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Effect of N fertiliser on soil respiration and winter wheat (*Triticum aestivum* L.) yield

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ABSTRACT

N fertiliser could indirectly influence soil respiration through modifying plant production and soil properties. However, there is limited information jointly researching soil respiration and wheat yield at different N levels in the Loess Plateau in China. The aim of this experiment was to study the influence of N levels on soil CO_2 emission and wheat yield to N levels in a winter wheat field in northwest China from October 2012 to June 2013, and from October 2013 to June 2014. A static chamber technique was applied to quantify the soil respiration, the quantities of five N levels (kg N ha^{-1}) were 0 (N0), 80 (N1), 160 (N2), 240 (N3), and 320 (N4). Results presented that soil CO_2 emission showed a strong seasonal trend, with the highest values recorded at anthesis stage and the lowest values was measured at wintering stage. The accumulated soil respiration was 3.1 t CO_2-C ha^{-1} in N0, N1, N2, N3, and N4 treatments significantly increased soil CO_2 emissions by 27%, 46%, 66%, and 120% when compared to N0 treatment. Soil CO_2 emission showed a significant positive exponential relationship with soil temperature. The temperature sensitivity of respiration (Q_{10}) was reduced from 2.37 in group N0 to 1.74 with the N4 treatment. Whereas no relationship was recorded between soil respiration and soil water content. Although N fertiliser significantly ($P < 0.05$) increased grain yields by 2 % to 5 %, no difference was recorded between N1 and N2, and between N3 and N4 treatments. The yield-scaled CO_2 emissions were significantly ($P < 0.05$) higher in N levels than in N0 treatment. Our results suggested that N fertilizer could increase soil respiration and yield-scaled CO_2 emissions in wheat field, but the magnitude thereof may vary according to the levels of N fertiliser addition.

Novelty statement
The integral study researching on the soil respiration and wheat yield under different N levels in the Loess Plateau in China was conducted. N fertilizer significantly increased soil CO_2 emission by 27%-120% when compared to N0 treatment. N fertilizer reduced the temperature sensitivity of respiration (Q_{10}). When compared with no fertilizer, N fertilizer increased yield scaled CO_2 emissions.

Keywords: soil CO_2 emission, soil temperature, yield-scaled CO_2 emissions, no tillage.

INTRODUCTION

In recent years, global warming, due to an increased concentration of greenhouse gas emissions in the atmosphere, is receiving more attention. CO_2 is the one of the most important GHGs, contributing to 60% of global warming [1]. Agricultural systems are estimated to contribute up to 25 % of global anthropogenic CO_2 emissions [2]. After gross primary productivity, soil respiration is the second largest CO_2 flux between the atmosphere and terrestrial ecosystems [3]. Even a minor change in soil respiration will lead to substantial changes in atmospheric CO_2 concentration, ultimately affecting global climate and warming [4]. Thus it is worthwhile measuring soil respiration in a cultivated field to estimate the carbon cycling of terrestrial ecosystems.

Soil respiration includes root respiration (autotrophic) and microbial respiration (heterotrophic). Soil respiration rates are influenced by many soil properties [5]. Additionally, long-term management practices (*e.g*. N fertilisation) will affect soil respiration by changing the characteristics of the soil [6,7]. Nitrogen (N) is one of the key factors influencing crop growth and the growth of living organisms across a wide range of ecosystems. However, there are controversial results among the effects of N fertiliser on soil CO_2 emission. On the one hand, N fertiliser might increase soil respiration by increasing plant growth and soil microbial activity, ultimately resulting in increased soil respiration [8]. On the other side, N fertiliser might reduce soil CO_2 emissions because N fertiliser decreases heterotrophic respiration [9], and rhizosphere respiration [10]. These inconsistent results may be due to the differences induced by fertiliser in soil microbial communities, soil microbial biomass, and differences in activity induced by different N fertilisation techniques and types [11,12].

Moreover, the temperature sensitivity of soil respiration, which is a key factor for predicting the response of the terrestrial carbon balance to future climate change, has been paid great attention in the study of global change [13]. To the best of our knowledge, few studies have addressed the effects of N fertiliser on soil respiration and its temperature sensitivity in semi-arid agricultural land. In addition, some studies reported that N fertiliser could increase the temperature sensitivity [14,15], however, others reported contradictory results [16,17]. Thus, the effects of N fertiliser on the temperature sensitivity of soil respiration remain unclear.

