Response of Saline-alkali Cropland Soil CO_2 Fluxes to Nitrogen Fertilization, Irrigation and Temperature via DAYCENT Modeling

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Abstract A growing global demand exists to formulate plans to lessen the greenhouse gas emissions produced by agricultural activities. The purpose of this study was to uncovered the changes in soil CO_2 fluxes under varying scenarios including nitrogen fertilization rates, irrigation rates, and air temperatures in the Hetao Irrigation District (HID) over the 38-year period. DAYCENT model was used to predict carbon dioxide (CO_2) fluxes from cultivated soils in the HID, Inner Mongolia from 2023 to 2060 (the year of achieving the "carbon neutrality" goal) in this study. Results showed that mean soil CO_2 fluxes in the sunflower field [1 035.13 g/(m^2.yr)] were significantly lower than those in the maize field [1 405.54 g/(m^2.yr)]. An increase in nitrogen fertilization rate led to a significant escalation in soil CO_2 fluxes. Moreover, elevating irrigation rates for washing salts by irrigation (WSBI) diminished soil CO_2 fluxes in the sunflower field while amplifying them in the maize field. A rise in air temperature resulted in an increase in soil CO_2 fluxes from the maize field, with annual increases observed, but a reduction in soil CO_2 fluxes from the sunflower field. The sunflower fields in the HID have a more substantial advantage than the corn fields in mitigating soil CO_2 emissions.

Key words Soil CO_2 flux; Nitrogen fertilization rate; Sunflower; Washing salts by irrigation; Rising temperature; DAYCENT model; Hetao Irrigation District
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Carbon dioxide (CO_2) is the most significant greenhouse gas affecting global warming[1]. Annually, agricultural soils are estimated to emit 5% -20% of the total CO_2 into the atmosphere[2]. The predominant pathway for soil carbon loss is the release of CO_2 to the atmosphere, which primarily comes from the decomposition of soil organic matter (SOM) and the respiratory activity of rhizosphere soil microorganisms[3]. In response, there is a growing global imperative to identify strategies for mitigating greenhouse gas emissions from agriculture. China has set a visionary national strategic objective of achieving "carbon neutrality" by 2060[4]. Therefore, it is an urgent and formidable challenge to reduce the negative environmental impacts of agriculture while enhancing productivity[5].

Hetao Irrigation District (HID) is in the Western Inner Mongolia, China, and borders the northern bank of the Yellow River. Agriculture in the HID is acutely reliant on irrigation, encompassing approximately 680 000 hm^2 of cultivated land by irrigation. The soil was characterized by a low mean surface SOM content (approximately 11.7 g/kg) and a high pH value consistently above 8[6]. Nitrate nitrogen (NO_3^--N) is the main form of soil nitrogen nutrients in the HID croplands[7]. The long-term extensive use of Yellow River water for large-scale flood irrigation has resulted in a shallow groundwater table, with an average annual depth ranging from 1.56 to 2.38 m[8-9]. This, coupled with a significant groundwater evaporation rate reaching up to approximately 2 200 mm per year, leads to seasonal secondary salinization of the cultivated soil layer[6], thereby resulting in a very low crop germination rate. To maintain high germination rates, the farmers in the HID must conduct a type of irrigation named wash salinity by irrigation (WSBI) before sowing annually. The WSBI employed uses basin irrigation method to facilitate the leaching of salts in topsoil into deeper soil, because the basin irrigation water has a vertical movement direction of "infiltration downward and evaporation upward" in the HID. However, this practice leads to the nitrogen leaching with the irrigation water. It has been reported that the nitrogen leaching resulting from the autumn irrigation (one of the WSBI; another is spring irrigation) in the HID corresponded to approximately 20.3% of the total nitrogen fertilizer applied for that year[10]. Therefore, the farmers must prompt an increase in nitrogen inputs to compensate for the lost nitrogen nutrients due to nitrogen leaching. Yet, such excessive nitrogen fertilizer applied cannot facilitate a gradual release, thereby resulting in higher emissions of CO_2 and nitrous oxide from the soil[11-13]. Historically, the water and salt transport, irrigation and washing salts, and nitrogen leaching control in the HID has been mainly investigated. However, the specific greenhouse emission factors tailored to the unique soil, climate, feralization strategy, irrigation method and crop varieties in HID remain largely unknown, especially the CO_2 fluxes from the soil of croplands in the HID.

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Therefore, the objectives of this study were to predict CO_2 fluxes from agricultural soils in the HID using the DAYCENT model[14], reveal the trends of soil CO_2 fluxes in the HID from 2023 through 2060 (the targeted year for achieving "carbon neutrality" in China) under scenarios of nitrogen fertilization rate, irrigation rate, and air temperature, and evaluate the impacts of the scenarios on soil CO_2 fluxes. The insights gained from this study can assist the development of agricultural strategies aimed at mitigating CO_2 emissions from similar HID soils in the world.

