Nitrogen fertilization increase soil carbon dioxide efflux of winter wheat field: A case study in Northwest China

Ruixin Shao a, *, 1, Lei Deng b, **, 1, Qinghua Yang a, Zhoucheng Shangguan b, **

a *Collaborative Innovation Center of Henan Crop, Agronomy College of Henan Agricultural University, the National Key Laboratory of Wheat and Maize Crop Science, Zhengzhou 450002, PR China
b **State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, PR China

A R T I C L E   I N F O

Article history:
Received 25 August 2013
Received in revised form 24 May 2014
Accepted 2 July 2014

Keywords:
Growing season
N fertilization
Non-irrigated land
Soil CO2 effluxes
Soil temperature
Soil water content

A B S T R A C T

As the largest reservoir of terrestrial carbon (C), soil is a source or sink for atmospheric carbon dioxide (CO2). Understanding the processes whereby soil CO2 is released into the atmosphere as a result of using inorganic nitrogen (N) fertilizers may provide us with knowledge of processes to offset the increasing concentration of CO2. The main objective of this study was to investigate the effects of different N levels on soil CO2 efflux with one controlled experiment. A field experiment was carried out in a non-irrigated winter wheat (Triticum aestivum L) – cropland in Northwest China to investigate the effects of N fertilization on soil CO2 efflux in two consecutive growing seasons (2007–2009). The soil CO2 efflux to which N was applied at four different levels (0, 90, 180, and 360 kg N ha–1) was measured during the growing seasons in 2007–2009. At most growth stages during the growing season, the soil CO2 efflux increased significantly with increased N application. The effect of N fertilization on the cumulative soil CO2 efflux was obvious. In the 10–20 cm soil layer, the seasonal variations in soil CO2 effluxes were influenced by soil temperature (ST) rather than by soil water content (SWC). When ST > 20 °C, however, the low soil CO2 efflux was mainly due to low SWC, which was close to the permanent wilting point (8.5 g H2O 100 g dry soil −1). In addition, soil CO2 effluxes after anthesis were higher than those at seedling stage and were highest nearby anthesis stage. The results indicated that N fertilization probably had a positive effect on both the seasonal and cumulative soil CO2 effluxes during the growing season.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Soil carbon dioxide (CO2) emission through soil respiration (SR) is one of the primary fluxes of carbon (C) between soils and the atmosphere (Iqbal et al., 2009), accounting for about 25% of the total annual exchange of C between the atmosphere and terrestrial sources (Post et al., 1990) and more than 11 times of the CO2 released from fossil fuel combustion (Marland et al., 2000), and is estimated to be 75 Pg C (Schlesinger and Andrews, 2000). Accordingly, a small variation in the turnover intensity of soil organic carbon (SOC) can result in a great change in the CO2 concentration in the atmosphere (Riley et al., 2005; Iqbal et al., 2009). However, it is difficult to directly measure these small variations in SOC in the field, due to high spatial variability and small changes in SOC content during a single growing season (Ding et al., 2007). Hence, soil CO2 efflux is commonly measured to investigate short-term SOC turnover.

The process of soil CO2 efflux is greatly altered by management practices (e.g., tillage operations) and weather conditions (e.g., rainfall events) (Ding et al., 2006; Morell et al., 2010; Ji et al., 2012). Additionally, long-term agricultural management practices affect soil CO2 efflux by changing the soil environment such as soil aeration, soil pH, soil moisture, soil temperature (ST), and C/ nitrogen (N) ratio of substances (Iqbal et al., 2009). These soil environmental conditions are characterized with a significant effect on soil microbial activity and the decomposition processes that transform plant-derived C to soil organic matter (SOM) and CO2 (Franzluebbers et al., 1995; Morell et al., 2010). In previous studies, it has shown that soil CO2 efflux is strongly related to ST and soil moisture conditions (Iqbal et al., 2008; Liu et al., 2008).

