Changes in Carbon and Nitrogen Mineralization in Soil Organic Matter Under High CO2 Concentrations

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Research Article

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Abstract

To investigate the effects of different organic materials on soil organic carbon accumulation and carbon and nitrogen mineralization under different CO$_2$ concentrations, field topsoil was used as the test soil and chicken manure, cow manure, and straw were mixed with soil samples as organic materials. The changes in organic carbon, carbon and nitrogen mineralization, and utilization of carbon sources by soil microorganisms were measured under high CO$_2$ (800–1000 ppm) and low CO$_2$ (400–500 ppm) concentrations. The results showed that adding organic material to soil can accelerate the mineralization of organic carbon and reduce the mineralization of nitrogen. While the addition of chicken manure and cow manure reduced the content of total organic carbon and active organic carbon in soil, straw increased the content of total organic carbon and active organic carbon in soil and reduced carbon utilization by the soil microbial community. Collectively, our findings revealed that, under high CO$_2$ concentrations, adding organic material to soil can accelerate the mineralization of organic carbon and reduce the mineralization of nitrogen.

Highlights

1: Content of total and active organic C was reduced by adding chicken or cow manure.

2: Content of total and active organic C was increased by adding straw.

3: Utilization of C sources by soil microorganisms differed under the CO$_2$ enrichment.

Introduction

The soil carbon and nitrogen cycles are an important part of the global carbon and nitrogen cycles, and deficiencies in carbon and nitrogen limit the quality and productivity of many soils (Katsaliroua et al., 2010; Lee et al., 2009). The mineralization of carbon is the process in which soil organic carbon is mineralized into inorganic carbon by microbial decomposers, resulting in CO$_2$ emission (Pires et al., 2017); furthermore, nitrogen mineralization is the process in which soil organic N is mineralized to inorganic forms, including NH$_4^+$ and NO$_3^-$ (Manzoni and Porporato, 2009; Xia et al., 2010). Essentially, the mineralization of soil organic carbon (SOC) and nitrogen through the decomposition of soil organic matter are fundamental biogeochemical processes that underpin soil fertility and crop production. Moreover, an increasing number of studies have investigated the effects of straw biochar on carbon mineralization (Junna et al., 2014; Zavalloni et al., 2011). Hence, in order to improve the management of soil fertility, which contributes to food security and climate change mitigation, a better understanding of SOC and N mineralization in soils is necessary.

It is well known that the global concentration of atmospheric CO$_2$ is steadily increasing. Especially, as an important source of atmospheric greenhouse gases, the amount of soil organic carbon is 2–3 times the amount present in the total atmospheric carbon pool; moreover, due to its role as a carbon source and
sink, the ability of soil to store carbon has also been controversial (Cookson et al., 2007; Lal, 2004; Rhodes, 2014). It has been shown that slight changes in the soil organic carbon pool lead to significant changes in atmospheric CO$_2$ concentrations (Haei et al., 2012). Consequently, CO$_2$ generation and emission caused by soil organic carbon mineralization has been regarded as an important basis for evaluating the soil greenhouse effect (Phillips et al., 2011). Several studies have reported a relationship between increased CO$_2$ concentration and the accumulation of soil organic carbon (Hagedorn et al., 2010; Johannes and Saran, 2008). Elevated CO$_2$ and temperature have been found to enhance the temperature sensitivity of SOM decomposition (Chen et al., 2015). Moreover, it has been reported that with elevated atmospheric CO$_2$, the rate of plant residue decomposition may be limited by N and the release of N from decomposing plant material may be slowed (Torbert et al., 2000). However, research on the mineralization of organic materials under increased CO$_2$ concentrations is still limited.

The interactions between microbial communities and their local environment not only have significant effects on microbial community structure, but also regulate many of the soil functions carried out by microorganisms (Chaparro et al., 2012; Sleutel et al., 2012). Interestingly, an increasing number of studies have explored the soil carbon mineralization responses to alterations in microbial diversity and soil structure. For example, it has been reported that biochar in soil can stimulate bacterial biomass in the short term (Prayogo et al., 2014) and soil microbial diversity may exert more control on SOC dynamics than soil structure, at least under these conditions and when the levels of diversity are very low (Juarez et al., 2013). All these data suggest that soil microorganisms may play an important role in the mineralization of organic materials. In addition, increased CO$_2$ concentration could affect the structure of soil microbial communities. Presently, there are many methods to study soil microbial diversity, including Biolog microplate technology. This technique is simple to operate, rich in data, and can intuitively reflect the overall activity of a microbial population; therefore, it can clearly identify the functional diversity of microorganisms in the environment. In addition, the Biolog ECO microplate method can be used to determine the differences in the degree of utilization of different carbon sources by microorganisms, which is a common currently used method for studying microbial community diversity (Demoling et al., 2009).

