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RESEARCH ARTICLE

Changes in soil aggregation characteristics and the sequestration of carbon and nitrogen after long-term slight nighttime warming in the farmland of central China

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Summary

The impact of long-term nocturnal warming on soil aggregate stability and carbon (C) and nitrogen (N) sequestration was examined in agricultural fields. Employing a passive warming system, the nighttime warming experiment involved two treatments: a control check (CK) and a nighttime warming treatment (WT), spanning the entire growth seasons of wheat from 2013 to 2021. The annual average temperature increase ranged from 0.3 to 1.3°C, with an average increment of 0.71°C over the eight years. Both dry and wet sieving methods showed that nighttime warming reduced the proportion of macroaggregates and increased microaggregates compared to CK, thereby diminishing soil aggregate (SA) stability. While nighttime warming had the potential to elevate the concentrations and contents of soil organic carbon (SOC) and total nitrogen (TN), significant effects were only observed in the concentrations and contribution rates of SOC and TN. The C/N ratios across different particle sizes within SA were not significantly affected by nighttime warming. Additionally, no significant correlation was found between the SOC/TN contents and contribution rates and the stability of SA. These results suggest that eight years of nighttime warming could undermine the stability of SA, yet it did not impact the pools of N and C in the agricultural lands of central China.

Keywords: long-term nighttime warming; farmland; aggregate stability; carbon and nitrogen sequestration

Introduction

Soil aggregates, the fundamental units of soil structure, are formed by the binding of mineral particles with organic and inorganic substances (Zhu *et al.*, 2023). The content of aggregates of each particle size, determined through dry and wet sieving methods, reflects their mechanical and water stability, respectively (Bronick and Lal, 2005; Guan *et al.*, 2018). Aggregates are typically classified into macroaggregates and microaggregates based on size, with a threshold of 0.25 mm (Lagomarsino *et al.*, 2012). Macroaggregates include those larger than 2 mm and those between 2 mm and 0.25 mm, whereas microaggregates are categorised into 0.25–0.053 mm (free microaggregates) and less than 0.053 mm (silt-clay aggregates) (Lagomarsino *et al.*, 2012). Soil organic carbon (SOC) and total nitrogen (TN) are crucial to the formation of soil aggregates (Bai *et al.*, 2023; Tolessa and Senbeta, 2018). A stable aggregate structure offers physical protection for SOC and TN, serving as a critical site for the transformation and

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metabolism (Bronick and Lal, 2005; Qiao *et al.*, 2021a, 2021b). Meanwhile, SOM and TN are significant factors influencing the formation and stability of soil aggregates (Bronick and Lal, 2005; Enwezor, 1967).

The C and N cycles are the most intricately connected of all elemental cycles in terrestrial ecosystems (Chen *et al.*, 2020; Qiao *et al.*, 2021a, 2021b). Variations in climate, soil type, and land management practices influence the soil SOC pool to emit and absorb sink of C (Dong *et al.*, 2017; Guan *et al.*, 2018; Wang *et al.*, 2016). Consequently, even minor alterations in the SOC pool can significantly affect atmospheric CO_2 levels and the global carbon balance (Ding *et al.*, 2017; Guan *et al.*, 2018). It has been demonstrated that increases in SOC (Welker *et al.*, 2004) and TN accrual in agricultural lands can mitigate greenhouse gas emissions and enhance soil quality (Dijkstra *et al.*, 2010; Walker *et al.*, 2018), thereby boosting crop yields (Walker *et al.*, 2018). Therefore, investigating the distribution and sequestration of C and N within soil aggregates is crucial for enhancing soil fertility and augmenting the reserves of soil C and N.

Since the industrial revolution, climate warming has become a significant environmental issue globally (IPCC, 2021). The average temperature in China is predicted to rise by 1.2–2.0°C by 2050 (Chavas *et al.*, 2009). This warming affects not only the adaptation strategies of terrestrial plants but also subsurface ecosystem processes. In particular, the C and N cycles, critical biogeochemical processes, are substantially influenced by climate warming (Dijkstra *et al.*, 2010; Xu *et al.*, 2024; Wilson *et al.*, 2016; Walker *et al.*, 2018). Tao *et al.* (2018) demonstrated through short-term cultivation experiments that increased temperatures could significantly enhance the decomposition of SOC. However, studies in alpine grassland ecosystems on the Tibetan Plateau suggest that while soil C and N cycles are generally accelerated by warming, the soil C and N stocks are less responsive (Chen *et al.*, 2020). Furthermore, Dijkstra *et al.* (2010) reported a more open N cycle in a semiarid grassland under warmer conditions. Additionally, Cui *et al.* (2021) found that elevated temperatures did not affect the influence of arbuscular mycorrhizal (AM) fungi on SOC or TN in a temperate meadow soil, despite the critical role of AM fungi in soil C and N dynamics.