N has been regarded as a significant factor controlling SR in N-deficient terrestrial ecosystems (Peng et al., 2011), especially in...
agricultural ecosystems (Ni et al., 2012). Currently, with increasing levels of anthropogenic N deposition and heavy application of fertilizer (Nie et al., 2012), much N enters terrestrial ecosystems and can lead to environmentally damaging pollution to soil and water. The effect of N addition on SOC has already been reported in some studies (Lai, 2008; Ghimire et al., 2012; Tao et al., 2013). On one hand, N fertilization has been shown to increase SOC through increasing biomass production, and hence, C inputs to the soil (Luo et al., 2010; Lu et al., 2013). On the other hand, N fertilization affects SR and C outputs from the soil (Ding et al., 2007; Sainju et al., 2008; Song et al., 2013). As a result, N fertilization may greatly affect the SOC content. However, N addition to soil has been shown to have different effects on soil CO2 efflux. Some studies have reported that N input remarkably increased SR (Pregitzer et al., 2000; Burton et al., 2002; Bowden et al., 2004), suggesting that the stimulatory effects of N loading on ecosystems can reduce ecosystem C storage (Ca and Woodward, 1998). Conversely, N fertilization has also been observed to reduce organic C decomposition and suppress SR, resulting in increased SOC (Burton et al., 2002; Foereid et al., 2004). With increasing application of N fertilizers, it is, therefore, necessary to further elucidate the real effects of N input on SR in diverse agricultural ecosystems and different planting regions.

In China, more than 50% of the total farmland is cropland located in arid and semi-arid regions (Shangguan et al., 2001), and the arable soils are intensively cultivated using high input of N fertilizers (Ding et al., 2010). Previous studies mainly focused on SR responses to N fertilization application in grassland (Li et al., 2012a), the paddy (Li et al., 2012b), or corn-cropland soils (Song and Zhang, 2009; Ding et al., 2010; Nie et al., 2012) in the region. To our knowledge, however, there is no information for wheat-cropland soils in arid and semi-arid regions of Northwest China, although one study was conducted on N fertilization in North China Plain, in which the climate in agricultural ecosystems is different from that in the arid and semi-arid regions (Chen et al., 2004).

Therefore, we conducted a controlled experiment to investigate the effects of different N levels on soil CO2 efflux in the arid and semi-arid regions of Northwest China. In the present study, a field experiment was carried out in a non-irrigated winter wheat-cropland to investigate effects of N fertilization on soil CO2 efflux over two consecutive growing seasons (2007–2009).

### Table 1
Selected soil physical–chemical properties in 0–20 cm soil layer before fertilization.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxonomy</td>
<td>Eum-Orthic Anthrosols</td>
</tr>
<tr>
<td>Texture</td>
<td></td>
</tr>
<tr>
<td>2000–50 μm (g kg⁻¹)</td>
<td>64</td>
</tr>
<tr>
<td>50–2 μm (g kg⁻¹)</td>
<td>694</td>
</tr>
<tr>
<td>&lt;2 μm (g kg⁻¹)</td>
<td>342</td>
</tr>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td>1.23</td>
</tr>
<tr>
<td>pH</td>
<td>5.43</td>
</tr>
<tr>
<td>Water holding capacity (g H₂O 100 g dry soil⁻¹)</td>
<td>23.6</td>
</tr>
<tr>
<td>Permanent wilting point (g H₂O 100 g dry soil⁻¹)</td>
<td>8.5</td>
</tr>
<tr>
<td>Total organic carbon (g kg⁻¹)</td>
<td>13.20</td>
</tr>
<tr>
<td>C/N</td>
<td>15</td>
</tr>
<tr>
<td>Total N (g kg⁻¹)</td>
<td>0.80</td>
</tr>
<tr>
<td>Available N (mg kg⁻¹)</td>
<td>25.10</td>
</tr>
<tr>
<td>Available P (mg kg⁻¹)</td>
<td>7.90</td>
</tr>
</tbody>
</table>

### 2. Materials and methods

#### 2.1. Research site and experimental setup

The study was conducted in Yangling, Shaanxi, Northwest China (108°3′50″E, 34°17′2″N, 500 m a.s.l.), located in the arid and semi-arid region of Northwest China. Selected soil physical and chemical properties in the 0–20 cm layer are presented in Table 1. Additionally, the soil texture of the experimental location was classified according to US taxonomy. The mean monthly temperatures and rainfalls of 2007–2009 in the study location are shown in Fig. 1. In light of the precipitation and its distribution in 2007–2009, the study years (2007–2009) were considered as regular years in this region.

