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RESEARCH ARTICLE

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# Dynamics of carbon budget and meteorological factors of a typical maize ecosystem in Songnen Plain, China

Yonggang GAO[1,2], Ming WANG[1,2], Lanqi JIANG[1,2], Fang ZHAO[1,3], Feng GAO[4*] and Huiying ZHAO[1,2]

*[1]Heilongjiang Institute of Meteorological Science, Harbin, Heilongjiang 150030, China. [2]Innovation and Opening Laboratory of Regional Eco-Meteorology in Northeast, China Meteorological Administration, Harbin, Heilongjiang 150030, China. [3]Harbin Meteorological Administration, Harbin, Heilongjiang 150030, China. [4]Heilongjiang Provincial Meteorological Data Centre, Harbin 150030, China.*

***Correspondence** should be addressed to Feng Gao: gaofeng0013@163.com; ywudde1x6e@21cn.com

## Abstract

*Aim of the study:* Understanding the carbon budget and meteorological factor impacts of farmland ecosystems is helpful for scientific assessment of carbon budget and low-carbon agricultural production practices.

*Area of study:* The Songnen Plain, NE China, in 2019.

*Material and methods:* Based on eddy-related flux and soil heterotrophic respiration observations from a typical maize farmland ecosystem, using mathematical statistics and carbon balance equation methods, were analyzed.

*Main results:* Soil respiration rate ($R_s$) and composition were influenced and controlled by the synergistic effect of surface soil temperature ($T_s$) and water content ($W_{cs}$). $T_s$ played a leading role, while $W_{cs}$ played an important role. $T_s$ and $W_{cs}$ had the greatest influence on the heterotrophic respiration rate ($R_h$), followed by $R_s$ and autotrophic respiration rate ($R_a$). Daily variations of net ecosystem productivity were correlated with daily mean air temperature, latent heat flux, and sensible heat flux. Annual carbon revenue was 1139.67 g C $m^{-2}$, annual carbon expenditure was 456.14 g C $m^{-2}$, and annual carbon budget was -683.53 g C $m^{-2}$ in 2019. While considering that maize grain yield (-353.44 g C $m^{-2}$) was moved out of the field at harvest, the net ecosystem carbon balance was -330.09 g C $m^{-2}$; then it was carbon sink in 2019. By fully utilizing climate resources and improving agricultural managements, carbon sink is increased in farmland ecosystems.

*Research highlights:* Soil respiration rate and composition were influenced and controlled by the synergistic effect of soil temperature and water content; the maize farmland ecosystem is carbon sink.

**Additional key words:** maize farmland ecosystem; soil respiration.

**Abbreviations used:** GHG (greenhouse gases); NECB (net ecosystem carbon balance); NEE (net ecosystem exchange); NPP (net ecosystem productivity); PFCs (perfluorocarbons); SOC (soil organic C). **Parameters:** $R_a$ (soil autotrophic respiration); $R_h$ (soil heterotrophic respiration); $R_r$ (soil root respiration); $R_s$ (soil respiration); $T_s$ (soil temperature); $W_{cs}$ (soil water content).

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# Introduction

Addressing climate change has become a joint global effort, and agricultural mitigation and adaptation to climate change is one of the focal points of the international community and national governments. The farmland ecosystem is an important part of the carbon (C) cycle of the terrestrial ecosystem, it is not only an important source of $CO_2$ emissions, but also an important carbon sink. The global farmland area is ~ $1.4\times10^9$ $hm^2$, accounting for ~ 12% of the total land area, the organic C storage is 157 Pg C in 1 m deep soil of global farmland (Jobbágy & Jackson, 2000), with Asia having the highest soil C storage, accounting for approximately one-third of the global total soil C storage (Ren et al., 2020). The changes in farmland soil C pool are closely related to the high and stable yields of crops (Oldfield et al., 2019; Lal, 2020), and have a dual role in ensuring food security and mitigating climate change (Lal, 2004; Paustian et al., 2016; Hunt et al., 2020), and the sustainability of farmland ecosystems is a prerequisite and important guarantee for the sustainable development of human society (Liu et al., 2015).

Direct $CO_2$ emissions from agriculture, forestry and land use account for 24% of anthropogenic GHG (greenhouse gases) emissions, with agriculture contributing 10-12% (IPCC, 2014). Despite accounting for only about 10% of terrestrial ecosystem C stocks, agroecosystems, as the most active C pool (Zhao et al., 2010), can be regulated by anthropogenic activities in the shortest possible time. Therefore, it has become a joint effort of researchers from various countries by conducting research on the C budget of farmland ecosystems, fully utilizing climate resources and optimizing field management measures to improve C sequestration capacity (Smith, 2013; Yang et al., 2022).

