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RESEARCH ARTICLE

Long-term warming altered soil physical structure and soil organic carbon pools in wheatland field

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Summary
The impacts of long-term warming on soil physical structure and soil organic carbon (SOC) pools are currently disputed and uncertain. We conducted an eleven-year warming experiment in wheatland field in Henan, China. We found that long-term warming significantly increased soil bulk density by 4.5%, and significantly decreased total porosity and non-capillary porosity by 3.4% and 5.0%, respectively. Besides, long-term warming decreased the >2 mm fraction proportion and increased <0.053 mm fraction proportion of dry and wet aggregates. The mean weight diameter value for dry and wet aggregates in long-term warming treatment was significantly decreased by 7.0% and 6.7%, respectively. Moreover, long-term warming significantly decreased the total SOC, very labile pool (F1) and labile pool (F2) content by 10.6%, 30.6%, and 43.6%, and significantly increased the less labile pool (F3) and non-labile pool (F4) content by 94.2% and 21.1%, respectively. Long-term warming increased the passive carbon pool percentage but decreased the active carbon pool (ACP) percentage. Our results suggest that long-term warming negatively affected the soil's physical structure and impaired soil ACP accumulation. The findings of this study help improve our understanding of the response of farmland soils in northern China to climate change and provide scientific basis for establishing carbon management measures in farmland.

Keywords: active carbon pool; warming; soil aggregate; soil organic carbon; wheatland

Introduction

The global surface temperature has risen by about 1°C than the preindustrial level and is expected to increase by 1.5°C from 2030 to 2052 (IPCC, 2022). Global warming can profoundly impact carbon (C) cycle of terrestrial ecosystems (Crowther *et al.*, 2016; Koven *et al.*, 2017; Lavallee *et al.*, 2020). Soils have the largest terrestrial C pool, which is about three times that of the atmosphere C pool and four times that of biotic C pool (Lal, 2016). Small changes in soil organic carbon (SOC) stock can have a significant impact on atmospheric CH_4 and CO_2 concentrations, thus influencing global climate change (Cox *et al.*, 2013). In addition to regulating climate, organic carbon is also important in ecosystem health and function, providing nutrients and energy for plants and microorganisms (Milne *et al.*, 2015). Thus, understanding the impact of climate warming on soil organic carbon pools is essential for accurately predicting carbon-climate models and better ecosystem management to alleviate the negative effects of global change.

Soil physical structure refers to the arrangement of the soil solid particles and the pore spaces, and plays a vital role in soil organic carbon dynamics (Bronick and Lal, 2005; Mustafa *et al.*, 2020). Soil aggregates are the basic components of soil structure. Good soil aggregate structure is essential for promoting fertility and plant growth, and maintaining appropriate environmental quality, especially for soil carbon sequestration (Ma *et al.*, 2020; Six *et al.*, 2002). Climate change has a significant impact on the formation and development of soil structure (Lal, 2020). Increasing greenhouse gas concentrations and global warming can influence soil aggregation by altering temperature and moisture conditions (Comegna *et al.*, 2012). Some studies observed that short-term warming ($<$5 a) increased the non-aggregate silt + clay fractions, and the aggregate stability decreased (Guan *et al.*, 2018). In the medium and long-term warming process (5–10 a), accelerated soil evaporation led to soil drying, which increased soil runoff and erosion, and then hindered the development of soil aggregate structure (Bronick and Lal, 2005; Xue *et al.*, 2011). In addition, some researches indicated that warming reduced SOC content and its availability, thereby reducing aggregate stability (Guo *et al.*, 2022). However, other researches have also shown that long-term warming had no effect on soil nutrients, meaning no effect on soil structure (Zhou *et al.*, 2013). In general, soil properties do not respond quickly when the surrounding environment changes (Guo *et al.*, 2022). Therefore, long-term warming experiments ($>$10 a) are more appropriate to study the influence of warming on soil structure, as they can more accurately reflect the variation of soil properties.

