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The effect of dolomite amendment on soil organic carbon mineralization is determined by the dolomite size

Hongtao Wu^{1,2}, Jinli Hu², Muhammad Shaaban³, Peng Xu², Jinsong Zhao² and Ronggui Hu^{2*} 

Abstract

Background: The size of lime material is vital for the efficiency of ameliorating soil acidity, thereby influencing soil biochemical processes. However, the effects of different sized lime material application on soil organic carbon (SOC) mineralization are yet to be elucidated. Therefore, a 35-day incubation experiment was conducted to determine the effects of three particle size fractions (0.5 to 0.25, 0.25 to 0.15, and < 0.15 mm) of dolomite on SOC mineralization of two acidic paddy soils.

Results: CO₂ emission was increased by 3–7%, 11–21%, and 32–49% for coarse-, medium-, and fine-sized dolomite treatments, respectively, compared to the control in both soils. They also well conformed to a first-order model in all treatments, and the estimated decomposition rate constant was significantly higher in the fine-sized treatment than that of other treatments ($P < 0.05$), indicating that SOC turnover rate was dependent on the dolomite size. The finer particle sizes were characterized with higher efficiencies of modifying soil pH, consequently resulting in higher dissolved organic carbon contents and microbial biomass carbon, eventually leading to higher CO₂ emissions.

Conclusions: The results demonstrate that the size of dolomite is a key factor in regulating SOC mineralization in acidic paddy soils when dolomite is applied to manipulate soil pH.

Keywords: Dolomite, Particle size, SOC mineralization, Acidic paddy soil

Background

Soil acidification is known to be a main factor restricting crop growth and yields since acidity influences the physicochemical and biochemical properties of soil (Fageria and Baligar 2008; Shaaban et al. 2017). Approximately 30% of the world's land surfaces are covered by acidic soils, and ~ 50% of global arable soils are acidic (Dai et al. 2017; Kunhikrishnan et al. 2016). In China, approximately 2.04 million km² of tropical and subtropical soils (mainly paddy soils) may have yield limitation due to low soil pH (Dong et al. 2012). Moreover, the soil pH

of major croplands decreased noticeably by 0.13–0.8 units from the 1980s to 2000s (Guo et al. 2010).

Liming is the most widely used agricultural practice for ameliorating soil acidity (Goulding and Blake 1998). The particle size of a lime material is one of the major factors that influences its efficiency of neutralizing soil acidity, because the reaction rate between lime material and H⁺ in the soil is dependent on the specific surface area (Huang et al. 2007). For a given lime material, the finer the particle size, the more rapid rate of dissolution in soil is, and thus, the more effective it is in modifying soil pH (Coleman et al. 1959).

Soil organic carbon (SOC) mineralization is an important process in carbon (C) cycle that is directly linked to soil carbon quality and climate change (Zamanian et al. 2018). Changes in pH, substrate, and nutrient

* Correspondence: rg.hu@mail.hzau.edu.cn

²College of Resources and Environment, Huazhong Agricultural University, Wuhan, China

Full list of author information is available at the end of the article

availabilities for microbes in the soil after liming can affect SOC mineralization. In general, liming has positive effects on SOC mineralization since it can ameliorate soil acidity and has the potential to increase microbial activity (Adams and Adams 1983; Carmeis Filho et al. 2017). Increase in soil pH may increase dissolved organic carbon (DOC), which can be rapidly mineralized (Ahmad et al. 2013; Marcelo et al. 2012), and induces a microbial respiratory flush in the first few days following lime application (Fuentes et al. 2006). There are several mechanisms responsible for the enhanced DOC content induced through increased soil pH: (1) increasing the hydrophilicities of the dissolved organic matter molecules because of enhanced net negative charge with the increase in soil pH (Filep et al. 2003); (2) enhancing the deprotonation of organic substances from hydroxides of iron and aluminum, and clay minerals (Jardine et al. 1989); and (3) increasing the organic matter degradation rate and resulting in more low molecular weight organic matter available for microorganisms (Filep et al. 2003). Liming increases the nutrient availability for microbes, and thus increases SOC mineralization (Baggs et al. 2010; Fageria and Baligar 2008). For example, Shaaban et al. (2017) reported that dolomite addition resulted in high N mineralization and thus enhanced respiration from acidic soils.

Although the effects of different sizes of lime materials on modifying soil pH are well understood, few studies have focused their impacts on SOC mineralization via affecting soil pH, substrate, and nutrient availabilities in acidic paddy soils. This question is very important, as different sizes of lime materials may be used in agricultural practices (Álvarez et al. 2009). To address this problem, different size fractions of dolomite were used in the present study. Dolomite was chosen because it is widely used as a good lime material in agriculture in China in the recent years and has the benefit of simultaneously providing Ca and Mg during the process of counteracting soil acidity (Radziemska et al. 2018; Shaaban et al. 2015; Wu et al. 2020). The specific objectives of this study were to (1) assess the effects of different sized dolomite on SOC mineralization and (2) assess the effects of dolomite application on SOC turnover rate in acidic paddy soils. We hypothesized that the contents of soil DOC and MBC would increase with the addition of dolomite and the magnitude of the increase would be greater for the finer particle size, therefore resulting in larger SOC mineralization and more soil CO₂ emission.

Materials and methods

Soils

Soil samples were collected from the surface layer (0–20 cm) of paddy fields located in Qichun (30° 09′ 26.3″ N, 115° 22′ 55.4″ E) and Chibi (29° 50′ 00″ N, 114° 09′

37″ E), Hubei Province, China, with a mid-season rice plus ratooning rice and rapeseed-rice cropping system, respectively. These two areas have a typical subtropical monsoon climate. The soil taken from Qichun (named S1) developed from gneiss, while the soil taken from Chibi (named S2) developed from the Quaternary red earth. Leaves, roots, and stones in the soils were removed by hand prior to soil homogenization. The collected soils were air-dried, ground, and sieved (2 mm) for the incubation experiment. The physical and chemical properties of the two soils are shown in Table 1.

Fraction of dolomite

Lumpy dolomite (3–5 mm), purchased from a mineral powder processing factory in Xingtang County, Hebei Province, China, was ground by a planetary ball mill and then separated into three particle size fractions (0.5 to 0.25, 0.25 to 0.15, and < 0.15 mm) with screen meshes. The fraction of dolomite larger than 0.5 mm was not used in the present study because this fraction of dolomite was proved to be less effective in offsetting soil acidity through a 12-day pre-experiment. The total carbon (TC), calcium oxide, and magnesium oxide contents of the lumpy dolomite are $9.55 \pm 0.30\%$, $30.5 \pm 0.5\%$, and $22.0 \pm 0.5\%$, respectively.