Materials and Methods

Experimental site

This study site is located at the Western Inner Mongolia, China, and borders the northern bank of the Yellow River. It has cold winters with litter snow and hot dry summers. The means of daily maximum and minimum temperature were 15.05 and 1.99 ℃, respectively, and the mean annual precipitation is 185.39 mm. The soil classification is the irrigated warped soil (Chinese Soil Taxonomy, the third edition, 2001), with a texture of silt loam. The proportion of sand, silt, clay particles in the soil at a depth of 0 – 40 cm was 31.33%, 52.67%, and 16.00%, respectively. The means of soil organic matter (SOM), pH, exchange sodium percentage, total salt content, TN content, and NO_3^- content after harvest were 8.58 g/kg, 8.23, 21.33%, 1.22 g/kg, 0.58 g/kg, and 4.32 mg/kg, respectively.

Building DAYCENT models

The DAYCENT model[14] (Stand-alone Version 08/17/2014) was used to predict the CO_2 fluxes from cultivated soils in the HID. The model, an enhancement of the CENTURY ecosystem model[14], can provide daily outputs for various parameters. It thoroughly examines ecosystems by simulating key ecological processes and their dynamics, which include SOM, plant productivity, nutrient cycling, CO_2 respiration and flux, soil moisture, and soil temperature fluctuations[15]. The model input data include the daily precipitation, maximum and minimum temperatures, soil texture, pH value, field water-holding capacity, wilting point, historical data on land-use, and details of field and crop management[14]. DAYCENT models can consider various environmental factors that affect soil CO_2 fluxes, such as temperature, moisture, and nutrient availability. It can be used for long-term simulations, which is useful for understanding the temporal dynamics of CO_2 fluxes and explore future climate scenarios. In saline-alkali croplands, it can potentially respond to the unique soil conditions and salinity levels. The accuracy of the model depends on the quality and accuracy of input parameters.

In this study, two distinct DAYCENT models were built to simulate soil CO_2 fluxes from cultivated lands: Model 1 (M1) designed for the sunflower field and Model 2 (M2) for the corn field. The input data for the two models were drawn from the Master thesis of Min Hu, focusing on sunflower cultivation[16], and the Doctoral dissertation of Yuexian Zhang, centering on corn cultivation[17], respectively. However, the simulation and predictive performance of the models depend on the accuracy with which it can be calibrated and validated using the local measured data[18-19].

CPTE (Combined Parameter Estimation and Trial-Error) method[20-21] was used for the calibration of the DAYCENT models. This method hybridizes the strengths of the PEST model[22], a computer-based reverse modeling strategy that compares observed with simulated data and iteratively refines the sensitive parameters of the DAYCENT model to meet calibration objectives, with the traditional trial-error approach. While the PEST model streamlines the calibration process through automated computer operations, it may overlook the nuanced conditions of the DAYCENT model. Conversely, the trial-error method, a manual technique, allows for direct adjustment of parameters in the DAYCENT model and comparison with observed data, but it is less efficient and may not achieve optimal parameter adjustments. The CPTE method effectively bridges these gaps by integrating both approaches, resulting in superior model calibration. Reference to our previously published paper enables a comprehensive understanding[20].

The calibration and validation of the DAYCENT model required measured data, which were sourced from the two papers[16-17] mentioned earlier for building the M1 and M2. During the data collection process, tabular or numerical information or values such as CO_2 fluxes and climate data in the papers were directly copied into Excel spreadsheets, while the values presented in figures were retrieved using the WebPlotDigitizer 4.5 software. Moreover, the model should be validated using crop yield data, as highlighted in the model manual: yield data is necessary for validating the model's accuracy. The M1 was built for the sunflower field with the measured CO_2 fluxes and yields of three years. The first two-year data were used for the M1 calibration, while the third-year data served as the M1 validation. The M2, designed for corn fields, possessed the measured CO_2 fluxes and yields of two years. The first-year data were used for the M2 calibration, and the second-year data were used for the M2 validation purposes.

To evaluate the performance of the calibrated and validated models for the HID, a comparative analysis was essential between the model-simulated soil CO_2 fluxes and the measured fluxes. Four evaluation criteria[23-24] for the comparative analysis were: the determination coefficient (R^2), the percentage bias (PBIAS)[25], the model efficiency coefficient (ME)[26], and the root mean squared error to standard deviation ratio (RSR)[27]. The acceptable thresholds for these criteria are as follows: R^2 should range from 0.5 to 1, PBIAS should be within the bounds of -25% to 25%, ME should fall between 0.5 and 1, and RSR should not exceed 0.7[24]. Compliance with these criteria indicates that the models are acceptable for simulating or predicting CO_2 fluxes from the soil on the sunflower and corn lands in the HID.