Nitrogen fertilizer was applied from the autumn of 2004. The location was under a stubble-free winter wheat–corn rotation and a chisel plow tillage system before the experimental design and its land use resulted in the development of Lou soil (Eum-Orthic Anthrosols). The treatments (four N levels) for winter wheat were designed: 0, 90, 180, and 360 kg N ha⁻¹, and N was applied in the form of urea [CO(NH₂)₂] each year of 2004–2009. At the same time, phosphorus (P) was applied as phosphate fertilizer coupled with CaSO₄ at 75 kg ha⁻¹ in every treatment each year. The fertilizers were evenly applied to the soil surface as the basal fertilizers, and

---

![Fig. 1. Monthly precipitations and air temperatures during the sampling periods in Yangling research farm between 2007 and 2009.](image-url)
then mixed with soil by plowing into 0–20 cm soil with a deep-
digger before wheat sowing, which is a common practice that
farmers apply nitrogen fertilizer in this region (Wang et al., 2014).
The study had 12 6 m² plots (each 2 m wide and 3 m long) with
a three-replication randomized block design for treatments. Slates
were buried vertically into soil 3 m deep along the four sides of
each plot. Plots were not irrigated and the same farming practices
were used for all. Winter wheat was usually sown at the beginning
of October and harvested at the middle of June in the next year. The
12 plots were fallow during July–September. The growth stages of
winter wheat were defined according to Zadoks et al. (1974).

The ST and soil water content (SWC) in different topsoil layers
(0–10 cm and 10–20 cm) were measured outside the rings when
soil CO₂ efflux was measured. ST was measured with a LI-8100
outfitted with a soil thermometer. Soil sampling was done in two
topsoil layers (0–10 cm and 10–20 cm) for ST and SWC determina-
tions with a drill of 3 cm diameter. Gravimetric SWC was
determined by weighing the soil before and after drying at 105 °C.

The soil samples were air-dried, ground and sieved with a 0.15-
mm sieve to determine their organic C contents and total N, and
samples for the determination of pH and available N (available N is
usually referred to be efficiently utilized by plant at one season in
forms of soil nitrate-N and ammonium-N) and P were sieved with a
1-mm sieve. These parameters were determined according to the
methods of Page et al. (1982). The pH was measured with a 1:2.5
soil:water suspension, using a digital pH meter (Basic PB-20,
Sartorius AG, Goettingen, Germany). The organic C content was
determined using the Walkley–Black acid digestion method
(Walkley and Black, 1934). Total N (digested with sulfuric acid)
and available N (extracted by 2 M KCl) were measured by titration
of the distillates after Kjeldahl sample preparation and determina-
tion. Available P (extracted by 0.05 M HCl-1/2H₂SO₄) was
measured by molybdenum blue colorimetry. All measurements
were repeated independently in triplicate.

2.2. CO₂ efflux measurement and calculation

The soil CO₂ flux was monitored using a static chamber
fabricated with polyvinyl (PVC) pipe. Two PVC rings with a
diameter of 22 cm were placed in each applied-N plot after wheat
seedlings had emerged in 2007. In the applied-N plots, one ring
was arranged in one wheat row, and the other was arranged
between two neighboring rows. In each PVC ring, the CO₂ flux was
measured twice with a LI-8100 automated soil CO₂ flux system (LI-
COR, USA) at each of growth period from sowing to maturity. Each
measurement of soil CO₂ flux took 2 min of time.

To take into account the effect of different temperature induced
by measuring order on soil CO₂ flux during daytime, we measured
the soil CO₂ flux of all the treatments once, and then repeated it by
inverted order. The two flux measurements were averaged as one
block's soil CO₂ flux, and then the average value of three blocks in
the same treatment was as one treatment’s soil CO₂ flux. When we
measured the CO₂ flux, we always choose the fine days in every
growth stage, and measured it between 09:00 and 11:00 am in
daytime.

