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Evaluating basalt weathering for organic-inorganic ‘double carbon’ stabilization of the soil priming effect

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Research Article

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Abstract

Aims

Basalt weathering has the potential to absorb soil CO_2 emission and stabilize the organic carbon by its weathering products, e.g. montmorillonite and kaolinite. However, the feasibility of basalt weathering on organic-inorganic 'double carbon' stabilization of soil priming effect (PE) remains unclear.

Methods

We conducted a 28-d incubation experiment by adding ^{13}C-glucose with or without basalt, montmorillonite or kaolinite to a farmland soil planted with peach (*Prunus persica* (L.) Batsch) for more than 20 years. CO_2 emission and its ^{13}C value were continuously measured to calculate the PE and soil net carbon balance.

Results

After 28-d incubation, the basalt treatment resulted in an increase in soil pH from 5.32 to 7.17. Additionally, compared to the control, the basalt treatment showed a 143.7% and 168.6% increase in dissolved organic carbon (DOC) and soil inorganic carbon (SIC), respectively. Subsequently, the basalt treatment induced the highest cumulative PE among all treatments, with the activities of β-glucosidase (S-β-GC), soil leucine amino peptidase (S-LAP), and soil catalase (S-CAT) being the highest. Furthermore, the kaolinite treatment showed significantly lower emissions of CO_2-C, glucose mineralization, and cumulative PE ($P < 0.05$). It is worth noting that all treatments significantly enhanced the net soil net carbon balance, with the most significant improvement observed in the kaolinite treatment.

Conclusions

Basalt and its weathering products can promote the organic-inorganic 'double carbon' stabilization in the PE. Basalt, in particular, has the most significant effect on SIC stabilization, while kaolinite has the highest potential for improving the soil net carbon balance.

Introduction

Priming effect (PE) refers to a strong short-term change in soil organic matter (SOM) mineralization rate induced by adding exogenous substrates (Fontaine et al. 2003; Huo et al. 2022). The low quality of SOM in the original soil limits the utilization of soil microorganisms, leading to a low mineralization rate of SOM. Due to the high availability of energy and nutrients released from the fresh organic matter, PE is usually considered to be the response to an increase in overall microbial activity (Zhu et al. 2018; Wu et al. 2020; Zhang et al. 2020). In 1946, Broadbent's experiment demonstrated that after adding ^{13}C-labeled plant residues, the amount of CO_2 released from the soil could increase by 4 to 11 times (Broadbent 1948). This high amount of 'extra' CO_2 release has stimulated extensive research on this phenomenon. Therefore, PE plays an important role in soil carbon pool sequestration and turnover, and has received widespread

attention both domestically and internationally (Kuzyakov et al. 2000; Hamer and Marschner 2005). Exogenous substrates involved in PE usually exist in surface soil as tender branch litter, senescent plant tissues or root exudates (Hicks et al. 2018; Tian et al. 2019). The addition of these exogenous substrates influences soil microbial metabolism and community structure through direct effects such as changes in microbial metabolism and growth after exogenous substrate addition; or indirect effects such as changes in SOM decomposition and utilization of exogenous substrates due to variations in atmospheric CO_2 concentration or temperature affecting soil microorganisms. Under the background of continuous rise in global atmospheric CO_2 concentration which brings more carbon input into the soil as well as more frequent and active microbial activities; many studies suggest that elevated CO_2 will result in an increase in newly stabilized plant-derived carbon which will stimulate microorganisms to decompose native stable SOM in the soil (Sayer et al. 2011). This is also the reason why atmospheric CO_2 concentration rises but soil carbon storage does not increase significantly (Langley et al. 2009). Despite the extensive research and development of carbon stabilization technologies for soil PE, a common challenge for all existing technologies is to achieve synergistic stabilization of both organic and inorganic carbon in stimulated soils. Thus, novel approaches and strategies are urgently required to realize organic-inorganic carbon stabilization in PE.

Basalt is a mineral that can weather rapidly in natural environments and is abundant. Beerling et al. (2020) using a chemical weathering model to estimate the global net carbon sequestration of basalt powder applied to farmland soils in major countries (including the United States, India, China, Brazil and European countries). The results showed that this scheme can remove 500 million to 2 billion tons of atmospheric CO_2 per year globally, which is comparable to the carbon sequestration potential of biochar (500 million to 2 billion tons per year), bioenergy carbon capture and storage (500 million to 5 billion tons per year), afforestation (500 million to 3.6 billion tons per year) and other measures. When basalt is added to soil, it undergoes a chemical reaction with carbonic acid ($CO_2 + H_2O$) in the soil, producing bicarbonate ions (HCO_3^-) that dissolve both atmospheric and soil CO_2 in water as inorganic carbon. This dissolved carbon is then transported to the ocean via surface runoff for long-term storage. The formation and turnover of soil inorganic carbon (SIC) traps atmospheric CO_2 and CO_2 emitted from soil organic carbon (SOC) decomposition as carbonate minerals underground, thus reducing the release to the atmosphere and lowering the atmospheric CO_2 concentration (Hartmann et al. 2009). This alleviates the pressure on the atmosphere to accommodate more CO_2 (Gaillardet and Galy 2008; Zhang et al. 2020). The use of basalt in agriculture has strong economic advantages (Augusto et al. 2021), as it can enhance soil fertility, release nutrients, improve soil pH value, and provide minerals essential for crop growth and soil health (Lewis et al. 2021).

Theoretically, in the primed environment where CO_2 concentration increases due to SOM mineralization by microorganisms after adding exogenous substrates, the increase of CO_2 partial pressure can promote the balance reaction of basalt weathering ($CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4$) to move to the right, thus stabilizeing inorganic carbon in PE. Meanwhile, During the weathering of basalt, its cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) are rapidly lost and Si^{4+}, Al^{3+} and Fe^{3+} are accumulated in weathering mineral assemblages,

forming clay minerals such as kaolinite and montmorillonite (Caner et al. 2014). Montmorillonite and kaolinite clay minerals produced by basalt weathering can stabilize exogenous input carbon and original SOC with strengths (binding energy) or modes (adsorption or encapsulation) (Newcomb et al. 2017), agglomerate with exogenous organic matter decomposition products to form agglomerates that physically isolate SOM from soil microorganisms and enzymes (Six et al. 2002). These processes make it possible for basalt weathering to stabilize organic-inorganic carbon in PE. We hypothesized that (i) basalt would increase SIC in the PE; (iii) basalt and its weathering products would decrease glucose mineralization and PE intensity; (iii) basalt and its weathering products will increase the net soil net carbon balance in the PE. To test aboved hypotheses, we used ^{13}C-glucose as a low molecular mass organic substrate model to simulate mineralised apoplast or root secretion, conducting a 28-day of incubation experiment to explore the effects of basalt and its weathering products on soil net carbon balance of the PE.

Materials And Methods

Soil sampling and material characterization

Soil samples used in this study were collected Yongkang City, Zhejiang Province, China (28° 57' N, 119° 58' E). The soil has been planted with peach (*Prunus persica* (L.) Batsch) for more than 20 years. According to the World Reference Base (WBR), this soil is classified as a Luvisol. The average annual precipitation and temperature in the area were 1534.6 mm and 19.4℃ respectively. A composite soil sample derived from 5 subsamples were taken from each plot (0 to 20 cm depth). The residual plant material, visible fauna and stones were removed, then the soils were air-dried and sieved through a 2 mm for incubation experiments. Table 1 shows the properties of the soil. To study the effects of different minerals on soil carbon cycle and its associated microorganisms, three different mineral materials, namely basalt, montmorillonite, and kaolinite, were used in the experiment. The natural minerals were all ground to a particle size of 0.15 mm and placed in a fume hood for 15 days to simulate natural weathering.