Due to the complexity of C cycling processes, models are an important tool to study C cycling in agroecosystems. Since the mid-20th century, model development has gone through three stages: i) C balance model (Pilli et al., 2013); ii) climate-vegetation relationship model (Fan et al., 2012); and iii) biogeochemical cycle model (Lü et al., 2022; Zhou et al., 2022; Wang & Zhang, 2023). The last one is a more comprehensive C budget model with a unified structural framework which describes internal processes between the vegetation and the environment. These mainstream models have been applied in China and have played an important role in describing the C budget mechanism of terrestrial ecosystems and the mutual feedback process with climate change, and in C budget assessment applications. Due to limitations of the models, atmospheric inversions, and remote sensing, there is uncertainty in estimating regional and global C cycle, water cycle, and energy exchange (Oechel et al., 2000; Baldocchi et al., 2001; Piao et al., 2022; Yang et al., 2022), the development of Eddy covariance techniques provides an accurate method for continuous and direct determination of material and energy exchange between the land surface and the atmosphere, facilitating the development of ecosystem matter and energy studies (Valentini et al., 2000; Piao et al., 2022), and has played an important role in climate change studies (Yao et al., 2018; Baldocchi et al., 2001; Baldocchi, 2003; Zhao et al., 2021). In the Asian region, terrestrial ecosystems are important C sinks, the intensity of which is driven by climate factors, $CO_2$ concentration, leaf area index, and N deposition conditions (Zhou et al., 2022); subtropical forest ecosystems in the 20°-40° NE Asian monsoon region are high C sink functional areas (Yu et al., 2020). There are still controversies about whether farmland ecosystems are C sources or C sinks, most studies believe that farmland ecosystems are C sinks (Ren et al., 2020; Zhao et al., 2021; Yang et al., 2022), and the C sinks of farmland ecosystems in coastal areas of China are obvious (Zhao & Qin, 2007). The effect of C sink of crop biomass is not obvious due to the short harvesting period of crops (Fang et al., 2007), or the aboveground biomass of crops can be used as silage feed to move out of farmland, and farmland ecosystems are C sources (Wall et al., 2020). In NE China, there are few research results on C sinks in the Liaohe Delta (Liang et al., 2012; Ye et al., 2022) and the Sanjiang Plain (Hao et al., 2007).

Songnen Plain is located in NE China, one of the three largest black soil regions in the world, with distinctive agricultural soil resources, high organic matter content and fertile soil; it is an important agricultural production area in China, where the total storage of organic C pool in farmland topsoil is 233.63 Tg C (Jiang et al., 2017), which plays an important role in C sequestration in China and the globe. However, due to the intensification of human interference for a long time, the organic C density of farmland soil has decreased (Jiang et al., 2017; Zhang et al., 2021), and its C storage changes have a significant impact on regional and global C balance.

Understanding the C budget changes in farmland ecosystems is the basis for increasing soil organic C (SOC) and C storage, but few research results have been reported on the Songnen Plain in China. Therefore, this work selected a typical maize （*Zea mays* L.） farming ecosystem in this region as the research object, where based on eddy-related, soil heterotrophic respiration, and meteorological and biological elements observations, the C budget dynamics of maize farmland ecosystem and the influence of meteorological factors were explored. It may be profit to increase the C sequestration capacity of farmland ecosystem, curb the loss of SOC and C pool, and enhance the contribution of Songnen Plain to C sequestration in China by making full use of climate resources and optimizing agricultural management measures. It is beneficial to promote low-C agricultural development goals of C sequestration, emission reduction, and production increase.

# Material and methods

## Overview of the test site

The test site was located in the Agricultural Meteorological Experiment Station (45°36' N, 126°49' E) in Acheng District, Harbin City, the hinterland of the Songnen Plain, China. It belongs to the cold-temperate continental monsoon climate zone, with a cold and dry climate in winter, warm and humid in summer, concentrated precipitation, rain, and heat in the same season, an annual average air temperature of 4.6°C, annual average precipitation of 529.5 mm, being the summer precipitation 65.8% of the total annual precipitation. The land in the test site is flat, and the soil is black calcium soil cultivated for many years with uniform and representative ground strength. In 0-30 cm, the contents are: average soil organic matter, 20.80 g kg$^{-1}$; total N, 0.144%; total phosphorus (P), 0.045%; total potassium ($K_2O$), 2.15%; and pH 5.35.

The test site and the surrounding farmland were not irrigated, mainly rainfed, and cultivated with a 30-cm tillage layer. In the non-growing season, there was no crop under the farmland and the surface was covered with bare soil; the crop growing season was one season. The planting varieties, farm management practices and fertilizer application were consistent with the surrounding farmland. Maize trial material in 2019 was the early to medium maturing spring variety 'Hongshuo 298', the main planted variety in Harbin, and the sowing method was mechanical start-up direct seeding. The sowing density of maize was 56,767 plants hm$^{-2}$ and the fertilizer was diammonium phosphate with compound fertilizer (1:2), with a fertilizer application rate of 525 kg hm$^{-2}$. Maize growing periods in 2019 were representative without agro-meteorological disasters. Dates for sowing, emergence, three-leaf, seven-leaf, jointing, staminate, filling and mature maize in the 2019 trial site were May 5, May 28, June 3, June 16, July 1, July 27, August 6, and September 22, respectively. The maize grain yield in 2019 was 1276.18 g m$^{-2}$ according to the composition factors of maize yield in the field. The content of carbohydrate $(C_6H_{10}O_5)_n$ in maize grains after harvest was 66.16%, which was detected by China Qingdao Kechuang Quality Inspection Co., Ltd.