In addition, global warming exhibits a distinct asymmetric characteristic, with temperature increases being more pronounced at night than during the day and more significant in spring and winter compared to summer and autumn (Cai *et al.*, 2015; Davy *et al.*, 2017). Field observations from various rice planting systems over four years indicate that nighttime warming below 1.0°C tends to shorten the pre-flowering period and extend the post-flowering period. Such warming has a notable impact on rice yields, although the extent varies across different tillage systems (Jin *et al.*, 2017). Cheng *et al.* (2024) reported that nighttime warming might reduce Cu accumulation in wheat grown in Cu-contaminated soil, particularly in the grains. This asymmetric warming process basically overlaps with the growth process of winter wheat. Moreover, the winter wheat is the main grain in the central of China. However, it is uncertain whether long-term warming will impact the farmland ecosystem in the context of global warming. Thus, it is essential to investigate the stability of soil ecosystem aggregates and the sequestration of carbon and nitrogen under prolonged nighttime warming conditions in representative winter wheat fields. Specifically, this study investigates (1) the changes in proportion of soil aggregates in each particle size and soil aggregate stability after nighttime warming; (2) the changes in concentration and content of SOC and TN, SOC and TN contribution rate and C/N ratio of each particle size in soil aggregates after nighttime warming; (3) the correlation among these indices of each particle size in soil aggregates. Considering the results of previous studies, we hypothesised that (1) nighttime warming would reduce the proportion of macroaggregates and increase microaggregates compared to CK, thereby diminishing soil aggregate stability, and (2) accelerate soil C and N cycles, not affect C and N stocks. Such research could aid in forecasting the response of carbon and nitrogen pools in farmland ecosystems to future climate warming.

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Materials and methods

Trial site, experimental design and soil sampling

This study was conducted at the Henan University of Science and Technology Farm in Luoyang, Henan Province, China (34°38′N, 112°22′E). The farm is situated in the hilly region of western Henan, characterised by a warm temperate, semiarid, and semi-humid monsoon climate. The area records an annual average temperature of 13.7°C and precipitation of 650.2 mm. Rain-fed winter wheat predominates as the primary crop. Two experimental treatments were established: a control check (CK) and a nighttime warming treatment (WT). Each treatment comprised three replicates, with each replicate covering an area of 4 m^2 (length: 2 m and width: 2 m).

From 2013 to 2021, wheat in farmland underwent WT during the growing seasons using a passive warming system (Tian *et al.*, 2012), which operates by intercepting long-wave radiation at night (from 19:00 to 7:00 the next day). The system, featuring a retractable cover and a horizontal frame set 15 cm above the wheat canopy, was not activated on rainy or snowy days. Soil temperature was monitored by five automatic recorders (ZDR-41, Hangzhou Zheda Electronic Instrument Co., Ltd., China), placed at the centre and the periphery (due northeast, due northwest, and due southwest, 1 m from the centre) of each plot. Readings were taken every 20 minutes throughout the growth cycle, and the data were averaged to calculate the nightly soil temperature for each treatment. Figure S1 displays the annual average temperatures and their increments between CK and the warming treatments over the eight-year period. The annual average temperature increase ranged from 0.3 to 1.3°C, with an average increase of 0.71°C under the nighttime warming conditions. All other management practices for CK were the same as for WT, except for the absence of the warming equipment.

Over the course of eight years, the wheat varieties and most management practices in the two treatments mirrored local conventional methods, with the exception of the warming management. The experimental soil, classified as carbonate cinnamon soil, referring to Chinese soil taxonomy (2001), had its physical and chemical properties documented in 2013 and 2021, as detailed in Table S1. Following the harvest of winter wheat in late May 2021, soil samples since 2013 were collected using a 3 cm diameter soil auger. To minimise the impact of mechanical processes on soil integrity, wheat was harvested manually. Soil samples were taken from eight random points within the topsoil layer of each replicate (Cheng *et al.*, 2024), ensuring no visible surface compaction occurred. Eight subsamples from each replicate were combined to form a composite sample. These samples were air-dried in a ventilated, shaded area and subsequently divided for analysis: one portion was sieved through a 10 mm mesh for soil aggregate composition assessment, and another through a 2 mm mesh to evaluate physicochemical properties.