We utilize Fourier Transform Infrared Spectroscopy (FTIR), X-Ray Diffraction (XRD), and X-ray Photoelectron Spectroscopy (XPS) techniques for the characterization of both basalt and its weathering products. FTIR results indicate that the mineral materials used in the study are consistent with basalt, montmorillonite, and kaolinite, respectively (SI Fig. S1, SI Fig. S4, SI Fig. S7). After conducting XPS analysis, it was found that basalt mainly consists of magnesium silicate, aluminum silicate, calcium silicate, and silicon dioxide. On the other hand, montmorillonite is primarily composed of silicon dioxide, aluminum silicate, magnesium silicate, and calcium silicate. Lastly, kaolinite is mostly made up of aluminum silicate, aluminum potassium silicate, and silicon dioxide (SI Fig. S2, SI Fig. S5, SI Fig. S8). The XPS data provides information on the relative quantities of different elements in basalt and its byproducts (SI Fig. S3, SI Fig. S6, SI Fig. S9). Supplementary material for more details.

Experimental design

The experiment included five treatments, each with 12 replicates, namely nonamended soil (S), soil amended with ^{13}C-glucose (SG), soil with 5% basalt and ^{13}C-glucose (SBG), soil with 5% montmorillonite

and ^{13}C-glucose (SMG), and soil with 5% kaolinite and ^{13}C-glucose (SKG). For the S and SG treatments, 100 g of air-dried soil was weighed, and for the SBG, SMG, and SKG treatments, 100 g of air-dried soil and 5 g of minerals were weighed and mixed thoroughly. All treatments were adjusted to 60% of the water-holding capacity using deionized water. The soils were then pre-incubated in glass jars at 25℃ in the dark for 15 days to activate the dormant microorganisms. After the pre-incubation, except for the S treatment, each treatment was added with a 5 atom% ^{13}C-labeled glucose solution (99 atom% ^{13}C-labeled glucose mixed with unlabeled glucose at a ratio of 1:19). The prepared glucose solution was carefully added dropwise onto the soil using a pipette gun, with the concentration and volume of glucose solution (5.6 ml) calculated to adjust the soil moisture content from 60–70% of the water-holding capacity and to provide an addition of 154.5 μg glucose-C g^{-1} soil, which is equivalent to 50% of microbial biomass C. The S treatment soils received the same volume of water. The jars were then capped with a sealing stopper and incubated for 28 days at 25℃.

The gas was sampled at 1, 3, 5, 7, 14, and 28 days after the start of incubation, and two CO_2 samples were collected at each sampling point, one for total CO_2 concentration measurement by gas chromatography (GC 2010, Shimadzu, Japan) and the other to measure gaseous $\delta^{13}C$ abundance by isotope ratio mass spectrometry (Isoprime 100, Elementar, Germany). The baseline concentration of CO_2 in the air of the jar was 418.6 ppm. Destructive sampling of soil samples was conducted on days 3, 7, 14 and 28, with part of them air-dried naturally for physicochemical properties analysis and the other part frozen at -80℃ for microbial biomass carbon and enzyme activity measurement.

Soil properties analysis

Soil pH was determined using a glass electrode with a 1:2.5 soil-to-water ratio. Soil organic carbon were measured by a Vario MACRO cube elemental analyzer (Elemen-tar INC, Germany).

The CO_2 content is measured by gas chromatography (Shimazu GC2010) FID and the abundance of ^{13}C-CO_2 is determined by an isotope mass spectrometer (Isoprime-100, trace Gas-IRMS).

Microbial Biomass C was measured by the fumigation extraction method (Vance et al. 1987). Briefly, three replicates of each treatment were taken, each consisting of two fresh soil samples (10 g oven-dry basis). One sample was placed in a vacuum drying desiccator and the other was sealed with a sealing film as the non-fumigated sample. The vacuum drying desiccator was filled with 20 ml of ethanol-free chloroform and evacuated to boil the chloroform for 2 min, then incubated with the non-fumigated sample in a light-proof environment at 25℃ for 24 h. The desiccator was then evacuated 5 times to completely remove the chloroform. Afterwards, 40 ml of 0.5 mol L^{-1} K_2SO_4 was added to the fumigated and non-fumigated soil samples and shaken at 220 rpm min^{-1} for 30 min, followed by filtration through filter paper. Analysis was performed with a Total Organic Carbon Analyzer (Multi N/C 3000, Analytic Jena, Germany).

The determination of SIC uses a Total Organic Carbon Analyzer (Multi N/C 3000, Analytic Jena, Germany) with an external inorganic carbon measurement module: a certain amount of soil sample is weighed into a reaction flask and a certain amount of phosphoric acid solution is added to the sealed reaction flask. At the

same time, the heater and magnetic stirrer are turned on. At this time, the inorganic carbon in the soil reacts with phosphoric acid to produce CO_2, which is carried by the carrier gas into the NDIR detector for detection. Before measuring the sample, a working curve was prepared using calcium carbonate as an inorganic carbon standard substance to establish a functional relationship between inorganic carbon content and CO_2 integration and quantitatively calculate the inorganic carbon content in the sample.

The activity of S-β-GC (EC 3.2.1.21) were determined on the basis of the concentration of p-nitrophenol (pNP) released when soils were incubated with pNP-linked substrates in a buffer of optimum pH according to the method described in Eivazi and Tabatabai (1988).The activities of S-LAP (EC 3.4.11.1) was determined on the basis of the concentration of p-nitroaniline (pNA) according to the method described in Sinsabaugh et al. (1999). The activity of S-CAT (EC 1.11.1.6) was measured by back-titrating residual H_2O_2 with $KMnO_4$ according to the method described in Johnson and Temple (1964).

Calculations and statistics analysis

The amount of glucose mineralization is calculated as follows:

$$\mathrm{CGPr} = (\delta 13\mathrm{CPr} - \delta 13\mathrm{CCK}) \,/\, (\delta 13\mathrm{CG} - \delta 13\mathrm{CCK}) \times \mathrm{CO2\text{-}CG}$$

1

Where $\delta^{13}C_{Pr}$, $\delta^{13}C_{CK}$, and $\delta^{13}C_G$ are the ^{13}C abundances of primed CO_2-C from glucose amended soils, CO_2-C from control soils and added glucose ($\delta^{13}C$ value of 4451‰), respectively. And CO_2-C_G is the CO_2-C evolved from glucose amended soil.

The PE induced by glucose addition was calculated as follows:

$$\mathrm{Primed\ C} = \mathrm{CO2\text{-}CG} - \mathrm{CGPr} - \mathrm{CO2\text{-}\ CCK}$$

2

Where CO_2-C_{CK} is the CO_2-C evolved from control soil.

The net soil C balance at the end of incubation was calculated as follows:

$$\mathrm{Net\ soil\ C\ balance} = \mathrm{glucose\text{-}derived\ SOC} - \mathrm{Primed\ C}$$

3

Where the glucose-derived SOC is the retention amount of glucose.