Soil organic carbon is a complex compound with varying turnover times. According to the turnover time of organic carbon, the C fractions can be divided into labile or active carbon pool (ACP) and stable or passive carbon pool (PCP) (Liu *et al.*, 2021; Majumder *et al.*, 2008). The labile or ACP has a short turnover time, is the main nutrient source of plants and the main energy source of soil microorganisms, and is susceptible to management measures and climatic conditions (Sahoo *et al.*, 2019). Compared with labile or aACP, stable or PCP has a longer turnover time, which is recalcitrant and is often used as a reliable index of C sequestration potential of a system (Song *et al.*, 2018). With global warming, soil carbon pools are significantly affected. At present, a large number of studies have reported the impact of global warming on soil organic carbon pools and obtained inconsistent conclusions. For example, Xu *et al.* (2015) and Samal *et al.* (2020) found that the ACP was very sensitive to temperature warming. In contrast, Lefevre *et al.*, 2014) reported that PCP was more sensitive to elevated temperature. Other studies suggested that ACP and PCP had similar responses to temperature increase (Fang *et al.*, 2005; Leifeld and Fuhrer, 2005). The highly incompatible results suggest that more attention should be paid to the effects of warming on soil organic carbon pools.

Wheat is one of the world's important food crops, and about 21% of the world's food comes from wheat (Ortiz *et al.*, 2008). China is the country that produces and consumes the most wheat in the world, and wheat is the third major production crop in China. In 2010, China's wheat production accounted for 17.6% (115 million metric tons) of the world, and wheat harvest area accounted for 11.2% (24 million hectares) of the world (FAO, 2013). Due to the pivotal status of wheat in the grain industry, the importance of maintaining the safety of wheat production cannot be overlooked, and the importance of soil physical structure and soil carbon pools in crop growth and nutrient supply cannot be ignored in the context of global warming. Our study aimed to identify the influence of long-term warming on the soil's physical structure, including soil pore and aggregate characteristics, and soil carbon pools in wheatland fields.

Materials and Methods

Experimental site

The long-term warming experiment was initiated in August 2012 in the Kaiyuan campus farm of Henan University of Science and Technology, Luoyang, Henan Province, China (34°38′N, 112°22′E). The climate at the study site was a warm temperate semi-arid semi-humid monsoon climate with a mean annual temperature of 13.7°C, and a mean annual precipitation of 650.2 mm. The soil at our site is a typical cinnamon soil with a medium loam texture. The main soil properties are as follows: pH (1:5, soil: H_2O) 7.4, bulk density 1.01 g cm^{-3}, soil organic matter 10.7 g kg^{-1}, total N 1.06 g kg^{-1}, available P 3.46 mg kg^{-1}, and available K 135.8 mg kg^{-1}.

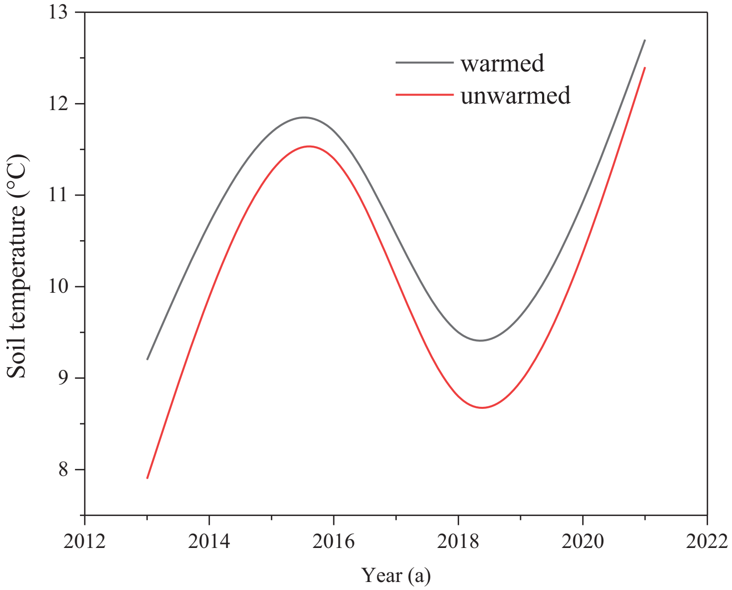

Figure 1. Differences in soil temperature between the warmed and unwarmed plots over the 2012–2022 growing seasons.