Predicting soil CO_2 fluxes

First, the above calibrated and validated models were used to predict soil CO_2 fluxes and yields for sunflower and corn fields over 38 years from 2023 to 2060, which aligns with the period of achieving "carbon neutrality" goal in China. Second, they were used to examine the alterations in soil CO_2 fluxes and yields resulting from different scenarios of nitrogen fertilization rates (N rate; conventionally applied and reduced by 20%, 30%, 40%, and 50%) over the next 38 years. Third, they were used to investigate the effects on soil CO_2 fluxes and yields when conventional irrigation rate (I rate) for the WSBI are reduced by 20%, 30%, 40%, and 50%. Fourth, they were used to track the development of soil CO_2 fluxes and yields as the scenarios of air temperatures (AT) rise incrementally by 0.5, 1, 1.5, 2, and 2.5 ℃ based on the daily air temperature in 1983–2020 (T0, baseline) (the reasons: the T0 dataset are relatively stable; the leap years in both periods align perfectly).

Estimating soil CO_2 emission quantities

Based on the predicted soil CO_2 fluxes [g/(m^2 · d)] and the total cultivated area of sunflower and corn fields in the HID (for comparability, this study assumed that the cultivated areas for both crops are 0.24 million hm^2), the total annual soil CO_2 emissions from the cultivated lands could be calculated. The formula is as follows:

Soil CO_2 emission quantity [kg/(hm^2 · yr)] = Annual soil CO_2 flux [g/(m^2 · yr)] /1 000 × 10 000 × Crop area (hm^2).

In the formula, 1 000 represents the conversion factor from grams (g) to kilograms (kg), and 10 000 represents the conversion factor from square meters (m^2) to hectares (hm^2).

Statistical analysis

NPAR1WAY method in SAS 9.4 statistical software (SAS, 2013) was used for non-parametric tests to compare the significant differences in predicted soil CO_2 fluxes across various scenarios, including different crops, nitrogen fertilization rates, irrigation rates for the WSBI, and air temperatures. Additionally, the "mblm" package in R statistical software[28], the Mann-Kendall test[29–31], and the Sen estimator[32] were used to determine whether there was a significant trend in soil CO_2 fluxes over time. The significance for all tests was $\alpha = 0.05$.

Results and Analysis

Calibration and validation of the DAYCENT models

The data of calibration and validation for the M1 and M2 are presented in Table 1, Table 2, and Fig. 1. Comparing the soil CO_2 fluxes simulated by the calibrated M1 with the measured CO_2 flux values in 2017 and 2018, an R^2 of 0.49, PBIAS of −0.51%, ME of 0.31, and RSR of 0.81 were obtained. These values were 3.5, 0.01, 0.08, and 0.38 times of those values obtained from the default model (*i.e.*, none-calibration model), respectively, indicating a significant improvement with the calibrated M1. When validating the M1 using the measured CO_2 fluxes in 2019, the four evaluation criteria (R^2, PBIAS, ME, and RSR) were 0.59, −2.98%, 0.53, and 0.65, respectively. When considering the combined data from 2017, 2018, and 2019, the criteria were 0.51, −1.53%, 0.50, and 0.69, respectively. For the sunflower yields from these three years, the criteria were 0.95, −8.25%, 0.60, and 0.52, respectively (Table 1). The measured soil CO_2 fluxes from sunflower field closely matched the simulated CO_2 using the calibrated M1 in both temporal trend and magnitude over these three years (Fig. 1a). These findings suggested that the calibrated M1 is acceptable and performs well in predicting soil CO_2 fluxes and yields in the sunflower field.

Table 1 Evaluation criteria values of calibrated and validated M1 using the measured soil CO_2 fluxes and yield from sunflower field in the Hetao Irrigation District

Evaluation criteria†	M1 calibration				M1 validation			
	CO_2 fluxes (2017–18)		CO_2 fluxes (2019)		CO_2 fluxes (2017–19)		Yield (2017–19)	
	Default	Calibrated	Default	Calibrated	Default	Calibrated	Default	Calibrated
R^2	0.14	0.49	0.15	0.59	0.10	0.51	0.11	0.95
PBIAS (%)	−50.8	−0.51	−65.51	−2.98	−56.85	−1.53	−46.00	−8.25
ME	−3.83	0.31	−1.35	0.53	−1.80	0.50	−3.57	0.60
RSR	2.13	0.81	1.45	0.65	1.64	0.69	1.75	0.52

Table 2 Evaluation criteria values of calibrated and validated M2 using the measured soil CO_2 fluxes and yield from corn field in the Hetao Irrigation District

Evaluation criteria†	M2 calibration				M2 validation			
	CO_2 flues (2019)		CO_2 flues (2020)		CO_2 flues (2019–20)		Yield (2019–20)	
	Default	Calibrated	Default	Calibrated	Default	Calibrated	Default	Calibrated
R^2	0.22	0.90	0.45	0.97	0.41	0.95	–	–
PBIAS (%)	−57.20	8.03	−69.90	0.50	−64.50	3.71	−59.50	−4.07
ME	−0.43	0.89	−2.57	0.97	−0.81	0.94	−259.40	−1.45
RSR	1.15	0.32	1.79	0.16	1.32	0.23	11.41	1.11

† R^2, determination coefficient, the range values of acceptable, good, and very good performance of model are [0.5, 0.65), [0.65, 0.75), and [0.75, 1), respectively. PBIAS, percentage deviation, [25%, 15%) for acceptable; [15%, 10%) for good; [10%, 0) for very good. ME, model performance coefficient, [0.5, 0.65) for acceptable; [0.65, 0.75) for good; [0.75, 1) for very good. RSR, ratio of RMSE to the standard deviation of the measured data, (0.60, 0.70] for acceptable, (0.50, 0.60] for good, and (0.00, 0.50] for very good, respectively.