## Experimental design

### Observation of soil respiration

Soil respiration refers to all metabolic processes by which undisturbed soil releases $CO_2$ to the atmosphere and consists of four main components: root respiration, soil microbial respiration, soil animal respiration, and chemical oxidation of C-containing materials (Micks et al., 2004). Depending on the source of respiratory substrates, soil respiration can be further divided into soil autotrophic respiration ($R_a$) and soil heterotrophic respiration ($R_h$) (Zhu & Cheng, 2013). Autotrophic respiration is soil root respiration ($R_r$), requiring substrates from the accumulation of photosynthetic C by plants; the heterotrophic respiration consumes substrates of soil sequestered C, but is usually neglected because the contribution of soil animal respiration and chemical oxidation of C-containing materials to total soil respiration is very small (O'Leary, 1988). Therefore, in this study, soil respiration rates ($R_s$) were calculated in unplanted maize areas set aside in the test area as the equivalent environmental $R_h$ rate; the $R_a$ was the difference between the $R_s$ in the maize planted area and the $R_h$ in the maize unplanted area: $R_a = R_s - R_h$.

Soil heterotrophic respiration rates were calculated in February to December 2019 at the Agricultural Meteorological Experiment Station test site. One set of soil respiration measuring instruments (RR-7330) was installed in the area reserved for unplanted maize to observe $R_h$ rate dynamics during the maize growing and non-growing periods. During the maize growing season between May and September in 2019, the other 2 sets of RR-7330 were fixedly installed between two maize plants on the ridge of the maize test area 5-m apart to calculate the $R_s$ dynamics during the maize reproduction period. Weeds and foreign matter were cleared from inside and outside the observation cylinders of the soil respiration instrument in the farm field during the observation period to avoid soil respiration observations being affected.

The soil respiration chamber in agricultural fields was automatically closed every hour to measure the change in $CO_2$ concentration, the pressure inside the gas chamber, and the temperature inside the gas chamber within 150 s at the soil surface, which was used as the basis for calculating $R_s$ (μmol m$^{-2}$ s$^{-1}$) and heterotrophic respiration rate, following the equation:

$$R_s = \frac{\Delta C \cdot V}{0.0224 \cdot \Delta t \cdot A} \frac{P_0}{P} \frac{T}{T_0} \qquad (1)$$

where $\Delta C$ is the difference in $CO_2$ concentration at the inlet and outlet of the respiration chamber, μmol mol$^{-1}$; $V$ is the volume of the gas path, m$^3$; $A$ is the covered soil surface area, m$^2$; $P_0$ and $P$ are the standard and actual atmospheric pressure, kPa, respectively; $T$ and $T_0$ are the gas temperature and temperature at standard conditions, ºK, respectively.

### Farmland carbon budget and related observations

Carbon budget and related observations for 2019 in the maize ecosystem of the Songnen Plain, China, were obtained from the Harbin Agrometeorological Experiment Station test site. The flux observation tower used an open-path Eddy covariance system (OPEC), which consisted of a data collector (CR5000), an ultrasonic anemometer (CSAT3, Campbell Scientiflic Inc., USA), and $CO_2$ and $H_2O$ analyzer (LI-7500A, LI-COR Inc., USA). With an observation height of 4.0 m and a data sampling frequency of 10 Hz, the system operates with online fluxes calculated by the vorticity correlation principle and stores 30 min of $CO_2$ fluxes ($F_c$), latent heat fluxes (*LE*) with sensible heat fluxes ($H_s$) and 10 Hz time series data. The observations were made with the CR-9200 microclimate gradient automatic monitoring system (Campbell Scientiflic Inc., USA) at a height of 4.0 m. The meteorological gradient observations included wind speed, wind direction, air temperature and humidity, 4-component radiation, soil water content and soil temperature at 5-100 cm below ground level. Meteorological data were recorded every 2 s and averaged over 30 min.

### *Data quality control*

Data quality control of the $R_s$ mainly includes: (1) during the observation process, insects often enter the respiratory chamber extraction holes, and occasionally the instrument fails during the observation process, so the corresponding data need to be excluded; (2) analysis by Jiang et al. (2014) showed that the highest values of $R_s$ in maize cropland in China were 10.36 μmol $CO_2$ $m^{-2}$ $s^{-1}$; therefore, the original observation data need to be excluded when the observation value is too large (> 20.0) or too small (< 0.0); (3) according to the PauTa criterion (3σ), when the absolute value of the difference between the observed value and the mean value exceeds 3 times the standard deviation, which is considered an abnormal value, must be excluded; (4) the data with a sudden and unreasonable jump in the time series of daily observations should also be excluded. For missing data, linear interpolation was used for ≤ 2 h; for > 2 h, a fitted model of the relationship between $R_s$ and soil temperature and water content was used for interpolation.