Experimental design

Random block design was used in this field experiment, which included two treatments: warmed and unwarmed control (unwarmed) (Fig. 1). Each treatment had three replicates. The area of each replicate plot was 8 m^2 (2 m × 4 m). In order to avoid heating contamination, adjacent plots were separated by 10 m.

The field warming device used in this study was similar to the device shown by Chen *et al.* (2014) and Zheng *et al.* (2017). Briefly, it consisted of horizontal steel tubes with adjustable height and reflective curtain fixed on the steel tubes. Except for rainy and snowy days, the warmed plots were covered with curtains from sunset (around 19:00) to sunrise (around 07:00). The unwarmed plots were not covered by curtains. The distance between curtains and wheat canopy was kept at 20–25 cm to reduce the influence of curtains on air exchange. Using a digital temperature monitor (ZDR–41, Beijing Jingcheng Huatai Instrument Co., Ltd., China) to automatically monitor the temperature of 0–10 cm soil layer every 20 minutes during the whole growth period.

Crop management

In this experiment, the local drought-resistant and high-yield wheat variety Luohan 11 (Triticum aestivum L. cv Luohan 11) was selected. Wheat seeds were sown in November by hand at a density of 225 plants m^{-2} with a row spacing of 20 cm. In June of the second year, the wheat was harvested piece by piece according to different maturity dates of each treatment. The fertilizer application rates of N, P, and K in each plot were 220, 75, and 75 kg ha^{-1}, respectively. Two days before sowing, total P, total K, and 40% N were applied as basal dressing. The remaining 60% of N fertilizer was applied at 30% and 30% ratios at the wheat jointing and heading stages. To maintain the same agronomic management system among different treatments, the same fertilizer was applied to each plot on the same date. If irrigation was required according to soil moisture, the same irrigation system was applied to each plot. Other field management measures, such as weed, pest control, and pesticide application, were implemented according to local wheat planting methods.

Soil sampling and analysis

Soil samples were collected in June 2019 after wheat harvest. Five undisturbed soil samples were collected with a hand auger (5 cm in diameter) at a depth of 0–15 cm surface layer in each plot. Then the five undisturbed samples were thoroughly mixed into one sample. At the same time, three core samples were obtained from the center of the 0–15 cm layers in each plot with ring knives for soil bulk density measurement. Finally, all soil samples were transferred to the laboratory to determine the soil physicochemical properties.

Soil bulk density, total porosity, capillary porosity, and non-capillary porosity were determined by the conventional core method (**Hao *et al.*, 2018; Peng *et al.*, 2020). The separation and stability of soil aggregates were determined by conventional dry and wet sieving methods (Kemper and Rosenau, 1986; Yoder, 1936). The detailed determination process was consistent with that of Wu *et al.* (2018). The wet oxidation method was used to analyze the content of SOC (Walkley and Black, 1934). The modified Walkley and Black method described by Chan *et al.* (2001) was adopted to determine the different pools of SOC. Briefly, three acid aqueous solution ratios of 0.5:1, 1:1, and 2:1 were prepared with 5, 10, and 20 ml of concentrated sulfuric acid solution (corresponding to 12 N, 18 N, and 24 N of H_2SO_4, respectively). Four different SOC pools were extracted according to the order of reduced oxidation capacity:

F1 (very labile carbon pool): organic C oxidized under 12 N H_2SO_4.

F2 (labile carbon pool): difference of oxidizable under 18 N and 12 N.

F3 (less labile carbon pool): difference of oxidizable under 24 N and 18 N.

F4 (non-labile carbon pool): difference of total SOC and oxidizable under 24 N.

Active carbon pool (ACP) is the cumulative value of F1 and F2, and passive carbon pool (PCP) is the sum of F3 and F4 (Chan *et al.* 2001).