All data were analyzed using Origin 9.0 and SPSS 20.0 software. One way ANOVA was used to analyze the treatment effects. Differences with values of $P < 0.05$ were considered statistically significant. All analytical data are the mean of triplicate determinations.

Results

Soil physical and chemical properties

The scanning electron microscope (SEM) is a type of microscope that can capture images of an object's surface. It has the benefit of producing images with a stereoscopic effect and a high depth of focus. Under the SG treatment, the soil particle surface appears relatively smooth without any complex structures, whereas soil particles subjected to SBG (Fig. 1b), SMG (Fig. 1c), and SKG (Fig. 1d) treatments have a layered, overlapping structure on their surfaces, resulting in a greater specific surface area and pore structure. Consequently, these treated soil particles exhibit carbon sequestration potential for basalt and its weathering products (Saidy et al. 2012).

Changes in soil pH were found to be dependent on the application of different minerals and did not exhibit correlation with incubation times. The results showed that the application of various minerals could enhance soil pH levels and maintain stability over a 28-day incubation period (Fig. 2a). The increase of soil pH experienced under the basalt treatment (SBG) was more significant ($P < 0.001$) than that observed in the case of montmorillonite and kaolinite. Basalt amendment (SBG) triggered a substantial increase in soil pH at each sampling time point, reaching around 7.1, and was considerably higher than all other treatments throughout the 28-day incubation period. Soil pH was also elevated under montmorillonite (SMG treatment), with pH rising by 17% to 6.22 as compared to the S treatment. The pH remained approximately 5.5 under SKG treatment, maintaining a status similar to that of the S treatment during incubation and, as a result, exerting less helpful effects in improving soil acidity.

At the end of the incubation period, the concentrations of cation exchange capacity (CEC) under SBG and SMG treatments were also found to be significantly ($P < 0.05$) higher than the other three treatments, corresponding to 1.47 and 2 times the control, respectively (8.87 and 12.11 $cmol^{+}\ kg^{-1}$) (Fig. 2b).

Soil carbon pool turnover

The addition of basalt had a significant impact on the soil dissolved organic carbon (DOC) at the end of the incubation period. Compared to the SG treatment, the DOC content increased significantly ($P < 0.001$) from 13.41 to 31.03 μg g^{-1} soil. This increase was 1.77 and 2.38 times higher than that in the SMG and SKG treatments, respectively, as shown in Fig. 3a.

On day 28, the SIC content in the SBG treatment increased significantly ($P < 0.001$) to 14.4 μg C g^{-1} soil, which was 168.6% and 154.5% higher than that of the S and SG treatments, respectively (Fig. 3b). The SOC content of the S treatment remained mostly stable throughout the incubation period (Fig. 4). On the other hand, in the SG treatment, which involved adding glucose, there was an initial increase in SOC followed by a decrease. The highest content was observed on the 7th day at 8.6 g kg^{-1}. This increase can be attributed to the activation of dormant microorganisms by the added external carbon (glucose). This acceleration of mineralization resulted in the storage of carbon inside microbial cells. However, as the incubation time progressed, microbial respiration continued to increase, while the external carbon input did not. This led to a decline in intracellular carbon. During the 28-day incubation period, the SOC showed a slow upward trend in the SBG, SMG, and SKG treatments. On the 28th day, the SOC content in the SKG treatment was the highest,

reaching 8.4 g kg^{-1}. However, the difference between the other treatments and the SG treatment was relatively small. Moreover, as the SOC of the basalt and its derivatives increased gradually, it is necessary to calculate the soil net carbon balance in the soil to assess the carbon-stabilizing ability of basalt and its derivatives in short-term PE, given the limitations of short-term PE experiments.

Turnover of exogenous substrate carbon

During the incubation process, the addition of various mineral amendments had a significant impact on CO_2 emissions, as demonstrated by Fig. 5a and Fig. 5d. Specifically, the inclusion of glucose resulted in a notably higher release of CO_2 compared to the S treatment. The treatments involving SG, SBG, and SMG showcased a positive PE, while the SKG treatment exhibited a negative PE (Fig. 5c and Fig. 5f). The elevated CO_2 emissions resulting from glucose mineralization and the PE were primarily observed during the first 14 days of incubation, following which the release appeared to stabilize (Fig. 5a). The soil amended with basalt exhibited the highest cumulative PE, which was approximately 73.5% significantly ($P < 0.05$) higher than that of the SG treatment (Fig. 5f). In addition, the SBG treatment emitted more CO_2 than the SG treatment on days 3, 5, 7, and 14 (Fig. 5c). However, the cumulative CO_2 emission in the SBG treatment was 2.8% lower than that of the SG treatment. The SKG treatment consistently resulted in a negative PE, with significantly significantly ($P < 0.05$) lower cumulative PE and cumulative CO_2 emission (Fig. 5d, Fig. 5f). Similarly, the SMG treatment demonstrated a comparable PE to the SG treatment, but with lower CO_2 emissions. Despite the intensive mineralization of glucose upon addition, distinct mineralizations were observed to be influenced by the presence of minerals. The addition of minerals resulted in lower cumulative glucose mineralization as compared to the SG treatment, with reductions ranging from 31–51% (Fig. 5e).

Changes in soil MBC and extracellular enzyme activity

The inclusion of glucose and minerals significantly affected both the microbiological and chemical properties of the soil (Fig. 6). The microbial biomass carbon (MBC) exhibited a sharp increase, followed by a decrease (Fig. 6a). By day 28, the microorganisms had almost fully utilized the added glucose, and the SBG, SMG, and SKG treatments showed a decrease in MBC compared to the S treatment, with reductions of 14.7%, 22.2%, and 12.3%, respectively. By the end of the incubation period, the SBG treatment had the highest activities of both the C-acquiring enzyme (S-β-GC) (Fig. 6b) and the N-acquiring enzyme (S-LAP) (Fig. 6c), with quantities of 8.69 and 6.67 μmol d^{-1} g^{-1} soil, respectively. Additionally, the SBG and SMG treatments significantly enhanced S-CAT activity (Fig. 6d).

Soil net carbon balance

At the conclusion of the incubation period, we determined the impact of mineral amendments on the net soil C balance by subtracting the CO_2-C loss resulting from PE from the amount of glucose remaining in the soil (Fig. 7a). In comparison to the SG treatment, the inclusion of basalt, montmorillonite, and kaolinite resulted in respective increases of 34.7%, 47.1%, and 61.1% in glucose retention, with the SKG treatment

exhibiting the highest retention at 117.5 μg C g^{-1} soil. The net soil C balance varied depending on the mineral species used, with the SMG and SKG treatments retaining more glucose with less CO_2-C loss, leading to significantly ($P < 0.05$) higher increases in soil net C balance of 91.8 and 146.4 μg C g^{-1} soil, respectively. These results support our hypothesis that basalt and its weathering products (montmorillonite and kaolinite) can improve soil net carbon balance, and play a vital role in carbon sequestration through the PE. Compared to montmorillonite and kaolinite, basalt-amended soil exhibited much lower net carbon sequestration, primarily due to its strong PE. It is hypothesized that the CO_2 released from the soil is converted into HCO_3^- through the weathering of basalt, which facilitates the formation of $CaCO_3$, thereby increasing inorganic carbon in the soil and improving the overall C balance (Fig. 7b). Analysis of the data showed a significant improvement about 27.1% ($P < 0.05$) in the net C balance of the SBG treatment compared to the SG treatment when SIC was taken into account.

