Wollastonite addition stimulates soil organic carbon mineralization: Evidences from 12 land-use types in subtropical China

Article *in* CATENA · May 2023

DOI: 10.1016/j.catena.2023.107031

11 authors, including:

Yongxue Yan
Chinese Academy of Sciences
3 PUBLICATIONS **42** CITATIONS
SEE PROFILE

Xiaohan Dong
Shenyang Institute of Applied Ecology, Chinese Academy of Sciences
2 PUBLICATIONS **30** CITATIONS
SEE PROFILE

Yankuan Zhang
Chinese Academy of Sciences
1 PUBLICATION **30** CITATIONS
SEE PROFILE

Qingpeng Yang
Institute of Applied Ecology, Chinese Academy of Sciences
59 PUBLICATIONS **874** CITATIONS
SEE PROFILE

Wollastonite addition stimulates soil organic carbon mineralization: Evidences from 12 land-use types in subtropical China

Yongxue Yan [a, b, d, 1], Xiaohan Dong [a, b, d, 1], Renshan Li [a, b, c], Yankuan Zhang [a, b, d], Shaokui Yan [a, b], Xin Guan [a, b], Qingpeng Yang [a], Longchi Chen [a, b], Yunting Fang [a], Weidong Zhang [a, b, *], Silong Wang [a, b, *]

[a] CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China

[b] Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences, Huitong, China

[c] Life Science Department, Luoyang Normal University, Luoyang 471934, China

[d] University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence author

[1] Equal contributions to this work.

E-mail address: wdzhang@iae.ac.cn

Chinese Academy of Sciences (CAS) Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Shenyang, China, No. 72, Wenhua Road, Shenhe District, Shenyang 110016

Abstract

Enhanced rock weathering through adding silicate rock powder to soil has been increasingly considered as an effective means of removing CO_2 from the atmosphere. However, the potential impact of silicate rock powder addition on the stability of soil organic carbon remains largely unknown, which adds an uncertainty to its effectiveness in mitigating atmospheric CO_2. In this study, the response of soil CO_2 efflux to wollastonite addition was evaluated for 12 land-use types in a subtropical region of China through an incubation experiment. Results showed that wollastonite addition significantly ($P< 0.05$) increased soil CO_2 efflux over the control by an average of 330.97 ± 29.25% during the incubation period. Approximately 90% of the variance in soil CO_2 efflux was explained by soil properties in this study. Increased soil pH, dissolved organic carbon and available silicon induced by wollastonite addition were the main reasons responsible for the increase in soil CO_2 emission. Soils having lower pH values responded to wollastonite addition with a higher increase in CO_2 emissions. Based on numerous land-use types, our study showed that wollastonite application will cause substantial increase in the mineralization of soil organic carbon in acidic soil, which may weaken the effectiveness of enhanced rock weathering strategies as a tool for CO_2 sequestration.

Key words: Soil organic carbon, Soil CO_2 emissions, Soil properties, Enhanced rock weathering, Silicate rock powder

1 Introduction

Climate change is one of the most serious environmental and societal issues currently faced by humanity (IPCC, 2018). The 2015 climate summit in Paris has agreed to take steps towards limiting the global mean annual surface air temperature increase to well below 2 °C above pre-industrial levels, and to pursue efforts towards a target of 1.5 °C (UNFCCC, 2015). Researchers generally believe that reaching this target requires a combination of decreasing CO_2 emission and increasing CO_2 removal from the atmosphere (IPCC, 2018; Strefler et al., 2018; Bellamy et al., 2019). Recently, enhanced rock weathering (ERW) by adding crushed, fast-reacting silicate rocks (e.g., wollastonite, basalt and olivine) to arable or forest soils has been demonstrated to be an effective practice to remove atmospheric CO_2 through immobilizing it to soil inorganic carbon (SIC) pool (Andrews and Taylor; 2019; Beerling et al., 2020; Goll et al., 2021).

Whereas before ERW can be recognized as an effective means of removing atmospheric CO_2, evaluations must be carried out on the potential influence of ERW on soil organic matter (SOC) mineralization, since a small change of which has substantial effect on atmospheric CO_2 concentration (Kirschbaum, 2004; Qiao et al., 2014). ERW likely contributes to SOC accumulation as it may increase the cationic species (e.g., Ca^{2+} ions) and silicates in soil, which can reduce the decomposition of organic matter by facilitating its adsorption to clay or aggregation (Song et al., 2014; Rowley et al., 2018). There are, however, also evidences that soils respond to silicate addition with an increase in CO_2 emission (Groffman et al., 2006; Borges et al., 2019; Taylor et al., 2021). In a potting experiment with leguminous beans (*Phaseolus vulgaris L.*) and nonleguminous corn (*Zea mays L.*), Haque et al. (2019) even found a decrease in SOC concentration following silicate addition. These unexpected results are mostly attributed to the silicate-induced increase in soil pH values, whereby the microbial decomposition raised. Therefore, the direction and magnitude to which SOC mineralization responds to silicate addition depends on the balance among its effects on diverse physicochemical and biological processes in soil. To date, information is still lacking with regard to the relative importance of these processes in determining the effect of ERW on SOC mineralization,

which will limit the use of ERW as a valid practice to mitigate atmospheric CO_2.