Laboratory analysis

The classification of soil aggregates adopts the method of combining dry sieving and wet sieving. The aggregate content of each size measured by the dry sieving method and the wet sieving method reflected the mechanical stability and water stability of the aggregates, respectively (Guan *et al.*, 2018). The dry sieving method referred to the method of Soil Physics Laboratory, Nanjing Institute of Soil Science, Chinese Academy of Sciences (1978). After the soil samples were air-dried, they were sieved with a stainless steel sleeve sieve to obtain four-grade mechanically stable soil aggregates (>2 mm, 2–0.25 mm, 0.25–0.053 mm, and <0.053 mm, respectively). According to the percentage of aggregates at all levels obtained by dry sieving, soil samples with a mass of 100 g (accurate to 0.01 g) were prepared for wet sieving analysis. Wet sieving referred to the method of Elliott (1986): the soil samples were placed on a stainless steel sieve with a 2 mm aperture, soaked in distilled water for 10 minutes at ambient temperature, and then passed through the stainless steel sieves of 0.25 mm and 0.053 mm, respectively, and oscillated vertically up and down 50 times. Afterwards, the soil samples on the soil sieves at all levels were collected to obtain water-stable soil

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aggregates >2 mm, 0.25–2 mm and 0.053–0.25 mm, and the aggregates <0.053 mm were obtained by sedimentation and centrifugation of the solution. Then, the proportion of mechanical stable/water-stable soil aggregates of each particle size (PMSA/PWSA) was obtained, and the soil in each particle was air-dried to determine the basic physical and chemical indicators of the soil.

The determination of soil physical and chemical properties referred to the method of Bao (2008): SOC and TN of soil and each particle size of soil aggregates were determined by $K_2Cr_2O_7$-external heating oxidation method and semi-micro Kjeldahl method, respectively; soil available P was determined by $NaHCO_3$ extraction-molybdenum antimony anti-colorimetric method-automatic flow analyzer; soil available K was determined by CH_3COONH_4 extraction-flame photometry; organic matter was determined by $K_2Cr_2O_7$ volumetric method (external heating method). For the plough layer soil between wheat rows, the ring knife method (volume: 100 cm^3) was used to determine the bulk density (Agricultural Industry Standards of the People's Republic of China, 2006); the pH was measured by a precision acidity metre.

Data analysis

The SOC/TN content of each particle size in soil aggregates (C_{SOC}/C_{TN}), the content of water-stable aggregates >0.25 mm ($WR_{0.25}$), the content of mechanical stable aggregates >0.25 mm ($DR_{0.25}$), the unstable aggregate index (E_{LT}), the percentage of aggregate destruction (PAD), the mean weight diameter (MWD), the geometric mean diameter (GMD), the contribution rate of SOC/TN (CR_{SOC}/CR_{TN}), and the C/N ratio in soil aggregates were obtained by calculation. The specific formulas are as follows.

The SOC/TN content of each particle size in the aggregate (C_{SOC}/C_{TN}, t/hm^2) (Wang *et al.*, 2018):

$$C_{SOC} = SOC_C \times W_i \times BD \times H \times 10^{-1} \tag{1}$$

$$C_{TN} = TN_C \times W_i \times BD \times H \times 10^{-1} \tag{2}$$

In the formula, SOC_C/TN_C is the SOC/TN concentration of each particle size measured by the elemental analyzer (g/kg); Wi is the mass percentage of water-stable aggregates of each particle size (%); BD is the soil bulk density (g/cm^3); H is the layer depth (cm).

These indicators related to aggregates stability (Kemper and Rosenau, 1986):

$$WR_{0.25} = \frac{W_{s>0.25}}{W_s} \times 100\% \tag{3}$$

$$DR_{0.25} = \frac{W_{r>0.25}}{W_r} \times 100\% \tag{4}$$

$$E_{LT} = \frac{(W_T - WR_{0.25})}{W_T} \times 100\% \tag{5}$$

$$PAD = \frac{(DR_{0.25} - W_{s>0.25})}{DR_{0.25}} \times 100\% \tag{6}$$

$$MWD = \sum_{i=1}^{n} W_i X_i \tag{7}$$

$$GMD = exp\left[\frac{\sum_{i=1}^{n} W_i \, ln \, X_i}{\sum_{i=1}^{n} W_i}\right] \tag{8}$$