The Loess Plateau, which is characterised by low soil fertility, has an area of approximately 64×10^4 km^2 and lies in northwest China. Under the pressure of increasing population, a significant amount of N fertiliser is being used. However, the unreasonable application of chemical fertiliser will not only decrease the efficiency of fertilisation, but also cause damage to the environment. Most of the previous studies conducted in this region mainly focus on grain yield under different N fertiliser regimes [18-20]. However, the environmental consequences are poorly understood. Thus, the purposes of this study were: (a) to assess the effect of N fertilisation treatments on soil CO_2 emission; (b) to study the sensitivity of temperature under different N levels; (c) to assess the influence of N fertiliser management by calculating the yield-scaled CO_2 emissions in this region.

MATERIALS AND METHODS

Site

The experiments were conducted at the Northwest A & F University, Yangling Town, Shaanxi Province, in China (longitude 108° 10´ E, latitude 34° 21´ N). The soil properties was described in detail by [21]. The physical and chemical soil properties in the top soil layer (0 to 20 cm) was reported by [22] in 2009. The climate conditions during the two wheat growing seasons are presented in Fig. 1. The total precipitation was 222 mm in 2012 to 2013, and 220 mm in the 2013 to 2014 winter wheat growing seasons, respectively. The maximum air temperature was 14.7 °C in the 2012 to 2013, and 14.8 °C in the 2013 to 2014 seasons, respectively (Fig. 1).

Design and soil treatment

The quantities of N added were 0 (N0), 80, 160, 240, and 320 kg N ha^{-1} and plots were designed, in 2010, in a randomised block trial with three replicates [23]. The plots area measured 3.2 m × 15 m, with a spacing of 0.5 m between plots. The winter wheat-summer maize (*Zea may* L.) rotation systems was applied. After rotary tillage, P (120 kg P ha^{-1}) as calcium phosphate ($Ca_2(PO_4)_3$) fertiliser was applied in all treatments. The amount of urea fertiliser was used (with manual application) according to the different N levels required. Weeds were controlled by the application of herbicides such as carfentrazone-ethyl ($C_{15}H_{14}Cl_2F_3N_3O_3$). No irrigation was applied to these crops during the growing season.

Winter wheat (*C.V.* Shaan mai-139) was sowed with the aid of a wheat drill (a 12-disc wheat planter, Xianyang, China) with the quantity of 208-210 kg ha^{-1}, on 18 October, 2012 and 2013. The space between rows was measured 16 cm. Three 1-m^2 areas were selected randomly *per* treatment and manually harvested to calculate the yields at maturity stage. Finally, the winter wheat was harvested by mechanical combine harvester. The winter wheat growth stages are listed in Table 1 according to [24].

Soil CO_2 emission and soil hydrothermal condition

Soil CO_2 emission, soil temperature and moisture were measured every stage in 2012 to 2013 and 2013 to 2014[21].

Q_{10} calculation

The effect of soil temperature on soil respiration was assessed using Q_{10}, which is the changes in CO_2 emission over a 10 °C increase in soil temperature: it is described by Eqns (2) and (3) [25].

$$F = a\, e^{bT} \quad (2)$$
$$Q_{10} = e^{10b} \quad (3)$$

where F is the soil respiration, T (°C) is the soil temperature, and a and b are parameters calculated by fitting Eq. (2) to the measured data in the field.

Statistical analysis

The data in the following figures are all presented in the form of average value ± standard error. The significance of any differences in measured total CO_2 emissions, above-ground biomass, wheat yields, yield-scaled CO_2 emissions, soil temperature, and soil moisture due to tillage (CT *versus* NT) were checked using a repeated measures ANOVA test. The statistical software package SPSS 12.0 (SPSS Inc., USA) was applied. The means among treatments were decided applying an LSD test with a significance level of $P<0.05$. The spearman rank correlation coefficients were used to deicide the relationships between soil respiration and its influence factors.