Therefore, in this study, to investigate the effect of different organic fertilizers on soil organic carbon accumulation as well as carbon and nitrogen mineralization, indoor culture experiments were carried out. Natural conditions were simulated using the surface soil from a field as test soil, and chicken manure, cow manure, or straw were used as organic materials. Moreover, the Biolog ECO method was used to study soil microbial diversity and the microbial utilization of different carbon sources.

**Materials And Methods**

**Study area and experiment design**
The surface soil samples (0–20 cm) were collected from Dongyang field, Shanxi province, China. The tested soil was clay loam with nutrient content as follows: 15.2 g·kg$^{-1}$ organic matter, 0.65 g·kg$^{-1}$ total nitrogen, 5.7 mg·kg$^{-1}$ nitrate nitrogen, 6.43 mg·kg$^{-1}$ available phosphorus, 105 mg·kg$^{-1}$ available potassium, pH 8.47, and 162 s·cm$^{-1}$ electrical conductivity. After multi-point mixing, the soil samples were transported to the laboratory, dried, and passed through a 2-mm sieve for use in the experiments.

Treatments with high CO$_2$ (800–1000 ppm) and low CO$_2$ (400–500 ppm) concentrations were utilized for the soil-only group (H1 and L1, respectively), the mixture of soil and chicken manure group (32 g/kg; H2 and L2, respectively), the mixture of soil and cow manure group (37 g/kg; H3 and L3, respectively), the mixture of soil and corn straw group (16.3 g/kg; H4 and L4, respectively). All experiments were repeated 10 times.

**Chemo-physical analysis**

The content of organic carbon and nitrogen in soil and organic materials (chicken manure, cow manure, and straw) were determined by dichromate oxidation and Kjeldahl digestion, respectively (Nelson et al., 1996). Briefly, for soil organic carbon analysis, 0.5 g of air-dried soil or soil organic materials was sieved through 0.15-mm sieves and placed in conical flasks. Next, 10 mL of K$_2$Cr$_2$O$_7$-H$_2$SO$_4$ solution was added, and the wetted soil samples were then baked for 30 min in an oven at 170–180°C. o-Phenanthroline was used as an indicator. For organic nitrogen analysis, 1-g (< 0.15 mm) soil samples were placed in a rigid test tube, and 10 mL H$_2$SO$_4$ was added. The N concentration of soil was measured using a 2300 Kjeltec Analyzer Unit (FOSS, Sweden).

**Organic carbon and nitrogen mineralization**

Organic carbon mineralization was measured using the lye absorption method (Ribeiro et al., 2010). Briefly, 300 g of soil was adjusted to 60–80% of field capacity with deionized water and incubated in a dark incubator at 25°C. Carbon dioxide and soil moisture were added regularly during the experiment, and NaOH solution was used to absorb CO$_2$ at 1, 9, 15, 30, 60, 90, 120, 150, and 180 days. After adding 3 mL of 1 mol·L$^{-1}$ BaCl$_2$ solution and 2 drops of phenolphthalein indicator, the samples were titrated to a colorless solution with 0.1 mol L$^{-1}$ HCl. The cumulative mineralization amount of organic carbon was calculated based on the amount of CO$_2$ released during the culture period.

Meanwhile, the amount of active organic carbon in the soil was determined after incubation for 180 days based on the potassium permanganate method. First, a soil sample of 1.50 g was placed in a 100-mL tripod bottle, and 25 mL of 33 mmol/L potassium permanganate solution was added and incubated in the dark for 24 h. Next, 0.5 mL of the supernatant was collected, and the volume was fixed in a 250-mL volumetric flask. Colorimetric analysis was performed at a wavelength of 565 nm. Assuming that every 1 mmol of potassium permanganate consumes 9 mg or 0.75 mmol of carbon, the soil sample organic matter oxidized by 33 mmol/L potassium permanganate solution was defined as highly active organic carbon; the soil sample organic matter oxidized by 167 mmol/L potassium permanganate solution was
defined as medium active organic carbon; and the soil sample organic matter oxidized by 333 mmol/L potassium permanganate solution was defined as active organic carbon.