Quality control of the C budget (*F*c) data mainly includes: (1) observation data that correct the effect of changing atmospheric hydrothermal conditions using the Webb, Pearman and Leuning (WPL) method, and the quadratic coordinate rotation to eliminate the possible influence formed by the uneven terrain or sensor non-vertical; (2) precipitation data during the same period; (3) data with excessive observation value (> 100.0) in the original flux data; (4) to eliminate the data with obvious anomalies in the flux time series using the difference method, taking the sensitivity value z as 4.0; (5) the flux data corresponding to the nighttime friction velocity below the friction velocity threshold (taken as 0.1 m $s^{-1}$). The missing data were interpolated by REddyProc (7.0.6) software using the look-up tables method (LUT).

## Research methods

### *Soil respiration in relation to soil temperature and water content and temperature sensitivity of soil respiration*

$R_s$ is usually exponentially correlated with soil temperature (Lloyd & Taylor, 1994; Gaumontguay et al., 2006) and can be expressed as an exponential equation $R_s = ae^{bTs}$ where $T_s$ is the soil surface temperature (°C), and *a* and *b* are fitting coefficients. Using the coefficients *b*, the sensitivity coefficient $Q_{10}$ of soil respiration to soil surface temperature can be derived, i.e. $Q_{10} = e^{10b}$. The value of $Q_{10}$ reflects the strength of the sensitivity of soil respiration to soil surface temperature. The model can be used to fit the relationship between $R_s$ and soil temperature and the temperature sensitivity coefficient of soil respiration.

$R_s$ is usually quadratically-related to soil water content (Mielnick & William, 2000; Wu et al., 2018) and can be expressed as a quadratic equation, i.e. $R_s = cW_{cs}^2 + dW_{cs} + f$, where $W_{cs}$ is the soil water content, and *c*, *d*, and *f* are regression coefficients. The quadratic curve relationship can be used to fit the relationship between $R_s$ and soil water content.

The relationship between $R_s$ and soil temperature and soil water content is expressed as a non-linear relationship equation, i.e. $R_s = ae^{bTs} (cW_{cs}^2 + dW_{cs} + f)$. Accordingly, the nonlinear relation equations of $R_s$, $R_h$ and $R_a$ were fitted.

### *Calculation of carbon budget*

Under natural conditions, the basic process of C cycling in terrestrial ecosystems is: organic C is formed from atmospheric $CO_2$ fixed by photosynthesis, soil organic matter is formed in the soil after plant roots and above-ground vegetation die off, and *SOC* is decomposed by microorganisms, releasing $CO_2$ back into the atmosphere. Net primary productivity (*NPP*) of terrestrial ecosystems, i.e. C fixed by photosynthesis (*GPP*, gross primary productivity) minus C emitted by plant respiration ($R_a$), and net ecosystem C exchange (*NEE*), i.e. C gained or lost by the ecosystem as a whole. The equation for estimating *NPP* can be expressed as:

$$NEE = R_h - (GPP - R_a) = R_h - NPP \tag{2}$$

$$NPP = R_h - NEE \tag{3}$$

Net ecosystem carbon balance (*NECB*) is used to represent changes in *SOC* content (Wall et al., 2020). In agricultural production, when maize grains are harvested and removed, maize stalks are crushed by agricultural machines and left in the field, therefore, *NECB* calculation formula is:

$$NECB = NEE - HR \tag{4}$$

where *HR* is the C content (g C $m^{-2}$) of maize grains removed from the farmland after harvest. *HR* can be calculated as follows:

$$HR = Y \times B \times B\mathrm{c} \tag{5}$$

where *Y* is maize grain yield (g $m^{-2}$); *B* is the content (%) of carbohydrates $(C_6H_{10}O_5)n$ in maize grains; *Bc* is the

**Table 1.** Coefficient of fitting soil respiration rate ($R_s$), auto respiration rate ($R_a$) and soil heterotrophic respiration ($R_h$) rate of soil surface temperature ($T_s$) and water content ($W_{cs}$) and its coefficient of determination for maize in 2019 (n=2532).

| Soil depth | *a* | *b* | *c* | *d* | *f* | $R^2$ | Sig. |
|---|---|---|---|---|---|---|---|
| | | | $R_s$ | | | | |
| 5 cm | 0.836 | 0.037 | 0.003 | -0.002 | 0.967 | 0.407 | ** |
| 10 cm | 3.287 | 0.046 | 0.000 | 0.022 | 0.022 | 0.401 | ** |
| 20 cm | -0.947 | 0.035 | 0.009 | -0.430 | 2.854 | 0.403 | ** |
| | | | $R_a$ | | | | |
| 5 cm | 1.215 | 0.038 | 0.002 | -0.061 | 1.214 | 0.185 | ** |
| 10 cm | 1.948 | 0.060 | 0.003 | -0.149 | 1.942 | 0.189 | ** |
| 20 cm | 5.170 | 0.050 | 0.010 | -0.438 | 5.154 | 0.180 | ** |
| | | | $R_h$ | | | | |
| 5 cm | -2.107 | 0.034 | 0.004 | -0.214 | 2.096 | 0.463 | ** |
| 10 cm | -0.014 | 0.049 | -0.103 | -0.073 | 0.010 | 0.410 | ** |
| 20 cm | 5.400 | 0.044 | -0.011 | 0.487 | -5.362 | 0.552 | ** |