The M2 was calibrated by using the measured CO_2 fluxes from 2019. From the R^2 of 0.90, PBIAS of 8.03%, ME of 0.89, and RSR of 0.32, which were 4.1, 0.14, 2.1, and 0.28 times of those values from the default model, respectively, it could be seen that the calibrated M2 outperformed the default model. When validated M2 using the measured CO_2 fluxes in 2020, the four evaluation criteria (R^2, PBIAS, ME, and RSR) were 0.97, 0.50%, 0.97, and 0.16, respectively. When considering the combined data from 2019 and 2020, the criteria were 0.95, 3.71%, 0.94, and 0.23, respectively. For the corn yields in these two years, the PBIAS was −4.07% (Table 2). Additionally, the measured CO_2 fluxes in corn field were in close agreement with the simulated values using the calibrated M2 in terms of both temporal trend and magnitude over 2019 and 2020 (Fig. 1b). These findings indicate that the calibrated M2 performs exceptionally well.

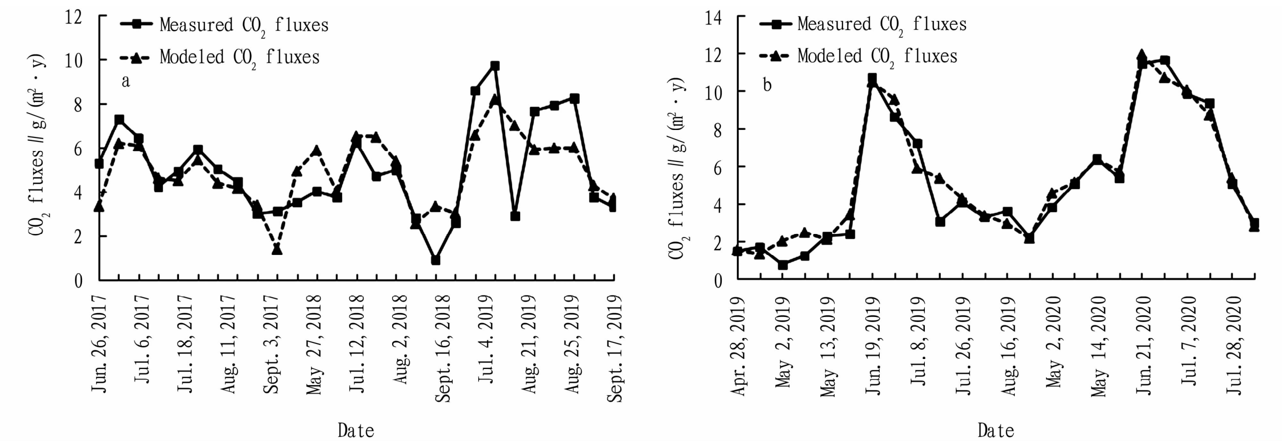


Fig. 1 Trends and magnitudes of measured and simulated soil CO_2 fluxes in the sunflower and corn fields with M1 and M2

Predicted soil CO_2 fluxes

Under the conventional N and I rates, the daily and annual soil CO_2 fluxes from sunflower fields were predicted to be 2.833 9 g/(m^2 · d) and 1 035.13 g/(m^2 · yr), respectively, which were significantly lower than those [3.848 0 g/(m^2 · d) and 1 405.54 g/(m^2 · yr)] from corn fields. The soil CO_2 flux in sunflower fields was 26.35% lower than that in corn fields. Considering an annual planted area of 0.24 million hm^2 in the HID, the total annual soil CO_2 emissions from sunflower and corn fields were 2.484 3 and 3.373 3 million t, respectively, with sunflower fields contributing to a 26.35% reduction in soil CO_2 emissions compared to corn field.