RESULTS

Soil respiration dynamics

The present study shows that soil respiration fluctuated significantly throughout the wheat growing season. Soil respiration decreased over time for all treatments after planting (Fig. 2). In the wintering stage (23 December), the minimum CO_2 emission was recorded. After that time, the soil CO_2 emission increased rapidly and the maximum soil CO_2 emission was recorded at the anthesis stage (5 April). At the filling stage, soil CO_2 emission again decreased.

The total soil CO_2 emissions in N1, N2, N3, and N4 treatments were 27%, 46%, 66%, and 120% higher (P < 0.05) than that in the N0 treatment, respectively (Fig. 3). Similarly, soil respiration increased with increasing of N fertiliser level throughout the growing season (Fig. 3).

Relationship between soil CO_2 emission and its impact factors

Soil temperature fluctuated with air temperature (Figs 1 and 4), after planting, the soil temperature decreased and, in the wintering stage, the minimum soil temperatures were recorded, the soil temperatures then increased until maturity. At the filling stage, the soil temperatures were reduced compared with the anthesis stage due to a higher soil moisture content (Figs 4 and 5). During the whole winter season, N4 significantly increased the mean soil temperature in the upper-most 10 cm layer by 0.7 ℃ when compared to the N0 treatment; similarly, the mean values of soil temperature at a depth of 10 to 20 cm were 10.1 ℃ for N0, 10.3 ℃ for N1, 10.3 ℃ for N2, 10.5 ℃ for N3, and 10.7 ℃ for N4 treatments, respectively (Fig. 4B).

Soil moisture content varied with precipitation, and the maximum soil moisture content was recorded at the filling stage due to 2 mm, and 114 mm, rainfall events which were recorded in April, 2013 and 2014, respectively (Fig. 5). At maturity, the soil moisture content decreased again: this was attributed to the high soil temperature.

As related to dry matter mass, an S-curve was seen under different N levels (Fig. 6). The dry matter mass increased rapidly from the wintering stage to the jointing stage. From filling to maturity, the increase in dry matter mass was small. As compared with N0 treatment, N levels significantly (P < 0.05) increased the average dry matter mass by 3 % for N1, 7 % for N2, 10 % for N3, and 8 % for N4, respectively. N fertiliser significantly increased root biomass from 16 % to 46 % in the top 10 cm of the soil, and from 19 % to 81 % in the top 20 cm (Fig. 7).

Soil respiration and its related influence factors under different N levels

The effects of soil temperature on soil CO_2 emission in the top 10 cm soil layer was more apparent than at depths of between 10 and 20 cm (Table 3). The Pearson's coefficients, in descending order were: soil temperature at 0 to 10 cm depth; soil temperature at 10 to 20 cm depth; air temperature. No correlation was found between soil CO_2 emission and soil moisture. There was a significant relationship between soil respiration and dry matter mass in the N4 treatment alone. Besides, a significant positive relationship between soil CO_2 emission and root biomass was recorded in the N0 treatment group.

The exponential function equation between soil CO_2 emission and soil temperature in the top 10 cm soil layer was analysed (Table 2). Soil temperature could account for 69 % to 88 % of the variability in soil CO_2 emission. When compared to the N0 treatment, N4, N3, N2, and N1 had significantly (P < 0.05) lower Q_{10} values of 8%, 20%, 24%, and 26% respectively. There was no difference in Q_{10} values between N3 and N4 treatments.

Effect of N levels on crop yield and yield-scaled CO_2 emissions

Grain yields were significantly increased by N fertiliser: N4, N3, N2, and N1 levels significantly (P < 0.05) increased wheat yields by 2 to 5 % as compared with the N0 treatment (Fig. 8A). There was no difference in grain yields between N1 and N2 levels. No difference in grain yields was recorded between N3 and N4 treatments. Similarly, N levels significantly ($P < 0.05$) increased yield-scaled CO_2 emissions when compared to the N0 treatment (Fig. 8B). Although, there was no difference in grain yields between N4 and N3 treatments, N4 significant increased yield-scaled CO_2 emissions (by 32 %) compared with the N3 treatment due to the higher total CO_2 emissions in N4 than in the N3 treatment.