2.3. Aboveground and belowground biomass measurements

The aboveground and belowground biomass of winter wheat at
the different N levels (0, 90, 180, and 360 kg N ha⁻¹) from anthesis
(April 05, 2008/2009) to maturity stage (June 03/06, 2008/2009)
were sampled when soil CO₂ effuxes were measured. The three
independent replicates with 12 plants each for aboveground and
belowground biomass were performed. Samples of root biomass
were ingathered in two topsoil layers (0–10 cm and 10–20 cm)
using a core sampler with a diameter of 20 cm. The roots in the

![Fig. 2. Cumulative soil CO₂−C emission of winter wheat field at the different N levels (0, 90, 180, and 360 kg N ha⁻¹) in 2007–2009. The cumulative CO₂−C emission was calculated from the sowing (October 27/25, 2007/2008) to maturity stages (June 03/06, 2008/2009). The values represent the means of two consecutive growing seasons ± SE. Different letters above bars indicate significantly different at P < 0.05.](image)

samples from the different topsoil layers were carefully removed,
and the samples were placed in micro-pore soil sieves, rinsed with
tap water, oven-dried at 80 °C for 48 h and weighed.

2.4. Data analysis

The cumulative soil CO₂ emission at a given time was calculated
using the following formula which is justified by Wilson and Al-
Kaisi (2008) and Mancinelli et al. (2010):

\[
\text{CO₂−C(} \text{kg ha}^{-1} \text{)} = \sum_{i=\text{first}}^{n=\text{last}} X_i + X_i\times K + X_i\times K + \ldots + X_i\times n \\
\times K
\]

![Fig. 3. Seasonal variations in soil CO₂ flux of winter wheat field at the different N levels (0, 90, 180, and 360 kg N ha⁻¹) from October 27/25, 2007/2008 to June 03/06, 2008/2009. Asterisks indicate significant differences among the four treatments at } P < 0.01. \text{ The values represent the means of two consecutive growing seasons ± SE.](image)
In which \( i \) is the first soil CO\(_2\) flux measured at the time of sowing, \( n \) is the last soil CO\(_2\) flux measured at the harvesting time, \( X \) represents the average soil CO\(_2\) efflux (kg C ha\(^{-1}\) day\(^{-1}\)) between two consecutive soil CO\(_2\) rate measurements, and \( K \) is the number of days between the two measurements.

There are three biological replicates (three plots) in every N treatment, and there are two technical replicates (two PVC rings) in each replicate. The value represented the mean value of the two growth season in 2007–2009. SAS system (SAS Institute, Cary, NC, USA) was used to test difference significances among the treatments at \( P < 0.05 \) and \( P < 0.01 \). One-way ANOVA was used to test differences among the independent groups, and the differences were then tested by Duncan’s multiple range test. Simple linear regression analysis was performed with Sigma Plot version 10.0 (Systat Software Inc., San Jose, CA, USA) to determine the relationship between soil CO\(_2\) – C efflux and ST, SWC, biomass, respectively.

3. Results

3.1. Soil CO\(_2\) flux dynamics

The cumulative doses (the difference in cumulative soil CO\(_2\) – C fluxes of winter wheat field from sowing to maturity stage) and seasonal variations in soil CO\(_2\) flux in the four treatments during the growing seasons of winter wheat are shown in Figs. 2 and 3.

![Graph of soil temperatures and water contents](image-url)

**Fig. 4.** Soil temperatures (A, 0–10 cm soil; B, 10–20 cm soil layer) and soil water contents (C, 0–10 cm soil; D, 10–20 cm soil layer) in the winter wheat field at the different N levels (0, 90, 180, and 360 kg N ha\(^{-1}\)) measured from sowing to maturity stages. The values represent the means of two consecutive growing seasons ± SE.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Available N in 0–20 cm soil layer (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sowing stage</td>
</tr>
<tr>
<td>N0</td>
<td>23.1c</td>
</tr>
<tr>
<td>N90</td>
<td>25.0b</td>
</tr>
<tr>
<td>N180</td>
<td>27.4a</td>
</tr>
<tr>
<td>N360</td>
<td>28.0a</td>
</tr>
</tbody>
</table>

Note: Different letters in the same columns mean significant differences at \( P < 0.05 \).
(0 kg N ha⁻¹). At the vigorous growth stages from 4/7 March to 21/20 April, soil CO₂ flux at 360 kg N ha⁻¹ was 21%, 9%, and 6%, lower than that in the 180 kg N ha⁻¹ treatment, respectively. After 5 April, when winter wheat plants approached maturity, the soil CO₂ efflux began to decrease. Decrease in SR at the maturity might also be explained by great decreases in soil moisture, root biomass, and soil available N, but there were no significant differences in the above parameters among the four treatments (Table 2, Fig. 4).