The differences in soil traits might also be important factors affecting the response of SOC mineralization to ERW (Hartmann et al., 2014; Bothe, 2015; Vicca et al., 2022). For instance, compared to higher pH soils, the addition of silicate rock powder in lower pH soils has more significant effects on soil chemistry or biology (Ramezanian et al., 2013; Ramezanian et al., 2015), which is considered an important factor affecting SOC mineralization (Stockmann et al., 2013). Moreover, most previous site studies on this topic regarded only a few soil types (Dietzen et al., 2018; Borges et al., 2019; Haque et al., 2020a), which inevitably would increase the uncertainty of the conclusion. Theoretically, this limitation can be in part overcome by meta-analysis study that involves a large number of soil types. While there is not enough data to conduct a meta-analysis on this topic at present, and not all of the properties of soil were provided in the original studies. Therefore, site studies that include various soil types with contrasting traits are highly urgent, since such studies have rarely been performed.

To fill this knowledge gap, we explored the effects of silicate rock (in the form of wollastonite) addition on the mineralization of SOC for 12 different land use types in a subtropical region of China using a laboratory incubation. Meanwhile, the effects of wollastonite addition on soil physicochemical properties mainly including soil pH and nutrients (available silicon, available nitrogen and available phosphorus, etc.), were also evaluated. This study aimed to clarify how SOC mineralization responds to wollastonite addition and the underlying mechanisms. We hypothesized that wollastonite addition will slow SOC mineralization, considering that the input of cationic species and silicates mediated by wollastonite may improve the SOC stability (Song et al., 2014; Rowley et al., 2018). Furthermore, we hypothesized that the wollastonite effect on soil organic carbon mineralization would depend on the soil properties change caused by wollastonite.

2 Materials and methods

2.1 Location

This study was conducted in the Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences (26°50′ N, 109°36′ E). This region, which belongs to sub-tropical monsoon humid climate, has a mean annual temperature of 16.5 ℃, and a mean annual precipitation of approximately 1,200 mm. The soil developed from shale is classified as Plinthudults according to the U.S. Soil Taxonomy system (Wang et al., 2013). Paddy fields and plantations are the primary land uses in the study area.

2.2 Soil sampling

We found 12 co-existing cover all land-use types at our study sites, namely *Oryza sativa* L., *Glycine max* (Linn.) Merr. and *Anorphophallus konjac* K. Koch fields; *Camellia sinensis* (L.) O. Ktze., *Camellia oleifera* Abel., *Citrus reticulata* Blanco, *Myrica rubra* (Lour.) S. et Zucc., *Cunninghamia lanceolata* (Lamb.) Hook., *Phyllostachys edulis* (Carriere) J. Houzeau, *Michelia macclurei* Dandy, *Schima superba* Gardn. et Champ. and *Pinus massoniana* Lamb. plantations. At each site, a rectangular area of approximately 20 m ×20 m was demarcated and 10-12 soil samples were randomly collected along an S-shaped route. The samples were mixed, and pooled to a composite sample. These soil samples were thoroughly homogenized and passed through a 2-mm-mesh sieve. The visible plant debris and stones in the soils were carefully removed by hand. Subsequently, these soil samples were divided into two parts. One of the two parts was stored at 4 ℃ was used for incubation and microbial measurement and the other part was air-dried for soil physical and chemical proprieties determination. Relevant information of soil physical-chemical proprieties for all sites is listed in Table1.

2.3 Incubation study

The moist-weight equivalent of 30 g of dry soil was placed into each 120 ml incubation bottles after being sieved to 2 mm. These incubation bottles had pierced lids that enabled gas exchange, but minimized evaporation and soil drying. Prior to the beginning of the treatments, all soils were pre-incubated at 25 ℃ for 7 days to minimize potential disturbances (Zhao et al., 2022). Our experiment

involved two treatments: wollastonite mineral (0.1 g g soil^{-1}) addition and no wollastonite mineral added as control. There were three replicates for each treatment and each land-use type, resulting in 72 incubation bottles in total. Wollastonite was chosen because of its simple chemistry and high dissolution rate (Haque et al., 2019). The wollastonite mineral in this study was sourced from Diaobing Mountain, Liaoning, China in the form of finely ground rock (≤ 50 μm). The major chemical compositions obtained from X-ray fluorescence analyses were CaO (42.51%), SiO_2 (53.14%), $CaCO_3$ (5%), Fe_2O_3 (0.25%), MgO (0.20%), Na_2O (0.11%), and K_2O (0.02%). The soils to be incubated were adjusted to a 60% water holding capacity (WHC) and incubated at 25 °C in the dark. Throughout the experiment, soil moisture was maintained at 60% WHC by adding de-ionized water at regular intervals.

Soil CO_2 efflux were determined based on the headspace of the closed chamber with an infrared gas analyzer (America, Li-Cor-820) connected via a closed loop. Measurements were taken on days 3, 5, 7, 9, 12, 16, 20, 25, 30, 38, 46, 54, 62, and 90 after the incubation began.