DISCUSSION

Soil respiration

The maximum values of soil respiration were observed at anthesis, and the minimum values were observed during wintering in all treatments. The highest soil respiration was recorded at the anthesis stage, which could have been due to the high crop growth and soil temperature at this time. Similar results were also recorded by [26] who reported that the maximum soil respiration in all treatments appeared during fast plant growth periods, such as their flowering stage, because of the higher temperature and the intensity of photosynthesis At the filling stage, soil respiration presented a slightly decreasing trend, which may have been due to the high soil water content, which could restrict the activity of soil microbes, thus reducing the oxidation of soil organic matter. Soil respiration has a trend of increasing again at maturity, which can be attributed to the increasing soil temperature.

In the present study, the total soil respiration was increased by by 27 to 120 % under different N levels, which was in line with the finding of previous studies [27,28]. Thus, the stimulation of soil respiration may be explained by the following mechanisms: first, N addition promoted plant growth ultimately increasing soil respiration (the positive Pearson's correlation coefficients between soil CO_2 emissions and above-ground biomass also supported this conclusion); second, higher temperatures during N fertilisation than in the N0 treatment promoted soil respiration (Table 2). The total soil CO_2 data (3.1 for N0, 3.9 for N1, 4.5 for N2, 5.1 for N3, and 6.7 t CO_2-C ha^{-1} for N4) were smiliar to those found by [29].

Impact factors

The Q_{10} values in the present study changed from 1.74 in N4 to 2.37 in N0, which lay within the range found by [30] who reported that Q_{10} fluctuated from 1.86 to 3.00. N levels reduced Q_{10} values from 8 to 26 % when compared to the N0 treatment, which agreed with published findings [14,15]. However, [16] found contradictory results which may be due to the fact that soil respiration comprises autotrophic and heterotrophic components, both of which exhibit different soil temperature sensitivities at different N levels [30]. So further research is warranted to separate soil respiration into its components to study the temperature sensitivity under different N fertilisation regimes, separately.

However, in the present experiment, no relationship was recorded between soil respiration and soil moisture. One possible reason was that the soil moisture fluctuated within a small range in all treatments (15 % to 24 %) throughout the wheat growing season: such a small range could not influence crop growth or soil microbial respiration. For another, the soil moisture was appropriate for crop growth and soil respiration during most of the winter wheat growth season, which lead to the effects of soil moisture on soil respiration being masked. The effect of soil moisture on soil respiration was covered by other influence factors or systematic error. A significant positively correlated relationship was recorded between soil respiration and above-ground biomass in the N4 treatment. There was a significant positive relationship between soil respiration and root biomass was recorded in the N0 treatment.

Crop yield and yield-scaled CO_2 emissions

N fertiliser increased grain yields by 2%-5% as compared with N0 treatment. However, there was no difference in grain yields between N1 and N2, or between N3 and N4. The current results indicated that N fertiliser would increase grain yields but extensive application of N fertiliser will not increase grain yields. The current results were supported by our previous study [23] in which it is reported that no difference in grain yield exists between the N3 and N4 treatments. In a manner similar to that of soil respiration, N fertiliser significantly increased yield-scaled CO_2 emissions; N2 significantly increased yield-scaled CO_2 emissions by 14 % when compared to N1, which was mainly due to the 15 % increase in total CO_2 emissions in N2 compared to the N1 treatment because no difference in grain yields was found between these two treatments. As compared with N3, N4 significantly increased the yield-scaled CO_2 emissions by 32 % due to its higher soil respiration than that recorded with N3 treatment.

Table 1 Winter wheat growth stages in Yangling town during the 2012–2014 growing season

Growth stage	Date	Growth stage	Date
Sowing	21-Oct	Heading	28-Mar
Emergence	11-Nov	Anthesis	05-Apr
Wintering	23-Dec	Filling	26-Apr
Jointing	11-Mar	Maturity	05-Jun

Table 2 The Pearson's coefficient between soil respiration and biotic and abiotic under different N levels