Discussion

Turnover of exogenous substrate carbon

Adding minerals to the soil can enhance its environment, and the CEC is a vital soil characteristic that controls significant soil functions such as the regulation of pH, the availability of nutrients, and the retention of water (Favre et al. 2006). Modifying the soil with basalt and montmorillonite significantly increased the CEC and caused a shift in soil pH from acidic to neutral. This observation aligns with previous studies (Gillman et al. 2001; Anda et al. 2015). Variations in pH can affect the PE, with stronger PE emerging under neutral soil conditions (Blagodatskaya and Kuzyakov 2008). Total CO_2 emissions comprise exogenous glucose mineralization and SOC mineralization, and the impact of minerals on overall emissions varies depending on the minerals that triggered substrate mineralization and the PE of substrate-induced SOC (Sheng and Zhu 2018). Despite our hypothesis, SBG demonstrated the most powerful PE and emitted the greatest amount of CO_2. This observation could, however, be attributed to the improved conditions for soil microbial survival subsequent to the basalt amendment. Despite the fact that cumulative CO_2 emissions were higher, basalt did restrict microbial decomposition of exogenous glucose. When basalt weathers, it releases alkaline cations that cause alkalinity, converting CO_2 in the glass jars into dissolved inorganic carbon (mainly HCO_3^-) stored in soil water. The CO_2 in the jars was continuously consumed through its interactions with the CO_2 present in the jars, resulting in the production of dissolved inorganic carbon. This may raise the CO_2 demand stemming from the PE (Renforth and Henderson 2017; Beerling et al. 2020). As we conducted a short-term experiment on the PE, it was observed that the stabilization of SOC by basalt and its weathering products was restricted due to incubation time and did not exhibit significant changes. However, the trend was generally upward and previous studies have suggested that montmorillonite and kaolinite can impede or retard the mineralization of SOC through physical, chemical, and biological protective mechanisms (Baldock and Skjemstad 2000).

In our study, the cumulative PE, CO_2 emissions, and glucose mineralization were lower in both the SMG and SKG treatments as compared to the glucose addition only treatment (SG), thus supporting our hypothesis.

The impact of basalt and its weathering products on soil microorganisms

Microorganisms play a crucial role in the mineralization of SOC, facilitating the PE as an inherent mechanism (Mondini et al. 2006; Qiu et al. 2020). It is well-known that exogenous organic substrates have the potential to alter the composition of soil microbial communities (Sheng and Zhu 2018). The MBC results indicate that there was a noticeable increase followed by a decrease, which was caused by the addition of glucose. This activated the microorganisms and provided a significant amount of exogenous substrates for them to utilize. However, the activation process ceased as the microorganisms detected a lack of continuous substrate input, causing their energy reserves and minerals to be depleted. As a result, their activity was hindered by the preservation of SOC, leading to a reduction in MBC (Mason-Jones and Kuzyakov 2017). The results revealed that minerals reduced the soil MBC and inhibited the microbial mineralization of SOC compared to the S and SG treatments at the end of the incubation. This was possibly due to the negative charge possessed by minerals, which can bind enzyme proteins through cation exchange and adsorption induced by van der Waals forces, cut ammonia bonds, etc (Dumat et al. 2000). The activity of N-degrading enzymes (S-LAP) in the SBG was relatively higher, indicating that soil microorganisms in the SBG treatment were limited by N in the later stage of growth. They produced more N-degrading enzymes to acquire N from the SOM, thereby corroborating the ‘N mining’ theory (Chen et al. 2021). It has been reported that S-β-GC activity increases with soil pH. This is a key enzyme for SOC degradation and nutrient conversion, which characterizes the soil carbon cycle (Wade et al. 2021) which reveals the enhancement in SBG. S-CAT is a crucial enzyme involved in biological respiration and various metabolic processes. Additionally, it contributes to the secretion of plant roots and soil animals and plays a role in the decomposition of residues. Its critical function in the soil is to eliminate hydrogen peroxide, which can be harmful to living organisms (Bandick and Dick 1999). In this study, the use of basalt resulted in an increase in S-CAT. This improvement ultimately contributed to the mitigation of the toxic effects of hydrogen peroxide and overall improvement of soil health. Additionally, the presence of high enzyme activity indicates that basalt enhanced the soil environment and promoted microbial growth. These microorganisms co-metabolized SOC, meeting their nutrient needs, and led to greater PE. This, in turn, translated to similar CO_2 emissions when compared to the SG treatment (Fontaine et al. 2003).

The net soil C balance

When assessing the effect of labile C addition on the net soil C balance, it is important to consider the retention of exogenous glucose-C in the soil, as it serves as a significant complement to the SOC cycle (Zhu et al. 2022). The addition of minerals has a profound impact on the soil net carbon balance of soil. Our hypothesis was confirmed by the observation that the addition of exogenous glucose in soils supplemented with basalt, montmorillonite, and kaolinite led to an increase in net soil carbon, primarily due to the protective effect of minerals on the substrate, inhibiting soil microorganisms' utilization of glucose, reducing CO_2 emissions and improving glucose-C retention. Basalt induced a greater PE on SOC due to the higher microbial and extracellular enzymatic activity, resulting in a lower increase in net soil carbon compared to weathering products. This phenomenon can be attributed to two aspects: 1) after the addition

of basalt, the rise in pH activated more microorganisms, which mineralized SOC to meet their nutritional needs; 2) basalt weathering facilitated the conversion of primed CO_2 to inorganic carbon, causing more CO_2 emissions, a stronger PE, and less carbon retention. SIC is a crucial component of the soil carbon pool, and its enhancement will certainly benefit the stabilization of the soil carbon sink. However, few studies have explored the interaction between SIC content and the carbon cycle in relation to the PE (Dang et al. 2022; Torn et al. 1997). Having considered the fact that basalt has the ability to capture primed CO_2 and stabilize it in the soil solution as inorganic carbon during the process of weathering, we included the content of SIC in the calculation of net C balance. The results showed that the SIC level in the basalt treatment increased steadily, with a significantly higher value on the 28th day compared to the other treatments. Moreover, after accounting for the inorganic carbon content, the net C balance showed an upward trend and was significantly higher than that of the glucose amendment treatment. Our findings suggest that basalt weathering could enhance the stabilization of organic-inorganic 'double carbon' in the soil and mitigate the effects of soil priming.

