Responses of CO 2 emission to external organic carbon input in the drying-rewetting cycles: a meta-analysis

Junjie Lin[1], Hongxin Dong[1], Dan Liu[2], Kehong Wang[1], Zhiguo Yu[3], and Amit kumar[3]

[1]Chongqing Three Gorges University
[2]Department of Agricultural and Forestry Science and Technology Chongqing Three Gorges Vocation College Chongqing 404000 China
[3]Nanjing University of Information Science and Technology

March 31, 2022

Abstract

In recent decades, global warming under rising CO $_2$ significantly influences external organic carbon (EOC) input and drying-rewetting processes in terrestrial ecosystems. However, little is known about how soil CO $_2$ emissions respond to these perturbations, which provides us with a chance to explore potential factors and variability. In this study, a meta-analysis on the responses of CO $_2$ emissions with or without EOC input in the soil drying-rewetting cycles (DWC) based on 291 observations (included 33 study sites and 11 variables) has been conducted. The results indicated that i) CO $_2$ emission with the increase of EOC by 284% relative to without EOC under DWC; ii) The effect size of CO $_2$ emission was the smallest in the forest (+15%) and the largest in the grassland (+1468%); iii) The CO $_2$ emission effect sizes were substantially greater in complex substrates (+288%) than in simple substrates (+132%), and iv) longer drought period in a DWC can induce more CO $_2$ emission. The study suggests that terrestrial CO $_2$ emission may be multi folds in the long drought-rapid rewetting processes under large input of EOC.

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Hongxin Dong[a], Dan Liu[b], Kehong Wang[a] , Zhiguo Yu[c], Amit Kumar[c], Junjie Lin[a*]

[a]Chongqing Key Laboratory of Water Environment Evolution and Pollution Control in Three Gorges Reservoir, Chongqing Three Gorges University, Chongqing 404100, China

[b] Department of Agricultural and Forestry Science and Technology, Chongqing Three Gorges Vocation College, Chongqing, 404000, China

[c] School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China

*Corresponding authors: Dr. Junjie Lin

E-mail addresses:*junjielin@sanxiau.edu.cn*(J. Lin)

Abstract:

In recent decades, global warming under rising CO_2significantly influences external organic carbon (EOC) input and drying-rewetting processes in terrestrial ecosystems. However, little is known about how soil CO_2 emissions respond to these perturbations, which provides us with a chance to explore potential factors and variability. In this study, a meta-analysis on the responses of CO_2 emissions with or without EOC input in the soil drying-rewetting cycles (DWC) based on 291 observations (included 33 study sites and 11 variables) has been conducted. The results indicated that i) CO_2 emission with the increase of EOC by 284% relative to without EOC under DWC; ii) The effect size of CO_2 emission was the smallest in the forest (+15%) and the largest in the grassland (+1468%); iii) The CO_2emission effect sizes were substantially greater in complex substrates (+288%) than in simple substrates (+132%), and iv) longer drought period in a DWC can induce more CO_2 emission. The study suggests that terrestrial CO_2 emission may be multi folds in the long drought-rapid rewetting processes under large input of EOC.

Keywords: Soil property; Carbon input; Carbon dioxide; Drought period; Climate change

Introduction

Soil is a key component in the terrestrial ecosystem and plays a critical role in the carbon (C) cycle (Hopkins et al., 2012). Soil C pool is two folds greater than the atmospheric C pool and three folds greater than the vegetation C pool (Delgado-Baquerizo et al., 2017). Soil carbon dioxide (CO_2) emission is a major pathway of carbon loss from soil pool to atmosphere C pool (Bond-Lamberty and Thomson, 2010). Even small fluctuations in soil respiration rate may have a profound impact on soil and atmospheric C storage (Reichstein et al., 2013). In recent years, due to rapid increase in temperature under rising CO_2 emission more frequent and unpredictable drought and flood events have occurred (Yang et al., 2017). Therefore, the frequency of soil moisture and temperature fluctuations are expected to increase in the future (Gao et al., 2020; Wang et al., 2020), thus further influencing microbial community and underground ecological processes such as soil and litter C decomposition (Zhang et al., 2016).

