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Temperature effects on soil organic carbon, soil labile organic carbon fractions, and soil enzyme activities under long-term fertilization regimes

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ABSTRACT

The effects of temperature changes on soil organic carbon (SOC), labile organic carbon fractions (microbial biomass carbon, MBC; dissolved organic carbon, DOC; particulate organic carbon, POC), and enzyme activities under long-term fertilization regimes as well as their relationships at different temperatures were investigated in this study. Soil samples were collected in the fluvo-aquic soil of a 26-year fertilizer trial in the North China Plain after maize harvest in 2012, and four treatments were selected: control of no fertilizer (CK), standard rate of mineral fertilizer treatment (SMF), standard rate of organic manure treatment with N input rate equal to SMF (SMA), and half-standard rate of organic manure plus half-standard rate of mineral fertilizer treatment (1/2(SMA + SMF)). We determined soil chemical properties and labile organic carbon fractions using standard methods and the activities of nine soil enzymes involved in C, N, and P cycling in a 21-day incubation experiment at different temperatures (5 °C, 15 °C, 25 °C, and 35 °C) by micro-plate fluorometric assay. Additionally, we investigated the relationships among them using redundancy analyses (RDA) at four temperatures. The results indicated that (1) temperature, fertilization, and their interaction had significant effects on SOC, MBC, DOC, POC, and most of the soil enzyme activities; (2) long-term organic manure treatments (SMA and 1/2 (SMA + SMF)) significantly improved SOC, MBC, DOC, and POC contents and seven hydrolytic enzyme activities (α-1,4-glucosidase, β-1,4-glucosidase, β-1,4-xylosidase, cellobiohydrolase, L-leucine amino-peptidase, β-1,4-*N*-acetylglucosaminidase, phosphatase) at different temperatures, compared with the mineral fertilized treatment (SMF) and CK. However, oxidoreductases (peroxidase and phenol oxidase) showed the opposite trend with hydrolytic enzyme activities and had higher values in SMF and CK treatments; (3) SOC, MBC, DOC, POC, and most of the soil enzyme activities decreased with increasing temperature; (4) RDA revealed that the dominant factors of SOC and soil labile organic carbon fractions affecting soil enzyme activities were POC and SOC at 5 °C, DOC and POC at 15 °C, DOC and SOC at 25 °C, and MBC, DOC, and SOC at 35 °C. In conclusion, temperature changes significantly altered soil enzyme activities by driving changes in the rates of SOC decomposition and the fractions of soil labile organic carbon. Our conclusions have clear implications for soil ecosystem and biogeochemical cycles under climate change.

1. Introduction

Soil enzymes with highly catalytic capacity are produced by soil microorganisms and are the main medium of controlling biochemical processes, such as soil organic carbon (SOC) decomposition and nutrient cycling (Dick, 1994; Allison and Jastrow, 2006). Changes in the activities of soil enzymes have been observed to be closely related to shifts in rates of SOC decomposition and patterns of turnover in organic carbon pools

Abbreviations: SOC, soil organic carbon; MBC, microbial biomass carbon; DOC, dissolved organic carbon; POC, particulate organic carbon; AG, α-1, 4-glucosidase; BG, β-1, 4-glucosidase; BXYL, β-1, 4-xylosidase; CBH, Cellobiohydrolase; LAP, L-leucine aminopeptidase; NAG, β-1, 4-N-acetylglucosaminidase; PHOS, phosphatase.

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(Bending et al., 2002; Sinsabaugh et al., 2005; Veres et al., 2015). For instance, a positive relationship between soil enzyme activities, such as soil phosphatase, β-glucosidase, cellulose and SOC increase has been found in agroecosystems (Böhme et al., 2005; Saha et al., 2008; Li et al., 2015); however, soil phenol oxidase activity showed negative correlation with SOC increase and the degree of soil humidification (Lin, 2010; Li et al., 2015). Soils with higher SOC content, especially higher labile organic carbon fractions such as microbial biomass carbon (MBC), potassium permanganate oxidizable carbon ($KMnO_4$ -C), and water-soluble carbohydrate carbon were also reported to have higher soil enzyme activities (Shi et al., 2006; Nayak et al., 2007; Bowles et al., 2014).

Both SOC including soil labile organic carbon fractions and soil enzyme activities were significantly affected by environmental factors, such as fertilization, tillage, irrigation, and temperature (Mandal et al., 2007; Lefevre et al., 2014). Many previous studies have demonstrated that long-term fertilization, especially organic manure input, could directly or indirectly influence SOC and soil enzyme activities in long-term experimental sites (Böhme et al., 2005). Liu et al. (2013) reported that SOC and labile organic carbon fractions [MBC, dissolved organic carbon (DOC), and particulate organic carbon (POC)] were significantly increased under long-term fertilization regimes, especially in treatment with organic manure application. Additionally, Saha et al. (2008) indicated that the application of organic manure over the long term could significantly increase soil cellulase, carbohydrate, acid and alkaline phosphatase, protease, and dehydrogenase activity; however, it had no effect on urease activity. Among environmental factors, climate change, particularly global warming, has been the major cause of accelerating global soil C losses (Knorr et al., 2005; Zhou et al., 2012), but, until now, the temperature sensitivity of SOC pools was still a topic for debate. Many researches revealed that soil labile organic carbon pools were more (Liski et al., 1999; Thornley and Cannell, 2001), less (Knorr et al., 2005) sensitive to warming than resistant organic carbon pools, or they responded similarly to global warming (Fang et al., 2005; Leifeld and Fuhrer, 2005). Recently, a range of studies have investigated the temperature sensitivity of soil enzyme activities in different soil ecosystems (Koch et al., 2007; Wallenstein et al., 2012; Stone et al., 2012). It was reported that the temperature sensitivity of soil enzyme activities decreased with increasing temperature (Stone et al., 2012), and these changes in the patterns of soil enzyme activities were demonstrated to be driven by changes in the patterns of soil labile organic carbon fractions under warming conditions (Zhou et al., 2013; Bowles et al., 2014). Zhou et al. (2013) indicated that a six-year warming trend increased the acid phosphatase and *N*-acetylglucosaminidase in surface soils but decreased β-glucosidase and acid phosphatase in the subsurface in temperate grassland due to changes in MBC.