Soil aggregate stability index calculation

The mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimension (D) were adopted to quantify soil aggregate stability. The larger the MWD and GMD, the stronger the stability of aggregates. The smaller the D, the better soil structure and higher soil stability. $R_{0.25}$ is the mass percentage of the >0.25 mm aggregates. These indexes were calculated using the following equations (Cao *et al.*, 2021; Kemper and Rosenau, 1986; Tyler and Wheatcraft, 1992):

$$\mathrm{MWD} = \sum_i^n xiwi \Big/ \sum_i^n wi \tag{1}$$

$$\mathrm{GMD} = exp\left(\sum_i^n wilnxi \Big/ \sum_i^n wi\right) \tag{2}$$

$$D = 3 - \lg\left[\frac{m(i < xi)}{mt}\right] \Big/ \lg\left[\frac{xi}{xmax}\right] \tag{3}$$

$$R_{0.25} = \frac{mi > 0.25}{mt} \tag{4}$$

Where x_i denotes the mean diameter of each aggregate fraction (mm); w_i denotes the proportion of *i*th size fraction (%); $m(i < x_i)$ denotes the mass of aggregates smaller than *i*th size fraction (g); m_t denotes the total mass of aggregates (g); and x_{max} denotes the maximum diameter of the soil aggregate fractions (mm).

Table 1. Soil bulk density, porosity, and solid: liquid: gas ratio in the unwarmed and warmed treatments

		Sil porosity (%)			
Treatment	Bulk density (g cm^{-3})	Total porosity	Capillary porosity	Non-capillary porosity	solid: liquid: gas ratio
unwarmed	1.12 ± 0.01^b	57.55 ± 0.29^a	24.43 ± 1.07^a	33.12 ± 1.05^a	1.65:1.22:1
warmed	1.17 ± 0.03^a	55.60 ± 0.42^b	24.15 ± 0.59^a	31.45 ± 0.55^b	1.74:1.23:1

Note: Values are means ± standard errors ($n = 3$). Different lowercase letters (a, b) in the same column denote a significant difference between treatments ($p < 0.05$).

Data analysis

All data analyses were performed with Excel 2007 and SPSS 19.0. Two-way analysis of variance with least significant difference test was used to determine the differences among treatment means with probability level <0.05. All data were tested by Shapiro-Wilk and Levene for normality and homogeneity of variance. Origin 9.0 was employed to visualize the data.

Results

Long-term warming affects soil bulk density and porosity

Soil bulk density, porosity, and solid, liquid, and gas ratio in the unwarmed and warmed treatments are presented in Table 1. The soil bulk density in the warmed treatment was significantly higher by 4.5% ($p < 0.05$) than that in the unwarmed treatment. The total porosity and non-capillary porosity in the warmed treatment significantly decreased by 3.4% and 5.0% ($p < 0.05$), respectively, when compared with those of the unwarmed; but the capillary porosity showed no significant difference between the two treatments ($p > 0.05$). Compared with unwarmed treatment, warmed treatment increased the proportion of solids.

Long-term warming affects size distribution and structural stability characteristics of soil aggregates

Figure 2 shows the size distribution of dry and wet aggregates in the unwarmed and warmed treatments. For dry aggregates, the 2–0.25 mm size fraction exhibited the highest proportion (60.3–61.1% of the total aggregates), followed by the >2 mm (24.2–29.5%) and 0.25–0.053 mm (8.1–11.6%) size fractions, the <0.053 mm fraction had the lowest proportion (2.1–3.1%) in the two treatments. Besides, the warmed treatment significantly decreased the >2 mm dry aggregates by 17.8% ($p < 0.05$), and significantly increased the 0.25–0.053 mm and <0.053 mm dry aggregates by 29.7% and 24.2% ($p < 0.05$), when compared with the unwarmed. For wet aggregates, the proportion of <0.053 mm size fraction (33.5–43.2%) was the dominant size class, followed by the 2–0.25 mm (30.2–31.8%) and 0.25–0.053 mm (16.4–25.8%) size fractions, the >2 mm fraction had the lowest proportion (8.6–10.4%) in the two treatments. Furthermore, the warmed treatment significantly decreased the >2 mm and 0.25–0.053 mm wet aggregates by 16.9% and 36.7% ($p < 0.05$), and significantly increased the 2–0.25 mm and <0.053 mm wet aggregates by 5.2% and 28.8% ($p < 0.05$), respectively, when compared with the unwarmed.