Over the past decades, increasing studies on carbon dynamics have demonstrated that soil organic carbon (SOC) decomposition can be influenced by drying-rewetting cycles (DWC), which is defined as the repeated change in the volumetric water content in soil pool from dry to wet states (de Oliveira et al., 2005). The rewetting event after a prolonged drought can destroy soil aggregating stability and microbial cell walls, resulting in releasing microbial necromass and aggregating protected C (Kim et al., 2010; Conant et al., 2011; Yao et al., 2011; Blazewicz et al., 2014). Consequently, the remaining stress-tolerant microorganisms can further utilize the readily C source for CO_2 emission. This phenomenon is known as the "Birch effect" (Birch, 1958). Global warming can increase the primary productivity of terrestrial ecosystems, resulting in more plant residues and root exudates entering the soil. The input of external organic carbon (EOC) into the soil can affect soil nutrients, water content, oxygen distribution, redox potential, pH, extracellular enzyme activity and microorganism community structure (Liu et al., 2019b; Zhou et al., 2019; Hall et al., 2020; Huo et al., 2022; Zhu et al., 2022). However, CO_2 emission from soils with EOC under DWC was poorly understood (Mikha et al., 2005; Citerne et al., 2021). Considering the expected increase of DWC events related to global warming, the effects of EOC on CO_2 emissions need to be further studied to understand the mechanism of DWC affecting the potential C cycles of EOC in soil.

Numerous studies have indicated that soil humidity is one of the main factors for litter C turnover in terrestrial ecosystems (Benesch et al., 2015). Suitable soil moisture is beneficial to litter decomposition and soil C storage (Bengtson et al., 2012). The interactions between EOC input and DWC may have a complex effect on soil C cycle. The relevant observations found that DWC raised CO_2 production in glucose and starch amended soils and decreased it in cellulose amended soil (Butterly et al., 2009). In contrast, some studies have reported that the CO_2 production in straw amendment soil does not increase under the DWC compared with those in constant-moisture control (Yemadje et al., 2016; Yemadje et al., 2017). The contrasting results may be caused by soil characteristics and experimental variables. Thus, quantitative synthesis of the effects of EOC input under DWC on atmospheric CO_2 flux is a hotspot in the scientific fraternity.

In this meta-analysis, a global data set of 291 paired observations from 34 publications that included 11 variables and 33 study sites were used. We hypothesized that (i) EOC input has the potential to increase cumulative CO_2 emission under DWC conditions and (ii) Effect size of EOC input on cumulative CO_2 emission is related to ecosystems type, experimental variable, and soil properties.

Materials and methods

2.1 Data sources

Peer-reviewed journal articles published before March 27, 2022, were searched using Web of Science with the following search term combinations: (drying rewetting OR dry rewet OR drought rewet OR drought rewetting OR dry rewetting OR rewet OR rewetting OR rewetted) and (carbon OR organic matter OR carbon dioxide OR CO_2 OR heterotrophic respiration OR soil respiration OR greenhouse gas OR basal respiration). A total of 291observations of 11 variables related to cumulative CO_2 emission were abstracted from 34 papers (Table S1). Several criteria were set to avoid bias in publication selection: (1) The study had an experimental treatment on organic carbon input (2) The experiment was carried out under DWC conditions (3) The experiments with flooding were not considered to avoid anaerobic respiration of soil; The sampling site included in this study are shown in Fig. 1.

In this meta-analysis, the data on the related environmental variables in these studies were collected, including the substrate quality, ecosystem type, soil-controlled temperature, SOC, total nitrogen (TN), C/N ratios (the ratio of soil organic carbon to total nitrogen), pH, soil clay content, input carbon content, D/T (the ratio of drying days in a DWC period), soil depth, DWC intensity (the difference between the highest and lowest soil moisture in a DWC event) and DWC number (the number of times the soil experienced completely in the article). When an original study reported results graphically, data were collected using Get Data Graph Digitizer (*http://www.getdata-graph-digitizer.com/index.php*). For studies that only provided soil organic matter (SOM), a conversion coefficient of 0.5 to convert SOM to SOC was used (Pribyl, 2010). For substrate quality, simple substrates refer to small molecule substrates (e.g., glucose, starch, and cellulose) that are easily utilized by microorganisms. Complex substrates are plant materials (e.g., straw, biochar and compost) with lower microbial availability (Zhang et al., 2013; Sun et al., 2019).