Under the N rate, in sunflower fields, a clear pattern of decreasing soil CO_2 flux was observed with the reduction in N rates. At the conventional N rate (100% N rate), the mean daily soil CO_2 flux was predicted at 2.833 9 g/(m^2 · d), which significantly exceeded the flux of 2.704 1 g/(m^2 · d) predicted at 80% N rate. The 80% N rate, in turn, was significantly higher than the 2.613 9 g/(m^2 · d) predicted at 70% N rate, which was significantly higher than the 2.473 1 g/(m^2 · d) at 60% N rate, and finally, the 60% N rate was significantly higher than the 2.137 7 g/(m^2 · d) at 50% N rate. Similarly, when examining the mean annual soil CO_2 flux under 100% N rate, the flux of 1 035.13 g/(m^2 · yr) was significantly greater than the 987.70 g/(m^2 · yr) at 80% N, which exceeded the 954.77 g/(m^2 · yr) at 70% N rate, the 903.34 g/(m^2 · yr) at 60% N rate, and the 780.82 g/(m^2 · yr) at 50% N rate. The same trends were replicated in corn fields, as detailed in Table 3.

Under the I rate, the mean daily soil CO_2 flux in sunflower fields under the conventional irrigation rate [100% I rate; 2.833 9 g/(m^2 · d)] was significantly reduced compared to when irrigated at 80% I rate [2.834 5 g/(m^2 · d)]. This trend persisted as 80% I rate was lower than at 60% I rate, with a flux of 2.835 2 g/(m^2 · d), and 70% I rate was lower than at 50% I rate, reaching 2.835 3 g/(m^2 · d). Conversely, as irrigation rate decreased, the soil CO_2 flux in corn fields increased. In corn fields, the mean daily soil CO_2 flux under conventional irrigation rate (100% I rate) was substantially higher than at 80% I rate, amounting to 3.841 7 g/(m^2 · d). The 80% I level was also higher than at 60% I rate, with a flux of 3.829 7 g/(m^2 · d), and 70% I rate was higher than at 50% I rate, reaching 3.837 0 g/(m^2 · d). Here, a decrease in the I rate corresponded with a reduction in the soil CO_2 flux. When considering the mean annual soil CO_2 flux, no significant difference was observed under different irrigation rates in sunflower and corn fields (Table 3).

Under different air temperature scenarios, the soil CO_2 fluxes in sunflower fields decreased as future temperature increased. The mean daily soil CO_2 flux at T0 [2.833 9 g/(m^2 · d)] was significantly higher than that at T0 + 0.5 ℃ [2.759 7 g/(m^2 · d)]; T0 + 0.5 ℃ was also significantly higher than T + 1 ℃ [2.6816 g/(m^2 · d)]; T0 + 1 ℃ was significantly higher than T0 + 1.5 ℃ [2.579 5 g/(m^2 · d)]; T0 + 1.5 ℃ was significantly higher than T0 + 2 ℃ [2.467 1 g/(m^2 · d)]; and T0 + 2 ℃ was significantly higher than T0 + 2.5 ℃ [2.367 1 g/(m^2 · d)]. The means of annual soil CO_2 flux in sunflower field showed similar trended to the daily fluxes (except for the insignificant difference between T0 and T0 + 0.5 ℃). However, in corn fields, the soil CO_2 fluxes increased as future temperatures increased. The mean daily soil

CO_2 flux at T0 [3.848 0 g/(m^2 · d)] was significantly lower than that at T0 + 0.5 ℃ [3.889 2 g/(m^2 · d)]; T0 + 0.5 ℃ was significantly lower than T0 + 1.5 ℃ [3.977 3 g/(m^2 · d)]; T0 + 1 ℃ was significantly lower than T + 2 ℃ [4.013 0 g/(m^2 · d)] and T0 + 2.5 ℃ [4.042 7 g/(m^2 · d)]; and T0 + 1.5 ℃ was significantly lower than T0 + 2.5 ℃. The means of annual soil CO_2 fluxes in corn fields showed a similar trend to the daily fluxes, but only the T0 ℃ was significantly lower than T0 + 2.5 ℃ (Table 3).

Table 3 Means of soil CO_2 fluxes and yields under different N rates, I rates, and AT in sunflower and corn fields