Treatments and incubation

Air-dried soil samples were pre-incubated at 40% of soil water holding capacity (WHC) by adding sterile deionized water in the dark at 25 °C for 7 days. Subsequently, aliquots of 250 g and 200 g (dry basis, for soil and gas sampling, respectively) of the soils were placed separately in 1-L bottles for further treatment. The incubation experiment of both soil samples was conducted by using four treatments including soils amended with no

Table 1 Selected characteristics of the two paddy soils prior to use in the present study

Parameters	Sampling sites	
	Qichun (S1)	Chibi (S2)
pH (1:2.5 H ₂ O)	5.19 ± 0.02	5.57 ± 0.03
TC (%)	2.22 ± 0.04	1.49 ± 0.01
TN (%)	0.24 ± 0.00	0.19 ± 0.00
DOC (mg kg ⁻¹)	70.67 ± 3.34	84.95 ± 0.55
NH ₄ ⁺ -N (mg kg ⁻¹)	3.29 ± 1.03	2.49 ± 0.53
NO ₃ ⁻ -N (mg kg ⁻¹)	2.12 ± 0.71	1.64 ± 0.04
WHC (%)	61.03 ± 0.86	42.76 ± 0.11
Clay (%)	26.07 ± 0.21	30.10 ± 0.28
Silt (%)	55.26 ± 0.36	67.83 ± 0.55
Sand (%)	18.66 ± 0.56	2.07 ± 0.76

Data are presented as mean ± standard deviation ($n = 3$)

TC total carbon, TN total nitrogen, DOC dissolved organic carbon, WHC water holding capacity

dolomite (termed CK), coarse-sized dolomite (0.5–0.25 mm, termed CS), medium-sized dolomite (0.25–0.15 mm, termed MS), and fine-sized dolomite (< 0.15 mm, termed FS). According to the 12-day pre-experiment with the proposal of determining the appropriate application rate of dolomite to increase soil pH to the target of 6.5, the rate of 3 g kg⁻¹ soil was employed for all dolomite treatments. Then, the soil moisture content was adjusted to 50% of WHC by adding sterile deionized water. Given that lime material is generally added to acidic soils 2 weeks before rice transplanting when soils are in dry conditions, the moisture content of 50% WHC was selected. Once the dolomite or sterile deionized water was added, the soil was thoroughly mixed to avoid any heterogeneity. After amendment, each incubation bottle was covered by a plastic film containing several small holes to allow gas exchange and reduce moisture loss. Then, the soils were incubated in the dark at 25 °C for 35 days in a biochemistry cultivation chamber. Each treatment had three replicates.

Gas sampling and analysis

Gas sampling was undertaken every day until day 18, and then every 2, 3, and 4 days up to days 24, 27, and 35 during incubation, respectively, to detect the concentration of CO₂. The plastic films were removed to allow adequate gas exchange between the interior of the bottles and ambient air for 20 min prior to sampling. The bottles were then sealed for 1 h using rubber stoppers. Immediately after closure and after 1 h, two gas samples were withdrawn from the headspace of the incubation bottles, using a gas-tight syringe as described by Shaaban et al. (2017).

The concentrations of the gas samples were analyzed immediately by using a gas chromatography system (GC-Agilent 7890A, USA) installed with a flame ionization detector (FID) for CO₂ as described by Shaaban et al. (2017).

Soil sub-sampling and analysis

Soil sub-samples were collected on days 1, 3, 5, 8, 13, 20, 27, and 35, and analyzed for pH, NH₄⁺-N, NO₃⁻-N, dissolved organic carbon (DOC), and microbial biomass carbon (MBC) contents. Sub-samples were also collected on day 0 (after pre-incubated) to identify the starting value of soil pH. Soil pH was determined in a 1:2.5 (w/v) soil-to-distilled water slurry by a pH meter (Sartorius, PB-10, Germany). Soil NH₄⁺-N and NO₃⁻-N were extracted with 1 M KCl at a 1:5 ratio of soil to extractant and detected using the phenol hypochlorite method (Scheiner 1976) and double-wavelength method (at 220 nm and 275 nm) (Lu 2000), respectively. Soil DOC was extracted with deionized water (at a 1:5 ratio of soil to water) and measured using a TOC analyzer (Elementar,

Vario TOC, Germany). Soil DOC content was calculated as the difference of total C (TC) and inorganic C contents in the extract. Soil MBC was determined by the modified alcohol-free chloroform fumigation extraction method (Wu et al. 1990). Briefly, soil fumigated with and without chloroform was incubated for 24 h and then extracted by 0.5 M K₂SO₄ (at a 1:5 ratio of soil to solution). The MBC was defined as the difference of organic carbon contents (measured by a TOC analyzer, Elementar, Vario TOC, Germany) between fumigated and non-fumigated samples with a conversion factor of 0.45.

Data calculation and statistical analysis

Mean net nitrification rates were calculated as the net changes of soil NO₃⁻-N over time. Given that pH is one of the most important factors affecting nitrification processes in soils, and the changes of pH among treatments of the two soils were more obvious during the first 20 days than that of 35 days (see the “Results” section), the mean nitrification rates were calculated during the first 20 days of incubation.

CO₂ emission fluxes were calculated as the following equation:

$$F = \rho \times V/m \times \Delta c/\Delta t \times 273.15/(T + 273.15) \times f \quad (1)$$

where F is the gas flux (mg CO₂-C kg⁻¹ dry soil h⁻¹), ρ is the density of gas in standard conditions, V is the volume of the headspace in the bottle (m³), m is the weight of the dry soil in the bottle (kg), $\Delta c/\Delta t$ is the change rate of CO₂ concentration of the headspace in the bottle during closure time (m³ m⁻³ h⁻¹), T is the temperature for incubation (°C), and f is the conversion coefficient.

The cumulative CO₂ emissions were calculated as the sum of the daily emissions during the incubation by the following equation:

Cumulative CO₂ emission

$$= \sum_{i=1}^n (F_i + F_{i+1})/2 \times (t_{i+1} - t_i) \times 24 \quad (2)$$

where F is the gas flux (mg CO₂-C kg⁻¹ dry soil h⁻¹), i is the i th measurement of CO₂, $(t_{i+1} - t_i)$ is the days between two adjacent measurements, and n is the number of sampling times.

The cumulative CO₂ emissions were fitted with a first-order model using the Origin statistical package (OriginPro 2017, Origin Lab Corporation, USA). The first-order model is expressed as follows (Fuentes et al. 2006):

$$C_{\text{emiss}} = C_e + C_0 \times (1 - \exp(-k \times t)) \quad (3)$$

where C_{emiss} is the cumulative CO_2 emission at time t ($\text{g CO}_2\text{-C kg}^{-1}$ soil), and C_e is the easily mineralizable carbon pool ($\text{g CO}_2\text{-C kg}^{-1}$ soil), which is rapidly consumed by microbes during the first few days of incubation (Fuentes et al. 2006). The parameter C_e might also have accounted for the initial abiotic flushes of CO_2 due to the reaction of soil with dolomite (Kunhikrishnan et al. 2016). The parameter C_0 is the potentially mineralizable carbon ($\text{g CO}_2\text{-C kg}^{-1}$ soil), reflecting soil labile C pools that accumulated due to inputs and lack of decomposition of C in the field in history (Costantini et al. 2006); k is the decomposition rate constant (day^{-1}); and t is the incubation time (day).