Statistical analyses

The formula for calculating cumulative CO_2 emission is (Lin et al., 2015).

$C_{t+1} = \frac{(j_{t+1}-j_t)\times(\ y_t+y_{t+1})}{2} + C_t(1)$

where C is the amount of CO_2 emission;y_t is the CO_2 emission rate on the t sampling time; j is the incubation duration, d.t =0, j_t =0, C_t =0.

Cumulative CO_2 emission effect size is the response ratio natural log. The RR was calculated in the following way (Gurevitch. et al., 2001):

RR = ln

(x_e/x_m) (2)

where x_e is the mean value of EOC input group, and x_m is the mean value of the group without EOC input. ThePercentage $(\%) = \left(e^{\mathrm{RR}} - 1\right) \times 100\%$ was used to convert RR.

The RR variance (v) was calculated by adopting the Hedges et al. (1999) formula:

$v = \frac{S_e^2}{N_e X_e^2} + \frac{S_m^2}{N_m X_m^2}$ (3)

where S_e is the standard deviation (SD) of EOC input group, S_m is the SD without EOC input,N_e is the EOC input group sample size, andN_m is the sample size of EOC input group. The conversion equation (SD= SE$\sqrt{n}$) was used to convert standard error (SE) to SD when the literature only reported SE; n is the sample size. If the paper had not reported the SD, we would have used the multiple imputations method to estimate the missing SD values (Zhang et al., 2020; Dong et al., 2021).

All data analysis were conducted using the "*metafor* " and "*randforest* " package in R version 4.1.1 (Viechtbauer, 2010). Regarding the mean effect size (RR_{++}), the random-effects model was chosen to calculate it, because are variations in effect sizes among studies (Koricheva et al., 2013). For the between-study variance

(τ^2), the restricted maximum likelihood was used to calculate it for the benefit of continuous data (Veroniki et al., 2016). The within- (v) and τ^2were used to calculate weighting factor [1 / (v + τ^2)]. For the 95% confidence intervals (CI) of the weighted RR, the bootstrapping with 9999 iterations were applied to calculate it. Furthermore, we chose the Rosenthal's fail-safe number and trim and fill methods were used to test and calculate the possibility of publication bias, *where t* he result well be robust if Rosenthal's fail-safe number is greater than $5n$ +10, where n is the data point number (Rosenthal, 1991). Generally speaking, the result is robust if recalculated effect size of trim and fill is not significantly changed (Duval and Tweedie, 2000). At the same time, the weighted random forest was established to explore the importance of the relative variables (Dong et al., 2021).

Results

3.1 Effect size of EOC input on cumulative CO_2emission under DWC

Inputs of organic carbon have a positive effect on the SOM balance and have the potential to disturb the carbon dynamics in the soil pool. Meta-regression analysis showed that cumulative CO_2emission after EOC input significantly increased by +263% compared without EOC input in DWC (Fig. 2). The effect sizes of cumulative CO_2 emission were substantially greater in complex substrates (RR_{++}: +288%) than in simple substrates (RR_{++}: +132%, Fig. 2). For the different ecosystem, cumulative CO_2 emission effect size of grassland (RR_{++}: +1468%) increased more than that of cropland (RR_{++}: +239%), wetland (RR_{++}: +250%) and forest (RR_{++}: +15%, Fig. 2).

3.2 Effects ofsoil chemical properties and experimental conditions

The impact of EOC input on cumulative CO_2 emission depends on the experimental variables and soil chemical properties. The cumulative CO_2 emission effect size showed a negative relationship with input C, SOC, TN, and soil depth, while the D/T showed a positive relationship between the cumulative CO_2emission effect size (Fig. 3 and Table 1). At the same time, the weighted random-forest analysis further showed that input C content was the most important factor mediating the effect of cumulative CO_2 emission (Fig. 4).