Soil nitrogen mineralization is the process in which N is mineralized into inorganic forms. After the pre-incubation period at 1, 30, 60, and 180 d, 5-g samples of the soil mixture (< 2 mm) were extracted with 50 mL of 2 mol/L KCl to examine the initial nitrate (NO$_3^-$) concentrations, which were quantified using an automatic discontinuous chemical analyzer (SMART CHEM 200).

**Microbial community structure analysis**

To determine the soil microbial community composition, 10 g of freeze-dried soil samples that were collected at 1, 30, and 180 d during the incubation period, were placed into 90 mL of sterile 0.85% NaCl solution. Diluted supernatant fluid was put into a Biolog ECO board and then incubated at 25–28°C. Every 24 h, the absorbance values of each ECO plate were recorded on the Biolog instrument. To determine the utilization of carbon sources by soil microorganisms, the average rate of color change (AWCD) was recorded.

**The activation effect of CO$_2$ on soil organic carbon mineralization**

The excitation effect value was calculated as follows (Luo et al., 2014):

\[
PE(\%) = \frac{(C_1 - C_2)}{C_2} \times 100%,
\]

where, $C_1$ is the amount of CO$_2$ from original organic carbon mineralized in the soil under high CO$_2$ concentrations and $C_2$ is the amount of CO$_2$ from soil organic carbon under low CO$_2$ concentrations. A PE value $> 0$ means that the addition of CO$_2$ causes a positive excitation effect on soil organic carbon. A PE value $< 0$ indicates that the addition of CO$_2$ causes a negative excitation effect on soil organic carbon and inhibits the mineralization of bulk organic carbon.

**Statistical analysis**

Statistical analyses were performed using SPSS 13.0, Microsoft Excel 2007, and Croeldraw X4. GPS package was used to draw a heatmap. All statistical data are described using mean ± standard deviation (SD). A P value less than 0.05 was considered to be statistically significant.

**Results**

**Basic soil properties**

The initial organic ingredients in soil and the mixture of soil and materials are summarized in Table 1. The content of C and N and C/N ratio were higher in the soil samples mixed with organic materials than in the soil-only group.
Table 1
The basic chemical compositions of soil and organic amendments

| Content   | Soil     | Chicken manure | Cow manure | Corn straw |
|-----------|----------|----------------|------------|------------|
| C(g/kg)   | 8.77     | 285.64         | 256.08     | 560.90     |
| N(g/kg)   | 0.65     | 13.85          | 5.58       | 6.10       |
| C/N       | 13.49    | 20.62          | 45.89      | 91.95      |

Soil C and N mineralization

The cumulative CO₂ release and release rate of different groups under different culture times were investigated. According to data shown in Fig. 1A–1B, the cumulative CO₂ release and release rate differed among soil samples in which different organic materials were added, in descending order, as corn straw > chicken manure > cow manure. Moreover, the cumulative CO₂ release and release rate were higher in high CO₂ concentrations than in groups treated with low CO₂ concentrations. During the culture period, the CO₂ release rate of each group gradually decreased and essentially stabilized after 60 days, which suggests that high CO₂ concentrations can accelerate the mineralization of organic carbon in soil containing with organic materials. More importantly, the effects of high CO₂ concentration on the levels of different organic materials are summarized in Fig. 1C–1F.

Meanwhile, as illustrated in Table 2, the content of total organic carbon and active organic carbon in soil increased after 180 days of incubation upon addition of chicken manure, cow manure, or corn straw. In addition, high CO₂ concentration resulted in less total organic carbon and active organic carbon in chicken manure or cow manure groups, respectively. Inversely, the total organic carbon and active organic carbon in the cow manure group treated with high CO₂ concentrations were significantly higher than those in group treated with low CO₂ concentration (both, P < 0.05).
Table 2
Organic carbon contents in soil under different treatments