N levels	Air temperature	Soil temperature		Soil moisture		Dry matter	Root biomass	
		10cm	20cm	10cm	20cm		10cm	20cm
N0	0.828*	0.870**	0.862**	0.286	0.290	0.716	0.858*	0.798*
N1	0.796*	0.843**	0.836**	0.224	0.223	0.648	0.734	0.721
N2	0.771*	0.811**	0.802*	0.199	0.201	0.643	0.586	0.563
N3	0.845**	0.901**	0.895**	0.304	0.306	0.740	0.547	0.423
N4	0.867**	0.924**	0.919**	0.344	0.341	0.799*	0.570	0.512

** P <5%, ** P <1%. n=7*

Table 3 Relationship between soil respiration and soil temperature at 10 cm layer during the two growing seasons under different N levels

Treatments	Exponential function	R^2	Q_{10}
N0	$F=7.01e^{0.0864T}$	0.7227**	2.37±0.13a
N1	$F=9.72e^{0.0775T}$	0.7438**	2.17±0.13b
N2	$F=12.52e^{0.0645T}$	0.6929*	1.90±0.12c
N3	$F=14.78e^{0.0595T}$	0.8295**	1.81±0.10d
N4	$F=16.56e^{0.0554T}$	0.8792**	1.74±0.10d

*Note: F, soil respiration; T, the soil temperature; R^2, the determination coefficient; *P <5%, **P <1%.Different letters in the same columns represent significant difference at P <0.05. n = 7.*

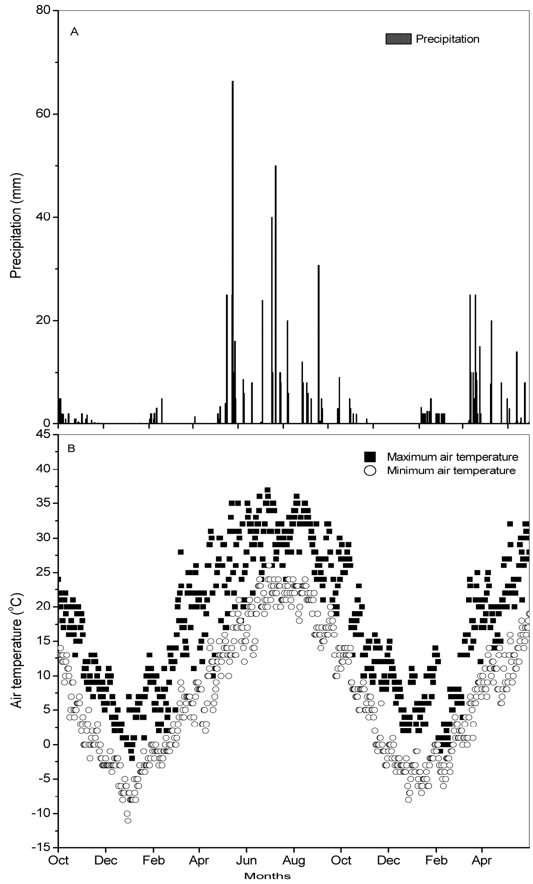

Fig. 1. Daily maximum and minimum air temperatures and precipitation during the two growing seasons (2012-14) in Yangling town. (A) Precipitation; (B) Daily maximum and minimum air temperatures

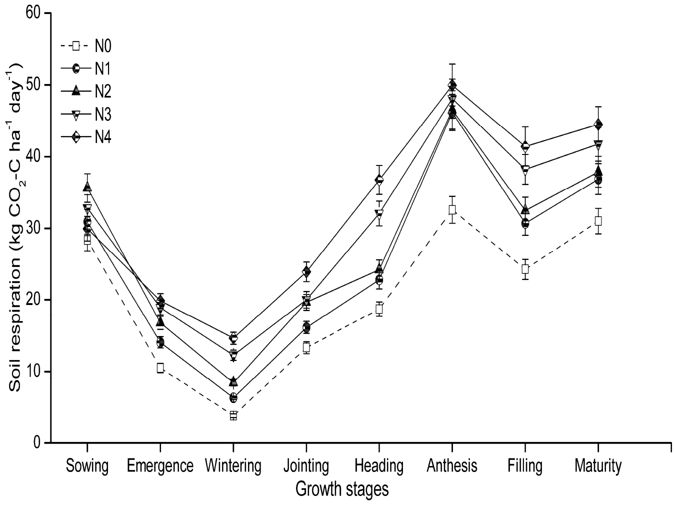

Fig. 2. Seasonal dynamics in soil respiration of winter wheat at the different N levels (0, 80, 160, 240, and 320 kg N ha^{-1}) from October 21, 2012/2013 to June 05, 2013/2014. The values represent the means of two consecutive growing seasons±SE