Conclusions

In this study, we utilized ^{13}C-labeled glucose as a tracer to investigate the impact of basalt and its weathering products, including montmorillonite and kaolinite, on the PE. We evaluated the effects on glucose mineralization, soil organic-inorganic carbon sequestration, and net C balance. Basalt had a significant effect on soil pH, promoting microbial activity and the production of extracellular enzymes. This led to a noteworthy increase in DOC and SIC content. Although our hypothesis posited that basalt would be more effective in reducing CO_2 emissions, the results indicated that there was no significant difference between the SBG and SG treatments. This may be attributed to the increased soil pH, which prompted soil microorganisms to mineralize more SOC to meet their energy demands. Additionally, the weathering of basalt increased the need for primed CO_2 for inorganic carbon formation, resulting in a stronger PE and more CO_2 emissions. However, the PE and CO_2 emissions of the weathering products of basalt, such as montmorillonite and kaolinite, were much lower. The effects of different mineral treatments on the soil net C balance were calculated based on the equation. Basalt and its weathering products showed an increase in soil net C balance, indicating better carbon sequestration. The addition of basalt significantly increased all three enzyme activities, suggesting that basalt could improve soil environment and promote the production of extracellular enzymes. The increase in S-LAP indicated the 'N mining' effect due to microbial energy deficiency. Besides, the increase in S-β-GC and S-CAT showed the improved ability of basalt to enhance soil environment and soil C cycle. However, the effect of basalt on the soil net carbon balance was not as good as expected. This is because our incubation experiment was conducted for only 28 days, while basalt weathering is a prolonged process, resulting in the accumulation of inorganic carbon and the formation of weathering products. Based on the experimental data, the full extent of the carbon sequestration effect of basalt remains ambiguous. Nevertheless, we anticipate that basalt boasts significant potential in terms of carbon sequestration and emission reduction, and this assertion warrants further confirmation through long-term trials. Given the long-lasting effect of basalt and its weathering products application on the soil net carbon balance in agro-ecological management systems, future studies

should prioritize assessing the long-term impact on the sequestration of organic and inorganic carbon in soil.

Abbreviations

PE: priming effect; DOC: dissolved organic carbon; SIC: soil inorganic carbon; S-β-GC: soil β-glucosidase; S-LAP: soil leucine amino peptidase; S-CAT: soil catalase

Declarations

Acknowledgments

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Author Contribution Statement

Junyan Xu: Investigation, Writing-original draft preparation. Qinglin Fu: Methodology, Funding acquisition, Investigation. Junli Liu: Investigation, Writing-Reviewing and Editing. Ming Zhang and Bin Guo: Supervision. Hua Li: Writing-Reviewing and Editing. Gaoyang Qiu: Conceptualization, Methodology, Funding acquisition, Writing-Reviewing and Editing, Supervision.

Competing Interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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Tables

Table.1 Soil Basic Properties

Soil type	Soil Classification	Location	pH	N	P	K	MBC	TC	TN	$\delta^{13}C$
				mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	μg g^{-1}	g kg^{-1}		‰
Farmland soil	Luvisol	28°57' N, 119° 58' E	5.52	60.2	11.2	75.4	309	8.24	0.82	-22.41

N: available nitrogen; P: available phosphorous; K: available potassium; MBC: microbial biomass carbon; TC: total carbon; TN: total nitrogen; $\delta^{13}C$: soil $\delta^{13}C$ abundance. Results are mean ± standard deviation of 3 plots.

Figures

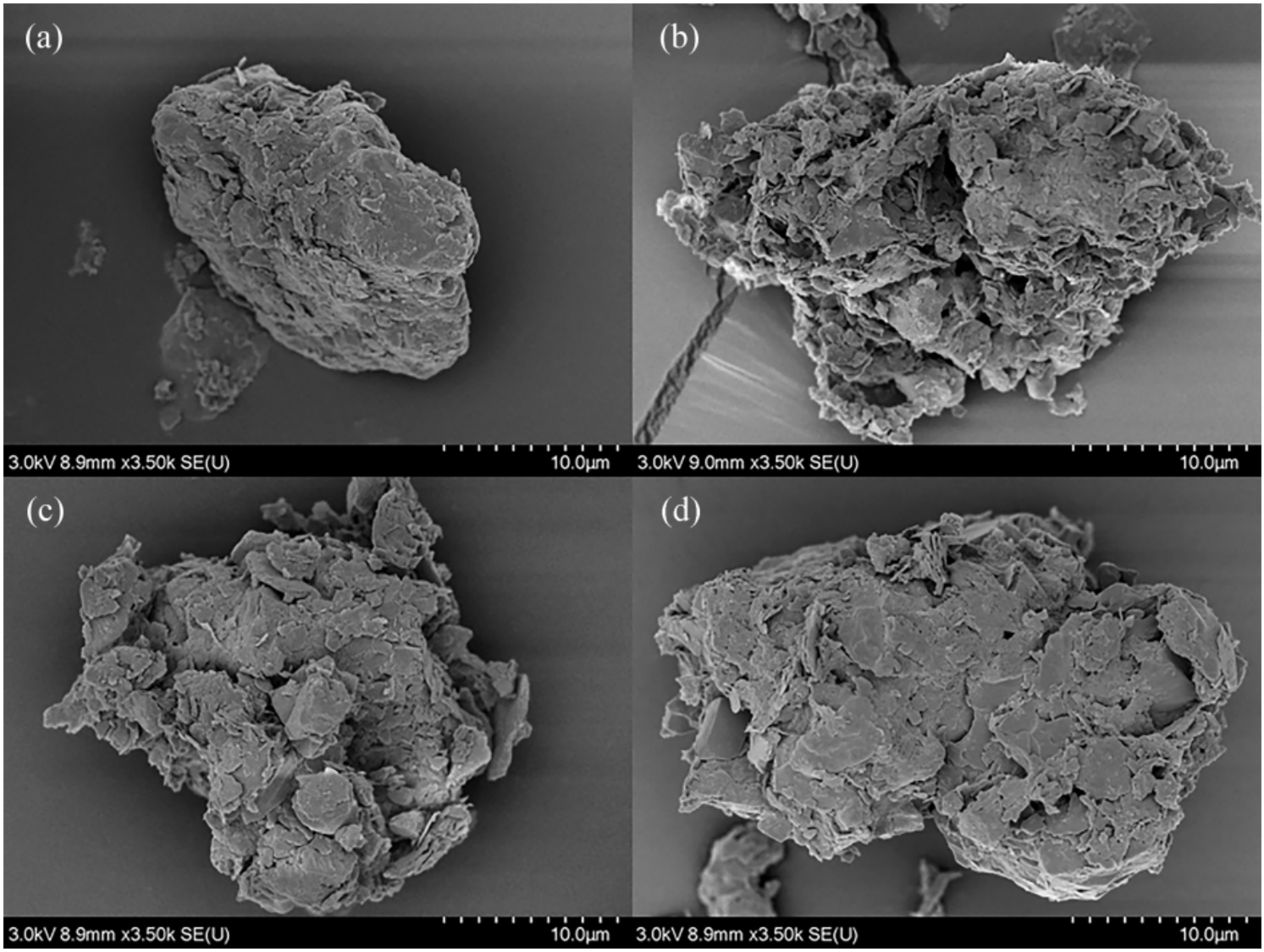


Figure 1

Scanning electron microscope image of soil particles combined with basalt and its weathering products, including treatments of SG (a), SBG (b), SMG (c), and SKG (d).