3.3 Publication bias

The calculated fail-safe numbers were *55, 466, 214* , indicating that the results were robust (Table S2). The trim-and-fill model also indicated that the results would not be changed by missing studies.

Discussion

EOC input effects on cumulative CO_2 emission under DWC

The study found that EOC input increased cumulative CO_2emission effect size under DWC conditions (Fig. 2). Literature suggested that litter input and moisture fluctuation will significantly increase cumulative CO_2 emission (Cosentino et al., 2006; Liu et al., 2015; Sun et al., 2017), which is consistent with our studies. On the one hand, EOC input increased SOC mineralization, and fresh and old substrates co-metabolism by soil microorganisms (Kuzyakov, 2010; Zhang et al., 2013; Shahzad et al., 2019). Furthermore, the effect sizes of cumulative CO_2 emission were substantially greater in complex substrates quality than in simple quality (Fig. 2). Because K-strategists are usually dominated under DWC, and thus more complex compounds are utilized for growth, which resulted in a stronger positive priming effect than simple substrates that are rapidly consumed by r-strategists (Fontaine et al., 2003; Li et al., 2021).

Simultaneously, the EOC input effect size on CO_2emission in forest ecosystems is less than that in cropland, wetland, and grassland (Fig. 2). A similar finding of lower cumulative CO_2 emission from forest soil compared to cropland and grassland soil was reported by Okolo et al., (2022). This different result may be caused by different SOC pools composition among ecosystem types. A meta-analysis reported that the impact of priming effect on fast turnover SOC pools (e.g., labile organic carbon) was greater than that on slow turnover SOC pools (e.g., semi-labile organic carbon and/or refractory organic carbon pool), which may be due to the different sensitivity of the fast and slow SOC pools to the EOC input (Huo et al., 2022). Another study investigated the SOC in forest, wetland, and grassland soil on Qinghai Tibet Plateau, and found that the fast-cycling SOC pools in forest soils degraded more slowly than they reported in case of grassland and wetland soils (Chen et al., 2019). Consequently, forest ecosystem has stronger priming effect resistance than other ecosystems and is stronghly helpful in mitigating future climate change.

4.2 Driving variables of EOC input effects on cumulative CO_2 emission under DWC

Soil nutrients (particularly, SOC, N, P) have been considered one of the important factors determining soil microorganisms and their physiological traits (Miransari, 2013). The effect sizes of cumulative CO_2 emission in soil with low SOC and TN content were found significantly higher than that of soil with high SOC and TN content (Fig. 3a, b and Table1). The possible reason for this result is that high SOC and TN meet the microbial demand for C and N sources and thus result in high growth efficiency by soil microorganisms (Diochon et al., 2016; Liu et al., 2019a). Consequently, more organic C substrates could be converted to microbial biomass carbon rather than CO_2. Another possible reason is that low C and N soils are dominated by starvation-tolerant microbial communities (de Jonge et al., 2017; Ning et al., 2021). Therefore, the low C and N soil microbes may better utilize the EOC input. Besides, with the increase of EOC input, the CO_2 emission effect size continuously decreased (Fig. 3c and Table 1). A study investigated biochar application on SOC mineralization, and results found a higher cumulative CO_2 emission in low-C biochar-amended soil rather than high-C biochar-amended soil (Xu et al., 2019). This may be caused by the input of higher EOC increased SOC content, increased the resistance of soil to DWC, and inhibited CO_2 emission (Dong et al., 2021). This may be related to the hydrophobicity of SOM (Borken and Matzner, 2009). Furthermore, the effect sizes of cumulative CO_2 emission were substantially greater in surface soil than in deep soil (Fig. 3d and Table1). It is well established that surface soils experience wide variation in moisture and temperature while deeper soil experienced a relatively constant environment (Fierer et al., 2003). So surface soils may be dominated by DWC tolerant microbial communities (Sun et al., 2018). The surface soil microorganisms can better use the EOC source during DWC.