The metabolic quotient ($q\text{CO}_2$) was calculated as $\text{CO}_2\text{-C}/\text{MBC}$ to indicate microbial activity.

Prior to analysis, all measured data were checked for normality using a Shapiro-Wilk test, and log-transformed if necessary. One-way analysis of variance (ANOVA) was used to analyze the significance of differences of cumulative CO_2 emissions, $q\text{CO}_2$, and the estimated parameters in Eq. 3 among the treatments (CK, CS, MS, and FS). The relationships between soil pH and DOC and MBC were explored via regression with OriginPro 2017 (Origin Lab Corporation, USA). The relationships between soil $\text{CO}_2\text{-C}$ fluxes and soil properties were also explored via regression. The differences of the cumulative CO_2 emission and the average of soil MBC between dolomite treatment and the control, termed as ΔCO_2 and ΔMBC , respectively, were calculated. The relationship between ΔCO_2 and ΔMBC was assessed using Pearson's correlation analysis. Two-way repeated measure ANOVA was used to test effects of size of dolomite and sampling time and their interaction on soil pH, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, DOC, and MBC, as well as CO_2 flux.

The path analysis was performed to further reveal the relationships among soil CO_2 flux, pH, DOC, and MBC. All statistical analyses were conducted using IBM SPSS Statistics 20.0 (SPSS, Inc., USA) at 95% confidence intervals, and all figures were plotted with OriginPro 2017.

Results

Soil properties

The two soils are acidic, while the pH of S1 (pH 5.19) is lower than that of S2 (pH 5.57) (Table 1). In addition, soil TC and total nitrogen (TN) contents of S1 are higher than those of S2.

Both S1 and S2 with dolomite application exhibited higher pH than that of the control throughout the study period (Fig. 1a, b). The application of dolomite significantly changed the pH for both soils ($P < 0.001$), and the dolomite with fine-size was more effective in neutralizing soil acidity than those with coarse- or medium-size (Fig. 1). In general, soil pH firstly increased and then decreased in both soils during the first 20 days of incubation (Fig. 1). Moreover, the decrease in soil pH was higher in S2 than in S1.

Soil $\text{NH}_4^+\text{-N}$ content for all treatments in both soils increased in the first 3–8 days of incubation, and it was higher for the fine-sized dolomite treatment than other treatments (Fig. S1a, b). Afterwards, soil $\text{NH}_4^+\text{-N}$ content began to decline until the end of incubation. Soil $\text{NO}_3^-\text{-N}$ content in both soils for all treatments increased during the whole incubation, but the increasing pattern differed in soils (Fig. S1c, d). Soil $\text{NO}_3^-\text{-N}$ content increased exponentially with a lag phase from day 1 to day 8 in S1, while $\text{NO}_3^-\text{-N}$ content increased nearly linearly until day 20 and then remained stable until the end of incubation in S2. In general, soil $\text{NO}_3^-\text{-N}$ content

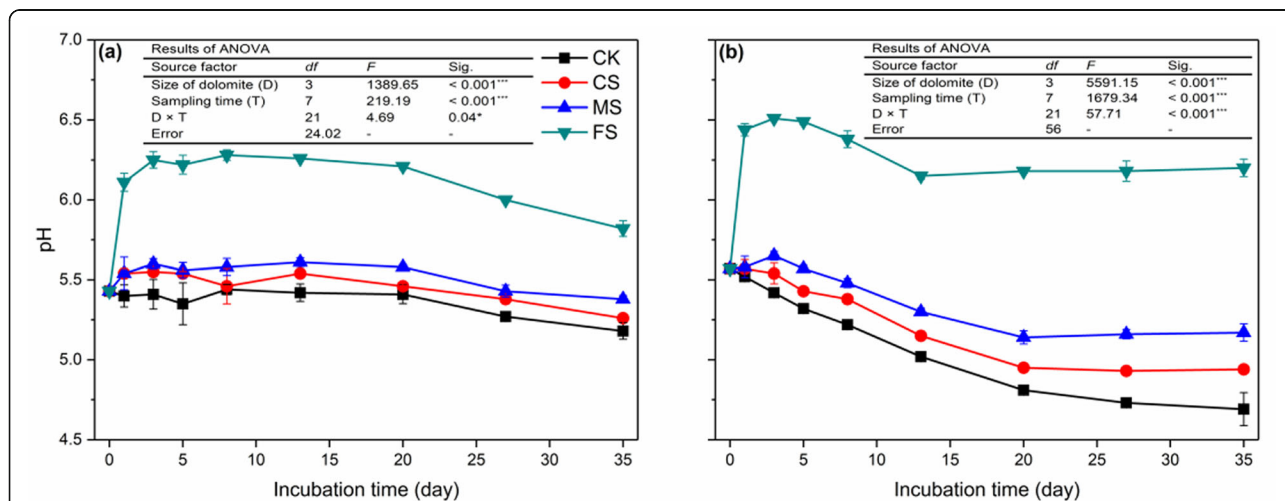


Fig. 1 Dynamics of soil pH in S1 (a) and S2 (b) as affected by different sized dolomite application. Error bars represent standard deviation of the mean values ($n = 3$). CK presents soil without dolomite amendment; CS, MS, and FS present soil with the coarse-, medium-, and fine-sized dolomite amendment, respectively. *** $P < 0.001$, * $P < 0.05$

was higher for the dolomite treatments than in the control, especially with fine-sized dolomite. The mean net nitrification rates of dolomite treatments in S2 were 2.72–5.99 times higher than those in S1 during the first 20 days of incubation (Table S1).