2.4 Soil physical-chemical properties analysis

The pH value was detected using the water extraction method (water: soil = 2.5: 1). The contents of dissolved organic carbon (DOC) were measured with a TOC analyzer (Multi N/C 3000, Germany). Soil microbial biomass carbon (MBC) was determined using the chloroform fumigation-extraction method (Brookes et al., 1985) and measured using the TOC analyzer. Soil available nitrogen (AN) and available phosphorus (AP) were measured in accordance with the methods described by Lu (2000) using a continuous flow analyzer (AA3, Seal Analytical, Germany). The soil exchangeable Ca cation contents were measured according to Lu (2000) using an atomic absorption spectrometer. The soil available silicon (ASi) concentration was determined using the acetate buffer method (pH 4.0) (Huang et al. 2020). Soil bulk density samples were obtained using a standard container with a fixed volume size of 100 cm3 and oven-dried at 105 °C to obtain their masses. The oven-dried soil mass and container volume were then used to quantify the bulk density. The soil C and N contents were

analyzed with an elemental analyzer (Elementer CARIO Macro, Germany), and the C: N ratios are presented as mass ratios.

2.5 Calculations and statistical analyses

Soil CO_2 efflux (R, mg C kg^{-1} soil day^{-1}) was calculated as follows:

$$R = \frac{C \times V \times M \times 273.15}{22.4 \times (273.15 + T) \times W \times t}$$

Where C is the measured CO_2 concentration (ppm); V is the effective volume of an incubation flask (L); M is the molar mass of C (12 g/mol); 22.4 (L) is the molar volume of an ideal gas at 1 atm and 273.15 K; W is the gram dry weight of the soil; t is the time of CO_2 accumulation (days); and T is the incubation temperature (25°C).

Cumulative soil CO_2 efflux (T, mg C kg^{-1} soil) was calculated as follows：

$$T = \sum_{i=1}^{n} \frac{R_i + R_{i+1}}{2} \times (t_{i+1} - t_i)$$

Where R_i and R_{i+1} are soil CO_2 efflux at ith and $(i + 1)$ th incubation time (mg C kg^{-1} day^{-1}), respectively; $t_{i+1}-t_i$ is the interval between the ith and $(i + 1)$ th incubation time (day); and n is the number of incubation times.

The intensity of treatment effects (Δ, %) was calculated by comparing the difference in T between wollastonite addition treatment and the unamended control.

$$\Delta = (\frac{treatment — control}{control}) \times 100\%$$

Shapiro-Wilk and Levene's test were used to check the normality and homogeneity of variances prior to the statistical analysis. One-way ANOVA and the least significant difference (LSD) test were adopted to determine the effects of wollastonite treatments among different land use types. Two sample t-tests were conducted to assess the differences in each measured variable between the treatment and control soils. The relationships between Δsoil CO_2 efflux and Δsoil properties were determined via linear regression analyses. Pearson correlation coefficients were utilized to analyze

relationships between Δsoil CO_2 efflux and initial soil properties. To calculate the relative influence of each initial soil factor, we also employed the hierarchical partitioning method to distinguish a single variable's contribution via the "rdacca.hp" package in R (Lai et al., 2022). All statistical analyses above were performed using R (version 4.1.1).

3 Results

3.1 Soil properties

We observed a strong wollastonite effect on the soil properties (Fig. 1). The addition of wollastonite markedly increased soil pH (+ 2.78 pH units on average) ($P< 0.001$). Wollastonite addition is conducive to improve of soil nutrients, particularly, the Ca, ASi, AN, DOC and MBC were significantly increased 17.54, 14.16, 1.63,2.04 and 1.75 folds respectively ($P< 0.05$). In addition, AP was not significantly affected by wollastonite (Fig. 1).

3.2 Soil CO_2 efflux

The soil CO_2 efflux at 12 sites drastically dropped until day 38, and then remained steady until the end of incubation (Fig. S1). The soil CO_2 efflux rate at all sites increased after wollastonite addition compared to the control (Fig. S1). Wollastonite addition significantly increased the cumulative soil CO_2 efflux ($P< 0.05$) (Fig. 2). Among all sampling sites, the overall percentage change in soil CO_2 efflux was 330.97 ± 29.25%. There are significant differences in CO_2 efflux among soils ($P< 0.05$), the lowest percentage change in soil CO_2 efflux with a value of 170.21% occurred at the *Amorphophallus konjac* field, and the highest value was 465.63% at the *Michelia macclurei* plantation ($P< 0.05$, Fig. 2).

3.3 Relationships between soil properties and CO_2 efflux

We performed regression analyses with Δsoil CO_2 efflux and Δsoil properties. The results showed that Δsoil CO_2 efflux was significantly positively correlated with soil ΔASi, ΔCa, ΔpH, ΔAP and