In the formula, $W_{s>0.25}$ and W_s represent the weight of water-stable aggregates with particle size > 0.25 mm and the total weight of water-stable aggregates (g), respectively; $W_{r>0.25}$ and W_r

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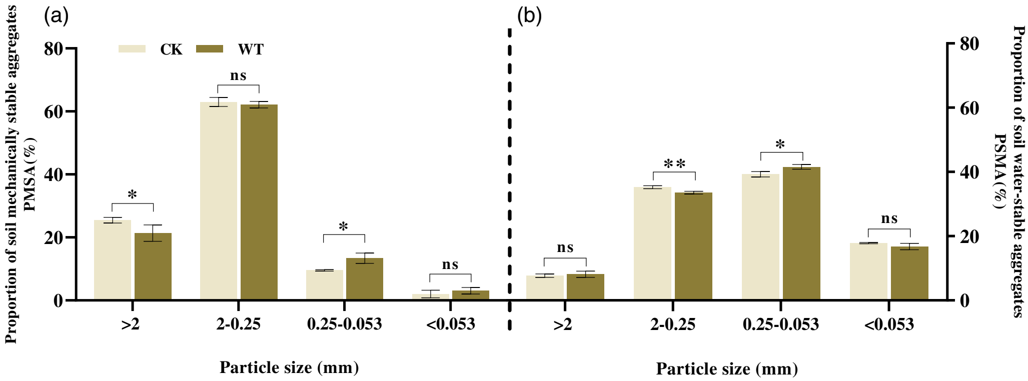

Figure 1. Proportion of mechanically stable aggregates (PMSA, Figure 1A) and water-stable aggregates (PWSA, Figure 1B) in soil. (CK, control check treatment; WT, warming treatment; *, $p < 0.05$; **, $p < 0.01$; ns, not significant). Data were analysed to compare the differences between CK and WT by an independent *t*-test. Abbreviations: PMSA, proportion of mechanical stable; PWSA, water-stable soil aggregates of each particle size.

represent the weight of mechanically stable aggregates with particle size >0.25 mm and the total weight of mechanically stable aggregates (g), respectively; W_T is the total weight of the tested soil (g); W_i is the mass percentage (%) of water-stable aggregates of each particle grade; and X_i is the average diameter (mm) of a certain level of ratio.

The contribution rate of the SOC/TN of each particle size in the aggregate (CR_{SOC}/CR_{TN}) (Qiu *et al.*, 2006):

$$CR_{SOC}(\%) = \frac{C_{SOC}}{\sum SOC} \tag{9}$$

$$CR_{TN}(\%) = \frac{C_{TN}}{\sum TN} \tag{10}$$

In the formula, C_{SOC}/C_{TN} is the SOC/TN content of each particle size in the aggregate, ΣSOC/ΣTN is the sum of the SOC/TN contents of the four particle sizes, respectively.

The C/N ratio of each particle size in the aggregate:

$$C/N = \frac{SOC_C}{TN_C} \tag{11}$$

In the formula, SOC_C/TN_C is the SOC/TN concentration of each particle size, respectively.

SPSS (version 24.0) (IBM Crop., Armonk, NY, USA) was used to perform the statistical and variance analyses. An independent t-test was carried out to compare the differences between CK and WT ($p < 0.05$; $p < 0.01$; $p < 0.001$). Graphics were drawn by SigmaPlot 8.2.1 software (Systat Software Inc., San Jose, CA, USA).

Results and discussion

Proportion of soil aggregates in each particle size

As shown in Figure 1A, the size of soil aggregates was primarily distributed in the 2–0.25 mm range (62.13%–63.00%), followed by >2 mm (21.37%–25.47%), 0.25–0.053 mm (9.53%–13.40%), and <0.053 mm (2.03%–3.07%). The distribution of these aggregates was consistent with the characteristics of carbonate cinnamon soil in central China (Qiao *et al.*, 2021a, 2021b). Except for the proportions of 2–0.25 mm and <0.053 mm particle sizes, the proportions of aggregates with

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Table 1. Soil aggregate stability under warming treatment

	$WR_{0.25}$ (%)	$DR_{0.25}$ (%)	E_{LT} (%)	PAD (%)	MWD (mm)	GMD (mm)
CK	43.07 ± 0.69	88.47 ± 0.99	56.93 ± 0.69	51.31 ± 0.90	0.62 ± 0.01	0.31 ± 0.01
WT	41.65 ± 0.92	83.51 ± 2.79	58.35 ± 0.92	50.01 ± 0.46	0.61 ± 0.02	0.31 ± 0.01
Sig.	*	*	*	ns	ns	ns