$R_s = R_a = R_h = ae^{bTs} (cW_{cs}^2 + dW_{cs} + f)$. * and ** represent highly significant correlations p<0.01 and p<0.001, respectively.

content of C in carbohydrate, which can be calculated by its molecular weight $(C_6H_{10}O_5)n$, and *Bc* = 41.86%.

*Data processing*

The processing of experimental data, statistics, analysis, and graphs were conducted through Excel 2007 and SPSS 20.0.

# Results

## Soil respiration rate

During the growing period of maize, $R_s$, $R_a$ and $R_h$ were affected by the synergistic effects of soil surface (5-20 cm) temperature and water content, and all of them passed the extremely significant statistical test ($p < 0.001$) (Table 1). Among them, $R_h$ was the most affected, accounting for 41.0-55.2% of the variation, what indicates that the decomposition of organic C in soil was mainly affected and controlled by meteorological factors such as temperature and water content. Instead, $R_a$ was the least affected, accounting for 18.0-18.9% of the variation, what indicates that $R_a$ was not only affected by soil temperature and water content, but also possibly by biological factors such as crop root biomass, number and activity of root microorganisms, and photosynthetic capacity. Under the action of $R_h$ and $R_a$, soil temperature and water content can explain 40.1-40.7% of $R_s$ variation, indicating that $R_s$ variation was obviously affected by soil temperature, water content and biological factors. According to statistics, the proportion of autotrophic respiration in soil respiration during the growth period of maize were fluctuated between 46.8% and 66.9%, the average proportion was 54.9%.

The influence of soil temperature and water content on soil respiration was further analyzed. The statistical analysis showed that $T_s$ of soil surface layer (5-20 cm) was able to explain 36.0-50.7% of the $R_h$ variation; $W_{cs}$ was 14.0-20.4% of the variation, with $W_{cs\_20cm}$ explaining the variation of $R_h$ best. $T_s$ was 40.8-49.1% of the $R_s$ variation, $W_{cs}$ was 8.6-12.0% of the $R_s$ variation. $T_s$ was 14.6-17.5% of the $R_a$ variation, $W_{cs}$ was 3.6-5.5% of the $R_a$ variation. The results showed that soil temperature played a leading role in the synergistic effect of soil temperature and water content on soil respiration in the study area, while soil water content played an important role.

In the annual variation of soil heterotrophic respiration rate, the heterotrophic respiration rate of agricultural soils showed a single-peaked curve. The high $R_h$ value stage was in mid July to early August, i.e., the same period of time for staminate stage and filling stage, with a peak (on July 20) of 3.75 g C $m^{-2}$ $d^{-1}$ (Fig. 1), which was consistent with the distribution of local air temperature and precipitation. In spring, as air temperature and ground temperature increase, the $R_h$ gradually increases; July-August with high air temperature and ground temperature, more rainfall, and wet soil, the $R_h$ is high; and in autumn as air and ground temperatures decrease, the $R_h$ gradually decreases. According to the conversion 1 g C $m^{-2}$ $d^{-1}$ = 1/1.0368 μmol $CO_2$ $m^{-2}$ $s^{-1}$ (Jiang et al., 2014), the amount of C released from farmland through heterotrophic respiration in the year and crop growing field (May 1 to September 30) was 456.14 g C $m^{-2}$ and 304.94 g C $m^{-2}$, respectively. The amount of heterotrophic respiration of the crop growing

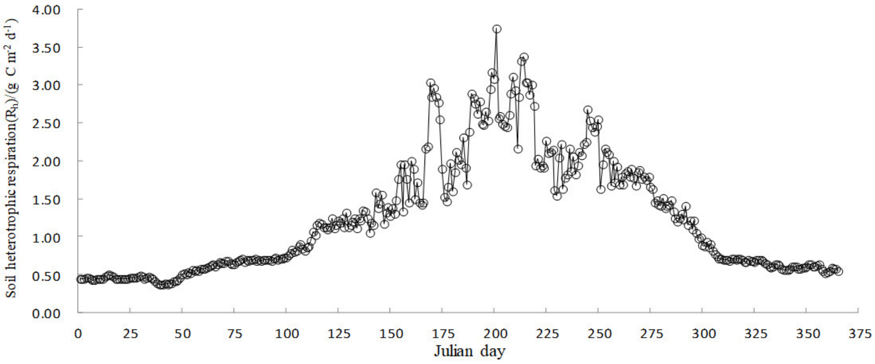

**Figure 1**. Seasonal variation of soil heterotrophic respiration ($R_h$) rate in maize farmland ecosystem (2019).

field accounted for 66.85% of the annual heterotrophic respiration.