3.2. Relationship between soil CO₂ flux and soil temperature, moisture, and plant biomass

To better understand the reasons for significant variation in soil CO₂ flux of winter wheat–cropland during the growing season, the soil microclimatic conditions, including ST and SWC, were further investigated (Fig. 4). ST was in the range of 4.2–40.9 °C during the growing season, and its average value in the zero–N treatment was 1 °C higher than those in the other treatments (Fig. 4). Generally, ST had a greater effect on soil respiration rate than SR. However, a sudden decrease in SR occurred around filling stage, suggesting that low soil CO₂ flux was probably due to the lowest SWC (<15% and close to the wilting point, Fig. 4), while ST was >20 °C, and the precipitation was low in April. In addition, SWC and ST in 0–10 cm soil varied significantly, and SWC in 0–10 cm was lower than in 10–20 cm soil; in contrast, ST varied oppositely in 0–20 cm soil at most sampling dates. Across the growing season, ST and SWC in different N treatments had similar trends, while ST and SWC were not consistent with each other; when ST was highest, SWC was at very low levels. The biomass of winter wheat (aboveground and belowground) measured after heading stage is presented in Fig. 5. In the 0–20 cm topsoil layer, the root biomass at 0, 90, 180, and 360 kg N ha⁻¹ levels at anthesis stage were 1.65, 2.26, 2.03, and 2.00 fold more than those at maturity, respectively. Although shoot biomass increased after heading, the crop was concentrated to seed filling rather than biomass, and so no further increase occurred at filling stage. But shoot biomass at 0, 90, 180, and 360 kg N ha⁻¹ levels increased remarkably at maturity stage, and they were 2.05, 1.28, 2.12, and 1.04 fold higher than those at anthesis, respectively.

As a whole, the effect of ST or SWC on soil CO₂ flux in 10–20 cm soil ($R^2 = 0.21, P < 0.001$ and $R^2 = 0.18, P < 0.05, n = 64$, respectively) was more apparent than in 0–10 cm soil ($R^2 = 0.18, P < 0.01$ and $R^2 = 0.11, P < 0.05, n = 64$, respectively) (Fig. 6). Moreover, soil CO₂ efflux was positively correlated with ST but negatively correlated with SWC (Fig. 6). Aboveground and belowground biomass was positively correlated with N levels in most stages. Furthermore, soil CO₂ flux was also positively correlated with plant biomass production (Fig. 7). The correlation of soil CO₂ flux with root biomass in 0–10 cm soil ($R^2 = 0.25$) was stronger than that in 10–20 cm soil ($R^2 = 0.20$). Moreover, the plant shoot biomass had little effect on SR ($R^2 = 0.05$) because of a lack of crop residues in soil.

4. Discussion

There are contradictory viewpoints concerning whether N applied to soils regardless of its forms increases soil CO₂ production (Johnston et al., 2009; Ramirez et al., 2010). Our study showed that the effect of N fertilization level on cumulative soil CO₂ effluxes was remarkable in winter wheat–cropland (Fig. 2). The cumulative soil CO₂ effluxes from soil with applied fertilizers at 90, 180, and 360 kg N ha⁻¹ level were 17%, 34%, and 38% higher than that in zero-N treatment (Fig. 2), respectively. Because it is difficult to determine this parameter every day, the approximation for CO₂ fluxes estimated between the two adjacent measurements can represent the realistic values to some extent. Most of the differences occurred in the jointing and anthesis stages (Fig. 3).

The present results might have some uncertainty because only one measurement was used in every growing stage, and the calculation method used in this study was based on that used in corn–soybean (Wilson and Al-Kaisi, 2008). However, our calculation results of SR are consistent with short-term increase observed in corn-cropland (Morell et al., 2010). As Khan et al. (2007) and Mulvaney et al. (2009) suggested that N fertilization may enhance the decomposition rate of soil C, and SOC may decline in response to N fertilization. However, adequate fertilization contributes to increasing SOC by promoting crop dry matter production and does not alter the decomposition of native SOC (Snyder et al., 2009). Al-Kaisi et al. (2008) reported that N fertilization in corn and soybean-cropland resulted in quick decreases in both efflux and season-long cumulative emission of CO₂ from soil. As a result, significant
increase or decrease in soil CO$_2$ efflux with increased N level may be related to crop species. In addition, N addition increased shoot biomass (Fig. 5), and with wheat growth proceeding, the quantities of C fixed through photosynthesis also increased. Root biomass in 0–20 cm soil layer also increased after adding N; however, this preceded the increase in shoot biomass. These root and shoot residue amounts added to soil could maintain higher equilibrium N and thereby enhance the total microbial biomass C in the soil system, which may accelerate decomposition rate of SOC. Moreover, it is not clear based on the present studies, whether the response of soil respiration to N fertilization is temporary or not, and whether there are differences in SR between N fertilized and unfertilized land following crop harvest and on an annual basis (Ding et al., 2007). Further year-round field experiments are required to determine this aspect.