Note: Data were analysed by T-test (CK, control check; WT, warming treatment; Sig., significant; ns, not significant; *, $p < 0.05$; **, $p < 0.01$). Abbreviations: $WR_{0.25}$, PWSA > 0.25 mm; $DR_{0.25}$, PMSA > 0.25 mm; E_{LT}, unstable aggregate index; PAD, percentage of aggregate destruction; MWD, mean soil aggregate mass diameter; GMD, geometric mean diameter.

diameter >2 mm and 0.25–0.053 mm significantly differed between CK and WT soils. Compared to CK, WT soils showed a reduced proportion of >2 mm diameter aggregates and an increased proportion of aggregates with 0.25–0.053 mm diameter.

Water-stable aggregates by wet sieving on the basis of mechanically stable aggregates (Figure 1B) showed a similar trend: 0.25–0.053 mm particle size was the largest, while aggregates with >2 mm diameter were least abundant. Under WT, the proportion of 0.25–0.053 mm aggregates increased significantly. Combining Figure 1A and 1B, it can be found that, whether after dry or wet sieving, compared with CK, the proportion of macroaggregates tended to decrease and shifted to microaggregates under WT, while the proportion of microaggregates gradually increased. Moreover, WT conditions caused a shift from macroaggregates to microaggregates, with a notable increase in 0.25–0.053 mm aggregates. This disintegration of macroaggregates under warming reduces aggregate stability, aligning with prior studies (Bronick and Lal, 2005; Guan *et al.*, 2018). Moreover, in laboratory culture trials, some researchers have also found that the water stability of soil aggregates decreases with increasing temperature, which is similar to our results (Wang *et al.*, 2016). These results might be explained due to the activity of microorganisms and the rate of decomposition of organic matter in soil. The specific reasons are as follows: (1) Microorganisms will produce enzymes and other decomposition products in the process of decomposing organic matter. When the microbial activity is enhanced by warming, the decomposed substances can destroy the organic-inorganic complex in the aggregates, resulting in the decomposition of large aggregates; (2) Organic matter is an important cementing agent for the formation and stability of aggregates. When the decomposition of organic matter is accelerated by warming, the cementing material in aggregates decreases, resulting in the stability of large aggregates decreases, and it is easier to decompose into small aggregates (Zhu *et al.*, 2023).

Overall, regardless of whether the aggregates were dry sieved or wet sieved, as the particle size decreased, warming could influence soil aggregate distribution characteristics. WT showed a trend of decreasing the proportion of macroaggregates and increasing the proportion of micro-aggregates than CK, and had the potential to significantly affect the proportion of >2 mm, 2–0.25mm, and 0.25–0.053 mm diameter aggregates.

Soil aggregate stability

Table 1 indicates that WT significantly reduced $WR_{0.25}$ and $DR_{0.25}$ while increasing E_{LT}, demonstrating its destabilising effect on soil structure. These findings align with Guan *et al.* (2018), suggesting that WT enhances erosion and runoff, hindering soil aggregation.

MWD, GMD, and PAD are key indicators of soil aggregate stability. Although these did not significantly change under WT, shifts in aggregate proportions (Figure 1) and other stability metrics ($WR_{0.25}$, $DR_{0.25}$, E_{LT}) suggest potential long-term effects on soil structure. Overall, the data in Table 1 indicated that WT showed a trend of weakening the stability of soil aggregates.