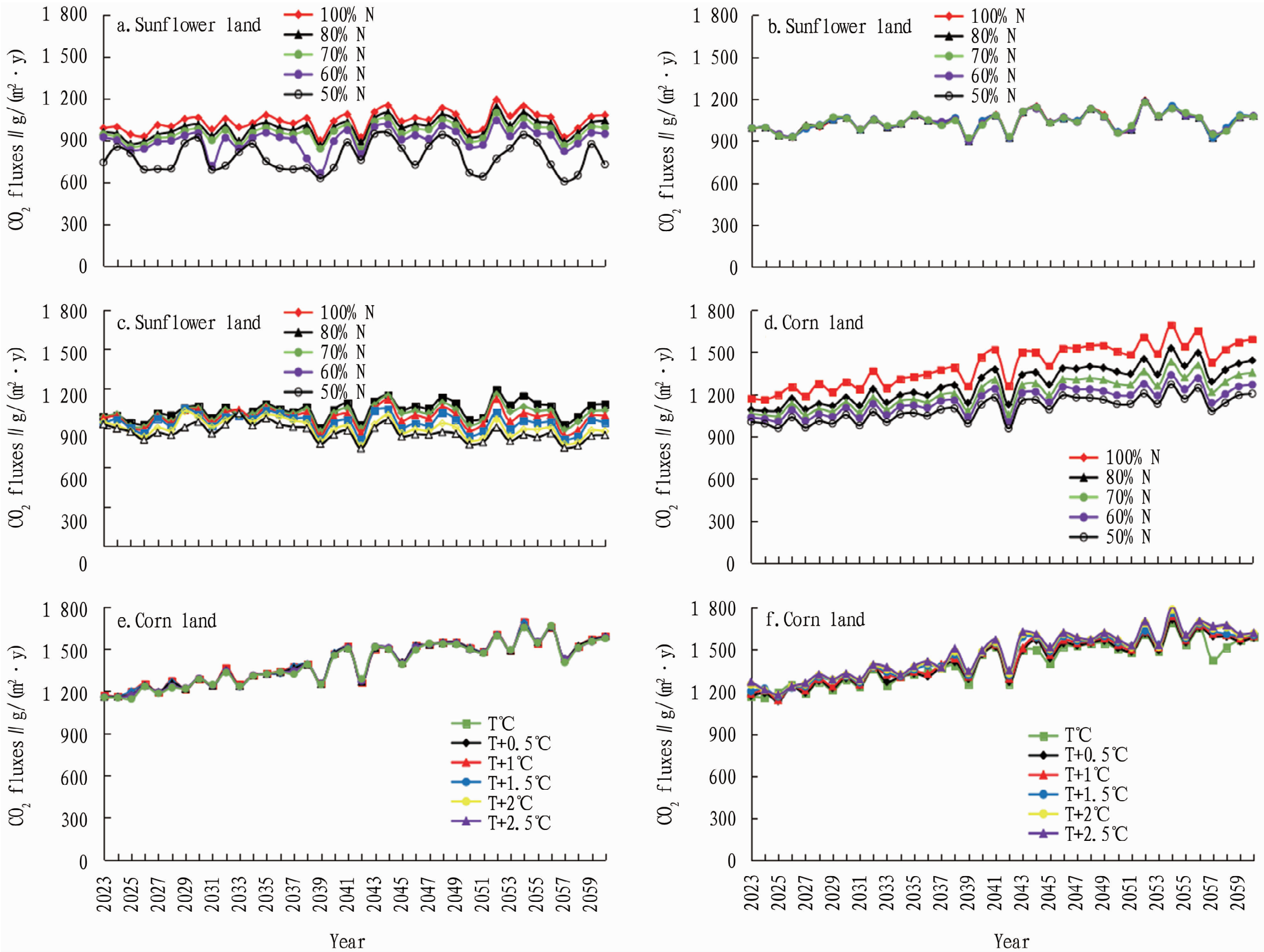
Treatments	Soi CO_2 fluxes				Yields	
	g/(m^2 · d)		g/(m^2 · yr)		kg/hm^2	
	Sunflower	Corn	Sunflower	Corn	Sunflower	Corn
N fertilization rate (N rate)						
100% N rate	2.833 9 a	3.848 0 a	1 035.13 a	1 405.54 a	4 296.74 a	7 797.58 a
80% N rate	2.704 1 b	3.488 1 b	987.70 b	1 274.09 b	4 066.17 b	7 740.42 b
70% N rate	2.613 9 c	3.312 1 c	954.77 c	1 209.80 c	3 911.88 c	7 682.20 c
60% N rate	2.473 1 d	3.153 2 d	903.34 d	1 151.76 d	3 640.89 d	7 590.90 d
50% N rate	2.137 7 e	3.000 8 e	780.82 e	1 096.07 e	2 868.32 e	7 443.15 e
Irrigation rate (I rate)						
100% I rate	2.833 9 e	3.848 0 a	1 035.13 a	1 405.54 a	4 296.74 a	7 797.58 a
80% I rate	2.834 5 cd	3.841 7 b	1 035.33 a	1 403.24 a	4 290.09 a	7 797.32 a
70% I rate	2.835 3 bc	3.837 0 bc	1 035.63 a	1 401.52 a	4 291.62 a	7 796.54 a
60% I rate	2.835 2 ab	3.829 7 cd	1 035.61 a	1 398.85 a	4 292.03 a	7 796.11 a
50% I rate	2.836 3 a	3.816 8 d	1 035.98 a	1 394.14 a	4 305.98 a	7 795.83 a
Air temperature (AT)						
T0 ℃	2.833 9 a	3.848 0 e	1 035.13 a	1 405.54 b	4 296.74 a	7 797.58 a
T0 +0.5 ℃	2.759 7 b	3.889 2 de	1 008.01 ab	1 420.59 ab	4 209.66 ab	7 788.50 ab
T0 +1 ℃	2.681 6 c	3.934 3 cd	979.49 c	1 437.07 ab	4 123.55 bc	7 772.53 b
T0 +1.5 ℃	2.579 5 d	3.977 3 bc	942.19 d	1 452.77 ab	4 040.79 cd	7 747.93 cd
T0 +2 ℃	2.467 1 e	4.013 0 ab	901.15 e	1 465.81 ab	3 956.16 de	7 716.19 de
T0 +2.5 ℃	2.367 1 f	4.042 7 a	864.62 f	1 476.66 a	3 829.64 ef	7 676.29 e