191 ΔDOC (R^2 values were 0.55, 0.33, 0.57, 0.17 and 0.26, respectively; $P < 0.05$, Fig. 3). The Δsoil
192 properties explained 90.70% of the variations in Δsoil CO_2 efflux induced by wollastonite addition
193 (Fig. 4), and ΔDOC, ΔASi and ΔpH were the main controlling factors for the Δsoil CO_2 efflux
194 accounting for 22.59%, 22.42%, and 22.30% of the variation, respectively. In addition, Δsoil CO_2
195 efflux was negatively correlated with initial soil Ca, ASi and pH (R^2 values were 0.29, 0.33, 0.55,
196 respectively; $P < 0.05$, Fig. 5).
197
198 **4 Discussion**
199 In the present study, the response of SOC mineralization to wollastonite addition was evaluated for
200 12 land-use types that are common in southern China. Wollastonite addition was found to promote
201 SOC mineralization as indicated by the increased soil CO_2 emission during the entire experimental
202 period (Fig. 2), thus no support was obtained for our first hypothesis. Similar trends have also been
203 reported in many previous studies (Groffman et al., 2006; Dietzen et al., 2018; Borges et al., 2019).
204 Based on a 11-year experiment in northeastern United States, Johnson et al. (2014) found a more than
205 40% decrease in the stock of SOC in the Oa horizon following wollastonite addition. As such, the
206 direction of the response of SOC mineralization to wollastonite addition appears to be irrespective of
207 the time the treatment has lasted. We admitted that our experiment might have induced a bias to the
208 estimation of SOC mineralization, given the wollastonite used contains 5% $CaCO_3$, which may be
209 one of the sources of CO_2. However, the CO_2 related to the interaction of $CaCO_3$ originating from
210 wollastonite and H^+ from soil is, at the most, equivalent to 1.01%-1.82% of the total CO_2 emission.
211 Therefore, we proposed that abiotic CO_2 emission could be ignored in the present study and that the
212 major CO_2 emission resulted from SOC mineralization.
213 We observed that approximately 90% of the variance in Δsoil CO_2 efflux was explained by Δsoil
214 property (Fig. 4), which supported our second hypothesis that wollastonite addition affects soil CO_2
215 emission by changing soil properties. For instance, the positive effects of wollastonite addition on
216 soil CO_2 efflux could be a consequence of the increased soil pH following wollastonite addition, as a

217 significant positive correlation was observed between the soil ΔpH and accumulated Δsoil CO_2 efflux
218 (Fig. 3). Increased soil pH value with silicate application has also been reported in many previous
219 studies due to the OH^- release caused by silicate hydrolysis (Groffman et al., 2006; Anda et al., 2015;
220 Xiao et al., 2016). There are two possible pathways for the decreased soil acidity to mediate the
221 influence of wollastonite addition on soil CO_2 emission. First, the acidic stress on the soil microbes
222 was in part loosened. Microbial growth and relevant SOC utilization are often limited in highly acidic
223 soils (Khalil et al., 2005; Kemmitt et al., 2006; Zhang et al., 2020), thus an increase in soil pH in
224 response to wollastonite addition may favor microbial activity and further the SOC mineralization
225 (Haynes and Naidu, 1998; Borges et al., 2019; Ribeiro et al., 2020). Many other studies involving
226 lime application also have published similar results as indicated by the increased soil MBC and
227 respiration as the soil pH increases (Fuentes et al., 2006; Wu et al., 2021). Second, more recalcitrant
228 C has been translated to labile form, an easily utilized fraction of soil C for microbes, as a response
229 to the soil pH increase. The release of DOC from organic soil layers has been positively related to
230 soil pH before (Andersson et al., 2001; Jokinen et al., 2006). The theories behind this phenomenon
231 included the enhanced deprotonation of organic substances in response to soil acidity decrease and,
232 as a result, the bonding between organic compounds and soil particles decreases, leading to an
233 increased amount of dissolved organic matter in the soil (Curtin et al., 1998; You et al., 1999).
234 Moreover, higher microbial activity generally enhanced the production rate of DOC (Gödde et al.,
235 1996; Andersson et al., 2000). DOC leaching and consumption in soil may further prompt microbial
236 decomposition of organic matter to obtain C, resulting in a lower SOC content.
237 Soil nutrients, in addition to pH, also played a vital role in relating wollastonite addition to SOC
238 mineralization (Nowinski et al., 2008). First of all, the silicon contained in wollastonite should have
239 accounted for a significant portion of the variance in SOC decomposition as Si can desorb organic C
240 from mineral binding sites (Reithmaier et al., 2017; Schaller et al., 2019). Recently, Ma et al. (2021)
241 also found that the amount of soil organic matter decreased after Si application to paddy soil. This
242 explanation was supported in part by the fact that ΔASi was positively correlated with Δsoil CO_2

efflux (Fig. 3). Furthermore, the higher Si availability also may stimulate microbial decomposition by improving the availability of some potential limiting nutrients, such as P, in the soil. Although wollastonite addition did not significantly increase the AP concentration in our study (Fig.1), this phenomenon is unsurprising given Si often strongly interfere with Fe mineralogy or Al-oxides to compete with P for binding sites, thereby increasing P mobilization and availability (Koski-Vähälä et al., 2001; Borges et al., 2019; Schaller et al., 2019). In addition, we also found a significant increase in the availability of Ca^{2+}, which is thought can stabilize SOC by enhancing its resistance to microbial decomposition (Rowley et al., 2021; Wan et al., 2021). Altogether, it seems that the increments in soil pH, DOC, and ASi have exerted a predominant effect over Ca^{2+} increase on microbial decomposition, resulting in a faster SOC mineralization following wollastonite addition. In our study, Δsoil properties explained relatively low variation of Δsoil CO_2 efflux (17%-57%), suggesting that there may be other influencing factors that contribute to the variation of soil CO_2 efflux. This point towards the need to pay further attention to the mechanisms behind the effect of wollastonite addition on SOC mineralization in the future.