## Net primary productivity (NPP)

The NPP of maize in the growing field (May to September) showed a unimodal curve (Fig. 2). After the seven-leaf stage of maize, the NPP increased rapidly. In July, the maize grows vigorously and the NPP was in a high value stage. The peak was at the beginning of the filling stage, 19.20 g C $m^{-2}$ $d^{-1}$. There were 19 days of continuous rain from August 6 to August 28, the maize photosynthesis was affected and the maize C sequestration capacity was weakened, the NPP value was lower during this period than in July, and the NPP gradually weakened after September. The NPP of maize during the growing field was 1113.51 g C $m^{-2}$.

## Net ecosystem carbon exchange (NEE)

In 2019, the seasonal variation of NEE in farmland showed a “V” shaped distribution, with a weak C source (125.04 g C $m^{-2}$) during the non-growing season due to the absence of crop photosynthesis to fix atmospheric $CO_2$ and mainly soil emissions of $CO_2$ to the atmosphere, as well as cold weather and weak soil microbial activity during this time. During the maize growing season, with the development of the maize reproductive process, although the amount of soil emissions $CO_2$ increased, the photosynthetic capacity and C sequestration during the growth of maize strengthened, far exceeding the amount of soil emissions $CO_2$ and showing a strong C sink (-808.57 g C $m^{-2}$), where the NEE peaked in early August (-15.81 g C $m^{-2}$ $d^{-1}$), weakened due to the influence of continuous rains in mid and late August, with a gradual weakening of NEE after September (Fig. 3). Agroecosystem NEE in 2019 was -683.53 g C $m^{-2}$, showing a strong C sink.

## Influence of meteorological factors on C budget of farmland

### *Influence of meteorological factors on C revenues*

Agroecosystems fix atmospheric $CO_2$ through crop photosynthesis and expel a portion of $CO_2$ through autotrophic respiration during crop growth, resulting in NPP (C income) of the ecosystem. During the crop growing

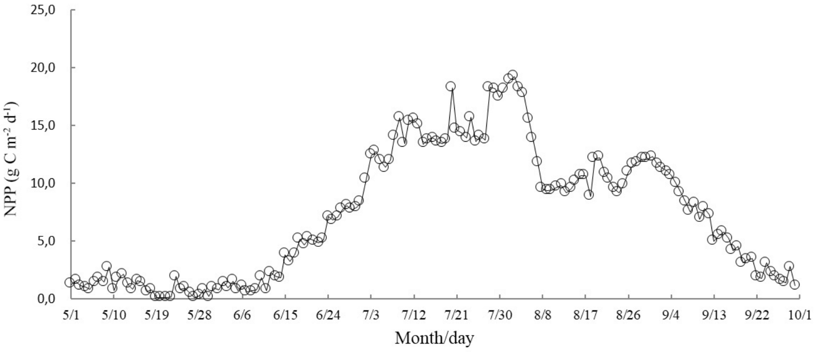

**Figure 2**. Net primary productivity (NPP) dynamics of crop growing season in maize farmland ecosystem (2019).

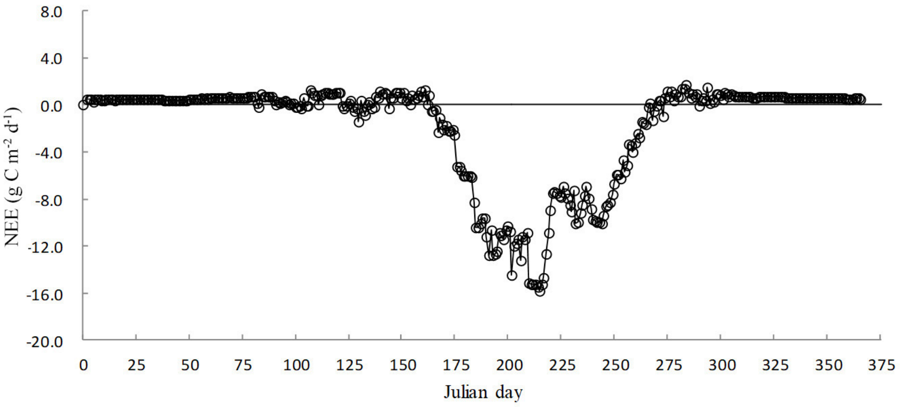

**Figure 3**. Net ecosystem carbon exchange (NEE) dynamics of one year in maize farmland ecosystem (2019).

season, the daily variation of NPP was significantly positively correlated ($p<0.01$) with the average daily air temperature ($T_a$) and the average daily latent heat flux (*LE)*, and negatively correlated ($p<0.01$) with the average daily sensible heat flux ($H_s$) (Table 2), indicating that with the increase of air temperature during crop growth, photosynthesis enhanced, crop evapotranspiration enhanced (latent heat flux enhanced) and sensible heat flux weakened. Agroecosystem C income (NPP) was enhanced, especially during the peak crop season in July to August, when soil moisture was abundant and most of the energy obtained by crops was used for latent heat fluxes. The synergistic effect of $T_a$, *LE*, and $H_s$ explained 56.06% of the variation in *NPP* ($NPP = 0.6411T_a + 0.0345LE - 0.0574H_s - 5.5390$, $R^2 = 0.5606$).