| Groups | Total organic carbon (mg/kg) | High active organic carbon (mg/kg) | Middle active organic carbon (mg/kg) | Active organic carbon (mg/kg) |
|--------|-----------------------------|-----------------------------------|-------------------------------------|-------------------------------|
| L1     | 7.00 ± 0.27a                | 0.68 ± 0.09a                      | 0.28 ± 0.15a                        | 0.75 ± 0.41a                  |
| H1     | 7.41 ± 0.19a                | 0.45 ± 0.13b                      | 0.45 ± 0.24a                        | 0.75 ± 0.23a                  |
| L2     | 10.25 ± 0.70a               | 0.83 ± 0.05a                      | 0.98 ± 0.34a                        | 1.55 ± 0.19a                  |
| H2     | 9.29 ± 0.07a                | 0.85 ± 0.03a                      | 0.85 ± 0.24a                        | 1.12 ± 0.18b                  |
| L3     | 10.12 ± 0.10a               | 0.90 ± 0.13a                      | 1.40 ± 0.10a                        | 1.67 ± 0.56a                  |
| H3     | 8.22 ± 0.04b                | 0.75 ± 0.05a                      | 1.05 ± 0.30a                        | 2.70 ± 0.09a                  |
| L4     | 15.79 ± 0.25a               | 1.85 ± 0.11a                      | 2.73 ± 0.21a                        | 2.67 ± 0.24a                  |
| H4     | 17.34 ± 0.10b               | 1.65 ± 0.16b                      | 2.93 ± 0.60a                        | 3.74 ± 0.09b                  |

Note: Values with different letters in the same column of group are significantly different at P < 0.05

As shown in Table 3, when compared with the groups treated with low CO₂ concentration, the NO₃⁻-N levels were significantly lower in groups treated with high CO₂ concentration (all, P < 0.05). The order of NO₃⁻-N content was chicken manure > cow manure > corn straw. During the culture period, the content of NO₃⁻-N in the control soil group and groups treated with chicken or cow manure increased gradually. On the contrary, the content of NO₃⁻-N in the soil with straw added was lower than that in the control soil, indicating that the addition of straw can reduce the NO₃⁻-N levels in soil. Collectively, high CO₂ concentrations can reduce the mineralization of organic N in soil with added organic materials.
Table 3
Nitrate nitrogen content in soil under different treatments

| Groups | 1      | 30     | 60     | 180    |
|--------|--------|--------|--------|--------|
| L1     | 11.95 ± 0.64a | 21.10 ± 0.77a | 35.68 ± 1.60a | 55.51 ± 0.78a |
| H1     | 10.20 ± 0.27b | 19.92 ± 0.60b | 29.26 ± 0.13b | 43.51 ± 0.11b |
| L2     | 153.88 ± 3.18a | 213.04 ± 12.30a | 221.57 ± 7.96a | 259.72 ± 1.34a |
| H2     | 160.03 ± 13.86a | 162.98 ± 15.45b | 183.58 ± 1.67b | 229.31 ± 1.32b |
| L3     | 45.86 ± 3.82a | 45.29 ± 0.79a | 61.83 ± 1.59a | 135.81 ± 0.69a |
| H3     | 37.44 ± 2.16a | 42.20 ± 0.56b | 37.69 ± 2.80b | 78.31 ± 0.41b |
| L4     | 8.66 ± 0.52a | 6.22 ± 0.31a | 6.56 ± 0.10a | 5.49 ± 0.53a |
| H4     | 9.54 ± 0.56a | 5.82 ± 0.11a | 6.20 ± 0.07b | 4.64 ± 0.75b |

Note: Values with different letters in the same column of group are significantly different at P < 0.05

**Microbial community composition**

In order to detect the carbon source utilization by soil microorganisms, the AWCD of soil microorganisms was determined after 1, 30, and 180 d of incubation. Under high CO\textsubscript{2} concentrations at the early stages of culture (1 and 30 d), the utilization of carbon sources by the microbial community was increased compared with that under conditions of low CO\textsubscript{2} concentration (Fig. 2A and 2B). However, in addition to the corn straw group, the utilization of carbon sources by the microbial communities in soils was decreased at 180 days upon adding chicken manure or cow manure under high CO\textsubscript{2} concentrations (Fig. 2C).