All of these facts strengthen the idea that due to the strong effects of temperature on microbial decomposition of SOC pools, enzyme activities are sensitive to the changes in temperature (Zhou et al., 2013). However, temperature effects on changes in soil enzyme activities and soil labile organic carbon fractions under long-term fertilization regimes, especially regarding the mechanisms driving temperature changes on the patterns of soil enzyme activities, remain unclear. Therefore, an incubation experiment was conducted in a 26-year fertilizer trial, and the objectives of this research were to (1) investigate the responses of soil enzyme activities, SOC, and soil labile organic carbon fractions (MBC, DOC and POC) to increasing temperatures in different fertilizer treatments and (2) explore the dominant factors of SOC and soil labile organic carbon fractions controlling the patterns of soil enzyme activities under warming conditions. We hypothesize that temperature changes could regulate soil enzyme activities under long-term fertilization regimes by changing the decomposition processes of SOC, especially in regard to soil labile organic carbon fractions. These observations could contribute to the understanding of responses of soil enzyme activities to climate change, which is critical for predicting SOC decomposition rates and nutrient cycling and providing impetus for understanding the ways in which climate change may affect the biochemical functioning of soil ecosystems.

2. Materials and methods

2.1. Site description and experimental design

The experimental site was established in 1986 at the Dezhou Station of the Chinese Academy of Agricultural Sciences, Yucheng, Shandong, China (36° 50′ N, 116° 34′ E). The region surrounding the site has a warm, temperate semi-humid monsoon climate with an annual average temperature of 13.4 °C and mean annual precipitation of 569 mm. The soil is a fluvo-aquic light loam (clay 21.4%, silt 65.5%, sand 3.0%) and the initial properties of the soil (0–20 cm) in 1986 were as follows: total organic carbon of 3.93 g kg^{-1}; total N of 0.51 g kg^{-1}; available N, P, and K of 37.5, 7.5, and 73.0 mg kg^{-1}, respectively; cation exchange capacity of 15.84 cmol kg^{-1}; water-soluble salt content of 0.96 g kg^{-1}; and a pH value of 8.56. The cropping system was a typical winter wheat–summer maize rotation cropping system of the North China Plain.

This experiment was described in detail by Li et al. (2015); it consisted of six treatments with four replicates in a randomized complete block design, and the size of each plot was 28 m^2 (4×7 m). Paving slabs (0.8 m) separated each plot from the others. The treatments were (1) control of no fertilizer (CK); (2) standard rate of mineral fertilizer treatment that reflects the practice of local (SMF); (3) standard rate of organic manure treatment with N input rate equal to SMF (SMA); (4) half-standard rate of organic manure plus half-standard rate of mineral fertilizer treatment (1/2(SMA + SMF)); (5) double rates of standard organic manure treatment (DMA); and (6) double rates of mineral fertilizer treatment (DMF). The mineral fertilizers (N, P, and K) were urea, superphosphate, and potassium sulfate with standard input rates of 375–450 kg N ha^{-1}, 225–300 kg P_2O_5 ha^{-1}, and 150 kg K_2O ha^{-1} per year, respectively. The organic manure used was cattle manure, which originated from the nearby dairy industry and was completely composted for several months prior to application. Its application rate was based on organic manure total N content, and the range of nutrient contents in cattle manure were 1.00–1.84% N, 0.58–1.67% P_2O_5, and 0.98–1.98% K_2O, respectively.

Total mineral fertilizer was applied twice per year; half was applied in October before the sowing of winter wheat (Jimai 22), and the other half was applied in June before the sowing of summer maize (Zhengdan 958). For winter wheat, 40% N and 100% P_2O_5 and 100% K_2O of mineral fertilizer were applied before sowing, and 60% N was applied at the jointing stage of winter wheat. For summer maize, 40% N was applied before sowing, and 60% N was applied during the elongation stage of summer maize. Organic manure was applied once per year before winter wheat sowing. Mineral fertilizer and organic manure were uniformly broadcasted onto the topsoil before plowing the soil. The seeds were sown by hand, and the seeding rates of winter wheat and summer maize were 112.5 kg ha^{-1} and 67500 plants ha^{-1}, and their row spacings were 30 and 60 cm, respectively. The field management was in accordance with the practice of local farmers.

2.2. Soil sampling

To determine the effects of different fertilizer managements with long-term equal N input rate as the practice of local farmers