The soil CO$_2$ effluxes differed among different N levels in the growing season, especially at the jointing and anthesis stages but were significant merely at anthesis ($P < 0.05$, Fig. 3) – similar to results of Al-Kaisi et al. (2008). Most often the greatest CO$_2$ efflux was related to N application (Fig. 3). The effect of N level on soil CO$_2$ efflux was inconsistent across the growing seasons (Fig. 3) and appeared to be positively related to ST and SWC variables in the field (Fig. 4). Soil C cycling was linked to soil water status, and a positive relationship has been reported between SR and soil moisture (Linn and Doran, 1984). In previous experiments, however, fluxes exhibited significant and negative relationships with soil moisture due to poor gas diffusion in surface soils and reduction in activity of obligate aerobic microbes caused by excessive water above the optimum SWC (Rochette et al., 1991; Bowden et al., 2004). This was similar to our results (Fig. 6).
Rochette et al. (1991) also proposed that ST and the presence of plants were the most important regulators of SR. In our study, soil CO₂ efflux was positively correlated with ST (Fig. 6). We also found that the highest ST occurred at the lower SWC, and there was a significant decrease in ST with increasing SWC after sowing. Therefore, we speculated that ST sensitivity of soil CO₂ efflux may depend upon SWC, similar to the previous results in mesic grassland (Crain and Gelderman, 2011). Further studies will be required to evaluate the interactions of both ST and SWC on soil CO₂ efflux in the field. It has been reported that ST or SWC dependence of soil CO₂ efflux was altered by N application in cropland (Song and Zhang, 2009). Our study also showed that higher N fertilization decreased ST but increased soil CO₂ efflux after anthesis (Figs. 3 and 4), which implied that N addition may reduce ST dependence of soil CO₂ efflux in arid and semi-arid regions of Northwest China.

The maximum CO₂ efflux was observed during the vigorous growth period from 4/7 March to 21/20 April, and this may imply a greater root respiration at this phase, in agreement with the results of Ding et al. (2007) and Al-Kaisi et al. (2008). In our study, the root biomass of winter wheat was highest close to anthesis stage (Fig. 5), and soil CO₂ efflux was positively correlated with root biomass production (Fig. 7). Therefore, it was speculated that increased root production might lead to the increased substrate availability and soil microbial activity, resulting in the increased soil CO₂ efflux. A similar result was also obtained in a semiarid Mediterranean region, in which root or microbial respiration resulted in more soil CO₂ efflux in N-fertilized soils than in unfertilized plots (Morell et al., 2010). In addition, C sequestration contribution for combined N, P, and potassium application is via promoting wheat growth and increasing the soil C due to wheat stubble and root input into soil. Therefore, evaluating the contribution rate of soil fertility in different regions will be helpful to define the amount of N application and improve N availability, and thus, reducing soil CO₂ efflux in Chinese farmland resulting from N fertilizer application is important for the global CO₂ emissions.

5. Conclusions

Two-year inorganic N fertilization at different levels affected the soil CO₂ efflux to some extent, whereas the difference between the four treatments was significant only at anthesis. Soil CO₂ flux of winter wheat-cropland was related to N levels, growth stages, ST, and SWC. The cumulative soil CO₂ effluxes at 90, 180, and 360 kg N ha⁻¹ were 17%, 34%, and 38% higher than that in zero-N treatment, respectively. Furthermore, SR was positively correlated with ST but negatively with SWC, and ST had a greater effect on SR activity than did SWC. Growth stages of wheat plants can explain the temporal variations in SR due to root biomass and seasonal variations in ST and SWC.

Acknowledgements

The study was financially supported by the National Natural Science Foundation of China (41390463) and the Basic Research Projects of Henan Province (122300410012).

References