In the present study, land use type was found to be a factor regulating the magnitude of the response of SOC mineralization to wollastonite addition (Fig.2). This phenomenon indicated that soils with various traits responded differentially to wollastonite addition in the SOC mineralization. For example, our results showed that the extent of wollastonite-induced increase in CO_2 efflux was related to soil pH, with soils having lower pH values received stronger wollastonite effect (Fig. 5). This finding was supported by that of Zhang et al. (2012), who even detected a 5%-12% decrease in soil CO_2 efflux after adding calcium silicate to a neutral soil (pH 6.5). In addition, larger treatment effect also took place in the soils with lower ASi and Ca cation (Fig.5). However, it should be noted that the initial soil physicochemical properties are still relatively low in in explaining Δsoil CO_2 efflux variation (29%-55%) (Fig.5), which indicated that the understanding of the regulation of wollastonite effect on SOC is limited in our study, and further research is needed for evaluating the wollastonite effect on SOC mineralization from the aspects of wollastonite addition concentration and more soil

types, and exploring its main regulation factors. Nevertheless, our study suggests to some extent that the increased SOC mineralization induced by the wollastonite addition may offset the effectiveness of ERW, especially in soils with lower pH.

Wollastonite application is likely of very limited values for these subtropical areas, which generally dominated by acidic soil, to remove CO_2 from the atmosphere, since the decomposition of organic C in acidic soils is highly sensitive to wollastonite addition. However, this speculation seems not that accurate, considering the potential influence of wollastonite addition on the plant-derived C input was not quantized and, whether wollastonite addition will negatively affect SOC accumulation is therefore unclear at this stage. Potentially, there are two pathways of plant production can be promoted following wollastonite addition, one being the loosened acidic stress on plants due to the soil pH increase, just as it did for microbes (Anda et al., 2013; Haque et al.2020b; Taylor et al., 2021); and the other is the increased availability of mineral nutrients, such as Ca, Si, P, and N, which stem from silicate rock dissolution (Basak et al., 2017; Kelland et al., 2020). We might therefore expect more root exudates and litter inputed to the soil after wollastonite addition, offsetting at least a part of the C loss associated with the enhancement in microbial decomposition (Kantola et al., 2017). To determine the net effect of wollastonite addition on SOC pool, future studies regarding the responses of soil and plants within a system are needed.

5 Conclusion

Before wollastonite addition can be considered an effective practice of removing atmospheric CO_2, what role it will play in determining SOC mineralization should be assessed first. Our results revealed that wollastonite addition did facilitate SOC mineralization for all 12 land use types included in this study, as indicated by the enhanced CO_2 emission. Wollastonite addition achieved its effect on SOC mineralization via increasing the soil pH value, Si and P availability, which partially loosened the limitations for microbial metabolism caused by soil acidity and nutrients shortage, resulting in a faster C utilization by microbes. Overall, our findings did not underpin that wollastonite addition can be

used as a C sequestration tool in the acidic soils at this stage. Taken together, our study contributes to a better awareness to the necessity of wollastonite addition as a practice of removing CO_2 from the atmosphere. We also acknowledge that our study lasted for a relatively short period, and whether the findings obtained can be applied to chronic situations still awaits further experimental evidences.

Conflict of interest statement

All authors have approved the submission and none declare any conflict of interest in the work performed or in the submission of the manuscript.

Acknowledgments

This research was funded by the National Key Research and Development Program of China (2022YFF1303003 and 2021YFD2201303) and National Natural Science Foundation of China (U22A20612). We gratefully acknowledged Dr. Shaobin Yan and Xuechao Zhao for his help in experiments and statistical analyses.

References

Anda, M., Shamshuddin, J., Fauziah, C.I., 2013. Increasing negative charge and nutrient contents of a highly weathered soil using basalt and rice husk to promote cocoa growth under field conditions. Soil Till. Res. 132, 1-11. https://doi.org/10.1016/j.still.2013.04.005.

Anda, M., Shamshuddin, J., Fauziah, C.I., 2015. Improving chemical properties of a highly weathered soil using finely ground basalt rocks. Catena 124, 147-161. https://doi.org/10.1016/j.catena.2014.09.012.

Andersson, S., Nilsson, S.I., Saetre, P., 2000. Leaching of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in mor humus as affected by temperature and pH. Soil Biol. Biochem. 32, 1-10. https://doi.org/10.1016/S0038-0717(99)00103-0.

Andersson, S., Nilsson, S.I., 2001. Influence of pH and temperature on microbial activity, substrate

availability of soil-solution bacteria and leaching of dissolved organic carbon in a mor humus. Soil Biol. Biochem. 33, 1181-1191. https://doi.org/10.1016/S0038-0717(01)00022-0.

Andrews, M.G., Taylor, L.L., 2019. Combating climate change through enhanced weathering of agricultural soils. Elements 15, 253-258. https://doi.org/10.2138/gselements.15.4.253.

Basak, B.B., Sarkar, B., Biswas, D.R., Sarkar, S., Sanderson, P., Naidu, R., 2017. Bio-Intervention of Naturally Occurring Silicate Minerals for Alternative Source of Potassium: Challenges and Opportunities. Adv. Agron. 141, 115-145. https://doi.org/10.1016/bs.agron.2016.10.016.