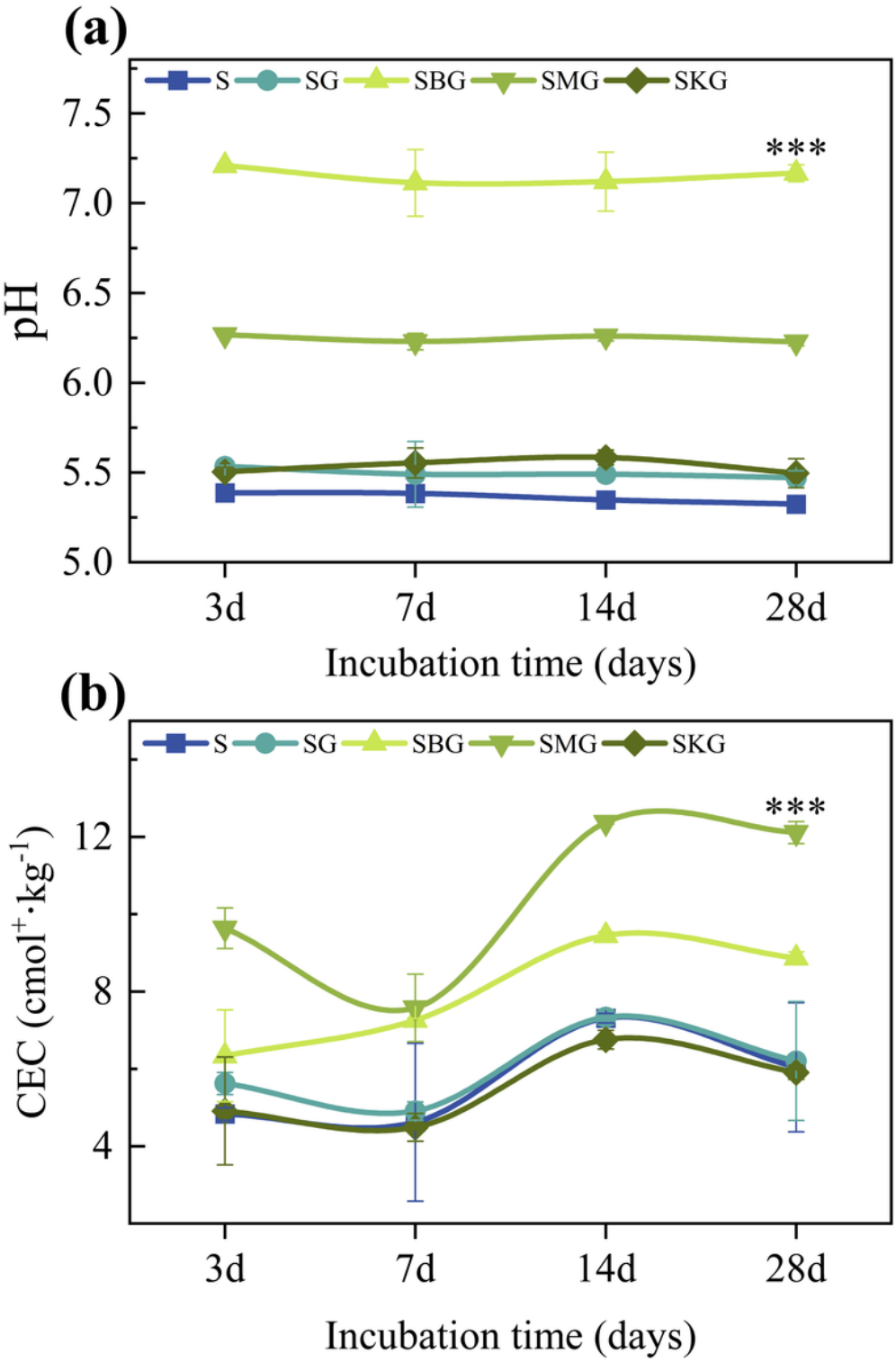


Figure 2

The influence of basalt and its weathering products (montmorillonite and kaolinite) on soil pH (a) and cation exchange capacity (b) during the 28-day incubation period. Vertical bars are standard errors of the means (n = 3). Significance level are expressed: ***P< 0.001.

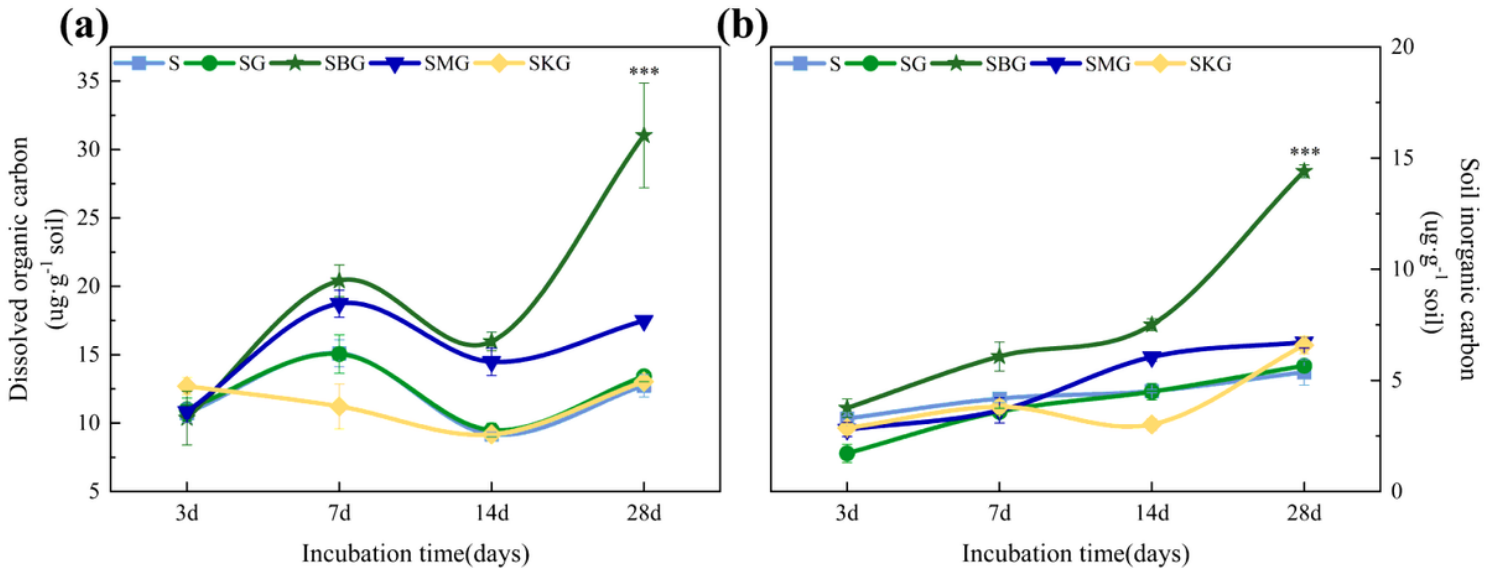


Figure 3

The influence of basalt and its weathering products (montmorillonite and kaolinite) on soil dissolved organic carbon (a) and soil inorganic carbon (b) during the 28-day incubation period. Vertical bars are standard errors of the means (n = 3). Significance level are expressed: ***$P < 0.001$.

