, but not soil microbial additives, increase the resilience of urban plant species to low water availability. Urban Ecosyst 26:1251–1261. https://doi.org/10.1007/s11252-023-01382-4

Meng Z, Huang S, Xu T et al (2020) Transport and transformation of Cd between biochar and soil under combined dry-wet and freeze-thaw aging. Environ Pollut 263:114449. https://doi.org/10.1016/j.envpol.2020.114449

Miao G, Noormets A, Domec J et al (2013) The effect of water table fluctuation on soil respiration in a lower coastal plain forested wetland in the southeastern U.S. J Geophys Res Biogeosci 118:1748–1762. https://doi.org/10.1002/2013JG002354

Myhre G, Alterskjær K, Stjern CW et al (2019) Frequency of extreme precipitation increases extensively with event rareness under global warming. Sci Rep 9:16063. https://doi.org/10.1038/s41598-019-52277-4

Newcomb CJ, Qafoku NP, Grate JW et al (2017) Developing a molecular picture of soil organic matter–mineral interactions by quantifying organo–mineral binding. Nat Commun 8:396. https://doi.org/10.1038/s41467-017-00407-9

Niu F, Chen J, Xiong P et al (2019) Responses of soil respiration to rainfall pulses in a natural grassland community on the semi-arid Loess Plateau of China. Catena 178:199–208. https://doi.org/10.1016/j.catena.2019.03.020

Pavao-Zuckerman MA (2008) The nature of urban soils and their role in ecological restoration in cities. Restor Ecol 16:642–649. https://doi.org/10.1111/j.1526-100X.2008.00486.x

Pavelka M, Acosta M, Marek MV et al (2007) Dependence of the Q_{10} values on the depth of the soil temperature measuring point. Plant Soil 292:171–179. https://doi.org/10.1007/s11104-007-9213-9

Peng S, Piao S, Shen Z et al (2013) Precipitation amount, seasonality and frequency regulate carbon cycling of a semi-arid grassland ecosystem in Inner Mongolia, China: a modeling analysis. Agric For Meteorol 178–179:46–55. https://doi.org/10.1016/j.agrformet.2013.02.002

Phillips OL, Aragão LEOC, Lewis SL et al (2009) Drought sensitivity of the Amazon rainforest. Science 323:1344–1347. https://doi.org/10.1126/science.1164033

Reichstein M, Tenhunen JD, Roupsard O et al (2002) Ecosystem respiration in two Mediterranean evergreen Holm Oak forests: drought effects and decomposition dynamics. Funct Ecol 16:27–39. https://doi.org/10.1046/j.0269-8463.2001.00597.x

Rey A, Pegoraro E, Tedeschi V et al (2002) Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. Glob Change Biol 8:851–866. https://doi.org/10.1046/j.1365-2486.2002.00521.x

Richardson AD, Andy Black T, Ciais P et al (2010) Influence of spring and autumn phenological transitions on forest ecosystem productivity. Philos Trans R Soc B Biol Sci 365:3227–3246. https://doi.org/10.1098/rstb.2010.0102

Robinson A, Lehmann J, Barriopedro D et al (2021) Increasing heat and rainfall extremes now far outside the historical climate. Npj Clim Atmos Sci 4:45. https://doi.org/10.1038/s41612-021-00202-w

Sagrilo E, Jeffery S, Hoffland E, Kuyper TW (2015) Emission of CO_2 from biochar-amended soils and implications for soil organic carbon. GCB Bioenergy 7:1294–1304. https://doi.org/10.1111/gcbb.12234

Salmond JA, Tadaki M, Vardoulakis S et al (2016) Health and climate related ecosystem services provided by street trees in the urban environment. Environ Health 15:S36. https://doi.org/10.1186/s12940-016-0103-6

Savage K, Phillips R, Davidson E (2014) High temporal frequency measurements of greenhouse gas emissions from soils. Biogeosciences 11:2709–2720. https://doi.org/10.5194/bg-11-2709-2014

Schmidt MWI, Noack AG (2000) Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. Glob Biogeochem Cycles 14:777–793. https://doi.org/10.1029/1999GB001208

Schwinning S, Starr BI, Ehleringer JR (2005) Summer and winter drought in a cold desert ecosystem (Colorado Plateau) part I: effects on soil water and plant water uptake. J Arid Environ 60:547–566. https://doi.org/10.1016/j.jaridenv.2004.07.003

Seo MW, Lee SH, Nam H et al (2022) Recent advances of thermochemical conversion processes for biorefinery. Biores Technol 343:126109. https://doi.org/10.1016/j.biortech.2021.126109

Shen Y, Yuan X (2023) Research advancement in molten salt-mediated thermochemical upcycling of biomass waste. Green Chem 25:2087–2108. https://doi.org/10.1039/D2GC04872H

Shi W-Y, Tateno R, Zhang J-G et al (2011) Response of soil respiration to precipitation during the dry season in two typical forest stands in the forest–grassland transition zone of the Loess Plateau. Agric For Meteorol 151:854–863. https://doi.org/10.1016/j.agrformet.2011.02.003

Singh H, Northup BK, Rice CW, Prasad PVV (2022) Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. Biochar 4:8. https://doi.org/10.1007/s42773-022-00138-1

Singh R, Singh H, Singh S et al (2017) Riparian land uses affect the dry season soil CO_2 efflux under dry tropical ecosystems. Ecol Eng 100:291–300. https://doi.org/10.1016/j.ecoleng.2017.01.002