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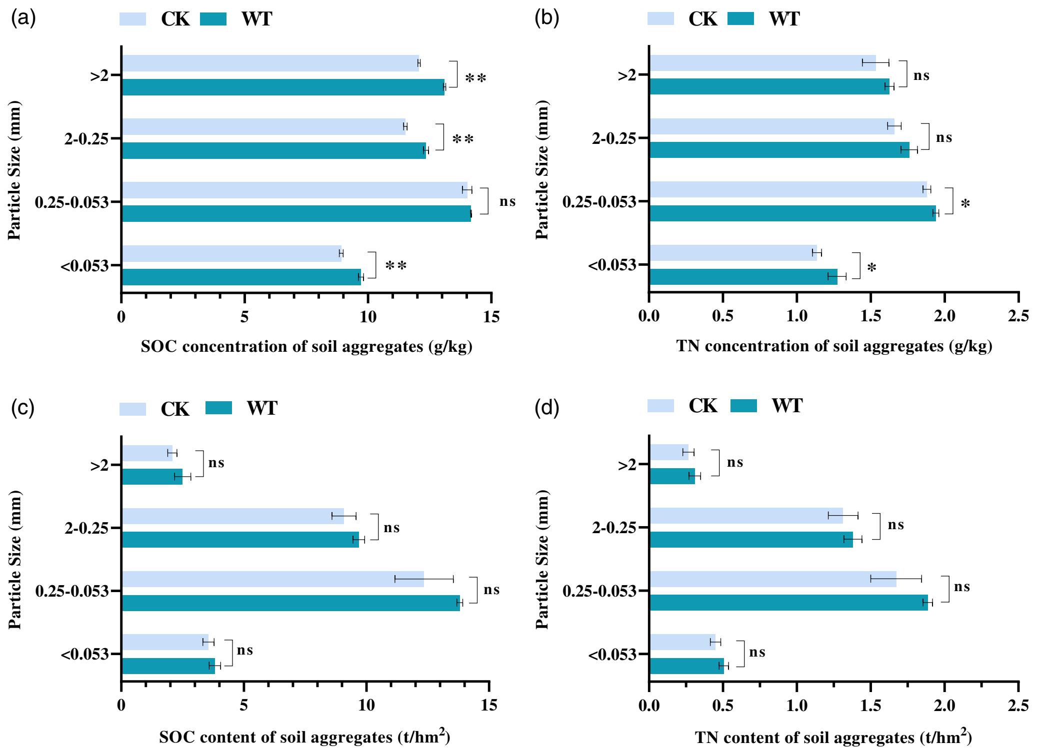

Figure 2. The concentration of SOC (A)/TN (B) and the content of SOC (C)/TN (D) in each particle size of SA. (CK, control check treatment; WT, warming treatment; *, $p < 0.05$; **, $p < 0.01$; ns, not significant). Data were analysed to compare the differences between CK and WT by an independent *t*-test. Abbreviations: SOC, soil organic carbon; TN, total nitrogen.

Concentration and content of SOC and TN of each particle size in soil aggregates

The response of SOC and nutrient storage cycles to climate change has become one of the hotspots in the study of C sink functions in terrestrial ecosystems (Bronick and Lal, 2005; Guan *et al.*, 2018; Six *et al.*, 2000). Studying the variation characteristics of SOC and TN is of great significance for understanding the changes in soil fertility and structure (Butler *et al.*, 2012). However, previous research on these parameters has focused on grassland ecosystems (Chen *et al.*, 2017; Chen *et al.*, 2020; Dijkstra *et al.*, 2010; Guan *et al.*, 2018), not farmland ecosystems. Therefore, the concentration and content of SOC and TN in wheat fields are studied and presented in Figure 2.

From Figure 2, the concentrations and contents of SOC and TN showed an increasing trend under WT, significantly so for SOC at all sizes of aggregates except 0.25–0.053 mm. TN concentrations were significantly higher at 0.25–0.053 mm and <0.053 mm aggregate diameters, reflecting the synchronous response of SOC and TN to warming due to their shared role in soil organic matter (Bronick and Lal, 2005; Wang *et al.*, 2011). These results about the content of SOC were similar to previous observations and meta-analyses from Chen *et al.* (2017), Ding *et al.* (2017) and Chen *et al.* (2020). Two possible mechanisms might explain the response of SOC to WT. (1) Under a limited warming period, it is difficult to observably alter the huge C pool in soil; (2) although WT increased C output through soil respiration (Chen *et al.*, 2020) and decreasing storage capacity of SOC due to reducing the proportion of macroaggregates (Figure 1; Davidson *et al.*, 2000; Davidson and Janssens, 2006), it also increased C input by plant productivity (Table S2; Chen *et al.*, 2020; Wang *et al.*, 2012), replenished organic matter in soil, and made no significant change in the SOC content (Chen *et al.*, 2020). As reported ago, soil drying (Table S2) enhanced the mineralisation of