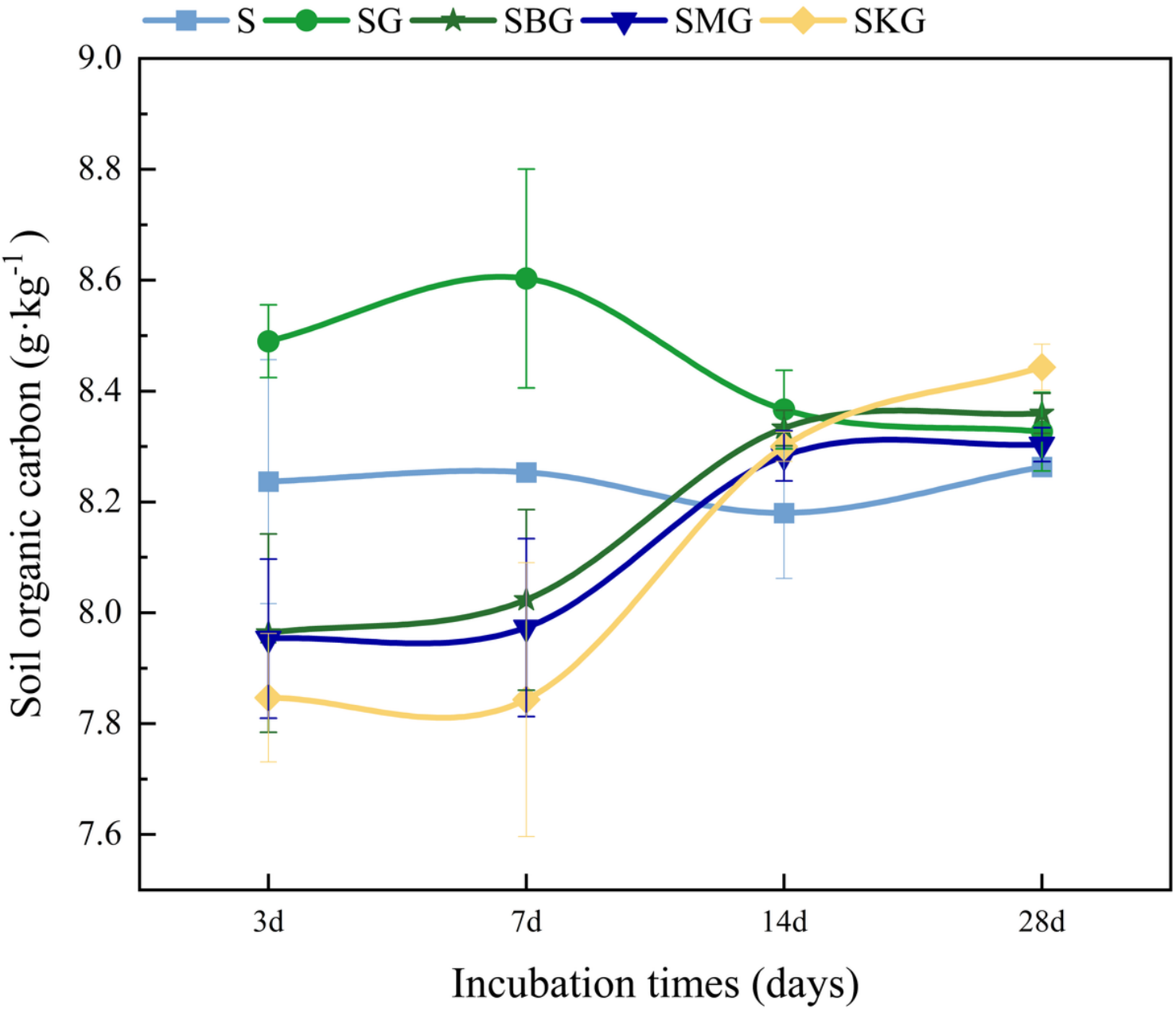


Figure 4

The influence of basalt and its weathering products (montmorillonite and kaolinite) on soil organic carbon over different incubation period. Vertical bars are standard errors of the means (n = 3)

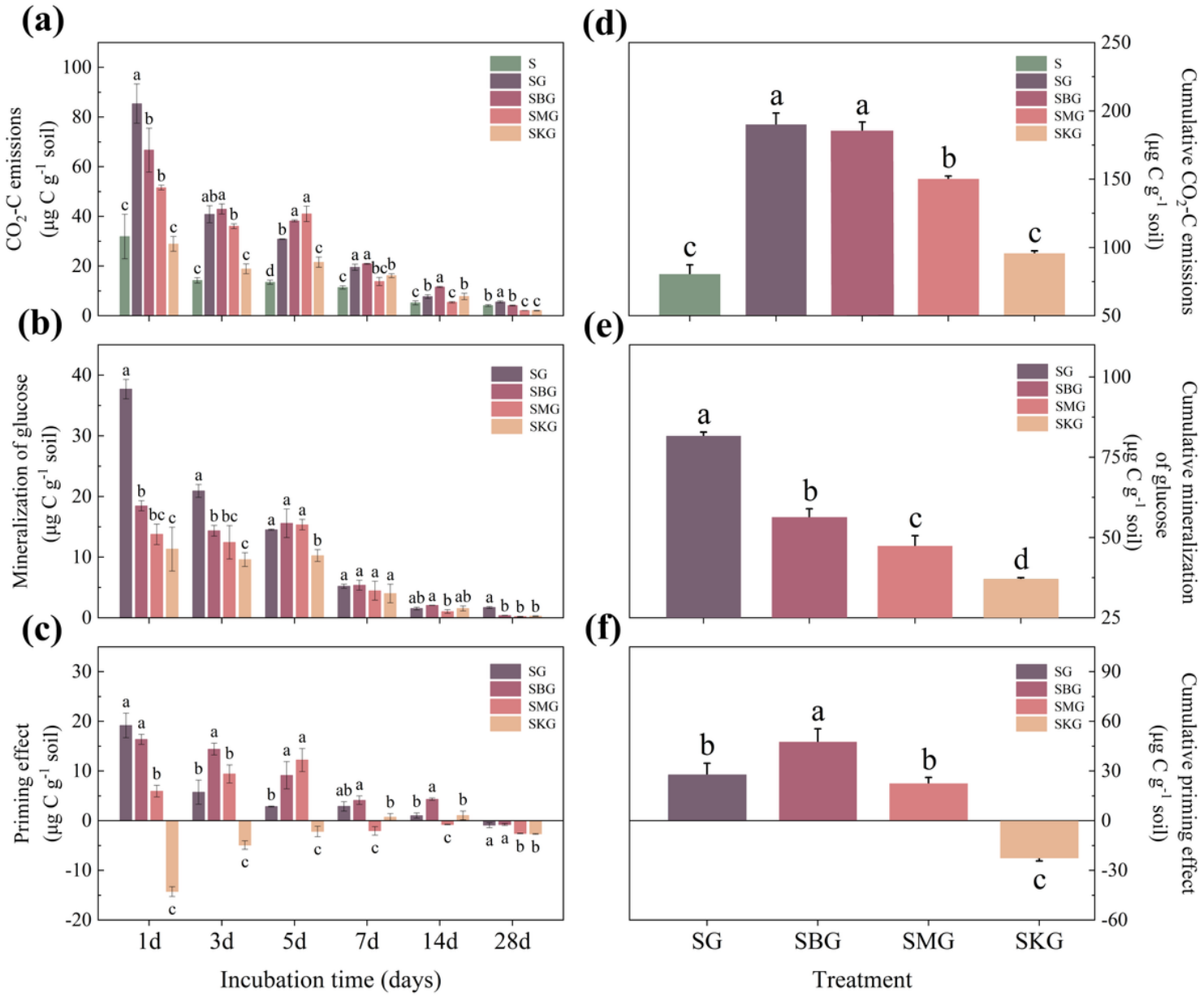


Figure 5

During the 28-day incubation period, basalt and its weathering products (montmorillonite and kaolinite) had an influence on: (a) CO_2-C emissions; (b) mineralization of glucose; and (c) priming effect at different incubation times. (d) Cumulative CO_2-C emissions; (e) cumulative mineralization of glucose; and (f) cumulative priming effect. Vertical bars are standard errors of the means (n = 3). Letters above the boxes indicate significant differences among treatments ($P < 0.05$).