Additionally, the results of soil microbial community diversity analysis showed that under high CO\textsubscript{2} concentrations at 30 d, the soil microbial community diversity index and richness index were increased compared with that under low CO\textsubscript{2} concentrations (Table 4). Principal component analyses (PCA) showed that the H1 and the H2 treatments were close to each other; whereas H3 and H4 treatments clustered separately (Fig. 2D–2F). Moreover, the heatmaps of microbial carbon source utilization showed that the utilization of 31 carbon sources by soil microbial communities differed among the experimental groups (Fig. 3). All these data indicate that high CO\textsubscript{2} concentrations can change the characteristics of the soil microbial community.
Table 4
The indexes of soil microbial community diversity under different treatments

| Days | Treats | Diversity index (U) | Diversity index (H') | Simpson index | Shannon evenness | Carbon source utilization richness index(s) |
|------|--------|---------------------|----------------------|---------------|-----------------|-------------------------------------------|
| L1   | 4.24 ± 0.22 | 2.34 ± 0.12 | 0.87 ± 0.02 | 1.02 ± 0.01 | 10.00 ± 1.00 |
| H1   | 5.10 ± 0.35 | 2.38 ± 0.08 | 0.89 ± 0.01 | 0.98 ± 0.01 | 11.33 ± 0.88 |
| L2   | 8.03 ± 0.42 | 3.04 ± 0.02 | 0.95 ± 0.01 | 1.00 ± 0.01 | 21.00 ± 0.01 |
| 1d   | H2     | 8.51 ± 0.31 | 3.03 ± 0.02 | 0.95 ± 0.01 | 0.99 ± 0.01 | 21.67 ± 0.67 |
| L3   | 8.58 ± 0.30 | 3.10 ± 0.02 | 0.95 ± 0.01 | 0.97 ± 0.01 | 24.67 ± 0.33 |
| H3   | 5.49 ± 0.40 | 2.96 ± 0.04 | 0.93 ± 0.01 | 0.99 ± 0.02 | 20.00 ± 1.53 |
| L4   | 8.81 ± 0.41 | 3.24 ± 0.04 | 0.96 ± 0.01 | 0.96 ± 0.01 | 29.33 ± 0.88 |
| H4   | 9.56 ± 0.20 | 3.26 ± 0.02 | 0.96 ± 0.01 | 0.97 ± 0.01 | 28.67 ± 0.33 |
| L1   | 1.69 ± 0.09 | 1.30 ± 0.23 | 0.65 ± 0.07 | 1.39 ± 0.16 | 3.00 ± 1.00 |
| H1   | 3.65 ± 0.33 | 2.19 ± 0.11 | 0.86 ± 0.02 | 1.06 ± 0.05 | 8.00 ± 0.58 |
| L2   | 5.09 ± 0.43 | 2.55 ± 0.06 | 0.90 ± 0.01 | 0.99 ± 0.01 | 13.33 ± 0.88 |
| 30d  | H2     | 5.34 ± 0.32 | 2.88 ± 0.01 | 0.93 ± 0.01 | 0.98 ± 0.02 | 19.00 ± 1.00 |
| L3   | 4.65 ± 1.09 | 2.55 ± 0.08 | 0.91 ± 0.01 | 0.99 ± 0.02 | 13.33 ± 1.20 |
| H3   | 4.88 ± 0.16 | 2.51 ± 0.16 | 0.90 ± 0.02 | 1.02 ± 0.02 | 12.33 ± 2.33 |
| L4   | 9.49 ± 0.20 | 2.89 ± 0.02 | 0.94 ± 0.01 | 0.97 ± 0.01 | 20.00 ± 0.01 |
| H4   | 9.87 ± 0.15 | 2.96 ± 0.07 | 0.94 ± 0.01 | 0.96 ± 0.01 | 21.67 ± 0.88 |
| L1   | 1.81 ± 0.43 | 1.45 ± 0.23 | 0.67 ± 0.08 | 1.55 ± 0.29 | 3.33 ± 1.33 |
| Days | Treats | Diversity index (U) | Diversity index (H') | Simpson index | Shannon evenness | Carbon source utilization richness index(s) |
|------|--------|---------------------|---------------------|---------------|-----------------|---------------------------------------------|
|      | H1     | 0.13 ± 0.01         | 2.02 ± 0.13         | 0.79 ± 0.05   | 0.01 ± 0.01     | 0.11 ± 0.01                                 |
|      | L2     | 4.17 ± 0.17         | 2.18 ± 0.01         | 0.87 ± 0.01   | 1.06 ± 0.04     | 8.00 ± 0.58                                 |
|      | H2     | 3.28 ± 0.20         | 1.93 ± 0.09         | 0.82 ± 0.02   | 1.14 ± 0.07     | 5.67 ± 0.88                                 |
| 180d | L3     | 2.87 ± 0.69         | 2.45 ± 0.19         | 0.89 ± 0.03   | 1.14 ± 0.10     | 10.33 ± 3.53                                |
|      | H3     | 2.22 ± 0.35         | 1.49 ± 0.20         | 0.70 ± 0.07   | 1.37 ± 0.27     | 3.67 ± 1.20                                 |
|      | L4     | 6.79 ± 0.60         | 2.84 ± 0.05         | 0.93 ± 0.01   | 0.97 ± 0.02     | 19.00 ± 2.00                                |
|      | H4     | 8.53 ± 0.19         | 3.00 ± 0.04         | 0.94 ± 0.01   | 0.96 ± 0.01     | 22.67 ± 0.33                                |