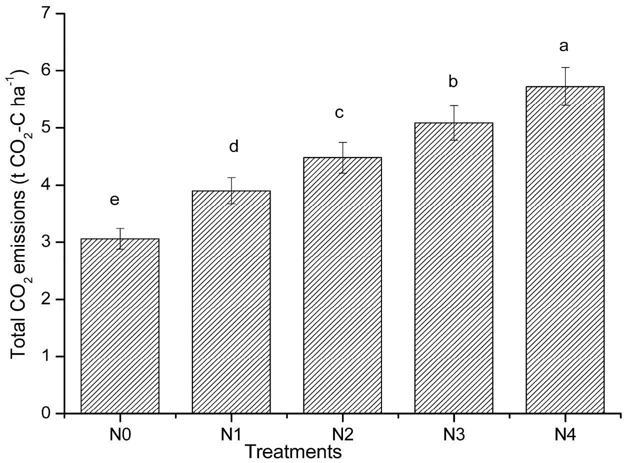

Fig. 3. Total soil CO_2 emissions of winter wheat at the different N levels (0, 80, 160, 240, and 320 kg N ha^{-1}) in 2012-2014. The total CO_2 emissions were calculated from the sowing (October 21, 2012/2013) to maturity stages (June 05, 2013/2014). The values represent the means of two consecutive growing seasons±SE. Different letters above bars indicate significant differences at P<0.05

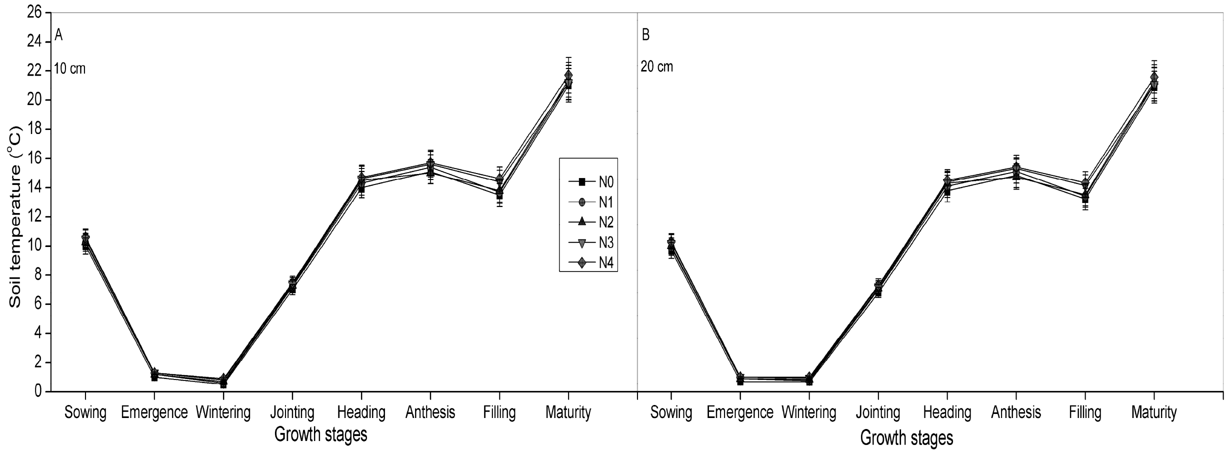

Fig. 4. Soil temperature (A, 10 cm soil; B, 20 cm soil layer) in the winter wheat field at the different N levels (0, 80, 160, 240, 320 kg N ha^{-1}) measured from sowing to maturity stages. The bars represent the means of two consecutive growing seasons±SE