Table 2 shows the structural stability characteristics of soil aggregates in the unwarmed and warmed treatments. For dry aggregates, the warmed treatment significantly decreased the MWD, GMD, and $R_{0.25}$ by 7.0%, 12.3%, and 4.9% ($p < 0.05$), and significantly increased the D by 4.0% ($p < 0.05$), respectively, when compared with the unwarmed. For wet aggregates, the warmed treatment significantly decreased the MWD and GMD by 6.7% and 15.4% ($p < 0.05$), respectively, when compared with the unwarmed. The D and $R_{0.25}$ of wet aggregates showed no significant difference between the two treatments ($p > 0.05$).

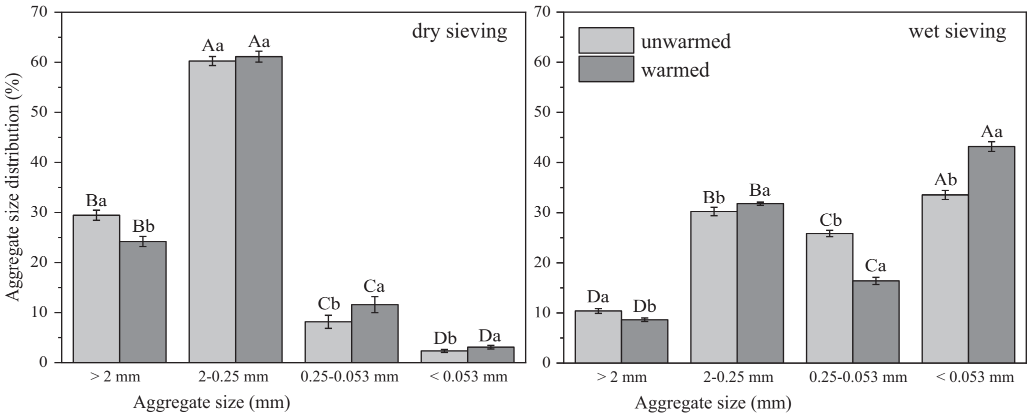

Figure 2. Soil aggregate size distribution in the unwarmed and warmed treatments. Different lowercase letters denote a significant difference between treatments ($p < 0.05$). Bars represent standard errors ($n = 3$).

Long-term warming affects soil carbon pools

Table 3 shows the content of different soil carbon pools in the unwarmed and warmed treatments. The SOC content in the warmed treatment was significantly lower by 10.6% ($p < 0.05$) than that in the unwarmed treatment. The F1 and F2 content in the warmed treatment were significantly lower by 30.6% and 43.6% ($p < 0.05$), respectively, than those in the unwarmed treatment. The F3 and F4 content in the warmed treatment were significantly higher by 94.2% and 21.1% ($p < 0.05$), respectively, than those in the unwarmed treatment. Compared with the unwarmed, the warmed significantly decreased the ACP by 40.0% ($p < 0.05$), and significantly increased the PCP by 38.2% ($p < 0.05$), respectively.

The percentage of different soil C pools to total SOC in the unwarmed and warmed treatments is shown in Fig. 3. Compared with the unwarmed, the warmed decreased the percentage of F1 and F2 from 44.3 to 33.4%, and from 22.3 to 14.1%, but increased the percentage of F3 and F4 from 7.8 to 16.9%, and from 25.5 to 34.6%, respectively. The warmed increased the PCP percentage but decreased the ACP percentage compared with the unwarmed.

Discussion

In the present study, long-term warming increased soil bulk density of wheatland field (Table 1). A similar result was reported by Bryk *et al.* (2017), who found that soil bulk density of the upper 0–5 cm layer was significantly negatively correlated with air temperature. This phenomenon is mainly due to the fact that soil bulk density is closely related to SOC content, and higher temperature tends to result in lower standing stock of SOC (Franzluebbers *et al.*, 2001), thereby leading to the decrease of soil bulk density. Soil pore system is an important aspect of soil structure, affecting the transport of water, solutes, and air (Kuncoro *et al.*, 2014; Menon *et al.*, 2020). Long-term warming decreased soil total porosity and non-capillary porosity (Table 1). Similar trends in the USA Great Plains were reported by Xue *et al.* (2011). The decrease in soil porosity in the warming system is due to the fact that increasing soil temperature reduces soil moisture (Scharn *et al.*, 2021). Dry soil usually has an unstable and poorly developed structure, resulting in high apparent density (compaction) and low porosity (Wen *et al.*, 2022). As the soil porosity decreased in the warmed treatment, the ratio of soil solids increased (Table 1).