## The activation effect of CO₂ on soil organic carbon mineralization

As illustrated in Fig. 4, at the initial culture stage, soil microbial activity increased under high CO₂ concentrations, which led to increased soil organic carbon mineralization. However, as culture time increased, soil microbial activity gradually decreased, and the microbial activity in soil gradually decreased after 50 days of culture in high CO₂ conditions.

Correlation analysis showed that cumulative CO₂ release was positively correlated with AWCD value, diversity index, and richness index (Table 5).
Table 5
Correlation analysis of soil microbial diversity index with AWCD value and carbon dioxide cumulative release

|                      | CO2 cumulative release | AWCD value | Diversity index (U) | Diversity index (H) | Simpson index | Evenness |
|----------------------|------------------------|------------|---------------------|---------------------|---------------|----------|
| AWCD value           | 0.823**                |            |                     |                     |               |          |
| Diversity index (U)  | 0.844**                | 0.977**    |                     |                     |               |          |
| Diversity index (H)  | 0.610**                | 0.835**    | 0.783**             |                     |               |          |
| Simpson index        | 0.512*                 | 0.691**    | 0.679**             | 0.933**             |               |          |
| Evenness             | 0.192                  | -0.005     | 0.099               | -0.328              | -0.370        |          |
| Richness index of C source utilization | 0.813** | 0.967** | 0.955** | 0.871** | 0.744** | 0.023 |

**Discussion**

Previous studies have suggested that accelerated SOM decomposition rates will result in greater quantities of CO$_2$ being emitted into the atmosphere, thus exacerbating the greenhouse effect; whereas the higher availability of other nutrients due to SOM decomposition can facilitate photosynthesis and growth, leading to enhanced sequestration of atmospheric CO$_2$ (Erhagen et al., 2013; Wang et al., 2015). Moreover, Chen et al. (Chen et al., 2015) revealed that elevated CO$_2$ and temperature greatly enhance the temperature sensitivity of SOM decomposition. However, data on the effects of CO$_2$ on the mineralization of SOM is limited. In our study, under high CO$_2$ conditions, the cumulative CO$_2$ release and CO$_2$ release rate of soil containing chicken manure, cow manure, or corn straw were higher than those under low CO$_2$ concentrations, suggesting the increased CO$_2$ promotes SOC mineralization. Additionally, the content of total organic carbon and active organic carbon in soil containing chicken manure or cow manure was reduced under the conditions of high CO$_2$ but was increased in soil containing corn straw under the same conditions. We speculated that this occurred because straw contains high levels of easily decomposed organic matter, which is conducive to the growth and activity of microorganisms, thus accelerating the transformation of organic carbon in straw and increasing the content of soil organic carbon.

As one of the essential nutrients for plant growth, nitrogen is mineralized into inorganic forms, including NH$_4^+$-N and NO$_3^-$-N, by microbial decomposition (Hu et al., 2019; Xia et al., 2010; Yuan et al., 2016); Gai et al. (Gai et al., 2019) found that long-term manure application and straw incorporation are beneficial for soil NO-N content retention. Additionally, Xie et al. (Xie et al., 2019) reported that management with an organic fertilizer can markedly reduce the levels of ammonium nitrogen (NH-N) and nitrate nitrogen (NO-N) (TK) in runoff water. Our data revealed that, compared with the groups exposed to low CO$_2$ concentrations, the content of NO$_3^-$-N was significantly decreased in groups treated with high CO$_2$.
concentrations, indicating that high CO₂ concentration can reduce the mineralization of organic N in soil with added organic materials. Moreover, a previous study suggested that increased NOFOX- concentrations in soil are due to the nitrogenization of NHFOX+ (Jien et al., 2017); however, the content of NHFOX+-N was not detected in the present study, it will be evaluated in future experiments.