In general, soil DOC content was increased by dolomite treatments and peaked at 54.21 ± 2.74 , 51.63 ± 4.20 , and $70.38 \pm 1.43 \text{ mg kg}^{-1}$ for the coarse-, medium-, and fine-sized dolomite treatments, respectively, in S1 on days 3–5 (Fig. 2a). It also peaked at 36.87 ± 4.57 , 32.79 ± 2.42 , and $48.71 \pm 3.08 \text{ mg kg}^{-1}$ for the coarse-, medium-, and fine-sized dolomite treatments, respectively, in S2 on day 3 (Fig. 2b). Afterwards, soil DOC content in both soils decreased gradually until the end of incubation. Moreover, the results of the two-way repeated measure ANOVA showed that DOC contents in both soils were significantly influenced by the particle sizes of dolomite ($P < 0.001$) (Fig. 2a, b). MBC of both soils increased with the application of dolomite and reached the highest values of 250.11 ± 0.94 , $223.01 \pm$

15.95 , and $271.67 \pm 15.34 \text{ mg C kg}^{-1}$ for the coarse-, medium-, and fine-sized dolomite treatments, respectively, on day 1 in S1 and 422.87 ± 9.33 , 409.13 ± 5.68 , and $453.79 \pm 9.04 \text{ mg C kg}^{-1}$ for the coarse-, medium-, and fine-sized dolomite treatments, respectively, on days 1–3 in S2 (Fig. 2c, d). Then, MBC of both soils decreased during the whole process after the peak time. The results of the two-way repeated measure ANOVA showed that MBC in both soils was significantly influenced by the particle sizes of dolomite ($P < 0.001$).

Soil CO₂ emission

CO₂-C flux of all dolomite treatments in both soils peaked at the initial stage of incubation (on day 1 for the fine-sized dolomite treatment and day 2 for the other two dolomite treatments), known as an initial flush of CO₂ evolution (Fig. 3a, b). Afterwards, CO₂-C flux drastically dropped until day 13 and then remained steady until the end of incubation. Moreover, dolomite

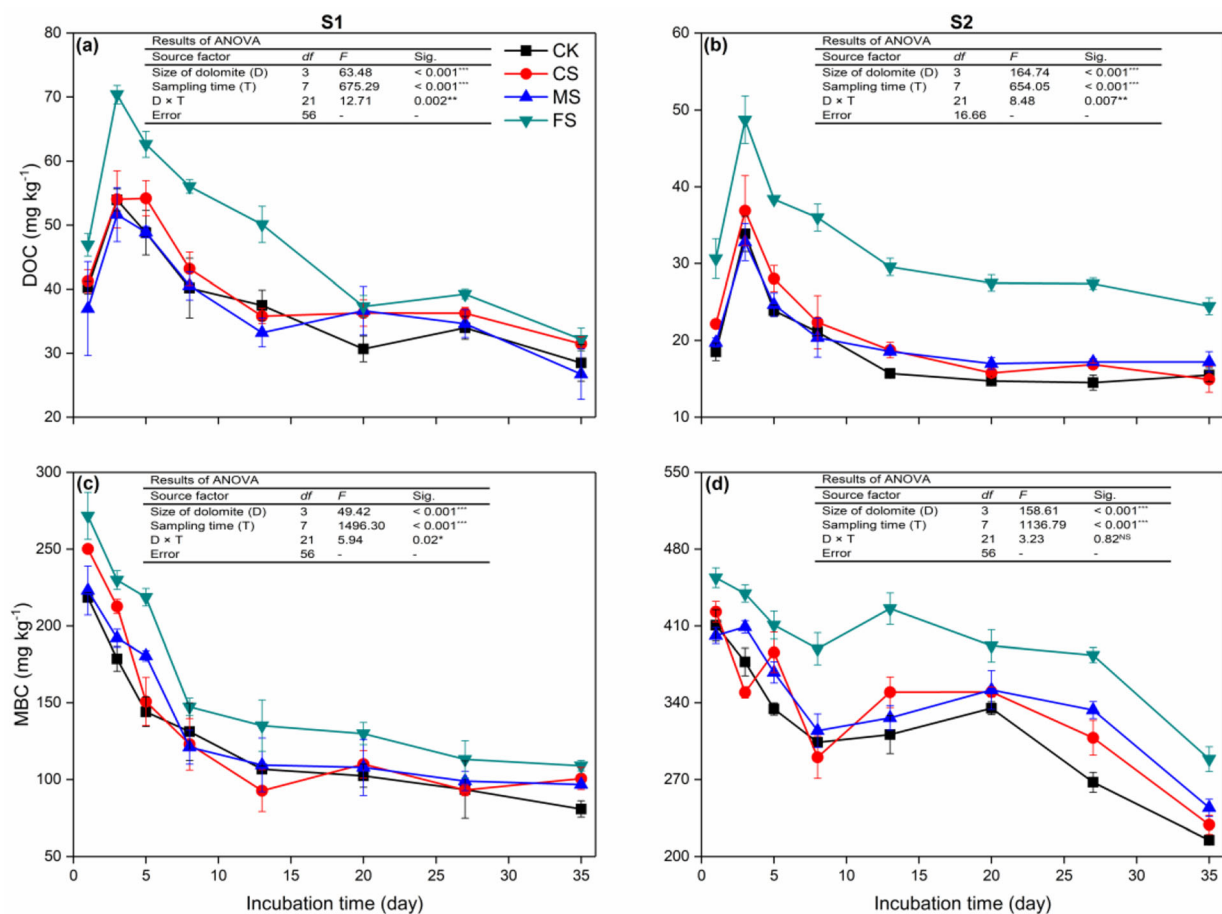
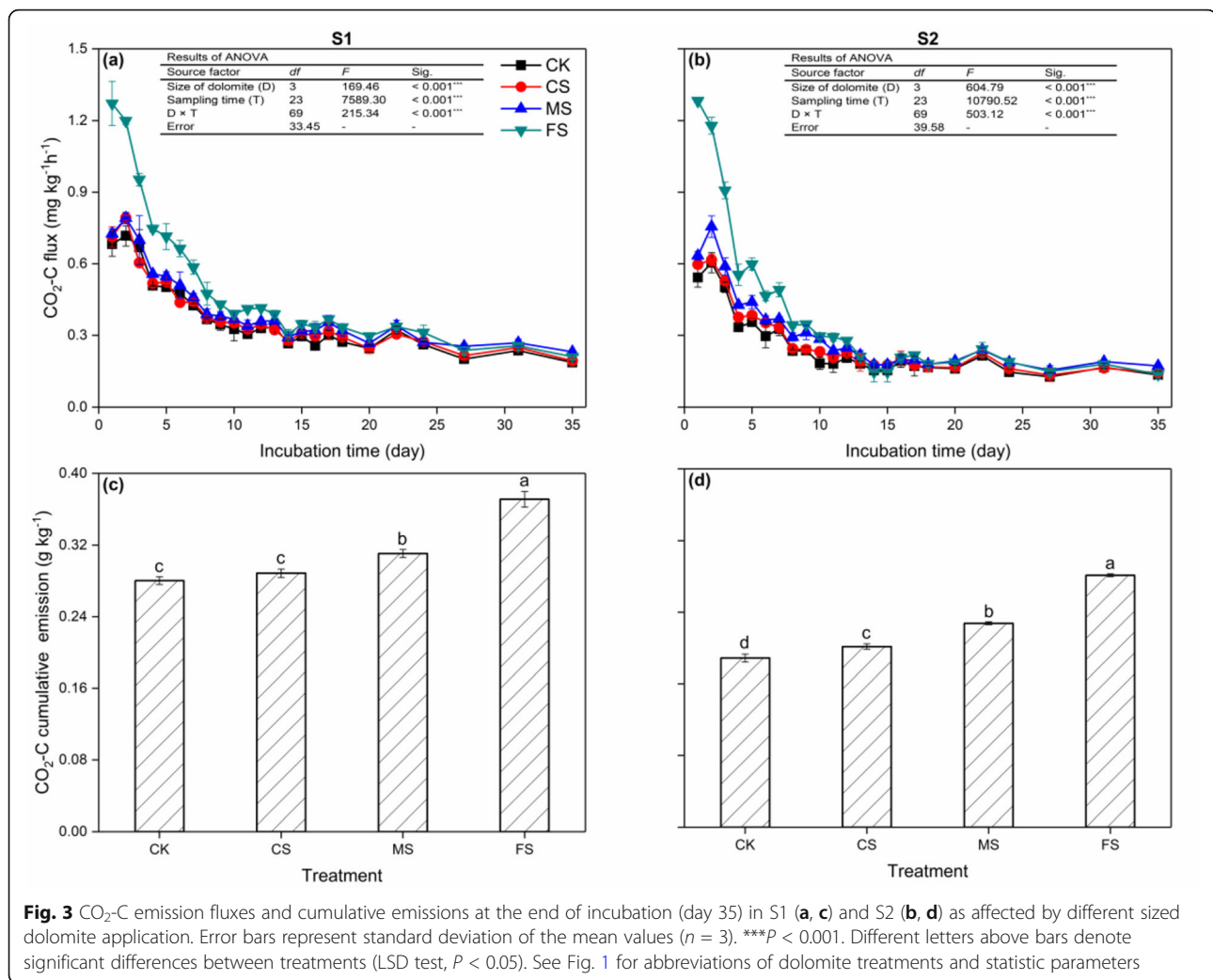