Beerling, D.J., Kantzas, E.P., Lomas, M.R., Wade, P., Eufrasio, R.M., Renforth, P., Sarkar, B., Andrews, M.G., James, R.H., Pearce, C.R., Mercure, J.F., Pollitt, H., Holden, P.B., Edwards, N.R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N.F., Janssens, I.A., Hansen, J., Banwart, S.A., 2020. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature 583, 242–248. https://doi.org/10.1038/s41586-020-2448-9.

Bellamy, R., Geden, O., 2019. Govern CO_2 removal from the ground up. Nat. Geosci. 12, 874-876. https://doi.org/10.1038/s41561-019-0475-7.

Borges, C.S., Ribeiro, B.T., Costa, E.T.D., Curi, N., Wendling, B., 2019. Effects of phosphate, carbonate, and silicate anions on CO_2 emission in a typical oxisol from cerrado region. Biosci. J. 35, 1153-1160. https://doi.org/10.14393/BJ-v35n4a2019-42239.

Bothe, H., 2015. The lime-silicate question. Soil Biol. Biochem. 89, 172-183. https://doi.org/10.1016/j.soilbio.2015.07.004.

Brookes, P.C., Landman A., Pruden G., Jenkinson D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil. Biol. Biochem. 17, 837-842. https://doi.org/10.1016/0038-0717(85)90143-9.

Curtin, D., Campbell, C.A., Jalil, A., 1998. Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. Soil. Biol. Biochem. 30, 57-64. https://doi.org/10.1016/S0038-0717(97)00094-1.

Dietzen, C., Harrison, R., Michelsen-Correa, S., 2018. Effectiveness of enhanced mineral weathering

as a carbon sequestration tool and alternative to agricultural lime: An incubation experiment. Int. J. Greenh. Gas. Con. 74, 251-258. https://doi.org/10.1016/j.ijggc.2018.05.007.

Fuentes, J.P., Bezdicek, D.F., Flury, M., Albrecht, S., Smith, J.L., 2006. Microbial activity affected by lime in a long-term no-till soil. Soil Till. Res. 88, 123-131, https://doi.org/10.1016/j.still.2005.05.001.

Gödde, M., David, M.B., Christ, M.J., Kaupenjohann, M., Vance, G.F., 1996. Carbon mobilization from the forest floor under red spruce in the northeastern USA. Soil Biol. Biochem. 28, 1181-1189. https://doi.org/10.1016/0038-0717(96)00130-7.

Goll, D.S., Ciais, P., Amann, T., Buermann, W., Chang, J.F., Eker, S., Hartmann, J., Janssens, I., Li, W., Obersteiner, M., Penuelas, J., Tanaka, K., Vicca, S., 2021. Potential CO_2 removal from enhanced weathering by ecosystem responses to powdered rock. Nat. Geosci. 14, 545-549. https://doi.org/10.1038/s41561-021-00798-x.

Groffman, P.M., Fisk, M.C., Driscoll, C.T., Likens, G.E., Fahey, T.J., Eagar, C., Pardo, L.H., 2006. Calcium additions and microbial nitrogen cycle processes in a northern hardwood forest. Ecosystems 9, 1289-1305. https://doi.org/10.1007/s10021-006-0177-z.

Hartmann, J., Moosdorf, N., Lauerwald, R., Hinderer, M., West, A.J., 2014. Global chemical weathering and associated P-release - The role of lithology, temperature and soil properties. Chem. Geol. 363, 145-163. https://doi.org/10.1016/j.chemgeo.2013.10.025.

Haque, F., Santos, R.M., Dutta, A., Thimmanagari, M., Chiang, YW., 2019. Co-benefits of wollastonite weathering in agriculture: CO_2 sequestration and promoted plant growth. 2019. ACS Omega. 4, 1425-1433. https://doi.org/10.1021/acsomega.8b02477.

Haque, F., Santos, R.M., Chiang, Y.W., 2020a. CO_2 sequestration by wollastonite-amended agricultural soils - An Ontario field study. Int. J. Greenh. Gas Con. 97, 103017. https://doi.org/10.1016/j.ijggc.2020.103017.

Haque, F., Santos, R.M., Chiang, Y.W., 2020b. Optimizing inorganic carbon sequestration and crop yield with wollastonite soil amendment in a microplot study. Front. Plant Sci. 11, 1012.

https://doi.org/10.3389/fpls.2020.01012.

Haynes R., Naidu R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr. Cycl. Agroecosys. 51, 123-137. https://doi.org/10.1023/A:1009738307837.

Huang, C.P., Wang, L., Gong, X.Q., Huang, Z.T., Zhou, M.R., Li, J., Wu, J.S., Chang, S.X., Jiang, P.K., 2020. Silicon fertilizer and biochar effects on plant and soil PhytOC concentration and soil PhytOC stability and fractionation in subtropical bamboo plantations. Sci. Total Environ. 715, 136846. https://doi.org/10.1016/j.scitotenv.2020.136846.

IPCC, 2018. Summary for Policymakers of the Special Report on the Global Warming of 1.5 °C.