Given that microbial biomass is generally C-limited in agricultural soil, the application of organic fertilizers presumably stimulates the growth and activity of microorganisms by increasing SOC labile fractions, which can lead to the changes in the mineralization rate of soil organic matter (Luo et al., 2014). Accumulating evidence suggests that the stimulatory effect of organic materials on SOM mineralization is determined by carbon stability and pore structure characteristics (Chen et al., 2018; Luo et al., 2011; Sun et al., 2014); Generally, the properties of organic materials containing different types of raw materials are quite different, which leads to different effects on soil microorganisms and enzyme activities (Lehmann et al., 2011; Lu et al., 2014). However, to date, the effect of biodiversity on soil carbon and nitrogen mineralization remains controversial (Hol et al., 2010; Johannes et al., 2009; Naidoo et al., 2008; Philippot et al., 2013). Results of the present study showed that soil microbial diversity was significantly correlated with soil carbon accumulation and mineralization. In particular, increased CO₂ concentration increased soil microbial diversity during the early incubation period, but in later stages of incubation, the soil microbial diversity decreased, which was in line with previous reports related to functional redundancy (Kelly et al., 2016; Loreau, 2010; Moya and Ferrer, 2016). Functional redundancy studies suggest that different species can perform the same function, and the loss of one species can be replaced by another species; therefore, reduced biodiversity does not have significant impact on the function of the ecosystem. Our study confirmed that increasing CO₂ concentration only affected soil microbial diversity during a certain period of time. We speculate that the microbial species in the soil were restored and adjusted after a period of time, and although the diversity was reduced, the community's functions were not affected, since species play redundant roles.

In conclusion, our results showed that adding organic materials to soil can accelerate the mineralization of organic carbon and reduce the mineralization of nitrogen under high CO₂ concentrations. Briefly, the content of total organic carbon and active organic carbon in soil could be reduced by adding chicken manure or cow manure, or increased by adding straw under high CO₂ concentrations. Moreover, after the addition of different organic materials, the utilization of carbon sources by soil microorganisms differed because under the conditions of CO₂ enrichment, soil microbial activity increased, which accelerated the mineralization of soil organic carbon and caused a positive excitation effect in the short term. However, with the extension of culture time, soil microbial activity decreased gradually, and a negative excitation effect occurred in the soil.

Declarations

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Competing Interests

The authors declare that they have no competing interests.

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Figures
Figure 1

The cumulative release (A, C–F) and the release rate of CO2 (B).
Figure 2

Utilization of carbon sources by soil microorganisms, and principal component analysis of soil microbial community metabolism under different treatment conditions. (A) The average rate of color change (AWCD) values after incubation for 1, 30, and 180 days, respectively. Soil microbial community structure and carbon source utilization pattern were changed by adding different organic materials and taking samples at different culture times (B).
Figure 3

The heatmaps of carbon source utilization rate of soil microorganisms cultured for 1, 30, and 180 d under different treatment conditions. B1, methyl pyruvate; C1, twain 40; D1, twain 80; E1, a-cyclodextrin; F1, glycogen; G1, d-fibrodissaccharide; H1, a-d-lactose; A2, ss-methyl d-glucoside; B2, D-xylose; C2, i-alginol; D2, d-mannitol; E2, n-acetyl-d-glucosamine; F2, d-glucosamine; G2, glucose-1-phosphate; H2, D, l-a-glycerin; A3, d-galactonate; B3, d-galacturonic acid; C3, 2-hydroxybenzoate; D3, 4-hydroxybenzoate; E3, r-hydroxybutyric acid; F3, itaconic acid; G3, a-buitanoic acid; H3, d-malic acid; A4, l-arginine; B4, L-asparaginic acid; C4 l-phenylalanine; D4, l-serine; E4, l-threonine; F4, glycol-l-glutamate; G4, phenylethylamine; H4, putamine.
Figure 4

Stimulatory effect of CO2 on soil organic carbon mineralization.