Fig. 2 Dynamics of soil dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in S1 (a, c) and S2 (b, d) as affected by different sized dolomite application. Error bars represent standard deviation of the mean values ($n = 3$). *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$. NS, no significance. See Fig. 1 for abbreviations of dolomite treatments and statistic parameters



application boosted soil CO₂-C flux with the fine-sized dolomite treatment causing the highest rate of soil CO₂ emission.

The cumulative CO₂ emissions increased by 3%, 11%, and 32%, for the coarse-, medium-, and fine-sized dolomite treatments, respectively, compared to the control in S1 (Fig. 3c), whereas those increased by 7%, 21%, and 49%, respectively, compared to the control in S2 (Fig. 3d). One-way ANOVA showed that the cumulative soil CO₂ emissions were significantly higher ($P < 0.05$) for the medium- and fine-sized dolomite treatments than for those of the control in S1 (Fig. 3c). The cumulative soil CO₂ emissions were significantly higher ($P < 0.05$) for all sizes of dolomite treatments than for the control in S2 (Fig. 3c, d). Moreover, there was a significant difference in the cumulative soil CO₂ emissions among dolomite treatments in both soils ($P < 0.05$).

The first-order model fitted the cumulative CO₂ emissions well for all treatments (Table 2; Fig. S2a, b). In both soils, the coarse- and medium-sized dolomite

treatments did not significantly influence the estimated easily mineralizable C pool (C_e) or the estimated decomposition rate constant (k) compared to the control ($P > 0.05$), while there was a significant increase in the C_e and k for the fine-sized dolomite treatments ($P < 0.05$). Only the medium- and fine-sized dolomite treatments significantly enhanced the estimated potentially mineralizable carbon (C_0) compared to the control in S1 ($P < 0.05$). In the case of S2, all sizes of dolomite treatments appreciably enhanced C_0 ($P < 0.05$).

Relationships between soil properties and CO₂ emission

The results of regression analysis showed that soil DOC was significantly and positively correlated with soil pH ($P < 0.05$) (Fig. 4a, b) and MBC ($P < 0.05$) (Fig. 4e, f) in both soils. Soil MBC was also significantly and positively correlated with soil pH in both soils ($P < 0.05$) (Fig. 4c, d). In both soils, CO₂ emissions had significantly positive correlations with soil pH ($P < 0.05$) (Fig. 5a, b), DOC ($P < 0.05$) (Fig. 5c, d), and MBC ($P < 0.05$) (Fig. 5e, f). The

Table 2 Estimated parameters for measuring the easily mineralizable C pool (C_e), potentially mineralizable carbon (C_o) and decomposition rate constant (k), and determination coefficients (R^2) using the first-order model of the cumulative soil CO_2 emission

Treatments	C_e (g kg ⁻¹)	C_o (g kg ⁻¹)	k (day ⁻¹)	R^2
S1				
CK	0.013 ± 0.002b	0.372 ± 0.010c	0.035 ± 0.002b	0.995
CS	0.014 ± 0.002b	0.392 ± 0.011bc	0.033 ± 0.002b	0.996
MS	0.014 ± 0.002b	0.433 ± 0.015a	0.032 ± 0.002b	0.995
FS	0.029 ± 0.003a	0.405 ± 0.009b	0.049 ± 0.002a	0.992
S2				
CK	0.014 ± 0.002b	0.222 ± 0.008c	0.041 ± 0.003b	0.986
CS	0.014 ± 0.002b	0.232 ± 0.006b	0.043 ± 0.002b	0.992
MS	0.015 ± 0.002b	0.258 ± 0.006a	0.045 ± 0.002b	0.992
FS	0.031 ± 0.003a	0.255 ± 0.005a	0.073 ± 0.004a	0.985

Values are presented as mean ± standard deviation of estimated parameters ($n = 3$)

CK presents soil without dolomite amendment; CS, MS, and FS present soil with the coarse-, medium-, and fine-sized dolomite amendment, respectively. Different letters in a column indicate significant differences between treatments in a single soil (LSD test, $P < 0.05$)

results of the path analysis further indicated that soil pH had apparent and direct effect on DOC and MBC in soil S2, but only on DOC in soil S1 (Fig. 6). Soil DOC had significant and direct effect on MBC in soil S1, but its effect was weak in soil S2. Furthermore, soil MBC rather than DOC had apparent and direct effect on soil CO_2 flux in both soils.

The results of Pearson's correlation analysis showed that ΔCO_2 also positively correlated with soil ΔMBC in both soils ($r = 0.972$, $P = 0.028$, and $r = 0.986$, $P = 0.014$, for S1 and S2, respectively).

Discussion

Effect of dolomite particle size on soil pH

In the present study, dolomite addition increased soil pH in acidic soils as compared with the control, and the fine-sized dolomite treatment was more effective at neutralizing soil acidity (Fig. 1a, b). Similar findings have been reported by previous studies (Jones 2016; Tjv and Lewis 1994), which all indicated that increasing the fineness of lime materials increased their efficiency of counteracting soil acidity. The scenario of increase in soil pH caused by the fine-sized dolomite addition was due to its greater specific surface area and more rapid dissolution rate in the soil (Huang et al. 2007; Jones 2016).