Johnson, C.E., Driscoll, C.T., Blum, J.D., Fahey, T.J., Battles, J.J., 2014. Soil chemical dynamics after calcium silicate addition to a northern hardwood forest. Soil Sci. Soc. Am. J. 78, 1458-1468. https://doi.org/10.2136/sssaj2014.03.0114.

Jokinen, H.K., Kiikkila, O., Fritze, H., 2006. Exploring the mechanisms behind elevated microbial activity after wood ash application. Soil Biol. Biochem. 38, 2285-2291. https://doi.org/10.1016/j.soilbio.2006.02.007.

Kantola, I.B., Masters, M.D., Beerling, D.J., Long, S.P., DeLucia, E.H., 2017. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. Biol. Letters 13, 20160714. https://doi.org/10.1098/rsbl.2016.0714.

Kemmitt, S.J., Wright, D., Goulding, K.W.T., Jones, D.L., 2006. pH regulation of carbon and nitrogen dynamics in two agricultural soils. Soil Biol. Biochem. 38, 898-911. https://doi.org/10.1016/j.soilbio.2005.08.006.

Kelland, M.E., Wade, P.W., Lewis, A.L., Sarkar, B., Andrews, M.G., Lomas, M.R., Cotton, T.E.A., Kemp, S.J., James, R.H., Pearce, C.R., Hartley, S.E., Hodson, M.E., Leake, J.R., Banwart, S.A., Beerling, D.J., 2020. Increased yield and CO_2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. Glob Change Biol. 26, 3658-3676. https://doi.org/10.1111/gcb.15089.

399 Khalil, M.I., Hossain, M.B., Schmidhalter, U., 2005. Carbon and nitrogen mineralization in different
400 upland soils of the subtropics treated with organic materials. Soil. Biol. Biochem. 37, 1507-1518.
401 https://doi.org/10.1016/j.soilbio.2005.01.014.
402 Kirschbaum, M.U.F., 2004. Soil respiration under prolonged soil warming: are rate reductions caused
403 by acclimation or substrate loss? Global Change Biol. 10, 1870-1877.
404 https://doi.org/10.1111/j.1365-2486.2004.00852.x.
405 Koski-Vähälä, J., Hartikainen, H., Tallberg, P., 2001. Phosphorus mobilization from various sediment
406 pools in response to increased pH and silicate concentration. J. Environ. Qual. 30, 546-552.
407 https://doi.org/10.2134/jeq2001.302546x.
408 Ma, C.Y., Ci, K.D., Zhu, J., Sun, Z.L., Liu, Z.X., Li, X.Y., Zhu, Y.L., Tang, C., Wang, P., Liu, Z.M.,
409 2021. Impacts of exogenous mineral silicon on cadmium migration and transformation in the
410 soil-rice system and on soil health. Sci. Total Environ. 759, 143501.
411 https://doi.org/10.1016/j.scitotenv.2020.143501.
412 Nowinski, N.S., Trumbore, S.E., Schuur, E.A.G., Mack, M.C., Shaver, G.R., 2008. Nutrient addition
413 prompts rapid destabilization of organic matter in an arctic tundra ecosystem. Ecosystems 11,
414 16–25. https://doi.org/10.1007/s10021-007-9104-1.
415 Lai, J., Zou, Y., Zhang, J., Peres-Neto, P.R., 2022. Generalizing hierarchical and variation partitioning
416 in multiple regression and canonical analyses using the rdacca.hp R package. Methods Ecol.
417 Evol. 13, 782-788. https://doi.org/10.1111/2041-210X.13800.
418 Lu, R.K. 2000. Methods of soil agricultural chemistry analysis. Chinese Agricultural Science and
419 Technology Press, Beijing (in Chinese).
420 Qiao, N., Schaefer, D., Blagodatskaya, E., Zou, X., Xu, X., Kuzyakov, Y., 2014. Labile carbon
421 retention compensates for CO_2 released by priming in forest soils. Glob Change Biol. 20, 1943-
422 1954. https://doi.org/10.1111/gcb.12458.
423 Ramezanian, A., Dahlin, A.S., Campbell, C.D., Hillier, S., Mannerstedt-Fogelfors, B., Oborn, I., 2013.
424 Addition of a volcanic rockdust to soils has no observable effects on plant yield and nutrient