Finally, we found that the effect size of cumulative CO_2emission showed a positive correlation with D/T (Fig. 3e and Table1). First, soil microbial community in long-term drought may be dominated by fungi (Barnard et al., 2013). This may be caused by the composition of the bacterial community varied with soil moisture, but the fungal community was more resistant to water stress and acquired labile C more efficiently under low moisture levels (Liu et al., 2022). Thus, during the DWC, fungal-dominated microbial communities were more likely to utilize EOC sources for respiration (Bapiri et al., 2010).

Conclusion

In recent decades, global warming under rising atmospheric CO_2 can potentially affect the carbon dynamics (source/sink) in terrestrial ecosystems. This study proved an important role of drying-rewetting cycles (DWC) and external organic carbon (EOC) on the potential of CO_2 emission. The results indicated that EOC input significantly increased cumulative CO_2emission effect size under DWC. On average, the cumulative CO_2 emissions effect sizes were substantially greater in complex substrates than in simple substrates. The cumulative CO_2 emission effect size was the smallest in the forest ecosystem and the largest in the grassland ecosystem. Moreover, the EOC input effect size was correlated with SOC, TN, input C content, soil depth, and D/T. It was believed that the relatively longer dry period combined with carbon input can increase CO_2 emission. Overall, our study provides a comprehensive quantitative assessment of the impact of EOC input on CO_2 emissions, which are helpful to further clarify the feedback of soil C cycles to regional and global climate change.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (31770592), the Science and the Chongqing Science and Technology Commission (cstc2020jcyj-msxmX0095, WEPKL2018ZD-05), and Technology Research Program of Chongqing Municipal Education Commission (KJZD-K202001203, KJZD-K202003501).

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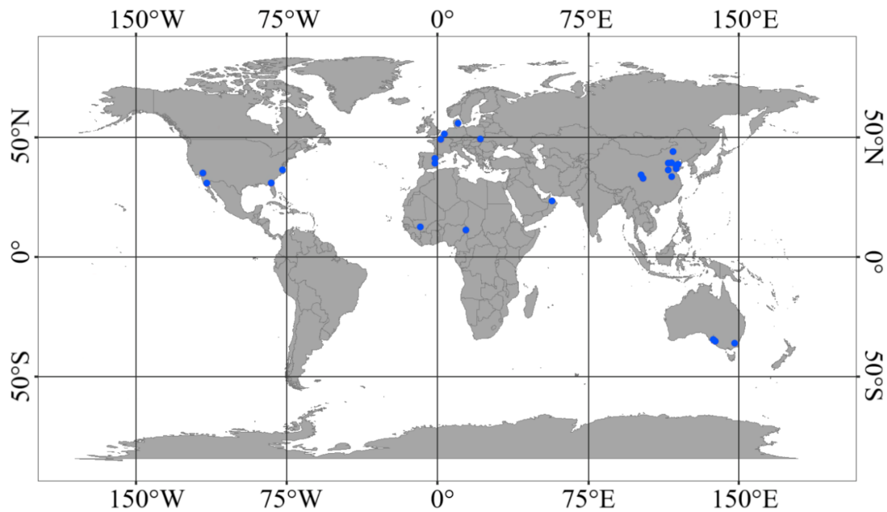


Figure 1 The soil sampling sites distribution included in the meta-analysis

Figure 2 The mean effect size (RR_{++}) of the cumulative CO_2 emission in response to response to external organic carbon input among different types of ecosystems and substrate under drying-rewetting cycles. The external organic carbon input effect on cumulative CO_2 emission was significant if the 95% confidence intervals (CIs) did not overlap with the zero line. The sample size for each variable is shown in the bracket.