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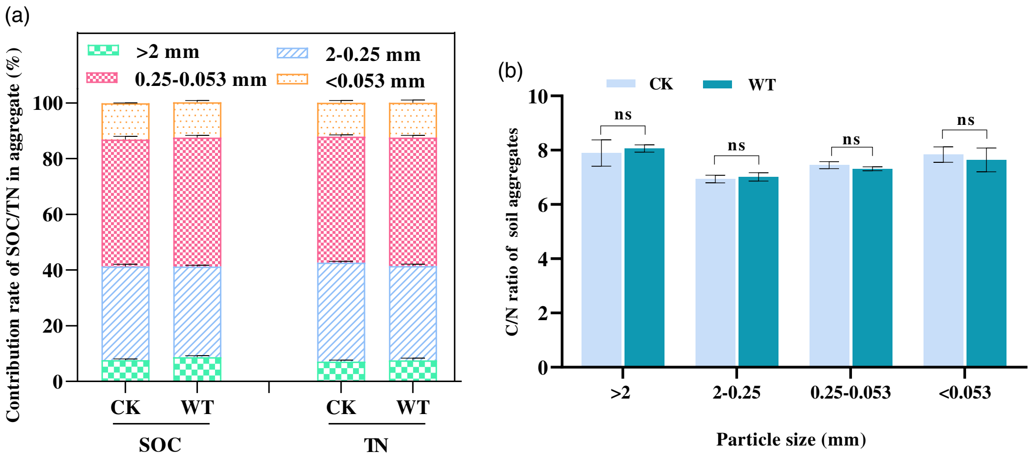

Figure 3. The SOC and TN contribution rate (A) and C/N ratio (B) from each particle size of SA. (CK, control check treatment; WT, warming treatment; ns, not significant). Data were analysed to compare the differences between CK and WT by an independent *t*-test. Abbreviations: SOC, soil organic carbon; TN, total nitrogen; SA, soil aggregates.

native (or old) soil organic matter (Enwezor, 1967), while it decreased the decomposition of fresh organic matter returning to the soil (Enwezor, 1967). For TN concentrations, they reached a prominent level only at 0.25–0.053 mm and <0.053 mm. For TN contents, no prominent change between WT and CK was found.

On the whole, WT showed a trend of increasing the concentrations and contents of SOC and TN, but the degree of influence varies with the particle size.

SOC and TN contribution rate and C/N ratio of each particle size in soil aggregates

SOC/TN contribution rate represents the proportion of SOC/TN content of each particle size to the sum of SOC/TN content of all particle sizes (Qiu *et al.*, 2006). In Figure 3, the SOC and TN contribution rates were highest in 0.25–0.053 mm aggregates, followed by 2–0.25 mm, <0.053 mm, and >2 mm, with no significant differences between treatments. Similarly, C/N ratios, which indicate soil quality and N balance, showed no significant changes across aggregate classes, likely due to a balance between C and N inputs and losses under warming conditions. These results are mainly related to the balance between input and output of carbon and nitrogen. Under warming conditions, the loss of carbon and nitrogen in soil may be offset by the input of more carbon and nitrogen from plant litter, resulting in no significant change in the contribution rate of carbon and nitrogen overall (Cheng *et al.*, 2024). Overall, warming had little effect on the contribution rate of SOC and TN and C/N ratio of each particle size in soil aggregates.

Correlation analysis heatmaps among these indices of each particle size in soil aggregates

For Figure 4, the stability and proportion of soil aggregates, the content of SOC/TN, and the contribution rate of SOC/TN of each particle size of soil aggregates were analysed by correlation analysis heatmaps. For the stability of soil aggregates, E_{LT} was negatively correlated with other indicators, and its correlation with $WR_{0.25}$, $DR_{0.25}$, and MWD reached a significant level. In addition to E_{LT}, there was a positive correlation between other indicators about stability of soil aggregates, among which only the correlation between PAD and $DR_{0.25}$, and between MWD and