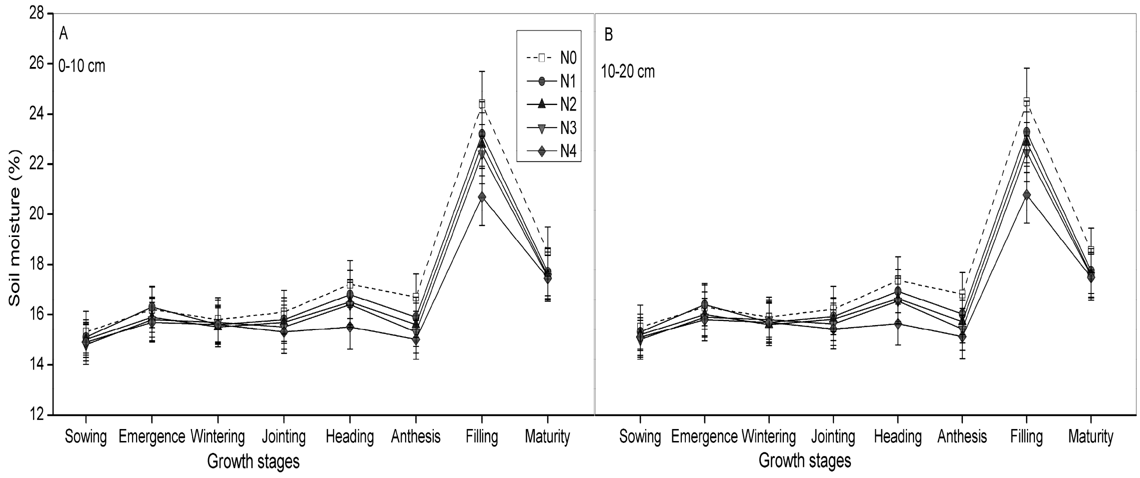

Fig. 5. Soil moisture (A, 0-10 cm soil; B, 10-20 cm soil layer) in the winter wheat field at the different N levels (0, 80, 160, 240, 320 kg N ha^{-1}) measured from sowing to maturity stages. The bars represent the means of two consecutive growing seasons±SE

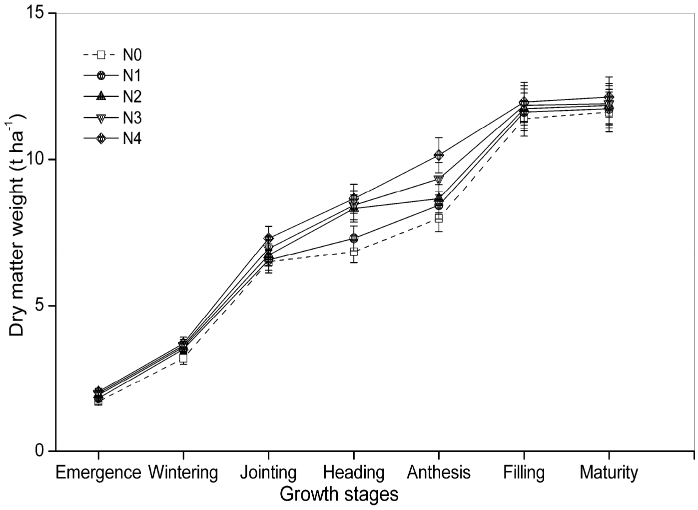

Fig. 6. Dynamics of dry matter weight of winter wheat at the different N levels (0, 80, 160, 240, 320 kg N ha^{-1}) measured from sowing to maturity stages. The bars represent the means of two consecutive growing seasons±SE