*Impact of meteorological factors on carbon expenditure*

Agroecosystem C expenditure is mainly a process of $CO_2$ excretion through soil respiration (autotrophic and heterotrophic respiration), $R_a$ occurs during the crop growing season for crop respiration consumption, which has been deducted in the ecosystem NPP calculation, and only soil heterotrophic respiration is discussed in this study. Soil heterotrophic respiration rates were mainly influenced and controlled by soil temperature and water content factors, in the synergistic effect of the two factors, soil temperature plays a leading role and soil water content plays an important role. In the non-crop growing season, soil temperature, $R_h$ and C expenditure were lower; in the crop growing season, soil temperature, $R_h$ and C expenditure were higher. $R_h$ was quadratically related to soil water content, and there was a threshold value of soil water content above which the $R_h$ rate tended to decrease and C expenditure decreased as soil water content increased. In this study, the quadratic curve between the $R_h$ rate and water content was derived and the soil water content thresholds were 24.8%, 26.1%, and 23.8% at 5, 10 and 20 cm depths, respectively, which were lower than the field water holding capacity (30.1%, 30.1%, and 26.1%).

# Discussion

## Carbon revenues

Agroecosystem C income is mainly the process of crop fixation of $CO_2$ by photosynthesis and consumption of $CO_2$ by autotrophic respiration during the crop growing season, resulting in NPP of the ecosystem. 2010 NPP of the crop growing season in the southern Songnen Plain of China was 674.00-832.00 g C m$^{-2}$ (Wang et al., 2016), and in this study, typical maize farmland ecosystem in 2019 crop growing season NPP was 1113.51 g C m$^{-2}$, and was higher than the former and C income increased because: (i) the former did not clearly divide the crop species, while the crop species in this study was the high-yielding crop maize, and (ii) due to the update of crop varieties and improvement of cultivation technology, NPP grew faster in recent years and NPP was higher than the level 9 years ago. In addition, there was also weak C sequestration in agroecosystems during the non-crop growing season due to the presence of sparse plants, mainly in mid-late April and early-mid October, and the

**Table 2.** Correlative coefficient of crop growing season between NPP and meteorological factors in 2019.

| Correlative coefficient | $T_a$ (°C) | $P$ (mm) | $R_n$ (W/m$^2$) | $LE$ (W/m$^2$) | $H_s$ (W/m$^2$) |
|---|---|---|---|---|---|
| *NPP* (g C m$^{-2}$ d$^{-1}$) | 0.66** | 0.12 | 0.08 | 0.47** | -0.47** |

* and ** represent significant and highly significant correlations $p<0.01$ and $p<0.001$, respectively

amount of C sequestered by agroecosystems during the non-crop growing season in 2019 was 26.16 g C m$^{-2}$. Thus, the C revenue of maize agroecosystems in the Songnen Plain of China in 2019 was 1139.67 g C m$^{-2}$.

The C income of farmland ecosystems is influenced by natural factors and agricultural management measures. Among them, natural factors include soil type, solar radiation, precipitation, air temperature, wind speed, saturated water vapor pressure, etc., different natural conditions cause differences in crop planting structure and planting type. Management measures include irrigation, fertilization, and arable farmland area, which directly or indirectly affect the C income of farmland ecosystems. Songnen Plain is an important maize planting region in China, precipitation and heat resources are in the same season. Under the background of climate change, agricultural heat resources in this region have been greatly improved, which is conducive to expanding the planting proportion of high-quality, high-yield, medium and late maturing maize varieties. Through reasonable fertilization management, both maize yield and C income of farmland ecosystem can be increased.

## Carbon expenditure

In $R_h$ for C expenditure in maize agroecosystems, the annual C release through $R_h$ in dry fields of the Sanjiang Plain in NE China was 285.00 g C m$^{-2}$ in 2004 (Hao et al., 2007), and in this study, the annual C release through $R_h$ in typical maize agroecosystems of the Songnen Plain was 456.14 g C m$^{-2}$ in 2019, of which the proportion of autotrophic respiration in soil respiration during the growth season of maize was 54.9%, which was similar to the results of Han et al. (2007) (54.5%). The crop growing season heterotrophic respiration accounted for 66.85% of the annual heterotrophic respiration, and the annual C release from $R_h$ in the Songnen Plain was higher than that in the Sanjiang Plain, which was attributed to the differences in soil texture, soil temperature, soil water content and other conditions between the two regions.