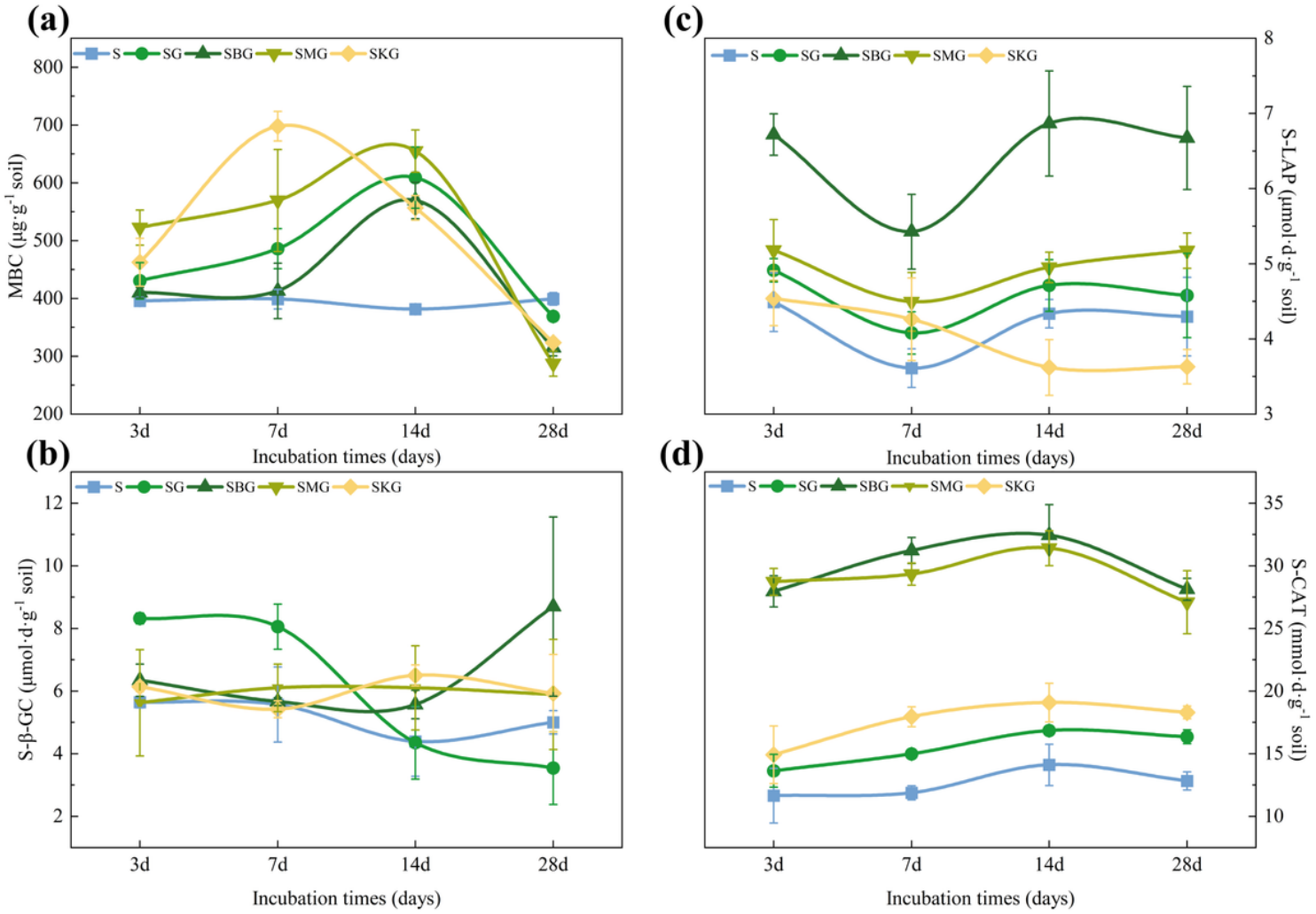


Figure 6

During the 28-day incubation period, basalt and its weathering products (montmorillonite and kaolinite) had an influence on the contents of MBC (a) and the activities of S-β-GC (b), S-LAP (c), and S-CAT (d). Vertical bars are standard errors of the means (n = 3)

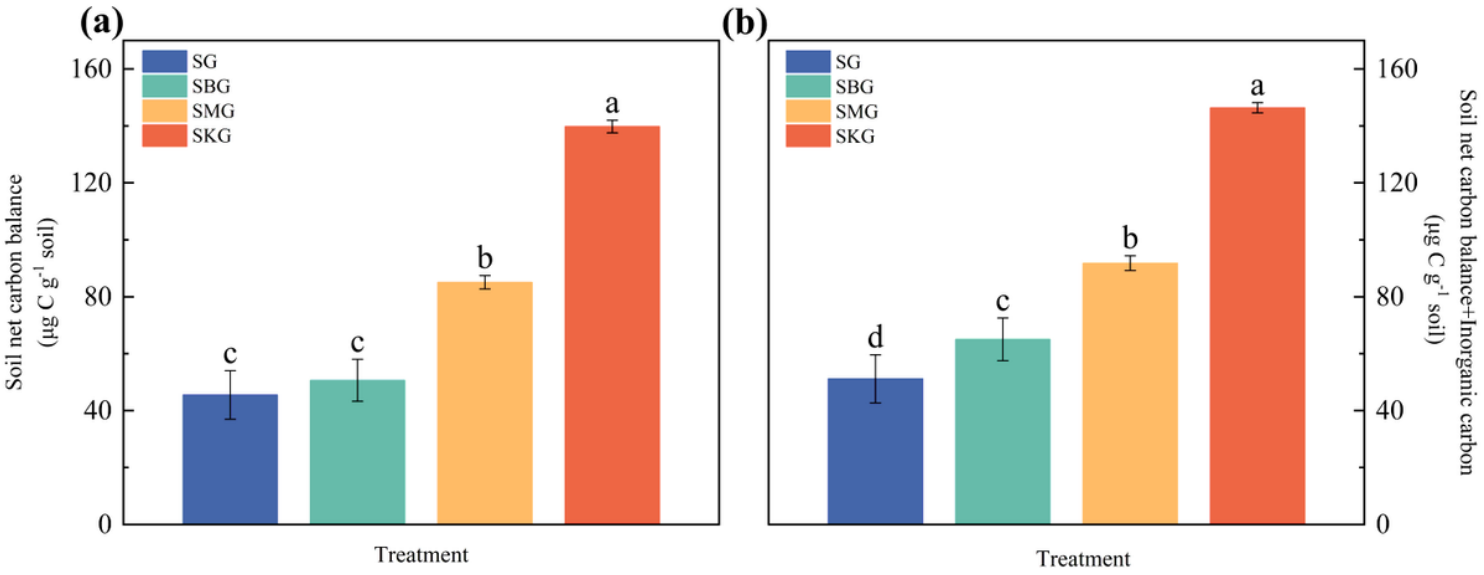


Figure 7

The soil net C balance depends on the different additions (glucose, basalt, montmorillonite and kaolinite) (a), whereas the changes in soil inorganic carbon content impact the soil net C balance (b). Vertical bars are standard errors of the means (n = 3). Letters above the boxes indicate significant differences among different treatments ($P < 0.05$)

Supplementary Files

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