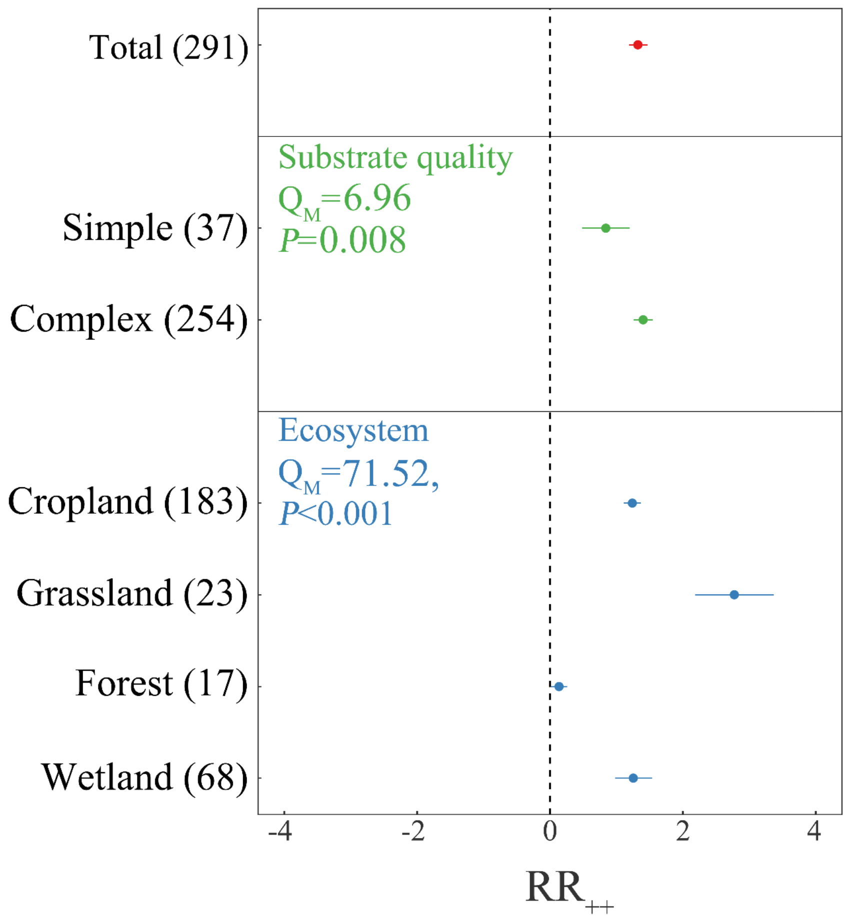
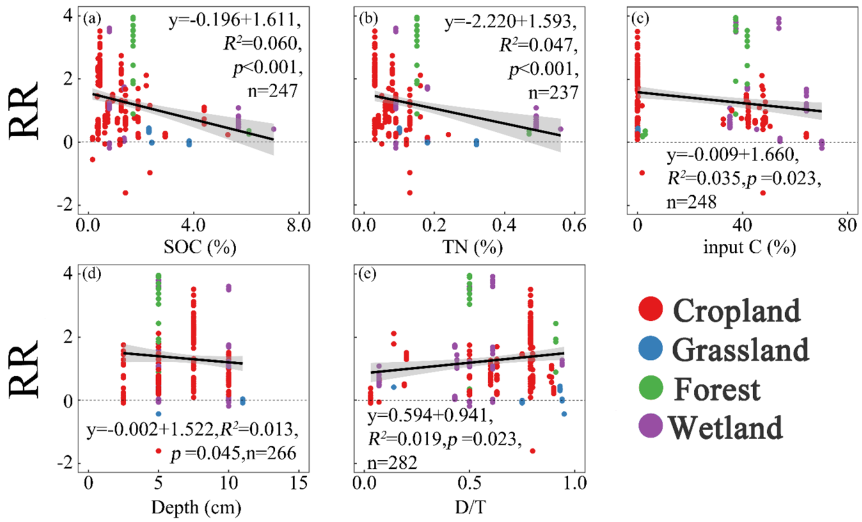


Figure 3 The relationships between the cumulative CO_2 emission effect size (RR) and variables under DWC. Grey area represents the 95% confidence interval of the linear regression. DWC, drying-rewetting cycles. Depth, mean soil depth. Input C, input external organic carbon content. SOC, soil organic carbon. D/T, the ratio of drying days in a DWC period. TN, total nitrogen. n, the data point numbers in the study.