In the next 38 years (from 2023 to 2060), the soil CO_2 fluxes in corn fields under different N rates, I rates, and ATs showed significant increasing trends ($P \leqslant 1.19E\text{-}07$, slope $\geqslant 7.182$). However, the soil CO_2 fluxes in sunflower fields exhibited different trends. Under different N and I rates, the soil CO_2 fluxes in sunflower fields showed significant increasing trends over the observed years ($P < 0.05$, $1.209 \leqslant$ slope $\leqslant 2.723$) except for the 50% N rate. At the T0 and T0 + 0.5 ℃, the soil CO_2 fluxes in sunflower fields showed a significant increasing trend ($P = 0.013$) and an increasing trend ($P = 0.145$) over the next 38 years, respectively. However, at the T0 + 1 ℃, T0 + 1.5 ℃, T0 + 2 ℃, and T0 + 2.5 ℃, the soil CO_2 fluxes in the sunflower field decreased significantly ($P = 0.94$), decreased ($P = 0.21$), decreased significantly ($P = 0.008$), and showed a significant decreasing trend ($P = 0.002$) over the observed years, respectively. In the increasing trends, the "slope" in sunflower fields was significantly lower than that in corn fields. Meanwhile, the Mann-Kendall test P value in the sunflower field was higher than that in corn fields (Fig. 2).

Discussion

Impacts of the nitrogen fertilization rate, irrigation rate, and air temperature on soil CO_2 fluxes

The results of this study showed that under conventional nitrogen fertilization rate, the mean soil CO_2 flux in sunflower fields was significantly lower (by 26.35%) than that in corn fields (Table 2). It was because that (1) the N application rate in sunflower fields was less than that applied in corn fields[33]. (2) During the crop growth period, the irrigation quota for sunflower fields was much lower compared to corn fields[33]. (3) There was a difference in soil quality between sunflower and corn fields. In the HID, the sunflower land is typically "poor land," which has a higher soil pH, exchange sodium percentage, and total salt content, but a lower SOM compared to corn land[33], resulting in a lower rate of SOM decomposition, thereby leading to less CO_2 emissions from soil in sunflower fields than for corn fields. Furthermore, the soil CO_2 fluxes increased accordingly with the increase in N rate for the sunflower land in this study (Table 2). However, studies have shown that the impacts of nitrogen fertilizer on soil CO_2 emission could be positive, negative, or have no effect[34-35]. The positive effect observed in this study was mainly attributed to the enhanced crop yield that resulted from the increased N rate (Table 2). It indicated that with the increased nitrogen fertilization rate, the pH of the soil decreased and became more favorable to microbial community metabolism as well as substrate utilization efficiency. Different crop root systems may be another reason leading to different CO_2 emissions. Sunflower with a taproot system lead less root respiration in the topsoil than corn with a fibrous root system which has a larger surface area in contact with soil and resulting higher root respiration. Sunflower roots can create larger pores and channels which promotes better aeration and water infiltration, reduced soil moisture levels in the root zone limite the activity of microorganisms, and potentially reducing the CO_2 emissions. Therefore, growing sunflowers have a more positive impact on soil carbon sequestration and lower CO_2 emissions compared to growing corn in the HID. Since sunflowers have a better performance in terms of mitigating CO_2 emissions, it could be more incentives and attractive for producers to grow sunflowers if governments can offer subsidies for sunflower cultivation. This would not only benefit the farmers financially but also drive the adoption of more sustainable crop management practices on a larger scale.



The slopes in the figure were estimated using the Sen estimator method, with positive slopes indicating an upward trend and negative slopes indicating a downward trend; the *P* value is the probability value obtained by using the Mann-Kendall test to examine whether the soil CO_2 flux shows a significant upward or downward trend over time. If $P<0.05$, the trend is considered significant upward (positive slope) or significant downward (negative slope).

Fig. 2 Trends in annual soil CO_2 fluxes over time (2023 – 2060) under different nitrogen fertilization rates (N), irrigation rates for the WSBI (I), and air temperatures (T) in sunflower and corn fields

The I rate for the WSBI negatively significantly impacted sunflower soil CO_2 fluxes and positively impacted corn soil CO_2 fluxes (Table 3). The possible reason for the inconsistent outcomes might be that the sunflower fields did not undergo irrigation after sowing, whereas corn field still underwent drip irrigation after sowing. The high I rate for the WSBI not only hindered the release of CO_2 from the soil pores into the atmosphere but also created an environment of hypoxia for the crops, consequently leading to a reduction in the overall CO_2 emissions from the soil[36 – 37]. In sunflower fields, after the WSBI (conducted 22 d before sowing), no irrigation was conducted, most likely resulting in an increasing trend in soil CO_2 fluxes with a reduction in the I rate for the WSBI. However, in corn fields, the WSBI was conducted 6 months before sowing (*i. e.*, the autumn irrigation, one of the WSBI), the impact of I rate on soil CO_2 fluxes was not only through the amount of water, but by reducing the topsoil salts to facilitate corn growth, thus influencing CO_2. In fact, the higher I rate for the WSBI in the corn, the lower topsoil salts, and the better soil moisture for next year's corn fields, thereby resulting in higher soil CO_2 fluxes.