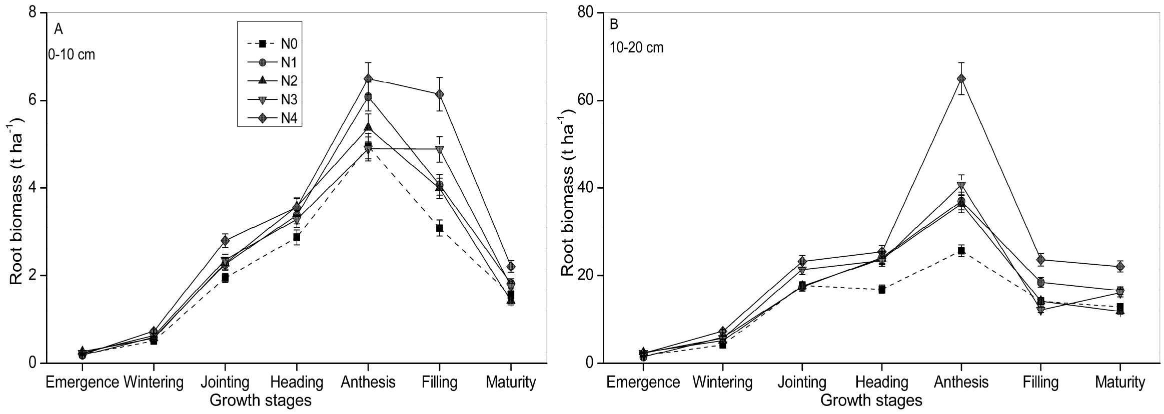

Fig. 7. Dynamics of root biomass of winter wheat (A, 0-10 cm soil; B, 10-20 soil layer) at the different N levels (0, 80, 160, 240, 320 kg N ha^{-1}) measured from sowing to maturity stages. The bars represent the means of two consecutive growing seasons±SE

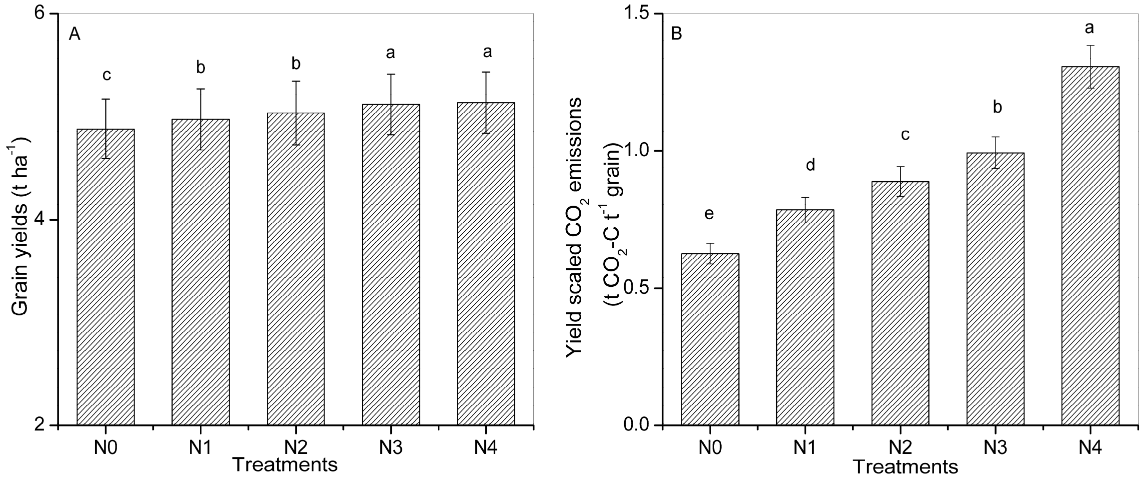

Fig. 8. Grain yields and yield scaled CO_2 emissions at the different N levels (0, 80, 160, 240, 320 kg N ha^{-1}) measured from sowing to maturity stages. The bars represent the means of two consecutive growing seasons±SE

CONCLUSION

In the present study, N fertiliser significantly increased soil respiration by 27 % to 120 %; however, N fertiliser significantly reduced Q_{10} values by 8 % to 26 %. Soil temperature could explain 69 % to 88 % of the CO_2 variability under different N treatments. No relationship between soil respiration and soil moisture was recorded due to the small range of soil moisture fluctuation which was beneficial to crop growth and microbial activity. N fertiliser increased grain yields by 2 % to 5 % as compared with the N0 treatment. However, no difference in wheat yield was recorded between the N3 and N4 treatments. In a manner similar to soil respiration, N fertiliser significantly increased yield-scaled CO_2 emissions by 24 to 108 %. As compared with N3, the N4 treatment significantly increased yield-scaled CO_2 emissions by 32 % mainly due to its higher soil respiration than that of the N3 treatment; however, further research was warranted to separate soil respiration and its components to study their temperature sensitivity under different N fertilisation regimes, separately.

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