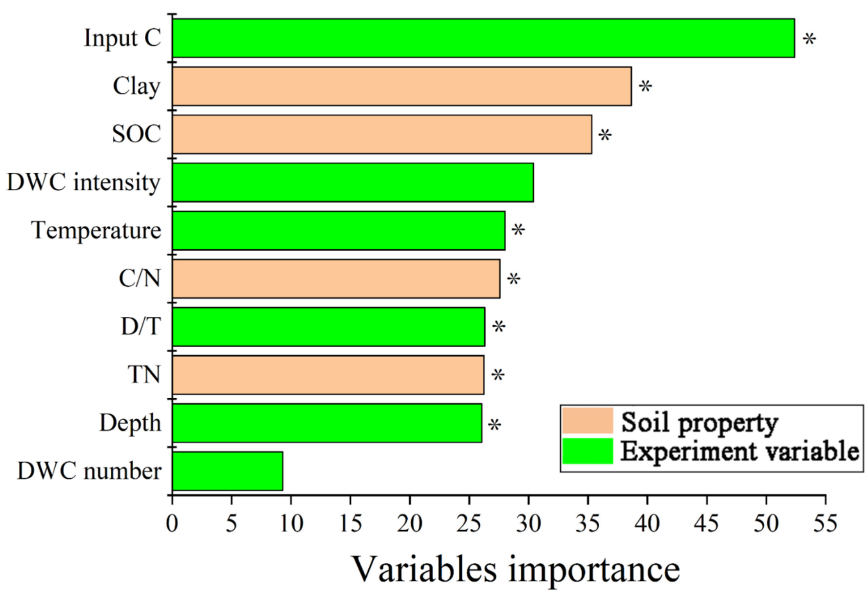


Figure 4 Variable's importance as moderators in the random forest model for the effect of input external organic carbon on cumulative CO_2 emission under drying-rewetting cycles. If the $P < 0.05$, we used the asterisks (*) to indicate significant moderators. Input C, Input external organic carbon content. DWC, drying-rewetting cycles. Temperature, soil-controlled temperature. Depth, mean soil depth. SOC, soil organic carbon. Clay, soil clay content. TN, total nitrogen. D/T: the ratio of drying days in a DWC period. DWC number, the number of times the soil experienced completely in the article. DWC intensity is the difference between the highest and lowest soil moisture in a DWC event.

Table 1 Relationships between the cumulative CO_2 emission effect sizes with soil variables concluded by the study. Q_T: total heterogeneity in cumulative CO_2 emission effect sizes Q_M: difference among group cumulative CO_2 emission effect sizes. Q_E: residual errors. DWC, drying-rewetting cycles. Temperature, soil-controlled temperature. Depth, mean soil depth. SOC, soil organic carbon. Clay, soil clay content. TN, total nitrogen. D/T: the ratio of drying days in a DWC period. DWC number, the number of times the soil experienced completely in the article. DWC intensity is the difference between the highest and lowest soil moisture in a DWC event. n, the data point numbers in the study.

Variables	Variables	Variables	Variables	CO_2	CO_2	CO_2
	n	Q_T	Q_M	Q_M	Q_E	P
Input carbon (%)	248	418807	8.24	8.24	418799	**0.004**
SOC (%)	247	410203	15.12	15.12	410188	**0.000**
TN (%)	237	403010	11.25	11.25	402999	**0.000**
C/N	237	406332	3.83	3.83	406328	0.050
Clay (%)	148	292154	0.08	0.08	292184	0.782
pH	158	394209	2.75	2.75	394206	0.097
D/T	282	499485	5.18	5.18	499480	**0.023**
DWC number	291	537292	0.02	0.02	537292	0.893
DWC intensity	123	341379	1.67	1.67	341377	0.198
Depth	266	486382	4.04	4.04	486378	**0.045**
Temperature	264	508296	1.55	1.55	508294	0.214

Supporting Information

The data that supports the findings of this study are available in the supplementary material of this article.

Table S1 List of publications used in the meta-analysis with specific variables extracted.

Table S2 Test results of publication bias and random-effect model.