In general, pH of the dolomite-amended soil firstly increased and then decreased in both soils during the first 20 days of incubation (Fig. 1a, b). The result was consistent with previous studies (Álvarez et al. 2009; Li et al. 2018). This decrease in soil pH might be attributed to nitrification, in which 2 mole protons are released per

mole NH_4^+ oxidized to NO_3^- (Haynes and Swift 1988). As exhibited in the present study, NO_3^- -N content increased during the incubation for all treatments in both soils (Fig. S1c, d), suggesting that nitrification occurred. The results also showed that the mean net nitrification rates of dolomite treatments in S2 were 2.72–5.99 times higher than those in S1 during the first 20 days of incubation (Table S1), probably resulting in a greater decrease in soil pH in S2 than in S1 (Fig. 1a, b). Differences in nitrification rates from the two soils could be due to different soil properties. Taking soil initial pH for example, since it was lower in S1 than S2 (Table 1), the acid-sensitive nitrifiers rather than acid-tolerant nitrifiers in S1 may not adapt to the increasing pH circumstance at the initial incubation (Cheng et al. 2013; Nugroho et al. 2007), leading to a lag effect of pH stimulation of nitrification and lower nitrification rate than S2 (Table S1).

Effect of dolomite particle size on SOC mineralization

As mentioned above in the “Materials and methods” section, besides microbial-mediated CO_2 emission, lime-derived CO_2 evolution may occur after liming. However, we proposed that there was no abiotic CO_2 emission or it could be ignored in the present study. This was supported by the following three aspects. Firstly, the results of regression analysis showed that there was a significantly positive correlation between CO_2 emission flux and soil MBC (Fig. 5e, f), the results of Pearson's correlation analysis showed that ΔCO_2 was also positively correlated with soil ΔMBC in both soils ($r = 0.972$, $P = 0.028$, and $r = 0.986$, $P = 0.014$, for S1 and S2, respectively), and the results of path analysis showed that soil pH had no direct effect on CO_2 emission flux, confirming that microorganisms played a major role in CO_2 emissions. Secondly, supposing that all H^+ consumed during the increase of pH was used for dolomite dissolution and abiotic CO_2 production, we calculated that only 0.57–1.57% and 0.26–1.09% of total CO_2 emission were attributed to abiotic CO_2 production in S1 and S2, respectively. Therefore, the quantities of abiotic CO_2 can be ignored. Finally, CO_2 emission occurs from the reaction between H^+ and carbonate minerals when soil pH < 5 (Hamilton et al. 2007), whereas, in the present study, soil pH of all dolomite treatments in both soils was above 5 during the incubation, except that pH of the coarse-sized dolomite treatment in S2 was slightly lower than 5 during days 20–35 of incubation (4.93–4.95), when CO_2 flux was fairly low and steady. Overall, the major CO_2 emission resulted from SOC mineralization instead of abiotic CO_2 evolution.

The present study showed that soil CO_2 emissions were increased by dolomite application in both soils (Fig. 3a, b), indicating that liming prompted SOC

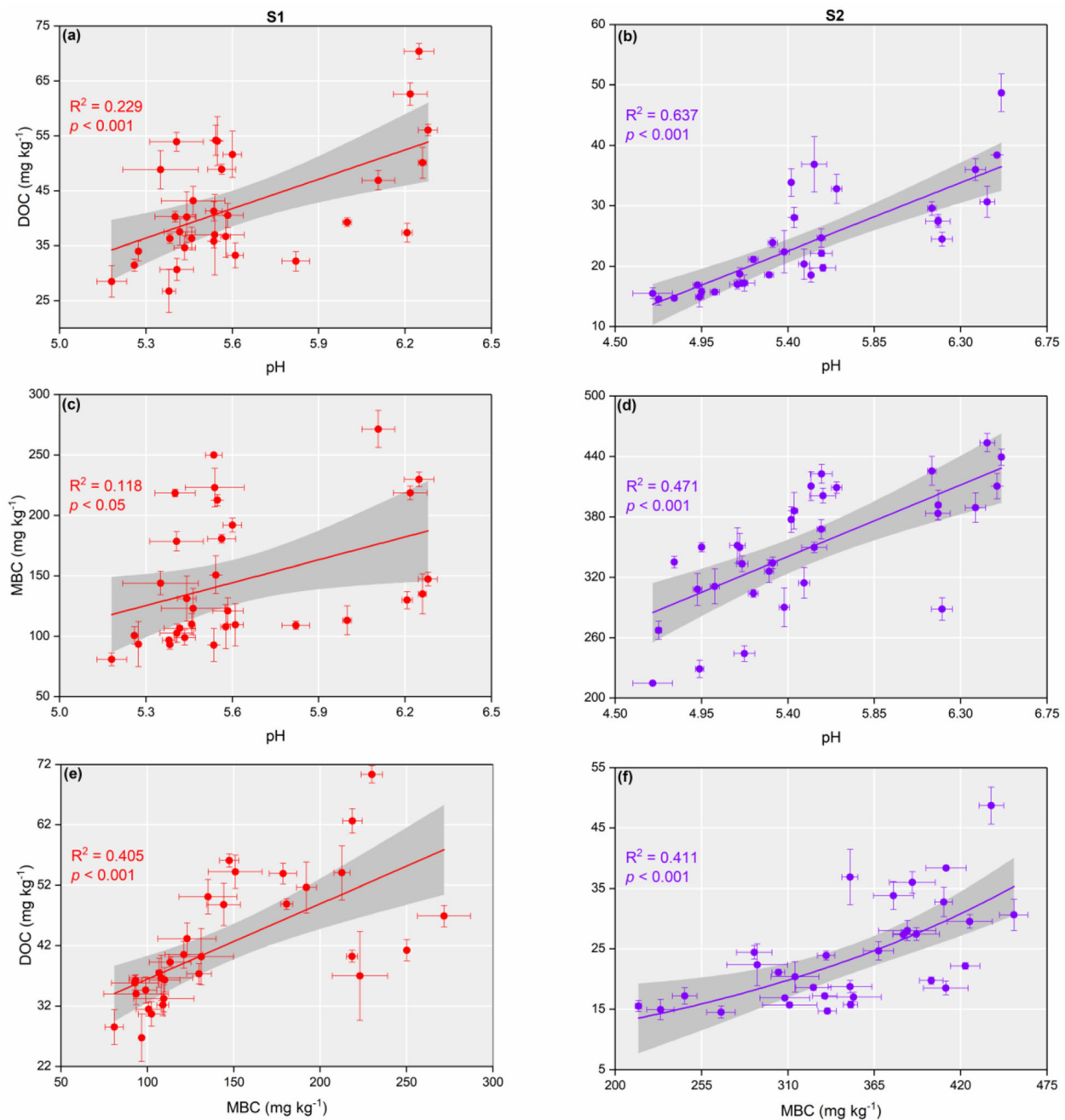


Fig. 4 Relationships among soil pH, dissolved organic carbon (DOC), and microbial biomass carbon (MBC) in S1 (a, c, e) and S2 (b, d, f). Shaded bands represent 95% pointwise confidence intervals. Error bars represent standard deviation of the variables ($n = 3$)