425 status or on soil microbial activity. Plant Soil 367, 419-436. https://doi.org/10.1007/s11104-012-
426 1474-2.
427 Ramezanian, A., Dahlin, A.S., Campbell, C.D., Hillier, S., OEborn, I., 2015. Assessing biogas
428 digestate, pot ale, wood ash and rockdust as soil amendments: effects on soil chemistry and
429 microbial community composition. Acta Agr. Scand. B-S. P. 65, 383-399.
430 https://doi.org/10.1080/09064710.2015.1014831.
431 Reithmaier, G.M.S., Knorr, K.H., Arnhold, S., Planer-Friedrich, B., Schaller, J., 2017. Enhanced
432 silicon availability leads to increased methane production, nutrient and toxicant mobility in
433 peatlands. Sci. Rep. 7, 8728. https://doi.org/10.1038/s41598-017-09130-3.
434 Ribeiro, I.D.A., Volpiano, C.G., Vargas, L.K., Granada, C.E., Lisboa, B.B., Passaglia, L.M.P., 2020.
435 Use of mineral weathering bacteria to enhance nutrient availability in crops: a review. Front.
436 Plant Sci. 11, 590774. https://www.frontiersin.org/article/10.3389/fpls.2020.590774.
437 Rowley, M.C., Grand, S., Spangenberg, J.E., Verrecchia, E.P., 2021. Evidence linking calcium to
438 increased organo-mineral association in soils. Biogeochemistry 153, 223-241.
439 https://doi.org/10.1007/s10533-021-00779-7.
440 Rowley, M.C., Grand, S., Verrecchia, É.P., 2018. Calcium-mediated stabilisation of soil organic
441 carbon. Biogeochemistry 137, 27-49. https://doi.org/10.1007/s10533-017-0410-1.
442 Schaller, J., Faucherre, S., Joss, H., Obst, M., Goeckede, M., Planer-Friedrich, B., Peiffer, S.,
443 Gilfedder, B., Elberling, B., 2019. Silicon increases the phosphorus availability of Arctic soils.
444 Sci. Rep. 9, 449. https://doi.org/10.1038/s41598-018-37104-6.
445 Song, Z.L., Muller, K., Wang, H.L., 2014. Biogeochemical silicon cycle and carbon sequestration in
446 agricultural ecosystems. Earth-Sci. Rev. 139, 268-278.
447 https://doi.org/10.1016/j.earscirev.2014.09.009.
448 Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny,
449 B., McBratney, A.B., de Courcelles, V.D., Singh, K., Wheeler, I., Abbott, L., Angers, D.A.,
450 Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell,

A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agr. Ecosyst. Environ. 164, 80-99. https://doi.org/10.1016/j.agee.2012.10.001.

Strefler, J., Amann, T., Bauer, N., Kriegler, E., Hartmann, J., 2018. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. Environ. Res. Lett. 13, 34010. https://iopscience.iop.org/article/10.1088/1748-9326/aaa9c4.

Taylor, L.L., Driscoll, C.T., Groffman, P.M., Rau, G.H., Blum, J.D., Beerling, D.J., 2021. Increased carbon capture by a silicate-treated forested watershed affected by acid deposition. Biogeosciences 18, 169-188. https://doi.org/10.5194/bg-18-169-2021.

UNFCCC, 2015. The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A., Peñuelas, J., Poblador, S., Rijnders, J., Sardans, J., Struyf, E., Swoboda, P., van Groenigen, J. W., Vienne, A., Verbruggen, E., 2022. Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes? Global Change Biol. 28, 711-726. https://doi.org/10.1111/gcb.15993.

Wan, D., Ma, M.K., Peng, N., Luo, X.S., Chen, W.L., Cai, P., Wu, L.H., Pan, H.B., Chen, J.B., Yu, G.H., Huang, Q.Y., 2021. Effects of long-term fertilization on calcium-associated soil organic carbon: Implications for C sequestration in agricultural soils. Sci. Total Environ. 772, 145037. https://doi.org/10.1016/j.scitotenv.2021.145037.

Wang, Q.K., Wang, S.L., Zhong, M.C., 2013. Ecosystem carbon storage and soil organic carbon stability in pure and mixed stands of Cunninghamia lanceolata and Michelia macclurei. Plant Soil 370, 295-304. https://doi.org/10.1007/s11104-013-1631-2.

Wu, H.T., Hu, J.L., Shaaban, M., Xu, P., Zhao, J.S., Hu, R.G., 2021. The effect of dolomite amendment on soil organic carbon mineralization is determined by the dolomite size. Ecol. Process. 10, 8. https://doi.org/10.1186/s13717-020-00278-x.

Xiao, L.L, Sun, Q.B., Yuan, H.T., Li, X.X., Chu, Y., Ruan, Y.L., Lu, C.M., Lian, B., 2016. A feasible way to increase carbon sequestration by adding dolomite and K-feldspar to soil. Cogent Geosci. 2, https://doi.org/10.1080/23312041.2016.1205324.

You, S.J., Yin, Y.J., Allen, H.E. 1999. Partitioning of organic matter in soils: effects of pH and water/soil ratio. Sci. Total Environ. 227, 155-160. https://doi.org/10.1016/S0048-9697(99)00024-8.

Zhao, X.C., Tian, P., Liu, S.G., Sun, Z.L., Zeng, Z.Q., Wang, Q.K., 2022. Cunninghamia lanceolata and understory ferns had positive rhizosphere effects on the temperature sensitivity of soil microbial respiration in a subtropical forest. Geoderma 408, 115593. https://doi.org/10.1016/j.geoderma.2021.115593.

Zhang, X.M., Guo, J.H., Vogt, R.D., Mulder, J., Wang, Y.J., Qian, C., Wang, J.G., Zhang, X.S., 2020. Soil acidification as an additional driver to organic carbon accumulation in major Chinese croplands. Geoderma 366, 114234. https://doi.org/10.1016/j.geoderma.2020.114234.

Zhang Y., Shao S., Guan L., Yan L., He L., Zhao K., 2012. Impacts of calcium silicate addition on brown earth basal respiration and calcium carbonate content. Soil and Fertilizer Sciences in China. 3, 40-42 (in Chinese).