Soil aggregate is an important index reflecting soil structure. The particle size distribution of soil aggregates influences material circulation and energy flow (Polakowski *et al.*, 2021). Long-term warming altered the particle size distribution of soil aggregates. Specifically, warming

Table 2. Soil aggregate structural stability characteristics in the unwarmed and warmed treatments

Sieving method	Treatment	MWD (mm)	GMD (mm)	D	$R_{0.25}$ (%)
Dry sieving	Unwarmed	1.28 ± 0.02^a	1.06 ± 0.04^a	2.26 ± 0.03^a	89.71 ± 1.55^a
	Warmed	1.19 ± 0.03^b	0.93 ± 0.05^b	2.35 ± 0.03^b	85.33 ± 1.95^b
Wet sieving	Unwarmed	0.60 ± 0.02^a	0.26 ± 0.01^a	2.80 ± 0.01^a	40.62 ± 1.24^a
	Warmed	0.56 ± 0.01^b	0.22 ± 0.00^b	2.83 ± 0.02^a	40.43 ± 0.44^a

Note: MWD, mean weight diameter; GMD, geometric mean diameter; D, fractal dimension; $R_{0.25}$ is the mass percentage of the >0.25 mm aggregates. Values are means ± standard errors ($n = 3$). Different lowercase letters (a, b) in the same column denote a significant difference between treatments ($p < 0.05$).

Table 3. The content of different soil carbon pools in the unwarmed and warmed treatments

Treatment	SOC (g kg^{-1})	F1 (g kg^{-1})	F2 (g kg^{-1})	F3 (g kg^{-1})	F4 (g kg^{-1})	ACP (g kg^{-1})	PCP (g kg^{-1})
unwarmed	13.34 ± 0.40^a	5.91 ± 0.27^a	2.98 ± 0.14^a	1.04 ± 0.19^b	3.41 ± 0.39^b	8.89 ± 0.26^a	4.45 ± 0.32^b
Warmed	11.93 ± 0.51^b	4.10 ± 0.35^b	1.68 ± 0.21^b	2.02 ± 0.35^a	4.13 ± 0.32^a	5.78 ± 0.18^b	6.15 ± 0.34^a

Note: SOC, soil organic carbon, F1, very labile pool; F2, labile pool; F3, less labile pool; F4, non-labile pool; ACP, active carbon pool; PCP, passive carbon pool. Values are means ± standard errors ($n = 3$). Different lowercase letters (a, b) in the same column denote a significant difference between treatments ($p < 0.05$).

decreased the >2 mm fraction proportion and increased <0.053 mm fraction proportion of dry and wet aggregates (Fig. 2). This indicated that warming promoted the breakdown of macroaggregates (>2 mm) into silt + clay-sized aggregates (<0.053 mm). This phenomenon is partly due to warming leading to soil drying, preventing soil aggregation and structural development (Bronick and Lal, 2005; Guan *et al.*, 2018). In addition, aggregate breakdown is a good measure for soil erodibility, because it increases the proportion of finer, more easily transportable microaggregates, thereby increasing the risk of soil erosion. Therefore, climate warming may increase the risk of soil erosion.

The stability of soil aggregates is a good indicator of soil degradation (Six *et al.*, 2004). Long-term warming decreased the MWD and GMD, and increased the D of dry and wet aggregates (Table 2), indicating that warming decreased the aggregate stability and corrosion resistance. This result was consistent with the findings of Guan *et al.* (2018) and Guo *et al.* (2022). Soil organic matter is very important for the formation of soil aggregates, which combine with small particles to form stable aggregate structures and promote the development of soil structures (Six *et al.*, 2004; Tisdall and Oades, 1982). Warming will increase the turnover rate of soil organic carbon and the consumption of unstable carbon pools (Guo *et al.*, 2022), leading to a decline in soil organic matter content. Therefore, the stability of soil aggregates will decrease under warming conditions.