mineralization and CO₂-C loss. This result is in line with many previous laboratory studies (Bertrand et al. 2007; Lochon et al. 2018; Persson et al. 1989; Xiao et al. 2018) as well as field experiments in cropland soils (Chan and Heenan 1999), forest soils (Nilsson et al. 2001; Persson et al. 1995), and grassland soils (Fornara et al. 2011; Mijangos et al. 2010). A possible explanation for the positive effect of dolomite application on the SOC stock

loss is that short-term dolomite treatment resulted in higher biological activity via increasing soil pH (Holland et al. 2017). Soil microbial activity is controlled by the physicochemical and biochemical properties of soil, especially soil pH which is one of the dominant factors (Adams and Adams 1983; Higashida and Takao 1986; Xiao et al. 2018). Liming increased microbial activity in soils (Andersson and Nilsson 2001; Paradelo et al. 2015)

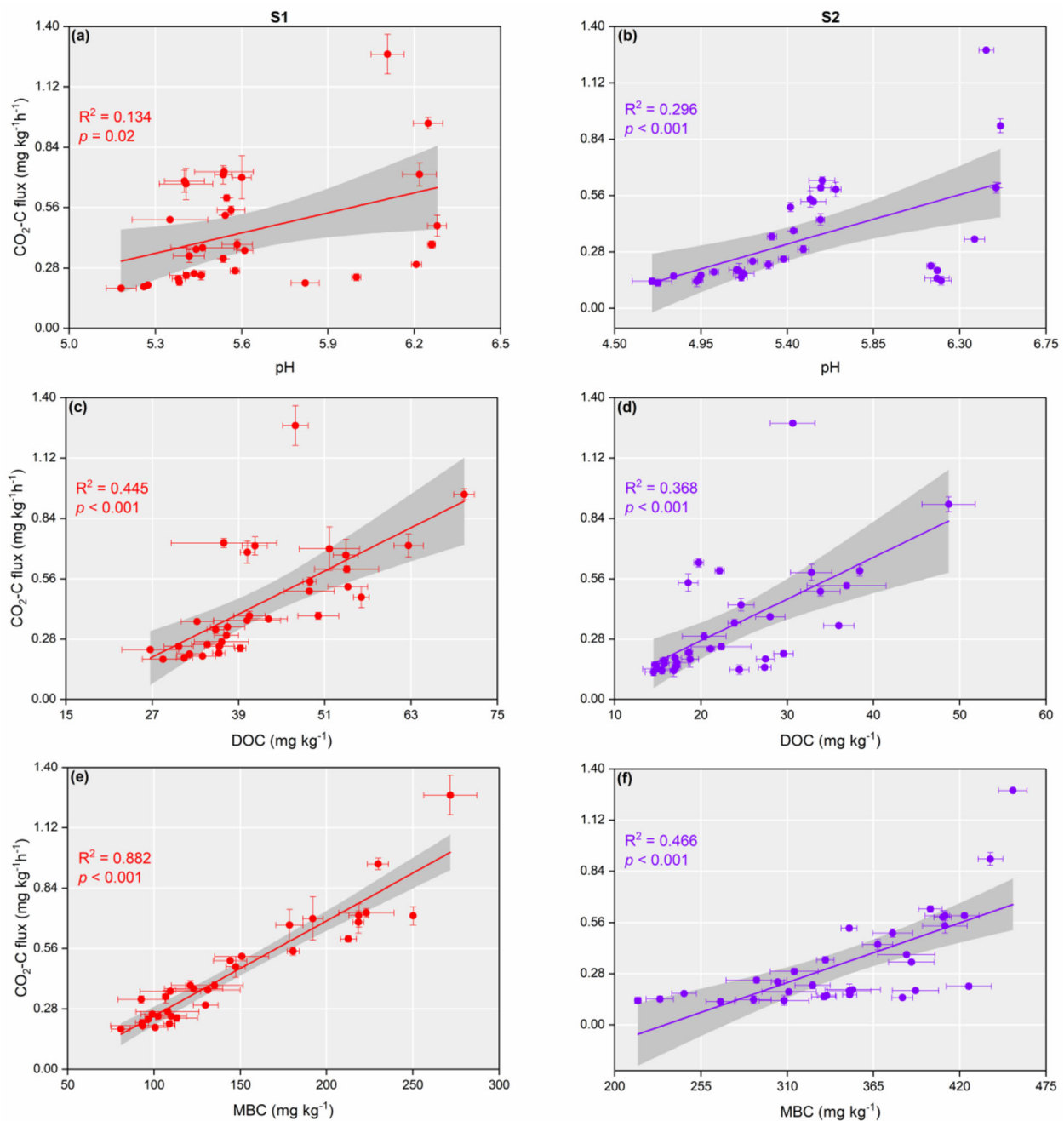


Fig. 5 Relationships between CO₂ emission flux and soil pH, dissolved organic carbon (DOC), and microbial biomass carbon (MBC) in S1 (a, c, e) and S2 (b, d, f). Shaded bands represent 95% pointwise confidence intervals. Error bars represent standard deviation of the variables ($n = 3$)

either by facilitating release of easily available C (e.g., DOC) to microbial consumption (Shaaban et al. 2017; Zelles et al. 1990) or by offsetting soil acidity and favoring microflora with a smaller C-use efficiency, thus resulting in more evolution of CO₂ in soils (Holland et al. 2017). Our results showed that soil MBC was positively correlated with both soil DOC content and CO₂-C flux (Figs. 4e, f and 5e, f), suggesting that MBC could be

an indicator of microbial activity (Mendham et al. 2002). In addition, the metabolic quotient (q_{CO_2}), as an indicator of microbial activity, was higher from soils treated with fine-sized dolomite than that with other treatments (Fig. S3). Moreover, both soil DOC and MBC contents, which were increased with the application of dolomite (Fig. 2a–d), were positively correlated with soil pH (Fig. 4a–d). These results provided evidence that both soil