Soil CO_2 emissions play a crucial role in global carbon cycle, an elevation in CO_2 emissions has the potential to intensity the greenhouse effect, predicting soil CO_2 emissions enables a more comprehensive understanding how the carbon cycle will react to impending environmental alterations, consequently, preemptive actions can be taken to mitigate the situation prior to its deterioration. Projections can also guide the implementation of sustainable land management strategies. As the temperatures rose, the soil

CO_2 fluxes in sunflower fields decreased, whereas the soil CO_2 fluxes in corn field showed an increasing trend (Table 3). Studies have confirmed that increased temperature can accelerate the decomposition of SOM, thereby leading to an increase in soil CO_2 fluxes[38]. In this study, the possible reason for the reduction in soil CO_2 fluxes in sunflower field was that sunflowers in the HID did not undergo flood irrigation after sowing due to the shallow groundwater table (with a mean annual depth of 1.56 – 2.38 m)[8–9]. Sunflower roots are well-developed, with the main root reaching a depth of up to 2.18 m[39]. Therefore, there is no need for flood irrigation after sowing. When temperature rises, evaporation intensifies, leading to a reduction in moisture content in the topsoil, which in turn reduces soil microbial activity, thereby decreasing CO_2 emissions.

From 2023 to 2060 (*i. e.*, the year when the "carbon neutrality" goal is achieved), the soil CO_2 flux in corn fields showed a more significant increasing trend compared to sunflower field. Furthermore, even after the temperature rose to 2 ℃, the soil CO_2 fluxes in sunflower fields turned into a significant decreasing trend (Fig. 2). It was possibly because that, as previously mentioned, the sunflower fields did not undergo flood irrigation after sowing, and the topsoil became drier as the temperature rose, leading to decreased microbial activity and organic matter decomposition rate. All these factors made a significant decrease in the soil CO_2 flux in sunflower fields.

Acceptability of the DAYCENT model calibration and validation

The measured data used for model calibration and validation in this study were derived from previously published papers. For the M1 calibration (using measured soil CO_2 flux data of sunflower fields from 2017 and 2018), although only PBIAS was within an acceptable range among the four criteria (R^2, PBIAS, ME, and RSR), the R^2 value (0.49) was close to 0.5. However, the four criteria for validation using the measured CO_2 data from 2019 and the measured CO_2 and yield data (2017 – 2019) were all within an acceptable range (Table 1), and the simulated CO_2 flux data from M1 had a good fit with the measured data (Fig. 1). Therefore, the M1 for sunflower fields is acceptable.

For the M2, due to only two-year soil CO_2 flux data available, the calibration was conducted using data from 2019, while data from 2020 were used for the validation. Moreover, yield data were limited to two years. Consequently, only the PBIAS value was considered valid among the four criteria. Nevertheless, this study conducted a re-validation using the two-year soil CO_2 flux data and found that the calibrated M2 met the excellent level for all four criteria (Table 2). Additionally, the simulated CO_2 fluxes from M2 had a high degree of fit with the measured values (Fig. 1). When combined with the excellent PBIAS level from yield validation, the M2 for corn fields is also considered acceptable.

Conclusions

Based on the above results and discussions, the following conclusions could be drawn. (1) The total soil CO_2 emissions from sunflower fields were significantly lower than those from corn fields. (2) Increased nitrogen fertilization rate can lead to an increase in soil CO_2 fluxes. High irrigation rates for the WSBI reduced soil CO_2 fluxes in sunflower fields while increasing them in corn fields. (3) Future temperature increases cannot significantly affect soil CO_2 fluxes in sunflower fields but could significantly enhance them in corn fields. (4) Soil CO_2 fluxes in sunflower fields changed little over the years, whereas those in corn fields increased significantly each year. (5) When it comes to mitigating CO_2 emissions from agricultural soil, cultivating sunflowers in the HID offers superior benefits compared to corn, which could be used as a reference for government policy maker to promote sunflower cultivation in HID areas. Overall, sunflowers perform better than corn in saline-alkali crop lands in cold-arid region of Inner Mongolia at different nitrogen fertilization, irrigation management and environmental temperature scenarios in terms of reducing CO_2 fluxes, while developing multi-scale modeling frameworks by coupling DAYCENT model with other models at different spatial and temporal scales is needed to enhance DAYCENT model representation.

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(Continued from page 55)
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