The C expenditure of maize farmland ecosystem is also affected by agricultural management measures such as tillage methods, stalks returning, fertilization (Wang et al., 2022). No tillage, less tillage and other tillage methods can reduce the $R_s$ and reduce $CO_2$ emissions from maize farmland (Fu et al., 2018); the $R_s$ is also increased with the increase of fertilization amount (Mao et al., 2019), stalks are crushed and returned to the farmland, soil C emissions is significantly increased, but SOC pool and crop yield are increased (He et al., 2016). In this experiment, the tillage method is shallow tillage and crushed stalks returning to the farmland, it is beneficial to increasing SOC and increasing crop yield. However, based on the perspective of low-C sustainable agricultural development, the agricultural management practices (no tillage, less tillage, reduced fertilization, and crushed stalks returning to the farmland) can reduce C expenditure of the farmland ecosystem and increase SOC storage.

In addition, GHG emissions from agricultural ecosystems also include $CH_4$, $N_2O$, perfluorocarbons (PFCs), etc. (Montzka et al., 2011). However, due to observation conditions, the contributions of $CH_4$, $N_2O$, PFCs, etc. to C and N expenditures were not analyzed. Further research is needed on the related issues.

## Carbon budget

NEE depends on C budget. Most researchers consider maize agroecosystems as possible C sinks. Continuous observations based on eddy correlation techniques found that maize farmland ecosystems in the north-central region of the USA (Hollinger et al., 2005) were C sinks in 1997, 1999, and 2001, with C budgets of -733.40 g C m$^{-2}$, -880.40 g C m$^{-2}$, and -702.40 g C m$^{-2}$ during the growing season. In Nebraska, USA, the C budget of maize farmland ecosystems under irrigated and non-irrigated conditions during the growing season was about -700.00 g C m$^{-2}$ (Verma et al., 2005). The average C budget of maize farmland ecosystems in Jinzhou, South NE China, in 2005 and 2008-2011 was -529.52 g C m$^{-2}$ (Han et al., 2009; Liang et al., 2012; Ye et al., 2022), showing strong C sinks. In this study, the 2019 growing season C budget of typical maize ecosystems in the Songnen Plain of China was -808.57 g C m$^{-2}$, the non-growing season C budget was 125.04 g C m$^{-2}$, and the 2019 C budget was -683.53 g C m$^{-2}$. However, in current agricultural production, one approach is to remove the aboveground biomass of maize from the farmland as silage feed (Wall et al., 2020), the other one is that maize stalks are crushed by agricultural machines and left in the farmland when maize grains are harvested and removed, and the latter approach is adopted in the Songnen Plain. Therefore, while considering that maize grain yield (-353.44 g C m$^{-2}$) was moved out of the farmland at harvest, the NECB was -330.09 g C m$^{-2}$, then the maize agroecosystem showed a C sink in 2019. However, the research results are lower than those of the United States (Hollinger et al., 2005; Verma et al., 2005) and Jinzhou in South Northeast China (Han et al., 2009; Liang et al., 2012; Ye et al., 2022) in observed maize farmland ecosystem, because the effect of maize grains moved out of farmland after harvest on NECB was not considered.

# Conclusion

Soil respiration rate and composition were influenced and controlled by the synergistic effect of surface soil temperature and water content. Soil temperature played a leading role, while soil water content played an important role, of which the heterotrophic respiration rate was influenced greatest, followed by soil respiration rate and autotrophic respiration rate. Daily variations of the net ecosystem productivity were positively correlated with daily mean air temperature, latent heat flux, and negatively correlated with sensible heat flux. Annual carbon revenue was 1139.67 g C $m^{-2}$, annual carbon expenditure was 456.14 g C $m^{-2}$, and annual carbon budget was -683.53 g C $m^{-2}$ in 2019. While considering that maize grain yield (-353.44 g C $m^{-2}$) was moved out of the field at harvest, the net ecosystem carbon balance was -330.09 g C $m^{-2}$, then was carbon sink in 2019. By fully utilizing climate resources and improving agricultural managements, carbon sinks can be increased in farmland ecosystems.

In this study, the influence of biological factors on soil respiration rate was not considered, and soil respiration assessment has certain limitations. In the future, this aspect research should be developed to adapt the needs of soil carbon budget assessment.

# Authors' contributions

**Conceptualization:** Y. G. Gao, F. Gao
**Data curation:** Y. G. Gao, M. Wang, F. Zhao
**Formal analysis:** Y. G. Gao, F. Gao, H. Y. Zhao
**Funding acquisition:** Y. G. Gao, H. Y. Zhao, M. Wang
**Investigation:** Y. G. Gao, L. Q. Jiang, F. Zhao
**Methodology:** Y. G. Gao, F. Gao
**Project administration:** Y. G. Gao, H. Y. Zhao
**Resources:** Y. G. Gao, F. Gao, F. Zhao
**Software:** Y. G. Gao, M. Wang, L. Q. Jiang
**Supervision:** Y. G. Gao
**Validation:** Y. G. Gao, M. Wang, L. Q. Jiang
**Visualization:** Y. G. Gao, M. Wang
**Writing – original draft:** Y. G. Gao, F. Gao
**Writing – review & editing:** Y. G. Gao, F. Gao

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