Singh Yadav SP, Bhandari S, Bhatta D et al (2023) Biochar application: a sustainable approach to improve soil health. J Agric Food Res 11:100498. https://doi.org/10.1016/j.jafr.2023.100498

Smebye A, Alling V, Vogt RD et al (2016) Biochar amendment to soil changes dissolved organic matter content and composition. Chemosphere 142:100–105. https://doi.org/10.1016/j.chemosphere.2015.04.087

Smith JL, Collins HP, Bailey VL (2010) The effect of young biochar on soil respiration. Soil Biol Biochem 42:2345–2347. https://doi.org/10.1016/j.soilbio.2010.09.013

Somerville PD, Farrell C, May PB, Livesley SJ (2020) Biochar and compost equally improve urban soil physical and biological properties and tree growth, with no added benefit in combination. Sci Total Environ 706:135736. https://doi.org/10.1016/j.scitotenv.2019.135736

Spokas KA, Novak JM, Masiello CA et al (2014) Physical disintegration of biochar: an overlooked process. Environ Sci Technol Lett 1:326–332. https://doi.org/10.1021/ez500199t

Steenberg JWN, Millward AA, Nowak DJ et al (2017) Forecasting urban forest ecosystem structure, function, and vulnerability. Environ Manage 59:373–392. https://doi.org/10.1007/s00267-016-0782-3

Sun J, Yang R, Li W et al (2018) Effect of biochar amendment on water infiltration in a coastal saline soil. J Soils Sediments 18:3271–3279. https://doi.org/10.1007/s11368-018-2001-8

Tian X, Wang Y, Zeng Z et al (2022) Research progress on the role of common metal catalysts in biomass pyrolysis: a state-of-the-art review. Green Chem 24:3922–3942. https://doi.org/10.1039/D1GC04537G

Utsumi N, Kim H (2022) Observed influence of anthropogenic climate change on tropical cyclone heavy rainfall. Nat Clim Change 12:436–440. https://doi.org/10.1038/s41558-022-01344-2

Vargas R, Le VH (2023) The paradox of assessing greenhouse gases from soils for nature-based solutions. Biogeosciences 20:15–26. https://doi.org/10.5194/bg-20-15-2023

Wang J, Xiong Z, Kuzyakov Y (2016) Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8:512–523. https://doi.org/10.1111/gcbb.12266

Wang L, O'Connor D, Rinklebe J et al (2020) Biochar aging: mechanisms, physicochemical changes, assessment, and implications for field applications. Environ Sci Technol 54:14797–14814. https://doi.org/10.1021/acs.est.0c04033

Williams CA, Hanan N, Scholes RJ, Kutsch W (2009) Complexity in water and carbon dioxide fluxes following rain pulses in an African savanna. Oecologia 161:469–480. https://doi.org/10.1007/s00442-009-1405-y

Woolf D, Amonette JE, Street-Perrott FA et al (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1:56. https://doi.org/10.1038/ncomms1053

Xu M, Shang H (2016) Contribution of soil respiration to the global carbon equation. J Plant Physiol 203:16–28. https://doi.org/10.1016/j.jplph.2016.08.007

Yan L, Chen S, Xia J, Luo Y (2014) Precipitation regime shift enhanced the rain pulse effect on soil respiration in a semi-arid steppe. PLoS ONE 9:e104217. https://doi.org/10.1371/journal.pone.0104217

Yan T, Song H, Wang Z et al (2019) Temperature sensitivity of soil respiration across multiple time scales in a temperate plantation forest. Sci Total Environ 688:479–485. https://doi.org/10.1016/j.scitotenv.2019.06.318

Yang Y, Sun K, Han L et al (2022) Biochar stability and impact on soil organic carbon mineralization depend on biochar processing, aging and soil clay content. Soil Biol Biochem 169:108657. https://doi.org/10.1016/j.soilbio.2022.108657

Yazdani MR, Duimovich N, Tiraferri A et al (2019) Tailored mesoporous biochar sorbents from pinecone biomass for the adsorption of natural organic matter from lake water. J Mol Liq 291:111248. https://doi.org/10.1016/j.molliq.2019.111248

Ye L, Camps-Arbestain M, Shen Q et al (2020) Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls. Soil Use Manag 36:2–18. https://doi.org/10.1111/sum.12546

Yoo SY, Kim YJ, Yoo G (2020) Understanding the role of biochar in mitigating soil water stress in simulated urban roadside soil. Sci Total Environ 738:139798. https://doi.org/10.1016/j.scitotenv.2020.139798

Zhang Q, Wang Y, Wu Y et al (2013) Effects of biochar amendment on soil thermal conductivity, reflectance, and temperature. Soil Sci Soc Am J 77:1478–1487. https://doi.org/10.2136/sssaj2012.0180

Zhou G, Zhou X, Zhang T et al (2017) Biochar increased soil respiration in temperate forests but had no effects in subtropical forests. For Ecol Manag 405:339–349. https://doi.org/10.1016/j.foreco.2017.09.038

Zhou Y, Yan W (2016) Conservation and applications of camphor tree (*Cinnamomum camphora*) in China: ethnobotany and genetic resources. Genet Res Crop Evol 63:1049–1061. https://doi.org/10.1007/s10722-015-0300-0

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