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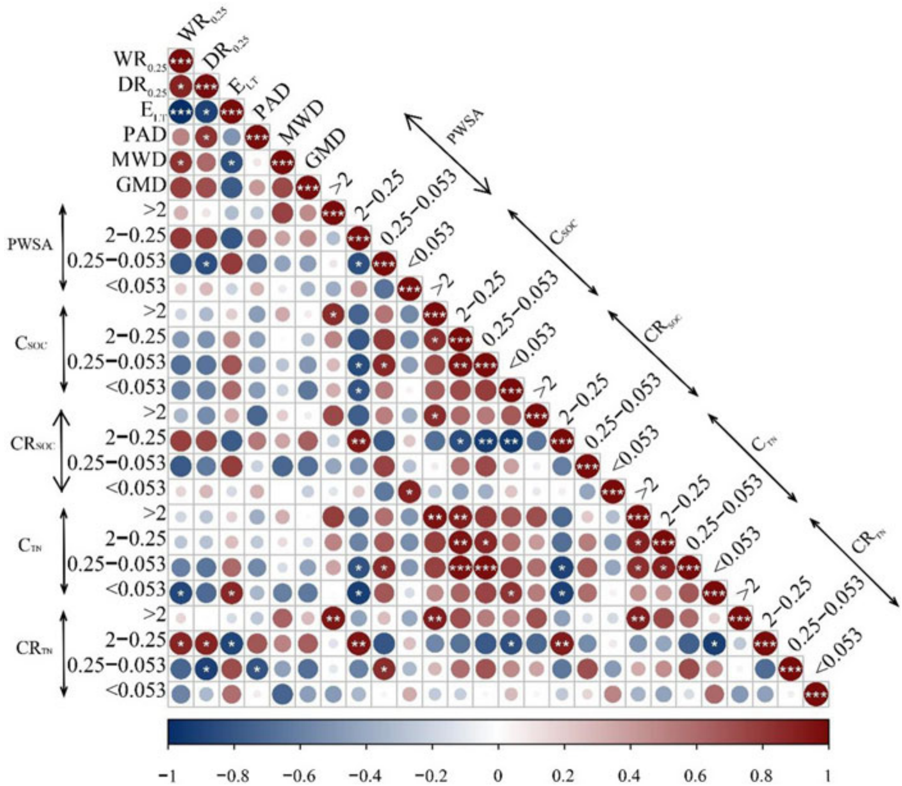

Figure 4. The clustered heatmaps among aggregates stability, the proportion of SA, the content and contribution rate of SOC/TN and of each particle size in each particle size of SA. Abbreviations: SOC, soil organic carbon; TN, total nitrogen; SA, soil aggregates; $WR_{0.25}$, composition of water-stable aggregates >0.25 mm; $DR_{0.25}$, composition of mechanical stable aggregates >0.25 mm; E_{LT}, unstable aggregate index; PAD, percentage of aggregate destruction; MWD, mean soil aggregate mass diameter; GMD, geometric mean diameter; PWSA, the proportion of water-stable SA from each particle size; C_{SOC}/C_{TN}, SOC/TN content of each particle size in SA; CR_{SOC}/CR_{TN}, contribution rate of SOC/TN of each particle size in SA.

$WR_{0.25}$ showed a significant change. Although $WR_{0.25}$ was the composition of water-stable aggregates >0.25 mm (Bronick and Lal, 2005; Guan *et al.*, 2018), a positive correlation between $WR_{0.25}$ and PWSA at >2 and 2–0.25 mm did not reach a significant level under warming condition.

For the relationship between the stability of soil aggregates and PWSA, no observably effect was affected. Regarding the relationship between PWSA and $C_{SOC}/C_{TN}/CR_{SOC}/CR_{TN}$: at >2 and 0.25–0.053 mm, a positive correlation was found between PWSA and each of them, while only the correlation between PWSA and C_{SOC}/CR_{TN} reached significantly level; at 2–0.25 mm, there was negative correlation between PWSA and C_{SOC}/C_{TN}, while there was positive correlation between PWSA and CR_{SOC}/CR_{TN}; at <0.053 mm, PWSA was only positively correlated with $CR_{SOC.}$ These results indicate that the correlation between PWSA and $C_{SOC}/C_{TN}/CR_{SOC}/CR_{TN}$ is significantly affected by particle size under nighttime warming.

Overall, these outcomes revealed that the correlation between the stability of soil aggregates and other indicators did not reach a significant level; a positive correlation between PWSA and CR_{SOC}/CR_{TN} was observed, but the degree of influence varied with different particle sizes; For the relationship between PWSA and C_{SOC}/C_{TN}, the type of correlation varied with particle size.

Conclusions

Long-term nighttime warming could weaken the stability of soil aggregates by decreasing the proportion of macroaggregates and increasing the proportion of microaggregates. In addition, though nighttime warming showed a trend of increasing the concentrations and contents of SOC and TN, and a positive correlation between the proportion of and contribution rate of SOC and TN was observed, it had little effect on SOC and TN contribution rate and C/N ratio of each particle size in soil aggregates.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479725000067

Data availability statement. All data generated or analysed during this study are included in this article, and be available from the corresponding author on reasonable request.

Author contributions. HXC, GC, and TK designed the work and performed the research. HXC, FL, and WL analysed data and wrote the paper. NXC, XL, and TK reviewed and checked all the details. All authors read and approved the final manuscript.

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Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval and consent to participate. Not applicable.

Consent for publication. All authors listed have read the complete manuscript and have approved submission of the paper.

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