Climate change significantly affects soil organic carbon pools (Sahoo *et al.*, 2019; Samal *et al.*, 2020). Our result suggested that long-term warming significantly decreased the SOC content (Table 3). This was consistent with previous researches suggesting that the increase in temperature had a negative impact on soil organic carbon content (Qi *et al.*, 2016; Wang *et al.*, 2016). This result can be attributed to the increase in the soil respiration rate and the utilization efficiency of soil microbes for SOC with increasing temperature (Allison *et al.*, 2010; Hou *et al.*, 2016; Lefevre *et al.*, 2014).

According to the turnover rate of SOC pools, SOC pools can be divided into ACP and PCP. The ACP, represented by the very labile (F1) and the labile pool (F2), refers to the fraction of organic C that is easily decomposed and poorly stable and is strongly influenced by microbial activity (Sahoo *et al.*, 2019). The PCP, represented by the less labile pool (F3) and the non-labile pool (F4), is considered to be the more stable form of organic C, and is insensitive to soil and crop management (Hazra *et al.*, 2018). In this study, long-term warming significantly decreased the content of F1 and

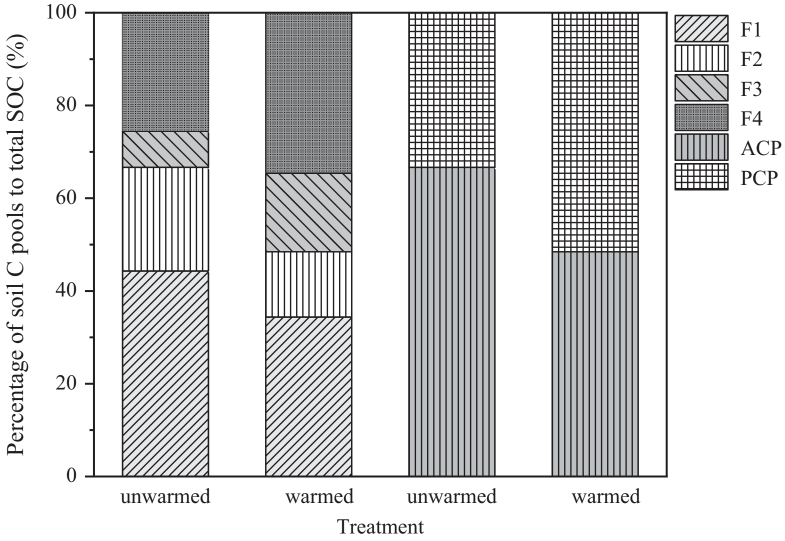

Figure 3. The percentage of different soil C pools to total SOC in the unwarmed and warmed treatments.

F2, while increasing the content of F3 and F4, suggesting that long-term warming decreased the ACP, and increased the PCP (Table 3). This finding was in conformity with Samal *et al.* (2020), who observed that under increased temperature, soil ACP was depleted, while PCP was enriched, and soil total organic carbon declined in subtropical humid climatic regions. The soil's ACP decreased in response to increased temperature due to the higher decomposition of labile carbon. The PCP increased in response to increased temperature may be due to the reduction of substrates available to microorganisms, resulting in a decrease in the temperature sensitivity of the remaining organic carbon, limiting further decomposition (Moinet *et al.*, 2018; Thiessen *et al.*, 2013). This leads to the accumulation of more PCP in warm.

Conclusion

An eleven-year warming experiment was conducted in wheat field. Our results indicated that long-term warming negatively impacted on soil's physical structure. The soil bulk density increased, while the total porosity and non-capillary porosity decreased in warmed treatment. Long-term warming treatment promoted the breakdown of macroaggregates (>2 mm) into silt + clay-sized aggregates (<0.053 mm), and decreased the soil aggregate stability of wheat field. Besides, long-term warming decreased the total SOC content and ACP, while increasing the PCP. Our study demonstrates that long-term warming may alter the soil's physical structure and affect the distribution and turnover of different soil organic carbon pools of wheatland field.

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