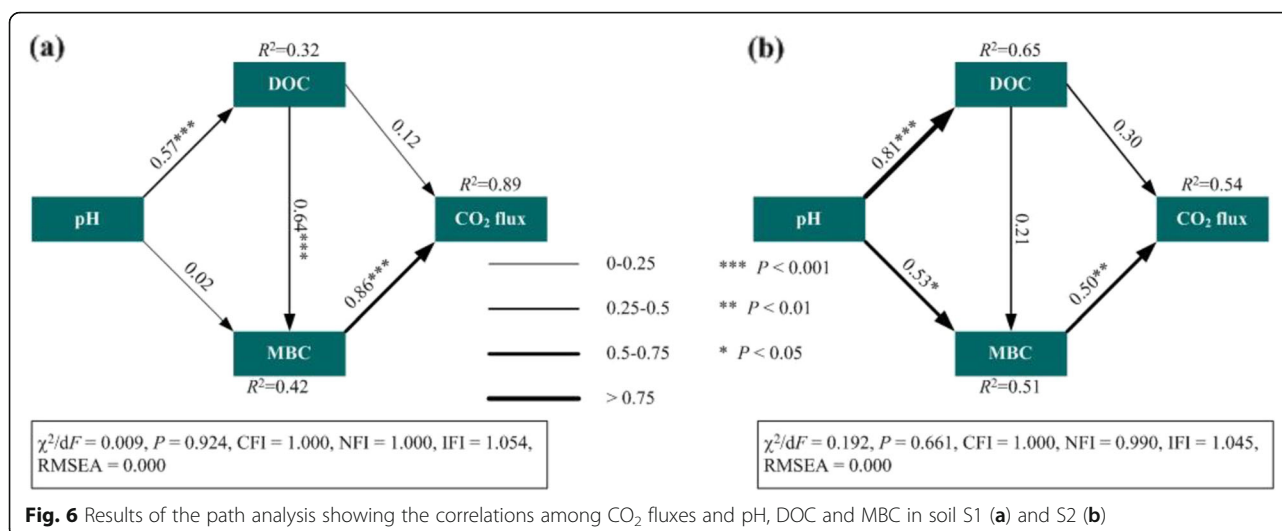


Fig. 6 Results of the path analysis showing the correlations among CO₂ fluxes and pH, DOC and MBC in soil S1 (a) and S2 (b)

microbial activity and easily available C substrate increased after the application of dolomite.

What is really noteworthy was that there was a significant difference in the cumulative CO₂ emissions between dolomite treatments in both soils (Fig. 3c, d), and higher cumulative CO₂ emission was observed from the finer particle sizes of dolomite treatment, suggesting that the magnitude of SOC mineralization was significantly affected by the particle size of dolomite. The possible reason for the results was that soil pH was significantly influenced by the particle sizes of dolomite and the finer particle sizes of dolomite treatment led to a higher increase in soil pH (Fig. 1a, b), consequently resulting in greater availability of C substrates for microorganisms (Fig. 2a, b) and higher microbial activity (indicated by MBC and $q\text{CO}_2$, Figs. 2c, d and S3), eventually leading to a significantly higher SOC mineralization (Fig. 3c, d).

Effect of dolomite particle size on SOC turnover rate

The decomposition rate constant (k) is usually used as an indicator of the turnover rate of SOC (Curtin et al. 1998; Fuentes et al. 2006). The fine-sized rather than coarse- and medium-sized dolomite treatment resulted in a significant increase in the value of k in both soils (Table 2), suggesting that the SOC turnover rate was dependent on the particle size of dolomite. The decomposition rate constant (k) was regulated by environmental factors and soil conditions (Campbell et al. 1994). Previous studies indicated that liming could increase the turnover rate of soil organic matter due to increase in soil pH thus facilitating microbial activity (Carneis Filho et al. 2017; Lochon et al. 2018). Soil pH is considered as a key factor governing the microbial turnover of organic carbon (Bertrand et al. 2007; Xiao et al. 2018). In addition, the value of k should be reduced in conditions with suboptimal pH values (Curtin et al. 1998). As

mentioned above, although soil pH of both S1 and S2 was significantly influenced by the particle sizes of dolomite, the fine-sized dolomite treatment was more effective at neutralizing soil acidity than other two dolomite treatments. Therefore, the probable reason for the significant positive effect of the fine-sized dolomite was that soil pH was increased enough to affect the SOC decomposition rates by the fine-sized dolomite treatment than other two sizes did.

Conclusion

The results indicated that dolomite application increased SOC mineralization via enhancing DOC production and stimulating microbial growth and activity, which resulted from the increase in soil pH. Moreover, the effect was greater for the finer particle size, suggesting that the particle size of lime material has the role in regulating the SOC mineralization and CO₂-C loss in acidic soils. The results suggested that the particle size of lime material influences not only the soil pH, substrate availability, and microbial activity, but also the soil carbon stock as well as soil fertility in acidic paddy soils. Therefore, the fineness of lime material should be appropriately considered to ameliorate soil acidity when addressing SOC budget.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13717-020-00278-x>.

Additional file 1: Fig. S1. Dynamics of soil NH₄⁺-N and NO₃⁻-N in S1 (a, c) and S2 (b, d) as affected by different sized dolomite application. Error bars represent standard deviation of the mean values ($n = 3$). CK presents soil without dolomite amendment; CS, MS, and FS presents soil with the coarse-, medium-, and fine-sized dolomite amendment, respectively. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$, ^{NS} no significance. **Fig. S2.** Changes in the cumulative soil CO₂-C emission and decomposition

kinetic curve for all treatments in S1 (a) and S2 (b). The curves were modeled by $C_{emiss} = C_e + C_o \times (1 - \exp(-k \times t))$. See Fig. S1 for abbreviations of dolomite treatments. **Fig. S3.** Dynamics of soil metabolic quotient (qCO_2) in S1 (a) and S2 (b) as affected by different sized dolomite application. Different letters above bars denote significant differences between treatments (LSD test, $P < 0.05$). See Fig. S1 for abbreviations of dolomite treatments and statistic parameters. **Table S1.** Mean net nitrification rates ($mg\ N\ kg^{-1}\ d^{-1}$) of two soils during the first 20 days of incubation.

Abbreviations

ANOVA: Analysis of variance; C: Carbon; DOC: Dissolved organic carbon; FID: Flame ionization detector; MBC: Microbial biomass carbon; SOC: Soil organic carbon; TC: Total carbon; TN: Total nitrogen; WHC: Water holding capacity

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Authors' contributions

HW and RH designed the experiment. HW and JH performed the experiment, processed the data, and performed the statistical analyses. The manuscript was drafted by HW, JH, MS, and PX which was finalized by HW, JZ, and RH. All authors have read and approved the final version of manuscript.

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Consent for publication

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Competing interests

The authors declare that they have no competing interests.

Author details

¹College of Urban and Environmental Sciences, Hubei Normal University, Huangshi, China. ²College of Resources and Environment, Huazhong Agricultural University, Wuhan, China. ³Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan.

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